EuroDisplay 2017

31 October – 2 November 2017
Meliá Berlin, Berlin, Germany

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- Displays
- Flexible electronics
- Memory
- NEMS/MEMS
- Neuromorphic systems
- Optoelectronics
- Organic electronics
- Power electronics
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- Spintronics
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Welcome to the EuroDisplay-2017

I am happy to welcome you in Berlin for the 33d international Conference EuroDisplay 2017 co-organized by the Society for Information Display and Institute of Physics.

The program of this three-days event is in the trend set by previous EuroDisplay Conferences (former International Display Research Conferences IDRC) in Strasbourg (1993), Birmingham (1996), Berlin (1999), Nice (2002), Edinburgh (2005), Moscow (2007), Rome (2009), Arcashon (2011), London (2013) and Ghent (2015). It has been 18 years since prof. E.Lueder was entrusted by SID to organize the EuroDisplay-1999 Conference and Exhibition in Berlin. I wish you a warm welcome to Berlin again and will trust you will find time to enjoy its many delights.

EuroDisplay 2017 will present the progress made in display research in a broad range of fields ranging from basic principles, display devices and display research to manufacturing and image quality will be presented at 8 sessions in two parallel tracks. Looking back over the past years, nobody could forecast the dramatic changes we have seen in the availability of very advanced flat-panel displays and other modern devices for broad areas of applications. I think that the worldwide display community made a tremendous job during last years and can be proud of what it has achieved.

This Proceedings includes 3 keynote addresses, 14 invited papers, more than 70 oral and 40 poster presentations from all over the world. The Conference program is structured around a number of topics, Liquid Crystal and OLED technologies are especially prominent. All camera-ready papers published in this Proceedings have been mainly preserved in their original form.

I especially acknowledge the very efficient contribution of Program Committee members who carefully reviewed all proposals in a short time. Thanks to all of them the number and quality of papers is unexpectedly high. We sincerely thank all the authors for their contribution.

The Sponsors who kindly provided the financial support for the Conference are deeply acknowledged.

I and other Organizing Committee’s members trust you will enjoy your stay in Berlin and of course find the Conference of enormous benefit.

I welcome all of you to EuroDisplay 2017, and wish you a professionally rewarding and socially enjoyable time in a great setting.

Many thanks for attending and have a great time!

Prof. Aliaksandr Smirnov,
EuroDisplay-2017 General Chair
Tuesday 31 October

07:45  **Registration**  
*Meeting Foyer, Melia Hotel*

08:45  **Welcome address**  
Y-S Kim (President, SID)  
Paul Lacey (VP Europe, SID)  
Poopathy Kathirgamanathan (Immediate Past-VP Europe, SID)  
Alex Smirnov (Conference Chair)

Keynote session  
Barcelona I  
Chair: Paul Lacey

09:00  **(Keynote) Merging the real & the virtual worlds**  
Achin Bhowmik, Intel Corporation, USA

09:35  **(Keynote) Overview on microdisplay technologies and applications, current status and perspectives**  
Gunther Haas, MICROOLED, France

10:10  **(Keynote) Low-cost scalable OTFT backplanes for OLCD applications**  
Josephine Socratous, FlexEnable, UK

10:45  Refreshments and exhibition - *Meeting Foyer and Barcelona III*

### Session 1 - Display materials and components
Barcelona I  
Chair: Ian Sage

11:15  **(Invited) Photoalignment by molecular rotation and applications to fabrication of optical elements**  
Hoi S Kwok, HKUST, China

11:45  **Electrically switchable and broadband scattering-type linear polarizers using polymer network twisted nematic liquid crystals**  
Ko-Ting Cheng, National Central University, Taiwan

12:05  **Grating aligned ferroelectric liquid crystals and their use in fast switching displays**  
Peter Wyatt, University of Leeds, UK

### Session 2 - OLED organic electronics
Barcelona II  
Chair: Kristiaan Neyts

11:15  **(Invited) OLEDs and QLEDs**  
Poopathy Kathirgamanathan, Brunel University, UK

11:45  Realization of RGB colors from top-emitting white OLED by electron beam patterning  
Elisabeth Bodenstein, Fraunhofer Institute for Organic Electronics, Germany

12:05  Pixel drive circuit design for AM OLED microdisplays  
Hanning Mai, University of Edinburgh, UK
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<th>Time</th>
<th>Session 1 continued - Display materials and components</th>
<th>Session 2 continued - OLED organic electronics</th>
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<tr>
<td>12:25</td>
<td>Liquid crystal phase grating devices for switching between transparent and translucent states&lt;br&gt;Tae-Hoon Yoon, Pusan National University, South Korea</td>
<td>Synthesis and characterization of metal oxide-graphene nanocomposites for QLED applications&lt;br&gt;Basavaraja B M, PES University, India</td>
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<tr>
<td>12:45</td>
<td>Lunch and exhibition - <em>Meeting Foyer and Barcelona III</em></td>
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<td>14:00</td>
<td>(Invited) Anisotropic-based approach for design of new materials, structured surfaces, sensors, photonic devices and displays&lt;br&gt;Vladimir Bezborodov, Belarusian State Technological University, Belarus</td>
<td>(Invited) Footsteps in the OLED material trail: A game changing technology revolutionizing the world of displays and lighting&lt;br&gt;Kris Krishnamutry, USA</td>
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<td>14:30</td>
<td>Simulation of the Uniform Lying Helix structures using the Q-tensor method&lt;br&gt;Sally Day, University College London, UK</td>
<td>Modelling pixel crosstalk in AMOLED displays&lt;br&gt;Lieven Penninck, Fluxim AG, Switzerland</td>
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<td>14:50</td>
<td>Novel helix-free FLCs: Electrooptics and possible applications&lt;br&gt;Igor Kompanets, P. N. Lebedev Physical Institute, Russia</td>
<td>A new dual shift register gate driver for external compensation OLED panel&lt;br&gt;Tae-Gung Kim, LG Display Co., Ltd, South Korea</td>
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<td>15:10</td>
<td>Refreshments and exhibition - <em>Meeting Foyer and Barcelona III</em></td>
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<td>15:50</td>
<td>(Invited) Experimental modeling and theoretical simulation of composite systems with inhomogeneous liquid crystal orientation for display devices with enhanced performances&lt;br&gt;Victor Belyaev, Moscow State Region University, Russia</td>
<td>(Invited) Directly patterned, Ultra-high brightness 2K x 2K full-color OLED microdisplays&lt;br&gt;Evan Donoghue, eMagin Corporation, Hopewell Junction, USA</td>
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<td>16:20</td>
<td>Realization of photoaligned vertical alignment by azobenzene sulfonic photoalignment material and polyimide composite&lt;br&gt;Chenxiang Zhao, HKUS Technology, Hong Kong</td>
<td>High efficiency cool white single stack hybrid OLED with blue thermally activated delayed fluorescent and yellow phosphorescent emitters&lt;br&gt;Gyeong Woo Kim, Kyung Hee University, South Korea</td>
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<td>16:40</td>
<td>Quantum dot materials for improved autostereoscopic color filter displays</td>
<td>MolecuLED®: Organic based down-conversion technology</td>
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17:00 Development of scattering media optics methods to calculate optical properties of polymer dispersed liquid crystal films
Valery Loiko, Institute of Physics of the National Academy of Sciences, Belarus, Institute of Physics of the SB of the RAS, Russia

17:20 Materials with controllable anchoring energy for nematic liquid crystals alignment
Veronica Bezruchenko, Physical Department of Belarusian State University, Belarus

17:40 Poster and exhibition reception - Meeting Foyer and Barcelona III

Wednesday 1 November

08:30 Registration
Meeting Foyer, Melia Hotel

Session 3 - LC beyond Displays
Barcelona I
Chair: Ian Sage

09:00 (Invited) Simple multifocal lens based on liquid crystals
Herbert De Smet, Ghent University and IMEC, Belgium

09:30 An IPS-VA spatial light modulator architecture for foveating application
Clément Abélard, Univ. Grenoble Alpes, France

09:50 Reverse mode switchable window assembled with inhomogeneous alignment surfaces
Cuiling Meng, Hong Kong University of Science and Technology, Hong Kong

10:10 A tuneable and switchable liquid crystal laser protection device
Ethan Jull, University of Leeds, UK

Session 2 - OLED organic electronics continued
Barcelona II
Chair: Kristiaan Neyts

09:00 (Invited) Organic vapor phase deposition (OVPD®) of OLED for organic display and lighting applications
Peter K Baumann, AIXTRON SE, Germany

09:30 Recent progress in highly efficient blue TADF emitter materials for OLED displays
Harald Flügge, cynora GmbH, Germany

09:50 Improved operational stability of inverted organic light-emitting diodes using Sn-doped zinc oxide nanoparticles as an electron injection layer
Tsubasa Sasaki, NHK Science & Technology Research Laboratories, Japan

10:10 Solution processed cavity control layer for high resolution AMOLED applications
Mi Jin Park, Kyung Hee University, Korea
10:30  **Optimization of thermoformed displays for smart contact lenses**  
Andrés Vasquez Quintero, Ghent University and IMEC, Belgium

10:50  **Cholesteric window shutter with wide-band reflection**  
Gyu Jin Choi, Yeungnam University, South Korea

11:10  **Liquid crystal micro-lens array assisted thin film photo-transistors flat panel imager**  
Dr Kun Li, University of Cambridge, UK

11:30  **Liquid crystal on silicon technology for high-power high-resolution laser projection and non-display applications in visible spectral band**  
Grigory Lazarev, Holoeye Photonics AG, Germany

11:50  **Refreshments and exhibition**  
Meeting Foyer and Barcelona III

**Session 5 - 3D Displays and NTE technologies**  
Barcelona I  
Chair: Ian Underwood

12:10  **(Invited) 3D display development at NTU’s advanced displays laboratory**  
Philip Surman, NTU, Singapore

12:40  **Image volume considerations in 3D displays**  
Wang Shizheng, NTU, Singapore

**Session 6 - Quantum dots**  
Barcelona II  
Chair: Poopathy Kathirgamanathan

13:00  **Lunch and exhibition**  
Meeting Foyer and Barcelona III

**Session 5 continued - 3D Displays and NTE technologies**  
Barcelona I  
Chair: Phil Surman

14:15  **Qualified viewing space determination of near-eye and head up displays**  
Richard Austin, Gamma Scientific, USA

14:35  **Dynamic 3D sequence capture and enhancement**  
Ljubomir Jovanov, Ghent University, Belgium

14:45  **Printed top gate metal oxide semiconductor thin film transistors**  
Nesrine Kammoun, University of Stuttgart, Germany

15:15  **(Invited) Barriers for plastic displays and lighting**  
Mikko Soderlund, Beneq, Germany
**EuroDisplay 2017**

14:55 **MicroLED displays: Hype and reality, hopes and challenges**
Pars Mukish, Yole Développement, France

15:05 Formation of polymer structures for mechanical stability in a flexible light shutter
Tae-Hoon Yoon, Pusan National University, South Korea

15:15 Poster and exhibition reception - *Meeting Foyer/Barcelona III*

15:25 Patterning process of silver nanowire networks for flexible displays and sensing applications by using field-assisted nanowire chaining
Mahshid Sam, University of Victoria, Canada

15:15 **Formation of polymer structures for mechanical stability in a flexible light shutter**
Tae-Hoon Yoon, Pusan National University, South Korea

15:25 Patterning process of silver nanowire networks for flexible displays and sensing applications by using field-assisted nanowire chaining
Mahshid Sam, University of Victoria, Canada

15:15 Poster and exhibition reception - *Meeting Foyer/Barcelona III*

16:45 Close

19:15 Conference banquet - *Tapas Bar and Restaurant Café Madrid, Melia Hotel*

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**Thursday 2 November**

08:30 **Registration** - *Meeting Foyer, Melia Hotel*

**Session 7 - Display applications**
Barcelona I
Chair: Aliaksandr Smirnov

09:00 (Invited) Mass production of holographic components for augmented reality applications
Christopher Russo, Luminit LLC, USA

09:30 Low-temperature fabrication of oxide-TFTs using improved and well-selected solutions assisted by UV irradiation techniques
Kyosuke Inui, Japan Advanced Institute of Science and Technology (JAIST), Japan

09:50 UV annealing of inkjet-printed In-Ga-ZnO films for thin film transistors
Younghak Song, Sungkyunkwan University, South Korea

10:10 **Glass handling tool for OLED TV mass production system**
Myungwoon Choi, YAS Co. Ltd, South Korea

10:30 Extremely stable and low work function conductive ceramic materials for display devices
Masayuki Nakamoto, Shizuoka University, Japan

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**Session 8 - Metrology, human factors and characterization**
Barcelona II
Chair: Timothy Leroux

09:00 (Invited) Advanced automotive display measurements - challenges and solutions
Karlheinz Blankenbach, Pforzheim University, Germany

09:30 **Metrology of OLED displays**
Jürgen Neumeier, Instrument Systems GmbH, Munich, Germany

09:50 Accurate colour control of solid-state reflective display (SRD®) pixels using optical monitoring during deposition
Graham Triggs, Bodle Technologies Ltd, UK

10:10 Present status and future of Fourier optics instruments for viewing angle measurements
Pierre Boher, ELDIM, France

10:30 How to evaluate the optical characteristics of LCD and OLED display under any parasitic light
Pierre Boher, ELDIM, France
10:50  **Temperature behavior of different liquid crystal displays**  
Pierre Boher, ELDIM, France

11:10  **Non-destructive automated in-line SEM for advanced process control in display manufacturing**  
Kulpreet Virdi, Applied Materials GmbH, Germany

11:10  **Refreshments - Meeting Foyer**

**Session 7 - Display applications continued**  
Barcelona I  
Chair: Vladimir Sorokin

11:40  **(Invited) Assembly of RGB light-engines for emissive displays via micro-transfer printing**  
António José Trindade, X-Celeprint, Ireland

**Session 8 - Metrology, human factors and characterization continued**  
Barcelona II  
Chair: Karlheinz Blankenbach

12:10  **Solution processed metal oxide self-aligned thin-film transistors for high-resolution displays**  
Ilias Katsouras, Technical University of Eindhoven, The Netherlands

12:20  **Wide color gamut solution based on scattered photon extraction**  
Devrim Köseoğlu, Ozyegin University, Turkey

12:30  **Light field subsample method for three dimensional lenticular display rendering**  
Jing Pei, University of Chinese Academy of Sciences, China

12:40  **Display light and its relevance in office environments**  
Achim Pross, Fraunhofer-Institute for Industrial Engineering (IAO), Germany

12:50  **Lunch - Meeting Foyer**

**Session 7 - Display application continued**  
Barcelona I  
Chair: TBA

14:00  **Displays based on dynamic phase-only holography**  
Neil Collings, Daqri Holographics, UK

14:20  **Design of high-performance InP quantum dot light-emitting diodes**  
Yohan Kim, Display Materials and Components Research Center, Korea Electronics Technology Institute (KETI), South Korea

14:40  **(Invited) From QD-LEDs to full color QD-LED Displays**  
Armin Wedel, Fraunhofer Institute for Applied Polymer Research, Germany
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<tr>
<th>Time</th>
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<tr>
<td>15:00</td>
<td>Reliability and DC-performance of In–Ga–Zn–O thin-film transistors with TEOS-based SiO₂ stack passivation</td>
<td>Aman S G Mehadi, Kochi University of Technology, Japan</td>
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<tr>
<td>15:20</td>
<td>Back-channel-etched TFT with copper S/D electrode and new molybdenum alloy copper barrier</td>
<td>Jung-Cheol Shin, KAIST, South Korea</td>
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<td>15:40</td>
<td>A novel, additive and ITO free process for the formation of metal mesh and TFT electrodes</td>
<td>Roger Massey, Atotech Deutschland GmbH, Germany</td>
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<td>16:00</td>
<td>Refreshments - Meeting Foyer</td>
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<td>16:30</td>
<td>High performance and singularity analysis of sol–gel IGZO TFT annealed by intense pulsed light compared with thermal annealing</td>
<td>Tae-yil Eom, Sungkyunkwan University, South Korea</td>
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<td>16:50</td>
<td>Gate insulators by spin on glass diluted with hydrogen peroxide</td>
<td>Sang Ho Hwang, Hoseo University, South Korea</td>
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<td>17:10</td>
<td>Closing remarks - Best oral and poster paper award ceremony</td>
<td>Best student paper award ceremony</td>
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Poster programme

Poster session 1 - Tuesday 31 October

P:01 The impact of boundary conditions on dynamic light scattering in nematic liquid crystals
Dmitrii P Shcherbinin, ITMO University, Saint-Petersburg, Russia

P:02 Fabrication of a polymer-stabilized in-plane switching liquid crystal cell through low-temperature UV curing process
Tae-Hoon Yoon, Pusan National University, South Korea

P:03 Bistable switching of a cholesteric liquid crystal cell using electro-hydrodynamic convection
Tae-Hoon Yoon, Pusan National University, South Korea

P:04 A novel bistable mode of twisted direction switching LCD using a dual frequency nematic liquid crystal
Noriki Shirai, Kogakuin University, Japan

P:05 Graphene domain monitoring by nematic liquid crystals
Yoonseuk Choi, Hanbat National University, South Korea

P:06 Structure of a molecular dimer of the CD-1 azodye for LC photoalignment
Victor Belyaev, Moscow State Region University, Russia

P:07 Evaluation method for induced condition of bistable characteristics in Nn* LC cells by using a concentric circle rubbing technique
Yukihiro Kudoh, Kogakuin University, Japan

P:08 Characterization of polyimide alignment film with atmospheric pressure plasma jet treatment
Yusuke Saito, Kogakuin University, Japan

P:09 Measurement of homeotropic anchoring energies of nematic liquid crystals using bistable latching
Sophie Jones, University of Leeds, UK

P:10 Application of low temperature encapsulation to foldable organic light-emitting diode
Jeonggi Kim, Kyung Hee University, South Korea

P:11 Improved ten point fiveth(10.5) generation linear source for AMOLED mass
Jungkyu Lee, R&D center of YAS Co., Ltd, South Korea

P:12 AC-driven efficiently tandem organic light-emitting devices
Xiang Zhang, Jilin University, China

P:13 White OLEDs with light-emitting unit composed of multiple host-free phosphorescent materials
Chun-Neng Ku, Industrial Technology Research Institute (ITRI), Taiwan

P:14 The structural study of high triplet host materials with carboline moieties for blue phosphorescent OLEDs
Yirang Im, Sungkyunkwan University, Korea

P:15 Green fluorescent organic light emitting diodes with a bulky side group on a green fluorescent dopant and an assistant dopant
Seung Bae Ji, Sungkyunkwan University, South Korea

P:16 Initiator-free photo-crosslinking systems for OLED applications
Matthew Aldred, Lomox Ltd, UK

P:17 Multilayer structure organic light emitting diode using structurally rigid soluble hole transport materials
Hye Won Choi, Sungkyunkwan University, South Korea

P:18 Angular structure of light scattered by normally illuminated monolayer of spherical particles
Valery Loiko, National Academy of Sciences, Belarus
Poster session 2 - Wednesday 1 November

P:19 Multi-projector 3D display
Nikolay Petrov, Scientific Research Center of Unique Instrumentation of the Russian Academy of Sciences, Russia

P:20 Compensating aberrations in holographic HUD
Hyun-Eui Kim, Electronics and Telecommunications Research Institute, South Korea

P:21 Flexible transparent thin-film transistors fabricated on plastic substrates
Han Dedong, Peking University, China

P:22 Evaluation of optical properties of a flexible light scattering liquid crystal device using a random deposited nanoparticle structure in a cell
Yu Kanazashi, Kogakuin University, Japan

P:23 In–Ga–Zn–O metal-semiconductor field effect transistor for flexible device applications
Mamoru Furuta, Kochi University of Technology, Japan

P:24 The effects of corrosion, fatigue and fatigue corrosion on ITO/Ag-alloy/ITO multilayer films coated PET substrates used in flexible electronics applications
Dilveen W Mohammed, University of Birmingham, UK

P:25 Self biased oxide TFT amplifier
Ye Lin Han, Hoseo University, South Korea

P:26 Development of an e-paper touch system using status LEDs for visible light data transmission for IoT safety and security
Karlheinz Blankenbach, Pforzheim University, Germany

P:27 Effect of SOG annealing ambient on IGZO TFTs
Yeong Jo Baek, Hoseo University, South Korea

P:28 Capacitive sensor pixel circuit with single a-IGZO thin film transistor for touch-fingerprint recognition
In Hye Kang, Hoseo University, South Korea

P:29 Fabrication of a-IGZO TFT using imprint lithography
Sung Jin Kim, Sungkyunkwan University, South Korea

P:30 The effect of light shielding on thin film transistor performance under simultaneous thermal and optical stress
Christiane Reinert-Weiss, University of Stuttgart, Germany

P:31 Device property engineering of oxide semiconductor vertical TFT by means of back-channel passivation via PEALD
Kwang-Heum Lee, Korea Advanced Institute of Science and Technology, South Korea

P:32 Low power integrated shift register circuit for in-cell touch applications
Jeongrim Seo, Kyung Hee University, South Korea

P:33 Enhancement of voltage holding property in low frequency driving fringe-field switching mode using carbon nanomaterials doping within an alignment layer
Jun-Chan Choi, Kyungpook National University, South Korea

P:34 Effect of hydrogen diffusion of passivation layer of self-aligned top-gate a-IGZO TFTs
Xiaodong Zhang, Peking University, China

P:35 Towards a phase-change metamaterial CMY subtractive display
Santiago García-Cuevas Carrillo, University of Exeter, UK

P:36 Two test methods of flicker, transformation relationship and mathematical analysis
Yu Chao, BOE Technology Group Co., Ltd., China

P:37 Lowest cost colorimeter for multiple use
Christoph Lehnert, Pforzheim University, Germany
P:38 Flexible OLED barrier lamination: a step towards R2R processing
Deborah Coleman, Henkel Electronic Materials, USA
Tuesday 31 October

**Keynote session**

**(Keynote) Merging the real & the virtual worlds**

A Bhowmik  
Intel Corporation, USA

With the rapid advances in 3D sensing, immersive displays, and perceptual computing technologies in the recent years, devices are being endowed with the abilities to “sense”, “understand”, and “interact” with us and the physical world. A new class of virtual and augmented reality technologies are increasingly blurring the border between the real and the virtual worlds. This keynote will examine the current status and outlook towards achieving truly life-like immersive and interactive experiences.

**(Keynote) Overview on microdisplay technologies and applications, current status and perspectives**

G Haas  
MICROOLED, France

Abstract unavailable

**(Keynote) Low-cost scalable OTFT backplanes for OLCD applications**

J Socratous  
FlexEnable, UK

Organic electronics will play a pivotal role in enabling flexible displays that break form factor constraints of glass and unlock new product applications and use cases. In particular, organic LCD (OLCD) technology opens a new avenue for LCD – it enables glass-free, conformable, high performance displays, combined with a low manufacturing cost that is driven directly by the uniquely low temperature process (sub 100°C) afforded by OTFT.

The presentation will describe the attributes of OTFT - now beyond amorphous silicon performance - and the benefits of using plastic instead of glass. It will reveal why OLCD is inherently suitable for mass production and the value it brings to specific applications and markets.
Session 1 - Display materials and components

(Invited) Photo-induced molecular rotation and its application to fabrication of optical elements
S Pan, C Zhao, V G Chigrinov and H-S Kwok
Hong Kong University of Science & Technology

Photo-induced molecular rotation is a simple and effective way to achieve anisotropic ordering of molecular thin films. It is a promising technique to achieve ultra-thin high-performance optical elements. Photoalignment using photo-induced molecular rotation has unique advantages in applications such as the realization of advanced optical elements liquid crystal (LC) Dammann grating, LC Fresnel lens, holographic polarizers and bifocal optical-vortex lens.

Electrically switchable and broadband scattering-type linear polarizers using polymer network twisted nematic liquid crystals
K Cheng, C Liu and W Chen
National Central University, Taiwan

We propose the intrinsic scattering of polymer network 90° twisted nematic liquid crystals (PN-90° TNLCs) are anisotropic based on the formation of homogeneous polymer networks through whole LC bulk. Briefly, it shows polarization selective scattering when an external voltage is applied, and the degree of polarization of the output light is 0.97. The ability can be removed when the applied voltage is switched off.

Scattering mode liquid crystal (LC) devices are used in various display fields. Light scattering in voltage-off (on) state and transparent in voltage-on (off) state is called normal (reverse) mode [1]. The polymer network twisted nematic LCs shows scattering state when an external voltage is applied due to mismatch of reflective index between no of nematic LC and ne of LC polymer. And it switches to transparent state when the applied voltage is switched off because of the matched reflective index. Such reverse mode polymer network twisted nematic LCs (r-PNLCs) show special scattering phenomenon due to the formation of nematic LC and LC polymer. In this study, we demonstrate a 90o twisted nematic LC as an asymmetric structure. In this case, the incident light with linearly polarized direction parallel to the rubbing direction of input substrate will be scattered strongly. On the contrary, scattering of the incident light with linearly polarized direction perpendicular to the rubbing direction of incident substrate can barely observed.

The polymer network TN LCs was fabricated by photo-polymerizing the reactive mesogen in the LC host (E7). The mixture was sandwiched between two ITO substrates with the treatment of planar alignment layer, and the cell gap was 12 µm. Rubbing direction of the substrates were orthogonal to each other. After that, the LC cell was exposed with a UV light to achieve photo-polymerization.

Figure 1 show the observations of the r-PNLCs with and without the application of external voltage under cross-polarizer polarized optical microscope (POM). The P and A show the transmission axes of the polarizer and analyzer, respectively, and the red arrow represents the rubbing direction of input substrate. The difference between Figs. 1(a) and 1(b) is the polarization direction of incident linearly polarized light, and both of them were at transparent state of TN r-PNLC. In Figs. 1(a) and 1(b), whether the polarization direction of the incident light was parallel or perpendicular to the rubbing direction of input substrate, they both appeared bright state without light scattering. Moreover, Figs. 1(c) and 1(d) show the scattering state when an AC voltage of 40 V is applied. When the polarization direction of the incident light was parallel to the rubbing direction of input substrate [Fig. 1(c)], it showed black color because of strong scattering. On the contrary, if the polarization
direction of incident light was perpendicular to rubbing direction of input substrate [Fig. 1(d)], the scattering phenomenon was very weak and the brightness was almost consistent with that shown in Fig. 1(b), which was a transparent state.

Figure 1: Observation under a POM

The degree of polarization (DOP) can be used to describe the scattering strength. The blue curve in Fig. 2 shows the DOP curve from transparent state to scattering state. Two red curves present the transmittance of two orthogonal polarization directions of output light. At transparent state, TN rPNLC does not scatter any incident light so the value of DOP was nearly 0. The DOP value increases with the increase of the applied voltage, and the maximum DOP is 0.97.

Figure 2: DOP of output light when an unpolarized probed light transmitt through TN r-PNLC.

The authors would like to thank the Ministry of Science and Technology (MOST 103-2112-M-008- 018-MY3).

Grating aligned ferroelectric liquid crystals for use in fast switching devices

P. Wyatt, J. Bailey, N. Solodkov, M. Nagaraj and C. Jones
University of Leeds, UK

We reintroduce the use of ferroelectric liquid crystals (FLCs) for their use in novel electro-optic devices and fast displays. Using a homeotropically aligned, micron-sized grating, ultra-fast switching and optical response times are shown, with the additional benefit of ‘self-healing’ properties of deformed smectic layers.

Calamitic nematic liquid crystals (NLCs) are commercially found in displays such as TVs, tablets, smart-phones etc. Ferroelectric liquid crystals dominated LC research in the 90’s and led to many applications such as the surface stabilized FLC device [1]. Such alignment allows ultra-fast optical response times of under 200 \( \mu s \) [2]. Unfortunately, such alignments are sensitive to shock induced flow, whereby the smectic layers are permanently displaced, yielding the display useless.

The prospect of novel alignment geometries has reopened our interest in FLCs for fast display applications. If FLCs can be shock stable in such alignments, then their potential for alternate applications may be revolutionary. Such applications include high frame rate displays and used for frame-sequential colour.

This work presents a novel alignment system for FLCs, achieved by the combination of a sinusoidal-like grating with micron-sized features, and homeotropic surface treatment. The surface treatment aligns the smectic layers while the grating aligns the \( \mathbf{c} \) director perpendicular to the grating vector, shown in Figure 1a. This appears black/dark when viewed between crossed polarizers, if the grating direction is aligned parallel to the polariser or analyser. In plane switching (IPS) electrodes are positioned at 45° to the grating such that when a field is applied, the \( \mathbf{c} \) director aligns perpendicular to the field to satisfy the half-wave plate condition. This state appears white/bright between crossed polarisers and is shown in Figure 1b. In addition, this design aids to remove the formation of defects within the LC by forcing \( \mathbf{c} \) to have only one preferential alignment direction upon relaxation.

Figure 1: The alignment of a FLC in a homeotropic grating alignment with (a) no field, and (b) an electric field, denoted by \( E \). The field is applied at 45° to the grating, in-plane, which aligns the \( \mathbf{c} \) director by the characteristic spontaneous polarisation, \( P_s \). The layer normal is depicted by \( a \) and the grating direction by \( g \).

This work continues to explore the effect of this homeotropic, grating stabilised alignment. Such an alignment that can be shown to “self-heal” when addressed, which fixes the difficulties experienced with the SSFLC geometry. We also apply such a device to more complex systems, such as the spontaneously ferroelectric bent-core liquid crystals, to create a design that exploits their exciting properties with the potential for yet faster switching modes.

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In this paper, we introduce an electrically switchable liquid crystal phase grating device for window display applications. This device exhibits outstanding features, such as low operating voltage, high transmittance, and wide viewing angle in the transparent state and a high haze in the translucent state.

Nowadays, window displays have attracted much attention as one of the next-generation displays because of their unique feature of offering simple information through windows. Liquid crystal (LC) technologies based on light scattering, such as polymer-stabilized liquid crystals, polymer-dispersed liquid crystals, and cholesteric liquid crystals, have been studied extensively [1]. These LC light shutter devices can be switched between the transparent and translucent states by applying an electric field. However, these light shutters suffer from a high operating voltage (> 40 V), low transmittance, and narrow viewing angle of the transparent state because of the refractive index mismatch between the LC and polymer matrices. These challenges can make it difficult to use them for window displays.

In this paper, we report an electrically switchable two-dimensional (2-D) LC phase grating device with high haze in the translucent state for window display applications [2]. This device exhibits a transparent state with high transmittance and little dependence on the viewing angle direction. Moreover, a large spatial phase difference is induced regardless of the azimuth angle when an electric field is applied to the LC cell so that it can be switched to the translucent state with a high haze value (~84%) at a low operating voltage (7 V). To obtain a higher haze value in the translucent state of the LC device, we also employ a polymer structure built through photo-polymerization of a UV-curable monomer. In addition to the diffraction effect caused by the change in the effective index of the LC layer, the scattering effect caused by the polymer structure contributes to a very high haze value (~93%) in the translucent state of this device.

We measured haze values in the translucent state of a 2-D grating cell without a polymer structure and a polymer-stabilized 2-D grating cell. The 2-D grating cell without a polymer structure showed a haze of 83.8% at an applied voltage of 7 V, whereas the polymer-stabilized 2-D grating cell showed a higher haze of 92.8% at the same applied voltage. The haze value in the translucent state of the polymer-stabilized 2-D grating cell is 10.7% higher than that of the 2-D grating cell without a polymer structure because of the simultaneous effects of scattering and diffraction. We captured images of a polymer-stabilized 2-D grating cell by placing it on a printed image. The photographs of the polymer-stabilized 2-D grating cell in the transparent and translucent states are shown in Fig. 1. As shown in Fig. 1, we can view the clear background image in the transparent state because of the high transmittance of this device. In the translucent state, the polymer-stabilized 2-D grating cell can hide the background view using the scattering effect owing to a polymer structure as well as the strong diffraction effect owing to a large spatial phase difference regardless of the azimuth angle.

Figure 2: Photographs of 2-D grating cells without and with polymer structure

The device exhibited outstanding features, such as a low operating voltage, high transmittance in the transparent state, and high haze in the translucent state. We believe that this device could be a potential candidate for window display applications.
Anisotropic-based approach for design of new materials, structured surfaces, sensors, photonic devices and displays

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The electrochemical anodization technique of inorganic films (aluminum, ITO) on a glass substrate can provide good alignment properties for anisotropic molecules on the substrate surface and can be one of the promising solutions for the design and production of different displays. We also reported novel approach to preparation of new generation of anisotropic compounds and materials.

The proposed approach for design of new sensors, photonic devices, displays, structured surfaces and anisotropic materials; modeling of various processes are based on the self-organization of dynamic structures (dissipative), chemical systems and organic molecules; on numerous data obtained in the last decades in the study of liquid crystals and ordered fluids; on the use of the anisotropy of the molecules of polyfunctional compounds for the design of new molecular structures (molecular engineering), films, liquid crystals, micelles, membranes, or anisotropic ensembles of molecules. [1,2]

Taking into account that polyfunctional 3,6-disubstituted cyclohex-2-enones, trans-2,5-disubstituted cyclohexanones, 3,5-disubstituted 2-isoxazolines, 5-substituted cyclohexan-1,3-diones, 1,2-disubstituted cyclopropanols and substituted unsaturated epoxyketones can be easily converted to the corresponding liquid crystalline and anisotropic compounds, we proposed to use them as the key intermediates for the preparation of different types of anisotropic substances and materials. Different reaction possibilities for the functional groups and the cyclic fragments allow transformations to be achieved selectively and give a chance of preparing anisotropic compounds and materials with novel combinations of the structural fragments of molecules, which are in their turn useful components for new sensors, photonic devices, displays and other practical applications.

The results of our investigations have shown that the nanoporous alumina or ITO layers and similar to them structured inorganic films on a glass substrate prepared by electrochemical anodisation can be one of the promising solutions for the design and production of next generations of displays, touch panels, solar cells. The cells, which have been prepared using the LC materials with negative dielectric anisotropy and the nanoporous alumina or ITO layers on glass substrate (alignment conditions) have several advantages in comparison with the cells containing commercial LC and alignment materials and possess switching time less than 3 ms (Figure 1) and the viewing angle 170-180°.

Figure1: Switching time of the LC cells under applied electric field

The presented results demonstrate that the combination of anisotropic materials, nanostructured films and surfaces, which are characterized by the ordered relief structure, opens the new approach of the creation of next generation of high quality displays with improved parameters. It is obvious that the proposed methodology is original and creative, and has a number of distinctive advantages in comparison with the well-known
technologies, and can be successfully used for the development of new sensors, photonic devices, displays with a wide range of practical application


Towards fastest switching nematic liquid crystals spatial light modulator

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In this paper, we disclosed the realization of a fast switching liquid crystal (LC) spatial light modulator (SLM) through the design and synthesis of a new LC mixture. The LC mixture possesses low dielectric anisotropy that suppresses the fringe field effect, as well as high optical birefringence for which $2\pi$ phase shift can be established at visible spectrum (450 nm – 650 nm) with thin cell gap, which enables fast response time and further inhibits the fringe field effect. The design has been experimentally verified from the transmission voltage curve of a single pixel spatial light modulator cell under simple electrically controlled birefringence mode (see Fig. 1 for measurement setup). Experimental results have shown a $\pi$ phase shift of the transmissive cell, and hence a required $2\pi$ phase shift using reflective substrate, is achieved using a 633 nm laser with a switching time of 2.5 ms at 30 °C, a fastest response time that has ever been reported while meeting the specifications of a SLM at the same time. By paving the way through the realization of the fastest SLM, it is anticipated the reported SLM design can be influential in the field of optics, including applications holographic display, optical trapping, and reconfigurable wavefront shaping.

Fig. 1. Optical setup for measuring the transmission voltage curve of a single pixel SLM cell to determine the phase retardation and the response time.
Simulation of the uniform lying helix structures using the Q-tensor method

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The Uniform Lying Helix structure shows promise as a new type of liquid crystal mode for display applications. Simulations of the director profile have been used to investigate the alignment.

Modelling of liquid crystal director structures have been in use since the early days of liquid crystal devices. Berreman’s computer programmes [1] were used to optimise the performance of Super-Twist Nematics and many other types of early displays based on nematic liquid crystals. As developments in liquid crystal displays have progressed the electrode structures and surface structures have been used to improve the display performance, so simulation methods have been developed to encompass the more complex structures. The method presented in this paper uses the tensor formulation [2] to describe the liquid crystal structure, which amongst other advantages allows defect formation in the simulation. We have applied it to a number of different liquid crystal devices including liquid on silicon (LCOS) [3], microwave applications and surface patterning [5]

The Uniform Lying Helix (ULH) is a recent display mode, which has potential for improved display performance. The twisted structure is rapidly varying through the liquid crystal cell, in particular the interactions of the alignment layers on the two surfaces of the substrates with the director profile are not fully understood. The rapid variation of the director requires a large number of elements in the numerical simulations and in this work a small 1 µm × 1 µm × 3 µm volume was used and the energy of the different elastic distortions was calculated as the elastic constants were varied. It was found that a variety of orientations of the helix could be obtained depending on the starting conditions of the simulation and the anchoring strength of the different surfaces. Figure 1. Shows the director profile in a section through the volume, half way and parallel to the alignment surfaces. This shows the ULH forming in two different directions within the volume.

Figure 1. Section through a 1 µm × 1 µm × 3 µm volume at y=0.5 µm, showing ULH formed in two directions. Alignment surfaces are at y = 0 and y = 1


Novel helix-free FLCs: Electrooptics and possible applications

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Reorientation of a helix-free FLC director is due to the movement of spatially localized waves - solitons arising at the transition to the Maxwellian mechanism of energy dissipation. In the transparent mode, the experimental samples of FLC display cells show the fast optical response (25 $\mu$s) and light modulation (up to 5 kHz) with the continuous gray scale at the control voltage of $\pm 1.5$ V. In the bistable light-scattering mode, a state with the intensive scattering can be switched ON and OFF for a few tens of microseconds and memorized for a few tens of seconds or till the arrival of a pulse of opposite polarity. Possible applications of helix-free FLCs are also considered.

The materials are specially designed helix-free FLC with the spontaneous polarization $P_s=40$ nC/cm$^2$, rotational viscosity $\gamma_\phi=0.7$ Poise, tilt angle $\Theta_0=23^\circ$ (at $20^\circ$C), smectic C$^*$ phase interval 2…70 $^\circ$C. In such FLC cells:

- The periodical spatial deformation of smectic layers takes place in the absence of the electric field, and FLC director reorients in the electric field due to soliton waves moving,
- Fast electro-optical response with continuous gray scale in transparent mode and fast electro-optical response in light scattering mode with data memorizing are possible at definite conditions.

Such a deformation occurs in helix-free FLC at a certain ratio between the values of essential parameters:

- The rotational viscosity is in the range of 0.3 < $\gamma_\phi$ < 1.0 Poise; if less, the transition to the shear viscosity $\gamma_\psi$ is not achieved, and the soliton mechanism of reorientation of FLC director is not realized; if more 1 Poise significantly the optical response time increases at higher frequencies also,
- The magnitude of spontaneous polarization $P_s$ is less than 50 nC / cm$^2$; if it is greater, the saturation voltage increases, the ferroelectric domains begin to form, and light scattering takes place, when the electric field is turned off,
- The value of elastic modulus $K$ determining deformation along the smectic layers is in the range (1-3) · 10$^{-12}$ Newton since in this range the smectic layers are stable and susceptible at the same time to periodic spatial deformation in the absence of an electric field.

Alternating electric field interacts with spontaneous polarization and changes a director distribution in each smectic layer. Development of this process results in appearance of a soliton (a zug of solitons). Motion of solitons reorients the director in the entire FLC layer. In transparent mode (with crossed polarizers), at the control voltage of $\pm 1.5$ V this provides the frequency of light modulation up to 5 kHz with the continuous gray scale and the optical response time of about 25 $\mu$s.

Experimental results confirm persuasively that helix-free FLC is very promising material for the next generation of displays, especially for 3D displays based on FLCOS and field sequential colors technique.

Scattering of light in FLC occurs on boundaries of spontaneously ordered regions, which are formed in helix-free FLC in the process of arising of waves of a stationary profile - solitons. Scattering occurs after changing the sign of the electric field and disappears when the motion of solitons reorients the director in all smectic layers.

Changing the direction of the electric field newly induces transient domain formation, and the process repeats.

In the bistable light-scattering mode, a state with the intensive scattering can be memorized for a few tens of seconds or till the arrival of a pulse of opposite polarity. Due to short-term (less than 50 $\mu$s) switching on-off light scattering the spatially non-uniform structures are formed in FLC layer with almost random distribution of refractive index gradients, which are the reason of a spatially non-uniform (across the beam) phase modulation of light with a depth of $\geq \pi$.

This approach is used in FLC cell as a despeckler to suppress speckle-noise in laser-generated images. Other possible applications are polarizer-free visible and IR optical shutters, screens of electronic books etc.
A new type of helix-free FLC with the soliton mechanism of director reorientation at the transition to the Maxwellian mechanism of energy dissipation is studied, and unique parameters of light modulation in FLC cell in transparent and scattering modes are achieved.

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**(Invited) Experimental modeling and theoretical simulation of composite systems with inhomogeneous liquid crystal orientation for display devices with enhanced performances**

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Recent experimental and theoretical results in area of LC cells with inhomogeneous orientation and composite systems with such cells are reviewed. Methods of controlling the LC surface performances and measuring them are described. Green and cheap technologies for synthesis the LC orienting films have been developed. Method of simulation of the LC alignment on solid film has been developed that will allow predicting the aligning substance molecular structure for different LC molecules. In addition optical properties of cells with sophisticated distribution of local optical axes of birefringent materials have been calculated that allow creating new optical compensators, LCD with wide viewing angles, LCD systems with nanoparticles or with porous substrates.

A few types of different systems with inhomogeneous liquid crystal orientation are illustrated in Figs.1-3.

**Fig.1.** Examples of typical LC cells with different types of the LC alignment: H (homogeneous), S (splay), B (bend) with surface pretilt angles $\Theta_0^{(1)}$ and $\Theta_0^{(2)}$. Such configurations are typical for conventional LCD as well as for optical films.

**Fig.2.** Different types of the heterophase systems with the LC. Top: a transparent isotropic material with spherical or cylindrical LC objects and a liquid crystal material incorporating an isotropic transparent or non-transparent spherical or cylindrical object. Bottom: Cross-sections of spherical LC objects with planar and vertical boundary conditions (left and center), with polar boojum structure (right).

Examples of such systems are PDLC, LC fiber, lyotropic LC in polarizing films, LC in micro- and nanogrooves, pores. For the second type there is an LC layer incorporating an isotropic transparent or non-transparent object like micro- and nanoparticles, spacers, protrusions in MVA LCD et al.
Realization of photoaligned vertical alignment by azobenzene sulfonic photoalignment material and polyimide composite

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Realization of photoaligned vertical alignment by mixing an azobenzene sulfonic material and vertical polyimide (PI) is introduced in this paper. This method avoids the surface damage caused by rubbing the conventional polyimide. Utilizing this composite, we can achieve suitable pretilt angle for vertical alignment application and even patterned alignment for various optical devices.

Conventional technology for realization of vertical alignment relies on rubbing of vertical PI. However, the rubbing process will bring contamination on the alignment layer to affect the quality of the products, which is the main reason that more and more attention has been given to photoalignment technology because of the non-contact property of this approach [1]. Moreover, it’s rather difficult for conventional PI to achieve patterned alignment. In this paper, a new composite of an azobenzene sulfonic material called SD1 [from Dai-Nippon Ink and Chemicals, Japan] and vertical PI is introduced, which can provide suitable pretilt angles and patterned alignment. SD1 has the property that its planar alignment can be generated upon exposure by polarized light, where the alignment direction is perpendicular to the light polarization direction and can be reoriented by an additional exposure with light in a different polarization direction [1].

It’s already been demonstrated that variable pretilt angles can be realized by nanostructured surface [2]. For the SD1 and vertical PI composite, the composition of the azimuthal anchoring force of SD1 and the polar anchoring force of PI can give the liquid crystal molecule a pretilt angle with accurate azimuthal direction. But, this also requires a pretilt angle of SD1, since the composition of two forces needs to have only one preferred azimuthal direction, as shown in Fig. 1.
Figure 1. Illustration of the composition of the forces of SD1 and vertical PI. (a) When the SD1 molecule doesn’t have a tilt angle; (b) When the SD1 molecule has a tilt angle.

Recently it’s been discovered that oblique un-polarized UV light can also align SD1 molecules and generate a small pretilt angle. Fig. 2 shows the pretilt angles of SD1 with different concentrations and exposure energy.

Figure 2. Pretilt angles of SD1 based on different concentrations and exposure time.

Fig. 3 (a) shows the pretilt angles of the composites of SD1 and vertical PI with different ratios of these two components. The overall concentration of the PI is fixed at 1 wt%. Fig. 3 (b) shows the patterned alignment of the composite, which is a dammann grating (DG) cell applied with voltage of 5V. The bright lines are the disclination lines at the border of two domains with orthogonal alignment.

Figure 3. (a) Pretilt angles of the composites; (b) Vertical DG pattern; (c) Diffraction pattern of the DG.

Photoaligned vertical alignment using the composite of SD1 and vertical PI has been demonstrated in this paper. And its patterning property can be much beneficial to many optical applications.

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Quantum dot materials for improved autostereoscopic color filter displays

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So far, we investigated and discussed wavelength selective autostereoscopic 3D arrangements, consisting of common LCD and RGB-color filter barriers. We determined computed advantages of wavelength selective barriers compared to conventional barriers like lenticular and parallax barriers. An experimental demonstration showed no satisfactory results using commercial displays. The common broadband wavelength spectra of backlights and filter technology can deliver high crosstalk and undesirable moiré effects. Nowadays, LCDs with quantum dot materials came into the market and compete with OLED by improved color and High-Dynamic Range. In this paper, we describe improved characteristics of autostereoscopic displays by using quantum dot materials and show the benefits of this technology.

Color separation by different wavelength spectra is one of the commonly known stereoscopic techniques. Anaglyph glasses used as image content separator in front of the human binocular eye system are a most prominent example. They are cheap and easy to handle but their delivered quality is quite limited by poor color representation. INFITEC® developed a more sophisticated RGB spectrum based system with special coated glasses. Nevertheless, glasses free 3D displays could be the next step to a more natural stereoscopic viewing experience. Like the INFITEC® system, sharpbordered spectra are a necessity. Classical LCDs with LED Backlight produce a broad illumination spectrum not usable for stereoscopic image splitter in 3D displays [1]. In contrast, Quantum dot LED or QLED spectra with their narrow band characteristic [2] are a promising candidate for such color filter splitter. We simulated different arrangements of RGB pixels in combination with advanced image processing algorithms for the design of highresolution glasses-free 3D stereoscopic displays [3].

By the use of color filters for stereoscopic image separation, we have to deal with a distinct loss in intensity. This is dependent on the optimization of different factors: filter arrangement, transparency and transmission efficiency. Therefore, we will discuss positive properties of QLEDs and their benefits for autostereoscopic displays in this paper.

Some advantages of quantum dot (QD) technology in relation to standard backlight and color filter based 3D glasses-free technology are

- Narrow bandwidth spectra
- High switching speed in the ns-range
- Arrangement in nm-range structures
- Very saturated colors.

The QLED development is still ongoing and can be distinguished in three stages related to novel color filter design.

In current QLED-TVs an additional QD-foil is inserted between a blue LED backlight and the common color filter. The nanometer sized QDs in the foil convert the blue LED backlight to green and red color. The positive consequences in 3D display application will be possible improvements in light management and energy efficiency and therefore reduction of crosstalk between neighboring viewing zones. The FWHM of the primary color peaks has to be in the range of 20 to 40 nm [2]. Additional edge filters will cut off the unwanted color wavelengths in the spectrum.

In a next step, QDs are part of the structured color filter itself. This will directly result in better light efficiency of our proposed 3D color filter design [3] and should significantly reduce the crosstalk values.

Finally, in a last development step blue backlight, first polarizer and LCD layer will be redundant by selfluminous QDs. This will be the condition for a color filter 3D display with maximized view separation and minimized crosstalk.

Development of scattering media optics methods to calculate optical properties of polymer dispersed liquid crystal films

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The aim of this investigation is: creation and development of methods to describe optical characteristics of the Polymer Dispersed Liquid Crystals (PDLC) films: light transmittance, reflection, scattering, polarization, etc. We based on: relaxation method to find distribution of local optical axis (local field director) inside the droplet; anomalous diffraction approximation (ADA), effective medium approach, Wentzel–Kramers–Brillouin (WKB) approach to analyze light scattering by a separate LC droplet; amplitude-phase screen (APS) model, Foldy-Twersky approach, interference approximation of the multiple wave theory to find scattered field in the far zone. Droplets shape anisotropy, size distribution, orientation, and director configuration are taken into account. Comparison of the theoretical predictions and experimental data is made.

Figure 1. Dependence of vv-component of the light intensity scattered by a monolayer of spherical LC droplets at different values of filling factor η. w=50%, c=5µm, λ=0.633µm, n_o=1.531, n_e=1.717, n_p=1.532. φ_s=0.

The electrooptical effect of symmetry breaking in the angular distribution of scattered radiation has been analyzed. This effect consists in the following: the intensities of radiation scattered at angles +θ_s and -θ_s relative to the direction of illumination in the scattering plane can be different. The effect is associated with asymmetry of the phase shifts of the wave fronts from individual parts of the droplet, which appears due to asymmetry of the director field structure in the droplet. The last is caused by nonuniform anchoring of liquid crystal molecules with the polymer on its surface [1]. In Figure 1 the angular structure of light scattered by a monolayer of droplets at different value of filling factor η is shown at the polarized light illumination. Parameter w in here characterizes the degree of the anchoring nonuniformity [1]; n_o, n_e are the ordinary and extraordinary refractive indexes of LC, n_p is the refractive index of polymer; φ_s and θ_s are the scattering angles; the notation vv means that the polarization vector of the scattered wave is parallel to the polarization plane of the incident wave.

Angular pattern of scattering by a monolayer of monodisperse droplets at unpolarized light illumination is illustrated by Figure 2.
Figure 2. Intensity $I(\theta, \varphi)$ of light scattered by the PDNLC monolayer of monodisperse spherical LC droplets under illumination by the unpolarized light.

The symmetry breaking effect is applicable in designing devices for masking optical information.

The developed methods and models are the valid tools to describe light scattering by PDNLC films. They can be used to forecast their optical properties.

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Materials with controllable anchoring energy for nematic liquid crystals alignment

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New polymer with photo-controllable anchoring energy and tunable pretilt angle within 90-0 degree range for nematic liquid crystals alignment were developed. Applying photosensitive alignment layers based on polymers with side benzaldehyde groups and hydrocarbon substituents, fabrication of optical devices with refractive index gradient, uniform cell gap and low operation voltage is possible. The developed materials suitable for simple fabrication of tunable liquid crystal lenses.

The development of new alignment materials is driven by permanent evolution of liquid crystal display technologies. Refractive index gradients of liquid crystal (LC) microlenses and bistable modes of LC devices are obtained on the bases of variable pretilt angle alignment layers. Special interests are alignment materials that allow technological process for tunable alignment properties, i.e. pretilt angle in the range from 90° to 0°[1] and anchoring energy.

Recently, the photoanisotropy of benzaldehyde-containing polymer layers was found in the form of photo-induced birefringence, while the surface anisotropy was verified for photoalignment of LC materials. Introducing the alkyl substituents into the chain of benzaldehyde polymers (Gradient Benzaldehyde Polymers or GBP), initial homeotropic orientation on the surface of the alignment layer is observed, which gradually decrease the pretilt angle into the planar alignment upon either polarized UV photoalignment or non-polarized photo-exposure after rubbing. At the same time the non-polarized photo irradiation of rubbed polymer layer increases the azimuthal anchoring energy and reduces the pretilt angle (Fig. 1).
The creation of LC lens and its arrays based on GBP is achieved via formation of a bell-shaped distribution of LC pretilt angles inside the LC cell. Similar distribution of the refractive index appears for the corresponding polarization of light causing voltage dependent focusing. Thus LC lens fabrication is subject to formation of local radially symmetrical exposure intensity distribution on the surface of the alignment layer. The radiation intensity is maximum at the center of the illuminated circle and gradually falls to the outer boundary.

Thin polymer layers (~80 nm) were deposited on two ITO glass substrates by rod-coating method. After drying at 70° one of the substrates was rubbed and exposed to non-polarized UV light with a compact fluorescent lamp of helical form UVB-Glo10-E27 (China) through the metal mask with round drilled hole of 1.5 mm in diameter. The light intensity and the exposure time were 4.8 mW/cm² and 12 min, correspondingly, to induced the bell-shaped gradient alignment properties. The distance between the mask and the alignment layer was d=0.7 mm. The second substrate with alignment layer was unexposed for vertical alignment. Next, two were stacked together to form a LC cell with uniform cell gap of 20 µm provided by spacer. The cell was filled with LC ZhK-1285 (NIOPIK, Russia), and hermetically sealed with UV glue Norland 65 (Norland, USA). On the photograph of hybrid aligned nematic (HAN) LC cell with tunable LC lens placed in-between parallel polarizers the rubbing direction is at 45° relative to the polarizer axes (Fig. 2).

Alignment properties of new gradient benzaldehyde polymer with UV light controllable pretilt angle and anchoring energy are presented. While the pretilt angle gradient is applied for LC lens fabrication, the anchoring energy increase with the increase of the exposure dose reduces the alignment defects and improves tuning efficiency upon voltage application.

Session 2 - OLED organic electronics

(Invited) Quantum dot electroluminescence to achieve saturated colours for REC2020 compatibility: A comparative study of CdSe/ZnS and Cd free QD systems

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Electroluminescent colloidal quantum dots have the potential to offer saturated colours satisfying the new more demanding REC 2020 (ITU-R-BT 2020) standard. This paper reports our attempt to match the REC 2020 colour co-ordinates with red CdSe/ZnS (0.708, 0.292), red CFQD® and green CFQD®. We report here red quantum dot based electroluminescent devices (QLEDs) that meet the colour co-ordinates requirement set by REC2020. We also report the world first dark red CFQD® (heavy metal free) ((x,y), (0.696, 0.303)) devices. The electroluminescent characteristics of devices of both CdSe/ZnS and cadmium free quantum dots are compared. The conduction mechanism and life-time will also be presented.

Realization of RGB colors from top-emitting white OLED by electron beam patterning

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We demonstrate the realization of RGB colors from top-emitting white OLED for display applications. In our approach, RGB colors are realized by microcavity-based mode selection from the spectrum of a white OLED. For the tuning of individual microcavities, the OLED hole-transport layer is patterned by an electron beam process.

In the field of electronic displays, organic light-emitting diodes (OLED) are efficient and reliable light-sources for the required colors of red, green and blue (RGB) in the visible range. However, one remaining drawback in the current technology of OLED displays is the lack of options for micropatterning such as photolithography, i.e. either shadow masks are used for OLED structuring and typically exhibit resolution limit, or color filters are applied to convert white light into RGB and result in low efficiency. Therefore, we present a new promising concept for OLED patterning that enables high-resolution displays without using color filters.

In our approach, RGB colors are realized by microcavity based mode selection from the spectrum of a white OLED. For the tuning of individual microcavities, we micropattern the OLED hole-transport layers applying a focused electron beam process.

The realization of RGB colors by mode selection from a broad white spectrum based on the microcavity effect is known from literature [1-3] and easily verified by optical simulations. Our simulation results demonstrate that the microcavity approach is superior to the application of color filters.

We built top-emitting white OLEDs on silicon substrates. The vacuum deposition process of the OLED stack was interrupted after the deposition of the hole-transport layer (HTL). The sample was transferred to an electron beam tool to perform a local ablation process. By depositing further HTL and repeating the ablation process,
different layer thicknesses of the HTL were realized before the white OLED stack was completed with common emission and electron transport layers (Figure 1).

We demonstrate the feasibility of the HTL micropatterning by electron beam patterning and the realization of RGB colors from a top-emitting white OLED. With regard to the high-resolution potential of the electron beam ablation process, the approach seems well suited for OLED patterning on silicon CMOS backplanes for microdisplay fabrication.

This research has been funded by the FhG internal program OEMS. We thank our partner company Focus for the technical support and fruitful discussions.

Figure 3: Concept of RGB-OLED patterning by electron beam ablation

Pixel drive circuit design for AM OLED microdisplays

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We report on new pixel drive circuits for Active Matrix Organic Light Emitting Diode microdisplays. We have implemented six pixel-driver arrays, with a pixel pitch of 5µm, in 130nm CMOS. A performance comparison of two of the pixel circuits is reported.

Microdisplays are ultra-miniature display panels designed to be viewed under optical magnification. The combination of emissive, fast response and low power consumption makes Organic Light Emitting Diode (OLED) a favored candidate for microdisplays. Onoyama et al. [1] reported a 2T Source-Follower (SF) pixel circuit with threshold voltage compensation. Wacyk et al. [2] reported a current-drive pixel in which the output current is highly sensitive to the voltage stored on the in-pixel storage capacitor, and a voltage-drive pixel with enhanced output dynamic range. We have implemented six pixel-drive circuits, including, as a baseline, a 2T1C PMOS circuit and a 2T NMOS SF circuit whose characteristics we report.

Figure 1. Photomicrograph of test array. The zoom inset shows the layout of the 4×6 array with dummy pixels

These two pixel driver circuits are implemented in small test arrays. A photomicrograph of a 4×6 test array, with surrounding dummy pixels, is displayed in Fig 1. The test arrays are deposited with an OLED stack. Circuit schematics for the two test pixels are shown in Fig 2.

Figure 2. Circuit Schematic (a) PMOS current source and (b) NMOS Source follower.

Figure 3 Simulation showing PMOS current source pixel output characteristics
Measurements are made using a custom PCB, 12-bit DACs and an Opal Kelly FPGA card. As expected, the output current of the 2T1C PMOS circuit (Fig 2(a)) is very sensitive to small variations of the internal voltage, \( V_C \). Fig 3 shows a simulation of output current versus input voltage (\( V_{DD} - V_{DATA} \)). The SF pixel (Fig 2(b)) shows lower sensitivity to \( V_C \), but low output voltage dynamic range. Fig 4 shows the SF pixel output voltage (red trace) versus input DATA voltage. Further characterization is ongoing to provide detailed optical measurements at the conference.

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Synthesis and characterization of metal oxide-graphene nanocomposites for QLED applications

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Recently graphene has attracted great interest due to its unique structure and numerous promising applications in electronics, sensors, Li-ion batteries etc. Semiconductor ZnO has attracted considerable attention in the development of light emitting diodes (LEDs) and photovoltaic cells due to its direct band gap of 3.3 eV at room temperature and large exciton binding energy of 60 meV. It has been considered as an ideal alternative to organic electron-transport layer due to its thermal stability and less sensitive to oxygen and moisture. In particular, it has higher electron mobility than organic semiconductors which facilitates efficient electron transport, thereby increases the efficiency of charge recombination. Moreover it has low cost and nontoxic. Thus ZnO is considered as suitable candidate for electron transport layer. Similarly CuO is considered as appropriate hole transport layer in QLEDs.

In recent years metal oxide - graphene nanocomposites have emerged as suitable candidates for the fabrication of novel class of optoelectronic devices, because such nanocomposites improve device performance in gas sensors, solar cells, fuel cells, lithium ion batteries and optoelectronic devices.

Thus in this work, we demonstrate a simple solution route for the synthesis of ZnO-graphene nanocomposite, CuO-graphene nanocomposites and investigate their structural and optical properties using various techniques. The structures, morphologies and optical properties of prepared materials were verified using X-ray diffraction (XRD), Scanning electron microscopy (SEM), Transmission electron microscopy (TEM), Energy-dispersive X-ray analysis (EDX), Raman Spectroscopy and Photoluminescence (PL) study.
(Invited) Footsteps in the OLED material trail: A game changing technology revolutionizing the world of displays and lighting

K Krishnamutry

USA

OLED has evolved as the key for the future advances in Displays (mobile phones, tablets, flat panel displays-TV) and the next generation of lighting. During the last 30 years, it has revolutionized the whole concept of Displays and Lighting industries. Year 2017 is the 30th anniversary of OLED technology. OLED technology is strongly influenced by the performance of complex organic and organometallic chemicals, which are very increasingly complex, difficult to synthesize, and commercialize. Almost all OLED materials require the use of palladium catalyzed cross coupling reactions discovered by Professors Suzuki and Negishi. For example, emitters, host, electron transport chemicals (ETL), hole transport materials (HTL), and hole injection materials (HIL). all have used Suzuki-Negishi coupling for synthesis of materials in very high purity, yield, and lower cost.

The presentation will also discuss the most recent, exciting, and futuristic developments.

Modelling pixel crosstalk in AMOLED displays

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Cross talk between neighbouring pixels is a problem in high pixel density OLED displays. We employ the electro-thermal 2+1D Finite Element software Laoss [1] to estimate parasitic current and emission based on the pixel layout, sheet resistance of common layers and IV curves of individual sub-pixels.

High-end AMOLED displays demand high pixel density, in particular for applications like VR, micro-displays and mobile display. For example in recent smartphones over 500 pixels per inch (PPI) are found. Cross-talk between neighboring pixels becomes more challenging as the pixel density increases. We present a numerical modelling approach to quantify the cross-talk. A 2+1D Finite Element Model is used. This model allows to run calculations on a standard desktop computer. The simulations are done using the commercial software Laoss 1.2 [1].

A brute force 3D approach to model charge current flow in an AMOLED display is computationally intensive. We simplify the problem as coupled planar (2D) electrodes, locally coupled by the microscopic IV behaviour of individual pixels.

Lateral current transport is carried by the anode and cathode layer, we specify the geometrical layout of the anode and cathode by a standard CAD file (DXF format). Conductivity of the thin electrode layer is expressed by the sheet resistance of the electrodes (unit Ohm per square).

Current between the electrodes is assumed to flow perpendicularly through the OLED stack. Even at high pixel density the pixel area is of the order of 10x10 µm, 2 orders of magnitude larger than the stack thickness (~100nm).

As an example, we evaluate the pixel cross talk in an RGB AMOLED display with 400 PPI. A cross section of the pixels is shown in figure 1. The bottom electrode is structured and connected to the transistor backplane. Only the ON pixel is actively driven by a voltage boundary condition, while all other pixel anodes are considered floating. The continuous hole injection and transport layer (HIL-HTL) provide a path from the electrode of the ON pixel to the surrounding pixels. The cathode is also continuous and kept at ground potential in our simulation.
In our simulation we have used separated RGB IV curves reported by Kwon et al. [2] Note that the turn-on voltage of at the blue pixel is higher than for green and red pixels (as expected). This explains why the cross talk is most severe when driving blue pixels. In this study we focus on driving of blue pixels.

The result are shown in figure 2, where the blue pixel is driven.

At low driving voltages the cross talk luminance amounts to around 40% of the intended luminance. This means that actual luminance will be higher than intended and the colour will shift from the intended blue primary towards red and green.

We have modelled the cross talk in AMOLED display by a 2+1D FEM model. Our software can analyze the influence of pixel layout and material choice on the cross talk emission.

The proposed gate driver consists of driving and sensing shift registers to secure sensing time during display time. It enables to detect the characteristics of internal driving devices in a large OLED display panel. The proposed gate driver IC is fabricated using a 0.35µm HVCMOS technology with 3.3V/40V devices and it is applied to an external compensated 55inch OLED panel.

OLED panel is the current driving active matrix system in general. Thus the uniformity correction system is required in OLED display panel. Methods to improve the image quality of the OLED panel are internal and external compensation systems. The external compensation system has a simple pixel structure and high aperture ratio. So it is suitable for large size OLED panel.[1] In the external compensation system, an additional sensing time is required to measure characteristics of pixels. However it is difficult to secure sensing time during display time.

To overcome this problem, a new dual shift register gate driver is proposed to measure at least one gate line in a frame time.

Figure 1 shows that 1 frame time consists of driving time to address a panel and sensing time to detect the characteristics of devices. This sensing time is used to transfer the characteristics of the display panel to the measuring device for the external compensation system.

Figure 1: Configuration of 1Frame Time

The sensing time is limited by driving time as shown in figure 1. At least, one gate line must be sensed during the sensing time. However, the problem is that the shift register of the gate driver is located at the last gate line when switching from driving time to sensing time. In this case, the conventional one shift register gate driver is not suitable for sensing a panel because it takes much time to move the shift register to the gate line for sensing.

A new dual shift register gate driver with a driving shift register and a sensing shift register is proposed as shown in figure 2. The sensing shift register is shifted to predefine sensing gate line during the driving time, so that the entire sensing time can be used only for sensing internal driving devices.

Figure 2: Conventional and proposed gate driver

Figure 3 shows a gate waveform that senses one gate line in a frame time using the proposed gate driver in a UHD display panel (3,840 x 2,160). A total of 2,160 frame times are required to sense the entire pixels.
Figure 3: Gate pulse at driving and sensing process

Figure 4 shows manufactured gate driver IC. It is fabricated using a 0.35µm HVCMOS technology with 3.3V/40V devices. The chip size is 17,380µm x 1,080µm with 432 driving channel. The proposed gate driver IC size is approximately equal to conventional structure because the dual shift registers is designed with low voltage devices.

The proposed gate driver is successfully verified on an external compensated 55 inch OLED panel.

Figure 4: Manufactured Gate Driver IC


(Invited) Directly patterned, Ultra-high brightness 2K x 2K full-color OLED microdisplays

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We present performance details of a 2Kx2K resolution OLED microdisplay with directly patterned side-by-side RGB emitters enabling a high brightness of >5,000 cd/m². The microdisplay is built on a specially designed CMOS-based silicon backplane with a 9.3 micron pixel pitch and a fill factor of 57%. Through further enhancements, the color gamut is increased to meet sRGB and DCI-P3 requirements.

OLED microdisplays offer many advantages for immersive augmented and virtual reality (AR / VR) applications such as their high resolution, contrast ratio and pixel density in a low power, lightweight display. However, the extremely small subpixel size (<5 µm) precludes the use of fine metal masks to pattern RGB side-by-side emitters and has led to the use of white OLEDs with RGB color filters on top of the thin film encapsulation. These color filters can absorb up to 80% of the emitted light, significantly reducing power efficiency and limiting the peak luminance to below what is required for AR and VR. In this presentation, we will describe recent efforts to fabricate high resolution OLED microdisplays with directly patterned emitters capable of reaching the high luminance necessary for AR / VR applications.

OLED microdisplays were fabricated using metal masks for all organic layers with the exception of the RGB emitter layers which were directly patterned using eMagin’s proprietary DP technology [1,2]. A fluorescent blue emitter was used in conjunction with phosphorescent red and green emitters (Universal Display Corporation). Displays were then processed following a standard process flow.

In order to fully exploit the capabilities of the novel side-by-side DP OLED technology, a new backplane architecture was developed with full color 2Kx2K resolution on a 9.3 µm pixel pitch. The backplane was designed to deliver high peak luminance, wide dynamic range, high frame rates, and variable persistence.
operation. The backplane also included a new 4T-1C pixel driver circuit that supports high pixel density and improved silicon manufacturability. The features provided by the OLED DP technology and the new backplane are aimed at meeting the requirements of future VR and AR applications.

Figure 1A shows a close-up image of a DP 2Kx2K OLED microdisplay and Figure 1B shows the luminance versus array current measured on a box comprised of 12.5% of the display area. As can be seen, the luminance reached over 5,000 cd/m², exceeding the minimum requirements for most AR / VR systems today. A full color image of the 2Kx2K microdisplay is shown in Figure 1C.

Figure 1D shows spectra for a standard DP display and one in which additional color enhancement layers were used to narrow and shift the individual color emission to more saturated color coordinates. Displays with this enhanced color gamut method reached 133% of the sRGB gamut (98% DCI-P3).

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High efficiency cool white single stack hybrid OLED with blue thermally activated delayed fluorescent and yellow phosphorescent emitters

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In this paper, we report highly efficient cool white organic light-emitting diodes (OLEDs) based on blue thermally activated delayed fluorescent and yellow phosphorescent emitters. Our single stack hybrid OLED comprising blue-yellow-blue multi emitting layers exhibits very high maximum external quantum efficiency of 24.4% and current efficiency of 42.9 cd/A with cool white emission (0.33, 0.34) at the luminance of 1,000 cd/m².

White organic light-emitting diodes (WOLEDs) has received great attention as a crucial technology for realizing large-area active matrix OLEDs (AMOLEDs). For this application, the WOLED should have cool white emission with CIE coordinates of (0.33, 0.33), high external quantum efficiency (EQE), low operating voltage and high stability [1]. The mostly simple WOLED for achieving these requirements is single stack hybrid structure. However, low efficiency blue fluorescent emitter provides big efficiency sacrifice of phosphorescent yellow to be a cool white spectrum. Recently, thermally activated delayed fluorescence (TADF) materials attract a great attention as an alternative to blue phosphorescent emitter due to a higher possibility to achieve highly efficient and stable deep-blue emission. In this study a hybrid WOLED system with TADF blue fluorescent and yellow phosphorescent emitter is investigated for the solution to satisfy cool white emission and high EQE at the same time in the single stack architecture.

Figure 9 (a) Host and dopant materials of blue TADF and yellow phosphorescent EML (b) Current efficiency and EQE of WOLED. Inset: Electroluminescence spectrum and CIE coordinates of white OLED at 1,000 cd/m².

To realize cool white emission and high EQE in the single stack hybrid WOLED, blue-yellow-blue emitting layer (EML) comprising deep blue thermally activated delayed fluorescent (TADF) and yellow phosphorescent emitters is introduced as shown in Figure 1 (a). Due to efficient reverse intersystem crossing process in blue TADF emitter, almost 100% IQE from fluorescence is realized, which makes it possible to achieve cool white emission with high EQE from the single stack hybrid WOLED. Moreover, blue-yellow-blue multi-EML system can easily control exciton-forming ratio at the each EMLs by adjusting position and thickness of the yellow EML in blue EML thus emission intensities of both color can be controllable. Therefore, cool white emission can be obtained without exciton losses. The thickness and position of the multi-EML was optimized with the consideration of exciton-forming ratio and optical field profile at the emission wavelength of the each emitters in order to balance blue and yellow emission. As a result, our hybrid WOLEDs exhibits extremely high maximum EQE of 24.4% and current efficiency of 42.9 cd/A and cool white emission (0.33, 0.34) at the luminance of 1,000 cd/m² as shown in Figure 1 (b). This results demonstrate superiority of our hybrid WOLED compared to previously reported hybrid WOLEDs.

Single stack hybrid WOLED structure is demonstrated by utilizing blue TADF and yellow phosphorescent emitters for cool white emission with high efficiency. Through the optimization of blue-yellow-blue multi-EML structure,
maximum EQE of 24.4% and current efficiency of 42.9 cd/A with CIE coordinates of (0.33, 0.34) were achieved. Our WOLED architecture will be applicable to large area and high resolution AMOLED display.

This work was supported by the Human Resources Development program (No. 20154010200830) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and grants funded by the Korea government Ministry of Trade, Industry and Energy.


**MolecuLED™: Organic based down-conversion technology**

E Cohen and D Szwarcman

StoreDot Ltd., Israel

StoreDot’s innovative MolecuLED layer, containing color-conversion and color-enhancing compounds, is intended for manufacturers of LCD TV displays and mobile devices, designed specifically to integrate in any backlight display or within the LCD panel module using active matrix enabled LCD processes. Comprising proprietary organic molecules, StoreDot’s MolecuLED technology emits vibrant colors that exceed the DCI-P3 color gamut. Hereby we describe the technology and benefits.

The ability to generate the best colors through the TV screen has improved largely due to the development of the Organic LED (OLED) technology and the development of a new color conversion layer for a Liquid Crystal Display (LCD), later improved with Quantum Dots. OLED and Quantum Dots, are two competing technologies that provide superior TV image quality. Each technology has its own advantages and disadvantage– OLED has better contrast, while Quantum Dot technology has the potential of having better color gamut. OLED has major production yield issues, while QD technology involves the usage toxic materials and the need of protective barrier films leading to high cost. OLED has larger contrast ratio.

StoreDot has developed an attractive organic-based technology, known as MolecuLED™. This technology which is fully organic (no metals), is a color conversion layer that provides wide-color-gamut. The MolecuLED production process is simple doesn’t need clean room or inert environment requirements. In addition to the technology breakthrough that shows for the first time a fully organic and non-toxic color conversion layer, it is also very attractive with its cost offering which is merely 10% of the QD competing technology. The MolecuLED solution is based on StoreDot proprietary developed molecules, embedded in a film that can be easily integrated into the TV BLU or within the LCD panel module.

Organic based fluorescent molecules possess high QY, relative high absorbance coefficients and emission peak tunability over the visible spectrum dictated by the fluorophore structure and chemical environment. The main drawback of organic fluorescent molecules is the sensitivity of their excited state to chemical and physical alterations that lead to degradation or photo-bleaching of the molecule. For such reasons most of color conversion films for wide color gamut, with the exception of StoreDot MolecuLED™ are currently made with inorganic Quantum Dots. Such materials consist of toxic metals and costly processing, and require humidity barrier films.

By manipulating the molecular structure of each active molecule together with the tailored embedment matrix, the properties of these molecules are tunable to optimize the HOMO-LUMO parameters and activation energy of the emitting layer. The ability to optimize the molecular structure enables to tune not only the RGB color peaks, but also the FWHM, PLQY and photostability parameters.

We also show the feasibility of incorporation of MolecuLED film within a modified LCD panel structure to enable high flux photostability adequate for HDR content and showing long photostability life time.
Wedge guides for mixed reality spectacles
A Travis
Microsoft Corporation, USA

How do we get a high quality virtual image in a device that looks as good as designer spectacles? I will describe an approach based on an adaptive projector near the ear, a wedge guide that curves round to the eye and a holographic combiner that steers the pupil.

Wednesday 1 November

Session 2 - OLED organic electronics continued

(Invited) Organic vapor phase deposition (OVPD®) of OLED for organic display and lighting applications
P K Baumann, S Hartmann, D Keiper, M Long, M Gersdorff, M Schwambera and M Heuken
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Organic Vapor Phase Deposition (OVPD®) is a key-innovative technology to deposit thin films of organic small molecules. It offers many advantages in the fabrication of OLED's for organic display and lighting applications. In particular multilayer stacks can be deposited in one OVPD® chamber. Also the compositions and the deposition rates of the layers can be precisely controlled by the inert gas flow that carries the evaporated materials to the substrate. AIXTRON offers enabling solutions for R&D and high-throughput production on large scale substrate sizes. These are based on the close coupled showerhead (CCS®) - and Short Thermal Exposure Sources (STExS™) technologies, enabling ultra-high deposition rates, in combination with the OVPD® technology. The combination of these technologies ensures the achievement of highest material utilization and deposition uniformity. For a Gen8 deposition area a material utilization of greater than 70% and deposition uniformity of ± 2% have been achieved. Overall this enables 30-40% lower cost of ownership in the deposition process compared to conventional vacuum thermal evaporation (VTE).

We will present an overview of this innovative deposition technology and results from advanced OLED process development for organic display and lighting applications. In particular performance and lifetime of the OLED will be discussed.

OVPD® technology has been exclusively licensed to AIXTRON from Universal Display Corporation, Ewing, N.J. USA for equipment manufacture. OVPD® technology is based on an invention by Professor Stephen R. Forrest et. al. at Princeton University, USA, which was exclusively licensed to UDC. AIXTRON and UDC have jointly developed and qualified OVPD® pre-production equipment.
Recent progress in highly efficient blue TADF emitter materials for OLED displays

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After introducing thermally activated delayed luminescence (TADF) conceptually, we give a status report concerning blue OLEDs based on this technology. Great progress was achieved in the last years, allowing for rapid commercialization for display applications.

Organic light-emitting diodes (OLEDs)\(^1\) successfully entered mass market applications and are now being used on a routine basis in products such as cellphones and smart watches. Future applications may cover large TV sets, OLED micro-displays in virtual reality headsets and new developments such as bendable or semitransparent devices or OLED lighting. Still, there is work to be done: Due to material limitations, blue AMOLED pixels are currently lacking satisfactory efficiency. Moving from the first emitter material generation, fluorescence, to second generation materials showing phosphorescence, was the key to combine efficiency, stability and a proper color point for green- and red-emitting OLEDs. However, all attempts in the past 15 years to do the same with blue phosphorescent materials have failed so far, indicating that physical limitations exist.\(^2\)

The need for increased efficiency in blue pixels for AMOLED displays is addressed with organic thermally activated delayed fluorescence (TADF) emitters as replacement for conventional fluorescent emitter systems. This allows for a reduced power consumption while maintaining deep blue colour coordinates.

While the mobile display market is strongly shifting towards AMOLED technology in order to enable curved and flexible displays, the demand for highly efficient OLED emitters is growing to reduce power consumption and increase display resolution at the same time. Although there are efficient green and red OLED emitters in mass production today, there is no efficient blue counterpart.

CYNORA’s approach to provide efficient blue OLED emitters is based on TADF technology. TADF emitter systems allow for an efficiency increase of up to four times compared to conventional fluorescent systems by utilizing both triplet and singlet excitons for the emission of light. At the same time, they maintain deep blue emission, i.e. CIE\(y\) < 0.2.

Herein, we review our recent progress on blue emitting materials by presenting their optoelectronic properties in organic light-emitting diodes. CYNORA presents several new blue TADF-based emitters, reaching >20% EQE at 1000 nits with lifetimes LT97 of >90 h.

Fig. 1. TADF offers the possibility to combine the high efficiency of blue phosphorescence with the stability of fluorescence to create superior OLED products.

Improved operational stability of inverted organic light-emitting diodes using Sn-doped zinc oxide nanoparticles as an electron injection layer

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We are researching air-stable inverted organic light-emitting diodes (iOLEDs) to demonstrate low-cost flexible displays. To fabricate iOLEDs on a plastic film substrate, we developed the low-temperature process of depositing an electron injection layer (EIL). We demonstrated iOLEDs having a long operational lifetime using tin (Sn)-doped zinc oxide (ZnO) nanoparticles (NPs), which are formed at a low temperature, as an EIL.

Flexible displays prepared on plastic films are expected to be used as mobile terminals and rollable displays in the future. ZnO has been used as the EIL of iOLEDs to realize air-stable iOLEDs [1]. Since high-temperature processes are required for fabricating a ZnO layer by sputtering, only a film that has heat resistance is adoptable as the substrate. In contrast, ZnO NPs are promising candidates for obtaining efficient EILs by a low-temperature process [2]. However, little is known about the operational stability of iOLEDs using ZnO NPs. In this study, we demonstrated iOLEDs having a long operational lifetime owing to the use of Sn-doped ZnO NPs, which are formed at a low temperature.

Figure 1 shows the device structure of the iOLEDs. We fabricated the iOLEDs on indium tin oxide (ITO)-coated glass as the cathode. In Device 1, the EIL was formed by spin-coating an alcohol solution of ZnO NPs at 2000 rpm for 45 s followed by annealing at 120 °C for 30 s. The ZnO NPs was purchased from Sigma Aldrich (particle size 10–15 nm). In Device 2, an alcohol solution comprising a mixture of tin(II) acetate [Sn(CH3COOH)2] and ZnO NPs was spincoated at 2000 rpm for 45 s and then annealed at 120 °C for 30 s. In Device 3, ZnO was deposited using a MirrorTron sputtering system (Choshu Industry Co., Ltd.). After that, the ZnO layer was annealed at 400 °C for 1 h in air. After forming each EIL, the other layers were formed in sequence.

The luminance (L)–voltage (V) characteristics of the iOLEDs with different EILs are shown in Figure 2(a). It is clear that the driving voltage of Devices 1 and 2 with the ZnO NP EIL decreased significantly compared with Device 3 having a ZnO EIL prepared by the sputtering method. From these results, we can conclude that the electron injection efficiency of the ZnO NP layer is extremely high. Figure 2(b) shows the luminance–time characteristics of the iOLEDs under a constant dc current with an initial luminance of 1,000 cd/m2. It was found that the operational lifetime of Device 1 with the ZnO NP layer is shorter than that of Device 3. However, Device 2, having a ZnO NP layer mixed with Sn(CH3COOH)2, has almost the same operation lifetime as Device 3. Thus, the operation lifetime was improved by doping ZnO NPs with Sn. By employing Sn-doped ZnO NPs as EIL, we demonstrated an operationally stable iOLED, which can be driven by low voltage.
We found that an OLED having Sn-doped ZnO NPs in the EIL has a long operational lifetime and can be fabricated by low-temperature processes. This result indicates that devices can be fabricated on plastic films with low heat resistance.


Solution processed cavity control layer for high resolution AMOLED applications
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In this paper, we describe solution processed cavity control layer for the high resolution AMOLED applications. The fabricated red-green-blue devices with this cavity control layer show the spectral peaks of 464, 526 and 600 nm with similar current density performance.

Organic light emitting diodes (OLEDs) have been adopted at the thin and light weight display applications because of its own thin film feature. Nowadays, there are some efforts on high resolution AMOLED display with these merits for augmented reality (AR) and virtual reality (VR) applications. For these applications, especially AMOLED requires the low power consumption, the high luminance and the high resolution. To make high resolution display, it is necessary to adopt top emissive OLED (TEOLED) structure with micro-cavity effect. In such case red-green-blue sub-pixels are mainly formed with the different cavity control layers (CCLs) by fine metal mask (FMM) method. However, the high resolution OLED panels for AR and VR application need the small pixel pitch less than 10 µm. Hence, it is difficult to align between FMM and substrate with this pixel pitch. Many researchers have reported about the white OLEDs with color filter (CF) to solve the limitation but this structure has an issue about 60 % high optical loss by the absorption of CFs.

In this work, we suggest a new cavity control layer for the high resolution AMOLED. A soluble transparent conductive oxide (TCO) material is used as a CCL. To obtain the high efficiency for the low power consumption, two stacked white OLED structure with the fluorescent blue and the phosphorescent yellow emitters is applied to micro-cavity TEOLEDs. The fabricated red-green-blue TEOLEDs show the current efficiencies of 41.6 cd/A (6.9 V), 41.3 cd/A (7.4 V) and 1.9 cd/A (7.2 V) near NTSC color coordinates, respectively. Such excellent performances are attributed to soluble CCL with good hole transport property.

Based on an optical simulation, we design the blue TEOLED with two stack white OLED structure without CCL as following: Strong reflective anode/HIL/HTL/Blue EML/ETL1/n-ETL1/HIL/HTL/Yellow EML/n-ETL2/EIL/Mg:Ag/Capping layer.

Blue TEOLED shows the only spectral peak of 464 nm with the current efficiency of 1.9 cd/A by extraction of only blue color from white spectrum. In order to shift from 464 nm to green and red spectral region, 70 nm and 95 nm of CCL thickness are formed on the strong reflective anode substrates by the spin-coating before HIL deposition. Figure 1 shows the shifted spectral peaks of the fabricated green and red TEOLEDs which are 526 nm and 600 nm, respectively. At the given constant current density of 1 mA/cm², the driving voltages of 7.4 V and 6.9 V are still similar to blue device without CCL. The current efficiencies are 41.6 cd/A and 41.3 cd/A for green and red devices. It indicates that our soluble IZO works as HIL and CCL. Detailed analysis on our devices with solution processed CCL for high resolution AMOLED will be discussed in the presentation.
We present the solution processed CCL for the low power consumption and the high resolution AMOLED applications. The fabricated red, green and blue TEOLED are almost similar current density performance regardless of CCL. It makes two stacked TEOLEDs have the minimum driving voltage with the high efficiency. Our CCL also well facilitate to shift the spectral peak. We propose that our solution processed CCL can be a solution for high resolution side-by-side pixel patterning.

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Effect of external micro-cavity on the improved color purity in OLEDs

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Color purity of the emission has been improved by using an external micro-cavity in OLEDs. Angular dependence of the emission intensity and spectrum were investigated and it was clarified that the external micro-cavity is more effective than the internal microcavity. Color coordinate \((x, y)\) was improved to \((0.16, 0.68)\) and emission efficiency increased 1.5 times.

OLEDs are well known as a high performance flat panel display. A possibility of flexible and transparent panels are attractive for the next generation display. Internal quantum efficiency of OLED has approaches to 100 % by using phosphorescent materials. However, EQE remains \(\sim 20\%\) due to the poor light extraction. Recently, international standard called BT.2020 was announced in a 4K/8K TV, in which wide color gamut is required for color reproduciability. However, it is difficult to satisfy its requirement because of broad emission spectra in OLEDs. One of methods may be internal micro-cavity effect, which is often used for an enhancement of the emission intensity [1]. In this paper, we will discuss the external micro-cavity effect on emission color and efficiency.

Fig.1 (b) shows a normal structure, which consists of an ITO electrode, PEDOT:PSS hole-injection layer, NPB hole-transporting layer, CBP:Ir(ppy)3 emissive layer, Bu-PBD electron transporting layer (ETL) and an Al cathode. Fig.1 (a) is a proposed structure with external micro-cavity, in which the cathode has three layers consisting of semi-transparent MgAg, ITO optical buffer layer (OBL) and Ag film. We call it “Multi-cathode structure”.

Figure 1. Device structure of green light emitting OLEDs with (a) Multi-cathode and (b) Normal structure.

Fig.2 (a) shows a variation of emission spectra with the thickness of OBL \((d_{OBL})\) in MLC structure. Peak intensity and wavelength \((WP)\) strongly depend on the \(d_{OBL}\) because of the external micro-cavity effect, in which the distance between MgAg and Ag layers is a critical factor to determine the optical interference phenomenon. Fig.2 (b) shows optical characteristics such as luminance, WP and CIE-x, CIE-y as a function of \(d_{OBL}\). Luminance takes a maximum around 140 nm in \(d_{OBL}\). As for the color purity, CIE-x, y becomes better in the region above 100 nm in \(d_{OBL}\).

Figure 2. Thickness dependence of the emission spectra in the normal structure. Luminance, CIE color coordinate \((x,y)\) and peak wavelength in the spectra were shown in the right.

Fig.3 shows an angular dependence of the emission spectra (lower graph) at 110 nm in \(d_{OBL}\) and intensity distribution (upper graph) at 60, 110 and 160 nm in \(d_{OBL}\). Emission spectra becomes sharp and narrow accompanying with a forward directional emission by introducing an external micro-cavity. Half width in the spectra is only 40 nm. Color coordinates \((x, y)\) of the emission is \((0.16, 0.68)\) as shown in the right. Color purity is improved by introducing external microcavity effect. In addition the efficiency was increased by a factor of 1.5.
although the result is not shown here. These results can be successfully explained as follows. MLC structure makes it possible to reduce huge surface plasmon loss in the cathode [2] and evanescent mode is converted to the propagation wave. In result, external micro-cavity acts effectively for light extraction of this propagation wave.

Figure 3. Angular dependence of the emission spectra in OLEDs with external micro-cavity. Upper graph is angular distribution in different dOBL. Color coordinate is plotted on CIE diagram with RGB color standard.


High-efficiency, ultra-pure green perovskite light emitting diodes achieving rec. 2020 color coordinates

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Pure green light emitting diodes (LEDs) are essential to realize an ultra-wide color gamut in the next-generation displays, as is defined by the Rec. 2020 standard. However, because the human eye is more sensitive to the green spectral region, it is not yet possible to achieve an ultra-pure green electroluminescence (EL) with sufficiently narrow bandwidth that covers >95% of the Rec. 2020 standard in the CIE 1931 color space. Here, we synthesize colloidal quantum-confined hybrid perovskites and demonstrate efficient, ultra-pure green EL for the first time. The quantum-confined colloidal perovskite films exhibit a high exciton binding energy up to 200 meV, resulting in a high photoluminescence quantum yield (PLQY) of ~94% in the spin-coated films. Our optimized LED devices show a maximum current efficiency of 25.0 cd A⁻¹, outperforming the typical fluorescent organic LEDs and representing one of the highest values ever reported in perovskite LEDs. More importantly, we report the color coordinates of (0.170, 0.780), which covers 98% of the Rec. 2020 standard in the CIE 1931 color space, the “greenest” LEDs ever reported by far. We further demonstrate large-area (up to 3 cm²) and ultra-flexible (bending radius of 2 mm) LEDs based on the colloidal perovskites.
160x120 pixel passive matrix bottom emitting OLED displays with graphene anode layer

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In this paper, we describe a newly developed 160x120 pixel 1-inch bottom emitting PMOLED display in which multilayered graphene is employed as the transparent anode layer. Graphene was grown on a nickel thin film by chemical vapor deposition and then transferred on to a glass substrate. A phosphorescent small molecule organic material was used as the green emitting layer. Graphene based devices demonstrated high brightness and efficiency. Fabrication challenges originating from the graphene production scheme is discussed.

Graphene is one of the candidate materials to replace the standard material ITO as the anode of the OLED displays. A major shortcoming of ITO is its lack of flexibility, a sought after property for the future electronics devices and displays. The key advantages of graphene among other candidates are its extraordinary flexibility, high optical transmittance together with very low reflectance. It is believed that graphene has a lot of room to improve in its conductance. Other technical issues that needs to be overcome is relatively high surface roughness of graphene synthesized by chemical vapor deposition (CVD).

In this paper, we explain our research results towards the development of graphene based OLED (GOLED) displays. The displays are in bottom emitting, passive matrix structure with 160x120 green emitting monochrome pixels and have 20x15 mm active size corresponding to 200 dpi pixel density. Graphene used in the anode layer of the displays was grown on a nickel thin film substrate by CVD method and transferred on to glass substrates. The PMOLED pixels were formed by physical vapor deposition of organic small molecules and cathode on the integrated shadow mask fabricated across the anode lines. An image generated by the GOLED display using a commercial PMOLED driver circuitry is presented in Figure 1.

Figure 1: A partial image of the 160x120 GOLED display showing its pixels in detail.

Some of the device characteristics of the OLED pixels has been demonstrated in Figure 2. GOLED pixels can reach 1000 Cd/m² brightness level at around 6 Volts with 64 cd/A current efficiency and 35 Lm/W power efficiency. Comparative results for ITO and graphene anode devices in terms of performance, efficiency, color and lifetime will be presented in the talk. Display fabrication challenges regarding the defective pixel rates originating from the production of the technology of the graphene anode layer will also be discussed.

Figure 2: Current density vs voltage and power efficiency and current efficiency vs luminescence (inset) characteristics of the GOLED device.
In this paper, we describe a simple approach to the fabrication of a switchable multifocal lens for smart contact lenses or other compact devices. A combination of a multi-zone static multifocal lens with a liquid crystal based zone selector yields the desired optical behavior.

Tunable lenses without moving parts have received a lot of attention in the last decade [1], with applications ranging from endoscopy [2] over smart phones to corrective eyewear [3]. Existing implementations include Fresnel-like or other circular grating-like diffractive optical elements in combination with a layer of liquid crystal (LC). The electrical tunability of the refractive index of the liquid crystal is used to generate a lens with tunable optical power. Although proven, the concept has a number of drawbacks. First of all, the tunability only works for one polarization of the light. That means that either a polarizer has to be added, thereby reducing the light transmission and increasing the thickness of the whole system, or a second component, whose preferred polarization is oriented perpendicularly to that of the first one, has to be stacked on top of it, also adding to the thickness as well as to the complexity of the system. Secondly, both the operating voltage and the response time of this type of components are higher than desired, due to the non-uniform LC layer thickness and the voltage drop across the thickest parts of the circular grating. Finally, the diffractive nature of the component can lead to severe color dispersion and the vertices of the Fresnel-like structures lead to scattering of light, manifesting itself as haze.

Other implementations are based on the so-called electrowetting effect or on piezo electric actuators. These approaches also work, but require very high voltage levels [4].

In this paper a much simpler implementation is proposed that can be used in active multifocal contact lenses. It is known from optics theory that a fragment of a broken lens still has the same functionality as the complete lens. We can use this to our advantage by composing a new lens from fragments of lenses with different optical power. In the simplest case, we can cut two lenses in half along a diameter and then combine one half of one lens with one half of the other, to come to a combined lens with 2 powers. Such a lens will have two focal lengths at the same time, and when used in an imaging system, it will superimpose the images of both lenses. Passive multifocal contact lenses use this approach to help presbyopia patients. The brain filters out the unwanted image. Unfortunately, only 40% of all patients are able to get used to this type of lenses.
By integrating into the lens described in section 2 a light modulating liquid crystal device (2-pixel display in the simplest case) whose pixels coincide with the different lens zones, it becomes possible to actively block the light crossing the undesired lens region. That way, the resulting image will only be formed by the 'correct' part of the lens. The system can be extended by having three or more lens zones with different power. To avoid the need for a polarizer, the guest-host liquid crystal mode can be used for the zone selector. This LC mode combines a moderate driving voltage with a sufficient modulation contrast, compatible with contact lens integration.


An IPS-VA spatial light modulator architecture for foveating application

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A novel pixel architecture of In-Plane Switching with vertically aligned (IPS-VA) liquid crystal cell designed in CEA-LETI provides a beam-steering behavior for small-angles. This cell is implemented in a large Field-Of-View (FOV) foveation optics in order to improve the compactness while keeping high performances. A foveated system is simulated with Zemax software in order to evaluate the maximum performances of this SLM in such system.

Utilization of LCD could reduce complexity, size and price of wide FOV foveated optics system. Such system has been developed with LCD SLM (2048x2048 pixels) integrated in a monocentric optical system by Martinez et al.[1]. Harriman et al.[2] also developed an antiparallel aligned nematic liquid crystal SLM with (1280x1024 pixels) for the same use [2]. Although, none of these SLM have pixel pitch below 15 µm and no IPS technology are used. A lower pixel pitch allows finer discretization of wavefront by using more pixels while keeping the size of the SLM constant.

A new architecture of an IPS-VA LCD with 5 µm pixel pitch has been designed with LCDMaster 2D (Shintech Inc) with the FEM algorithm [3]. For an application as a Spatial Light Modulator (SLM) the performances of the Phase Shift/Optical Path Differences (OPD) and beam steering were investigated[4].

In this work, simulations of foveated optics system integrating this new SLM are made with raytracing software. The simulations are aiming to determine the system size and appropriate pixel number to reach the desired performances.

In a previous work, an ideal profile of phase shift/OPD has been simulated for 2 modules of 10 pixels at 550 µm. With this two modules, the correction was done modulo 2π for a refracted ray angle less than 0,63° on 10 pixels [4]. Taking into account these constraints, the maximum performances could be investigated in simulation by Zemax. The system in figure 1 is designed with a two steps approach. First, two spherical lens are chosen as a starting point for the optical system. The SLM, in idle state, is thus modeled as a plane-parallel plate. Lenses parameters (curvature(R), thickness(T)) are optimized in order to get the best image definition at the center of the field of view (dark blue) with the smallest spot size in order to use a small sensor. Secondly, the optimized parameters of the lenses are freezeed and a polynomial function is applied to the front side of the SLM. The wavefront behavior is reproduced and optimized to reach the best focus of the edge rays (azure) The RMS spot size = 2µm, this size become compatible with several standard sensors pixel size. It is also a strong size improvement for such a system.
The results in the figure 2 indicate that a correction between $1\lambda$ and $2\lambda$ is needed. It shows that the correction of these areas need at least a square between 10x10 and 20x20 pixels and so far it is reachable with our SLM with this pupil dimension. Further investigation will refine the results and different FOV will be tested with the exact number of pixels needed to cover the pupil.


Reverse mode switchable window assembled with inhomogeneous alignment surfaces

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In this paper, we describe a reverse mode switchable window with inhomogeneous alignment layer. The proposed smart window operates at a very low voltage (10~15V) but shows a very good haze state. The inhomogeneity on the alignment layer greatly enhances the voltage-on scattering effect.

The field of switchable materials is ever expanding with many types of new markets and technologies. This category covers any visible switchable technology useful for glazing, mirrors and transparent displays. Currently, the commercialized smart window is based on polymer dispersed liquid crystals (PDLC) [1], however, this type of window is working on high driving voltage (up to 50V) and operates at a normal mode leading to much electrical power consumed to keep a preferred clear state. Electrochromic (EC) windows and suspended particle device (SPD) windows are also the common types [2, 3], but which both suffer from a long switching time. Here, we propose a reverse mode window driven by a low voltage and owning very high haze state. The inhomogeneous surface with small amount of liquid crystal polymer (LCP) in filling LC together promote the scattering effect.

A LCP material with 20% concentration in a commonly used PGMEA solvent is spin-coated on ITO glass substrate, and then soft-baked at 100 °C for 5 min, giving a 650nm thick solid film (measured by Ellipsometer). In order to make an inhomogeneous surface, the substrate is covered by a mask with certain pattern (Fig. 1b) and exposed to UV light for 6min. The exposed regions are polymerized, while the covered areas can be erased by the PGMEA solvent. Therefore, the mask pattern can be precisely transferred to LCP layer. After that, a commercial vertical PI alignment layer was spin-coated on top as second layer and then heat-cured at 180°C for 60min. Thus, an inhomogeneous VA aligning layer is created.

Fig. 1. Inhomogeneous surface formed by regionally curing of LCP layer.

Two well-prepared substrates are sandwiched with the LCP bars perpendicular to each other. The cell gap was controlled at 5µm. The filling LC is negative type doped with a little amount of LCP (~5%). UV curing is needed again after the filling to polymerize the LCP molecules in cell to form a highly random network.

After the end sealing of the cell, 12V AC power with 1 kHz frequency is applied to the cell. Strong scattering comparable to a scotch tape appears at a fast speed (Fig. 2). The mechanism behind it is different from PDLC system, where a huge amount of polymer are required. In voltage-off state, the cell shows a clear state due to the vertical alignment. The average height and width of the surface roughness can be well-controlled to maintain a clear state and also enhance the scattering effect.

Fig. 2. The cell scattering effect.

In summary, a novel reverse mode switchable window is demonstrated. The inhomogeneous surfaces and the LCP network formed in cell together reinforce the voltage-on scattering. The ease of the processing further enables large-size and even flexible smart window fabrication.
A tuneable and switchable liquid crystal laser protection device

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The use of a liquid crystal Lyot filter as a simple and compact switchable laser filter is demonstrated. The filter OFF state exhibits a wavelength independent transmission and the ON state rejects a selected wavelength. The response time of the filter is < 110 ms, dependent on the rejected wavelength, with the ability for faster switching, < 5 ms, when using a lower order rejection band. A rejection tuning range of 480-640 nm is demonstrated, with the potential to operate outside of the visible spectrum. In the ON state the transmission at other wavelengths allows for partial observations through the filter even when in protection mode.

High-powered handheld lasers with high intensity and coherent radiation can dazzle and cause permanent damage to sensor systems. Such lasers are becoming increasingly easy to acquire and therefore, there is an urgent demand for protective devices.

Tuneable liquid crystal (LC) Lyot filters (Figure 1) have a wavelength dependent transmission spectrum, \( T = \cos^2(\frac{\pi\Delta n d}{\lambda}) \) [1], where \( d \) is cell gap, \( \Delta n \) is birefringence, and \( \lambda \) is wavelength. This is due to the retardance applied to light passing through aligned polarisers. The half wave-plate condition is utilised for laser protection, \( \lambda = \frac{d\Delta n}{(m - \frac{1}{2})} \), resulting in rejection of a specific wavelength.

Figure 6: A schematic of a LC Lyot filter is shown. The polariser and analyser are at 45° to the x-axis, whilst the LC director is aligned. Image redrawn from G. Yang et al. [2].

A planar aligned LC cell was filled with 4-pentyl-4′-cyanobiphenyl (5CB). The transmission spectrum, measured between 400-800 nm, was normalised with respect to the polariser and experimental losses. Voltages between 0-30 Vrms were applied, allowing variations in the transmission spectrum to be observed. The response times were quantified through photodiode intensity measurements. Testing of protection provided against a laser diode, \( \lambda=532 \) nm, was also evaluated.
Application of 30 Vrms results in the birefringence approaching zero, giving the OFF (transmitting) state. Removal of the applied voltage results in the ON (blocking) state, demonstrated in Figure 2(a).

Figure 2: (a) The transmission spectrum for a single stage LC Lyot filter for the OFF and ON state (30 and 0 Vrms). (b) The change in intensity for protecting against a laser diode, $\lambda=532$ nm.

Tuning is achieved over a wide spectral range by varying the applied voltage between 0.67-1.06 Vrms. Upon increasing voltage the spectrum blue-shifts and the rejected wavelength can be directly related to the voltage, $V$,

$$\lambda_{\text{ref}}(\text{nm}) = -471V + 976(\text{nm}),$$

allowing calculations of blocking voltages for specific laser wavelengths.

By coupling these abilities, the response time for switching to protect against common laser wavelengths, as well as between wavelengths, was measured to be between 45-130 ms. Laser protection testing, Figure 2(b), with a blocking voltage of 0.940 Vrms gave a response time of (60±10) ms.

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Optimization of thermoformed displays for smart contact lenses

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In this paper, the monitoring of the display cell gap of a spherical cap shaped liquid crystal display for smart contact lenses is described. This monitoring is important for further optimization of the display performance.

Over the past few years technological progress was made towards the development of smart contact lenses. Application fields for these contact lenses include virtual reality viewing, biomedical control and vision correction. Within the field of vision correction, for both focal-length related conditions as for iris conditions, smart contact lens solutions are being investigated. For the latter two applications a liquid crystal display (LCD) is presented as the main component of the used smart contact lens and a guest-host LCD is currently being developed by us. The first prototypes were described in [1] and further improvements and alterations are ongoing [2].

The current design of the display cells consists of two flexible, transparent substrates of polyethylene terephthalate (PET) separated by cylindrical spacers to assure a controlled and uniform cell gap. In initial designs, the spacers were made out of SU-8 resist and the cells were sealed using a UV glue only at the border of the cell. Recently, we reported the use of a photosensitive adhesive (PA-S321) which has the advantage of serving both as a spacer structure and as a glue, thereby allowing the spacers to be attached to both PET substrates and thus providing a more uniform cell gap. In order to fit the curvature of the eye, the display is also thermoformed into a spherical cap. Also here a controlled and uniform cell gap remains important for proper behavior of the liquid crystals allowing a desired display functioning.

As this cell gap is an important parameter for the optimization of the display, it was monitored during the process flow described in [2] before and after bonding, after laser ablation and after thermoforming. To bond the cell, a 50 µm thick PET substrate is put on top of a 75 µm PET substrate which is patterned with 10 µm high PA-S321 spacers and this stack is heated and pressurized using a wafer substrate bonder. Before bonding, the height of the spacers is measured using scanning white light interferometry. After bonding, after laser ablation and after thermoforming, the cell gap is monitored using cavity interferometry.

It was observed that the bonding step leads to an increase in the radial direction and a decrease of the height of the cylindrical spacer, thus resulting in a reduced cell gap. Moreover, the larger the initial radius of the spacer, the smaller its radial increase and height decrease. From this observation a relationship was deduced between the initial spacer radius and the cell gap after bonding, as illustrated in Figure 1 with an example for a 10 µm spacer radius.

After bonding, the display cells are cut out using laser ablation for which no influence on the cell gap is observed. After thermoforming an increase in cell gap was measured, but no unambiguous relation could be deduced to predict the cell gap change. This outcome can be related to the dimensions of the thermoforming mold which is designed for a cell gap of 10 µm. However, spacer structures with an initial height of 10 µm, become smaller during bonding, leading to a non-optimal pressure distribution on the mold. Further investigation and optimization is needed here.
Cholesteric window shutter with wide-band reflection

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In this paper, we propose a cholesteric window shutter that can adjust the indoor temperature by controlling the reflection and transmission of infrared region using cholesteric liquid crystal reflecting lights of wide spectra. Infrared (IR) with strong thermal action affects the indoor environment. In the summer, people pull down the blinds or curtains to prevent increase of the indoor temperature by IR, but then, visible light entering the room environment is blocked and we cannot see outside [1]. Thus, a functional window device that can control the transmittance of IR and visible light is needed newly. The specific pitch of the cholesteric liquid crystal (CLC) reflects lights of specific spectra by Bragg reflection [2]. However, the reflection spectrum of the conventional CLC is very narrow about 50 to 100 nm which is not sufficient to cover IR with thermal action. Therefore, in this paper, we present a wide IR-reflection-band window shutter for blocking heat more effectively. It is characterized by polymer stabilized network generated between negative CLC under strong vertical electric field which leads to local distortion.

To broaden the reflection spectrum of cholesteric liquid crystals, a photo-curable reactive monomer (RM) is used with a chiral material to make a polymerstabilized network in dual frequency liquid crystal (MLC-2048) and 20 µm cell thickness. In this case, the liquid crystal mixed with the RM and the chiral material becomes broader in the width of the reflection spectrum due to local distortion region whose pitch is decreased according to the voltage applied vertically in the negative dielectric constant region. In such experimental manner, we can obtain broad IR-reflection-band as shown in Fig. 1. It's bandwidth is approximately 450 nm that covers almost near-IR. As a result, we expect obviously that the electrically tunable and wide band CLC window shutter that reflects a wide band of the near-infrared can control indoor temperature very effectively by electric field. Therefore, it can be utilized as a functionally improved window shutter.

Figure 1: Reflection bandwidth widened by electric field.

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Liquid crystal micro-lens array assisted thin film photo-transistors flat panel imager

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We propose and demonstrate a concept of using a liquid crystal micro-lens (LCML) array to improve the image contrast of a pixelated thin film photo-transistors (TFPTs) flat panel imager, to image contents on a flat surface for displaying a magnified version for elderly or visually impaired people.

As estimated by the World Health Organisation in 2014 around 285 million people worldwide are visually impaired, of which 65% are aged 50 and over. In order for elderly and visually impaired people to read prints on papers such as books, newspapers, and product tags/labels more efficiently, electronic magnifying viewers are developed.

A high-resolution (254 ppi) active-matrix flat-panel imager has been demonstrated using poly-Si thin-film phototransistors (TFPTs) [1]. However, during the imaging process, outline of characters is blurry and image contrast between the background and characters is limited. In this work, we propose the use of a tuneable liquid crystal micro-lens (LCML) [2] array to improve imaging contrast of the TFPTs flat panel imager.

A ZEMAX simulation is carried out with a test pattern of black and white line pairs of 5 lp/mm. Each line corresponds to one column of TFPT pixels. The white lines are represented with a LED light source (un-polarised) of Lambertian distribution. The LCML array is represented with spherical plano-convex lenses.

Without a LCML array, light rays from the white lines will be detected by the corresponding TFPT pixels and neighbouring ones as shown in Figure 1(a), and the imager will have high crosstalk. With a LCML array, the LCML will converge much light towards the centre of the corresponding TFPT pixels as shown in Figure 1(b), and reduce crosstalk.

Simulated light intensities are normalised according to an equation and presented in Figure 1(c) for six columns of TFPT pixels, corresponding to three line pairs. The TFPT imager cannot resolve the line-pair pattern without the LCML. The column 3 and 5 pixels corresponding to black lines have higher intensity values than ones corresponding to white lines. With the LCML array, the imager can resolve the line-pair pattern with lower light intensities corresponding to black lines and higher intensities corresponding to white lines, which result in a valid contrast of 4% via .
The fabricated LCML array was tested experimentally on its own with a good light focus ability. When tested together with a TFPT imager, it showed that the contrast of the recorded images can be improved more than twice. The designed LCML arrays can be manufactured with an existing LC display assembly line with an additional laser machining step that is compatible with large scale production.


Liquid crystal on silicon technology for high-power high-resolution laser projection and non-display applications in visible spectral band

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We report about the implementation of liquid crystal on silicon (LCOS) high-resolution spatial light modulators (SLMs) for high-power applications in visible spectral band. We present data on reflectivity, electro-optical response, diffraction efficiency, contrast. The devices feature the reflectivity of up to 98% and can handle over 80W of optical power.

LCOS technology has many applications in both industry and consumer electronics [1]. Some of promising applications, e.g. laser material processing, high-power laser projection, automotive headlight would require the ability to handle the intensity levels exceeding 100W/cm² [2, 3].

The LCOS cell was implemented using vertically aligned nematic (VAN) mode, which suits well for both phase- and intensity-modulation applications. The high-reflectivity dielectric mirror was deposited on the backplane for the reflectivity improvement.

Figure 1 Reflectivity over spectrum for the high-reflectivity VIS panel

The reflectivity data over the spectrum is presented on the Figure 1. The reflectivity exceeds 98% in reddish part of the spectrum and is overall over 94% between 440 nm and 740 nm (with very little exceptions). The reference panel without the reflectivity improvement is shown on the same Figure 1 (in green color). The reflectivity value is oscillating around 70%. The phase response of the phase-modulating samples was evaluated and linearized. The Figure 2 is showing the linearized phase response measured at 633 nm (calibrated to 2.1π). The Figure represents the mean measured values as well as the maximum deviation for each of them. The standard deviation over all values was 0.01π.

Figure 2 Phase response (mean value and noise margins) in units of π at 633 nm versus addressed 8 bit values

The first tests on diffraction efficiency at 633 nm have shown 87% in the first diffraction order by using the 16-levels blaze grating. The zero order was 1.5% and the ghost order (-1) was 1%. The amplitude-modulating
panels have shown the contrast of 15000:1 using the He-Ne laser at 633 nm and the compensation plate (on-axis retarder).

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Session 4 - Quantum dots

(Invited) Aligned quantum rods for LC backlights with high color purity and high efficiency

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Quantum rods consisting of a CdSe quantum dot embedded in a CdS rod emit polarized light when illuminated with blue light. The nanorods are aligned parallel with each other by an electric field. A polymerized film with aligned quantum rods can be used in an LCD backlight in order to reduce the losses in the polarizers.

Red and green quantum dots are now widely used in LCD TVs to obtain pure colors. The quantum dots are embedded in the backlight and emit unpolarized red or green light with high quantum efficiency after excitation by the blue light of an LED. In this paper we propose the use of aligned quantum dots to generate polarized light and reduce losses in the polarizers. The alignment is realized by the application of an electric field over a dispersion and subsequent polymerization.

Electric field alignment of quantum rods Quantum rods with a length of 50 nm containing CdSe quantum dots (Fig 1d), are dispersed in dodecane and aligned in an electric field of the order of 15 V/µm. The quantum rods are charged and have an intrinsic electrical dipole moment. Because of the small size, Brownian rotation restores random orientation within a few µs (Fig 1a and 1b). The dynamics of the reorientation has been studied by measuring the variation of the absorbance A as a function of time in an ac electric field [1] as shown in Fig. 1c.

Figure 1: Alignment of quantum rods; a) random orientation at zero field; b) full orientation for V applied; c) variation of absorbance and electric field; SEM image of nanorods
Different methods for the alignment of nanorods have been reported in literature. In this paper we describe methods based on the alignment in an electric field. In one approach an ac voltage between interdigitated electrodes is applied during the evaporation of the solvent [2]. In a second approach the quantum rods are embedded in a liquid crystal, which is polymerized during the application of an electric field [3]. In this approach aggregation of quantum rod is avoided. A free-standing polymer sheet emitting polarized photoluminescence has been demonstrated. This sheet can obtain similar color saturation and efficiency as quantum dot sheets that are currently used in LC backlights, but the losses in the polarizer can be reduced considerably, by using the design in Figure 2.

Figure 2: a) free standing polymerized foil with polarized photoluminescence (central region); b) backlight design with blue LEDs and aligned quantum rods

In this paper we demonstrate that quantum rods can be aligned in an electric field and immobilized by polymerization. The result is a thin film that emits polarized light and greatly reduces the losses when used in the backlight of an LCD.


Efficient quantum dot light-emitting diodes fabricated using ZnS-AgInS2 solid-solution nanocrystals as cadmium-free quantum dots

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Quantum dot light-emitting diodes (QD-LEDs) using ZnS-AgInS2 solid-solution (ZAIS) nanocrystals as cadmium-free QDs were fabricated and their electroluminescent properties were investigated. The QD-LEDs fabricated using ZAIS emitted red light under DC voltage bias. External quantum efficiency was 1.6% which was one of the highest values reported for Cd-free red QD-LEDs.

Quantum dot light-emitting diodes (QD-LEDs) fabricated using CdS- or CdSe-based QDs have been reported to exhibit highly saturated color emissions and high external quantum efficiencies (EQE) over 10% [1]. However, the utilization of these QDs in practical devices has been severely limited due to the content of toxic element Cd and thus, it is desired to develop Cd-free QDs. Torimoto et al. reported a novel strategy to synthesize ZnSAgInS2 solid-solution nanocrystals (ZAIS NCs) via a facile solution route [2]. In this study, we achieved efficient Cd-free QD-LEDs by adopting efficient ZAIS NCs and optimizing the device structure.

ZAIS NCs with different fractions of the ZnS were synthesized by the previously reported method: The precursors of Ag(CH3COO), In(CH3COO)3, and Zn(CH3COO)2·2H2O with a mole ratio of x:x:2(1-x) were reacted with thiourea in a mixture solvent of oleylamine and 1-dodecanthiol at 250 °C for 10 min [2]. By changing the value of x, we could control bandgap of ZAIS NCs. ZAIS with x= 0.7 emitted red photoluminescence (PL). Two types of QD-LEDs using ZAIS NCs, which consist of inverted and conventional structures, were fabricated (Figure 1).

The quantum yield of PL (PLQY) for synthesized ZAIS NCs (x=0.7) was 74%. Figure 2 shows the PL spectrum of ZAIS NCs (x=0.7) in n-hexane and the electroluminescence (EL) spectra of the devices. The EL spectra showed broad peaks in the wavelength region from 500 to 800 nm, originating from ZAIS NCs. Figure 3 shows the voltage–current and voltage–luminance characteristics of devices I and II. The threshold voltages for emission were approximately 2.0 and 3.6 V for devices I and II, respectively. Device I showed a very low threshold voltage because the current of device I was very high, which results from the high electron mobility of ZnO. The luminance of devices I and II reached approximately 200 cd m-2. The EQE of devices I and II were 0.18 and 1.6%, respectively. The EQE of 1.6% is much higher than that of previously reported QD-LEDs with similar QDs of zinc-alloyed silverindium-sulfide nanocrystals (EQE=0.02%) [3]. The improvement of EQE in our devices was achieved because of the high PLQY of ZAIS and the optimization of the device structure and materials.


In this paper, we study the performance changes of the InP quantum dot light-emitting diodes (QLEDs) depending on the charge carrier balance in inverted device structure. Different conditions of quantum dot (QD) layer and carrier transport layer were considered to improve device performance and stability.

Quantum dot light-emitting diodes (QLEDs, or QD-LEDs) has been actively researched due to the potential impacts to display and lighting industry base on the unique properties of quantum dots (QDs) itself such as size-dependent bandgap tunability, narrow emission spectrum, and low-cost solution-based processing [1]. However, the most of promising results used cadmium (Cd) contained II-VI semiconductor nanocrystals. Therefore, a considerable future task is to substitute Cd-containing QDs with less toxic materials such as InP-based III-V semiconductor [2]. However, the performance of QLEDs fabricated with InP-based QDs still need lots of improvements. Here, we investigated the performance of inverted QLEDs fabricated with synthesized InP/ZnSe/ZnS QDs and ZnO NPs in terms of charge carrier balance, considering the thickness of QD film.

The InP/ZnSe/ZnS multishell QDs were synthesized by a simple and reproducible heating-up method [2]. The inverted QLEDs were fabricated with the following structure; ITO/ZnO/QDs/HTL/MoO3/Ag. The ZnO nanoparticle and QD layer were deposited by spin-coating, and the hole transport layer (HTL) and MoO3/Ag layer were thermally evaporated.

In order to design high-performance QLEDs using InP-based QDs, the charge carrier balance is the most important factor. Since InP/ZnSe/ZnS QDs have heterojunction structure of type I and the QDs are capped with the organic ligands, the thickness of QD layer in the device has a significant effect on the charge carrier balance. First, there is a trade-off between maximum luminance and efficiency with different QD layer thickness, shown in Figure 1. Second, a reverse optimization trend is observed depending on various QD layer thicknesses. These trends are originated from the change of exciton recombination zone (RZ) in the multilayered device structure. The RZ moves to near of ZnO/QD interface when the device is fabricated with thinner QD film; however, the RZ changes to near of QD/HTL interface with thicker QD film. Since the hole mobility of InP/ZnSe/ZnS QD is slower than the electron, the hole transport would be more hindered than the electron as the QD layer thickness increases, which consequently changes the carrier balance and the charging behavior in the whole device system.

InP/ZnSe/ZnS QDs are the promising candidate for the Cd-free QLEDs. The thickness of QD layer changes the carrier balance trends in the multilayered device structure by locating the RZ in different region, which also influences the carrier charging behavior of the QLEDs.

The authors thank Mr. C. Pries and Dr. C. Ippen for helps in QD synthesis.
Colloidal quantum dots (QDs)-based light-emitting diodes (QD-LEDs) have been intensively researched due to the potential impacts to the display and lighting industry based on the unique properties of QDs itself such as size-dependent bandgap tunability, narrow emission spectrum, and low-cost solution-based processing. In this paper, we present our concepts for a full color QD-LED display in which the green and red QDs are realized with Indiumphosphid (InP) and the blue ones with Zincselenide (ZnS). Finally, all solution-based layers can be easily ink-jet printed.

The performance of QD-LEDs has been increased enough to compete with phosphorescent OLEDs (PhOLEDs) by the combination of various device structure (inverted) and charge transport materials. However, the most of promising results used cadmium (Cd) contained II-VI semiconductor nanocrystals. Therefore, a considerable task was to substitute Cd-containing QDs with less toxic materials. InP-based QDs is a promising material among the III-V semiconductor nanocrystals.

InP-based QDs have been identified as most material for green and red emission in displays, but have lagged behind in terms of efficiency and low FWHM (Full Width at Half Maximum). In recent years, we have developed a method to improve the luminescence efficiency of InP QDs by coating a ZnSe/ZnS multishell instead of a ZnS single shell. ZnSe exhibits an intermediate lattice constant of 5.67 Å between those of InP (5.87 Å) and ZnS (5.41 Å) and thus acts as a wetting layer. The ZnSe shell is synthesized e.g. from zinc stearate and triocetylphosphine selenide, the ZnS shell from zinc stearate and cyclohexyl isothiocyanate. Both reactions are carried out at 280 °C and in a one-pot fashion, i.e. without intermediate particle purification [1].

By changing a few synthesis parameters like concentration, temperature or amount of ripening agent, we obtain differently sized InP QDs suitable for efficient QD-LEDs with green, yellow and red emission color, which show excellent color purity exceeding the sRGB color gamut [2].

Further we substantially improved the purity of our InP QDs, which finally led to highly efficient QD-LEDs with current efficiency over 11 cd/A and luminance up to 24,000 cd/m² for red (610 nm).

For blue QD-LEDs, we employed colloidal ZnSe/ZnS QDs in a slightly adjusted device structure with a first promising luminance of about 25 cd/m².[3]

With ink-jet printing you can print very easily any type of pixels of different shape and size for display application. An InP based QD-QLED hybrid device has been assembled using InP/ZnSe/ZnS multishell QDs. The devices were assembled successfully by inkjet printing of these QDs to thin films, using N,N'-Bis(3-methylphenyl)-N,N'-diphenylbenzidine (TPD) as hole transport and 2,2',2''-(1,3,5-Benzinetriyl)-tris(1-phenyl-1-H-benzimidazole) (TBPi) as electron transport material (evaporated) in the device, respectively. PEDOT:PSS (Clevios™ CH8000, Heraeus) has been used as hole injection layer and was also inkjet printed.

Finally, we show how InP QDs can be used to realize advanced display applications like flexible QD-LEDs, semitransparent QD-LEDs as well as a 40x40 pixel passive matrix display panel. [Figure 1]
We like to thank the Korean Ministry of Knowledge and Economy and the BMBF project 13N14421 in Germany.


Session 5 - 3D Displays and NTE technologies

(Invited) 3D display development at NTU's advanced displays laboratory

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The Advanced Displays Laboratory (ADL) is developing various types of viable glasses-free 3D displays. In this paper, we give a brief history and state of the art of 3D displays in order to put the different approaches in context, and then describe why we have chosen stereoscopic, light field and super multiview (SMV) displays as suitable candidates. Finally, we will describe the various displays under development and future plans for these.

Certain display types were not considered as being viable for a mass-market product that will be available within the next decade. Holographic displays are currently too complex and their image volume too small to be considered. Volumetric displays tend to have large and complex hardware, and simpler constructions generally show transparent images, rendering them unsuitable for the presentation of natural images. Light field displays in some embodiments have a compact structure and do not require a massive bandwidth, but others where, for example, a large number of projectors are used, are deemed to be impractical for widespread commercial use.

Prototypes of three types of glasses-free 3D display are under development at ADL. For each type, two approaches are being investigated.

The light field display (Figure 1) comprises two or three layers where the image on the back display passes through one or two transparent layers in order to provide a hologram-like light field display [1]. The processing to produce the images is computationally intensive and work is ongoing to make the processing capable of running in real-time. We are perfecting the required algorithms to improve depth of field, viewing angle and image resolution. We are also investigating a horizontal parallax only version where the computation speed is increased.

Another of our approaches uses head position tracking in order to control an active LCD backlight [2]. There are two systems under development; one of these uses a high-density LED array to provide a series of independently moving sets of exit pupils that follow the eyes of several users over a large viewing region. The same function, but with the use of a white laser and fast spatial light modulator (SLM) is also being developed in another prototype.
Current content can be used and the prototypes in the lab incorporate stripped-down 3D televisions that are synchronized with the backlight.

A longer-term system is the SMV display [3] that potentially provides a very large number of views using a fast OLED display and spatio-temporal multiplexing. This requires the development of novel components including a light steering screen. The ultimate aim of the work is to produce a display that can give in excess of 100 views but within the dimensions of a flat panel display. A capture and processing system that can handle the large amount of information necessary by utilising redundancy is also being developed.

As a suitable fast flat panel is currently only available in a small size (2.8") a high frame-rate pico projector version is also under development.

In addition to the direct-view glasses-free displays, we are also investigating near-to-eye displays as these will play a more important role as displays in the future.

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The extent of the image volume is important in 3D displays as although a relatively pleasing image is obtained with a depth in the order of tens of millimetres, a much more realistic and immersive experience is obtained with depths that occupy a greater proportion of the viewing distance. In this presentation, we define the derivation of the units required to express the extent of the volume.

The limitations are determined by criteria that are dependent on the display type. Images that display a separate image to the left and right eye are referred to here as 2-image displays and these give better performance when crosstalk is a minimum. These displays do not exhibit motion parallax. All other displays are referred to as motion parallax displays and include; volumetric, multiview, super multiview (SMV) and light field.

The criteria determining image volume size are completely different for each basic display type. For 2-image displays, the criteria based on accommodation/convergence conflict effects are well established and for motion parallax displays, new criteria and definitions are determined here.

The depth of field of 2-image displays is determined by the accommodation/convergence conflict (A/C conflict) problem. To avoid visual fatigue, the disparity must be kept within certain limits and this is the subject of research by several other authors.

A definition for DOF is given in the SID manual on display measurement but there is no explanation of how this is derived. Different display types in this class must be accounted for. The determination of viewing volume of volumetric displays is simply determined boundary of the swept volume of the real or virtual that forms the image.

In multiview and SMV displays, a series of discrete images is produced across the viewing field at the optimum viewing distance (OVD).

The formation of the zones requires the display to have angular resolution where the light from a given point on the screen varies with direction. Expressed in radians, the angular resolution is the viewing zone width divided by the OVD and is equal to the angular resolution A that enables image formation within the volume of space around the screen.

We introduce the concept of precision for screen resolution. In Figure 1(a), consider an edge in the scene that is displayed in the plane of the screen. Dependent on its exact position, it might be displayed at either of the lower red arrows; in this case the precision of the display is the distance between the arrow tips and is clearly the pixel pitch. We can now extend the idea of precision into the image space where the precision S is the distance D of the edge from the screen multiplied by the angular resolution in radians and the edge could appear at any of the upper blue arrows.

\[ S = P + AD \] .......(1)

Where: \( S \) = lateral precision in image space, \( P \) = precision of display screen, \( A \) = angular resolution (radians), \( D \) = distance from screen
This situation is more complicated in a slanted lenticular multiview display where multiple edges are seen (Figure 1(b)) giving multiple discrete values of $A$; in this case it must be decided which angle is used for the definition of DOF.

In some light field displays, notably the multi-layer Tensor Display and the Holagrafika display there are not the quantised pixels as such that conventional displays have. However, these displays behave as low-pass filters, so in this case it is most appropriate to give performance in terms of spatial cut-off frequency in units of cycles/metre and angular output in terms of cycles/radian.

We propose in this paper that definitive criteria should be applied to the measurement of 3D display viewing field volume and suggest this is based on either image precision for multiview, and spatial and angular cut-off frequencies for certain light field displays. The concepts described here are used as the basis for measurement techniques that will be described in the Conference presentation.

**Dynamic 3D sequence capture and enhancement**

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Highly accurate acquisition of dynamic, textured 3D models is still an open issue in the area of computer graphics. In this paper, we describe a new method for the capture of dynamic 3D meshes, relying on a multiple depth and color cameras. We evaluate the accuracy of the proposed method by means of calibration objects of a known geometry and size.

While images and videos are widely used to represent the scene, the only way to faithfully represent objects is via textured 3D models. In the last few decades various methods for 3D capture have been proposed. Some of these methods are passive, like stereo, shape-from-motion, shape-from-(de)focus etc., meaning that energy is not radiated towards the scene. The other class are active methods, which means that energy is radiated to measure the 3D profile of the object in the scene. The second relevant classification of 3D capture methods is according to their capability to capture dynamic scene. While highly accurate 3D capture of static scenes is possible using laser scanners, these are still not capable of capturing dynamic scenes.

Recently, an improved camera for joint capture of 3D and color information, based on time-of-flight principle was presented in [1]. Although the accuracy of this type of camera is not as high as the accuracy of laser scanners, it is capable of acquiring a sequence of 3D snapshots of the whole scene. Using intelligent processing, it is possible to improve the accuracy and the resolution of the 3D information provided by the camera. Moreover, using multiple of these cameras it is possible to acquire a complete, dynamic 3D profile of the object in the scene.

While in the past most users of 3D visualization were professionals, in the recent years wider audience started showing interest in this type of content, due to the availability of low-priced 3D visualization devices like Google Cardboard in combination with smartphones. However, content viewed on these devices is mainly artificial, which reduces its attractiveness for the user.

In this paper we present a system for multiview 3D reconstruction of dynamic scenes and objects. The proposed system uses a hybrid setup consisting from three Kinect One cameras [1] and three DS325 [2] cameras to provide a full 360° 3D profile of the object. Assuming that the intrinsic parameters of the camera are known, we perform joint extrinsic calibration using a spherical target object. Once extrinsic calibration of depth and color camera set is completed, we perform 3D reconstruction of the scene.
In order to achieve the best possible quality of the reconstructed 3D objects, we combine 3D information acquired using depth cameras with the sparse multi-stereo matching of color images. Moreover, information from depth cameras is also used to initialize the sparse multiview stereo matching. To introduce additional details in the reconstructed 3D model, we rely on the high frequency content from color images. To prevent the mapping of details contained in the color image we rely on jointly learned filters, which rely only on high frequency content from the color image, collocated in both depth and color to perform the upsampling of the depth image. In order to obtain temporally stable 3D meshes we perform temporal filtering over the estimated motion trajectories. Using the motion trajectory information, we were also able to increase the density of the estimated 3D information.

Finally, we evaluate the accuracy of the proposed method using a benchmark object of a known size.


MicroLED displays: Hype and reality, hopes and challenges

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With the increasing success of OLED, and mounting interest in QLED, emissive technologies have already proven their worth and enabled a variety of consumer products with stunning display performance. But microLED could very be another disruptive display technology for a variety of applications. Since the acquisition of startup Luxvue by Apple in 2014 and that of InfiniLED by Facebook-Oculus last year, inorganic LEDs have generated a lot of attention.

Compared to existing LCD and OLED displays, microLEDs offer the promise of high brightness, dramatically reduced power consumption and improved image quality. MicroLED displays could serve the needs of and benefit most applications, spanning from wearable and mobile devices to AR/VR, TVs and even large video displays as demonstrated recently by Sony. So what's missing? The science is here, but the success of the technology will depend on overcoming a variety of engineering and manufacturing challenges.

The presentation will provide an overview of \( \mu \)LED display technologies, key benefits and drawbacks, technology challenges, industry landscape and market opportunity.
Printed top gate metal oxide semiconductor thin film transistors

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This work describes top gate bottom contacts staggered oxide semiconductor TFTs manufactured by using only one lithographic step for source-drain electrodes patterning, followed by inkjet printing of the other structures. The presented process is particularly time and costs saving, and still yields to good performant TFTs, with mobility values in the range of 2 to 6 cm²·V⁻¹·s⁻¹ and an on-off current ratio going from 10⁴ to 10⁶.

Compared to well-established amorphous silicon (a-Si) TFTs, amorphous metal oxide TFTs have better device performance such as higher mobility, better sub-threshold swing, and lower off-state current [1]. While many printed OTFTs have been reported [2, 3], there are relatively fewer studies investigating printed metal oxide TFTs. Presented TFTs with printed metal oxide, up to this point are manufactured by using high annealing temperatures typically 500 °C to 600 °C [4]. In this work, not only a metal oxide ink, iXsenic, an Evonik product, has been inkjet printed, but also the gate insulator and the gate structures are inkjet printed too. This particularly simple process uses a maximal temperature of 300 °C, which ensures more compatibility with panel industry requirements.

Figure 1 illustrates the setup of the manufactured TFTs, and a microscope picture of a printed TFT. Indium tin oxide (ITO) source-drain electrodes are sputtered onto glass substrates and structured by photolithography. This fulfills the high resolution requirement on the TFT-channel dimensions, which can’t be met by the inkjet printing. Afterwards the semiconductor is printed using a Dimatix 2800 inkjet printer. The semiconductor iXsenic-ink contains mainly an Indium oxoalkoxide precursor. It is annealed at 300 °C. Afterwards the dielectric material is also printed using the Dimatix printer, and then annealed at 150 °C. Two organic materials were used in this study: SU-8 and Zeocoat ES2110. The printing process was in both cases optimized in order to achieve a homogeneous insulator layer. And at last a silver nano-ink: Metalon JS-B40G is printed as gate structure and annealed at 200 °C.

Figure 10: Cross-section of a top gate TFT

Figure 2 shows typical printed TFT characteristics, on the left with SU-8 as dielectric and on the right with Zeocoat.

The mobility of the printed TFTs is in the range of 2 to 6 cm²·V⁻¹·s⁻¹, the SU-8 TFTs have slightly better mobility values but lower on-off current ratio, about 10⁶ compared to 10⁵ to 10⁶ in the case of Zeocoat TFTs. The threshold voltage is positive mainly in the range of 1 to 3V.
The so-manufactured TFTs have the optimal channel dimensions, because of the use of the lithographic step, and still offer a huge gain of time, material and costs because of the additive patterning of the other structures. The performance is good enough, and almost comparable to sputtered metal-oxide TFTs. This mainly maskless and non-vacuum process presents a very attractive future alternative for the panel industry.


Formation of polymer structures for mechanical stability in a flexible light shutter

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We fabricated flexible light shutters with polymer structures. They use light scattering and absorption at the same time so that it can hide objects behind a see-through display panel and provide a black color. Polymer structures were formed for mechanical stability in a flexible light shutter.

Recently, flexible see-through displays have been considered as one of the next-generation displays. Among flexible see-through displays, organic light emitting diodes (OLEDs) have been actively studied [1-2]. However, they may suffer from poor image quality because of their transparent window area. To provide high-quality images in a see-through display, we need to hide objects behind a see-through display and obtain the black color by positioning a flexible light shutter behind a flexible see-through display. We fabricated light shutters with polymer structures on flexible substrates and confirmed their mechanical stability against bending.

Polymer structures formed for mechanical stability of a flexible light shutter effect electrically switching of liquid crystal (LC). In the initial state, the light shutter is transparent because LC and dye molecules are aligned vertically by homeotropic alignment layers. In this state, light scattering and absorption by LC and dye molecules are minimized. It can be switched to the opaque state by applying an electric field between the two substrates. In this state, LC and dye molecules are randomly oriented because of the polymer structure. Light scattering and absorption by LC and dye molecules are maximized in the opaque state.

To improve mechanical stability against bending of flexible light shutters, we use polymer structures, such as polymer-stabilized LC (PSLC), polymer-networked LC (PNLC), and polymer-walled LC (PWLC). Because these polymer structures support to maintain the cell gap uniformly when a flexible light shutter is bent. To confirm the mechanical stability of flexible light shutters with polymer structures, a cell was attached to a cylinder with the
diameter of 30, 50, and 70 mm for 24 hours. After 24 hours, it was detached from the cylinder and we measured electro-optic characteristics of the light shutter. It was compared with electro-optic characteristics of the light shutter before bending. If its mechanical stability is insufficient to bear against bending, the degradation of electro-optic characteristics can be observed. As a result, we found performance degradation in a PSLC light shutter. However, there was no degradation in PNLC and PWLC light shutters. Electro-optic characteristics of a PNLC light shutter before and after bending is shown in Fig. 1.

We fabricated flexible light shutters with polymer structures. We confirmed mechanical stability against bending. They can hide objects behind a see-through display panel. We expect that they can be applied to various smart window devices.

Fig. 10. Electro-optic characteristics of a PNLC light shutter before and after bending the cell for 24 hours.

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**Patterning process of silver nanowire networks for flexible displays and sensing applications by using field-assisted nanowire chaining**

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We present a new patterning technique, field-assisted nanowire chaining, for fabricating transparent electrodes (TEs). This patterning technique is compatible with both rigid and flexible substrates. We fabricated TEs with 96% transparency and Rs = 70 Ωsq⁻¹.

Indium tin oxide (ITO) is commercially used in many displays and touch screen devices, providing the best electrical and optical properties. However, the high material and manufacturing costs for large ITO panels motivates work towards alternate transparent electrodes. Recent studies show that nanowires (NWs) can provide better flexibility than ITO and therefore many research efforts have focused on fabricating transparent electrodes (TEs) using NWs [1,2]. Reliable, simple and cost-effective patterning techniques that provide large-area coverage are sought for fabrication of optoelectronic devices.

We have developed a technique to fabricate high performance flexible as well as rigid TEs by creating multiple long chains of NWs on glass or polymeric film [3]. We use dielectrophoretic (DEP) force [4], a force exerted on polarizable NWs in a medium, to connect NWs and create long chains of NWs. This is a cost-effective technique and the fabrication cost does not scale up with the size of the substrate.
Figure 1 (a) shows rigid transparent electrode with X-pattern metal lines and Y-pattern NW chains. Figure 1 (b) shows Y-pattern NW chains on a polymeric substrate. A second layer of polymer with X-pattern can be stacked on top of the Y-pattern layer. Using field-assisted NW chaining, we can pattern substrates with different geometries such as parallel or criss-cross lines of chained NWs without using a laser ablation process.

In field-assisted NW chaining [3], NW-NW connection is directed by dipole-dipole interaction as well as DEP force, and therefore, less NW concentration can be used to achieve a required sheet resistance compared with NW spray or spin coating processes. By tuning the concentration of NWs, we fabricated flexible and rigid TEs with light transmission of more than 90% and sheet resistance less than 100 Ωsq⁻¹.

On a rigid substrate, metal lines are patterned using photolithography. NW chains are generated by applying an AC electric field to the metal lines while NW suspension is introduced to the substrate.

Figure 1: (a) SEM image of metal lines and NW chains on a rigid substrate. (b) NW chains on a polymeric substrate, (c) peeling the flexible TE.

In flexible TEs, a polymeric layer is coated on top of interdigitated electrodes, to which an AC electric field is applied. After introducing NW suspension on the polymeric film, NW chains are created on the polymer. A second layer of polymeric substrate with NW chains can be stacked on top of the first layer followed by peeling the multi-layer TEs (Figure 1 (c)) and transferring them to a desired substrate.

This work was financially supported by Canadian agencies NSERC, CFI, BCKDF and MITACS and made use of the 4D LABS at Simon Fraser University.


Holographic optical elements (HOEs) provide transparent and narrow band components with arbitrary incident and diffracted angles for near-to-eye commercial electronic products for augmented reality (AR), and virtual reality (VR). Luminit is currently emplacing the manufacturing capacity to serve this market, and this paper will discuss the capabilities and limitations of this unique facility.

Compared to HOEs, conventional optics present several disadvantages for near-to-eye commercial electronic products for AR, and VR. Refractive and reflective optical systems are heavy, bulky and nonergonomic. The nonergonomic designs are a consequence of being limited to the laws of refraction and reflection. HOEs are thin and can be custom fabricated for ergonomic input and output angles with relative ease. The flexibility provided by HOE fabrication allows production of an attractive, conformable, useful, and easy to use consumer electronic product. Volume HOEs operating in the thick regime are especially suited to provide the required transparency while overlaying the images with high efficiency. Although surface relief diffractive optical elements are easy to manufacture by embossed replication, they add scattering and multiple diffraction orders, causing ghosting, reducing efficiency, and compromising see-through operation.

Recording in holographic media results in a spatial modulation of the refractive index of the host material, as shown in Figure 1.

![Figure 1: (Left) HOE parameters. (Right) Interferometric recording setup (from)[2].](image)

The modulation is induced by interfering two wavefronts that give rise to an interference pattern with a period and slant angle. In this sense, the grating can be thought of as a dielectric with a periodic structure that interacts with an incident electromagnetic wave $E(z)$ as it travels through. Controlling the period and slant angle of the grating, arbitrary diffraction angles can be achieved. Thickness and index modulation allow to control the efficiency and bandwidth.

At Luminit, we have prototyped heads-up displays (HUD) and head- (and helmet-) mounted displays (HMDs) using a pair of holographic optical elements. Example prototypes developed with this technology are shown in Figure 2.
To emplace a manufacturing capability for transparent holographic components (THC), we have developed a manufacturing platform that allows for all modes of fabrication: mastering and replication in either transmission or reflection. A photo of the machine is shown in Figure 3. Luminit currently operates four independent RGB mastering set-ups and has installed capacity to make 1 million AR-sized replica holograms per year.

Figure 3: Luminit THC roll-to-roll manufacturing.


Low-temperature fabrication of oxide-TFTs using improved and well-selected solutions assisted by UV irradiation techniques

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In fabrication of oxide TFTs by solution process, we demonstrated the combination of improved solutions and processes at reduced processing temperature while maintaining the properties of TFTs. Main layers of the TFT were solution processed, where the solutions were carefully selected, synthesized and modified. UV irradiation techniques was fully utilized taking some variations. As a result, we succeeded to develop TFTs having good properties and an active-matrix array for electrophoretic displays at 200 °C.

We have studied solution processing of oxide thin-film transistors and recently succeeded to fabricate them at a low-temperature of 200 °C. The main layers, including the channel (InO), gate insulator (LaZrO) [1], channel stopper (SiON) and passivation layer (SiOR), were solution processed. Autoclave (AC) treatment led to a good LaZrO insulator at 200 °C when combined with UV annealing. A good interface between a channel and gate insulator was realized using an aqueous solution of In nitrate and UV annealing at 200 °C [2]. To form a SiON channel stopper and SiOR passivation layer, we used polysilazane and silsesquioxane, respectively. For them, UV treatment was also very effective and an elaborated UV irradiation technique was especially developed for the latter [3]. Here, an active-matrix electrophoretic display (EPD) was demonstrated at 200 °C process.

The pixel pitch of the EPD was 250 µm × 250 µm, leading to the resolution of 101.6 ppi. The display area and the number of pixels were 6 mm × 6 mm and 24 × 24, respectively. Figure 1 shows the structure of the TFT used as the pixel transistor.

In our process, the maximum temperature was limited to 200 °C. For the LaZrO film, a 0.2 mol kg⁻¹ lanthanum solution and a 0.2 mol kg⁻¹ zirconium solution were prepared by dissolving La(CH₃COO)₃ and Zr(OC₄H₉)₄ in propionic acid, respectively. Then, the two solutions were mixed to provide a LaZrO solution. Finally, the solution was AC-treated at 180 °C for 5 h. The obtained solution was spin-coated and dried, and finally, UV-annealed at
200 °C. This cycle was repeated until the desired thickness was achieved. For the InO film, a 0.4 mol kg\(^{-1}\) indium solution was prepared by dissolving \(\text{In(NO}_3\text{)}_3 \cdot x\text{H}_2\text{O}\) in pure water. After spin-coated and dried, the film was UV-annealed at 200 °C. As for the channel stopper, a polysilazane-based solution was spin-coated and dried. Then it was cured under UV irradiation at room-temperature, followed by annealing in \(\text{O}_3\) ambient at 200 °C. For the SiOR passivation film, a diluted silsesquioxane was spin-coated, dried, and then cured under a high pressure mercury UV lamp, followed by further curing using a low pressure mercury UV lamp, and finally, annealed at 200 °C. The gate electrode, the source-line/drain electrode and the pixel electrode were deposited by sputtering.

Figure 2 shows the properties of the TFT used for the active-matrix array and the photograph of pixels. The field effect mobility was 0.8 cm\(^2\)V\(^{-1}\)s\(^{-1}\), the sub-threshold swing was 1.8 V/decade, the threshold voltage was -1.9 V, and the on/off ratio was ~10\(^5\). The EPD was successfully fabricated and its operation was confirmed, meaning usefulness of our technologies for oxide films and oxide devices.

Figure 11: Cross section of the TFT

Figure 2: TFT transfer characteristics and the photo of pixels (inset)

UV annealing of inkjet-printed In-Ga-ZnO films for thin film transistors

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In this study, we employ UV photo annealing method to anneal ink-jet printed InGaZnO films for TFTs. We measured the electrical characteristics of the films and compare with those of thermally-annealed device. The filed-effect mobility and on/off current ratio of the UV-annealed device are 3.28 cm²/V·s⁻¹ and over 10⁷, respectively, which suggest that UV annealing could be a viable route for annealing InGaZnO films at a low temperature.

Metal oxide semiconductor has been used commercially as thin film transistors (TFT) for active matrix backplane in displays. Recently, In-Ga-Zn oxide (IGZO) for TFT has attracted the interest of researchers due to their transparency, flexibility and high field effect mobility, compared to conventional a-Si and poly-Si. In particular, solution-processing based methods offer an attractive way to decrease manufacturing costs and open various routes for flexible applications [1]. However, in order to use solution processing for IGZO on a plastic flexible substrate, the annealing temperature should be below Tg(<250°C) of the plastic substrate. Photo-annealing methods enable annealing at a low temperature, as reported in other studies [2]. In this study, we annealed inkjet-printed IGZO films at a low temperature through UV-assisted annealing, and investigates the effects of UV-assisted annealing on the electrical performance.

IGZO ink was synthesized by dissolving indium nitrate hydrate, gallium nitrate hydrate, zinc nitrate hydrate (chemical composition ratio of In:Ga:Zn = 6.8:1:2.2) in 2-methoxyethanol. After mixing all components, the solution was stirred at 80°C for 24h. TFT devices were fabricated on a heavily doped silicon substrate with a 200 nm-thick thermal oxide film. A 40 nm-thick Al layer was thermally evaporated as the source and drain electrodes with a channel width/length of 1000um/50um. We used a DMP 2850 inkjet printer (Fujifilm Dimatix, Santa Clara, CA, USA) for printing the IGZO ink. The surface-to-print head distance was 0.7mm. The temperatures of printer head and plate were maintained at 35°C and 50°C, respectively. The droplets were deposited with a dot spacing of 5μm. To investigate the UV-annealing effects of IGZO semiconductor device, we fabricated both thermally annealed and UV-annealed IGZO, and compared their performance. Thermal annealing was performed at 350°C on a laboratory furnace under atmospheric conditions for 2h. Deep-ultraviolet (DUV) light from a low-pressure mercury lamp was used for UV annealing under nitrogen purging condition for 2h as shown in Figure 1. The transistor performance of the IGZO TFTs was measured using a semiconductor parameter analyzer (Agilent 4155C, Santa Clara, CA, USA).

Figure 1: Schemes showing Inkjet printing of IGZO and annealing step by UV

Figure 2 shows transfer characteristics plots (I DS-V GS at V DS = 30 V) for TFTs with differently annealed IGZO films and field-effect mobilities in the saturation regime. It can be seen that the UV-annealed devices exhibit device performance comparable to that of thermally annealed devices. The UV-annealed TFT shows the field-effect mobility of 3.28 cm²/V·s⁻¹ and on/off current ratio of over 10⁷. The thermally-annealed TFT shows a comparable mobility (3.15 cm²/V·s⁻¹) and a slightly better on/off current ratio (over 10⁸). These results suggest that UV-annealing is a viable annealing method for IGZO TFTs, in particular, for flexible electronics applications.
Glass handling tool for OLED TV mass production system

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In this report, the new method for Glass handling tool for the In-line production line for White Organic Light-emitting Diode (WOLED) TV is described. The production system structure of WOLED TV is horizontal glass moving and upward deposition type. To transport the substrate horizontally, the chuck is required. We have developed the new chuck with Pressure Sensitive Adhesive (PSA). It is being used in 8.5G White OLED TV MP System with 27 k/m capa.

OLED display has been considered as an ideal generation Flat Panel Display (FPD). The commercialized WOLED MP system is horizontal moving of glass and upward deposition of organic and metal materials. This can be minimized defects caused by particles. To transport a large size of thin glass horizontally, the chuck is required because of its bending. In order to apply a chuck to WOLED MP System, it should have low outgassing property, also be repetitive useable, no residue of PSA on the glass, and available for long periods of time. We have developed adhesive chuck (Gluon Chuck) to handle a large glass and to transport that horizontally in a vacuum chamber. It has been applied to the world’s first WOLED MP System [1].

The main principle of Gluon Chuck is holding a glass with a Van der Waals force between a glass and PSA. The adhesive materials has been tested with both conventional method and specially designed method. The structure of the body of chuck plate for flatness of glass has been designed.

To hold 8.5G glass (2200mm x 2500mm x 0.7t, 10.4kg), we designed the chucking force 30 gf each point on chuck plate. The gluon film (PSA)’s adhesive force has been defined by 180° peel off test. The results of the adhesive material are shown in Figure 1(a). To evaluate its outgassing properties, gluon materials are tested in the vacuum chamber. The residual gases were analyzed by RGA while the materials were heated. Finally the materials were verified in the OLED Test system to compare the device properties with and without that materials (the results are not shown here). The result of the test about De-chucking force to separate a glass from chuck is shown in figure 1 (b).

Figure 1 Gluon material characteristics
The peel off strength, de-chucking force, and repeated use of the gluon material is highly dependent on the surface status of attached materials [1].

To minimize the glass sagging, the body of chuck plate should be flat on the roller for transport with minimum weight. Al6061 has been used for the body material. To minimize the weight and sagging of the Al body, we designed the body like a pocket considering moment of inertia as shown in figure 2.

The bending of Gluon chuck was measured at 2.7 mm using 3D measurement instrument.

A new concept for glass handling tool has been developed for horizontally substrate transport and upward deposition system. It has low outgassing rate, less than 3mm glass sagging, and also can be used multiple times. We have applied the gluon chuck to the In-line WOLED MP system, which produces 27 k/month of 8.5G glass.

We thank to LG Display for providing verification and opportunity to supply our works in production system.


Extremely stable and low work function conductive ceramic materials for display devices

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Extremely stable and low work function conductive ceramic materials have been developed by using multi-sputtering method to realize reliable cathode electrodes for quantum dots light-emitting diodes (QLEDs), organic light-emitting diodes (OLEDs), field emission displays (FEDs) and so on. The work function of conductive ceramic materials exhibits as low as 1.8 eV, that is the lowest work function among display materials, ever reported, being compared with 1.9 eV of Cs. The low work function ceramic materials have good conductivity. The Transfer Mold field emitter arrays (FEAs) by using low work function conductive ceramic emitter materials, showed one of the lowest turn-on field of 10.7 V/µm, ever reported. No deformation of emitter-tip-shape occurred by the oxygen radical treatment. The low work function conductive ceramic materials are suitable for highly reliable and efficient QLEDs, OLEDs, and FEDs.

Conventional low work function materials such as Cs and LiF, are very difficult to be applied for highly stable and reliable devices, because of their strong degradation properties due to highly chemical reactivity. However, the conductive ceramic materials have the low work function as well as the good chemical stability. In this work, stable and low work function conductive ceramics have been developed to realize efficient QLEDs, OLEDs, FEDs, and so on.

Conductive ceramic materials were fabricated by the multi-sputtering method. The work function was evaluated by the ultraviolet photoelectron spectroscopy. Conductive ceramic FEAs were fabricated by the Transfer Mold emitter fabrication method [1]. The morphology for the emitter tip of Transfer Mold FEAs was evaluated by a FE-SEM. Field emission characteristics were evaluated at the short anode-emitter distance of less than 10 µm.
Surfaces of FEAs were in-situ treated by using highly reactive oxygen radicals to evaluate stable emission characteristics in harsh environments [2].

Figure 1(a) shows the relation between resistivity and SiO₂ ratio of ceramic materials. Resistivities of 0.07–1.24 mΩ·cm, were similar to 0.1 mΩ·cm of a brass and 1–10 mΩ·cm of n-doped Si. The work function exhibits as low as 1.8 eV, is the lowest value in display materials, ever reported, being compared with 1.9 eV of Cs. Transfer Mold FEAs have the emitter base-length of 1.6 µm, the 3.5–4.7 nm tip radius and 0.7–0.9 nm standard deviations of the tip radii. Figure 1(b) show the I-V characteristics of conductive ceramic FEAs and Mo FEAs. Those turn-on fields were as low as 10.7 V/µm and 13.3 V/µm, respectively. The value of 10.7 V/µm is one of the lowest turn-on field, ever reported. Turn-on field of conductive ceramic FEAs was lower than that of Mo FEAs because of lower work function. The low work function conductive ceramic FEAs are suitable for highly efficient vacuum devices. Figure 2 shows SEM images of conductive ceramic FEAs and Ni FEAs without and with oxygen radical treatment. No deformation of emitter-tip-shape for conductive ceramic FEAs, occurred by the oxygen radical treatment. However, Ni FEAs were deformed and destroyed by the arcing because of unstable or abnormal emission during field emission evaluation due to an oxidized Ni surface.

![Figure 12: (a) Relation between resistivity and SiO₂ ratio and (b) I-V characteristics of Transfer Mold conductive ceramic FEAs and Mo FEAs, respectively.](image)

Figure 12: (a) Relation between resistivity and SiO₂ ratio and (b) I-V characteristics of Transfer Mold conductive ceramic FEAs and Mo FEAs, respectively.

![Figure 2: SEM images of conductive ceramic FEAs (a) without and (b) without radical treatment. Those of Ni FEAs (c) without and (d) with radical treatment.](image)

Figure 2: SEM images of conductive ceramic FEAs (a) without and (b) without radical treatment. Those of Ni FEAs (c) without and (d) with radical treatment.

The conductive ceramic materials have low work function as well as good conductivity. Extremely stable and low work function conductive ceramic materials can be applied for highly reliable and efficient QLEDs, OLEDs and FEDs to a great extent.


Temperature behavior of different liquid crystal displays

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Two LCD displays have been measured at different temperatures using Fourier optics viewing angle and response time measurement systems. We find that the temporal performances are very dependent on the temperature especially below 0°C where the response times increase drastically. Viewing angle properties are also affected by the temperature. An increase of temperature produces a reduction of the optical index and of the birefringence that affect the liquid crystal cell rotation efficiency.

Physical properties of the LC are the most important factor that affect the electro-optic characteristics of LCDs such as the driving voltage, transmittance, viewing angle and response time. It is easy to find literature on the temperature dependence of liquid crystals themselves [1-2]. The refractive index behavior of different LCs versus temperature has been for example published by Li [1]. Both the refractive index and the birefringence are strongly decreasing when the temperature increase. The variation can be of several percent per decade near room temperature. The rotational viscosity is also strongly affected by the temperature. Rao [2] has for example shown that rotational viscosity of two commercial liquid crystal mixture follow a modified Arrhenius law with a strong variation below 0°C. Since the LC cell is working as a polarization modulator inside all the LCDs, it is clear that the change of optical properties with temperature will affect the viewing angle properties. In addition, the change of viscosity will affect their response time properties.

In the proposed paper we will present experimental results obtained on two commercial LCDs, one Twisted Nematic (TN) and one In-Plane Switching (IPS), using two instruments, Optiscope S.A system to perform the response time measurements [3], and EZContrastL80 Fourier optics instrument for viewing angle measurements [4].

Grey level response times measured for all the grey level transitions and at 2 temperatures on the two displays are reported in figure 1. The strong influence of the temperature is obvious especially below 0°C. Also obvious is the larger distribution of values versus grey levels when operating at low temperature.

As shown in figure 2, for the TN LCD, the luminance contrast is reduced when the temperature increases with an additional horizontal shift due to the reduction of rotation of the LC which becomes less efficient.

![Figure 13: Response time measured on TN LCD (top) and IPS LCD (bottom) for 9x9 grey level transitions and 2 temperatures -20°C (left) and 60°C (right)](image-url)
The next generation of emissive displays require assembly techniques that can precisely mass transfer miniaturized inorganic LEDs (iLEDs) onto panel substrates. Heterogeneous integration enables new opportunities for future devices through added capabilities and improved performance by making use of the best dedicated in-class material systems. Platforms where fully functional components are tightly integrated can be micro-Transfer Printed to target substrates as a completed/finalized device.

For display applications, ‘light-engine’ platforms featuring different RGB light emitters were transferred to form full-colour displays.

We report slot-die coating of the indium oxide-based iXsensic S® precursor solution, and its first integration into high-performing thin-film transistors with a self-aligned architecture (SA-TFTs). We demonstrate excellent performance and uniformity of the resulting TFTs and high resolution AMOLED backplanes based on this technology.

The resolution and size of active matrix liquid crystal and organic light emitting diode displays (AMOLED) is increasing, pushing the limits of the TFT backplane, both in terms of performance and large area uniformity. The latter sets requirements on film homogeneity and composition control over large-areas. By using soluble metal oxides, which enable deposition methods such as slot-die coating [1], a vacuum step is removed from the fabrication process and facile up-scaling to very large substrates (Gen10), while maintaining an excellent uniformity and process repeatability, is ensured [2]. We have previously demonstrated high-performing etch-
stop-layer (ESL) TFTs by slot-die coating on mass-production-ready tools [3], integrated into a fully functional 85 ppi QVGA AMOLED display.[3]

The resolution and performance aspects can be addressed by further scaling down the TFTs, opting for a self-aligned gate architecture. Then coplanar homojunction thin-film transistors with highly doped contact regions are a prerequisite.[4]

In this work, we report the first integration of slot-die coated iXsenic S® into SA-TFTs. We demonstrate the excellent performance and uniformity of the resulting TFTs and their integration in a 200ppi SA TFT AMOLED backplane.

TFT backplanes with SA TFT architecture, which is schematically presented in the upper inset of Figure 1, were fabricated on Gen1 glass substrates (320 mm x 352 mm). iXsenic® precursor ink (www.ixsenic.com) was slot-die coated by Evonik Resource Efficiency GmbH. Following patterning, the conversion into a semiconductor layer took place during a two-step functional process under ambient conditions at a maximum temperature of 350°C, using standardized large-area, non-vacuum processing equipment. The semiconductor film thickness, as measured over 10 points in the coated area by spectroscopic ellipsometry (SENTECH SE800 DUV), is 6.3 nm, with a variation of less than 0.3 nm, showing the extreme uniformity of the slot-die coating process. The TFTs were finalized using standard FPD industrial fabrication processes.

The transfer characteristics of 10 SA TFTs with a channel width of 10µm and a channel length of 3µm are presented in Figure 1. The TFT measurements were performed in an 5x2 matrix spanning the slot-die coated area. The transistors show excellent uniformity, with an average turn on voltage of -1 V. and a subthreshold swing in the order of 300 mV/dec. The on-off ratio is >10^7. The average linear mobility, as extracted at a gate bias of 20 V, amounts to 7 cm^2/Vs. An optical micrograph of a 200ppi AMOLED backplane based on SA TFTs is shown in the lower inset of Figure 1.

![Figure 12- Transfer characteristics of SA TFTs. Upper inset shows a schematic of the self-aligned architecture, while the lower inset shows an optical micrograph of a 200ppi AMOLED TFT backplane based on SA TFTs](image)

Light field subsample method for three dimensional lenticular display rendering

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In this paper, a light filed subsample rendering method by reproducing real object light field distribution is proposed. Arbitrary number viewpoints display is set up effectively and large FOV eye-tracking display without loop display can be adaptive rendered for lenticular display.

Three-dimensional (3D) display technologies have been studied for decades with various ways to produce high fidelity 3D scenes. However, there are still two major problems needing urgent attention, one of which is that the inability to completely isolate left/right image channels for left/right eyes often results in crosstalk. The rendering method based on light filed acquisition is simple and superior enough for crosstalk reduction [1]. The other problem is the small FOV and loop display in lenticular 3D displays, which critically affect the display quality. In this paper, a light filed subsample rendering method by simulating real object light field distribution is proposed. Based on modifying sampling frequency, arbitrary number viewpoints display is set up simply and effectively. Though the subsample rendering method, the light filed sampling method can be FOV-extensible for wide viewing angle lenticular display without loop display phenomenon.

When lenticular sheet and LCD plane put in front of the observers, we wish that the spreading of the light filed from the real object everlasting. In a real lenticular display system, since LCD plane is clung to the lenticular sheet, rays won’t deflect when enter the lenticular sheet. If we want to keep the light direction unchanged, we just need to ensure that the defection won’t occur when rays come out from the lenticular sheet. So rays must pass through the panel point C of the cylindrical lens. That is each ray will pass through three points - sample point, panel point and the viewpoint. Since two points confirm a line, after the viewpoints and panel point determined, the sample point can be obtained. The light filed sampling process rendering the model by propagating the color of the corresponding sample point to the subpixel. However, multiple lines may pass through the same subpixel. In that situation, we need consider how the subpixel should be assigned by the ray’s mergence method [2].

During the actual viewing process, the region circularly distributes on the best viewing plane, which is the loop display phenomenon. This is because that when at the first viewing point of the “A” viewing region, $V_A$, the observer see the rays emitting from “a” and “b” subpixels on the LCD plane and going through the “c” and “d” cylindrical lens on the lenticular sheet. And when the observer move to the first viewing point of the “B” viewing region, $V_B$, he or she will see the rays emitting from “a” and “b” subpixels on the LCD plane and going through the “d” and “e” cylindrical lens on the lenticular sheet. Similarly, the second viewpoint of the “A” region corresponds to the second viewpoint of the “B” region … So “B” area actually is a copy of the “A” area, and
there are several copies distributing on the best viewing plane. When the viewpoints determined, adaptive synthetic image can be rendered, through adjusting the sampling point value on LCD plane, based on eye-tracking. As shown in Figure 2(b), when human eyes move from $V_{A1}$ to $V_{B1}$, the value of subpixel “k” on the LCD plane changes from the value of sampling point “m” to “n”. Thereby, eye tracking for lenticular display can be achieved and expand the field of view angle.

<table>
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<th>Method</th>
<th>Crosstalk</th>
<th>FOV</th>
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<tr>
<td></td>
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Session 7 - Display application continued

Displays based on dynamic phase-only holography

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Static holographic displays of high quality are works of art. We are creating commercial displays using dynamic phase only spatial light modulators (SLMs). The main advantages of this approach are light efficiency and fault tolerance. When polarized lasers are used as the illumination source, there is no requirement for polarizers in the light engine. Moreover, the illumination beam can be directed towards bright points of the image and away from dark regions. Due to the many-to-one correspondence between the pixels in the SLM and the points in the image, faults in high complexity SLMs will be annealed in the image. Compared with normal displays where etendue is of overriding importance for light efficiency, holographic displays favour small pixel devices. On two separate counts in each case, light efficiency is improved and device manufacturing costs reduced.

This work has grown from student work [1] to commercialization within 10 years. Lasers and phase-only holograms (kinofoms) are around 50 years old, but spatial light modulators of sufficient complexity have been developed only over the last 20 years. The light efficiency advantage of phase-only holograms in information optics was recognized around 30 years ago. The final piece of the jigsaw which allowed exploration of this area for display was the availability of fast Fourier transform electronics around 20 years ago.

The first display holograms were based on off-axis holograms recorded on photographic plate [2]. The limited space bandwidth product (SBWP) of current SLMs (1-10 megapixels) does not allow off-axis holograms. Moreover, the coding of a fully complex hologram on current SLMs can further reduce the limited SBWP. Therefore, on-axis, phase-only holograms are used. Coding efficiency and the resulting image quality favours Fourier holograms rather than Fresnel holograms. In addition, the many-to-one correspondence is accentuated in the Fourier case. Finally, the Fourier hologram allows more efficient zero order removal because the zero order can be focused to a point.

The use of iterative algorithms to calculate phase-only holograms in real-time [3], made computationally efficient using the two-dimensional fast Fourier transform, has traditionally not achieved an acceptable level for use in commercial products. The latest generation of iterative algorithms can now achieve good display quality within 10 iterative cycles: a mean square error of less than 1; and a contrast ratio of greater than 10000:1.
There were no phase-only SLMs when this work started at the beginning of this century. However, the availability has improved so that a small number of devices can be used in experimental systems [4]. However these devices struggle to deliver the required phase modulation characteristics required for high quality dynamic phase only holography. Commercial systems have invested in proprietary devices necessary to overcome these limitations.

The first commercial application of this technology has been the holographic head-up display (HUD) (Fig.1).

Figure 1 Head-up display in automobile

Having demonstrated the viability of the technology in an extremely challenging operating environment, there is now growing interest in the use of dynamic phase only holography for head mounted displays where the efficiency and compact optical system demonstrate significant advantage.

A study on hybrid-phase microstructural ITO-stabilized ZnO TFTs with different gate insulators and electrodes

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In this paper, we investigated the influence of gate insulators and electrodes on top-gated TFTs with hybrid-phase microstructural ITO-stabilized ZnO channels. Different processes and materials were found to affect device performance significantly.

Thanks to advantages like reasonable electrical properties, low manufacturing costs/temperature as well as excellent optical transparency, oxide TFTs have drawn great attentions recently. Although a-IGZO is quite prevalent as active layers nowadays, its insufficient performance especially in device stability still prompts people to develop other better alternates. Previously, we demonstrated a new type of hybrid-phase microstructural ITO-stabilized ZnO TFTs in the top-gated bottom-contact architecture, which exhibited excellent electrical characteristics and reliability [1]. As known, oxide TFTs are very sensitive to the processes and materials. Therefore, how to form gate insulators and choose gate electrodes after active layer deposition are worthy of investigation in our top-gated devices. In this work, we compared the electrical performance of TFTs that capped by different gate insulators and gate electrodes.

The whole processes started from 4-inch p-type silicon wafers coated with 500-nm-thick thermally oxidized SiO\textsubscript{2}. A 50-nm-thick ITO-stabilized ZnO active layer was then deposited by co-sputtering ITO and ZnO targets, followed by wet etch in diluted hydrofluoric acid. On one hand, to investigate the influence of gate insulator formation, PECVD processes employing both tetraethyl orthosilicate (TEOS) and silane (SiH\textsubscript{4}) sources were used for 150-nm-thick SiO\textsubscript{2} deposition. Afterwards, 100-nm-thick Al was sputtered and patterned as gate electrodes. On the other hand, to investigate the influence of gate electrode materials, 100-nm-thick Al and ITO electrodes were chosen to cap on the top of SiO\textsubscript{2} gate insulators, which were deposited using TEOS-PECVD process. The devices above all were finally annealed in O\textsubscript{2} atmosphere at 300 °C for 2h. The electrical characteristics of TFTs were measured in the probe station using a semiconductor parameter analyzer (Agilent 4156C).

As shown in Figure 1(a), device channels with TEOS-PECVD SiO\textsubscript{2} layers are found to perform good switch behavior, whereas those capped by SiH\textsubscript{4}-PECVD SiO\textsubscript{2} gate insulators are short-circuit, even though they are annealed in O\textsubscript{2} atmosphere for a long period. The secondary ion mass spectrometry results illustrates that hydrogens introduced by SiH\textsubscript{4}-PECVD process is more active to play as donor-like defects though their content is actually less than that in TEOS-PECVD process. Meanwhile, an inter-diffusion phenomenon between SiO\textsubscript{2} and ITO-stabilized ZnO at their interface, and the degree in SiH\textsubscript{4}-PECVD process is much more significant, and such silicon-doping effect may be also responsible for the lack of switch behavior.

Although the devices capped by TEOS-PECVD SiO\textsubscript{2} and Al perform very well, they are still operated in depletion mode, which is not welcomed in low-power-consumption applications. Since ITO owns higher work function (~4.7 eV) than Al (~4.2 eV), $V_{on}$ of devices may positively shift when Al gate electrode is replaced by ITO. Besides, ITO is gas permeable whereas Al is not. When devices are annealed in O\textsubscript{2} atmosphere, oxygen can permeate through gate electrodes and gate insulators more effectively, and compensate defects. Therefore, device channels are less conductive with further positive $V_{on}$. Figure 1(b) verifies this assumption, and $V_{on}$ moves from ~2 V to only ~0.5 V.

Figure 13. Transfer curves of top-gated TFTs with different (a) gate insulators and (b) gate electrodes.

TFTs with SiH\textsubscript{4}-PECVD SiO\textsubscript{2} gate insulators were found to loss switch behavior while the ones with TEOS-PECVD SiO\textsubscript{2} performs very well. Meanwhile, ITO gate electrodes could result in more positive $V_{on}$ of devices compare with Al gate.
High performance a-IGZO TFT with hole-array structure for flexible device

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We demonstrated the first mechanically flexible amorphous Indium Gallium Zinc Oxide Thin Film Transistor with hole-array structure on 125 um polyimide substrate for durable flexible device. The a-IGZO TFTs with hole array structure exhibits high on/off ratio of >10^6 and field effect mobility of >6 cm^2/V·s even after high bending radius.

Recently, bendable thin-film transistors (TFTs) have been intensively studied as switching and driving devices for application to flexible electronics. In particular, amorphous indium gallium zinc oxide (a-IGZO) TFTs was considered as one of immense attracted switching component owing to their high optical and electrical characteristics than conventional hydrogenated amorphous silicon (a-Si:H) TFTs. Most of the research on the bendable a-IGZO TFTs has focus on standard structure of TFTs such like planar and vertical types on flexible plastic substrates. In this case, TFTs was easily occurred electrical failure by micro-cracks in conditions of prolonged mechanical bending strain. In this study, we propose a-IGZO TFTs with hole-array structure to improve their electrical and mechanical characteristics in unfavorable bending conditions.

An IGZO TFT with hole-array structure was fabricated on manufactured 125 um-thick polyimide film. First, a 100 nm-thick Cr was deposited and patterned by using DC magnetron sputtering system and conventional photolithography as gate metal. Next, 200nm-thick SiO2 insulator layer was deposited using PECVD at 350°C. Then, 80 nm-thick a-IGZO channel layer was sputtered and patterned by a wet etching process. To enhance the a-IGZO TFT performance and device stability, thermal annealing process was performed in an air ambient at 300 °C for 1 h. Subsequently, gate via was formed by a photolithography and a reactive ion etching (RIE) method. Next, a 100 nm-thick Al layer was deposited and patterned by evaporator and a lift-off process. Finally, the hole-array structure was formed on channel and source/drain region by using dry etching method.

The top view image of flexible a-IGZO TFT with hole-array is shown in Fig. 1 (a) by using scanning electron microscope (SEM) system. Two types of a-IGZO TFTs were fabricated, which have with and without hole-array structure. Fig. 1 (b) shows the transfer characteristics with and without hole of a-IGZO TFTs as function of hole diameter. The device performance shows a high field effect mobility of > 6 cm^2/V·s, a subthreshold slope of > 700 mV/decade, drain current on-off ratio of > 10^6 in both types of a-IGZO TFTs. The bending test of a-IGZO TFTs on the polyimide substrate was performed using semicircular shaped curvature. The bending radius was set to 100 mm by considering minimum bending radius (tensile strain of 0.22 % perpendicular to the channel current flow). The a-IGZO TFTs with hole-array remarkably reduced electrical failure caused by micro-cracks induced mechanical strain than TFT without hole-array samples.

Figure 14: SEM image of a-IGZO TFT with hole array (a) and trasfer characteristics
In conclusion, we demonstrated high performance and flexible a-IGZO TFTs with hole-array on polyimide substrate and investigated the variation in the electrical characteristics as a function of hole area and radius. The a-IGZO TFTs with hole-array device performance shows good electrical characteristics and the mechanical strain reduced remarkably in hole-array structure as compared with the TFT without hole-array. Thus, hole-array structure of a-IGZO TFTs can give an important merit to use flexible devices.


Reliability and DC performance of In–Ga–Zn–O thin-film transistors with TEOS-based SiO₂ stack passivation

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In this report, the effect of the deposition temperature of TEOS based SiO₂ passivation layer on the bottom gate amorphous IGZO TFT has been studied. We fabricated a-IGZO TFTs with a stacked passivation film to enhance TFT's performance and reliability.

In–Ga–Zn–O (IGZO) thin-film transistors (TFTs) have been received considerable attention for use in next-generation active-matrix displays because they exhibit higher electron mobility (\( \mu_{FE} > 10 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \)) compared to conventional amorphous Si TFTs [1]. Bottom-gate structure with an etching-stopper (ES) is widely utilized for the IGZO TFTs. We reported a hydrogen diffusion from silane-based SiOₓ-ES to IGZO channel influenced on the threshold voltage (\( V_{th} \)) and sub-threshold swing (S.S.) of the TFT [2]. In this study, we present highly reliable IGZO TFT with high-temperature (380°C) deposited SiOₓ passivation layer where tetra-ethyl-ortho-silicate (TEOS) and O₂ were used as source gases. A TEOS is nonpyrophoric, noncorrosive chemical, and safer alternative for depositing SiOₓ instead of silane.

A heavily doped n-type silicon with thermally grown SiO₂ was served as a substrate. The IGZO channel and source/drain electrodes were deposited by sputtering and patterned by shadow masks. Then a 100-nm-thick SiO₂ was deposited by plasma-enhanced chemical vapor deposition (PE-CVD) used TEOS/O₂ as source gases for passivation layer. A single layer passivation was deposited at 180 and 380°C, whereas a 20 nm of 380°C film was deposited sequentially without breaking the vacuum for the stacked passivation layer. The TFTs were annealed at 350°C in ambient for one hour to. The channel length and width were 350 and 1400 \( \mu \text{m} \), respectively.

The measured initial characteristics of the a-IGZO TFTs with single-layered (180°C and 380°C) and stack-layered passivation films are shown in Fig. 1. Table I. shows the electrical parameters of the IGZO TFTs with different passivation. All the TFTs demonstrated good DC performances; however, a small S.S. degradation was found in case of the TFTs with the single-layered passivation deposited at 180°C.
Fig. 1. Transfer characteristics of the IGZO TFTs with passivation layers deposited at 180, 380°C, and stack film.

Table I. Summary of the TFT properties in Fig. 1.

<table>
<thead>
<tr>
<th>Substrate Temperature</th>
<th>180°C</th>
<th>380°C</th>
<th>Stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ [cm$^2$/V·s]</td>
<td>15.02</td>
<td>15.63</td>
<td>15.81</td>
</tr>
<tr>
<td>S [V/dec.] (10-100 pA)</td>
<td>0.12</td>
<td>0.61</td>
<td>0.11</td>
</tr>
<tr>
<td>$V_{th}$ at $k=1$ nA [V]</td>
<td>0.75</td>
<td>-2.64</td>
<td>-0.38</td>
</tr>
<tr>
<td>$\Delta V_{th}$ [V]</td>
<td>0.13</td>
<td>0.22</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Fig. 2. Variation in $\Delta V_{th}$ as a function of stress time during PBTS under $V_{dd}$ of +20 V at 75°C

Although the TFTs with the single-layered passivation deposited at 180°C exhibited very good DC performances, however, the threshold voltage shift under positive gate bias and temperature stress (PBTS) was worse than the others. In contrast, the TFTs with the stack-layered passivation demonstrated excellent TFT properties with high reliability.

This result indicates that the back channel of the IGZO TFT might suffer damages during high temperature deposition of TEOS-SiOx, which can be prevented by inserting a thin low temperature deposited film.

In this study, Mo-Al-Ti is suggested as a new Cu barrier material in back channel etched (BCE) thin film transistor (TFT). Mo-Al-Ti shows better etch selectivity for active layer than Mo-Ti, and higher oxidation resistance than Mo, while maintaining good Cu barrier properties. We present the performance of InGaZnO BCE TFT with Cu source/drain(S/D) and Mo-Al-Ti Cu barrier.

For large-sized high resolution displays, Cu is considered as the best electrode of TFT due to its low resistivity. However, Cu diffuses easily into active layer to degrade TFT performance. Additionally, Cu has poor adhesion to oxide semiconductor and SiO2. Several studies have been proposed to solve this problem by adopting Cu diffusion barrier layer such as Mo or Mo-Ti.

In case of pure Mo, however, it is easily oxidized and forms porous oxide in the deposition or annealing process [1]. Instead, Mo-Ti, Mo-Nb, and Mo-Al-Ti alloy have been suggested as Cu barriers. In fabrication of InGaZnO (IGZO) BCE TFT, securing etch selectivity between SD and IGZO films is the hardest process. Mo-Ti, known as a good Cu barrier, however, has poor etch selectivity for the active layer by H2O2-based Cu etchant. Meanwhile, Mo-Al-Ti shows better etch selectivity than Mo-Ti, while maintaining good Cu diffusion barrier properties. It improves oxidation resistance of pure Mo, because Al and Ti tend to form a very thin protective oxide layer on the surface, preventing further oxidation.

Here, we propose Mo-Al-Ti for a Cu barrier material of IGZO BCE-TFT for the application to the large sized high resolution AM display.

**Figure 1**: O1s spectra of XPS measured at the surface of (a) as-deposited and (b) etched IGZO film.

For the application to S/D in IGZO BCE TFT, we investigated etch properties of Mo-Al-Ti using H2O2+F- containing Cu etchant. XPS depth profile was measured to scrutinize damage of IGZO film caused by the Cu etchant during S/D etching. As shown in Figure 1, O1s peaks of each film resolved into 3 components centered at ~530eV(O1s_1 : M-O related peak), ~531eV(O1s_2 : V0 related peak), and ~532eV(O1s_3 : -OH related peak) [2]. The etched sample shows higher V0 related peak(O1s_2) and -OH related peak(O1s_3). Thus, it seems necessary to compensate the reduced V0 during the passivation process of TFT.

Etch selectivity between Cu barrier materials and active layers was investigated. As shown in Table 1, etch rate of Mo-Al-Ti is higher than that of Mo-Ti. Owing to high etch rate of Mo-Al-Ti, the active layer can be less exposed during S/D etching, being less damaged.

**Table 14**: Etch rate of Cu barrier materials and active layer by H2O2-based Cu etchant

<table>
<thead>
<tr>
<th>Etch rate (nm/s)</th>
<th>Mo-Ti</th>
<th>Mo-Al-Ti</th>
<th>IGZO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.76</td>
<td>1.38</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Mo-Al-Ti with good oxidation resistance is proposed as a new Cu barrier material. Because Mo-Al-Ti has higher etch selectivity, active layer can be less damaged by the H2O2+F- based etchant during S/D etching. We fabricated and analyzed IGZO BCE-TFT with Cu S/D and Mo-Al-Ti Cu barrier layer for the first time. We will compare it with BCE-TFT adopting other Cu barrier materials to show possibility of Mo-Al-Ti as a Cu barrier layer.
This research was funded by PLANSEE SE. Authors thank to Dongwoo Fine-Chem Co., Ltd. for the supply of the etchant.


A novel, additive and ITO free process for the formation of metal mesh and TFT electrodes

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This paper discusses a novel and complete manufacturing approach to produce metal mesh and TFT electrode patterns for use in advanced touch screen and display panels. Selective deposition of Copper layers greater than 1um in thickness can be readily achieved and leads to direct formation of fine structures without the need for additional mask and etching steps after Copper deposition. Through the use of existing seed layers, Electroless deposition of Copper is shown to offer benefits over, and be a viable alternative to the current vapour based processes.

Indium Tin Oxide (ITO) has been widely used for the formation of transparent films common to touch screen and display products as it offered acceptable conductivity without impairing the users view.

However, as display technology and screen size has developed, the low conductivity of ITO has limited its use in large area and high resolution TFT applications. There is a similar story for touch screen, where ITO has historically been used as the sensor material in projected capacitance screens. In this case, while display size remains an issue, an additional concern is around the development of curved and flexible touch screens, where the brittle nature of ITO again excludes it from use.

There has been much work reported about the switch away from the use of ITO towards materials with higher conductivity and better mechanical properties suitable for flexible screens, but the manufacturing of these either continues to revolve around the existing vapour based processes, which require additional masking and etching steps in order to create the final structure, or rely on the use of ink systems which often require sacrifices in electrical or optical properties.

Copper offers the best combination of low resistance which is ideal for use in large displays, with the mechanical properties required for flexible or curved screens. Further its bulk cost is lower than competitive materials for metal mesh technology such as Silver, and with minimal effort, Copper can be deposited selectively allowing for the removal of post deposition process steps such as masking and etching.

Electroless Copper has been widely used in the Printed Circuit Board (PCB) industry since the 1960s as it offers a simple, repeatable method for large area processing. Similar to the vapour technologies, electroless deposition can be seen as a “blanket” process in that it will fully cover an active surface with metal, but unlike the vapour process, deposition will only occur where a suitable seed layer is available. As such, if the seed layer has been structured, say through printing, the electroless process will only deposit metal where the final structure is required.

Electroless deposition typically occurs from a wet chemical media and as such the deposition rates can be controlled. Plating rates of up to 250nm/min are achievable, with the final deposit thickness being dependent mainly upon the dwell time in the solution. This makes for a simple, scalable and easy to control process.
Electroless processing is compatible with the typical rigid and flexible substrate materials.

Electroless Copper plating requires compatible seed layers. Experience has shown that these can be a printed, catalytically active ink through to certain sputtered metals. In the case of inks, the final design can be directly printed and for sputtered layers, the metal should then be masked and etched to the final pattern.

A fine grained Copper layer is deposited directly onto areas of the active seed layer. Deposition rates of 100-250 nm/min are typical, with thicker deposits being achieved by increasing immersion time.

In order to minimize the visibility of the Copper tracks, an additional blackening process is applied. This immersion process coats all available Copper surfaces with a thin, uniform low reflection black metal layer.
High performance and singularity analysis of sol-gel IGZO TFT annealed by intense pulsed light compared with thermal annealing

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In this study, we fabricated sol-gel processed IGZO TFTs in sub-second using intense pulsed light (IPL) annealing. In addition, superior electrical properties were obtained compared to thermal annealing, and we analyzed the reason by XPS O₁s peak. Especially, unusual rapid rise of off current in IPL-annealed TFT was analyzed by investigating N₂ defects found in XPS N₁s peak.

Oxide semiconductor IGZO is currently being developed and commercialized as a material of backplane for LCD and OLED. Currently, it is important to secure a high-performance TFT to maximize the size of TV's, signage, etc. In terms of price competition, there are issues such as solution processability, process temperature, and time. In recent years, there have been studies using intense pulsed light to reduce not only processing temperature but also processing time to sub-second range [1]. We have fabricated TFTs with high mobility compared to conventional thermal annealing by using IPL on IGZO coated by sol-gel method, and we studied the superior, unique properties acquired by IPL.

Figure 1(a) shows the transfer curves and their mobility of the TFTs fabricated by thermal annealing and IPL, respectively. In case of thermal annealing, the sample was heated at a high temperature of 400°C for 2 hours on hot plate, and the temperature is increased to about 250°C at the IPL process. However, the mobility was higher in IPL case than thermal annealing case, which was 6.7 cm²/Vs and 4.6 cm²/Vs, each.

We conducted XPS analysis to explain the differences, and figure 1(b) is XPS O₁s data for thermal and IPL annealing. When the total peak is divided into three sub-peaks, the higher the intensity ratio of the lowest binding energy to highest binding energy, the better the carrier path becomes well-formed in the thin film. In this regard, data show that the formation of IGZO structure is more complete in the case of IPL despite the short process time.

Next, we found that the off-current in the transfer curve increased sharply when the processing time was increased during the optimization process in IPL (figure 1(c)). We figured out that it was because of the increase in carrier concentration through the hall-effect measurement. We confirmed that oxygen vacancy is not responsible for this, and we could find the cause in XPS N₁s data. Figure 1(d) shows the XPS N₁s data obtained by IPL for 20s, and a sub-peak of ~403 eV unusually soared. This peak corresponds to a kind of defects, N₂ in oxygen vacancy, and it acts as double donor [2]. This peak is not found in the thermally annealed sample, and we consider it as a main cause of the off current rise occurring when the IPL is exposed for a long time.

Figure 1: (a) Transfer curve and mobility, (b) XPS O₁s data of thermally, IPL annealed TFTs and film, (c) Transfer curve of IPL annealed TFT for 14~20s, (d) XPS N₁s data of IPL annealed film.

In this study, we fabricated sol-gel IGZO TFTs through IPL and obtained great electrical characteristics. In addition, we found off current rise, and analyzed the phenomena, which could be important to clearly
understand mechanism of photo-annealing. Based on the findings by the analysis, the IPL technology can be well-optimized to contribute to the fabrication of high mobility TFTs in low temperature and short time, and to the development of next generation displays.


Gate insulators by spin on glass diluted with hydrogen peroxide
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1Hoseo University, South Korea 2Electronic Materials R&D, NEPES institute of Science & Technology, South

Top gate oxide thin film transistors (TFT) with hydrogen peroxide spin-on-glass (SOG) insulator layers were investigated. The methyl siloxane based SOG was used for the buffer layer, gate insulator, and passivation layer. The device properties were improved with addition of hydrogen peroxide to the diluted methyl siloxane. With SOG insulators, we get mobility of 3.77 cm²V⁻¹s⁻¹, threshold voltage of 1.63 V, subthreshold slope of 0.51 V/dec, and on/off ratio of 5.19 X 10⁶.

Flexible and transparent displays have attracted much attention. The printable solution process is suitable for the flexible display and has an advantage of low cost compared to the vacuum process. The solution process which has advantages of the simple and low cost, was investigated to develop the oxide TFTs (thin film transistors). The SOG (spin-on-glass) can be processed on large area substrate and gives the advantage of the planarization [1]. Hydrogen peroxide was added to the diluted SOG solution to improve the properties of insulator layer. We applied SOG insulator for the buffer and passivation layers as well as gate insulator. The top gate oxide thin film transistor developed is shown in Fig 1(a).

The methyl siloxane [SiO₂CH₃]ₙ based solution was used as shown in Fig 1(b). it was spin coated on glass with 3500rpm. The coated methyl siloxane is transformed into an inorganic material by curing at 450°C under nitrogen atmosphere. For TFT, after the buffer SOG layer IGZO active layer was deposited by sputtering and patterned. After gate insulator by SOG, gate was formed with Cr metal. After etching of gate insulator source/drain region was doped by oxygen plasma. Contact hole was formed after SOG passivation layer. Source/drain electrodes were formed with Al metal. We did not anneal after fabrication of TFT due to annealing during SOG passivation.

Fig 2 show the transfer characteristic of the top gate a-IGZO oxide TFT with SOG insulators. The mobility in the saturation region and the threshold voltage were 3.77 cm²V⁻¹s⁻¹ and 1.63 V, respectively. The on/off current ratio was 5.19 X 10⁶, and the subthreshold swing was 0.51 V/dec.

The leakage current through the insulator degrades the performance of the TFT. In order to reduce the leakage current of the insulator, diluted solution was coated several times after dilution and addition of hydrogen peroxide. The film became more flat and the leakage current reduced by a factor of 10 compared to the undiluted solution.

Figure 1: (a) Cross sectional structure of the top gate TFT with SOG.
(b) Chemical structural formula of methyl siloxane \([\text{SiO}_2\text{CH}_3]_n\).

**Figure 2:** Transfer curves of the IGZO TFT with SOG insulators

SOG insulator diluted with hydrogen peroxide was applied for the fabrication of the top gate a-IGZO oxide TFTs. The solution process, which is free from plasma ion damage, was used to avoid the defect generation by ion bombardment. We observed that the dilution of SOG with hydrogen peroxide can improve the gate dielectric property and the device properties of the SOG based TFTs. The developed TFTs revealed the mobility of 3.77 cm²V⁻¹s⁻¹ and subthreshold voltage 1.63 V.


**Session 8 - Metrology, human factors and characterization**

*(Invited)* **Advanced measurements for automotive displays**

K Blankenbach

Pforzheim University, Germany

The trend in automotive displays is towards more, larger, higher quality and flexible panels. Their requirements differ largely from consumer displays. Advanced procedures and measurements have to be applied like ambient light reflections.

Starting with Seg 8 clocks, automotive displays have reached “glass cockpit” status in some luxury cars. Therefore it is essential to achieve a high quality. Figure 1 visualizes three major challenges for state-of-the-art automotive displays:

- **Challenge 1** “Read the display (□)” in terms of e.g. eye adaptation vs. luminance, reflection, ...
- **Challenge 2** “Reproduce image “1” on a display”: Luminance value and range, gamma, vision, ...
- **Challenge 3** “Eye matching resolution and seam-less integration”: peak luminance, color gamut, flexible, response time, high frame rate, ...

**Figure 15:** Three challenges for automotive displays [1]

It is essential to evaluate the display performance by measurements. Standards like ICDM [2] or ISO are created mainly for consumer and industrial displays, SAE refer to some automotive measurements. That was the motivation for major German car manufacturers (OEM) to team up and issue a dedicated requirements specification [3]. The corresponding “DFF Display Measurement Specification” [4] was created by specialists of the German Flat Panel Forum. Many measurement procedures refer to basic methods of [2] and other
standards. However it is obvious that for high quality premium automotive displays, many topics must be added. This paper presents a few selected topics, additional information incl. the approach to implement new automotive measurements can be found in [5].

Temperature and lifetime evaluations are performed in climate chambers but the display temperature $T_{DS}$ differ from moving air temperature $T_{CC}$ (Figure 2).

![Figure 16: Temperature measurement for automotive](image)

This results in effects shown in Table 1. Therefore the display surface temperature and circulation have to be defined and measured for automotive use.

**Table 1: Effects of fan speed and circulation**

<table>
<thead>
<tr>
<th>Circulation</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{DS}$ vs. $T_{CC}$</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Luminance for LCD and OLED</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Lifetime for LCD and OLED</td>
<td>Shorter</td>
<td>Longer</td>
</tr>
<tr>
<td>LCD contrast</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>LCD response time</td>
<td>Faster</td>
<td>Slower</td>
</tr>
</tbody>
</table>

Integrating spheres (Figure 3 left) are mostly used for measuring contrast with simulated ambient light. When color shift is as well essential, it is better to measure “just” the reflectance (less 1% for specular included for OFF display). An AG surface results in blurry pixels for high resolution displays [5]. A visual assessment as shown in Figure 3 right uses MTF-like checkerboard cards of different box sizes.

![Figure 17: Ambient light evaluation methods](image)

Compared to CE and industrial displays, automotive displays require more evaluation effort. Some new approaches like climate chamber measurements and reflectance were presented in brief. Other examples are LCD response time and gamma.

[1] Sources: MERCEDES, SPECTRACAL
[3] Display Specification for Automotive Application by German OEMs, via [www.displayforum.de](http://www.displayforum.de)
Metrology of OLED Displays

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Instrument Systems GmbH, Munich, Germany

Employing different types of measurement devices such as spectroradiometers and imaging colorimeters we take a closer look at spatial, directional and temporal variations of luminance and chromaticity of OLED displays and compare them with LC displays. The results show that OLED displays still have to catch up to LCDs in some respects.

OLED displays are considered as high-end display technology. Regarding color gamut, contrast, or form factor OLEDs are doubtlessly superior to other display technologies in the market. However, above characteristics are not the only important properties of a display. Lateral and temporal uniformity of luminance and color or directional dependencies (i.e. viewing direction dependence) as well play an important role for consumers.

In this paper, we show the results of spatial, directional, and temporal variation measurements of luminance and chromaticity of OLED displays and compare them with state-of-the-art LC displays. Moreover, based on the evaluation of a broad data basis, we point out the implications for accurate metrology of OLED displays.

Figure 1 shows spectra of LCD and OLED mobile phones. In each case, the measurements were performed with one specific mobile phone model, but different samples. As expected (left graphs), the results underline the well-known difference between LCD and OLED emission: the spectra of the OLED primaries are more pronounced and narrow-banded.

Interestingly, it can also be seen that the OLED spectra of different samples of the same type of mobile phone vary significantly whereas the LCD spectra almost perfectly resemble each other (right). This means that “golden sample” calibrations of (low-cost) colorimeters as often used in production lines are not sufficient, but spectral measurement is needed.

Figure 2 shows the variations of luminance and chromaticity of LCD and OLED mobile phones with inclination at different azimuths. The above diagrams show the viewing direction dependence of luminance for OLED and LC displays. Obviously, LCDs suffer from a stronger dependence on viewing direction (from about 600 down to 100 Cd/m² for an inclination of θ=0° to 70°) than OLED displays (~180 down to 45 Cd/m²). However, it is by no means negligible and has to be taken into account during testing. The bottom frame shows the chromaticity shift Δxy, (compared to perpendicular observation). Surprisingly, OLEDs show a very significant dependence on inclination up to Δxy=0.09 whereas the LCD display showed the smallest variation of all samples in that test.
Beside the results shown above we will present additional evaluations as lateral uniformity and temporal properties of OLEDs. In sum, the results reveal significant DUT to DUT variations as well as strong temporal and viewing direction dependencies of luminance and chromaticity. Considering all facts we recommend using spectroradiometric measurement devices rather than filter-based devices to achieve the required measurement accuracy.

### Accurate colour control of solid-state reflective display (SRD®) pixels using optical monitoring during deposition

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Solid-state reflective display (SRD®) pixels consist of an ultrathin layer of phase-change material (PCM) situated between two dielectric spacer layers. This stack is deposited by sputtering on a mirror/microheater substrate [1]. Crystallising or amorphising the PCM layer alters its refractive index on a µs timescale, enabling switching between two stable, high contrast colour states, and zero power consumption between switching [2].

This exciting new display technology offers low energy consumption, vivid colour, and excellent performance in bright ambient light. Furthermore, the pixels are fabricated using conventional methods that are scalable to large areas, and widely available materials that have already been established for re-writeable DVDs.

The reflected colour is set by the thickness of the layers within the stack, affording a wide gamut of possible colours [3]. As well as high-contrast two- colour displays, there is potential for full colour display by switching subpixels from saturated red, green or blue (see figure 1) to dark “off” states, or to pale states to yield a pale or high-brightness white.

However, during deposition, a drift in the refractive index, density, growth rate, and film thickness can occur. These minor changes can significantly alter the reflected colour and they are difficult to control.
In this paper, we show that by monitoring the reflectance from the sample at specific wavelengths during the deposition, it is possible to achieve excellent control of the optical thickness, thus giving consistent and repeatable reflected colour across many deposition runs.

Furthermore, to fine-tune the colour of the pixels, we match measured reflectance spectra to simulations, and iteratively update the values used for the simulations. This results in excellent colour predictability (see figure 2).

Figure 2: (top) Example match between predicted colour and measured colour (inset photograph shows actual colour on large-area (1x1cm) sample). (bottom) microscope images of a 56µm x 56µm pixel after switching from the amorphous (pink) state to the crystalline (green) state.


Technical bases of the Fourier Optics Technology (OFT) for viewing angle measurement of displays and the increasing capacities of the ELDIM systems over the years are first presented. A new generation of more compact OFT systems devoted to quality control is then introduced. It can be used on a robotic arm to offer a cost effective solution for quality control of displays with any kind of size and shape. In spite of a much smaller optic, excellent performances in terms of angular aperture, angular resolution and collection efficiency are achieved and the detection is made with a new generation of high resolution CMOS camera allowing very short measurement times.

Viewing angle properties are certainly among the most common characteristics measured on LCDs since the beginning of this technology in the eighties. Historically, the goniometer was the first equipment used to perform angular measurements. Various mechanical movements allow scanning of the complete display viewing field with a directional detector which generally results in very long acquisition times. ELDIM was founded in 1991 to promote an innovative display measurement based on Fourier optics. A specific optic is designed in order to convert angular field map into a planar one allowing very rapid measurements of the full viewing cone with high angular resolution. This fast viewing angle measurement was first publicly introduced at Eurodisplay’1993 in Strasbourg [1]. The first generation of system measured luminance in a cone of ±60° with an angular resolution around 1° and a maximum spot size of 1mm. Recently hemisphere based imagers have been introduced [2]. These systems suffer from very poor light collection efficiency, tradeoffs between angular resolution and efficiency and important parasitic light [3]. In practice OFT systems are now used by 99% of the customers for research and development. Our systems have been improved throughout years to reach extremely high performances at every level and also new capacities (spectral, polarization...) [4].

In the first part of the proposed paper the principle of the Fourier optics will be presented and the different constraints to realize an instrument with optimized collection efficiency, high angular aperture and high angular resolution explained. The optical setup patented by ELDIM will be in particular discussed and the characteristics of the ELDIM commercial laboratory systems summarized. In a second part, a new generation of OFT systems devoted to quality control VCProbe will be presented [5-6]. In spite of a more compact size, the VCProbe optic shows excellent performances in terms of resolution and collection efficiency. A new ultra-dark Fourier optics allows reduced stray light and the detection is made with a new generation high resolution CMOS camera resulting in very short measurement times. In addition, the probe is much smaller and perfect for quality control when used with a robot (cf. figure 1). Innovative strategies to measure panels with spot size of the order of the pixel size will be presented. Finally recent ELDIM developments concerning multispectral real time OFT systems will be also presented.

Figure 1: Photograph of the VCProbe system on its robotic arm


How to evaluate the optical characteristics of LCD and OLED display under any parasitic light

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We use a multispectral Fourier optics viewing angle instrument to realize full diffused reflectance and BRDF measurements on different types of displays in order to predict their properties under any type of parasitic illumination. These measurements need to be spectral to allow simulation with any type of illuminant. Combined with the emissive properties, the luminance contrast or color gamut degradation at any angle for any illumination can be deduced. In addition, knowing the grey level dependence of each primary color, the display aspect of any color image can be simulated in real time for a viewer at any position in front of the display with any lighting environment.

When used outdoors in sunlight conditions, most of the displays that present excellent properties indoor are often disappointing. Even if this aspect is crucial for all mobile application, few measurement methods have been developed to quantify this problem. Most of the standard methods evaluate reflection characteristics of displays using specific collimated or diffused daylight sources on goniometric benches [1-2]. These techniques are efficient to compare displays in fixed given illumination conditions but there are quite complex and difficult to apply. In addition, the measurement time can be prohibitive if many illuminations and detections conditions are required. Bidirectional reflectance distribution function (BRDF) is generally used to characterize the reflective properties of any type of surface. It is generally measured with goniometric systems and the measurement time is always an issue when medium or high angular resolution is needed. Most of the display surfaces are generally anisotropic and so various BRDF measurements with different incoming light beams at various incidences and azimuths must be performed which makes the technique unusable using goniometric techniques.

In the proposed paper we use a Fourier optics instrument that allows fast spectral BRDF measurements with high angular aperture and high angular resolution [3]. The reflective and emissive properties of the displays are measured rapidly and accurately and used to predict performances under any type of parasitic illumination. Display aspect is also computed [4].

Emissive and reflective properties of a 55" curved OLED TV from LG are reported. BRDF measured at 689nm for a collimated beam at 40° of incidence along horizontal is shown in figure 1. The surface of the display is very glossy and additional anisotropic haze contributions due to diffraction along pixel rows and columns are observed. Simulated luminance contrast (between GL31 and GL255) is reported in figure 2. Contrast reduction is important even for angles outside specular position of more than 10° along the two diffraction directions.

Figure 19: BRDF measured at 689nm on OLED TV for an incident beam 40° incidence and 0° azimuth
Figure 2: Simulation of luminance contrast \( \frac{l_{255}}{l_{31}} \) at 30°, 35°, 45° and 50° along horizontal


Non-destructive automated in-line SEM for advanced process control in display manufacturing

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Applied Materials GmbH, Germany

With the constantly decreasing pixel size, display test engineers require tools to meet challenges of process control at these small dimensions where optical tools become futile. Applied Materials automated EBR offers a multi-faceted approach for in-line process control offering inspection at energies ranging from 0.2keV to 15keV maintaining high throughput. This allows for automatic control over grain size in annealed poly-Si, defect review and critical dimension control on various layers.

Rapid expansion in the display industry for mobile displays and an impending further shift of displays to accommodate technologies like virtual reality have fuelled the decreasing pixel size in thin-film-transistor (TFT) based displays. The tough competition in the market has placed tremendous load on the display manufacturers to keep yield high. The decrease in pixel size has brought with it technological complexity in the lithography, etch and annealing process steps where owing to the reduced dimensions the traditional light based inspection tools are reaching the limits to provide information for process control. Laboratory based analytical tools like SEM / FIB / AFM need the panel glass to be cut and samples processed to get the requisite information. Such methods deliver results very slowly, at a small statistical basis and are destructive. Applied Materials E-Beam Review (EBR) system allows for in-line nondestructive automated inspection of TFT glass and flexible substrates for advanced process inspection within minutes.

Applied Materials EBR is based on the underlying principle of scanning electron microscopy whereby a convergent electron beam scans the TFT glass to be inspected. A primary beam energy as low as 0.2keV can be chosen which effectively allows for damage-free inspection. The low-voltage SEM inspection utilizing an immersion type objective lens and a multi-perspective in-lens detector allows for superior resolution till 5-10nm. The primary energy can be increased up to 15keV for inspection using backscattered electrons (BSEs) and furthermore be coupled with an X-ray based energy dispersive spectroscope (EDS) to obtain elemental composition. Effective design allows for maximizing detector efficiency with fast image acquisition time and high signal-to-noise-ratio SEM image.
Multi-column design decreases the footprint of the tool and allows for automated inspection of pre-selected positions suggested by other inspection tools. The automated operation allows for increase in throughput to a level unattainable by human operators and thereby decreases the cost of ownership.

Fig 1: EBR System 25k

In the recent years excimer laser annealing (ELA) has become a standard method to generate poly-Si at low temperatures from a-Si. Effective control of ELA grain size and protrusion density is critical for effective device performance. EBR allows for fully automated control anywhere over the complete glass surface monitoring the grain-size and protrusion density within production lots.

The test engineer in the fab requires an in-line method to keep track of various critical dimensions (CD) on process layers ranging from photoresist, indium doped tin oxide (ITO) to metal lines. EBR allows for choice of optimal beam energy to perform non-destructive metrology till 5-10nm resolution.

Automated inspection of defects in coordination with location supplied by other inspection tool allows the test engineer to review defects with multi perspective topographical and furthermore classify them in conjunction with EDS based elemental information.

The EBR offers a comprehensive set of process control mechanisms to the test engineer for controlling yield: ELA grain size, critical dimensions after lithography and etching, and defect review at any stage of the manufacturing. The automated operation increases the throughput to a level not attainable by human operators and thereby decreasing the cost of ownership.

Highly compatible display gamma & bit-depth for HDR and SDR contents

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LG Display, South Korea

We propose a highly compatible display single gamma and bit-depth to avoid the degradation of image quality for High Dynamic Range (HDR) and Standard Dynamic Range (SDR) format contents. Our experimental results show that the display is required at least above 2.7 and 10 bits-depth to represent HDR, SDR contents without visually compromising quality.

Recently, many TV manufacturers have released TVs which support two different types of content - HDR and SDR. However, since HDR and SDR content has each transfer function, SMPTE ST.2084 and ITU-BT.1886, TVs to support both two types should have two gammas or compatible single one [1]. TV makers usually use a display single gamma to avoid cost increasing, and which have problem with low gradation representation of HDR. In this paper, we studied to find out highly compatible a display single gamma and bit-depth.

We fabricated 65" UHD OLED display featuring max luminance 1000 cd/m² nits and 2.2 gamma using dither algorithm to examine the gamma and bit-depth of the display from 2.2 to 4.5, 8 to 12 bits. Tone-mapping algorithm, which is clipping at 1000 cd/m², is used to match the display gamma to HDR. We used gradation patterns as test image because difference is more visible than using complexity image. Luminance section of the gradation patterns was divided into 3 sections of low gradation (0~10nits), middle gradation (10~100nits)
and high gradation (100~1000nits), and when two random patterns appeared, a natural one was selected. Figure 1 shows experimental images.

Figure 1: Experimental images

For HDR input (10bits / PQ EOTF), there are some difference in gradation areas, but minimum level of 1JND for PQ reference is display 2.7 gamma and 10 bits-depth [2]. Detailed result is shown in Figure 2.

Figure 2: Result of Display to HDR

For SDR input (8bits / 2.2 gamma), regardless of display gamma, if display bit-depth is more than 10 bits, it satisfied 1JND level. Detailed result is shown in Figure 3.

Figure 3: Result of Display to SDR

When considering both HDR and SDR inputs, a highly compatible display gamma and bit-depth condition is respectively at least 2.7 and 10 bits-depth.

Wide color gamut solution based on scattered photon extraction

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The color gamut of liquid crystal displays (LCD) depends on the backlight unit spectrum. For the light emitting diode (LED) based backlight units (BLU), either phosphors or quantum dots are used to convert the blue light of the LEDs to red and green bands. On-chip phosphor and quantum dot configurations are not only optically and thermally inefficient but also reduce the lifetime of the LED chips. In this study, we concentrate on remote phosphor backlight configurations where the light conversion is done away from the chips. We use GaN based blue flip-chips which are more efficient in terms of the light output and thermal management. A phosphor layer was placed in the backlight unit as a thin film in order to produce green and red bands. Furthermore, the emission spectrum of this layer should be compatible to the color filters of the cell, so that the red, green, and blue bands efficiently expand the color gamut.

The aim of this study is develop wide color gamut LCD panels based on scattered photon extraction which is also known as remote phosphor method \cite{1, 2, 3}.

We have tried blended phosphor films with different compositions and thicknesses. These films were excited with flip-chip LEDs (Figure 1). We also checked the dependence of BLU spectra to the LED wavelength (Figure 2). The color space and gamut values were calculated (Figure 3 and Table 1). It is shown that the color gamut can be increased to nearly full NTSC and DCI coverage.

Figure 1: The spectral measurement of $\beta$-SiAlON & CASN phosphor blend for different thicknesses (0.6mm & 1.0mm) and R2R film with respect to white LED BLU

Figure 2: The PL spectral measurement of R2R film with different excitation wavelengths

Figure 3: Standard LED TV vs RP Design TV Color Gamuts
Table 1: Color gamut coverage in the NTSC and DCI

<table>
<thead>
<tr>
<th>Color Gamut</th>
<th>Referans BLU CIE1931</th>
<th>Referans BLU CIE1976</th>
<th>pSiAlON-CASN 1.0mm CIE1931</th>
<th>pSiAlON-CASN 1.0mm CIE1976</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTSC</td>
<td>72%</td>
<td>90%</td>
<td>86%</td>
<td>105%</td>
</tr>
<tr>
<td>DCI</td>
<td>75%</td>
<td>82%</td>
<td>90%</td>
<td>95%</td>
</tr>
</tbody>
</table>

This work was supported by the Scientific and Technological Council of Turkey (TUBITAK TEYDEB Project No. 3160965).


We present the results of measuring workplaces with different lighting and display configurations. The proportion of light emitted from the display goes up to 35% of the vertical illuminance. Furthermore, we measured the blue light hazard of displays.

Light has extensive effects on humans. Not only the artificial lighting inside buildings plays a role, but also the light emitted from displays can have a demonstrable effect on humans [1]. Particularly the blue light causes a suppression of the hormone melatonin, which is an important timer for the regulation of the circadian rhythm. It affects well-being, alertness and is responsible for sleep. Melatonin also has an antioxidant effect on the aging process of cells and thus has a positive effect on regeneration processes. The suppression of melatonin at night has serious health consequences. An increase in cancer risk, sleep disturbances, concentration disorders and depression.

Furthermore, fatigue processes such as "computer vision syndrome" (CVS) and damage to the retina also play a role. High-energy blue light produces photochemical damage to the retina. The blue light increases the metabolism of the receptors so far that they are damaged by oxidation. CVS is not yet considered in this work.

We measured the spectral illuminance at the eye in 27 different workplace situations and determined the composition from ambient light, daylight and display light. Depending on the display size, three categories of working places were defined. Category 1 has a display area smaller than 1600 cm². Category 2 has a display area between 1600 cm² and 2300 cm². Category 3 has a display area greater than 2300 cm².

Further, the measurements of various display models were evaluated for their risk of blue light hazard. A BTS256-LED light meter with a cosine diffuser plate was used to measure the spectral illuminance. For the standardized evaluation of the workplaces, the horizontal illuminance in the usage level was measured according to the standard DIN EN 12464-1:2011-08. The evaluation of the effect of light on humans was made by measuring the vertical illuminance at the eye and the conversion into the melanopic daylight equivalent Illuminance (MDEI) according to DIN SPEC 5031-100:2015-08. For the evaluation of photobiological safety the contents of the standard DIN EN 62471:2009-03 were applied to display systems. This standard divides luminaires into risk groups according to their radiation power. The limit value for the non-risk group is 100 W/m²sr in the visible wavelength range (without UV and IR) with an exposure of more than 10000 s. The measurement is performed with a gigahertz optics X1-3 blue-light hazard optometer and a 200 mm tube adapter. Control measurements of the spectral composition was performed with a Konica Minolta CS-2000A spectroradiometer.

At a workplace that meets the 500 lx horizontal illuminance required by the DIN standard, approx. half of this illuminance can be measured vertically at the eye. Measuring the total vertical illuminance (with display), the proportion of the light emitted by the displays in the different categories are:

- In category 1 (20" – 24"): approx. 12%
- In category 2 (24" – 27"): approx. 16%
- In category 3 (>27"): approx. 28%

Without daylight, for example working at night with standard illuminance at the workplace, the proportion of the display light in category 2 is approx. 35%. The melanopic evaluation of such a workplace depends on the color temperature of the illumination. Approx. 64% of the melanopic lux at the eye originate from the displays because of its high color temperature.

In the DIN lamp safety standard, a risk group 0 is defined, which includes all the examined displays. For displays with a luminance of approx. 400 cd/m², the measurements and evaluations with the spectral weighting function for the blue light hazard, the result was a radiation 0.3 W/m²sr, which is a factor of 1/300 below the
limit value. The measurements shows that none of the examined displays has a blue light hazard according to DIN EN 62471.

Poster session 1 - Tuesday 31 October

**P:01 The impact of boundary conditions on dynamic light scattering in nematic liquid crystal**

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We have carried out the investigations of the polarization-independent dynamic light scattering in a nematic liquid crystal. The effect of orienting layers on the interphase boundaries on light scattering was shown. The switching modes between the transparent and scattering states were investigated. The switching-off time was reduced twice by high-frequency electric field.

The effect of dynamic light scattering (DLS) in nematic liquid crystals (LCs) is used in photonic devices, such as optical switches and photonic crystals in a wide spectral range [1,2]. The DLS effect requires high voltages, and has slow switching times from the scattering to the transparent state. These issues limit the possible application of DLS effect.

We studied optical, electrical, and switching characteristics of the DLS effect in LC cells with different initial boundary conditions. The LC cells were a sandwich structure consisting of two glass substrates coated with a transparent electrode and different orienting layers. The vertical orientation of LC molecules was achieved by molecular layers of chromolane deposited on both electrodes. For planar orientation, polycrystalline SiO2 layers and polyimide polymer layers were used. In cells with a hybrid orientation, one electrode was covered with a chromolane, the other with planar orienting layers.

The polarization-independent dynamic scattering effect was observed when a constant voltage was applied. In crossed polarizers, modulation of light was observed in the same cells when a high-frequency field was applied (Figure 1.)

![Figure 1: The change of LC cell transparencies under DC and AC electric fields](image)

The DLS effect is associated with electrohydrodynamic instability in nematic LC with negative dielectric anisotropy. The instability occurs due to the flow of ion current. The instability results in the dynamic light scattering. Studied cells had different ionic conductivity due to the barrier effects of the layers on LC cells interphase boundaries and their influence on the injection and extraction of charge carriers. The cell with the highest conductivity had the highest attenuation of light (16.4 dB).

One of the significant drawbacks of the DLS effect is the slow switching from the scattering to the transparent state. We proposed a method for accelerating the switching between transparent to diffusing state. Faster switching to the transparent state was achieved by applying a high-frequency field. Figure 2 shows oscillograms of the LC cell transmission by the use of and in the absence of a high-frequency field. Due to the use of the combined mode, it was possible to accelerate the switching process by almost 2 times.
Figure 2: The oscillograms of the LC cell transmission.


P:02 Fabrication of a polymer-stabilized in-plane switching liquid crystal cell through low-temperature UV curing process

J-H Woo, T-H Choi, B-G Jeon and T-H Yoon

Pusan National University, South Korea

The low-temperature UV curing process that leads to a fast response while maintaining high contrast ratio and low operating voltage is demonstrated. The curing temperature was found to make a considerable impact on the response time. Using the low-temperature UV curing process, we have reduced the response time of a polymer-stabilized IPS cell with the low concentration of UV curable monomer while minimizing the increase of the operating voltage and light scattering in the dark state.

In-plane switching (IPS) liquid crystal displays (LCDs) have been widely used in various applications due to their advantageous characteristics, such as wide viewing angle, small color shift, and pressure resistance for touch panels. However, an IPS cell suffers from a slow response time, which causes motion blur and deteriorated image quality. The response time of the IPS cell can be reduced through the formation of the polymer networks, but they exhibit several negative effects including a transmittance decrease, an operating voltage increase, a dark state degradation, etc [1].

In this paper we demonstrate the low-temperature UV curing process that leads to a fast response while maintaining high contrast ratio and low operating voltage. We found that the response time of a polymer-stabilized LC cell with the low monomer concentration could be reduced with little light scattering in the dark state and a low operating voltage through low-temperature UV curing process.

Among the several fabrication parameters that affect the electro-optic performances, the low curing temperature contributes to a smaller average domain size, leading to an increase of anchoring effect by the polymer network [2].

To confirm the effect of curing temperature on the electro-optic characteristics in polymer-stabilized LC cells, we fabricated polymer-stabilized LC cells as the curing temperature was varied from 20 °C to -20 °C. To measure the response time of the fabricated cells, we applied a voltage corresponding to the maximum
transmittance to each cell and then removed it after several seconds. The measured temporal switching behaviors of the LC cells are shown in Fig. 1. As the curing temperature decreases, the measured response time of a polymer-stabilized LC cell was reduced. The response time of a polymer-stabilized LC cell with monomer concentration of 1 wt% fabricated at -20 °C was remarkably reduced when compared with that of the pure LC cell and there was little difference with a polymer-stabilized LC cell with monomer concentration of 3 wt% cured at 20°C.

![Graph showing normalized transmittance vs time for different curing temperatures and monomer concentrations]

Fig. 1. Measured optical switching behaviors of the fabricated cells.

We have demonstrated that the low-temperature UV curing process leads to a fast response while maintaining high contrast ratio and low operating voltage. We found that the response time of a polymer-stabilized LC cell with low monomer concentration could be reduced with little light scattering in the dark state and a low operating voltage through low-temperature UV curing process. We believe that our experimental results can be practical when manufacturing polymer-stabilized LC cells and the technique can be used to improve the performance of IPS LCDs.

This work was supported by National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP). (No. 2017R1A2A1A05001067).


P:03 Bistable switching of a cholesteric liquid crystal cell using electro-hydrodynamic convection

J-H Kim, J-W Huh, S-M Ji, Y-S Jo, B-H Yu and T.H Yoon
Pusan National University, South Korea

To reduce power consumption by light shutters, bistable light shutters using cholesteric liquid crystals have been proposed. However, they require complicated switching methods, such as the patterned electrode structure or dual-frequency liquid crystals. In this paper, we propose a simple switching method for a bistable light shutter using polymer-stabilized cholesteric liquid crystal cell for smart window applications.

Liquid crystals (LCs) have been used to make smart privacy windows. To realize these devices, light scattering property which can hide the objects behind the windows is essential. Various technologies based on light scattering, such as polymer-dispersed LC, polymer-networked LC, and cholesteric LC (ChLC), have been studied. However, these devices consume power continuously to maintain the transparent or translucent state. To realize a bistable light shutter for low power consumption, a light shutter using polymer-stabilized ChLC (PS-ChLC) has been studied [1]. However, light shutters using PS-ChLC require complicated switching methods, such as the patterned electrode structure or dual-frequency LCs. In this paper, we propose a bistable PS-ChLC light shutter switchable between transparent homeotropic and translucent focal-conic states with simple switching method using electro-hydrodynamic convection (EHC).

The proposed light shutter uses EHC [2] for switching between transparent and translucent states. In the homeotropic state, vertically-aligned LCs minimize scattering of the incident light so that the light shutter is transparent. Since the homeotropic state is stabilized with polymer structure, it is stable without external voltage. The light shutter can be switched from the homeotropic to the focal-conic state by EHC with an applied DC field. In the focal-conic state, the randomly oriented LCs can scatter the incident light so that the light shutter is translucent. There is an energy barrier between these two states, and the focal-conic state cannot return to the homeotropic state with specific UV curable monomer concentration. Therefore, the focal-conic state is stable without external voltage as well. The light shutter can be switched from the focal-conic to homeotropic state when an AC field is applied. Under this circumstance, the aligning effect of the dielectric interaction is dominant so that LC molecules tend to be perpendicular to the substrates since we use a positive LC.

To investigate electro-optic characteristics of the fabricated bistable light shutter, we measured the transmission spectra of the fabricated cell. We measured the transmission spectra of the cell in the homeotropic and focal-conic states for the entire range of visible wavelengths from 380 nm to 780 nm, as shown in Fig. 1. The transmittance in the homeotropic state was 80.7%. On the other hand, in the focal-conic state, the measured transmittance was 15.0%.

We realized a bistable light shutter which can be switched using EHC. In addition, since the homeotropic state is used for the transparent state, it is possible to dope a dichroic-dye to the proposed cell so that we can use light scattering and absorption at the same time.
A novel bistable mode of twisted direction switching LCD using a dual frequency nematic liquid crystal

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Kogakuin University, Japan

A bistable mode of twisted direction switching LCD (BTDS-LCD) using De>0 or De<0 LC materials has been proposed in our previous research. In this study, BTDS-LCD using dual frequency LC (DFLC) was developed. By using DFLC, the bistable switching was realized with a simple electrode structure without such FFS/IPS electrodes. A maximum contrast ratio (CR) of 9.7 was obtained.

The BTDS-LCD is a bistable display with memory function having a feature that the twisted angle of the LC director in the cell can be arbitrarily set[1]. By apply the DFLC material to our BTDS-LCD, each bistable state can be switched by changing the frequency of the applied ac voltage with a simple electrode structure. Here, the DFLC material doped with the chiral material and the UV curable LC [De>0] was used. To realize a memory function, a UV curable treatment was carried out under the splay-TN orientation.

A vertical alignment film RN-1338 (Nissan Chem. Ind.) was formed on glass substrates coated with patterned ITO electrodes. After rubbing treatment, the empty cell was assembled with 40° of the rubbing directions. A chiral material CB-15 (Merck) and UV curable LC monomer UCL-017A 3 wt% (DIC) were doped to the DFLC as d/p = 0.08, and injected into the empty cell with the isotropic phase. After cooling down, the UV light (150 to 300 mJ/cm²) was exposed under applying the voltage with 20 V, 50 kHz of square to the cell for a polymer stabilized treatment. Then, the CR of the cell was measured under the polarized microscope with white light.

Photos of each memory state of the bistable cell under the fabrication condition with the UV irradiation energy of 300 ml/cm² were shown in Fig. 1. The bistable switching was successfully realized by changing the frequency of the applying ac voltage, since it seemed that the director configuration could be stabilized under the quasi-splay-TN state by polymer networks. However, the pure black state was not obtained under the vertically orientation state, it seemed that the optical scattering occurred in the cell due to the influence of the polymer stabilization. Figure 2 shows the measurement result for the set up condition to obtain the max CR for the cell and the analyzer angles against the polarizer, the measurement was done as following steps; the polarizer was fixed and it was defined as an origin of the angles, the cell was rotating in 5°, here, qcell was the angle between the polarizer and the rubbing direction with lower substrate of the cell. Then, the angle of the analyzer qA which obtained the maximum CR was searched, and this process was repeated. From this measurement, 9.7 of the maximum CR was obtained at qcell = 55°. and qA = 86°.
We would like to thank Nissan Chem Itd. for supplying the polyimide material. We also thank to Merck Co., Ltd. for supplying the chiral material. We also thank to DIC Ltd. for supplying the chiral material.

In this paper, we investigate the alignment of nematic liquid crystals on the graphene substrate. The alignment of nematic liquid crystal is very sensitive to the characteristics of contacting surface which can be applied to the domain visualization. Also, the anisotropy of liquid crystal leads easy monitoring system without any complex equipment.

The phenomenal properties of graphene have made it one of the most widely studied two-dimensional materials. These properties are strongly influenced by the sizes and boundaries of its domains and defect distribution [1-3]. Therefore the direct observation of the domain size and defect distribution in graphene is very important for the development of electronic applications involving graphene. Conventional approaches for domain visualization, which are based on microscopy and spectroscopy, are only effective for domains that are less than a few micrometers in size; hence require sophisticated optical systems and complex sample preparation procedures [4-5].

In this letter, we report a simple and cheap monitoring method in direct visualization of domain sizes, boundaries and defect distribution of arbitrarily large graphene surface. The various alignment of nematic liquid crystals was analyzed. We found out that the liquid crystal molecules align differently with respect to the graphene domain characteristics and exhibit distinct optical response due to intrinsic birefringence. The method relies on a correspondence between the orientation of the liquid crystals and that of the underlying graphene, which we use to determine the boundaries of macroscopic domains [6-7]. These properties can be used to image the graphene domains based on polarizing system which is rather simple compared to conventional complex system such as atomic force microscopy.

P:06 Structure of a molecular dimer of the CD-1 azodye for LC photoalignment

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1Moscow State Region University, Russia, 2RUDN University, Russia, 3Hong Kong University of Science and Technology, China

To control LC orientation parameters in a photoalignment process and improve image quality formed by an LCD, special properties of the azodye CD-1 dimer structure were investigated. Values of a parameter \( <\cos^2\theta> \) which characterize orientation of both molecules and dimers in electric field were obtained as well as energy of the orientation process. Number of cooperatively oriented dye molecules was estimated. The dimers have dipole transition moments normal to the maximum polarizability direction of the dimer.

Current work is dedicated to the investigation of the dye molecules orientation via laser radiation. One of the most perspective methods the oriented LC layers obtaining is photoalignment in the LC-dye system. Investigation of the dichroism of the oriented dyes showed that absorbance of the polarized light is more intensive when the light polarization plane is normal to the polarization of laser radiation used for the dye orientation. Dipole transition moments in the dye molecules are aligned along their long axis. That is why in many publications the authors believe that the dye molecules are oriented normal to the polarization of the laser radiation. This conclusion is supported also by current photoalignment theories. However these theories don’t consider some important factors, e.g. energy of the unexcited molecules in the electric field.

Experimental data on the anchoring energy in the system LC-dye were explained by using our hypothesis of the formation of flat dimers of SD-1, CD-1 and other dyes via hydrogen bonds [1]. A comparison of dyes’ spectra of the absorption of both polarized and natural light proved that the dye molecules orient in the layer plane. Using a valence-optical scheme, taking in the account exaltation of the polarizability anisotropy obtained with quantum-chemistry calculations, values of the polarizability components of the CD-1 dimers were obtained.

Energy of both molecules and dimers in the electric field was calculated by using an equation

\[
U = -\sum \alpha_{j,k} E_i E_k / 2
\]

where \( j, k = x, y, z \) and \( \alpha_{j,k} \) - components of the polarizability tensor in the laboratory coordinates \( x, y, z \); \( E_i, E_k \) - components of the electric field in the same coordinates. If the dimers’ maximum polarizability forms an angle less than 30° with their long axes the dimers orient predominantly in the direction of \( E \) vector.

Number of molecules in a cooperatively oriented group was calculated from the equality of \( kT \) and orientation energy of the molecular cluster. An angular distribution function of the dimers in the electric field was derived.

Transition dipole moments of some dye molecules and their dimers were obtained by using quantum-chemical calculations performed with GAMESS package. We discovered that the transition dipole moments of the molecules form small angles with the direction of the maximum polarizability whereas there are transition dipole moments in dimers that are almost normal to the direction of the maximum polarizability of the molecule. Therefore, when dimers are oriented, their dipole transition moments become almost normal to the electric field. It corresponds to experimental data.

In paper [1] it is shown that the structure of the dye dimer affects the ratio of the polar to the azimuthal anchoring energy of the LC. This ratio influences the LC alignment quality that determines the quality of a picture formed by the LCD.

Current work was performed in part under support of the Russian Foundation of basic Researches (RFBR), grant #16-57-00089_Bel_a.
Evaluation method for induced condition of bistable characteristics in Nn* LC cells by using a concentric circle rubbing technique

Y Kudoh, H Tajima, S Dohi and T Takahashi
Kogakuin University, Japan

A bistable mode of twisted direction switching LCD (BTDS-LCD) has been proposed in our previous research. In this study, a novel evaluation method for induced condition of bistable characteristics by using a concentric circle rubbing treatment was proposed.

An electronic paper features rewritable displays, low power consumption, display memory performance for a long time, thinness like papers, etc. In previous research, we have proposed BTDS-LCD as an electronic paper mode using liquid crystal (LC) [1]. At present, we aimed to develop a device with improving a contrast ratio by using a pure dark state under the vertical alignment state, therefore, a nematic LC with negative dielectric anisotropy ($\mu < 0$) was used. However, it was difficult to derive the fabrication conditions that the BTDS with memory function because there were many combinations of rubbing angles and $d/p_0$ ratios. In this research, we applied a concentric circular rubbing method [2] in which the angle formed by the rubbing directions on each substrate continuously changed, i.e., the cell that had all twisted angles was realized in the single cell for evaluating the bistable conditions of BTDS-LCD, was proposed.

A vertical alignment film using RN-1338 4wt% [Nissan Chem. Ind.] was formed on glass substrates coated with ITO. Then, the rubbing treatment was done: the bottom substrate were treated with the conventional method, and, for the upper substrate, the circle rubbing treatment was done. After that, cells were assembled and the nematic mixture with negative type doped with a chiral material CB-15 (right hand twist, Merck) was injected into the cell with isotropic phase and cooled down to the room temperature. In this experiment, multiple samples were fabricated with different $d/p_0$ from 0 to 0.82.

Figure 1: Photos of a sample cell (a) before (b) immediately after and (c) steady state 10V of applying voltage. (c) twist states of LC directors in the cell.
Figure 1 shows the photos of a sample cell with \((d/p_0 = 0.67)\) before and after applying 10 V of the voltage. A disclination line which appearing at the LC discontinuous orientation was observed at the position \(\phi = -174^\circ\) in the cell just after applying the voltage, after that, the disclination line was split off in two and each line was moved for opposite direction, then, those lines stayed at \(\phi = -92^\circ\) and \(-234^\circ\). Figure 2 shows the measurement results of \(\phi\) for the multiple samples. It was observed that the \(\phi\) was shifted in the negative direction when \(d/p_0\) increased. When a voltage was applied, LC directors became parallel to the substrate, and the effective tilt angle became low. Then, the influence of the effective chiral power became stronger, i.e., the pitch \(p_0\) became shorter. Therefore, as \(d/p_0\) increased, the region of the left twisted state was narrowed.

The BTDS-LCD with memory function might exists in the region between two disclination lines in the cell after applying the voltage: for example, the BTDS cell with \(d/p_0 = 0.4\) has a possibility to show the memory function under the condition between \(\phi = 20^\circ\) to \(-185^\circ\).

We would like to thank Merck Co. Ltd. for supplying the LC material. We also thank to Nissan Chem. Ind., LTD. for supplying the polyimide material.

Controlling the pretilt angles by using an atmospheric pressure plasma treatment was proposed by K. Takagi et al. In this research, the pretilt angle and the anchoring energy of alignment films treated with atmospheric pressure plasma were evaluated by using the magnetic null method and the capacitance vs. voltage (C-V) characteristic when a low voltage was applied. As a result, it was suggested that the pretilt angle can be controlled while sustaining the anchoring strength constant.

Recent years, material's surface reforming by atmospheric pressure plasma jet (APPJ) treatment has attracted attention as a low costs process that does not require any vacuum equipment. In the field of an alignment for liquid crystal (LC) molecules, it has been reported that the effect of lowering a pretilt angle by using the APPJ treatment to the polyimide alignment film. And, it was expected to control the pretilt angle by using the APPJ [2]. However, it has not been clarified in what extents the pretilt angle can be controlled by APPJ treatment. In order to use the alignment film modified by APPJ treatment as an alignment film of a practical liquid crystal display, it was necessary to clarify an anchoring strength. Therefore, we fabricated LC cells by using alignment films modified by APPJ treatment. Then, the pretilt angle and the polar anchoring strength against the nozzle gap were measured, in this experiment.

A vertical alignment film SE-1211 4 wt% [Nissan Chem. Ind.] was formed on the glass substrates coated with the Indium Tin Oxide (ITO). After the rubbing treatment, the APPJ was irradiated to the substrate surface while scanning in 20 × 20 mm of the region with the interval of 1mm at the scanning speed of 2.5 mm/s, and the scanning was repeatedly done for 20 times. The plasma processing intensity was varied using nozzle gap (distance between the substrate surface and the plasma irradiation nozzle) and samples were prepared with respective intensities. Then, the cell was assembled with a homogeneous orientation configuration prepared using substrates in the above step. The nematic mixture, ZLI-4792 (Merck), was injected with the isotropic phase into the empty cell and cooled down to the room temperature.

A polar anchoring strength was estimated by fitting method which was used the C-V curve of the sample LC cell compared with that of the theoretical calculation using a measured pretilt angle of the sample cell by magnetic null method [3].

Figure 1 shows measurement results of pretilt angles and polar anchoring strengths. The pretilt angle decreases as the nozzle gap closer, however, the polar anchoring strength was not changed in $1 \times 10^{-4}$ J/m² was obtained. From this result, it could be said to use the APPJ treatment might control the pretilt angles without significantly affecting the polar anchoring strength.
We would like to thank Nissan Chemical Industries Ltd. for supplying the alignment material. We also thank to Merck Co., Ltd. for supplying the LC material.


**P:09 Measurement of homeotropic anchoring energies of nematic liquid crystals using bistable latching**

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Bistable latching thresholds are used to determine the homeotropic anchoring strength of different photopolymers and silanation techniques in a zenithal bistable nematic liquid crystal cell using pentylycyanobiphenyl (5CB) to benefit from its wealth of characterization.

The zenithal bistable device (ZBD) is a nematic phase liquid crystal display which exhibits bistability due to a homeotropic-anchoring surface grating which exhibits two stable director alignments. The anchoring strength at this grating surface must be finely controlled in order to give a good operating window for the device. This must also strike a balance between too-strong anchoring, which gives monostability in the continuous (C) state, and too-weak anchoring, in which the director lies instead along the grooves. This alignment will be termed the planar (P) state [Fig 1].

![Diagram of ZBD surface relief grating](image)

Figure 1: A schematic view of the ZBD surface relief grating showing the possible director alignments for three states above the grating surface. Bistability is seen between the continuous (C) and defect (D) states.

The homeotropic anchoring strength was determined using bipolar latching pulses. Each pulse is defined by a pulse amplitude/voltage and a pulse width/duration. The threshold values for these were determined using polarizing optical microscopy to distinguish between the light and dark states. These thresholds give the anchoring strength of the surface when fit to a theoretical expression [1,2].

This work was conducted in two parts. First, two homeotropically aligning photopolymers, PPA and PPB, were mixed in varying quantities. Both were found to give bistability, one with weaker anchoring than the other. It was hypothesized that mixing the two would give tunability over this strength. In the second part, a third photopolymer, PP2, was surface treated to give alignment. The anchoring strength in this case was varied with C8 silane exposure time, in addition to the use of other common surface treatment methods.
The mixing of PPA and PPB proved successful in giving linear tuneability in the effective anchoring strength of the grating surface [Fig 2]. Silane treatment was shown to give different values for the anchoring, depending on which transition was measured (continuous to defect or defect to continuous).

![Graph of the anchoring energy fitting results for the mixture of photopolymers PPA and PPB, continuous to defect transition. A linear trend is included.](image)

Figure 2: Graph of the anchoring energy fitting results for the mixture of photopolymers PPA and PPB, continuous to defect transition. A linear trend is included.

The authors would like to thank Displaydata Ltd. for funding this work through a CASE award. JCJ wishes to thank Displaydata Ltd. for funding this work through a CASE award.


**P:10 Application of low temperature encapsulation to foldable organic light-emitting diode**

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A low temperature multilayer barrier structure composed of parylene and silicon nitride (SiN₃) has been investigated for foldable organic light-emitting diode (FOLED) applications. Parylene/SiN₃/parylene were deposited on the FOLED for encapsulation. The FOLED encapsulated with parylene/SiN₃/parylene multilayer is operational even after extreme bending of 20,000 times at the radius 0.3 mm. The proposed multilayer barrier structure is a promising candidate for application in foldable display.

Foldable organic light-emitting diodes (FOLEDs) are of increasing attention due to their advantage of high mechanical flexibility in display applications [1]. Currently, OLEDs are being fabricated onto glass substrate and then sealed with metal or glass lids. To replace the metal or glass lids with a flexible encapsulation, inorganic materials are commonly used as the vapor and oxygen barrier layer due to their excellent moisture and oxygen barrier even when they are extremely thin [2]. As a barrier layer, the residual permeation and brittleness of inorganic materials are their major disadvantages. Hybrid organic/inorganic multilayer structures have been proposed to solve the problems. In this study, multilayer barrier structure composed of parylene/silicon nitride (SiN₃)/parylene has been investigated for the FOLED applications. The current density and operating voltage of FOLED are almost unchanged until 20,000 times extreme bending at the radius of 0.3 mm.
First, polyimide (PI) is spin-coated and followed by curing at 400 °C for 1 h. Gas barrier composed of silicon dioxide (SiO₂) and SiNₓ layers were deposited by plasma-enhanced chemical vapor deposition (PECVD) onto the PI layer. Indium-zinc-oxide (IZO) was deposited by sputtering on gas barrier layer as the anode. The device structure of FOLED was IZO/HAT-CN/NPB/TCTA/TCTA:TPBi:12% Ir(ppy)₃/ TPBi/LiF/Al. Parylene (1 µm)/SiNₓ (100 nm)/parylene (1 µm) layers were deposited on the FOLED for encapsulation. The parylene was deposited by CVD at room temperature, and SiNₓ was deposited by PECVD at 100 °C. To evaluate the folding stability of the FOLED encapsulated with parylene/SiNₓ/ parylene, the sample was placed on the bending machine and was measured in the flat state and after extreme bending at an angle of 90°.

In this study, FOLED is fabricated using low temperature parylene/SiNₓ/parylene multilayer as encapsulation. The FOLED encapsulated with parylene/SiNₓ/parylene exhibits good folding stability with a bending radius of 0.3 mm. The current density, and brightness are almost unchanged until 20,000 times extreme bending at the radius of 0.3 mm. The current and power efficiencies of FOLED also are unchanged until 20,000 times extreme. The low temperature parylene/SiNₓ/parylene multilayer is attractive for foldable display as encapsulation.

Figure 1: Device performances of foldable green OLED encapsulated with parylene/SiNₓ/parylene

This work was supported by the Industrial Strategic Technology Development Program (10045269, Development of Soluble TFT and Pixel Formation Materials/Process Technologies for AMOLED TV) funded by MOTIE/KEIT.


YAS developed 10.5G linear source which is about 3000mm in length. Also, YAS improved the performance of 10.5 G linear nozzle source with reference to the development experience of 8G linear nozzle source. there are several technical problems; Uniformity problem caused by loading effect, and long time stability caused by Problem of structure. We will introduce 10.5G linear source and several idea to overcome such problems.

Crucible is divided into two same shaped. Nozzle is also divided into two parts. Total length of nozzle is about 3000 mm which is the same as the substrate length. We can make uniform thin film by just same length nozzle because of the special edge nozzle which is filled by many small holes inclined to the outside substrate. Using it, we can make the deposition chamber small and material utilization be maximized. To be able to adjust various deposition conditions, we made center nozzles can be replaceable. We prepared several nozzle array sets which can be applied to various deposition rates and various deposition conditions using our own flux simulation tool that is based on Monte-Carlo method. Especially, we put the special inner plate between crucible and nozzle to prevent film thickness uniformity from changing as operation time goes on. Because of long crucible length (<3 m), the temperature along the crucible can be varied. So, when the material in crucible is almost exhausted, the remaining material at each position can be different along the crucible. At that time, the flux distribution and film thickness uniformity can be changed. To prevent from flux change problem, we put the special shaped inner plate (center hole inner plate). It can cancel out any influence of the shape of remaining material in crucible by making neck point of flux at the center of crucible.

Heater also divided into two parts for individual control of each crucible. Two quartz crystal sensors which detect deposition speed are located at each edge of the linear source. These two sensors are connected with PID controller and heater part at same side. So, heater can control each crucible independently. As mentioned before, main problem of large size linear source is crucible temperature nonuniformity along the crucible. In general case, if we use uniform density heater, the temperature at center position in long direction is higher than that at edge of crucible. So, we should modify the density of heater by changing the number of filament turns within same area. And we should modify reflectors. Finally, we can make temperature nonuniformity be under 60C within about 3m crucible length. (Nevertheless, the deferent remains problem still happens, so we should use center hole inner plate.).

Loading effect is caused by the distance between floating pin and crucible. If there is gap between floating pin and crucible, the position of the crucible is changed each maintenance. When the position of the crucible is changed, it becomes properties of flux change. Which is the loading effect. So, we can solve loading effect by decreasing gap between crucible and floating pin. Crucible loading position was fixed where it decrease gap between the cap and the floating pin.

10.5G linear source that previously has been developed, there is a problem when it has been used for a long time. Mainly occurring problem is the material remains on top of the cap. The material remains on the cap due to the temperature of the cap is low. We had decided to change that contact between cap and top heater, in order to solve this problem. When the cap contacts the top heater, the temperature rises, so that the remained material is evaporated.
We checked thickness uniformity during 336 h (2 weeks) (Figure 1). During 2 weeks, the thickness uniformity keeps under 3%. We checked the difference of thickness distribution under quite abnormal conditions such as we put the material just one side edge and all other regions keep empty. Even in that abnormal case, the thickness uniformity keeps under 3%. We decrease the gap between floating pin and crucible, through this way we have solved the loading effect. Also We have solved the material remain issue by using the contact cap.

We thank to LGD for providing inspiration and opportunity to supply our works in mass production system.


### Table 1. Basic specifications of 10.5G linear source

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniformity (%)</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>Material utilization (%)</td>
<td>&gt; 70</td>
</tr>
<tr>
<td>Operation time (h)</td>
<td>&gt; 336h</td>
</tr>
<tr>
<td>Mixing homogeneity (%)</td>
<td>&gt; 95</td>
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</tbody>
</table>

In this paper, an alternating current(AC)-driven tandem white organic light-emitting device(WOLED) in which an invert unit is piled up on a normal unit with [Ag/4,7-Diphenyl-1,10-phenanthroline(Bphen)]n interconnecting layers(ILs) has been successfully demonstrated. It’s transient electroluminescence intensity and the spectral response to the AC voltage so that emission color can be tuned independently by changing AC bias signals.

Until now, almost reported OLEDs are typically operated by direct-current (DC) bias, while the household power supplies employ AC power. To translate AC to DC, rectification circuit and filter will complicate the driven circuit and waste power. Ideal solution for this problem is to design AC-driven OLEDs. Compared with DC-driven devices, the color and brightness of AC-driven OLEDs can be tuned by changing the polarity and period of the AC-driven voltage. Furthermore, it is helpful to extend the life of the devices and reduce the efficiency roll-off since AC-driven OLEDs could prevent charge carriers accumulation to some extent. Here, an efficiently AC WOLED is fabricated and shown excellent performance.
Figure 1. The structures of AC-WOLED.

The WOLED is deposited by thermal evaporation technique. Ag (5 nm)/Bphen(5 nm)/Ag(5 nm) is used as charge generation layer, and Bphen(1 nm)/Ag(1 nm)/Bphen(1 nm)/Ag(1 nm) is the buffer layer for electron injection to inverted emitting unit. The working mechanisms of ILs are investigated. By introducing (Ag/Bphen)n ILs, the performance of the device improves significantly. The maximum blue and yellow brightness is 5151 cd/m² and 3736 cd/m², respectively. And the maximum current efficiencies are 8.4cd/A and 13.7cd/A, respectively.

Under forward bias (the ITO electrode is positively biased while the Ag electrode is grounded), blue emission color is observed. Similarly, yellow emission color is also observed under reverse bias. When a sufficient high frequency (like 50HZ) is used, human eyes cannot resolve the separate emission from each unit, but instead a mixed color. The transient electroluminescence intensity and the spectral changes as AC voltage change. Based on this, it’s easily to tune the emission color perceived by human eyes by modifying the pulse width and/or pulse height ratios of AC signals.

Figure 2. The transient electroluminescence (T-EL) intensity and the spectral (-EL) response to AC voltage.

In summary, an efficient AC-driven OLED in which an invert yellow emitting unit is connected to a normal blue emitting unit is fabricated with (Ag/Bphen), interconnecting layers. The color emission could be changed from blue through cold white and warm white to yellow by suitable combinations of positive and negative bias.

We gratefully acknowledge the support from the National Natural Science Foundation of China (Grant Nos. 61474054, 61475060).


We describe a light-emitting unit in white organic light-emitting devices (OLEDs), which comprises multiple host-free phosphorescent materials. This can provide an easy control in luminous spectrum of white OLEDs by modifying the quantity of phosphorescent materials. The device using this light-emitting structure exhibits high efficiency and color stability.

White organic light-emitting devices (WOLEDs) should include at least two emissive colors such as blue/yellow or red/green/blue. Light-emitting layers in a well-known OLED structure were formed by mixing host and dopant. The ratio between host and dopant influences the efficiency of OLEDs. To achieve WOLEDs with high efficiency and small color shift, the doping concentration and the thickness of the light-emitting layers must be carefully controlled.

A WOLED with dispersing a host-free yellow phosphorescent material between two blue phosphorescent emitting layers has been reported [1]. The device performance is comparable to that of using a host–dopant system to form the yellow and blue. In this article, we demonstrate the WOLED with a light-emitting unit of multiple host-free phosphorescent materials can achieve a smaller color shift under various operating brightness. We also try to make a WOLED with a light-emitting unit comprises four host-free phosphorescent materials.

Three devices were fabricated to evaluate device performance and feasibility of the light-emitting unit with the multiple host-free phosphorescent materials.

<table>
<thead>
<tr>
<th>Device</th>
<th>mA/cm²</th>
<th>V</th>
<th>cd/A</th>
<th>lm/W</th>
<th>CiEx</th>
<th>CiEy</th>
<th>Ra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device1</td>
<td>1.587</td>
<td>3.27</td>
<td>63.80</td>
<td>61.37</td>
<td>0.429</td>
<td>0.483</td>
<td>50</td>
</tr>
<tr>
<td>Device2</td>
<td>1.594</td>
<td>3.35</td>
<td>63.71</td>
<td>59.37</td>
<td>0.420</td>
<td>0.484</td>
<td>51</td>
</tr>
<tr>
<td>Device3</td>
<td>2.232</td>
<td>3.35</td>
<td>44.59</td>
<td>41.83</td>
<td>0.439</td>
<td>0.469</td>
<td>67</td>
</tr>
</tbody>
</table>

Figure 2 shows the emissive spectrum of “Device3” which consists of four phosphorescent materials with

Figure 15: The chromaticity coordinate CIE (x, y) is altered with the operating brightness
different color. The emissive spectrum demonstrates that each material emitted light. Additionally, the ratios among various phosphorescent materials can be modified to obtain devices with high color rendering index and different color temperature.

This work was supported by the Bureau of Energy of the Ministry of Economic Affairs.

The structural study of high triplet host materials with carboline moieties for blue phosphorescent OLEDs

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Three carboline derivatives, 9,9'-m-phenylenedi-α-carboline (NmCP1), 9,9'-m-phenylenedi-β-carboline (NmCP2), 9,9'-m-phenylenedi-γ-carboline (NmCP3) were synthesized as high triplet energy host materials for blue phosphorescent organic light-emitting diodes (PHOLEDs). Three carboline derivatives had nitrogen atom at different positions, which was correlated with the photophysical properties of host materials and device performance.

Carboline moiety has gained great attention because of high triplet energy and bipolar charge transport properties[1,2]. In this work, we synthesized three high triplet energy carboline derivatives as host materials to study the effect of heteroatom position of carboline by analyzing actual crystal structure. And we also investigated on the photophysical properties and device performances of the carboline derivatives.

The substitution of nitrogen at β position increased the Eg of the carboline derivatives. The substitution of nitrogen at γ position stabilized the HOMO and LUMO levels of the carboline derivatives. Triplet energy levels of NmCP1, NmCP2, and NmCP3 can be assumed to be 2.88, 3.02, and 2.97 eV, respectively. High triplet energy was obtained in the carboline derivatives with the nitrogen at β and γ position. The triplet energy of the carboline derivatives was high enough for energy transfer to deep blue emitting FCNIrpic dopant materials. It can be summarized that the β substitution increase the bandgap and triplet energy of the host materials and γ substitution stabilizes the HOMO and LUMO levels of host materials.

X-ray crystallographic analysis revealed all NmCP1 molecules adopted regular and face-to-face packing on the whole. It can be assumed that the NmCP1 molecule exhibit higher transport capacity than NmCP2 and NmCP3. Within one column along b-axis, phenyl ring in the β-carboline unit adopt slipped face-to-face packing. The shortest C-C distance between adjacent β-carbolines is 3.300 Å. Thus, there is no typical π-π interaction. NmCP3 molecules have densely intermolecular interaction between adjacent molecules compare with NmCP1 and NmCP2.

The HOMO of NmCP1, NmCP2, and NmCP3 was distributed over the entire molecules. The LUMO of NmCP1 and NmCP2 was concentrated on the one side carboline, while that of NmCP3 was located at the central phenyl ring. The difference of HOMO and LUMO distribution is influenced by the orientation of nitrogen atoms and may affect hole and electron injection and transport in the devices. Therefore, we fabricated hole only and electron only devices of the carboline derivatives. Both hole and electron current densities of NmCP1 device were higher than those of NmCP2 and NmCP3. This indicated that α substitution of the nitrogen is better than β or γ substitution to increase the hole and electron densities in the emitting layer. Comparing the hole and electron densities of the three carboline derivatives, relative charge carrier balance of NmCP1 is superior to that of other host materials. It can be presumed from the hole and electron only device data that carrier recombination can be efficient in the NmCP1 device. The NmCP1 device showed the lowest driving voltage due to high hole and electron current densities in the single carrier devices.

In conclusion, we synthesized three high triplet energy host materials base on carboline moiety to investigate the position effect of nitrogen atom. It was proved that photophysical properties of materials as well as device performance can be control according to substitution position of nitrogen atom in the carboline unit. Also it was demonstrated that the crystal and electronic structures exert dramatic influence on the optical property and carrier transport ability.

Therefore, this study proposed a guideline to design carboline derivatives as the host materials for PHOLEDs. Also, it can be helpful to further understand the correlation between molecular packing, photophysical property and carrier mobility.
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High efficiency green fluorescent organic light emitting diodes(OLED) were developed by suppressing Dexter energy transfer to the green fluorescent dopant. The effect of tert-butyl group of thermally activated delayed fluorescence(TADF) assistant dopant and fluorescent dopant was carried out using a host, TADF assistant dopant and fluorescent dopant structure in the emitting layer. The device performance of the tert-butyl group in the chemical structure of the TADF assistant dopant and fluorescent dopant showed improved external quantum efficiency than that of without bulky side groups in the chemical structure. Tert-butyl group of the TADF assistant dopant and fluorescent dopant could reduce the molecular orbital overlap between host-fluorescent dopant and TADF assistant dopant-fluorescent dopant, therefore Dexter energy transfer could be minimized in the emitting layer. The maximum external quantum efficiency of a green fluorescent device with a tert-butyl group was 15.1%.

Organic light-emitting diodes(OLEDs) are now predominant in displays and their application is being expanded to lighting. Still many scientific and technological innovations are occurring in this field. Fluorescent OLEDs exhibit similar efficiency to the phosphorescent OLEDs due to the development of thermally activated delayed fluorescence(TADF). However, efficiency roll-off at high brightness and operational stability are the problems to be solved.

In this work, we studied the effect of tert-butyl group of emitting materials on the green fluorescent OLEDs with a TADF assistant dopant and fluorescent dopant. And observed high efficiency in a device with a tert-butyl group in the fluorescent dopant chemical structure.

OLEDs were fabricated with a device structure of ITO (150 nm) /PEDOT:PSS (60 nm)/TAPC (20 nm)/mCP (10 nm)/emitting layer (25 nm)/TSPO1 (45 nm)/LiF (1 nm)/Al (200 nm). 3Cz-PFP was used as a host material of the emitting layer, 4CzIPN or t-4CzIPN were used as TADF assistant dopant and PPA or tBPA was used as fluorescent dopant.

Figure 1. Quantum efficiency-luminance curves of green fluorescent devices.
Figure 1 shows EQE curves of the green fluorescent dopant with a t-4CzIPN assistant dopant and fluorescent dopants. The tBPA device with a tert-butyl group in the chemical structure showed higher EQE of 15.1% compare the PPA device without a tert-butyl group of 12.8% in the chemical structure. Tert-butyl group of the fluorescent dopant could reduce molecular orbital overlap between host-fluorescent dopant and TADF assistant dopant-fluorescent dopant, Dexter energy transfer to the fluorescent dopants were suppressed, thus OLEDs with a tert-butyl group showed higher efficiency. Tert-butyl group of the fluorescent dopant could.

By using bulky tert-butyl group in fluorescent dopant, Dexter energy transfer probability could be reduced. As a result, this Green fluorescent device showed high quantum efficiency of 15.1%.

This research was supported by the MOTIE (Ministry of Trade, Industry & Energy (10051350) and KDRC (Korea Display Research Consortium) support program for the development of future devices technology for display industry


P:16 Initiator-free photo-crosslinking systems for OLED applications

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In this paper, we describe the UV-curing of emissive materials for solution processable organic light-emitting diode (OLED) applications without the use of photo-initiators. Low energy and fast curing times using commercially available UV-light sources have been demonstrated in which the resulting thin film is rendered insoluble in common organic solvents.

From the earlier discoveries by Eastman Kodak (small molecular-organic light emitting diode: SM-OLEDs) and the Cavendish Laboratory (polymer light-emitting diode: PLEDs) to the more recent discoveries by Baldo et al. (phosphorescence organic light-em: PHOLEDs) and Kyushu University (thermally activated delayed fluorescence-organic light emitting diode: TADF-OLEDs), OLED development has progressed significantly over the past decades. As part of this multi-disciplinary research area, synthetic chemistry has played a vital role in the design and synthesis of novel and state-of-the-art organic semiconductor materials, with improved stability, charge-carrier mobilities, fluorescence efficiencies, electrochemical properties, etc. Additionally, due to advances in organic chemistry, OLED-based materials can be suitably functionalised to impart the molecule with specific properties that can improve their solution processability.

Due to limitations of vacuum thermal evaporation technology the continued development of solution processable OLED materials is of crucial importance. Developing alternative methodologies to improve the multi-layer capabilities of printable OLEDs is key to improving OLED performances of multiple layer stacking, which can achieve more efficient charge balance in the device. Although the use of orthogonal solvents has had some success in achieving this aim, perfect orthogonality of solubility is difficult. Alternatively, UV-curable organic semiconductors are a class of materials that can be used in the wet deposition fabrication of OLEDs with multiple layers and are thus of noteworthy importance. In this latter case, when a thin film of a photo-crosslinkable charge transporting or emissive material is irradiated with UV-light, polymerisation can occur, via a free-radical or cationic initiated polymerisation mechanism, a rigid and insoluble crosslinked thin film is subsequently formed. Owing to the formation of a three dimensional insoluble polymer network with high crosslinking density crystallisation of the thin film is strongly inhibited and solution processable multi-layer OLEDs can be realised. The synthesis and development of highly efficient and stable UV-curable
crosslinking systems that do not require photo-initiator chemicals has been a focus of interest for Lomox over recent years to deliver multi-layer structures as well as photopatterning (contact or maskless lithography). In addition to our interests in crosslinkable hole transport layer (HTL) materials, here we demonstrate the proof of concept of highly efficient photo-crosslinking systems applied to the emissive layer of an OLED device.

Ideal photo-crosslinking process features such as complete crosslinking, fast processing, substrates at ambient temperature conditions, and the use of commercially available UV-curing equipment, have all been demonstrated. LOMOX materials can be fully crosslinked within seconds using various conventional commercial UV curing systems, such as metal halide lamps, 365 nm LEDs and 385 nm LEDs. Figure 1 compares LOMOX’s green-emissive crosslinkable system to a conventional system. It shows that LOMOX materials crosslink to nearly 100% within seconds while the conventional system is still only 5% crosslinked. Negligible degradation of the emissive material is observed after the UV-curing process.

Figure 1: Initiator-free photo-crosslinking sensitivity plot for Lomox green-emissive system versus a conventional crosslinking system.


Solution processed multilayer structure organic light emitting diodes (OLEDs) were developed using a crosslinkable hole transport material (X-HTM). We developed crosslinkable HTM using hole transport type core, carbazole and diphenyl amine, with a styrene unit. Exothermic peaks of the hole transport material using the thermal property characterization and increase of solvent resistance after thermal annealing of hole transport layer were observed. Device with a crosslinkable hole transport layer shows maximum quantum efficiency of 15%.

Organic light-emitting diodes (OLEDs) have become a great application for a lighting and a display and for these applications an operational stability and a high efficiency of the devices are required. The OLEDs should have a multi-layer structure to satisfy those requirements. The dissolution of the preformed bottom layer by the upper layer solvent and a mixing of bottom materials and upper materials which is difficult to control are problems to be solved in order to fabricate a multi-layer structured OLEDs by a solution process. In this work, we developed thermally crosslinkable hole transport material to increase solvent resistance after film deposition and fabricated multilayer structured OLEDs using a solution process.

Thermally crosslinkable hole transport materials (HTM) were synthesized by using the hole transport core unit with a thermally crosslinkable styrene unit. We measured thermal properties with DSC and exothermic peak was observed in the 1st scan. With the DSC curve, we realized that crosslinking ability of thermally crosslinkable HTM. To confirm solvent resistivity after thermal annealing, we compared the UV-vis absorption spectra after rinsing with several solvents. Hole transport layer (HTL) was spin-coated on the top of the PEDOT:PSS hole injection layer and annealed for 30 minutes at 200°C. And film was rinsed with toluene or chlorobenzene. Figure 1 shows UV-vis absorption spectra of thermal annealed hole transport layer, there was no difference of spectrum between before and after rinsing. Therefore, we fabricated the multilayer structure OLEDs using a solution process with a developed HTM. The device structure was ITO/PEDOT:PSS/crosslinkable HTL/EML/ETL/LiF/Al. PEDOT:PSS, crosslinkable HTL and EML were spin coated with a solution, and from the ETL to the Al metal cathode were thermal vacuum deposited. Device performance of solution processed OLEDs were compared with or without HTL. Maximum quantum efficiency of 16% was observed in the device with crosslinkable HTL and quantum efficiency of 14% was observed in the device without HTL.

We synthesized new cross-linkable HTL materials with styrene crosslinking group. They have good solvent resistivity after thermal annealing. The devices using these materials demonstrate higher quantum efficiency of 16% compared to the references.
P:18 Angular structure of light scattered by normally illuminated monolayer of spherical particles

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The method to describe the angular distribution of light scattered by normally illuminated monolayer of monodisperse spherical particles is developed. It is based on the quasicrystalline approximation (QCA) of the theory of multiple scattering of waves. The scattering spectra of partially ordered monolayer and monolayer with imperfect triangular lattice are calculated and analyzed.

In the development and manufacturing of displays, solar cells, LEDs, etc. the problem to describe angular distribution of light scattered by a particulate (disperse) layers is arisen. There are solutions of this problem obtained in the single scattering and interference approximations. However, they give physically incorrect results for concentrated layers of wavelength-sized particles due to neglecting the multiple scattering of waves between particles. In 1980, Hong solved the problem of finding, with taking into account the multiple scattering, the coherent component (forwardly transmitted and specularly reflected) of light scattered by normally illuminated particulate monolayer [1]. In the present work we expand his approach to describe the incoherent component: angular distribution of scattered light intensity and coefficient of incoherent scattering. Our solution is based on the QCA. It takes into account multiple scattering of EM waves and has no restrictions on distance between particles. The monolayers of homogeneous monodisperse spherical particles are considered.

To obtain the equations describing the intensity of incoherently scattered light we used the QCA and vector spherical wave function expansions of EM fields and tensor Green’s function. The equations are written in terms of scattering coefficients.

The intensity (divided by the intensity of incident light) \( I_{\text{inc}}^{\text{rd}} \) (reduced intensity) of light incoherently scattered by monolayer can be written as follows:

\[
I_{\text{inc}}^{\text{rd}} = \frac{\eta}{2\pi^{2}r^{2}} S_{2}(2x \sin \theta) \left\{ \sum_{j=0}^{\infty} \frac{(2j+1)}{j(j+1)} \left( \pi_{j}^{(1)}(\mu)z_{j} + \tau_{j}^{(1)}(\mu)y_{j} \right)^{2} \right\}
\]

where \( \eta \) is the filling factor of monolayer, \( x \) is the size parameter of particles, \( \pi_{j}^{(1)}(\mu) \) and \( \tau_{j}^{(1)}(\mu) \) are angular functions, \( \mu = \cos \theta \), \( \theta \) is the polar scattering angle, \( z \) and \( y \) are scattering coefficients [2] taking into account multiple scattering of waves, \( S_{2} \) is the structure factor of monolayer:

\[
S_{2}(2x \sin \theta) = 1 + 8\eta \int_{0}^{\infty} [g(u) - 1] J_{0}(2xu \sin \theta)u \, du
\]
\( g(\phi) \) is the radial distribution function [2], describing the structure of monolayer. \( J_0 \) is the Bessel function.

The scattering coefficient is defined as:

\[
F_{\text{inc}} = 2\pi \int_{0}^{\pi} I_{\text{inc}}^{\text{rd}}(\theta) \sin \theta \, d\theta
\]

The wavelength \( \lambda \) and angular \( \theta \) dependences of \( I_{\text{inc}}^{\text{rd}} \) are shown in Figure 1. One can see the influence of spatial order of particles on the angular and spectral distribution of light scattered by monolayer. For the highly ordered monolayer with imperfect lattice the clear diffraction pattern is observed. The dependence for partially ordered monolayer shows typically diffuse scattering. The results can be used to optimize optical characteristics of displays.

Figure 1: Dependences of intensity of light scattered by monolayer with imperfect triangular lattice (a) and by partially ordered monolayer (b).


Poster session 2 - Wednesday 1 November

P:19 Multi-projector 3D display
Multiview 3D display system consisting of the modules of capturing three-dimensional objects, image processing and display screen is developed. Multi-projector system with four projectors is designed and 3D images on 30-inch screen are demonstrated.

There are different types of the real 3D display systems, including multi-view, holographic and integral imaging methods [1, 2]. Integral imaging 3D display is one of the promising displays that provide different perspectives according to viewing direction. Integral imaging is the most simple and suitable method of creating real 3D image. It has essential advantages in comparison with other methods (absence of the complicated mechanical and optical system, use of inexpensive materials in manufacture, possibility of simultaneous vision by the several viewers and others), which allow producing autostereoscopic 3D display with satisfactory color image. However, there are still some physical limitations, including the poor viewing angle, small depth and low resolution.

In this paper the multi-view 3D display which includes the modules of capturing three-dimensional objects, image processing (creation of 3D image files) and display screen for the 3D image displaying based on integral imaging technology is developed. Real-time integral imaging scheme is also realized and experimentally demonstrated. Large display screens using multi-projectors are created. The holographic diffuser to increase the contrast and brightness of the images was used in the display screen. Multi-projectors are used for improving the performance, such as viewing resolution, viewing angle, etc. Preliminary results obtained using multiprojectors are discussed. One of the prototypes has a 30-inch screen with a horizontal field of view of 45°.

The integral imaging method and capturing object from different directions using a rotating platform and a conventional camera were used. The drawback of the integral imaging method for capturing is the small depth. Capturing object from different angles with a camera allows the higher depth to be obtained.

Optical simulations of lenticular and two-dimensional microlens arrays were performed with the aim to determine optimal lenticular sheets, view angle, view number, depth, etc. using Zemax software. Effects of crosstalk and ghost-imaging were studied both numerically and experimentally.

Aspheric lenticular and two-dimensional microlens arrays were designed with increased view angle and depth.

We used full HD DLP projectors (with resolution 1920 x 1080 pixels). 3D image has a “look-around” capability. Objects, which are hidden for the view in one view angle, become visible at another viewing angle. 3D images with 6-8 views were created using own developed software program in MatLab.

Lenticular sheets with different thicknesses and diffuser layers were used in the experiments.

It is followed from the experiments that the greater the viewing angle, the less the image resolution and the depth range. The image resolution can be increased using multiple projectors. To increase the depth the lenticular arrays with aspheric surface profiles should be developed. Two-dimensional microlens arrays were designed in order to obtain motion parallax in vertical direction.

Thus, optical design of display screen (lenticular array and directional diffusers) and the algorithm for creation of 3D digital files taking into account the characteristics of the display screen and DLP matrix of projectors allow to develop the 3D systems, which are superior in characteristics (view angle, depth and absence of the discomfort for viewers) in compare to the conventional stereoscopic 3D displays. The additional viewpoints, i.e. motion parallax give the necessary perception set of the 3D-scenes perspectives and have the property of “looking around” an object.

Proposed displays have a wide range of potential applications including 3D TVs and projection systems, mobile phones, as well as the systems for videoconference and medical applications.
Compensating aberrations in holographic HUD

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The acquisition and compensation methods for optical aberrations occurring in the holographic HUD optical system are discussed.

The HUD (head-up display) is attracting attention as a form of a see-through display for augmented reality. The 3D display method using the holography technique can reconstruct images on arbitrary depth through the phase control of light so that it provides an accurate monocular parallax to the user. Therefore, holography is a suitable technology for the purpose of HUD.

However, conventional holographic display optical systems are too large and heavy to apply to HUD. It is necessary to construct the optical system with light and compact form factor using DOEs (diffractive optical elements) and folded optics. However, such optical systems involve optical aberrations because it has a structure in which light waves are propagated through an optical system having asymmetric aspherical surfaces. Wavefront aberrations are factors that hinder the performance of the display, such as distortion and deterioration of the reconstructed hologram images, therefore a compensation method is required. In order to reduce optical aberration in conventional HUD, compensators such as a freeform mirror and aspheric lens have been used. However, these approaches make the optical system larger and heavier. In addition, the manufacture of optical elements of a specific size or more is limited, and high cost is required.

In this study, the optical aberration compensation function of the existing compensator was replaced by the aberration correction hologram reconstruction using the SLM constituting the holographic HUD system. The proposed aberration correction method can optimize the optical system in the off-axial optical system, therefore it is expected that various types of display design will be possible.

To verify the proposed method, the holographic HUD optical system is constructed as shown in Fig1. Phase SLM was used for modulation of the light wave, and HOE was used for HUD combining and forming the eye box. The HOE is an off-axial component in which the output light propagates at an angle of 30 degrees with respect to the input light, so astigmatism and coma occur. The optical aberration generated in the display optical system was obtained by ray tracing at the exit pupil of the optical system modelled using the optical simulator and converted into the Zernike polynomial form, which is an orthogonal function for the unit circle. This shows the distortion tendency of the image due to the specific aberration.
Experiments were conducted to verify the effectiveness of optical aberration compensation using SLM and wavefront aberration acquisition method through optical simulation. Figure 2 is a reconstructed holographic image observed when the observer pupil is placed in the eye box of the HUD. (a) is a test image to be reconstructed, and (b) is a reconstructed image through actual optical setup. (c) is the result of compensating the optical aberration using a hologram. Compared with (b), it can be confirmed that the image of (c) is relatively reduced in optical aberration and deterioration in image quality, and the image close to the original image is reconstructed.

Figure 2. Image reconstruction of the test object; (a) test image; (b) reconstructed image without compensation; (c) reconstructed image by correcting the aberration


P-21 Flexible transparent thin-film transistors fabricated on plastic substrates

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In this paper, flexible fully transparent Tin-Zinc-Oxide thin-film transistors (TZO TFTs) had been successfully fabricated on plastic substrate by RF sputtering. Excellent properties of TZO TFT were realized. Mechanical stability of flexible TZO TFTs was investigated by bending tests. The flexible TZO TFTs exhibited good electrical performance, good uniformity, and good flexibility. Thereby, we demonstrated the feasibility of high-performance TZO TFTs for flexible display applications.

TFTs fabricated on plastic substrates play an important role in flexible applications such as flexible displays, smart textiles and electronic skins [1 ~ 3]. Oxide semiconductors TFTs were regarded as the promising candidates for high performance flexible TFTs. Recently, a large amount of research based on oxide semiconductors such as IZO and IGZO, have been carried out and high-performance metal oxide TFTs were fabricated [4 ~ 6]. While In is a rare element and toxic. So a non-In active channel layer such as Tin doped ZnO (TZO) is badly needed. Several research groups had carried out experimental studies on flexible TZO TFTs, while the results were undesirable. So high-performance TZO TFTs fabricated on flexible substrate are still of interest.

In this paper, we successfully demonstrated high-performance transparent bottom-gate TZO TFTs fabricated on flexible plastic substrate at low temperature. All processing temperatures were below 100°C. As for as-fabricated TZO TFTs, we demonstrated devices with high-performance, which compare favorably to the performance of the reported IZO-TFTs or IGZO-TFTs fabricated on flexible substrate and represent a dramatic improvement in the electrical and optical performance for TZO TFTs. What is more, good flexibility were
obtained, which highlights high performance stable TFTs can be realized in flexible TZO TFTs. Fig.1 illustrates the typical transfer curves and mobility curves of the TZO TFTs fabricated on flexible PET substrate. Excellent electrical performance was obtained.

![Typical transfer and mobility curves of flexible Tin-Zinc-Oxide thin-film](image)

Fig.1 Typical transfer and mobility curves of flexible Tin-Zinc-Oxide thin-film


**P:22 Evaluation of optical properties of a flexible light scattering liquid crystal device using a random deposited nano-fiber structure in a cell**

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Optical properties of a light scattering liquid crystal device in which nano-fibers of cellulosic polymer material were randomly deposited within cells were evaluated. As a result, it was found that a maximum haze value of 59.2 % was obtained for the cell with a fiber spinning time of 240 s. A scattering device shown higher scattering performance can be obtained as the spinning time becomes longer.

Light scattering liquid crystal (LC) devices have attracted attention for the purpose of application to highly efficient optical shutters such as a privacy window, and they can fabricate without any alignment treatment and light polarizing plates. A cellulose-based polymer dispersed LC has already been proposed as one of the methods of light scattering LC (LSLC) devices [1], in this research, we propose a novel flexible LSLC device structure as shown in Figure 1. Flexible substrates were applied to fabricate it and nano-fibers with cellulosic polymer material was used for not only obtaining the optical scattering but also retaining the cell gap. Nano-fibers were spun by the electro-spinning (ES) method [2], and there is a possibility of obtaining a LSLC device with a higher haze by increasing the randomness of deposited fibers. In this paper, in order to evaluate the basic optical characteristics, haze of the LSLC cell in which piled up fibers consist of hydroxypropyl cellulose (HPC) on glass substrates coated with PEDOT/PSS[3] which is a conductive polymer material with respect to the amount of deposited fibers were measured.

The hydrophilic treatment was applied to surfaces of cleaned glass substrate coated with ITO, and then a PEDOT/PSS solution TC-09 (Denshikako) was coated using a bar coater #8 (13 nm). After drying process at 120 °C for 15 min., nano-fibers were piled up on the substrate by ES with spinning time of 10, 20, 60, 120 and 240 s using a 20 wt% solution of HPC (0.15 ~ 0.70 Pa·s, Aldrich) in ethanol (Wako). After drying process at 100 °C for 20 min., substrates were bonded together and LC E7 (Merck) was injected into the empty cell with isotropic phase and cooled down.

![Figure 1: Structure of a flexible LSLC cell.](image)

![Figure 2: Haze with respect to applied the voltage.](image)

Then, the light scattering performance was evaluated by haze value under applying the AC voltage 0 to 50 V (square wave 15 Hz) using a digital haze computer (Suga Test Instruments).

Figure 2 shows haze characteristics of the LSLC cell with respect to the applied voltage. As the spinning time of the HPC solution became longer, the haze value increased and the maximum haze value of 59.2 % was obtained in the spinning time of 240 s. This was thought to be due to the fact that as the amount of HPC fibers piled up on the substrate surface increased, fibers were piled more complicated, LCs inside the cell...
were more randomly oriented and the scattering property was improved. However, as the amount of piled up fibers increased, the driving voltage also increased.

For the LSLC device containing the randomly arranged fibers, optical characteristics were evaluated under varying the amount of piled up fibers. As a result, it was concluded that the scattering device with better scattering performance could be fabricated by increasing the amount of piled fibers, and haze value was saturated under the condition at 120 s of the spinning time in our experiments.


P:23 In–Ga–Zn–O metal-semiconductor field effect transistor for flexible device applications
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In this paper, we present a method for controlling turn-on voltage (Von) and off-current (Ioff) of In–Ga–Zn–O metal-semiconductor field effect transistor (MES-FET). The MES-FET was fabricated at a maximum processing temperature of 150 ºC, which is applicable for flexible devices.

An amorphous oxide semiconductor (AOS) of In–Ga–Zn–O (IGZO) is expected to be used as a channel material of thin-film transistors (TFTs) for flexible devices because the IGZO TFTs exhibit field-effect motility (µFE) of over 10 cm²/Vs and good uniformity even fabricated at room temperature. The oxide TFTs with metal-insulator-semiconductor (MIS) structure have been widely employed; however, maximum processing temperature of 300-400 ºC is required to guarantee the performance and reliability of the TFTs. In contrast, metal-semiconductor field effect transistor (MES-FET) has several advantages for flexible devices since a Schottky gate can be formed at low temperature with AOS. There are a few reports of AOS based MES-FET; however, a stable and good Schottky contact has not been established on the AOS. In this presentation, the IGZO MES-FET with silver oxide (AgOx) Schottky gate was fabricated at a maximum processing temperature of 150 ºC.

The IGZO MES-FET was fabricated as follows; First, a 200 nm-thick IGZO film was deposited on a glass substrate by DC magnetron sputtering from InGaZnOx (In:Ga:Zn=1:1:1 mol.%) target. Deposition pressure was kept at 1.0 Pa, while the O2 gas ratio during the IGZO deposition \( R(O_2)=O_2/(Ar+O_2) \) was varied at 0.66 and 0.80%. The IGZO film was patterned into an active channel by conventional photolithography and wet etching. The IGZO channel was then annealed at 150 ºC for one hour in ambient air. A 120 nm-thick AgOx was deposited by DC reactive sputtering, and Au was deposited on the AgOx by vacuum evaporation. The AgOx/Au Schottky gate was patterned by lift-off. Finally, Mo source and drain electrodes was formed by lift-off. Width/length of the MES-FET was 100/10 μm.

IGZO MES-FETs with single- and stack-layered channel were fabricated. The \( R(O_2) \) of 0.66 and 0.80% were used for single-layered channel. For stack-layered channel, upper and lower channels were deposited at the \( R(O_2) \) of 0.80 and 0.66%, respectively. The thickness of upper/lower (d1/d2) channels were varied at 100/100 and 50/150 nm. Figure 1 shows transfer characteristics of the MES-FETs. For single-layered channel, turn-on voltage and off-current were very sensitive to the \( R(O_2) \) of the IGZO channel. By decreasing \( R(O_2) \) only from 0.8 to 0.66%, transfer curve shifted to negative gate voltage direction and off-current increased over four orders of magnitudes. In contrast, turn-on voltage of the stacked channel was successfully controlled by the thickness ratio of the channel. Moreover, the off-current of the stacked channel remained below a few pA, result in an increase of on/off current ratio to \( 3.4 \times 10^8 \). However, the µFE was 1.12 cm²/Vs which was much smaller than the Hall mobility (8.55 cm²/Vs). Improvement of the µFE in MES-FETs is a future research work.
P:24 The effects of corrosion, fatigue and fatigue corrosion on ITO/Ag-alloy/ITO multilayer films coated PET substrates used in flexible electronics applications

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ITO/Ag-alloy/ITO coated polymer film is widely used as transparent conductive electrode in many flexible electronic devices such as organic light-emitting, flat-panel displays and photovoltaic solar cells. The surrounding atmosphere where the flexible solar cells are sometimes used such as marine environments are rich with chlorine. Also, photolithographic patterning processes for thin films in the fabrication of electronic displays devices such as liquid crystal displays can be achieved by wet chemical etching in solutions such as HCl solutions [1] using roll-to-roll etching machines comprising incorporating etching baths [2]. The residual Cl- after the etching processes using HCL (described above) can cause degradation of functional properties.

As it is well known that chlorine deteriorates Ag-based film, therefore the electrical and optical properties of ITO/Ag-alloy/ITO film in NaCl corrosive media are investigated in this work. Also the effects of bending fatigue combined with aggressive environments provided by salt are studied. Greater changes in electrical resistance were found at higher concentrations. In addition, changes in electrical resistance were observed to be high for specimens subjected to fatigue conditions, higher applied strains and a higher number of cycles. Also, it is shown that exposure to salt can cause the ITO/Ag-alloy/ITO performance to degrade over time. Furthermore, the combination of stress and corrosion by aqueous sodium chloride solution was found to significantly reduce the conductivity of the ITO/Ag-alloy/ITO film.

Self biased oxide TFT amplifier

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Oxide TFTs, which have higher electron mobility and less leakage current than amorphous silicon TFTs, have been studied by many researchers and are being used in display backplanes. In this work, an amplifier circuit with oxide TFTs is presented. The voltage gains of 4.5 (13 dB) was obtained with cascade class A amplifier, and it operates well for the threshold voltage change of the transistors from -0.5 to 1.5 V.

For portable audio amplifier, low power and compact design are necessary. For the compact and flexible devices, fully integrated circuit on a substrate is necessary. Among the possible devices for integrated circuits, thin film transistor (TFT) with oxide semiconductor material is one of the candidate due to its higher field effect mobility than amorphous silicon TFT and simple process compared to low temperature polycrystalline silicon (LTPS) TFT [1-2]. The audio amplifier with oxide TFT was investigated and optimized for threshold voltage change without distortion of the waveform. The proposed amplifier circuit does not require a bias voltage divider and also auto biased according to threshold voltage change because it is selfbiased with inverter circuit instead of resistive divider.

To get high amplification gain, we designed a common source amplifier in which n-channel oxide TFT was used as a load resistor as shown in Fig. 1(a). The input operation point is important, and the conventional way to get the operation voltage is resistor divider. The proposed amplifier circuit is composed of 6 TFTs, and it was optimized by the adjustment of channel width of each TFT. For simulation, the common-source amplifier was biased by VDD = 12 V and VSS = GND. The sine wave with 0.1 V amplitude was used for the input voltage. The input frequency was 2 kHz. The first block of amplifier circuit is to set the operation point of the TFT T3.

The characteristics of the oxide TFT are subject to change due to process variations. It is, therefore, important to set the operation point well using the appropriate bias voltage. However, if a bias is applied to each transistor, the power consumption is large and the circuit becomes complicated. In this paper, we have solved this problem by generating one stage bias at the circuit input side. The advantage of the inverter for the operation voltage is self-optimization, even the TFT threshold voltages vary. The DC operation voltage for the input gate electrode is important. The comparison for output waveforms with correct operation point and incorrect operation point are shown in Fig. 1(b). The second block and the third block are cascaded commonsource amplifiers. After optimization of sizes of TFTs, we could obtain the voltage gain of 4.5 (13 dB). Since the capacitance needs large electrode area which can decrease the yield of the circuit fabrication, we removed the capacitors between each block. Each block was directly connected after optimization to keep the output of a block as optimum operation voltages to the next block.
We developed class A audio amplifier with oxide TFTs. The auto bias circuit was used instead of resistor voltage divider. The voltage gains of 4.5 (13 dB) was obtained with three cascaded amplifiers. Since the characteristics of the oxide TFT can be varied according to the process conditions, we optimized the operation point after adjusting the sizes of the TFTs. The proposed circuit operates well for the threshold voltage change from -0.5 to 1.5 V.


Development of an e-paper touch system using status LEDs for visible light data transmission for IoT safety and security

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Developing, installing and operating internet of things (IoT) devices in terms of safety and security is challenging because they have usually no display. We report on an add-on device with 3.8" e-paper touch display using the status LED of IoT devices for visible light communication (VLC) displaying IoT data. This approach requires only a few lines of code in the IoT device.

Internet of Things (IoT) is one of today’s most interesting technologies. Sensor data are sent to the cloud and big data analysis and local visualization are possible. To detect software bugs (on IoT device or cloud computing; data integrity → safety) or corrupted data (unauthorized access → security) [1], it is helpful to read e.g. sensor data and parameters directly on the IoT device. This is visualized in Figure 1: Local and cloud data can be directly compared at the place of the IoT installation. One approach is an IoT device equipped with a display (which is costly) or to transmit data from the IoT device via visible light communication (VLC) via LEDs to a remote device (cost saving). The latter approach is presented in this paper.
The optical transmission of data is well known from optical fibers (the backbone of the internet) or IR remote controls. Visible light communication [2] is pushed by e.g. LED lighting. Even status LEDs can be used for data transmission or dedicated LEDs. This is the basic idea behind our project: Easing IoT commissioning and raising data safety & security via VLC. This principle is visualized in Figure 3.

Figure 3 shows our add-on device: The PCB (backside of the device, left) with VLC receiver (blue box), microcontroller (red box, ATMEGA 1284P) and e-paper controller (yellow box, EPSON S1D13522). The e-paper display is reproduced on the right: E Ink’s ED038TH1 has a size of 3.8” with a resolution of 600 x 600 pixels and 2-8 gray levels. Its high reflectance, wide viewing angle, bistability, ultra-low power consumption, the front light and touch screen makes this display perfectly suitable for an IoT clip-on VLC device. We have successfully evaluated the functionality with our own low cost [3] and professional IoT devices regarding safe VLC transmission and the efficient use of the HMI with touch operation for supervision and control.

Figure 3: IoT hardware (add-on for VLC, left) with attached E Ink touch display (right)

We have developed an e-paper system which can be temporarily or permanently added to IoT devices using a simple status LED to detect software errors and corrupted data from IoT devices via a cloud to the end user. Existing devices can be retrofitted by a few lines of code. Future smartphones may have built-in VLC functionality.
P:27 Effect of SOG annealing ambient on IGZO TFTs

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The effect of annealing conditions of spin-on-glass(SOG) on the top gate In-Ga-Zn-O Thin film transistor (IGZO TFT) was investigated. After SOG was spin coated on a IGZO layer, the curing step was carried out under three ambient conditions of nitrogen, air, and oxygen. Annealing under the nitrogen ambient showed the best characteristics of IGZO TFTs due to the nitrogen diffusion down to the IGZO layer.

The solution process has advantages of low cost and low process time compared with the vacuum process. Spin-on-glass (SOG) is used widely as an interlayer dielectric and siloxane based SOG gives higher planarity compared to other SOG. In this study, siloxane based SOG was used for the gate insulator and passivation in the top gate In-GaZn-O Thin film transistors (IGZO TFTs). We investigated the annealing effect of SOG.

Figure 1: The structure of fabricated TFT

In this experiment, we used siloxane based SOG as the gate insulator and passivation layer. The gate electrode was Cr, and the source/drain was Al. IGZO was deposited on the Glass by RF sputtering and patterned by photolithography. After preheating at 80°C for 20 minutes, SOG was spin coated and soft bake was carried out at 80°C for 1 minute and 180°C for 1 minute. And then, it was annealed in a furnace at 450°C for 1 hour under nitrogen, oxygen and air ambient to evaluate the effect of the annealing ambient. The Cr and Al was deposited using a DC magnetron sputter and patterned by photolithography.

Figure 2 shows transfer characteristics TFTs with nitrogen, air, oxygen annealing ambient. Annealing in nitrogen ambient shows the best TFTs characteristics in terms of on-current, threshold voltage, mobility and subthreshold slope. In contrast, annealing in oxygen ambient shows the lowest on current. It can be explained by the nitrogen content at the interface between SOG and semiconductor. Figure 3 shows depth profile of nitrogen content by SIMS.
Figure 2: Transfer curves for TFTs with different annealing conditions analysis. The depth profile shows nitrogen accumulation at the interface between SOG and Si. The accumulation of nitrogen at the interface between the SOG and the semiconductor has a beneficial effect on the IGZO layer, which helps to improve the characteristics of the TFTs. It was reported that defects inside IGZO are reduced by structural relaxation during annealing in a nitrogen ambient at elevated temperatures [1].

Figure 3: SIMS analysis on nitrogen contents in SOGs with different annealing ambients.

We fabricated IGZO TFTs using siloxane based SOG and investigated the annealing effect of SOG with different ambient conditions. The improvement of electrical characteristic in IGZO TFTs annealed under nitrogen ambient was attributed to the nitrogen diffusion down to IGZO interface.

Capacitive touch-fingerprint recognition sensor with a-IGZO TFT was studied for application to front side of the display. A capacitive type sensor is a sensor that detects changes in capacitance between the surface of the finger and the sensor electrode. The proposed circuit consists of two lines, one capacitor and one TFT. It showed good sensitivity only with single TFT in a pixel. The simulation result of the voltage difference between the ridge (touch) and the valley (non-touch) was 5.1V.

As for fingerprint recognition users feel little resistance and its certification performance is good compared with other methods, it has been used widely. The optical type is difficult to realize the fingerprint sensor in a small package at a low cost [1]. So, we chose a capacitive type that can be made with a compact size. To integrate this into the display, we used amorphous In-Ga-Zn-Oxide (a-IGZO) which has higher field effect mobility than the a-Si:H TFT [2] and is cheaper to manufacture than LTPS (Low Temperature Polycrystalline Silicon) TFT. Thus, we studied capacitive type fingerprint sensor, where capacitive change by touching the fingerprint can be detected.

Figure 1 shows schematics of newly proposed capacitive sensor circuits for touch-fingerprint. This circuit consists of two lines (SCAN, READOUT), one capacitor and one TFT. (C2 is capacitor between the finger and the sensing electrode.) It can be suitably used in a small pixel pitch by using only one TFT while not losing sensitivity.

When the finger touches the pixel (the ridge), the capacitance (C2) between the pixel and the finger is relatively large compared with touch with valley. Even if the voltage of scan line increases, the gate voltage of the TFT does not increase due to the large capacitance of C2. Therefore, the current flowing between the source/drain electrodes of the TFT does not increase. On the other hand, if the finger does not touch the pixel (the valley), the capacitance (C2) is relatively small. When scan line voltage increases, the gate voltage and the current flowing through the TFT increase. This current is detected through the read-out line and it is possible to recognize the fingerprint through the touch sensor array. The coupling between scan line and gate electrode increases the gate voltage of TFT and sensing voltage.

Figure 2 shows simulation results for the proposed capacitive sensor circuit. The area of sensing electrode was 2449µm² in a pixel area of 80×80µm². The width and length of TFT were 10 and 11µm, respectively. For the simulation, the circuit is biased by $V_{SCAN} = 0\sim15V$, $V_{READRESET} = -5\sim25V$. The obtained voltage difference between the ridge sensing and the valley sensing were 5.1V.
We proposed simple and small area fingerprint sensor circuit. The proposed circuit used only one TFT, and showed good sensitivity with small sensing electrode. The simulated voltage difference between the ridge touch and the valley touch was 5.1V.


P:29 Fabrication of a-IGZO TFT using imprint lithography

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In this paper, a-IGZO TFT was fabricated by imprint lithography. It shows typical electrical performance with a field-effect mobility of 6.3 cm²/V·sec, subthreshold swing of 1.0 V/decade, and on/off ratio of > 10⁷.

Recently, as interest in OLED flexible displays has increased, research on them has become more and more active. Especially, OLED rollable display is a future display, and efforts for product development in terms of product design, commercial usability and portability are increasing. However, there are many technical issues to improve. In this study, oxide TFTs were fabricated on flexible film for rollable display. The imprint lithography method is considered to have high throughput and low cost to make a rollable display using roll-to-roll method because it can self-aligned to plastic substrate deformation[1-2].

The imprinted layer of 4 stack is shown in Fig. 1(a) after forming the five layers sequentially. As shown in Fig. 1(b) and (c), a-IGZO TFTs (W/L=100/50 μm) of bottom gate type were fabricated by using self-aligned imprint lithography method.

Figure 1 : Layer structure of a-IGZO TFT
First, 3D structure was formed by deep reactive ion etching (DRIE) using a 4-step photo process on 6” wafer. Fig. 2 shows that 3D structure is defined a master template. TFT pattern structure of PDMS mold transferred on master template. Al (100 nm)/SiNx (300 nm)/IGZO (50 nm)/Cr (100 nm) thin films were deposited on the substrate by sputter and PECVD[3-4].

Finally, polymer resin (NOA 63, Norland) was uniformly coated to 7 μm thickness. Specimen of 5 layers was imprinted by the prepared mold and then was patterned by the dry ashing and etching process. Fig. 3 (a) shows an optical micrograph image of a patterned a-IGZO TFT. Active, source, drain and gate lines were well formed. As shown in Fig. 3 (b), (c), a-IGZO TFT demonstrated a field-effect mobility of 6.3 cm²/V.s, sub-threshold swing of 1.0 V/decade and on/off ratio of > 10⁷.

We have investigated fabrication of a-IGZO TFT (W/L=100/50 μm) of bottom gate type by imprint lithography for rollable display.

The authors gratefully acknowledge the support of their collaborators including: ITRC, Wonik IPS, Avaco, Ulvac Korea, SKKU ADND Lab and SKKU SAINT OED Lab.

The effect of light shielding on thin film transistor performance under simultaneous thermal and optical stress

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In this paper, the behavior of the three semiconductors most commonly used for thin film transistors in active matrix displays is examined under thermal and optical stress with and without light shielding.

Amorphous silicon (a-Si) is still the standard semiconductor for thin film transistors (TFTs). It is cost efficient but with low charge carrier mobility and therefore needs large geometries. Low temperature poly silicon (LTPS) TFTs are the opposite, expensive but with high charge carrier mobility making them ideal for mobile high resolution applications. The characteristics of amorphous indium gallium zinc oxide (IGZO) TFTs puts them in between the two silicon based TFT technologies.

But considering new applications of active matrix displays, outside of TVs or mobile applications [1], new parameters have to be considered to find the most suitable semiconductor technology for them.

Therefore the effects of simultaneous thermal and optical stress and the influence of light shielding on these TFT types is discussed in this paper.

All test were conducted with five TFTs of each technology and the results were averaged. The channel geometry of all measured TFTs is 5µm x 5µm. To quantify the influence of the different stress types, thermal and optical stress were first measured separately before being applied simultaneously.

The thermal stress measurements compare the input characteristics at room temperature (20°C) and 80°C. For the silicon based TFTs higher temperature leads to a higher charge carrier mobility while for IGZO the mobility decreases. All three TFT technologies show a threshold voltage ($U_{th}$) shift in negative direction and a lowered $I_{on}/I_{off}$ ratio.

To determine the impact of optical stress alone, input characteristics were measured at ambient light and with 20Mlx incident directly on the semiconductor.

For high illuminance both amorphous silicon and IGZO TFTs degrade so much under optical stress that they no longer work as transistors. LTPS TFTs show the same performance as under thermal stress.

When exposed to 20Mlx illuminance and 80°C both amorphous TFTs degrade to being non-functional, as expected. LTPS TFTs still show a good performance with mainly the $I_{on}/I_{off}$ ratio being negatively affected.

As the high illuminance is the main cause for degradation of the TFT performance under combined thermal and optical stress, the effect of a light shield (LS) protecting the semiconductor against high illuminance was tested. To estimate the impact of a LS with the same TFTs as in the previous tests the gate of the transistors was used as a light shield.

With light shielding a-Si and IGZO TFTs are functional even at 80°C and 40Mlx, while LTPS TFTs do not profit from the light shielding compared to 80°C and 20Mlx.

LTPS TFTs are the most stable of the three tested TFT types being able to operate under thermal and optical stress without adjustments. Both amorphous semiconductors need to be shielded against high illuminance. Using the gate as a LS is a simple and effective solution to keep a-Si and IGZO TFTs operational even at 80°C and 40MLx illuminance.

The summary of the results is shown in Table 1.
Table 1: Average Results

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<th>Ambient Light</th>
<th>20Mlx Direct</th>
<th>40Mlx LS</th>
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<td>20°C 80°C</td>
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<th>20°C 80°C</th>
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<td>$\sim 10^{13}$</td>
<td>$\sim 10^8$</td>
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</tbody>
</table>

P:31 Device property engineering of oxide semiconductor vertical TFT by means of back-channel passivation via PEALD

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Recently, VR (Virtual Reality) and AR (Augmented Reality) are emerging as powerful driving force towards development of the next-generation display. However, there still remain several obstacles that hinder expansion of those new technologies, and one of them is the low resolution of display. To solve this problem, higher pixel density of several thousand PPIs is strongly required.

In that point, oxide semiconductor vertical thin-film transistor (VTFT) is thought to be a good candidate. Its vertical channel structure makes it possible to reduce its footprint size. Moreover, it is possible to downsize the channel length under 1 $\mu$m by using the pre-existing photolithography equipment for the display industry. This can give us enhanced current drivability [1, 2]. With these motivations, we fabricated oxide semiconductor VTFT and tried to improve its electrical properties.

Oxide semiconductor VTFTs were fabricated on thermally oxidized Si wafer substrates. Figure 1 shows the overall structure of the fabricated VTFTs.
We used ITO for the source/drain electrodes, SiO₂ for the spacer, InOₓ via plasma-enhanced atomic layer deposition (PEALD) method for the active layer, and Al₂O₃ for the protective layer (PL) + gate insulator. PL layer was adopted to reduce gate leakage current. All patterning steps except for the active and PL layer were conducted by dry-etching.

We introduced a very thin SiO₂ layer on the dry-etched side of spacer, which acts as back-channel region, to cure the damaged surface. After deposition of the SiO₂ layer by PEALD, opening top contact regions of the electrodes was conducted by dry-etching. Thanks to the vertical structure, we did not need to use extra PR mask for this process due to the anisotropic dry-etching mechanism and superior thickness uniformity of PEALD.

As figure 2 shows, we could observe improved sub-threshold swing property, less negative Von value, and additionally verified broader process window for the post-annealing by adopting the back-channel passivation process. This indicates the possibilities of device property enhancement for VTFT through the optimization of the back-channel region.

In this paper, we investigated the effect of back-channel passivation process on the device characteristic of oxide semiconductor VTFT. Through this result, we will proceed to conduct experiments for the optimization of the back-channel passivation process, and the device properties of VTFT.

This work was supported by ‘The cross-Ministry Giga KOREA project’ grant from the Ministry of Science, ICT and Future Planning, Korea [GK15D0100]

This work was supported and funded by LG Display Co., Ltd.


P:32 Low power integrated shift register circuit for in-cell touch applications

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This work proposes a low power shift register circuit integrated in in-cell touch panels where touch sensing and display scanning operations are conducted by time division driving method. The proposed circuit reduces the area as well as the power consumption.

To achieve the high signal-to-noise ratio in in-cell touch displays, touch detecting and display scanning are conducted separately by time division driving method [1]. Because some shift registers in the gate driver circuit should maintain the charging state during the long period of the touch sensing, the transition characteristics of gate pulses might be non-uniform leading to the block artifacts. This paper proposes a low power and small area shift register circuit that resolves the non-uniformity issue of gate pulses.

Figures 1 and 2 show the schematic and timing diagram of a proposed gate driver circuit that is composed of 9 TFTs and one bootstrapping capacitor. RES indicates scanning and sensing periods by VGH and VGL levels, respectively. A[n] is the node that maintains the charging state to generate the gate pulse after the touch sensing is finished. Although Q[n] is discharged during the touch sensing period, Q[n] is charged and bootstrapped again by A[n]. Consequently, the stress of all pull-up TFTs (T8) becomes equivalent, which ensures the uniform transition characteristics of gate pulses.

When the input pulse Vg[n-1] is asserted through T1, A[n] is charged to the high level. When RES is high in the scanning period, Q[n] is also charged to be ready for the output pulse. Otherwise, in the sensing period, Q[n] is discharged and T8 is released from the voltage stress. Then, once RES changes to VGH, Q[n] is programmed according to the stored voltage level of A[n]. Therefore, the gate driver circuit continues to generate the gate pulses.

The circuit is simulated with low temperature poly-Si (LTPS) TFTs that have mobility of 37.907 cm²/Vs and threshold voltage of 1.94 V. Compared with a previous circuit of Ref. [2], the numbers of TFTs, capacitors, and signals for one shift register are reduced from 11, 3, and 3 to 9, 1, and 2, respectively. Furthermore, the power consumption of 160 shift registers is substantially lowered from 12.77 mW to 9.12 mW by 28.6 % for a 60 Hz FHD display with the 120 Hz touch report rate.

Figure 23: Proposed in-cell touch shift register
This research was supported by IDEC (EDA Tool) and the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2016R1A2B4009787).


**Enhancement of voltage holding property in low frequency driving fringe-field switching mode using carbon nanomaterials doping within an alignment layer**

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We demonstrated the doping effect of the carbon nanomaterials in alignment layer for enhancing the holding property of fringe-field switching (FFS) liquid crystal (LC) mode. According to doping ratio, the holding properties were enhanced from 63 to 99% even for extremely low frequency driving of 0.5 Hz.

Fringe-field switching (FFS) liquid crystal (LC) mode has been widely used in portable devices because of its high optical efficiency and low power consumption. Since the power consumption is linearly proportional to the driving frequency, low-frequency driving method has been applied to reduce the power consumption of LC display (LCD). However, low frequency driven FFS mode shows the flickering effect because the elongated holding time induces the degradation of voltage holding property. In particular, due to the low resistivity of the negative dielectric LC (n-LC), the voltage holding properties of the FFS mode using n-LC (FFS n-LC) are significantly degraded within a frame and it induces the severe transmittance drop.

In this paper, we doped the carbon nanomaterial in alignment layer to enhance the voltage holding property of the low frequency driven FFS n-LC by trapping the ionic charge from the LC layer. We evaluate the variation of the mobile ion density in LC layer according to the doping ratio of the carbon nanomaterial. In addition, the effects of these mobile ion density values on voltage holding property were investigated. Finally, we proposed the adequate doping condition of carbon nanomaterial in alignment layer to enhance the voltage holding property in 0.5Hz.
Figure 1(a) shows the current properties of the FFS n-LC cells according to the doping ratio of the carbon nanomaterial. The mobile ion density could be evaluated using the current variation caused by the ionic charge transfer under electric field between both electrodes. For this experiment, we operated the prepared LC cells by applying a triangle wave signal of 0.1 Hz at the voltage of 10 V. For non-doping case, measured ion density was 2.07 nC/m³. This result is similar level as previously reported value [1]. As the doping density increased by 0.001, 0.01, and 0.05 wt.%, the ion density decreased by 1.01, 0.32, and 0.03 nC/m³, respectively, because of the ion trapping behavior of carbon nanomaterials.

![Current properties of FFS n-LC cells](image)

**Figure 16:** (a) Current properties and (b) time varying brightness variations by doping condition

To confirm the holding property enhancement by reduced ion density, we measured the time varying brightness variations of FFS n-LC cells at 0 and 0.05 wt.% doping ratio. Applied signal was the square wave of $V_{20}$ at the rate of 0.5 Hz ($V_{20}$ indicates the voltage at 20% of the full brightness level in each cell.). Contrast to non-doping case, we verified that the 0.05 wt.% doping case, which had low ion density in LC cell, showed the superior holding property as shown in Figure 1(b).

We enhanced the holding property of FFS n-LC cell by control the mobile ion density. To control the mobile ion density, the carbon nanomaterial was doped in alignment layer. From this result, we obtained the 99% holding property at 0.05 wt.% doping ratio in 0.5 Hz.

This work was supported by the Technology Innovation Industrial Program funded by the Ministry of Trade, Industry & Energy (MI, Korea) [10052667]

In this paper, self-aligned top-gate (SATG) amorphous indium-gallium-zinc-oxide (a-IGZO) thin-film transistors (TFTs) were fabricated. The conductive source/drain regions were formed by hydrogen incorporation during the deposition of SiO\(_x\) or SiN\(_x\) passivation layer using plasma-enhanced chemical vapor deposition (PECVD). It was found that the source-drain parasitic resistance (R\(_{sd}\)) was effectively reduced during the deposition of SiN\(_x\) passivation layer than SiO\(_x\). However, hydrogen lateral diffusion into channel region resulted in the shrinkage of effective channel length and deterioration of performance of short-channel device.

Recently, a-IGZO TFTs have attracted much attention as one of the promising candidates for next generation flat-panel displays attributing to the advantages of high mobility, low processing temperature and large area uniformity [1]. The self-aligned top-gate structure for a-IGZO TFTs is preferred to drive high resolution displays due to the low parasitic capacitance and short channel length compared to bottom gate structure. However, the formation of conductive source/drain regions is the key process in SATG a-IGZO TFTs.

In this paper, the conductive S/D regions were formed by hydrogen incorporation with the deposition of SiO\(_x\) or SiN\(_x\) passivation layer by PECVD. The effect of hydrogen diffusion was investigated.

The schematic of self-aligned top-gate a-IGZO TFTs was shown in the insert of Figure 1 and the fabrication process was described in our earlier work [2]. The devices were named as device A-D with the passivation layer of 150 °C SiO\(_x\), 150 °C, 200 °C, and 250 °C SiN\(_x\), respectively.

As shown in Figure 1, there was almost no difference between device A and B. However, the V\(_{th}\) and mobility of device B-D decreased as the deposition temperature increased. Transmission line method was applied to extract \(\Delta L\) (\(\Delta L=L_{M}-L_{eff}\)) and R\(_{sd}\). The device with SiN\(_x\) obtained lower width-normalized R\(_{sd}\) (R\(_{sd}\)W) and larger \(\Delta L\) compared to SiO\(_x\) due to higher concentration of hydrogen incorporation into source-drain regions as shown in Figure 2. Hydrogen lateral diffusion became more serious as the deposition temperature increased, leading to the increased \(\Delta L\).
Figure 2. Schematic of the effect of hydrogen diffusion from passivation layer of SATG a-IGZO TFTs.

The effect of hydrogen diffusion of SiOx or SiNx passivation layer of self-aligned top-gate a-IGZO TFTs was investigated. SiNx passivation layer could effectively reduce the Rsd of SATG a-IGZO TFTs compared to SiOx. However, the hydrogen lateral diffusion into channel region resulted in the shrinkage of effective channel length and deterioration of the performance of short-channel device.


P:35 Towards a phase-change metamaterial CMY subtractive display

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A phase-change based metal-insulator-metal metamaterial absorber structure is proposed for the creation of cyan, magenta and yellow (CMY) pixels that could provide the first steps towards the realization of a fast, non-volatile CMY-type subtractive display

Chalcogenide phase-change materials (such as Ge2Sb2Te5 or, as used in this paper, GeTe) exhibit a large refractive index change when switched between their amorphous and crystalline phases. Such switching can be achieved by electrical, optical or thermal means, and is fast, reversible and non-volatile. These properties have recently been exploited to develop entirely new types of phase-change based reflective optoelectronic RGB-type displays based on a Fabry-Perot resonant cavity design [1]. Such displays can provide ultra-high resolution, ultra-fast frame rates and, since they are non-volatile, require no power to maintain an image.

In this paper we explore a possible alternative approach for the provision of phase-change based reflective displays, namely that based on subtractive colour generation. One of the first steps towards a subtractive approach is the development of cyan, magenta and yellow (CMY) pixels. To provide such CMY pixels we take advantage of recent advances in optical metasurfaces that allow us to control the amplitude and phase of reflected light via its interaction with arrays of metallic resonators [2]

Our CMY pixel structure is formed by a layer of the phase-change alloy GeTe sandwiched between a bottom metal layer and a top ITO layer, on top of which is an array of lithographically-defined circular metal ‘dots’. A unit-cell for such a structure is thus as shown in Fig. 1 (here with all metal parts shown as Al, though other
metals may be used). The resonant frequency (wavelength) of such a structure was adjusted to produce the necessary CMY colour pixels (see Fig. 2) by changing the geometrical parameters that form the optical cavity, namely the size of the Al ‘dot’ and the thickness of the ITO layer. Our design also maximizes the coupling strength of the light incident on the device when the GeTe layer is in the crystalline phase. However, when the GeTe layer is switched to the amorphous phase, the resulting change in refractive index decouples the cavity from its resonant absorption state, resulting in a relatively flat spectral response (i.e. it generates a ‘white’ reflectance spectrum – see Fig. 2).

The high resolution, non-volatility, simplicity and low power consumption of our CMY subtractive colour approach has possible applications in areas such as wearables, signage, security identifiers and e-paper.

![Figure 1: Unit-cell of the CMY phase-change pixel](image)

![Figure 2: Reflectance spectra for pixels of the form shown in Fig. 1 and with the GeTe layer in the crystalline (solid lines) and amorphous (dashed lines) state; inset shows pixel colour (for GeTe crystalline) for the CIE Standard Illuminant D65.](image)

SG-CC acknowledges funding from the EPSRC CDT in Metamaterials (EP/L015331/1), CDW and HB via the EPSRC WAFT project (EP/M015173/1).


Two test methods of flicker, transformation relationship and mathematical analysis

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1BOE Technology Group Co., Ltd., China, 2Hebei University of Technology, China

As a common technology product in life, display screen has been deeply embedded in various fields, and the optical characteristics are the key indicators to determine the quality of display products. The evaluation of screen flicker is one of the key control parameters to evaluate the optical performance of the screen. In the display product industry, there are two methods of the evaluation of the Flicker: comparison method and JEITA method. This paper makes an analysis for the two evaluation methods in time-frequency domain. Particularly, using the way of nonlinear regression of the mathematical statistics, this paper deduces the relationship of the two methods of the evaluation in the normal data field. Also, this paper gives accurate empirical formula and the precision analysis. By using the empirical formula, the complexity of existing test equipment can be simplified, the cost and test time can be saved greatly.

Lowest cost colorimeter for multiple use

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Pforzheim University, Germany

Optical display measurement devices are relative expensive. We developed a luminance and color device for displays and reflective color sensing with a hardware price of less than 10 USD including a color display. Applications are e.g. mobile measurements for airport monitors or sorting of objects.

Evaluating the optical parameters of displays is essential for today’s high quality products. The market offers a wide range of luminance and color meters which are costly (starting at about 1,000 USD for luminance) and of limited mobility. On the other hand, many displays/monitors should be evaluated after installation like airport e-signage displays for e.g. luminance (lifetime decay) or grey scale reproduction (gamma). This was the motivation to develop a lowest cost colorimeter which should be able to perform fundamental display measurements like luminance, gamma and color, even under bright ambient light conditions.

Fundamental measurement and calibration methods are described in e.g. [1] and [2]. 𝑉(𝜆) and Color Matching Functions characteristics of the optical sensor determine its precision. Our first approach to low cost USB luminance sensors is described in [3]. The goal of this work is to develop a true mobile luminance and color sensing device with a display.
After surveying color sensors, microcontrollers and displays regarding lowest cost, we selected [4] a TAOS/AMS TCS230 (spectral sensitivity see Figure 1) and an ARDUINO NANO V3 with a 1.8” color TFT LCD (128 x 160 pixels). Total cost is about 10 USD in low quantities. The system is shown in Figure 2 incl. USB power pack. The acquisition, calibration and HMI software was developed by us.

![Figure 1: Spectral sensitivity of TCS230][4]

We started evaluation by measuring the repeatability using LCDs and OLEDs. The white luminance was within 1% for the same display. We calibrated luminance and color with a KONICA MINOLTA CS 200 for several displays and were able to get reasonable accuracy for displays of the same type.

The luminance of various displays is typically in the range of 10% due to a mismatch of “clear” (see Figure 2) and $V(\lambda)$ sensitivity. As the sensor has no gain control, contrast ratio measurements are limited to about a CR of 100:1 which is however good enough for bright ambient light evaluation. The gamma value (calculation by relative values) can be obtained by higher precision as the luminance of same display is measured for 10+ grey levels. The absolute precision for color co-ordinates is limited due to RGB sensors (see Figure 2). However reflective colors (by using the LEDs) could be classified by hue. It is clear that the lowest cost TCS230 is not comparable in performance with e.g. MAZET’s true color sensors (like AS73211) which are significantly more expensive.

Our 10 USD mobile stand-alone color measurement device can compare displays of the same series or sensing object colors for e.g. sorting. It is clear that this system cannot compete in terms of accuracy with professional colorimeters which are orders of magnitude more expensive but of limited mobility.

[1] SID ICDM: Information Display Measurements Standard (IDMS, free download)
P:38 Flexible OLED barrier lamination: a step towards R2R processing

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Roll-to-roll (R2R) processing has the potential to be useful for large scale manufacturing of flexible Organic-Light-Emitting-Diodes (“OLED”). A major bottleneck in existing R2R manufacturing of flexible OLEDs is the barrier deposition process. There expensive vacuum deposition of inorganic and organic layers is used, with the objective of reaching the required water vapor transmission rate of 10-6 g/m²/day. Off-line barrier lamination on a finished device decouples this process and removes vacuum deposition steps. This paper discusses our results in developing an alternative encapsulation technology by direct lamination of R2R produced barrier foil on the OLED’s cathode. Various moisture barrier adhesives (“MBAs”) are tested and compared for their ability to retard water vapor permeation in the lateral direction using calcium button tests. Using experimental and modeling data the lateral side ingress can be extrapolated for 20°C/50%RH conditions with the best performing adhesive being able to achieve as low as 7 mm dead edge for 10 years lifetime. The calcium button test data is complemented with device testing where different barrier lamination configurations and different barrier adhesives have been tested for the best device shelf life. A R2R lamination run has shown the potential of applying a laminated top barrier in a production line. Devices tested from the lamination run have survived 1000 h at 60°C/90%RH shelf life test without showing cosmetic blemishes.