Status and Opportunities for Phosphorescent OLED Technology

COLOR IS UNIVERSAL

December 2016
IP innovator, technology developer, patent licensor and materials supplier for the rapidly growing OLED markets
OUR COMPANY

- Global University Sponsored Research Programs
- Multi-disciplinary Chemistry Organization
  - Discovery (Experimental and Computational)
  - Applied Research - synthesis & process dev.
- Commercial Development
- Volume Production
- Broad Physics and Engineering Organization
  - Discovery (Failure Mechanisms)
  - Device Research
  - Device Engineering
  - Processing Engineering
- Business Localization and Support
  - UDC Korea, Japan, Taiwan and China teams
In The Beginning...not very long ago

- 1987: Tang & Van Slyke, Eastman Kodak
  - Fluorescent SMOLED

- 1988: Burroughes, Friend et al., Cambridge University
  - Fluorescent Polymer OLED

- 1990: Forrest, Thompson, Baldo et al., Princeton University, University of Southern California
  - Phosphorescent OLED

- 1991: Pioneer
  - 1st commercial OLED display: car audio display
OLED Timeline

Source: Acuity Brands.
NEW OLED SMARTPHONES

Huawei Enjoy
Google Pixel
TCL 950
OPPO F1 Plus

One Plus 3
ZTE Axon 7
Moto Z Force
BLU Energy XL

Colawe W550
Micromax Canvas Sliver 5
Asus Zenfone 3 Deluxe
Gionee M6
MORE OLED PRODUCTS

- Samsung Galaxy TabPro S
- Dell Alienware 13
- Porsche Mission E Car
- Galaxy Gear Series
- LG 65” 4K TV
- ZTE Axon Watch
- LG G Flex 2
- Apple Watch
- Samsung Gear VR Innovator
- Oculus Rift
- Sony PlayStation VR
- LG Watch Urbane 2
- Huawei Watch
- ASUS ZenWatch 3
An Organic Light Emitting Diode (OLED) is a series of organic thin films between two conductors. When electrical current is applied, bright light is emitted. OLEDs can be used for displays and lighting. OLEDs are not just thin and efficient - they can also be made flexible and transparent.
AMOLED versus AMLCD – Display Modules

AMLCD

- Drivers
- Polarizer
- Colour filter plate
- Liquid Crystal
- Active matrix plate
- Polarizer
- Diffuser
- Inverter
- Backlight guide
- Prism sheet
- Fluorescent lamp
AMOLED versus AMLCD – Display Modules

AMOLED

1. Considerably lower material cost than LCD
2. Better performances
3. Potential to replace cover glass and Polariser by thin-films

- Drivers
- Inverter
- Backlight guide
- Prism sheet
- Fluorescent lamp
- Diffuser
- Polarizer
- Liquid Crystal
- Cover glass

Active matrix plate with OLED thin film structure
**LCD VS. OLED**

- Lower BOM (bill of materials)
- Better Performance, More Efficient
- Thinner and Flexible Form Factor
- Vivid Colors and Superior Contrast Ratio

Image source: LG
Why AMOLEDs for Mobile Devices?

Fundamentally simpler structure than LCDs
- AMOLEDs are thinner and lighter

Better display performance compared to LCDs
- Simply, AMOLEDs look better and are more attractive!

TFT-LCD vs. AMOLED

- Self-Emissive
- Vivid Color

- No Color Filter
- No Backlight
- Thin & Light
Why OLED TVs

- Thinner and flexible form factor
- Lower BOM (bill of materials)
- Better performance, more efficient
- Vivid colors and superior contrast ratio

Image source: LG
Chart comparing power consumption (mW) for Galaxy S7 versus leading AMLCD display for equivalent 5” displays operating at 400 cd/m². OLED is operated with 50% pixels on.
### OLED Displays vs OLED lighting

<table>
<thead>
<tr>
<th></th>
<th>Displays</th>
<th>Lighting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maturity</strong></td>
<td>Many small sized commercial products, tablets, notebooks and 55” -77” TV available</td>
<td>Early entry commercial products</td>
</tr>
<tr>
<td><strong>TFT Backplane</strong></td>
<td>Challenging – major yield limitation and high capital cost for manufacturing plant</td>
<td>TFTs are not needed</td>
</tr>
<tr>
<td><strong>Full color patterning</strong></td>
<td>Issue for large size substrates</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Blue requirement</strong></td>
<td>Need high performance, deep saturated blue</td>
<td>Warm whites require less deep blue than displays</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>BOM costs soon to be lower than AMLCD</td>
<td>Major challenge, but $25 per klumen now possible in 2018</td>
</tr>
<tr>
<td><strong>New Form Factors</strong></td>
<td>Thin, lightweight, rugged, transparent,</td>
<td>Thin, lightweight, rugged, transparent, arbitrary shapes</td>
</tr>
</tbody>
</table>
## Strong OLED Display Market Drivers

### Lower Power Usage
- **RED** Phosphorescence reduces power consumption by 25%
- **Add GREEN**: 45% cumulative reduction
- **Add BLUE**: 74% cumulative reduction
- Enabled by PHOLEDs

### Superior Aesthetics
- Improved image quality
- Thinner form factor
- 180 degree viewing angle
- 1,000,000 : 1 contrast ratio – TRUE BLACK
- Real-time video speeds – excellent for 3D
- Self-emissive display
- On cell touch without sacrificing fill factor
- Low UV output
- **Flexible**

### More Cost Effective
- Fewer manufacturing process steps
- Low cost bill-of-materials
  - No backlight required
  - No color filter required
  - No liquid crystal required
- Reduced driver IC costs
- Enables non-glass substrates
OLED Market Expansion

- **Power consumption**
  - PHOLED
  - Materials integration
  - Device and panel architecture

- **Lifetime**
  - Materials integration
  - Device and panel architecture
  - Encapsulation

- **Manufacturability**
  - Low Cost
  - Vacuum thermal evaporation
  - Solution and vapor printing

- **Form factor**
  - Flexible
  - Unbreakable
  - Thin film barrier

**Commercialization Timeline**

- Smart Phones
- Flexible
- Wearables
- Tablets / TV
- Lighting
### How Will Flexible Lighting and Displays Develop?

<table>
<thead>
<tr>
<th>Low Power</th>
<th>Rugged</th>
<th>Bendable</th>
<th>Rollable</th>
<th>Free Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin and light</td>
<td>Light and slim</td>
<td>Light and slim</td>
<td>Compact</td>
<td>Total flexibility</td>
</tr>
<tr>
<td>Low power</td>
<td>Unbreakable</td>
<td>Wearable</td>
<td>Low power</td>
<td>Paper-like</td>
</tr>
</tbody>
</table>

**Low Power**  
- Thin and light
- Low power

**Rugged**  
- Light and slim
- Unbreakable

**Bendable**  
- Light and slim
- Wearable

**Rollable**  
- Compact
- Low power

**Free Form**  
- Total flexibility
- Paper-like
Key Challenges:

1) TFT Same as On-Glass
2) Low Cost Thin Film Encapsulation
3) Compatible with Existing Fab

Flexible OLED
- Flexible Anode & Cathode

Thin Film Encapsulation
- Processing Time
- Cost of Ownership

Flexible Module
- Reliability
- Bendability
- Thin Polarizer/Touch

TFT Process Architecture
- Low Temp. TFT Process
- TFT with High Reliability

Plastic Substrate
- Moisture Barrier
- Delamination After Completion
**Paths to Increase OLED Market – Form Factor**

**Form factor**
Thin Film Barrier

**Impact:**
- Lower cost – more displays per sheet and no dessicant or sealant
- Single layer enables very narrow bezel
- Enables flexible devices – game changer!!!
The Introduction of “Curved Phones”

LG G Flex
Future Growth: Flexible

Unbreakable

Lighter

New Form Factors

Thinner
The Universal Communication Device (UCD)

Changing the way you view the world!
OLED Products for Wearable Applications

- Ideal display and lighting technology for wearable applications
- Thin, light and flexible (but needs encapsulation)
- Energy efficient – only uses power when visible
- Cool in operation – no heat sink required
- Low blue content – does not impact sleep
OVJP – Organic Vapor Jet Printing
Organic Vapor Jet Printing

OVJP: Printing with gas ‘solvent’

First Printed Lines at UDC Pilot Line
Moving to higher resolution: needs and considerations

- **Industry needs:**
  - Lower cost solution for pixel patterning
  - New architectures for very high resolution and longer LT

- **Design considerations:**
  - Avoid high resolution OLED patterning
  - Improve display LT
    - maximize pixel fill-factor/maximize blue display LT
  - No power penalty
  - Can implement in bottom or top emission
  - Lower OLED manufacturing cost

**Proposed new: ‘BYcolor’ architecture**
Novel BY Display Architecture

- Combining the best of shadow mask patterning and color filter technology
- High performance
  - Large blue (and yellow) pixels maximize display lifetime and efficiency
  - Separate color filters only for red and green
- Low cost
  - Can be used for large area substrates – mobile displays and TVs
  - Shadow mask can be sturdier – only half the resolution of the display
Applying SPR (Spatial Resolution) to BY color Architecture

- **Y mask opening**
- **B mask opening**

- **Mask is ½ the display resolution**
- <3 sub-pixels and data lines per pixel
- 4 display colors
- Eye is less sensitive to resolution of deep blue (~5%)
OLED Lighting

- Energy efficient – environmentally friendly
  - Low drive voltage
  - Low operating temperatures, cool to touch
  - Long lifetime
  - Easy to control
- Highly desirable color quality
  - Wide range of CCT, high CRI possible
  - Color tunable
  - Instant “ON”, Dimmable without flicker
  - No glare, no noise
  - Low UV content
- Novel form factor
  - Thin and lightweight surface lighting
  - Transparent
  - Non-breakable, Flexible, Rollable…..
- Low cost potential
  - Scaling advantage - roll to roll process
OLED Lighting Around the World
# 2015 OLED Panel Performance Specs

Panels from LG Chem: PHOLED Technology from UDC

<table>
<thead>
<tr>
<th>TODAY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CCT</strong></td>
</tr>
<tr>
<td><strong>Color Consistency</strong></td>
</tr>
<tr>
<td><strong>Luminance</strong></td>
</tr>
<tr>
<td><strong>L70</strong></td>
</tr>
<tr>
<td><strong>3000K</strong></td>
</tr>
<tr>
<td><strong>3500K / 4000K</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>HIGH CRI</th>
<th>STANDARD CRI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficacy</strong></td>
<td>55 - 60 lm/W</td>
<td>80 lm/W</td>
</tr>
<tr>
<td><strong>CRI</strong></td>
<td>85-90</td>
<td>80</td>
</tr>
<tr>
<td><strong>R9</strong></td>
<td>24-41</td>
<td>&gt; 0</td>
</tr>
</tbody>
</table>

From Acuity Brands
Pixel Efficacy: Status & Targets

**Pixel Efficacy** $\propto$ LER x IQE x OC x EEF

- **LER** = Luminous Efficacy of Radiation ( = Max efficacy of emission spectra)
- **IQE** = Internal Quantum Efficiency
- **OC** = Outcoupling Efficiency
- **EEF** = Electrical Efficiency Factor ( = Optical Energy Gap − Applied Voltage)

<table>
<thead>
<tr>
<th></th>
<th>Target and Practical Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>LER [lm/W]</td>
<td>350</td>
</tr>
<tr>
<td>IQE [%]</td>
<td>95%</td>
</tr>
<tr>
<td>OC [%]</td>
<td>60%</td>
</tr>
<tr>
<td>EEF [%]</td>
<td>90%</td>
</tr>
<tr>
<td><strong>Pixel Efficacy [lm/W]</strong></td>
<td><strong>180 (at 3,000 cd/m²)</strong></td>
</tr>
</tbody>
</table>

- White PHOLEDs already emit with IQE $\approx$ 100% at low luminance. Challenge is to maintain IQE $\approx$ 95% at 3,000 cd/m².

**UDC White OLED Pixel Efficacy Target = 180 lm/W**
OLED and LED Lighting – Living Together
# 2015 DOE Roadmap for OLED Lighting

## Table 6.3 Breakdown of OLED Luminaire Efficiency Projections

<table>
<thead>
<tr>
<th>Metric</th>
<th>2014</th>
<th>2017</th>
<th>2020</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel Efficacy¹ (Im/W)</td>
<td>60</td>
<td>125</td>
<td>160</td>
<td>190</td>
</tr>
<tr>
<td>Optical Efficiency of Luminaire</td>
<td>100%</td>
<td>100%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Efficiency of Driver</td>
<td>85%</td>
<td>85%</td>
<td>90%</td>
<td>95%</td>
</tr>
<tr>
<td>Total Efficiency from Device to Luminaire</td>
<td>85%</td>
<td>85%</td>
<td>81%</td>
<td>86%</td>
</tr>
<tr>
<td>Resulting Luminaire Efficacy¹ (Im/W)</td>
<td>51</td>
<td>106</td>
<td>130</td>
<td>162</td>
</tr>
</tbody>
</table>

**Notes:**
1. Efficacy projections assume CRI >80, CCT 3000 K
## Table 1.6 OLED Panel Cost Estimated Progress ($/m²)

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2014</th>
<th>2016</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Substrate</td>
<td>250</td>
<td>200</td>
<td>150</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Organic Deposition</td>
<td>600</td>
<td>500</td>
<td>250</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>Assembly and Test</td>
<td>350</td>
<td>300</td>
<td>200</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Overhead^d</td>
<td>300</td>
<td>200</td>
<td>100</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Total (unyielded)</td>
<td>1,500</td>
<td>1,200</td>
<td>700</td>
<td>180</td>
<td>80</td>
</tr>
<tr>
<td>Yield of Good Product (%)</td>
<td>25</td>
<td>40</td>
<td>70</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Total Cost</td>
<td>6,000</td>
<td>3,000</td>
<td>1,000</td>
<td>240</td>
<td>100</td>
</tr>
</tbody>
</table>
Flexible OLED Lighting

Conventional Lighting

Flexible OLED Lighting

Courtesy: HK Chung
Novel Form Factor – flexible & rugged

Safety Clothing by GE (concept)
Application of Tunable OLED Luminaires
Application of OLED Luminaires

OLED luminaires can be used in:

- Retail stores
- Offices
- Hospitals
- Galleries
- Supermarkets
Application of OLED Luminaires

The luminaires can be used in:

• Retail stores
• Offices
• Hospitals
• Galleries
• Supermarkets

CCT=4,000K
CCT=3,500K
CCT=2,700K
DOE analysis compares corridor lighting scenarios

**Energy Savings Potential in 2020**

From DOE

**Traditional design with fluorescent troffers**

**OLED design with vertical and pendants**

**COMPARED TO TRADITIONAL LIGHTING DESIGNS, USING OLEDs IN CORRIDORS COULD SAVE . . .**

- 73% Energy reduction
- 163 tBtu
- $1.7B per yr.

Which equates to And saves businesses In 2020 From DOE
Luminaire with Color Tunable WOLED Panels

- 32x 6” x 6” panel PHOLED Luminaire
Automobile Applications for OLED Lighting

- OLEDs offer the ability to create shapes of any size
- OLEDs provide extremely uniform light

Source: BMW

Audi
Thank you.