The state of OLED
Technology markets and participants

Barry E Young
OLED Association

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Course instructor

Barry Young is vice president of Young Market Research (YMR) and a primary-lighting analyst. He also serves as managing director of the OLED Association, where he solves industry-wide issues, such as the development of standards for the OLED display and lighting industries. He is also working with a group of OLED suppliers to produce the first US-based national laboratory for OLED lighting. A long-time principal, senior advisor and consultant to DisplaySearch, Young is one of the leading authorities on OLEDs and flexible displays, and has authored DisplaySearch’s OLED, flexible-display, small/medium-display and technology reports. He has visited and consulted most of the OLED manufacturers worldwide, published in technical-display journals and spoken across the globe on the display industry. Before joining DisplaySearch, Young was CEO and president of OWL Displays, where he co-developed innovative driver technology for amorphous silicon (a-Si) and polysilicon (p-Si) TFT LCDs, and was awarded key patents for driving low-temperature polysilicon TFT LCDs. Before OWL, he was vice president and general manager of Tandem’s integrity system division. He has also served as managing partner at Booz Allen & Hamilton, executive vice president at Wells Fargo Bank, senior vice president at Citibank and president and CEO of Lexar, an early developer of an all-digital PBX.

Course overview

OLED technology was first commercialised for displays in 1999, but it took until late 2007 for it to reach mass production in the active matrix mode. Now OLEDs are challenging LCD technology in the handheld market and will soon target the largest markets for flat panels - TVs and notebooks. OLED technology offers significant performance improvements over LCD and plasma technology, e.g., faster response time, wider viewing angles, higher contrast, improved colour and lower power consumption.

This presentation addresses the challenges facing OLEDs to expand their market, what the leaders are doing, when they will gain a formidable position and how the manufacturers can exploit the existing TFT-LCD infrastructure. Another group of manufacturers are developing solid-state lighting (SSL) applications, which promise to improve lighting efficiency, increase lifetime and reposition a significant portion of the US$100bn lighting industry. Osram, Philips and Lumiotec have introduced OLED SSL products, while Panasonic, GE, Konica Minolta, Mitsubishi and Samsung are at the development phase. The session also examines the challenges and opportunities facing the manufacturers.

Any comments?
Please contact Grace Hung at grace.hung@clsa.com
OLED Association

- Promote the development and commercialisation of OLED products
- Foster the development and use of OLED-specific performance standards
- Serve as a source of OLED industry information for the media and financial community

Overview

- OLED technology
  - Semiconductor basics
  - Displays/lighting
- Performance
- Manufacturing
- OLED lighting
- Summary
Semiconductor basics - Inorganic LEDs

- Fermi level
- Vacuum level
- Conduction band: $e^-$
- Band gap
- Valence band: $h^+$
- Light
Semiconductor basics - OLEDs

Two types of excitons are possible

**Triplet**
- Spin of the LUMO electron does not pair with the spin of the HOMO electron
- Can only recombine to emit light in a phosphorescent material (slow)

**Singlet**
- Spin of the LUMO electron can pair with the spin of the HOMO electron
- Can recombine to emit light in any material (fast)

Spin statistics suggest a 3:1 ratio of triplets:singlets - not necessarily the case for all materials
Key points

- HOMO level - Conduction band
- LUMO level - Valence band

Electrons and holes recombine forming either a triplet or singlet exciton

- Singlets decay to emit light in fluorescent and phosphorescent materials
- Triplets can only decay to emit light in phosphorescent material
- Non-radiative (thermal) decay is present in any material

OLED performance
**OLED display stack**

- **Substrate**
- **Cathode**
- **EIL**
- **Light emitting layer**
  - **HBL**
- **Anode**
- **Substrate**
- **Power**
- **Micro cavity**

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**Power consumption comparisons**

- **White background**
  - **TFT LCD**: 100%
  - **AMOLED**: 160%

- **Still Image**
  - **TFT LCD**: 100%
  - **AMOLED**: 70%

- **Movie**
  - **TFT LCD**: 100%
  - **AMOLED**: 15%

*Source: LG Display*
OLED material performance progress

- OLED: 3.7” WVGA 300 cd/m² (40% Pixels On)
- LCD: 3.7” WVGA cd/m² (100% Pixels On)

Source: LG Display

Colour reproduction

- AMOLED maintains 100% of NTSC colour gamut at all gray levels
  - TFT LCD - 75% at 100% saturation; 11% at 10% saturation
  - AMOLED - 100% at all levels

Source: Samsung (SMD)
Perceived brightness

- Perceptual contrast-length comparison of LCDs and AMOLEDs expressed on CIECAM02 colour space

- The luminance values of LCDs and AMOLEDs are 256.3 and 189.9 cd/m². Note: only 110.9 cd/m² is required for AMOLEDs to achieve the same perceptual contrast length as LCDs.

Source: Samsung (SMD)

3D performance

- Stereoscopic (requires glasses) 3D TV is being pushed as the next display technology and is expected to increase TV margins.

- There is a plethora of content under development:
  - 70 films scheduled for production
  - 3D channels planned (ESPN)

- Best 3D implementations have the fastest response time

- OLED response times are faster than either LCDs or PDPs

- OLED may have to produce 3D TV to justify the wider margins.

Source: Samsung (SMD)
**Lighting technology performance**

**2013-15 timeframe**

<table>
<thead>
<tr>
<th>Units</th>
<th>AMOLED</th>
<th>CCFL</th>
<th>LED Edge</th>
<th>LED Full</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminance</td>
<td>cd/m²</td>
<td>Same</td>
<td></td>
<td></td>
<td>None</td>
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<tr>
<td>Brightness</td>
<td>cd/m²</td>
<td>OLED</td>
<td>~1.5x brighter</td>
<td>6M:1</td>
<td>Power</td>
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<tr>
<td>Contrast ratio (CR)</td>
<td>¥</td>
<td>~1000:1</td>
<td>5000:1</td>
<td>6M:1</td>
<td>Dark images</td>
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<tr>
<td>Ambient contrast ratio @ 125 lux</td>
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<td>&gt;2,000:1</td>
<td>&gt;2,000:1</td>
<td>&gt;2,000:1</td>
<td>High lux</td>
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<tr>
<td>Black levels</td>
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<td>0.001</td>
<td>0.8</td>
<td>0.1</td>
<td>0.001</td>
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<td>CR</td>
<td>100%</td>
<td>0.8</td>
<td>0.1</td>
<td>20:1</td>
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<tr>
<td>Response time</td>
<td>ms</td>
<td>0.001</td>
<td>5</td>
<td>3</td>
<td>3</td>
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<td>Gray scale performance</td>
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<td>Poor lower gray scales</td>
<td>Movies</td>
<td></td>
<td></td>
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<tr>
<td>Frame rate</td>
<td>Hz</td>
<td>&gt;240</td>
<td>None</td>
<td></td>
<td>None</td>
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<tr>
<td>42&quot; power consumption</td>
<td>W</td>
<td>15</td>
<td>~120</td>
<td>~80</td>
<td>~60</td>
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<tr>
<td>Lifetime</td>
<td>hrs to 1/2 luminance</td>
<td>~60k</td>
<td>~70k</td>
<td>~70k</td>
<td>Initial LCD</td>
</tr>
<tr>
<td>Differential ageing</td>
<td>Yes</td>
<td>None</td>
<td>Strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image sticking</td>
<td>Some</td>
<td>Minor</td>
<td>Strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form factor</td>
<td>mm</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
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</table>

Source: YMR

**White pixel progress**

Source: Universal Display
Display capacity

A word about substrate sizes

2007
730x920

2011

Gen 11

<table>
<thead>
<tr>
<th>Generation 3.5</th>
<th>Generation 4</th>
<th>Generation 5</th>
<th>Generation 6</th>
<th>Generation 7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>620mm x 795mm</td>
<td>880mm x 890mm</td>
<td>1100mm x 1300mm</td>
<td>1500mm x 1860mm</td>
<td>1920mm x 2250mm</td>
</tr>
</tbody>
</table>

14.1" x 6 | 35" x 6 | 27" x 6 | 37" x 6 | 47" x 6 |
**Revenue by technology/application**

- PMOLED
- AMOLED S/M
- AMOLED TV

**Display revenue history & forecast**

- PMOLED sub-displays/MP3
- AMOLED smartphone/tablets
- AMOLED TVs

Source: YMR
OLED display capacity

Source: YMR

AMOLED shipment/revenue forecast

Source: YMR
AMOLED pixel architecture

- **Technical status of OLED backplanes**
  - LTPS with excimer lasers similar to LTPS LCDs, but OLEDs require a “two TFT, one capacitor” design, while LCDs use one TFT and one capacitor.
  - Compensation, four to five TFTs are added to compensate for non-uniformity.
  - Major difference is that the second TFT (Dr.) has a duty cycle of more than 90%.
  - a-Si used by most LCDs is susceptible to Vth changes as it heats up and has not been used to drive AMOLEDs, although there are compensation approaches that are being tested.
  - The capital expense for LTPS used in the array process is c.2x the capital cost of a-Si, the total average cycle time (TACT) is longer and the yields are lower.
Excimer laser size is currently limited to 4th gen with a beam length of c.450 x 4 mm. Companies such as JSW and TCZ are developing beam lengths as long as c.800mm to support 6th gen fabs.

Primary alternatives to LTPS include:
- a-Si with compensation
- Super grain silicon (SGS)
- Solid phase crystallisation (SPC)
- Oxide TFTs
- μC TFTs
- cSi TFTs

Making finely patterned sub-pixels with small molecule material requires the use of vacuum thermal evaporation using a fine metal mask, where the substrate and mask are held in a horizontal position.

Size limits are defined by the sagging of the mask.

To achieve more than 200ppi, AMOLEDs utilise Pentile technology, which reduces the pixel size from 3 sub-pixels to 2 sub-pixels/pixel. To scale beyond ½ 4th gen, VTE must be changed from positioning the substrate horizontally to holding vertically as implemented by Tokki, Uvexc, Sunic and AMAT.

New approaches include the use of CNT by Unidym and nanowires by Cambrios.
Patterning options

- **Alternative approaches include:**
  - Polymers and small molecule in solution which can be printed
  - Laser induced thermal imaging (LITI) as developed by 3M and SMD
  - Eliminating patterning by using white material with a colour filter

- **The most likely for the gen 5.5 is vertically held substrates**

- **Beyond gen 5.5 some form of printing will be required**
  - Ink Jet - Panasonic, Epson
  - Slot - DuPont
  - Roll-to-roll process - VTT, Fraunhofer

OLED lighting
## OLED displays vs lighting

<table>
<thead>
<tr>
<th>Category</th>
<th>Units</th>
<th>Display</th>
<th>Lighting</th>
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</thead>
<tbody>
<tr>
<td>Lifetime</td>
<td>hrs</td>
<td>100K to L50 @ 1000 cd/m²</td>
<td>50k to L70 @ 10,000 lm/m²</td>
</tr>
<tr>
<td>Efficacy</td>
<td>lm/W</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>Patterning</td>
<td></td>
<td>Subpixel</td>
<td>Large pixels</td>
</tr>
<tr>
<td>Blue</td>
<td></td>
<td>NTSC standard</td>
<td>&lt;NTSC</td>
</tr>
<tr>
<td>Active matrix</td>
<td>p-Si</td>
<td>Not required</td>
<td></td>
</tr>
<tr>
<td>Light enhancement</td>
<td>Microcavity</td>
<td></td>
<td>Light extraction layer</td>
</tr>
<tr>
<td>Distribution grid</td>
<td>Not Required</td>
<td></td>
<td>Required</td>
</tr>
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</table>

## OLED lighting stack

```
<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
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<tbody>
<tr>
<td>Substrate</td>
<td></td>
</tr>
<tr>
<td>Cathode</td>
<td></td>
</tr>
<tr>
<td>EIL</td>
<td>Light Emitting Layer</td>
</tr>
<tr>
<td>ETL</td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td></td>
</tr>
<tr>
<td>HIL</td>
<td>Light Extraction Layer</td>
</tr>
<tr>
<td>HBL</td>
<td></td>
</tr>
</tbody>
</table>
```

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Performance characteristics & roadmap

- **Material**
  - Red
  - Green
  - Blue

- **OLED architectures**
  - Single stack
  - Tandem stack

- **Light extraction layer**

- **Flexible backplanes**

OLED market participants

Many companies developing prototypes and pilot lines, including:

- Philips - small molecule - fluorescent/phosphorescent
- Osram Opto - small molecule - fluorescent/phosphorescent
- GE - solution-based phosphorescent, R-T-R
- Panasonic - small molecule - fluorescent/phosphorescent
- Konica Minolta - solution-based phosphorescent, R-T-R
- Lumiotec - small molecule - fluorescent/phosphorescent
- Zumtobel/Thorne Lighting/Ledon/Fraunhofer - Polymer-based
- Mitsubishi/Pioneer - small molecule - fluorescent/phosphorescent
- Kaneka - small molecule
- AUO - small molecule - phosphorescent
- Moser Baer Technology - small molecule - phosphorescent
- Samsung - small molecule - phosphorescent, 2nd gen fab
- LG Display - small molecule - phosphorescent
- ModisTech - polymer, R-T-R
- NEC Lighting - small molecule - fluorescent/phosphorescent
- Visonox - small molecule - phosphorescent
Primary market

- Currently, OLED lighting is limited to demonstration programmes and decorative/architectural lighting

- Future - three to five years away
  - Fluorescent luminaire replacements
  - Integrated into acoustic ceiling tiles
  - Compete with LEDs

Sample demonstrators

- Mitsubishi panel features:
  - Size: 14cm x 14cm
  - Efficiency (typical): 28 lm/w
  - Types of materials: small molecular OLED (as emitter)
  - Types of lighting: Planar thin OLED Lighting, partially using solution OLED
  - Color temperature tunable (2700K-6500K), and RGB colour tunable
  - Lifetime(LT70, typical): 8000 hours
  - CRI (typical): 80 (R9=66)
  - OLED lighting panels will use printable OLED as under layer (=hole injection layer)

- Schedule
  - Samples - 2010
  - MP - 2011
Sample demonstrators (continued)

- **Osram panel features:**
  - Size: 88mm diameter x 2.1mm
  - Efficiency (typical): 23 lm/w
  - Types of materials: small molecular OLED (as emitter)
  - Color temperature tunable (2580K-3320K), and RGB colour tunable
  - Luminance - 1,000 cd/m² @ 186 mA
  - Lifetime (LT70 typical): 8000 hours
  - CRI (typical): 75

- **Schedule - Shipping**

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Sample demonstrators (continued)

- **Lumiotec panel features:**
  - Size: 14.5cm diameter x 14.5cm x 2.3mm
  - Efficiency (typical): c.25 lm/W
  - Types of materials: small molecular OLED (as emitter)
  - Luminance - 4,000 cd/m²
  - Lifetime (LT₅₀ typical): c.4,000 hours at 4,000 cd/m²
  - CRI (typical): 80

- **Schedule - Shipping**
Sample demonstrators (continued)

- **Philips panel features:**
  - Size: 11.9cm diameter x 3.7cm x 2.3mm
  - Efficiency (typical): c.15 lm/W
  - Types of materials: small molecular OLED (as emitter)
  - Color temperature tunable (3,200 K), and RGB colour tunable
  - Luminance - 3,000 cd/m2
  - Lifetime(LT50 typical): c.10,000 hours @ 1,000 cd/m2
  - CRI (typical): 80

- **Schedule - 4Q10**

Sample prototypes

- **Konica Minolta panel features:**
  - Size: 15.0cm diameter x 15.0cm x 1.5mm
  - Efficiency (typical): c.64 lm/W
  - Types of materials: phosphorescent OLED (as emitter)
  - Luminance - 1,000 cd/m2
  - Lifetime(LT50 typical): c.10,000 hours @ 1,000 cd/m2
  - CRI (typical): NA

- **Schedule - 2011**
## Spec summary

<table>
<thead>
<tr>
<th>Spec</th>
<th>Units</th>
<th>Mitsubishi</th>
<th>Osram</th>
<th>Lumiotec</th>
<th>Philips</th>
<th>Konica</th>
<th>Minolta</th>
<th>Average</th>
<th>Target</th>
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<tr>
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<td>lm/W</td>
<td>28</td>
<td>23</td>
<td>25</td>
<td>15</td>
<td>64</td>
<td></td>
<td>31</td>
<td>100</td>
</tr>
<tr>
<td>Power</td>
<td>W</td>
<td>2.2</td>
<td>3.0</td>
<td>10.6</td>
<td>2.8</td>
<td>1.1</td>
<td></td>
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<td>Color Temperature</td>
<td>K</td>
<td>2,700-6,500</td>
<td>2,580-</td>
<td>na</td>
<td>3,200</td>
<td>na</td>
<td></td>
<td>79</td>
<td>2,700-3,500</td>
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<tr>
<td>CRI Temperature</td>
<td>°K</td>
<td>80</td>
<td>75</td>
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<td>4,000</td>
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<td>10,000</td>
<td></td>
<td>5,000</td>
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</tr>
<tr>
<td>Luminance</td>
<td>cd/m²</td>
<td>1,000</td>
<td>1,000</td>
<td>4,000</td>
<td>3,000</td>
<td>1,000</td>
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<td>69</td>
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<td></td>
<td>109</td>
<td>500-1,000</td>
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<tr>
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<td>cmxcm</td>
<td>14</td>
<td>8.8</td>
<td>14.5</td>
<td>11.9</td>
<td>15</td>
<td></td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

¹ 1,000 cd/m²

## Cost forecast

### 6x6” OLED panel costs dependent on process, volume and manufacturing maturity

![Graph showing cost forecast](image)

- **Manuf. Cost (6” panel)**
- **$/km**
- **$/m² (RHS)**

Source: YMR

Panel or mo: 5k

2012 2013 2014 2015 2015 (US$/km) (US$/m²) 0 50 100 150 200 250 300 350 400 450 500 550 600 0 1000 2000 3000 4000 5000 6000
6x6” OLED panel cost distribution

- At 100k/month, the key cost elements are depreciation, labour and the substrate

Varying share of costs:
- Substrate
- Organic
- Encapsulation
- Electronic
- Labor
- Depreciation
- Building/Support

Source: YMR

---

OLED performance forecast

- Lifetime (L70) 30,000 to 50,000 hours

Source: YMR
### OLED lighting projection

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
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</thead>
<tbody>
<tr>
<td>Substrates (000)</td>
<td>180</td>
<td>360</td>
<td>720</td>
<td>1080</td>
</tr>
<tr>
<td>Utilisation</td>
<td>60%</td>
<td>70%</td>
<td>80%</td>
<td>85%</td>
</tr>
<tr>
<td>Yield</td>
<td>50%</td>
<td>75%</td>
<td>80%</td>
<td>85%</td>
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<tr>
<td>Units shipped (m)</td>
<td>3</td>
<td>9</td>
<td>22</td>
<td>37</td>
</tr>
<tr>
<td>LEDs/Lamp</td>
<td>29</td>
<td>26</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>Luminaries (m)</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Lamps m)</td>
<td>98</td>
<td>126</td>
<td>327</td>
<td>666</td>
</tr>
<tr>
<td>Total (m)</td>
<td>105</td>
<td>135</td>
<td>336</td>
<td>677</td>
</tr>
<tr>
<td>Total LED (m)</td>
<td>3045</td>
<td>3510</td>
<td>7728</td>
<td>13540</td>
</tr>
<tr>
<td>OLED share (per fab)</td>
<td>2%</td>
<td>7%</td>
<td>7%</td>
<td>6%</td>
</tr>
<tr>
<td>OLED fabs</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total OLED share</strong></td>
<td><strong>5%</strong></td>
<td><strong>27%</strong></td>
<td><strong>39%</strong></td>
<td><strong>50%</strong></td>
</tr>
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</table>

Fab size: 730 x 920mm 45 6” panels/substrate

Source: YMR

### SSL/fluorescent replacements

<table>
<thead>
<tr>
<th>Year</th>
<th>OLED fabs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>2</td>
</tr>
<tr>
<td>2013</td>
<td>4</td>
</tr>
<tr>
<td>2014</td>
<td>6</td>
</tr>
<tr>
<td>2015</td>
<td>9</td>
</tr>
</tbody>
</table>

Source: YMR
Summary

Small molecule/LTPS

- SMD
  - Gen 4 with c.25k substrates/month
  - Doubling capacity in 2010
- LG Display
  - Gen 2 with c.7.5k substrates/month
  - Adding Gen 4 with 15k substrates/month in 2010
- Sony - Gen 3 partial use
- Innolux (Toppoly) - 2-Gen 3s partial use - exiting
- AUO
  - Gen 3 pilot
  - Gen 3.5 production in 2011
  - Gen 4.5 production in 2012
- Canon - prototyping only

Polymer/LTPS

- Panasonic - Gen 2 prototyping
- Sumitomo - Gen 2 prototyping
- Casio - Gen 2 prototyping

Status
Comparing performance: AMOLEDs vs TFT LCDs

- OLED performance will be a differentiator for high-end TVs; especially in 3D, sports and movies because of the viewing angle, the fast response time, and gray scale performance.
- OLED TVs are likely to compete with full LED backlighting and 3D LCDs.
- OLED panels will use c.½ the power of LED backlit panels, but the same for the TV components, so the TV difference will be 25% to 30%.
- OLEDs recreate the lower gray levels better than LCDs, which is a differentiator in video, where the average colour saturation is c.20%.
- Longer-term AMOLED TVs cost may be less than LCDs and cause most manufacturers to switch technologies.
- OLEDs will be challenged to compete in bright ambient conditions.
- Differentiated ageing could be a factor unless material lifetimes improve by at least 2x.
- The issue of image burn-in, which has not been an issue for smartphones, may require attention due when news tickers are considered.

**AMOLED capacity**

[Graph showing AMOLED capacity from 2008 to 2015 across different generations (Gen 2, Gen 3.5, Gen 4.5, Gen 5.5, Gen 5.5 f, Gen 8) with YoY Growth.]

Source: YMR
Companies

- **Material**
  - Universal Display R G Dopant
  - DS Hi Metal HTL/HIL
  - Novaled HTL/HIL
  - Jeil Textile, HTL/HIL, ETL
  - LG Chemical, ETL
  - DoSan-CS, Green Host
  - Dow Chemical Red Host
  - Sun Fine Chemicals, Blue Host and Dopant
  - Novaled, HTL/HIL; ETL/EIL
  - Hodogaya, Blue Host/Dopant

- **Encapsulation ALD - Synos**

- **Laser Crystallization** TCZ, a Cymer Company

- **LITI**
  - N-Light
  - AP systems

- **Deposition/Patterning**
  - VTE
    - AMD
    - Tokki
    - ULVAC
    - SNU Precision
    - YAS
    - SFA Engineering
  - Printing
    - DuPont - Dai Nippon Print
    - IJP - Epson, Panasonic

Questions

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