The Development Trend of Flexible OLED Display and Its Technologies in SONY

M. Noda

Display Development Division
Sony Corporation
1. Introduction
2. Development Trend
3. Oxide TFT Driven Flexible OLED Display Developed in SONY
4. Summary
Evolution of Display

Display has become
- large size with small footprint
- thin and lightweight

1968 CRT
1997 flat CRT
2002 LCD
2007 OLED display
201x flexible OLED display
Application Images of Flexible OLED

“features of OLED”

i) excellent display properties
   full color, fast response time, high contrast ratio, wide viewing angle

ii) suitable for flexible display
   all solid state device

<flexible tablet> • thin • lightweight • durable

<new smartphone> • wearable

<roll-up OLED TV> • large size and stored in small space
Issues of Flex OLED

“schematic cross section of top emission Flex OLED”

- **cover film**
- **barrier**
- **CF**
- **OLED**
- **TFT**
- **flexible substrate**
- **supporting glass**

“issues”

- **barrier film technology**
  - high barrier against moisture with low cost

- **OLED fabrication including CF**
  - large size with high resolution even in case of using flexible substrate

- **TFT fabrication**
  - low temperature fabrication process with high performance and high reliability

- **flexible substrate material**
  - high heat resistance, low CTE

- **handling method of flexible substrate**
  - high heat resistance, scalable
1. Introduction

2. Development Trend

3. Oxide TFT Driven Flexible OLED Display Developed in SONY

4. Summary
Barrier Film Technologies

**WVTR (g/m$^2$/day)**

- **low**
  - $10^{-1}$
  - $10^{-2}$
  - $10^{-3}$
  - $10^{-4}$
  - $10^{-5}$
  - $10^{-6}$
  - $10^{-7}$

- **barrier property**
  - for e-paper
  - for OLED

**“SiO$_x$ barrier film”**
- SiO$_x$ on PET
- 8x10$^{-2}$ g/m$^2$/day
- SiO$_x$ @PECVD
- "flexible flat panel displays", WILEY SID Series Display Technology

**“Kyung Hee Univ.”**
- Al$_2$O$_3$/ZrO$_2$, 5stack
- 5x10$^{-5}$ g/m$^2$/day
- ALD

**“FUJIFILM”**
- organic/inorganic
- $\sim$10$^{-6}$ g/m$^2$/day
- n stack

**“MITSUBISHI PLASTICS”**
- PET/SiOx/glue/SiOx/PET
- 1x10$^{-4}$ g/m$^2$/day
- SiO$_x$ @evaporation

**“Holst center”**
- SiN/organic/SiN
- $\sim$10$^{-6}$ g/m$^2$/day
- SiN @PECVD

http://www.fujifilm.co.jp/corporate/jobs/aboutus/technology/01/review07.html

SiD’13 18-3, F-M. Li et al
# Technologies for OLED Fabrication

<table>
<thead>
<tr>
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<td><img src="image4.png" alt="Schematic" /></td>
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<td></td>
<td>• high efficiency of material usage</td>
<td>• high resolution</td>
<td>• superior productivity</td>
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<td>issues</td>
<td>• large area production</td>
<td>• Material performance</td>
<td>• donor film cost</td>
<td>• additional process: CF</td>
<td>• drying control of ink</td>
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<td></td>
<td>• mask sagging</td>
<td>• material supplier</td>
<td>• delamination process</td>
<td></td>
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<td></td>
<td>• aliment accuracy</td>
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# Flexible Substrate

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<thead>
<tr>
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<th>PET (high heat)</th>
<th>PEN (high heat)</th>
<th>PES</th>
<th>PI</th>
<th>Metal Foil</th>
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<tr>
<td>heat resistance</td>
<td>150°C</td>
<td>200°C</td>
<td>220°C</td>
<td>350°C</td>
<td>&gt; 400°C</td>
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<tr>
<td>CTE</td>
<td>15 ppm/K</td>
<td>13 ppm/K</td>
<td>54 ppm/K</td>
<td>17 ppm/K</td>
<td>4-20 ppm/K</td>
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<tr>
<td>transparency</td>
<td>&gt; 85%</td>
<td>&gt; 85%</td>
<td>90%</td>
<td>yellow</td>
<td>0%</td>
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<tr>
<td>barrier property</td>
<td>poor</td>
<td>poor</td>
<td>poor</td>
<td>poor</td>
<td>excellent</td>
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Ref. “flexible flat panel displays”, WILEY SID Series Display Technology
## Handling method of Flexible substrate

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<thead>
<tr>
<th>method</th>
<th>EPLaR</th>
<th>SUFTLA</th>
<th>Bond-Debond</th>
<th>Coat-Debond</th>
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<td>Coating</td>
<td>Lamination</td>
<td>mechanical release</td>
<td>Coating</td>
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<td>plastic film</td>
<td>plastic film</td>
<td>mechanical release</td>
<td>plastic film</td>
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<tr>
<td>schematic</td>
<td>glass support</td>
<td>glass support</td>
<td>glass support</td>
<td>glass support</td>
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<tr>
<td>schematic</td>
<td>excimer laser aberration</td>
<td>excimer laser aberration</td>
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<tr>
<td>advantages</td>
<td>· high heat resistance</td>
<td>· high heat resistance</td>
<td>· low cost</td>
<td>· low cost</td>
</tr>
<tr>
<td>issues</td>
<td>· throughput</td>
<td>· large area throughput</td>
<td>· heat resistance of adhesive</td>
<td>· sticking force control between plastic and glass</td>
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## Flexible OLED driven by a-Si TFT

<table>
<thead>
<tr>
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<th>Kodak Princeton Univ.</th>
<th>UDC Kyung Hee Univ.</th>
<th>UDC LG Display L3 Comm.</th>
<th>Arizona State Univ. UDC ARL</th>
<th>LG Display</th>
<th>ITRI</th>
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<tbody>
<tr>
<td><strong>pixel number</strong></td>
<td>---</td>
<td>160×120</td>
<td>320×3×240</td>
<td>320×240</td>
<td>480×3×320</td>
<td>108×3×240</td>
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<tr>
<td><strong>panel size</strong></td>
<td>---</td>
<td>3”</td>
<td>4”</td>
<td>4.1”</td>
<td>4.3”</td>
<td>4.1”</td>
</tr>
<tr>
<td><strong>resolution</strong></td>
<td>70 ppi</td>
<td>67 dpi</td>
<td>100 ppi</td>
<td>98 dpi</td>
<td>134 ppi</td>
<td>64 ppi</td>
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<tr>
<td><strong>mobility</strong></td>
<td>0.3 cm²/Vs</td>
<td>0.51 cm²/Vs</td>
<td>0.35 cm²/Vs</td>
<td>0.77 cm²/Vs</td>
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<td><strong>process temp.</strong></td>
<td>300°C</td>
<td>350°C</td>
<td>200°C</td>
<td>180°C</td>
<td>---</td>
<td>200°C</td>
</tr>
<tr>
<td><strong>substrate</strong></td>
<td>Metal Foil</td>
<td>Metal Foil</td>
<td>Metal Foil</td>
<td>PEN</td>
<td>Metal Foil</td>
<td>Transparent PI</td>
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<tr>
<td><strong>pixel circuit</strong></td>
<td>2Tr-1C</td>
<td>2Tr-1C</td>
<td>---</td>
<td>2Tr-1C</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>bending radius</strong></td>
<td>---</td>
<td>2.5 mm</td>
<td>50 mm</td>
<td>---</td>
<td>50 mm</td>
<td>50 mm</td>
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<tr>
<td><strong>OLED</strong></td>
<td>Top Emission W+CF</td>
<td>Top Emission</td>
<td>Top Emission</td>
<td>Bottom Emission</td>
<td>Top Emission</td>
<td>Bottom Emission</td>
</tr>
<tr>
<td><strong>reference</strong></td>
<td>SID '06 64-3</td>
<td>SID '08 30-3</td>
<td>SID '09 10-1</td>
<td>SID '09 65-4</td>
<td>SID '10 70-2</td>
<td>SID '10 54-1</td>
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<td>Y. Hong et al</td>
<td>R. Ma et al</td>
<td>R. Ma et al</td>
<td>D. Loy et al</td>
<td>S. H. Paek et al</td>
<td>C-C. Lee et al</td>
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## Flexible OLED driven by poly-Si TFT

<table>
<thead>
<tr>
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<th>UDC PARK Vitex L3 Comm.</th>
<th>Samsung SDI</th>
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<th>Samsung Mobile Display Kyung Hee Univ.</th>
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<th>LG</th>
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<tbody>
<tr>
<td><strong>pixel number</strong></td>
<td>320×3×240</td>
<td>160×3×350</td>
<td>240×3×240</td>
<td>240×3×400</td>
<td>960×3×540</td>
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<td><strong>panel size</strong></td>
<td>4”</td>
<td>5.6”</td>
<td>2.8”</td>
<td>5”</td>
<td>4.3”</td>
<td>5”</td>
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<tr>
<td><strong>resolution</strong></td>
<td>100 ppi</td>
<td>66 ppi</td>
<td>166 ppi</td>
<td>93 ppi</td>
<td>257 ppi</td>
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<td><strong>mobility</strong></td>
<td>59 cm²/Vs</td>
<td>71.2 cm²/Vs</td>
<td>124.1 cm²/Vs</td>
<td>95.3 cm²/Vs</td>
<td>59.2 cm²/Vs</td>
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<td><strong>process temp.</strong></td>
<td>350°C</td>
<td>450°C</td>
<td>&gt; 400°C</td>
<td>---</td>
<td>&lt; 400°C</td>
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<tr>
<td><strong>substrate</strong></td>
<td>Metal Foil</td>
<td>Metal Foil</td>
<td>Plastic</td>
<td>Plastic</td>
<td>PI</td>
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<td><strong>pixel circuit</strong></td>
<td>2Tr-1C</td>
<td>2Tr-1C</td>
<td>6Tr-2C</td>
<td>6Tr-1C</td>
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</tr>
<tr>
<td><strong>bending radius</strong></td>
<td>---</td>
<td>70 mm</td>
<td>---</td>
<td>5 mm</td>
<td>50 mm</td>
<td>---</td>
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<td><strong>OLED</strong></td>
<td>Top Emission</td>
<td>Top Emission</td>
<td>Top Emission</td>
<td>Top Emission</td>
<td>Top Emission</td>
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<td><strong>reference</strong></td>
<td>SID ’06 64-2 A. Chwang et al</td>
<td>SID ’06 64-1 D-U. Jin et al</td>
<td>SID ’10 47-2 S. An et al</td>
<td>SID ’11 16-2 M. Kim et al</td>
<td>IDW’12 OLED 6-1 H-H. Hsieh et al</td>
<td>SID’13 exhibition</td>
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# Flexible OLED driven by Oxide TFT

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<th></th>
<th>Samsung Mobile Display</th>
<th>Sony</th>
<th>Toshiba</th>
<th>Holst Centre Polymer-Vision</th>
<th>Arizona State Univ.</th>
<th>SEL Sharp</th>
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<tr>
<td><strong>pixel number</strong></td>
<td>160×3×272</td>
<td>960×3×540</td>
<td>1920×3×1200</td>
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<td><strong>panel size</strong></td>
<td>6.5”</td>
<td>9.9”</td>
<td>10.2”</td>
<td>3.5”</td>
<td>14.7”</td>
<td>3.4”</td>
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<tr>
<td><strong>resolution</strong></td>
<td>85 ppi</td>
<td>111 ppi</td>
<td>223 ppi</td>
<td>119 ppi</td>
<td>81 ppi</td>
<td>326 ppi</td>
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<tr>
<td><strong>mobility</strong></td>
<td>13.0 cm²/Vs</td>
<td>13.4 cm²/Vs</td>
<td>9.5 cm²/Vs</td>
<td>---</td>
<td>13.5 cm²/Vs</td>
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<td>300°C</td>
<td>300°C</td>
<td>---</td>
<td>200°C</td>
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<tr>
<td><strong>substrate</strong></td>
<td>PI</td>
<td>Flexible Sub.</td>
<td>Transparent PI</td>
<td>PEN</td>
<td>PEN</td>
<td>Plastic</td>
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<tr>
<td><strong>pixel circuit</strong></td>
<td>2Tr-1C</td>
<td>2Tr-2C</td>
<td>2Tr</td>
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<td>2Tr-1C</td>
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</tr>
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<td><strong>bending radius</strong></td>
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<td>150 mm</td>
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<td>Top Emission W+CF</td>
<td>Bottom Emission</td>
<td>Top Emission W+CF</td>
<td>Bottom Emission</td>
<td>Top Emission W+CF</td>
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<tr>
<td><strong>reference</strong></td>
<td>SID ’10 47-1 D-U. Jin et al</td>
<td>SID ’12 74-1 M. Noda et al</td>
<td>SID’13 70-1 N. Saito et al</td>
<td>SiD’13 18-3 F-M. Li et al</td>
<td>SID’13 70-2 B. O’Brien et al</td>
<td>SID’13 18-2 A. Chida et al</td>
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<td>Kung Hee Univ.</td>
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<td>NHK</td>
<td>Sony</td>
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</tr>
<tr>
<td>16×16</td>
<td>48×48</td>
<td>128×64</td>
<td>160×3×120</td>
<td>320×3×240</td>
<td>240×3×432</td>
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<td>2”</td>
<td>2.5”</td>
<td>5.0”</td>
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<td>resolution</td>
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<td>mobility</td>
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<td>1 cm²/ Vs</td>
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<td>0.4 cm²/ Vs</td>
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<td>180°C</td>
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<td>substrate</td>
<td>PEN</td>
<td>PET</td>
<td>PES</td>
<td>PES</td>
<td>Plastic</td>
<td>Flexible Sub.</td>
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<td>2Tr-1C</td>
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<tr>
<td>bending radius</td>
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<td>---</td>
<td>---</td>
<td>4 mm</td>
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<td>OLED</td>
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<td>Bottom Emission</td>
<td>Bottom Emission</td>
<td>Top Emission</td>
<td>Top Emission</td>
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# Comparison of TFT Technologies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>a-Si</th>
<th>organic TFT</th>
<th>LTPS</th>
<th>oxide TFT</th>
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<tbody>
<tr>
<td>Mobility (cm²/Vs)</td>
<td>&lt; 1</td>
<td>~ 5</td>
<td>&lt; 150</td>
<td>10 ~ 50</td>
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<tr>
<td>Stability</td>
<td>fair</td>
<td>fair</td>
<td>excellent</td>
<td>good</td>
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<td>Uniformity</td>
<td>good</td>
<td>good</td>
<td>fair</td>
<td>good</td>
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<td>Flexibility</td>
<td>fair</td>
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<td>fair</td>
<td>fair</td>
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<tr>
<td>Productivity</td>
<td>good</td>
<td>good</td>
<td>fair</td>
<td>good</td>
</tr>
<tr>
<td>Process temp. (°C)</td>
<td>&lt; 350</td>
<td>&lt; 180</td>
<td>&gt; ~ 400</td>
<td>~ 300</td>
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</table>
Future Prospects

**enhancement of heat resistance in handling method of flexible substrate**

- “bond-debond”
  - high heat resistance of adhesive, flexible substrate

- “coat-debond”
  - varnish material with high heat resistance
  - sticking force control

**decrease of process temp.**

- “Low-temp. fabrication process”
  - gate insulator (oxide)
  - post annealing (oxide)
  - de-hydrogenation (LTPS)
  - dopant activation (LTPS)

- “oxide semiconductor applicable to low-temp. fabrication”
  - post annealing free

**basic technology common to flexible OLED**

- “barrier technology”
  - high reliable
  - low cost

---

![Max. process temp. chart](chart.png)

<table>
<thead>
<tr>
<th>temp. (°C)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
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</table>
1. Introduction

2. Development Trend

3. Oxide TFT Driven Flexible OLED Display Developed in SONY

4. Summary
Developmental History of Flexible OLED Display in SONY

- **Durable / Light weight**
  very important for mobile electronics

- **Bendable**
  design enhancement human affinity

- **Rollable / Foldable**
  design enhancement storage

**flexibility**

**technology**

SID 2012, 74-1, M. Noda et al
Key Technologies

“schematic cross section of display”

i）Flexible CF Technology

- low temperature fabrication process
- wide color gamut by optimization of thickness and fabrication process of RGB resins and B.M.

ii）Direct Fabrication Method of Oxide TFT on Flexible Substrate

- coating-debonding process
- flexible substrate with high heat resistance and low CTE

SID 2012, 74-1, M. Noda et al
Fabrication Flow

OLED panel
- Resin coating (flexible sub.)
  - Flexible sub.
  - Supporting glass
- Oxide TFT
- OLED

Flexible CF
- Lamination (flexible sub.)
  - Flexible sub.
  - Adhesive
  - Supporting glass
- Black Matrix
- RGB resin
  - Flexible sub.

Assembly
- Debonding

SID 2012, 74-1, M. Noda et al
Surface Roughness of Flexible Substrate

- high surface flatness with Ra of 0.5 nm

SID 2012, 74-1, M. Noda et al
Small Thermal Expansion of Flexible Substrate

- high overlay accuracy between layers of less than ±1 μm

SID 2012, 74-1, M. Noda et al
Characteristics of Oxide TFT

active layer: sputtered amorphous IGZO

gate insulator: SiOx deposited by PECVD

Substrate comparison:

<table>
<thead>
<tr>
<th>Substrate</th>
<th>μ (cm²/Vs)</th>
<th>S.S. (V/dec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>glass</td>
<td>13.3</td>
<td>0.2</td>
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<tr>
<td>flexible sub.</td>
<td>13.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- high performance comparable to that on glass

SID 2012, 74-1, M. Noda et al
Influence of Debonding Process

- no significant change in transfer characteristics after debonding process

SID 2012, 74-1, M. Noda et al
Fabrication Flow

**OLED panel**
- resin coating (flexible sub.)
  - flexible sub.
  - supporting glass
- oxide TFT
- OLED
  - OLED

**Flexible CF**
- lamination (flexible sub.)
  - flexible sub.
  - adhesive
  - supporting glass
- Black Matrix
- RGB resin
  - flexible sub.

**Assembly**
- debonding

SID 2012, 74-1, M. Noda et al
Fabrication of Flexible CF

“handling method”
- bonding

flexible sub.
adhesive
supporting glass

photolithography

“Flexible CF”
- Max temp. < 100°C

* Small distortion of flexible substrate due to low-temperature fabrication process

* cf. Akamatsu et al. “Flexible color A4 size e-paper driven by low temperature a-Si TFTs”, SID 2011

SID 2012, 74-1, M. Noda et al
Characteristics of Flexible CF

flexible color filter array (CFA) film

optical micrograph of CFA

228 μm

color gamut

this work 106%

C.I.E.1976 Chromaticity Diagram

SID 2012, 74-1, M. Noda et al
Display Structure

- flexible CF (RGBW)
- white OLED
- oxide TFT
- flexible sub.

“top emission structure”
“all solid state”

- thin display with thickness of 110 μm

SID 2012, 74-1, M. Noda et al
## Specification of Display

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display Size</td>
<td>9.9”</td>
</tr>
<tr>
<td>Number of Pixels</td>
<td>960 × RGBW × 540 (qHD)</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>228 μm × 228 μm</td>
</tr>
<tr>
<td>Resolution</td>
<td>111 ppi</td>
</tr>
<tr>
<td>Number of Colors</td>
<td>16,777,216</td>
</tr>
<tr>
<td>Pixel circuit</td>
<td>2Tr -1C</td>
</tr>
<tr>
<td>OLED</td>
<td>White OLED+ WRGB CFA</td>
</tr>
<tr>
<td>Thickness</td>
<td>110 μm</td>
</tr>
</tbody>
</table>

SID 2012, 74-1, M. Noda et al
Oxide TFT Driven Flexible OLED Display

still images

moving image

SID 2012, 74-1, M. Noda et al
1. Introduction
2. Development Trend
3. Oxide TFT Driven Flexible OLED Display Developed in SONY
4. Summary
Key issues for flexible OLED display were discussed.
- barrier film technology
- OLED fabrication method
- TFT technology
- flexible substrate materials
- handling method of flexible substrate

For commercialization of flexible OLED display, it is expected that high reliable barrier technology with low cost will be developed. Decrease of process temperature and enhancement of high heat resistance of substrate handling method are also key issues.

Oxide TFT driven flexible OLED display was developed in SONY. Mainly two key technologies were introduced.
- flexible CF
- handling method of flexible substrate with high heat resistance
Thank you for your kind attention.