NanoWeb®

Advanced Manufacturing of Nanostructured Transparent Conductors and Light extraction structures for OLED Lighting devices

Dr. Boris Kobrin
CEO/Founder
ROLITH, Inc.
OLED SSL cost requirements

Example of cost structure decrease for OLED lighting material

Report includes detailed breakdown: Manufacturing, encapsulation, extraction, organic material, substrate, electrodes.

(Daydream & Yole Développement, February 2014)
Incumbent electrodes technology: Indium-Tin-Oxide (ITO)

- **Problems:**
  - Indium - rare earth material; **cost** of ITO has escalated in recent years because of the jump in price of the element indium
  - ITO is ceramic – it is **brittle**; problem for flexible substrates
  - migration of **indium and oxygen** from ITO into organic semiconductors during OLED operation causes device degradation
  - the electrical properties of ITO greatly depend on the film preparation
  - the **rough surface** of the deposited ITO film and the work function of ITO, ca. 4.7 eV, limit the efficiency of the hole injection
  - The typical **sheet resistance** of a 100 nm thick ITO layer on glass, 10–40 Ω/□, is still high, which causes a voltage drop along the addressing line, thus limiting the operation of a large-area passive matrix OLED array
<5 Ohm/sq is needed for >100 mm x 100 mm OLED panel

Konica Minolta©
Benefits of large panels

To maximize the benefit of planar lighting device, size is an important factor.

1 module : 9 panels
Available emissive area : 83.6%
(Bezel width:3mm)

1 module : 1 panel
Available emissive area : 94.4%
(Bezel width:3mm)

Large area panel is effective for low cost module fabrication.

✓ Low tiling cost
✓ Low wiring cost
✓ High materials utilization

Konica Minolta©
Non-ITO Transparent conductors

NanoWeb: low sheet resistance and high transmission with invisible wires
# Metal mesh competition

<table>
<thead>
<tr>
<th>Company</th>
<th>Mesh Material</th>
<th>Trace Width, μm</th>
<th>Percent Transmission</th>
<th>Sheet Resistance, Ω/square</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M, U.S.</td>
<td>Ag</td>
<td>&lt;2</td>
<td>&gt;89</td>
<td>40-80</td>
</tr>
<tr>
<td>Atmel, U.S.</td>
<td>Cu</td>
<td>4</td>
<td>87-90</td>
<td>10</td>
</tr>
<tr>
<td>DNP, Japan</td>
<td>Cu</td>
<td>3</td>
<td>N/A</td>
<td>0.3</td>
</tr>
<tr>
<td>Epigem, U.K.</td>
<td>Ni</td>
<td>8</td>
<td>&gt;84</td>
<td>1.1</td>
</tr>
<tr>
<td>Fujifilm, Japan</td>
<td>Ag</td>
<td>N/A</td>
<td>94</td>
<td>50</td>
</tr>
<tr>
<td>Gunze, Japan</td>
<td>Ag</td>
<td>20</td>
<td>78-88</td>
<td>1-3</td>
</tr>
<tr>
<td>Hitachi Chemical, Japan</td>
<td>Ag</td>
<td>5</td>
<td>&gt;89</td>
<td>120</td>
</tr>
<tr>
<td>O-Film, China</td>
<td>?</td>
<td>5</td>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td>Poly IC, Germany</td>
<td>Ag or Cu</td>
<td>10</td>
<td>85</td>
<td>0.4-1</td>
</tr>
<tr>
<td>Rolith, U.S.</td>
<td>Ag or Al</td>
<td>0.15</td>
<td>94</td>
<td>14</td>
</tr>
<tr>
<td>Toppan, Japan</td>
<td>Cu</td>
<td>5</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>UniPixel, U.S.</td>
<td>Cu</td>
<td>6</td>
<td>92</td>
<td>10</td>
</tr>
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</table>

N/A: data not available

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## NanoWeb® modeling

<table>
<thead>
<tr>
<th></th>
<th>Line width (microns)</th>
<th>Pitch (microns)</th>
<th>Height (microns)</th>
<th>Ag - Sheet resistance $\Omega/\square$</th>
<th>Transmission (%)</th>
<th>Haze (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demo (samples)</td>
<td>0.60</td>
<td>30.0</td>
<td>0.50</td>
<td>3</td>
<td>95</td>
<td>4</td>
</tr>
<tr>
<td>Touch - small</td>
<td>0.3</td>
<td>140</td>
<td>0.50</td>
<td>30</td>
<td>99</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Touch - large</td>
<td>0.6</td>
<td>100</td>
<td>0.50</td>
<td>11</td>
<td>99</td>
<td>1</td>
</tr>
<tr>
<td>OLED/Solar</td>
<td>0.6</td>
<td>14</td>
<td>0.50</td>
<td>1.5</td>
<td>92</td>
<td>&gt;4</td>
</tr>
<tr>
<td>Solar/EMI</td>
<td>1.2</td>
<td>10</td>
<td>2.0</td>
<td>0.13</td>
<td>77</td>
<td>&gt;4</td>
</tr>
</tbody>
</table>
Metal mesh integration issues

- Planarization layer
- Mesh design optimization:
  - Line shape
  - Line height
  - Linewidth
  - Pitch
Planarization example
RML®

“Rolling Mask Lithography”

large area
low cost
high resolution
continuous printing solution
Rolith Proprietary Technology:

**large area low cost continuous optical lithography (RML®)**

- **Technology:**
  - Phase shift cylindrical photomask
  - High resolution: down to 150 nm with i-line exposure
  - High throughput: up to 1 m²/min
  - Low cost: down to $5/m²
- **Extraordinary scalability:** up to Gen-8 (2.2 m)

Disruptive technology for **printed electronics, touch screen displays, OLED lighting, architectural and solar industries**

IP portfolio: 21 patents
Proprietary lithography equipment
Gen-2 RML-2 system

Built in partnership with SUSS MicroTec AG

Substrate type: plates & wafers, laminated films
Substrate size: 1m x 0.3m
One Meter Nanostructured Glass panels patterned at Rolith

1m x 0.3 m

Nanostructure: Hexagonal array of 300 nm pillars
Nanostructured flexible films (processed as sheets)

Nanopillar array:
- 300 nm dia
- 600 nm pitch
- 1 micron height in photoresist on PET film, 76 micron thick
NanoWeb® process integration

**Metal etch**

1. Metal deposition
2. Photoresist deposition
3. Photoresist patterning using RML
4. Metal etch
5. Photoresist strip

**Lift-off**

1. Photoresist deposition
2. Photoresist patterning using RML
3. Metal etch
4. Metal (Photoresist strip)
5. Metal Lift-off (Photoresist strip)
NanoWeb®

*sub-micron* transparent metal mesh

- **Al on glass** (by RML™ + etching)
- **Ag on glass** (by RML™ + lift-off)
- **Ag on PET film** (by RML™ + lift-off)
Aluminum mesh on glass (RML™ + etching)

HIGH TRANSPARENCY

\[ T = 96\% \]

LOW SHEET RESISTANCE

\[ R = 3.5 \, \Omega/\square \]

- Invisible submicron lines
Silver mesh on glass (RML™ + Lift-off)

HIGH TRANSPARENCY

\[ T = 95\% \]

LOW SHEET RESISTANCE:

\[ R = 3 \, \Omega/\square \]

• Invisible submicron lines
Silver mesh on PET (RML™ + Lift-off)

HIGH TRANSPARENCY

$T = 96\%$

LOW SHEET RESISTANCE

$R = 5 \, \Omega/\square$

- Invisible submicron lines
Bending/flexing/crash tests of NanoWeb® on PET film

NanoWeb conductor survives (sheet resistance stays constant) bending, flexing and crash of PET film

http://www.youtube.com/watch?v=f3drofWHOXE
NanoWeb® reliability tests

Terminal resistance change ratio ($R/R_o$)

N=3

with OCA

- 240h
- 500h
- 750h

85°C, -40°C, 60°C 90%, 85°C 85%
## NanoWeb® advantages

<table>
<thead>
<tr>
<th></th>
<th>NanoWeb</th>
<th>Other metal mesh</th>
<th>AgNW</th>
<th>ITO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visibility of mesh wires</td>
<td>NO &lt;1 micron lines</td>
<td>YES 2-7 micron lines</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>low R/high T%</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>low R/low Haze</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Scalability to large areas</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Integration with traces patterning</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Flexibility/foldability</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Cost estimation ($/m²)</td>
<td>&lt;$15 (Q4-2015)</td>
<td>$30-40</td>
<td>$33</td>
<td>$41</td>
</tr>
</tbody>
</table>
Fast prototyping (uniform mesh)

Mask with uniform mesh $\rightarrow$ Printing uniform mesh $\rightarrow$ Mesh trimming (laser/photolithography) $\rightarrow$

High volume production (integrated mask)

Integrated mask with mesh and traces $\rightarrow$ Printing mesh and traces
Rolith, Inc. wins the 2013 Best Manufacturing Technology Award From the Printed Electronics Industry for it’s NanoWeb® product.
RML®
for light extraction enhancement (outcoupling)
Loss Mechanisms for OLED Emission

Internal modes: normal and leaky waveguiding modes, plasmon modes

Substrate modes: TIR within OLED substrate / encapsulation

Only about 20% of internal electroluminescence is outcoupled!

2X (100%) enhancement of outcoupled efficiency results in:
- Up to 50% reduction in OLED pixel power consumption
- Significant reduction in OLED power consumption
- Up to 3X–4X increase in OLED lifetime
Micro-nano-structuring

+100% enhancement of extraction by Bragg scattering structures
+40% additional enhancement by AR-structures
Rolith Technology commercialization traction:

Anti-Reflective Glass for Architectural (windows), Display and Automotive Markets

*Joint Development (since 2012) with the Largest Glass Manufacturer – Asahi Glass Co.

Current technology (PVD oxides) | Nature (Moth eye) | Rolith Technology (Lithographically-defined nanostructures)

“Moth eye” glass surface
Height ~ 2.2 micron
Aspect Ratio = 3.6:1

5/12/2014
Reflectivity data for Rolith’s “anti-reflective” glass

< 0.12% at 5 deg incidence
< 0.075% at 30 deg incidence
Flat spectral performance
Low index SiO2 grid on top of ITO has reported to increase efficiency 2.8x

Grid can be used as an electrode and light extraction layer at the same time!

# Cost structure

<table>
<thead>
<tr>
<th>Stage</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<tbody>
<tr>
<td>Year</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Depreciation</td>
<td>$/m^2</td>
<td>880</td>
<td>390</td>
<td>159</td>
</tr>
<tr>
<td>Labor</td>
<td>$/m^2</td>
<td>735</td>
<td>195</td>
<td>50</td>
</tr>
<tr>
<td>Organic Materials</td>
<td>$/m^2</td>
<td>30</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Substrate</td>
<td>$/m^2</td>
<td>15</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Electrodes</td>
<td>$/m^2</td>
<td>20</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Light Extraction</td>
<td>$/m^2</td>
<td>20</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Encapsulation</td>
<td>$/m^2</td>
<td>60</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Other Materials</td>
<td>$/m^2</td>
<td>20</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Total Direct Costs</td>
<td>$/m^2</td>
<td>1780</td>
<td>700</td>
<td>290</td>
</tr>
<tr>
<td>Total Direct Cost</td>
<td>$/klm</td>
<td>570</td>
<td>150</td>
<td>37</td>
</tr>
</tbody>
</table>

**Table 5. Projected Costs of OLED Lighting Panels**

DOE Solid-State Lighting Manufacturing Workshop, June 24-25 2009, Vancouver, WA
Collaboration/ Partnership

- We offer flexible collaboration models:
  - Joint development with partners:
    - Developing superior NanoWeb® manufacturing process for specific OLED lighting design
  - Licensing of Rolith manufacturing processes:
    - NanoWeb® metal mesh technology
    - Proprietary RML® lithography equipment & photomasks
  - Investment or equity model
    - Participation in ser. B round
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