Roll-to-Roll deposition for Organic Light Emitting Diodes (OLED)

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COMEDD

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OUTLINE

- OLED introduction
- Fraunhofer IPMS and COMEDD
- Why OLED for Lighting?
- Processing on glass substrates
- Motivation for continuous metal strip coating
- The ROLLEX project
- Top emitting OLED on rough metal substrates
- Thin film encapsulation
- Roll-to-Roll Coater
- Summary and Outlook
WHY OLED FOR LIGHTING?

- Very thin and light weight
  - Total thickness < 2mm

- Broad perspective (wide view angle)
  - Diffuse Lighting, Lambert emission

- Huge selectivity of materials
  - Polymer (Spin-Coated) and Small-Molecule (Evaporated) Material
  - Non toxic materials

- Low cost manufacturing with simple structure

- Large area possible

- Low power consumption

- Highly efficient
  - Green (130 lm/W)
  - White (64 lm/W)

- Low material consumption (~1 gr. material/m²)

- Low surface heating
PILOT SYSTEM FOR OLED LIGHTING AND OPV ON RIGID SUBSTRATES

- Modular and fully automated system
  - cycle time down to 3 min
  - supplier: Sunic System, Ltd. (Korea) and Aixtron AG (Germany)
- Substrate size 370 x 470 mm²
- Plasma pretreatment
- Organic film deposition
  - Organic Vapour Phase Deposition OVPD (up to 6 layer*)
  - Vacuum Thermal Evaporation (up to 6 layer*)
- Metal film deposition
  - e.g. Aluminium and Silver
- Connection to encapsulation system

*Including dopand and host material
MOTIVATION

- Roadmap of the US Display Consortium for OLED-lighting
  - Absolutely not possible to reach by using OLED display materials and techniques

- New technologies for high efficient and simultaneously low-priced OLEDs needed to meet special requirements of general lighting market:
  - Roll-to-roll-concept: noticeable lower coating costs in comparison to cluster or inline concepts
  - Low-priced metal foil as substrate for very efficient OLED


Glass encapsulated metal sheet processed in the VES400
OLED-Layer structure

- **Bottom emission**
  - reflective top contact
  - organic layers
  - transparent bottom contact
  - glass substrate

- **Top emission**
  - transparent top contact
  - organic layers
  - reflective bottom contact
  - opaque substrate
OLED-STACK: P-I-N-TYPE

- High efficiency OLEDs require pin-structure:
  - p-type doped hole transport layer
  - intrinsic emission layer (may be emitter doped)
  - n-type doped electron transport layer

- Benefits of doping charge carrier transport layers
  - low voltage drop
    - low operating voltage
    - highest power efficiency
  - easy charge carrier injection
    - easy OLED integration on arbitrary electrode materials
    - efficient top emission
  - thick transport layer
    - flattening substrate roughness
    - stable production, higher yield

- Concept of electrical doping can be applied to organic semiconductors

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e.g.: M. Pfeiffer, K. Leo, X. Zhou, J.S. Huang, M. Hofmann, A. Werner, J. Blochwitz-Nimoth, Organic Electronics 4, 89 (2003)
## TYPICAL DEFECTS ON BARE METAL SUBSTRATE

- Defects and scratches on Al foil
- Visible texture from the fabrication process
- Cleaned and Ag coated Al sheet

<table>
<thead>
<tr>
<th>Substrate</th>
<th>RMS (Ra)</th>
<th>Mean roughness (Ra)</th>
<th>Roughness peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al foil with non-conductive smoothing dielectrical surface</td>
<td>1.6 nm</td>
<td>1.3 nm</td>
<td>31.1 nm</td>
</tr>
<tr>
<td>Al foil with evaporated Ag at IPMS</td>
<td>2.5 nm</td>
<td>2.0 nm</td>
<td>24.9 nm</td>
</tr>
<tr>
<td>Glass substrate evaporated with Ag at IPMS</td>
<td>2.7 nm</td>
<td>2.1 nm</td>
<td>21.6 nm</td>
</tr>
</tbody>
</table>

Typically OLED are deposited on very smooth ITO substrates
- RMS < 1 nm,
- spikes < 10 nm
**RED OLED ON ROUGH METAL SUBSTRATES**

- In 2\textsuperscript{nd} thickness maximum:
  - Low leakage currents!
  - High efficiencies
- Low operating voltage
- Very sharp emission spectrum due to cavity effects

**Optical Simulation with ETFOS**

**15 nm Ag**
- Electron Transport Layer
- Hole Blocking Layer
- Emission Layer
- Electron Blocking Layer
- Hole Transport Layer
- Al substrate with oxide layer

**Optimisation of HTL thickness OLED in 2\textsuperscript{nd} Maximum**

**In 2\textsuperscript{nd} thickness maximum:**
- Low leakage currents!
- High efficiencies

**Low operating voltage**

**Very sharp emission spectrum due to cavity effects**
PROCESSING OF METAL SHEET TEST SAMPLES

- Processing of metal sheets in existing vacuum deposition systems for rigid substrates at Fraunhofer IPMS
- Cleaning using a wet bench
- Substrate patterning by screen printing of a non-conducting passivation layer
- Deposition of organic layer stack and metal top cathode by vacuum evaporation through shadow masks
- Encapsulation by gluing conventional cavity glasses

Light emission out of a 4 Quadrant test substrate during electrical test (current efficiency 6-7 cd/A)
- Thin hole transport layer used
- High reverse leakage current
- 3 different deposition runs
- diode size 2x2 mm² (Q1) and 5x5 mm² (Q2), resp.

<table>
<thead>
<tr>
<th>Layer</th>
<th>nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>200</td>
</tr>
<tr>
<td>HTL</td>
<td>30</td>
</tr>
<tr>
<td>EBL</td>
<td>10</td>
</tr>
<tr>
<td>EL-Y</td>
<td>5</td>
</tr>
<tr>
<td>EL-B</td>
<td>23</td>
</tr>
<tr>
<td>HBL</td>
<td>10</td>
</tr>
<tr>
<td>ETL</td>
<td>85</td>
</tr>
<tr>
<td>Cathode</td>
<td>15</td>
</tr>
</tbody>
</table>
- Thick hole transport layer used
- Reduced reverse leakage current
- Very good reproducibility

- 4 different deposition runs
- diode size 2x2 mm² (Q1) and 5x5 mm² (Q2), resp.

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</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>200</td>
</tr>
<tr>
<td>HTL</td>
<td>195</td>
</tr>
<tr>
<td>EBL</td>
<td>10</td>
</tr>
<tr>
<td>EL-G</td>
<td>10</td>
</tr>
<tr>
<td>HBL</td>
<td>10</td>
</tr>
<tr>
<td>Cathode</td>
<td>15</td>
</tr>
</tbody>
</table>
GREEN OLED ON 200X200 MM² processed in VES400

<table>
<thead>
<tr>
<th></th>
<th>100cd/m²</th>
<th>1000cd/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_e$ [cd/A]</td>
<td>18, 0 – 20, 5</td>
<td>15, 3 – 17, 0</td>
</tr>
<tr>
<td>$\eta_p$ [lm/W]</td>
<td>20, 1 – 24, 0</td>
<td>10, 6 – 15, 1</td>
</tr>
<tr>
<td>$\eta_Q$ [%]</td>
<td>4, 6 – 5, 3</td>
<td>4, 1 – 4, 31</td>
</tr>
</tbody>
</table>
**ROLL-TO-ROLL COATER FOR METAL STRIP**

- Batch type Roll-to-Roll Coater
- Substrate width 300 mm, thickness 0.2 … 0.5 mm
- Pretreatment by ion beam and heating

**Coating Stations:**
- up to 9 novel linear evaporators for organic materials in total (5 double, 4 single)
- 2 evaporators for metals
- 1 DC/RF magnetron

**OLED-specific substrate handling**
- strip guidance w/o front side roller contact
- un/rewinding with plastic liner
- transfer of coated substrate under inert atmosphere
LINEAR ION SOURCE AND COOLING TRAP

Plasma treatment

Cooling trap below -100 °C
Deposition cylinder can be heated for moisture reduction on the foil surface.

Cylinder deposition speeds between 0.01 – 1 m/minute is possible.
NEW LINEAR EVAPORATION SOURCES FOR ORGANICS

- horizontal orientation with rotatable (360°) deposition tube enables deposition in top-down and bottom-up geometry
- new primary evaporator with distributed surface*
  - High rates at moderate temperatures (reduced degradation)
- directly heated deposition tube with high temperature homogeneity
- scalable design
- allows inert refill of organic compounds

*Patent pending
STATIC RATES OF ORGANIC LINEAR EVAPORATOR

The diagram illustrates the static rates of organic linear evaporator as a function of crucible temperature. The graph shows the static rate in A/s on the y-axis and the crucible temperature in °C on the x-axis. Three different materials are compared:

- Alq3 (blue line)
- TNATA (red line)
- DCM (green line)

The rates increase significantly as the temperature increases for all materials, with Alq3 showing the highest static rates at higher temperatures.
Thickness homogenity of R2R organic evaporation of Alq3

- Organic linear evaporator in ROLLEX 300 system by VON ARDENNE
- Evaporator to substrate distance 150 mm
- Thickness measurement determined on Alq3 evaporated plastic foil using the Lambda 900 spectrometer
Thick homogeneity of R2R silver evaporation

- Metal evaporator in ROLLEX 300 system by VON ARDENNE
- Thickness measurement determined on silver evaporated plastic foil using the Optical thin film monitor GSM210 (Balzers)
Encapsulation against water and oxygen diffusion is needed to avoid degradation of flexible electronic devices.

Highest permeation barrier requirements: OLED
- water: $< 10^{-5}$ g/(m²d)
- oxygen: $< 10^{-5}$ cm³/(m²d bar)

“Be flexible” – only with thin film encapsulation techniques

Common understanding: Permeation only through defects in barrier layer

Barrier improvement by minimizing effect, size and number of defects

Multilayer concept for direct encapsulation
- defect decoupling: tortuous path for moisture and oxygen permeation
- increased lag time of permeation
- reduce mechanical stress in the layer stack

More details, see the presentation from Nicolas Schiller (FhG-FEP) “Transparent Barrier Coatings on Polymer Films“ in the Vacuum Materials Session.
SUMMARY AND OUTLOOK

- To fabricate large area lighting devices existing OLED display fabrication technologies have to be adapted in several aspects
  - High efficient bottom emitting OLED on glass was shown
  - Highly efficient manufacturing
  - Low cost materials

- Metal strips and R2R deposition have potential for low cost production of lighting devices - First results promising
  - High efficient and stable top emitting OLED on metals substrates are possible
  - Unique approach for an OLED R2R coater using new evaporator concept
  - Promising results of thin film encapsulation

- Outlook
  - Development of white OLED stack in R2R deposition process
  - Further developments in R2R thin film encapsulation
  - Roll-to-Roll process integration: cleaning, patterning, lamination
  - Implementation of R2R defect monitoring
  - Processes also to be used for Organic Solar Cells
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  - J. Drechsel, CreaPhys

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- Further Information: www.rollex-projekt.de