ADDING AN ‘O’ TO LEDS
STATUS AND PERSPECTIVES OF ORGANIC LIGHT EMITTING DIODES
PAWEL E. MALINOWSKI, TUNGHUEI KE
LIVING ROOM NOT SO LONG AGO...
LIVING ROOM NOW...

Source: Philips
LIGHTING
FROM BULBS TO PANELS
NEW FORM FACTORS FOR OLED LIGHTING
OLED LIGHTING: INSTALLATIONS

OLED Works

OSRAM

Konica Minolta

Sumitomo

OLED Works
OLED LIGHTING: AUTOMOTIVE

BMW M4

Astron Fiamm

Audi TT RS

Audi
OLED LIGHTING: PANELS

Acuity

IKEA

aerelight

LG Chem

LG Chem
DISPLAYS
LCD VS. OLED
~15 MM PANEL VS. ~5 MM PANEL
AMOLED DISPLAYS TODAY

BOE

Sharp

Samsung

Tianma

Apple/LG

AUO
AMOLED DISPLAYS: SMARTPHONE

Apple

Samsung

Google

Huawei

LG
AMOLED DISPLAYS: TV

LG

Sony

LG

Samsung
CURVED DISPLAYS

Source: LG Display
FLEXIBLE DISPLAYS

Source: LG Display
THE “O”
ORGANIC LIGHT EMITTING DIODES
ULTRA-THIN LAYERS EMITTING LIGHT

Organic semiconductor:
- small molecule → vacuum evaporation
- polymer → solution processing

First small molecule OLED in 1987
  Tang et al in Applied Physics Letters
First polymer OLED in 1990
  Burroughes et al in Nature
MODERN ORGANIC LED STRUCTURE FOR SINGLE COLOR
MORE EFFICIENT MULTILAYER OLED STRUCTURE

Reducing turn-on voltage
Increasing recombination
Increasing light outcoupling

Doped Emission Layer for increasing internal quantum efficiency

Single color OLED:
5-10 layers, 10-15 materials, 100-200 nm thick
MODERN ORGANIC LED STRUCTURE FOR WHITE
EVEN MORE LAYERS FOR EFFICIENT WHITE

**Improved OLED structure:**

<table>
<thead>
<tr>
<th>Cathode Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETL: NET-18 + NDN-26</td>
</tr>
<tr>
<td>HBL</td>
</tr>
<tr>
<td>Green EML</td>
</tr>
<tr>
<td>Yellow EML</td>
</tr>
<tr>
<td>HTL</td>
</tr>
<tr>
<td>P-doped layer: NPB + NDP-9</td>
</tr>
<tr>
<td>Buffer layer</td>
</tr>
<tr>
<td>N-layer: NET-18 + NDN-26</td>
</tr>
<tr>
<td>HBL</td>
</tr>
<tr>
<td>Blue EML</td>
</tr>
<tr>
<td>HTL</td>
</tr>
<tr>
<td>HIL</td>
</tr>
<tr>
<td>Anode: ITO</td>
</tr>
<tr>
<td>Glass Substrate</td>
</tr>
</tbody>
</table>

**White OLED:**

- **stacking** different colors
  Separate layer for phosphorescent red and green and for fluorescent blue

- 8-15 layers, 20+ materials
OLED VS. LED
DIFFERENTIATOR IS TRANSPARENCY AND FLEXIBILITY

Adapted from: IDTechX

100...150 lm per Watt (200 lm/W in R&D)
60 lm per Watt (150 lm/W in R&D)
200-500$/klm
10$/klm
50,000 hours
40,000 hrs
OLED PERFORMANCE
BRIGHTNESS AND EFFICIENCY REQUIREMENTS

• Brightness – depending on application:
  • lighting: 1000-2000 cd/m² (more – better)
  • TV: 200 cd/m²
  • viewfinder: 200-300 cd/m²
  • smartphone: 500-800 cd/m²
  • augmented reality: 3000-5000 cd/m² (not sufficient lifetime at present)
  • head up display in cars: 10k-20k cd/m² (not sufficient lifetime at present)

• Efficiency – depending on brightness, color point, lifetime, operation condition, barrier, integration process flow:
  • red: 15-30 cd/A
  • green: 50-80 cd/A
  • blue: 5-15 cd/A
OLED LIGHTING MARKET

LARGE GROWTH ESTIMATED – BUT THE ESTIMATES SHIFT

• 2014 IHS: market will grow tenfold by 2020 to reach $26 million
• 2015 Nanomarkets: $1 billion OLED lighting market in 2020
• 2015 ElectroniCast: to almost $2.4 billion in 2020 and $6.7 billion in 2023
• 2016 Yole Developpement: $1.5 billion OLED lighting market in 2021
• 2016 UBI: growth from $114 million to $1.6 billion by 2020
• 2017 UBI: OLED lighting market will reach $1.9 billion by 2021
• 2017 IDTechEx: OLED lighting market will reach $2.5 billion in 2027
IMEC (LEUVEN, BE) / HOLST CENTRE (EINDHOVEN, NL)

wafer fabs: 6 / 8 / 12 inch

plate line: GEN1 (35x32 cm)
IMEC: INDEPENDENT R&D HUB

NANOTECHNOLOGY
SINCE 1984
3500 PEOPLE
77 NATIONALITIES
>600 PARTNERS
THIN-FILM ELECTRONICS PROGRAM

FLEXIBLE DISPLAYS
TFT TECHNOLOGY
AMOLED
PROTOTYPING
R&D ON DEMAND

PROTOTYPING FACILITY FOR THIN-FILM ELECTRONICS

- From fundamental research to tech transfer
- Collaboration in shared and dedicated projects
- 6 inch and Gen 1 (350x320 mm²) lines
- FPD compatible processes
- Low-volume: 100-10,000 components
FLEXIBLE OLED ROADMAP

Making OLEDs flexible

Seamless integration & ease of assembly

Adaptive Electronics

Integration with driving chips

Dynamic colour changing

Smart surfaces: Combination with sensors, actuators & logic

Interaction

Tunable colour & shape

Foldable

“Self”-powered

Form factor

Sheet-to-sheet Flexible OLEDs

>5 years lifetime

60% Transparency

Active shape changing

Real 3D

Self-healing

Upscaling

< €100 /m²
< €1 /100 lm
> 10 million m² /yr
> 20 years lifetime

Pilot production up to 5000 m²/year

Roll-to-roll barrier tool

Roll-to-roll tool for solution processed OLEDs

Mass customisation

S2S Thin film encapsulation

>20 years lifetime in products

80% Transparency

Seamless integration & ease of assembly

Foldable

Cuttable

Self-healing

80% Transparency

60% Transparency

Interaction

Form factor

2006

2016

2026

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VISION FOR FLEXIBLE OLED INTEGRATION

80% transparent or imperceptible

3D ultra-thin shapeable or stretchable form to seamlessly follow contours
PROTOTYPE OF FLEXIBLE OLED INTEGRATION INTO CAR CONSOLE UNIT

IN-MOLD ELECTRONICS
WIRELESS CONTACT OF FLEXIBLE OLED LIGHTING AND SIGNAGE

OLED powered by NFC
TRANSPARENT FLEXIBLE OLED SIGNAGE FILM IN AUTOMOTIVE DEMONSTRATOR
OLEDS WITH A SOFT FORM FACTOR
FLEXIBLE ROLL-TO-ROLL OLEDS

Holst Centre R2R moisture barrier film
Fraunhofer FEP R2R ITO + R2R evaporated OLED

1.8 m x 30 cm
(15 m made in each run)
AMOLED DISPLAYS @ HOLST CENTRE
FUTURE MIXED REALITY DISPLAYS

Hi-Res TFT backplane
Hi-Brightness OLEDs
Efficient data processing
Sensors (e.g. eye-tracking)
User interface (haptic feedback)
Power management
OLED DISPLAYS @ HOLST CENTRE
IMEC/HOLST AMOLED DISPLAYS

- IGZO backplane
- OLED frontplane
- GEN1 substrate
- 165 process steps

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagonal</td>
<td>4.0 inch</td>
</tr>
<tr>
<td>Resolution</td>
<td>QVGA, 320 ppi</td>
</tr>
<tr>
<td>Pixel Circuit</td>
<td>2T1C</td>
</tr>
<tr>
<td>OLED Type</td>
<td>Top-Emission</td>
</tr>
<tr>
<td>Display Driving</td>
<td>IC / in-panel</td>
</tr>
<tr>
<td>Substrate</td>
<td>PEN or PI</td>
</tr>
</tbody>
</table>

![Diagram of OLED display technology]
1250 PPI 2-COLOR PASSIVE OLED DISPLAY
TOUCH TAIWAN 2017 DEMO

Only 1\textsuperscript{st} color

Only 2\textsuperscript{nd} color

1\textsuperscript{st} and 2\textsuperscript{nd} color together

Zoom of the array

Display video
PASSIVE OLED DISPLAY DEMO

standard smartphone LCD

2500 ppi passive OLED display

100 µm
SUMMARY
THE “O” IN LEDS

SUMMARY

- OLEDs are here to stay
  - market getting larger and healthier
  - improvements still needed in TRL and MRL

- OLED R&D platform at Holst Centre
  - from screening materials, through process development and prototyping to fab transfer
  - international collaborations from academia to industry
embracing a better life
IMEC / HOLST ORGANIC PATTERNING TRACK RECORD

- P.E. Malinowski et al. “Photolithography as enabler of AMOLED displays beyond 1000 ppi”, paper 44.1 (invited talk), SID Display Week, Los Angeles, 2017.
- P.E. Malinowski et al. „Photolithographic patterning of organic photodetectors with a non-fluorinated photoresist system,” Organic Electronics 15 (10), 2014
- P.E. Malinowski et al. “Patterning of multicolor OLEDs with ultra-high resolution by photolithography”, 21st International Display Workshops, IDW’14, Niigata, JP, 2014 (Best Paper Award).