QUANTUM DOTS FOR SOLID STATE LIGHTING

JASON HARTLOVE
Nanosys Created the Market for QD Display

- Over 250 SKUs shipped using Nanosys technology
- Over 15MU to date in the field
- ~100% of all products shipped in 2019 from Nanosys supply chains
- Over 470 granted and pending patents worldwide

Track Record of Demonstrated Growth and Performance

- 26% CAGR
- Over 250 SKUs shipped using Nanosys technology
- Over 15MU to date in the field
- ~100% of all products shipped in 2019 from Nanosys supply chains
- Over 470 granted and pending patents worldwide
QUANTUM DOT FOR DISPLAY

1. **QDEF**
   Quantum Dot Enhancement Film
   Enabling a new generation of brighter, more efficient displays with lifelike colors, QDEF gives LCD technology an important edge as it battles new entrants such as WOLED.

2. **QDOG**
   Quantum Dot on Glass
   QDOG Delivers all of the color and brightness benefits of QDEF in an incredibly thin package. This lower cost QD implementation eliminates the need for barrier films and enable 5mm-thin LCD TVs.

3. **QDCC**
   Quantum Dot Color Conversion
   Printed or photo lithography-patterned Quantum Dot Color Conversion technology improves LCD, microLED and OLED displays. With QDCC, new levels of color volume performance and manufacturing throughput are possible for all three technologies.

4. **QDEL**
   Quantum Dot Electroluminescent
   The future emitter material for emissive displays, QDEL will finally make low-cost, ultra-thin and flexible displays a reality.

NANOSYS ROADMAP

Exclusively focused today on display industry.
• QDPL for optical down converters
  - Narrower red for high efficiency
  - Cyan down converter for color tuning

• QDEL for diffuse light source
  - Introduction
  - Advantages of QDEL
  - Challenges of QDEL and how DOE can help
• All layers except Al are solution processed
QDEL ADVANTAGE: EFFICIENCY EQE

\[ \eta_{EQE} = \eta_{IQE} \eta_{OC} \]

- **Efficiency as high as phosphorescent OLED system**
- **Up to 100% IQE**
- **More OC techniques due to solution process**

\[ \eta_{EQE} = \eta_{IQE} \eta_{OC} \]
### QDEL ADVANTAGE: EFFICIENCY LOW VOLTAGE

*Power Efficiency* \( \sim \frac{\eta_{EQE}}{V} \)

<table>
<thead>
<tr>
<th>V @500nits</th>
<th>PHOLED</th>
<th>QDEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>2.9(^*)</td>
<td>2.1</td>
</tr>
<tr>
<td>Green</td>
<td>3.9(^**)</td>
<td>2.5</td>
</tr>
<tr>
<td>Blue</td>
<td>5.5(^***)</td>
<td>3.7</td>
</tr>
</tbody>
</table>

\(^*\) DOI: 10.1021/acsami.6b14438  
\(^**\) DOI: 10.1126/sciadv.aar8332  
\(^***\) DOI: 10.1021/cm3010453
**Fluorescent OLED**

- **S**
- **T**
- **HTL**
- **Host**
- **Dopant**

**PHOLED**

- **S**
- **T**
- **ISC**

**QD-LED**

- **Dopant**
- **QD**

---

- Lifetime not dependent on high triplet energy host

---

Precisely producing the desired spectrum also leads to higher power efficiency (no “waste”)
QDEL ADVANTAGE: BRIGHT

CASE STUDY: AUTOMOTIVE LIGHT

Brightness [cd/m²]:

Today
2,000
Tail light

Center High mounted brake light
12,000
Brake light
20,000
Direction indicator -rear-
50,000

OLED

<table>
<thead>
<tr>
<th>Device</th>
<th>Anode</th>
<th>Voltage (V)</th>
<th>cd/m²²</th>
<th>lm/W</th>
<th>cd/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2S</td>
<td>IZO</td>
<td>10.4</td>
<td>900</td>
<td>7.8</td>
<td>26</td>
</tr>
<tr>
<td>1st R2R device</td>
<td>IZO/Metal/IZO</td>
<td>18</td>
<td>700</td>
<td>3.2</td>
<td>20</td>
</tr>
<tr>
<td>2nd R2R device</td>
<td>IZO/Metal/IZO</td>
<td>12.8</td>
<td>750</td>
<td>4.2</td>
<td>19</td>
</tr>
</tbody>
</table>

Module size: 20cm x 5cm
Device: 3 Tandem deep red
Substrate: plastic


Source: Audi presentation, OLED Summit (2019)

Source: ITRI presentation, OLED Summit (2019)
QDEL ADVANTAGE: LOW COST

Inkjet Printed QDEL Display

Future Gravure Printed QDEL

QDEL vs OLED - 55” Panel Production Cost

*Source: DSCC, QD Forum 2019
Highly efficient InP QDs with narrow spectra for red and green

<table>
<thead>
<tr>
<th>Material</th>
<th>Color</th>
<th>PWL (tunable)</th>
<th>FWHM</th>
<th>QY</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP</td>
<td>Green</td>
<td>520-540 nm</td>
<td>34 nm</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>InP</td>
<td>Red</td>
<td>620-640 nm</td>
<td>37 nm</td>
<td>&gt;95%</td>
</tr>
</tbody>
</table>
**BLUEQDS**

- PWL tunable in 430 to 470 nm range
- High QY, narrow FWHM

<table>
<thead>
<tr>
<th>Material</th>
<th>Color</th>
<th>PWL</th>
<th>FWHM</th>
<th>QY</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnSe</td>
<td>Violet</td>
<td>433 nm</td>
<td>15 nm</td>
<td>90%</td>
</tr>
<tr>
<td>ZnTeSe</td>
<td>Blue</td>
<td>451 nm</td>
<td>21 nm</td>
<td>90%</td>
</tr>
</tbody>
</table>

Crystalline particles
Conformal shells

[Graph showing PL intensity vs. wavelength for ZnSe and ZnTeSe QDs]
QDEL EQE MILESTONES

<table>
<thead>
<tr>
<th>Color</th>
<th>EQE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>16.9%</td>
</tr>
<tr>
<td>Green</td>
<td>17.6%</td>
</tr>
<tr>
<td>Blue</td>
<td>12.5%</td>
</tr>
</tbody>
</table>
QDEL LIFETIME MILESTONES
SUMMARY

- **QDEL has great potential as diffuse light source**
  - High power efficiency – up to 100% IQE; low voltage; more ways for light extraction
  - Spectrum engineering for color management and high efficiency
  - Super bright at low voltage
  - Low cost solution process and easy color patterning
  - Compatible with many aspects of OLED lighting: substrate, light extraction, encapsulation, driving...

- **QDEL challenge**
  - Only significant challenge is to improve lifetime for commercial applications (EQE is already good, can be easily improved further)
  - DOE funding would make a huge impact at this stage of development