Continued Improvement of UV LEDs for Curing Applications

Craig G. Moe
Crystal IS, Green Island, NY
Outline

- Introduction
  - Crystal IS
  - Our UVC LED Products and Process
- III-Nitride Technology for UV LEDs
- Epitaxy and UVC LED fabrication
- Device Reliability
- Surface Applications
CRYSTAL IS TODAY

- Location: Green Island, NY
- Facility Size: ~1600 m²
- Employees:
  - 55 Crystal IS and growing
  - 25 in Japan (Asahi Kasei)
UVC LEDS for a Range of Industries

Our UVC LEDS are used in monitoring, purification and sterilization applications for water, food, air and healthcare industries. UVC LEDs are also suitable for curing applications. We are currently working with OEMs and product integrators to incorporate our UVC LEDs into their products.
# UVC LED Products

<table>
<thead>
<tr>
<th></th>
<th>Optan</th>
<th>SMD PRODUCT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application</strong></td>
<td>Instrumentation</td>
<td>Disinfection</td>
</tr>
<tr>
<td><strong>Package</strong></td>
<td>TO-39</td>
<td>SMD</td>
</tr>
<tr>
<td><strong>Output power</strong></td>
<td>1-5 mW</td>
<td>10 - 30 mW</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>3000 hours @ 100 mA</td>
<td>&gt; 1000 @ 300 mA</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>5 nm bins from 250 - 280 nm</td>
<td>250 - 280 nm</td>
</tr>
<tr>
<td><strong>Appearance</strong></td>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
</tr>
<tr>
<td><strong>Output angle</strong></td>
<td>15°</td>
<td>100°</td>
</tr>
</tbody>
</table>

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Our Manufacturing Process

1. ALN Crystal Growth
2. Substrate Fab
3. Epitaxial Growth
4. Device Fabrication
5. Packaging
6. Test

Crystal IS (Green Island, NY) → AK Microdevices → Subcontractors → Crystal IS
MAKING LIGHT-EMITTING DIODES (LEDS) WITH III-V TECHNOLOGY
III-V Optoelectronics

- Semiconductor material deposited on near defect-free substrates
- Atom size determines emission wavelength (smaller -> shorter)
- Single peak emission
- Electrons added or removed (holes) from layers by substituting elements with more or less unpaired electrons (Si, Mg)
- Electrons and holes recombine in the active region (multiple-quantum well) to produce light
- Any defect creates a non-light generating recombination, reducing the efficiency of the device
III-V Optoelectronics

![Graph showing the relationship between energy gap ($E_g$) and lattice constant (Å) for various III-V compounds. The graph includes points for BN, SiC, GaN, InN, GaP, AlP, AlAs, GaAs, InP, InSb, and GaSb.]
Near and Mid-Ultraviolet

- **UVC**
  - Shortest MQW LED
  - Bandgap of AlN
  - 200 nm

- **UVB**
  - Mercury lamp
  - 227 nm

- **UVA**
  - Bandgap of GaN
  - 365 nm

**Light Sources**

- **AlGaN Active Region, AlN or Al₂O₃ substrate**
- **InGaN**

**Characteristics**

- **Very dim, inefficient**
- **Increasing likelihood of defects on AlN**
- **Increasing likelihood of defects on AlN**

- **Solid-state lighting technology**
  - **High power, high efficiency**
UV LED Efficiency

Advantages of Bulk AlN for UVC LEDs

- Low dislocation density transferred to light-emitting layers, enabling high performance
- Transparent to UV-C radiation
- High thermal conductivity (~3 W/cm-K)
- Using bulk AlN substrate for AlGaN semiconductor devices mimics traditional semiconductor processing
Comparison to Sapphire Technology

**Heteroepitaxy-Current Commercial Technology**

<table>
<thead>
<tr>
<th>Dislocation Density:</th>
<th>Still many dislocations in device layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sim 10^8,\text{cm}^{-2})</td>
<td>Dislocations needed to accommodate Crystal lattice mismatch</td>
</tr>
</tbody>
</table>

Sapphire wafer is inexpensive, but has wrong crystal structure

**Bulk Crystal Growth-CIS Technology**

<table>
<thead>
<tr>
<th>Dislocation Density:</th>
<th>Bulk AlN grown on a single crystal seed. Minimum stress at interface resulting from exact lattice match. Low dislocation density in bulk crystal.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sim 10^3,\text{cm}^{-2})</td>
<td></td>
</tr>
</tbody>
</table>

**UVC LEDs Based on Aluminium Nitride have fewer crystal defects**
266 nm Pseudomorphic UV-C LED

- Output power measured at Army Research Lab.
- 266 nm LED, 66 mW at 300 mA CW, 125 mW pulsed at 500 mA
  - 4.7% EQE, 2.7% WPE at 300 mA CW
  - 5.4% EQE, 2.6% WPE at 500 mA pulsed
280 nm Pseudomorphic MUVLED

- Output power measured at Army Research Lab.
- 280 nm LED, 76 mW at 300 mA CW, 145 mW pulsed at 500 mA
  - 5.7% EQE, 2.7% WPE at 300 mA CW
  - 6.6% EQE, 2.6% WPE at 500 mA pulsed
RELIABILITY AND LIFETIME MEASUREMENTS
Reliability Testing

- Lifetime testing is performed on fabrication lots of 10 to 20 Optan™ devices per test
  - Each fabrication lot consists of LEDs from multiple substrates and multiple epitaxial runs
- Parts tested to a minimum of 1,000 hours with data taken roughly every 150 hours.
  - First 300 hours of data eliminated from before evaluating with model
  - 7/10 lots can predict L50 point from 1,000 hours of testing, others require further testing
- Degradation is modeled as with the visible TM-21 standard, an exponential least squares fit of relative output power versus time
LED Reliability

- Ten groups of 10 LEDs (100 LEDs total) were evaluated.
- No group showed L50B50 failure through 2,500 hours.
- Half of the groups showed L50B50 of longer than 4,500 hours.

![Graph showing cumulative failure rate over time.](image)
Lifetime Decrease with Cycling (Hg)

Philips Mercury Lamp on/off cycle

1,000,000 switches per 3 hours

Output Power (mW) vs Current (mA)

- 0.4% Duty Cycle, 40 µs pulse width
- CW

Percentage of Rated Life vs Number of Switches per 3 Hours

180
140
100
60
20
0
30 10 3 1 0.3 0.1 0.03

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Accelerated Testing Results - Failure

- Failure rate in 1000 hours (fraction of devices <50% of initial power at 1000 hours.
- Activation energy of 0.54 eV calculated from 300 mA data.

<table>
<thead>
<tr>
<th>Case Temp. (C)</th>
<th>Current (mA)</th>
<th># of devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>25</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>55</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>85</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>85</td>
<td>300</td>
<td>30</td>
</tr>
</tbody>
</table>
Failure Analysis of Accelerated Testing

- Leakage paths identified through emission response imaging at reverse bias.
- Defect in substrate -> locally large defect density in epi layers.

-2V bias, 95 µA

No bias
# UVC LEDs vs. Mercury Lamps

<table>
<thead>
<tr>
<th></th>
<th>Mercury Lamp</th>
<th>UVC LED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heavy Metals</strong></td>
<td>Mercury (20-200mg)</td>
<td>None</td>
</tr>
<tr>
<td><strong>Warm Up Time</strong></td>
<td>1-15 Minutes</td>
<td>Instantaneous</td>
</tr>
<tr>
<td><strong>Robustness</strong></td>
<td>Fragile quartz lamp</td>
<td>Shock-resistant</td>
</tr>
<tr>
<td><strong>Design Flexibility</strong></td>
<td>Typically straight and long</td>
<td>Small footprint with versatile design options</td>
</tr>
<tr>
<td><strong>Voltage</strong></td>
<td>110 - 240V AC</td>
<td>6 - 12V DC</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>0.5 - 2.0 A</td>
<td>0.02 - 0.3 A</td>
</tr>
<tr>
<td><strong>Heat Management</strong></td>
<td>Radiated heat</td>
<td>Back side heat extraction</td>
</tr>
</tbody>
</table>
APPLICATIONS
Surface Sterilization

Applications:
- Decontaminating equipment and packaging in food and beverage industry
- Sterilization of medical devices and instruments

UV LED Advantage:
- Wavelength specific
- Mercury-free
- Compact and lightweight
- Instantaneous
- Environmentally-friendly
- Energy efficient
Sterilizing Strip

Used only that area for coverage
Pictures during operation
Vial Disinfection

28mm

81mm

LEDs

Detector Image: Incoherent Irradiance

3/5/2015

Detector 13, NSCG Surface 1: Detector Size 30.000 W x 30.000 H Millimeters, Pixels 500 W x 500 H, Total Hits = 139840

Peak Irradiance: 1.9713E+000 Milliwatts/cm²

Total Power: 2.0976E+000 Milliwatts
Vial Disinfection - Alternative Design

Detector Image: Incoherent Irradiance

Detector 24, NSG Surface 1: Detector Size 66.000 W X 30.000 H Millimeters, Pixels 500 W X 500 H, Total Hits = 4006661

Peak Irradiance: 7.4041E+000 Milliwatts/cm²

Total Power: 2.0033E+001 Milliwatts
Summary

- First commercial product based on single crystal AlN substrate
- Improved performance possible because of low defect density
  - Higher internal efficiency
  - Superior reliability
  - Higher current density
- Accelerated lifetime testing carried out to study effect of increased current and temperature on lifetime.
  - Typical lifetime much greater than 3,000 h.
  - Primary failure mechanism is leakage current increase and associated power degradation.
- Modeling shows LEDs to be suitable for many surface treatments unachievable through conventional mercury lamps