Fundamental aspects of Deep UV Light emitting diodes and failure reduction of LEDS grown on AlN Substrates

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Crystal IS, Green Island, NY
Outline

• Introduction
• III-V Technology for UV LEDs
• UVC LED fabrication
• Device Reliability
• Summary
WE ARE CRYSTAL IS

- **Location:** Green Island, NY
- **Employees:** 50 employees
- **Technology:** *From crystal growth to packaged die*
  - Aluminum Nitride (AlN) crystal growth
  - Die fabrication
  - Packaged UVC LEDs
  - 34 Patents
- **Products:**
  - Optan: High spectral quality and long lifetimes for measurement and monitoring.
  - Klaran: High power and compact footprint for disinfection of air, water and surfaces.
- **ISO 9001:2008 Certified Company**
UVC LED Markets and Advantages

UVC LEDs are:
- Compact
- Safe and environmentally friendly
- Instantaneous
- Long-lasting
- Wavelength specific

The future of these devices is dependent on offering:
- High power
- Long lifetime
OUR PRODUCT OFFERINGS

<table>
<thead>
<tr>
<th></th>
<th>Optan</th>
<th>Klaran</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Instrumentation</td>
<td>Disinfection</td>
</tr>
<tr>
<td>Package</td>
<td>TO-39 and SMD</td>
<td>SMD</td>
</tr>
<tr>
<td>Output power</td>
<td>1-5 mW</td>
<td>&gt; 20 mW</td>
</tr>
<tr>
<td>Lifetime</td>
<td>3000 hours @ 100 mA</td>
<td>&gt; 1000 @ 400 mA</td>
</tr>
<tr>
<td>Wavelength</td>
<td>5 nm bins from 250 - 280 nm</td>
<td>250 - 280 nm</td>
</tr>
<tr>
<td>Output angle</td>
<td>15°; 100°; 115°</td>
<td>105°</td>
</tr>
</tbody>
</table>

We are developing products to meet the performance requirements of our customers.
Radiation Spectrum
We deliver long-life, high performing LEDs with a well-controlled supply chain and industry-leading production facility.
Our Approach: Pseudomorphic UV LED (PUVLED) Structure

We have demonstrated smooth surface morphology throughout our device structure.

Transition to p-GaN

Starting AlN substrate surface finish is critical!

Cathodoluminescence confirms TDD density in MQW < $10^5$ cm$^{-2}$
ADJUST THE BAND GAP TO GET THE SPECIFIC WAVELENGTH DESIRED

- Bandgap increases with increasing Al concentration.
- Wavelength, $\lambda = \frac{1240}{E}$
Crystal IS Advantage :: Bulk AlN for UVC LEDs

- Low dislocation density enables 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
  - Easier to scale at larger diameters

Bulk AlN allows for more reliable devices with longer lifetimes and higher power than other substrates.
RELIABILITY AND LIFETIME MEASUREMENTS
Experimental Procedure

• Lifetime testing was 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
• Temperatures described are case temperatures unless otherwise specified
  • Junction temperatures can be estimated from measured package capability
## UVC LED Products Tested

<table>
<thead>
<tr>
<th></th>
<th>Optan TO-39</th>
<th>Optan SMD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application</strong></td>
<td>Spectroscopy</td>
<td>Biofilm Prevention</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>&gt; 2 mW</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>3000 hours @ 100 mA</td>
<td>3000 hours @ 100 mA</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>5 nm bins from 250 - 280 nm</td>
<td>260 - 275 nm</td>
</tr>
<tr>
<td><strong>Output angle</strong></td>
<td>15°</td>
<td>100°</td>
</tr>
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</table>
The Lifetime of Crystal IS Optan LEDs

Lifetime >> 1000 hours
Projected Optan Lifetime

- Parts tested to a minimum of 1000 hours with data taken roughly every 150 hours.
  - First 300 hours of data eliminated before evaluating with the model
- Degradation is modeled as with the visible TM-21 standard, an exponential least squares fit of relative output power versus time.
Temperature Dependence at 100 mA

- Degradation increases with increasing temperature (0.25 % per °C above room temperature)
- Greater than expected degradation at -40 °C (corresponding to higher reverse leakage at -5 V)
Accelerated Testing

- Devices operated at various case temperatures and current to accelerate the degradation and failure of the LEDs.
- Three case temperatures and three currents with devices from three different lots

<table>
<thead>
<tr>
<th>Case Temperature (°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>
Accelerated Testing Results :: Degradation

Junction temperature (Tj) estimated from thermal resistance, input power and case temperature.

Accelerated degradation only seen at high junction temperatures.
Accelerated Testing Results :: Failure

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

\[
\text{Ea} = 0.54 \text{ eV}
\]
Effect of Current and Temperature on Leakage

- Devices stressed at 100 mA for 48 hrs, then at 300 mA for 1000+ hrs
- Established leakage current failure spec at >1 mA at -5 V
- >35% of leakage failures occur at first test after 300 mA stress (all temperature conditions)
- Leakage failures likely to have a significant current component
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

Defect in substrate

AlN epi/substrate interface
APPLICATIONS
# 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>
Lifetime Decrease with Cycling (Hg)

Instant on/off capability of UVC LEDs offers up to 1,000,000 switches per 3 hours
NARROW VERSUS WIDE VIEWING ANGLE

Optan Ball Lens

Simulation Result (1mW, 10mm away from detector)

Unit: mW/cm²

Optan SMD

Simulation Result (2.5mW, 10mm away from detector)
Summary

• First commercial product based on single crystal AlN substrate
• Accelerated lifetime testing studied the effect of increased current and temperature on lifetime.
  • Typical lifetime much greater than 3000 hours
  • Identified junction temperature as the primary acceleration factor over the ranges tested.
  • Further work continues to verify acceleration mechanisms.
• Low defect density of AlN substrates provides improved performance for customers
  • Higher internal efficiency
  • Superior reliability
  • Higher current density
Questions?