Outline

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II. ESD/EOS failure of GaN-based LEDs
III. ESD/EOS Protection Devices
IV. Characteristics of TVS Zener Diodes
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VI. Issues on Vc Minimization for HBLED
VII. Summary
I. Introduction

Causes of Electrical Overstress

- ESD (Electrostatic Discharge)
- EOS (Electrical Over Stress)
  - driven over the maximum rated current or voltage
    - Energized power supply
      - hot plugging (in-rush current)
    - Transient event
      - transient over-current (current spike)
      - transient over-voltage (voltage spike)
    - Over-driving
      - driver circuit (intentional or not)

ESD Failure (OSRAM)
EOS Failure (leakage)

Fabrication: 26%
ESD/EOS: 38%
Assemly: 14%
Good: 4%
Mobile Ion: 3%
Unknown: 15%
II. ESD/EOS failure of GaN-based LEDs
ESD Engineering of GaN-Based LEDs

- LED with 900°C-grown p-cap layer could only endure negative 1100 V ESD pulses while the LED with 1040°C-grown p-cap layer could endure ESD pulses as high as negative 3500 V.

Typical ESD/EOS Failure of LED (OSRAM)

- ESD pulse < 100 ns (3 kV)
- EOS pulse > ms

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ESD/EOS Protection Devices

- Over voltage protection
- Over current limiter
- Over current protection

ESD

CRD/CLD
Resettable current limiter

heating

In-rush current protection (hot plugging)

passive type
Active type

Bidirectional ESD Protection Device

Strong Transient Voltage (ESD, Surge, EFT)
Weak Clamped Voltage

Forward

Bypass Excess Current

Circuit /Device to protect

Reverse

TVS diodes offer the most desirable characteristics for board level protection

- Industry standard requirements
  - ESD, EFT, Lightning
  (ENxxx or IEC standards)
- Smaller IC components
- Higher Pin density ICs

\[ V_p \approx \pm 8 \text{ kV} \]
\[ V_C \approx 20 \text{ V} \]
ESD Protection of GaN-based LEDs

High Brightness White/Blue/Green LED lamps with Sapphire substrate are basically fragile by ESD Surge.

Zener Diodes are used for the safeguard of LEDs to prevent from ESD surge.

III. ESD Protection Devices
## Options for Addressing ESD Problem

<table>
<thead>
<tr>
<th>Devices</th>
<th>Merits</th>
<th>Demerits</th>
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</thead>
<tbody>
<tr>
<td><strong>Crowbar</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GDT, Spark gap</td>
<td>High power</td>
<td>Slow</td>
</tr>
<tr>
<td>SCR, Thyristor</td>
<td>High current</td>
<td>Snap back, Latch up</td>
</tr>
<tr>
<td><strong>Clamping device</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramic</td>
<td>Cheap</td>
<td>Poor ESD robustness</td>
</tr>
<tr>
<td>Polymer</td>
<td>Small, Cheap, Low capacitance</td>
<td>Poor ESD robustness, Low temperature(&lt;85 °C), Short lifetime</td>
</tr>
<tr>
<td>Schottky</td>
<td>Small capacitance, if circuit</td>
<td>Weak ESD robustness</td>
</tr>
<tr>
<td><strong>Zener</strong></td>
<td>Fast, Cheap, DC voltage &amp; power regulation</td>
<td>High Vc, Large VC/VBR</td>
</tr>
<tr>
<td>TVS diode</td>
<td>Rugged, Fast (few ps), Small Vc, Low clamping heat, Good protection efficiency, Moderate VC/VBR, Small leakage current,</td>
<td>Chip size dependent power</td>
</tr>
<tr>
<td>MOV</td>
<td>Rugged, good stability, High Vc, Bidirectional, AC power line</td>
<td>Slow(500~1000 ps), Poor stability (aging) Low dc breakdown, Large leakage current,</td>
</tr>
<tr>
<td><strong>Combination (Filter)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DT-BJT, C-R-C, Z-R-Z</td>
<td>Rugged, Fast (few ps), Small Vc/VBR, Good stability, Small leakage current, Good protection efficiency, Ideal Vc</td>
<td>Large size, Expensive</td>
</tr>
</tbody>
</table>

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### I-V Characteristics of Zener Diode

- \( I_R \): reverse leakage current
- \( R_Z \): differential resistance
- \( V_Z \): Zener voltage

**\( P_{TOT} \): steady state power dissipation**

\[
V_z + (R + R_z)I_d = V_S
\]

\[
I_d = \frac{V_z}{R + R_z} + \frac{V_z}{R + R_z}
\]

\[
P_{TOT} = 2V_Z^2 \left( \frac{1}{R_S} + \frac{2R_Z}{R_S^2} \right)
\]
TVS (Transient Voltage Suppressor) Zener Device

- $V_{BR}$: breakdown voltage at $I_T$
- $I_T$: test current
- $V_{ST} (= V_{RWM})$: stand-off voltage usually 80% of $V_{BR}$
- $V_{RWM}$: reverse working maximum voltage (max. off-state voltage)
- $I_R$: reverse leakage current
- $I_{PP}$: maximum peak pulse current
  - maximum permissible surge current to be protected by the device (i.e., 100 A)
- $V_C$: maximum clamping voltage

Comparison of Clamping Voltages

TVS zener diodes and Metal Oxide Varistors are popular voltage clamping devices.

For HBM (8 kV)

- $Z_S = 1.5$ kohm, $V_S = 8$ kV, $V_{BR} = 7$ V
- $Z_{Zener} = 30$ ohm
- $V_{CM} \approx 7 + (30/1,500) \times 8,000 \approx 167$ V
- $I_{PP} = 6$ A

For IEC 61000-4-2 (30 kV)

- $Z_S = 330$ ohm, $V_S = 30$ kV
- $Z_{TVS} = 1$ ohm
- $V_{CM} \approx 7 + (1/330) \times 30,000 \approx 98$ V
- $I_{PP} = 98$ A

Benefits
- Excellent clamping capability ($V_{CL} < V_{BR} + 0.1$ V)
- Reduce noise signals during normal operation

Drawbacks
- Expensive
- Large chip size

ESD Protection using Pi Filters (Z-R-Z, C-L-C)

Zener (30 Ω)

TVS Zener (1Ω)

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V. Characteristics of TVS Zener Diodes
Performance (Conventional Zener A)

**P-Top structure**

Catastrophic destruction @ 50~120mA

**N-Top structure**

Catastrophic destruction @ ~110mA

Performance (Conventional Zener B)

**P-Top structure**

Note:
- Biasing from forward to reverse direction
- Failure occurs above 60mA

Note:
- Re-measure: Catastrophic destruction !!!
Performance (Conventional Zener B)

N-Top structure

Note:
- Biasing from forward to reverse direction
- Failure occurs above 60mA

Note:
Re-measure: Catastrophic destruction !!!

Performance (TVS Zener, Sigetronics)

P-Top structure

Vz: ~7 V

Vz: ~12.5 V
Performance (TVS Zener, Sigetronics)

N-Top structure

![Graph showing voltage vs. current for N-Top structure with Vz: ~7 V and Rz: 7.0Ω (@5mA) and 6.5Ω (@10mA).]

Leakage Current Comparison

- Power loss
- Reliability
- Noise

![Graphs comparing leakage current for P-Top and N-Top structures, showing significant reduction after ESD surge (HBM +/- 8kV, 10 times).]
Thermal & ESD Stability (TVS Zener)

- Flood exposure of heat and light from LEDs

P-Top structure

- RT, 120, 150, 180°C
- 150°C ± 8kV HBM

Temperature coefficient:
+1.6mV/C

ESD stability at elevated temperatures is excellent

ESD Robustness (TVS Zener, Sigetronics)

Package (SOD923) finished data

- ESD per IEC61000-4-2
  - C = 150 pF, R = 330 ohm
- ESD proof up to ± 30kV
  - IEC61000-4-2 level-4 compliance

Current (A)

Voltage (V)

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### Lateral Bidirectional TVS Zener (Sigetronics)

**Lateral Bi-directional Structure**

**PNP (Double Pad)**

- **$V_z$: ~7 V**
- **$R_z$: 9 Ω**

**NPN (Double Pad)**

- **$V_z$: ~7 V**
- **$R_z$: 12 Ω**

### Vertical Bidirectional TVS Zener (Sigetronics)

**Vertical Bi-directional Structure (Single PAD)**

**PNP structure**

- **Forward**
  - **$V_z$: 7 V**
  - **$R_z$: 3.5 Ω @5mA**
- **Reverse**
  - **$R_z$: 0.5 Ω @5mA**

**NPN structure**

- **Forward**
  - **$V_z$: 6.5 V**
  - **$R_z$: 1.6Ω @5mA**
- **Reverse**
  - **$R_z$: 8.7 Ω @5mA**

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### TLP & VFTLP for Bidirectional TVS Zener (±7 V)

#### TLP I-V Characteristics
- Rise time/pulse width: 10 ns/100 ns
- Peak triggering voltage: 7 V
- Leakage current: <10 pA
- ESD capability: > 18 A
- Clamping voltage: 14 V @18 A

#### VFTLP I-V Characteristics
- Rise time/pulse width: 100 ps/10 ns
- Peak triggering voltage: 8 V
- Leakage current: <10 pA
- ESD capability: > 20 A

![Characteristics Graph]

- \( R_D = 0.15 \sim 2 \Omega \)

(Measurement at Barth Electronics)

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### Excellent Features of Bidirectional TVS Zener

- **Bidirectional ESD protection**
- **Precise reliability control**
- **Small leakage current (x 1/10)**
  - Unidirectional: 30 pA (@4 V, Vz=7 V)
  - Bidirectional: 2 pA (@± 4 V, Vz= ±7 V)
- **High light emission efficiency**
- **High speed operation (small cap.)**
  - Unidirectional: 15 pF (@0 V, Vz= ±7 V)
  - Bidirectional: 8 pF (@ 0 V, Vz= ±7 V)
- **Small leakage current increase at HT**
  - Unidirectional: 17 pA/°C (@4 V for Vz=7 V)
  - Bidirectional: 3 pA/°C (@ ± 4 V for Vz= ±7 V)
- **Stable operation at HT (small TC)**
  - Unidirectional: 1.6~2 mV/K
  - Bidirectional: 0.8 mV/K
- **Current driving capability**
  - Zener: 60~120 mA
  - TVS Zener: 100~500 mA
- **Small differential resistance**
  - Zener: 20~50 ohm
  - TVS Zener: 0.5~10 ohm

![Features Diagram]

**Voltage clamping**

<table>
<thead>
<tr>
<th>Device</th>
<th>Rz</th>
<th>Estimated Vc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HBM(8kV)</td>
</tr>
<tr>
<td>Zener</td>
<td>30 ohm</td>
<td>167 V</td>
</tr>
<tr>
<td>TVS Zener</td>
<td>&lt; 5 ohm</td>
<td>&lt; 34 V</td>
</tr>
</tbody>
</table>

**Current flow direction**

- Unidirectional → DC operation only
- Bidirectional → both DC&AC operation
Process Capability Index (Sigetronics)

<table>
<thead>
<tr>
<th>LSL</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>USL</td>
<td>8.0</td>
</tr>
<tr>
<td>Mean value</td>
<td>6.852</td>
</tr>
<tr>
<td>Cpk</td>
<td>3.6</td>
</tr>
<tr>
<td>Sample #</td>
<td>144</td>
</tr>
</tbody>
</table>

Process Margin Test for Die Attach (Silver Paste)

- Original Chip
- A-Die: Well attached
- B-Die: Ag paste roll-up
- C-Die: Ag paste roll-up (contact to metal pad)
### Performance Summary (P-Top)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>A</th>
<th>B</th>
<th>Sigetronics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>-</td>
<td>Conventional (Diff)</td>
<td></td>
<td>TVS (Epi)</td>
</tr>
<tr>
<td>Max Zener current</td>
<td>I&lt;sub&gt;z,max&lt;/sub&gt;</td>
<td>50~120 mA</td>
<td>50~100 mA</td>
<td>&gt; 100 mA</td>
</tr>
<tr>
<td>Zener resistance</td>
<td>R&lt;sub&gt;z&lt;/sub&gt; @5mA</td>
<td>23 Ω</td>
<td>30 Ω</td>
<td>5 Ω (P-TOP) 7.5 Ω (PNP, forward) 0.5 Ω (PNP, reverse)</td>
</tr>
<tr>
<td>Leakage current</td>
<td>I&lt;sub&gt;R&lt;/sub&gt; @4V</td>
<td>2.3 nA</td>
<td>1.4 nA</td>
<td>200 pA</td>
</tr>
<tr>
<td>ESD intensity</td>
<td>HBM</td>
<td>-</td>
<td>-</td>
<td>&gt; ± 8 kV</td>
</tr>
<tr>
<td>ESD intensity @180C</td>
<td>HBM</td>
<td>-</td>
<td>-</td>
<td>&gt; ± 8 kV</td>
</tr>
</tbody>
</table>

Note:
1. The parameters were obtained using on-wafer test.

### Performance Summary (N-Top)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>A</th>
<th>B</th>
<th>Sigetronics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>-</td>
<td>Conventional (Diff)</td>
<td></td>
<td>TVS (Epi)</td>
</tr>
<tr>
<td>Max Zener current</td>
<td>I&lt;sub&gt;z,max&lt;/sub&gt;</td>
<td>~ 110 mA</td>
<td>50~100 mA</td>
<td>&gt; 100 mA</td>
</tr>
<tr>
<td>Zener resistance</td>
<td>R&lt;sub&gt;z&lt;/sub&gt; @5mA</td>
<td>15 Ω</td>
<td>39 Ω</td>
<td>7Ω (N-TOP) 1.6 Ω (PNP, forward) 8.7 Ω (PNP, reverse)</td>
</tr>
<tr>
<td>Leakage current</td>
<td>I&lt;sub&gt;R&lt;/sub&gt; @4V</td>
<td>2.3 nA</td>
<td>1.5 nA</td>
<td>200 pA</td>
</tr>
<tr>
<td>ESD intensity</td>
<td>HBM</td>
<td>-</td>
<td>-</td>
<td>&gt; ± 8 kV</td>
</tr>
<tr>
<td>ESD intensity @180C</td>
<td>HBM</td>
<td>-</td>
<td>-</td>
<td>&gt; ± 8 kV</td>
</tr>
</tbody>
</table>

Note:
1. The parameters were obtained using on-wafer test.
V. ESD Protection Test

I-V of LED after ESD (HBM) Zap

ESD Strike: ± directions, 5 times each

Blue LED

Zener
P-top 12 V
(Sigetronics)

Current (A)

Voltage (V)

-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4

10^-9
10^-8
10^-7
10^-6

LED #1

RT

ESD
0.2 ~ 2.0 kV, 0.2 kV Step
2.5 ~ 8.0 kV, 0.5 kV Step

Blue LED (Cree)

Zener (Sigetronics)
Reverse Leakage Current

ESD Zap on LED with/without Zener Diode

- **Room Temp.**
- **Reverse Voltage**
  - 5 V
  - 6 V
  - 10 V

- **Reverse Leaks (A)**
  - Before ESD Zap
  - ESD ±8kV, 5 times

- **ESD Voltage (kV)**

---

ESD Zap on LED with/without Zener Diode

- **Acceleration Test at High Temperature**

- **Current (A)**
  - 25 °C
  - 70 °C
  - 110 °C

- **Voltage (V)**

---
VI. Issues on Vc Minimization for HBLED

Components of Clamping Voltage

Requirements
- Fast response time (<1 ns)
- Low clamping and operating voltage
- Do not degrade

\[ V_c = V_{BR} + R_D \times I_{PP} + L_D \times \frac{dI}{dt} \]

Inductive voltage component
\[ V_L = L_D \times \frac{dI}{dt} \]

Resitive voltage component
\[ V_L = R_D \times I_{ESD} \]

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Key Elements for Surge Protection (HBLED)

- TVS device – dynamic resistance
- Flip chip package – inductance
- Sub mount (silicon, ceramic, metal) – inductance, thermal stability, EOS

Thermal conductivity
Thermal expansion coefficient

<table>
<thead>
<tr>
<th>Package Dependent Surge Clamping Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package</td>
</tr>
<tr>
<td>Shape</td>
</tr>
<tr>
<td>V&lt;sub&gt;CL&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Examples (Cree)

ESD Protection (using Bidirectional TVS Device)

1. Over current protection
2. Over current limiter
3. In-rush current protection (active, passive)
4. Over voltage protection

XLamp LEDs

Over current driven EOS damages

- Burned wires
- Broken wires
- Damage near bond pads
Examples

CMD: LuxGuard (UHB-LED)
Silicon sub mount & side mount
(using Bidirectional TVS Diode)

ESD: 8 kV or 15 kV
- Cost effective
- Thermal match (mismatch between LED and lead frame)
- Robust ESD protection (bidirectional TVS sub mount)

OnChip:
Silicon sub mount for vertical LED
(Bidirectional Device)

VII. Summary

- ESD protection → TVS (IEC61000-4-2 > ± 30 kV)
- Clamping voltage → Bidirectional (± 7, ± 12, ± 14, ... V)
- Resistance → Dynamic resistance (< 1~10 Ω)
- Inductance → Flip Chip → Sub Mount (EOS)
- Leakage current (reduce the afterimage in display panel)
- Current driving capability (EOS)
- Reliability
- Lifetime
- High temperature operation (T_j < 120 °C)
- Light absorption (photo reflector, small ESD chip)
- Reliable process control for die bonding
- Capacitance → Small & Bidirectional (high speed)
TVS Protection Applications

- Input Devices
  - Mice
  - Keyboard
  - Remote Control
  - Digitizing Tablets
  - Trackballs

- Digital Photography
  - Digital Photo Frames
  - Digital Still Cameras
  - Portable Webcams
  - Webcams

- Gadgets
  - PDA
  - GPS
  - NES

- Game Controllers
  - Gaming Pads
  - Joysticks
  - Steering Wheels
  - PS2 or PSP
  - XBOX

- Modems & Telephony
  - 56K USB Modems
  - Cable Modems
  - Internet Telephony
  - ISDN Modems
  - xDSL Modems

- Networking
  - Bluetooth Adapters
  - Direct Connect
  - USB Ethernet
  - USB Phone Line Network
  - USB Wireless Network

- Storage
  - CD RW
  - CD ROM
  - DVD Drivers
  - Ext Floppy Dr
  - Flash Mem Readers
  - HD
  - Removable Disks Dr
  - Solid State Drivers

- Printing & Scanning
  - Photo Printers
  - Card Scanners
  - USB Film Scanners
  - Flat bed scanners

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Our TVS Zener diode is to protect your valuables against electrical shocks…

Thank you…