

Effect of chip geometry on breakdown voltage of GaInN light-emitting diodes

J. Cho, D. Zhu, E.F. Schubert and J.K. Kim

Reverse leakage current characteristics of GaInN/GaN multiple quantum well light-emitting diodes (LEDs) with various chip geometries are examined. The effect of chip geometry on the reverse leakage current is negligible at a low voltage, but becomes apparent at a high voltage. The reverse breakdown voltage of LEDs decreases as the angle of vertex in the chip geometry decreases presumably because of a highly localised electric field strength near the vertex. This suggests that a chip geometry with a rounded vertex is suitable for reliable high-power LEDs.

Introduction: GaInN-based light-emitting diodes (LEDs) have attracted increasing interest, especially for solid-state lighting applications [1]. For general illumination purposes where LEDs are operated at high current densities, the reliability of LEDs is crucial. The degradation rate of LEDs is known to be closely related to the reverse leakage current, thus it is important to understand this characteristic in order to develop highly reliable LEDs [2]. GaN-based pn-junction devices are wide bandgap semiconductors and thus should have very small reverse saturation currents generated by diffusion and recombination in the space-charge region. However, experimental measurements show that the reverse leakage current far exceeds the theoretically expected current, and has a strong voltage dependency, indicating the presence of another dominant mechanism such as tunnelling [3]. The band-to-band tunnelling current with reverse biased semiconductors is given by [4]:

$$I_{\text{tun}} = \frac{(2m^*)^{1/2} e^3 EVA}{4\pi^2 \hbar^2 E_g^{1/2}} \exp\left(-\frac{\theta m_0^{1/2} E_g^{3/2}}{e\hbar E}\right) \quad (1)$$

where m^* is the effective mass of the tunnelling carrier, m_0 the free electron mass, E the electric field, V the applied voltage across the junction, A the junction area, E_g the direct bandgap, and e is the electron charge. θ is a dimensionless quantity given by $\theta = \beta(m^*/m_0)^{1/2}$, where β is a constant describing the characteristic of the barrier shape. According to (1), the reverse tunnelling current shows a strong dependence on the electric field, but does not show a dependence on the chip geometry although it is a likely factor influencing the reverse leakage for laterally structured GaInN LEDs.

For GaInN-based LEDs grown on sapphire substrates, the electrodes on p - and n -type GaN are typically formed on the same side of the device owing to the insulating nature of sapphire. A design rule for such laterally structured LEDs has been focused on the decrease in the operating forward voltage as well as alleviating current crowding [5]. However, the effect of LED geometry design on the reverse leakage current characteristic has not been explored although current transport in laterally structured LEDs could cause a localised high-electric-field region where an excessive reverse current caused by tunnelling and breakdown occur. In this Letter, we present the reverse current characteristics of GaInN/GaN multiple quantum well (MQW) LEDs with various chip geometries. The effect of chip geometry is not apparent at low bias voltages, but it does make a distinct difference in the reverse breakdown voltage of the LEDs.

Experimental method: The epitaxial LED wafers used in this study were grown on (0001) sapphire substrates using metal organic vapour phase epitaxy. The LED structure consists of a 5 μm Si-doped n -type GaN layer, nine pairs of GaInN/GaN MQWs, a 50 nm Mg-doped $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ cladding layer, and a 0.1 μm Mg-doped p -type GaN layer. The electron and the hole concentration obtained by the Hall measurement were 3×10^{18} and $5 \times 10^{17} \text{ cm}^{-3}$, respectively. A standard LED fabrication process was used, where the p -type GaN was partially etched to form mesas by using a chemically assisted ion-beam etching system after thermal activation for p -type GaN. Ti/Al/Ni/Au was deposited on the etched n -type GaN and annealed, and reflective Pd was deposited on the p -type GaN for n -type and p -type ohmic contacts, respectively. It should be noted that a non-alloyed Pd contact was used to prevent unintentional surface leakage current caused by metal migration [6]. Current-voltage (I - V) characteristics were measured using a four-point probe station combined with a parameter analyser (HP4155B) under dark, ambient conditions. Two widely used values are measured and compared to each other: one is the reverse current,

I_R , at the reverse voltage of -5 V and the other is the breakdown voltage, V_R , at the reverse current of $-10 \mu\text{A}$.

Results: Fig. 1 shows the schematic illustration of devices with same area, but different geometric shapes of the mesa and p -type contact; circle, square, triangle, and two deformed polygons. A critical angle was defined as the minimum angle of the vertex in the geometric shape of the mesa and p -type contact for convenience in distinguishing devices. The critical angles of the devices are 180° , 90° , 60° , 45° and 27° , as shown in Fig. 1. Two sets of devices were prepared. One set has an area of 0.09 mm^2 , and the other set has an area of 0.25 mm^2 . According to (1), because of the area (A) dependence of tunnelling current, the value of I_R should be lower and the value of V_R should be higher for small area LEDs than those for large area LEDs. However, the reverse tunnelling current of devices should be identical if they are made with the same area in a uniform wafer. Fig. 2 shows reverse current at -5 V , I_R , against critical angle. There is no remarkable difference in I_R between the devices with the same area, but with different geometries. The value of I_R for 0.09 mm^2 -area LEDs is in the range of nanoamperes, and that for 0.25 mm^2 -area LEDs is one order of magnitude larger. This indicates that the chip geometry with the same area does not affect the reverse current at low bias voltage, as expected theoretically.



Fig. 1 Schematic structure of various mesa and p -type contact geometries: a circle, a square, a triangle, and two irregular polygons

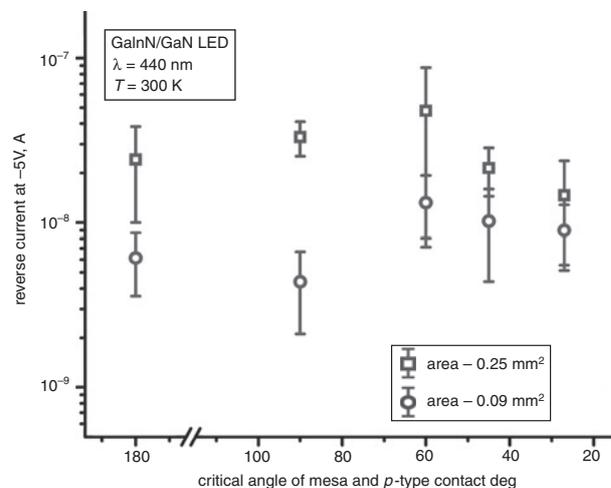


Fig. 2 Reverse current at -5 V , I_R , against critical angle for GaInN LEDs with different device geometries

However, the breakdown voltages of the devices at the reverse current of $-10 \mu\text{A}$, V_R , show a strong dependence with chip geometries, as shown in Fig. 3. As the critical angle decreases, the value of V_R also decreases. The average value V_R of the circle LEDs is 20.3 V (0.09 mm^2 LEDs) and 15.6 V (0.25 mm^2 LEDs), but that of the polygon LEDs, with a critical angle of 27° , is 17.6 V (0.09 mm^2 LEDs) and 14.4 V (0.25 mm^2 LEDs), respectively. This result can be explained as follows; an LED with a low critical angle of its mesa and p -type contact is more likely to have a weak area near the vertex where the electric field strength is locally high enough for tunnelling. The possibility of having such a weak area increases when the critical angle of the geometric shape decreases. Considering that current crowding is typical for the lateral-structured GaInN LEDs, the localised high electric field region could be more easily generated near the vertex.

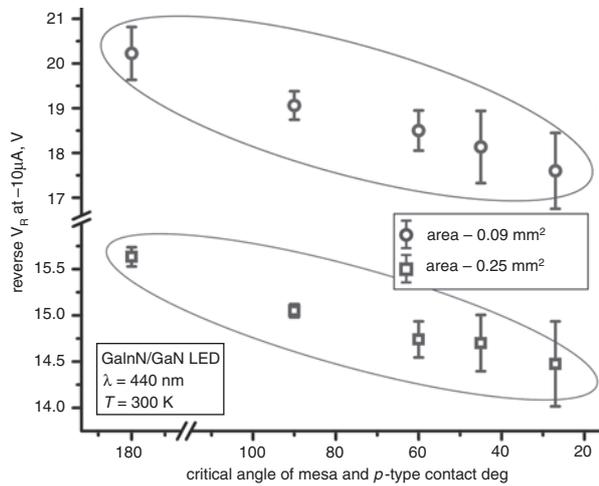


Fig. 3 Reverse breakdown voltage at reverse current of $-10 \mu\text{A}$, V_R , against critical angle for GaInN LEDs with different device geometries

The breakdown voltage can be expressed as [7]:

$$V_R = \frac{\epsilon_s E_c^2}{2eN_D} \quad (2)$$

where ϵ_s , E_c , e , and N_D represent the permittivity of the semiconductor, the strength of the electric breakdown field, the electrical charge, and the ionised impurity concentration, respectively. For n -type GaN, the ionised impurity concentration is almost the same as the electron concentration. The strength of the electric breakdown field was calculated from (2) and is plotted in Fig. 4. The E_c is between 4 and 5 MV/cm and shows a linear relationship with the critical angle of the LED devices. It is important to note that the strength of the electric breakdown field can be enhanced by increasing the critical angle of the geometric shape. The typical critical angle of commercial LEDs is 90° . Rounding the edges of squares and fingers would be very beneficial in increasing the strength of electric field, and hence, in improving the reliability of high-power LEDs.

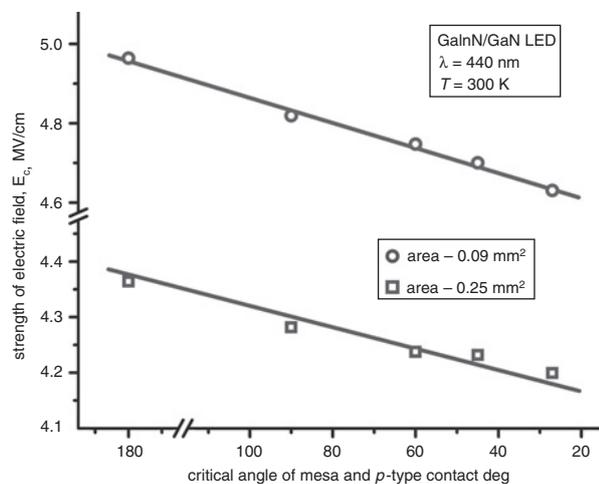


Fig. 4 Strength of electric breakdown field against critical angle for GaInN LEDs with different device geometries (solid line is for clarity)

Conclusion: The reverse leakage current characteristics in GaInN/GaN MQW LEDs with various critical angles were analysed. The smaller the critical angle of the mesa and p -type contact, the lower the reverse breakdown voltage becomes. This is attributed to a locally increased electric field near the vertex of the LEDs which facilitates tunnelling of carriers. The strength of the electric breakdown field is influenced by the geometrical shape. The result suggests that chip geometry with a rounded vertex of mesa and p -type contact is suitable for reliable high-power LEDs.

Acknowledgments: The authors gratefully acknowledge support by the National Science Foundation under the Smart Lighting Engineering Research Center, the Department of Energy, New York State, Sandia National Laboratories, Rochester Institute of Technology, Crystal IS Corporation, Samsung Electro-Mechanics Company, and Troy Research Corporation.

© The Institution of Engineering and Technology 2009
18 February 2009
doi: 10.1049/el.2009.0470

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