Analysis of reverse tunnelling current in GaInN light-emitting diodes

J. Cho, A. Mao, J.K. Kim, J.K. Son, Y. Park and E.F. Schubert

The characteristics of the reverse leakage current of GaInN/GaN multiple quantum well light-emitting diodes (LEDs) are examined with various *n*-type GaN doping concentrations and interpreted by using a tunnelling current model. Changing the doping concentration of the *n*-type GaN influences the tunnelling probability of electrons into the conduction band and thus the reverse leakage current. Reducing the doping concentration of the top 150 nm portion of the *n*-type GaN layer by half decreases the tunnelling probability, resulting in decrease of the reverse leakage current by 80% at −10 V without deterioration of any forward electrical properties of LEDs.

Introduction: Rapid improvements in the luminous efficiency of light-emitting diodes (LEDs) offer new applications for display and general illumination [1]. The requirement for long-term reliability under high power operation is one of the primary concerns when incorporating these LEDs into sophisticated optoelectronic systems. Therefore, understanding the characteristics of the reverse current of LEDs becomes more important, since it is believed that the degradation rate of LEDs is related to the reverse leakage current [2]. Even though the saturation current of diodes should not depend on reverse bias, the reverse current increases nearly exponentially with increasing applied voltage. The reverse leakage current can be attributed to diffusion, recombination, tunnelling, and, when illuminated, the photocurrent in the space-charge region. There have been also some studies on nitride-based LEDs that attributed the leakage current to a high threading defect density of the devices [3, 4], metal migration [5], and surface diffusion [6]. However, in the case of nitride-based LEDs, tunnelling of electrons into the conduction band is the most likely cause of reverse leakage current because the other mechanisms are small in magnitude owing to a wide bandgap of nitride-based LEDs and have rather weak voltage dependence. Nonetheless, the tunnelling phenomenon in GaInN/GaN LEDs has not fully been understood until now. In this Letter, we present the reverse leakage current from GaInN/GaN LEDs having different *n*-type GaN doping concentrations and the results are interpreted using a tunnelling current model [7]. By changing the *n*-type GaN doping concentration, the tunnelling probability is influenced and thus causes different reverse leakage current of LEDs.

Experimental method: The epitaxial LED wafers used in this study were grown on (0001) sapphire substrates using metal organic vapour phase epitaxy. The device structure shown in Fig. 1 consists of a 5 μm Si-doped *n*-type GaN layer ($n \sim 5 \times 10^{18}$ cm^{-3}), five pairs of GaInN/GaN MQWs, a 50 nm Mg-doped AlGaN cladding layer, and a 0.1 μm Mg-doped *p*-type GaN layer. The hole concentration of *p*-type GaN obtained by Hall measurement was about 5×10^{17} cm^{-3}. As shown in Fig. 1, sample A, the reference LED, has the top 150 nm portion of the *n*-type GaN layer with a doping concentration of 3×10^{18} cm^{-3}. Sample B has a lightly doped *n*-type GaN layer in the top 50 nm portion of the *n*-type GaN layer with a concentration of 1×10^{18} cm^{-3}, and sample C has the top 150 nm portion of the *n*-type GaN layer with a concentration of 1.5×10^{18} cm^{-3}. Lowering the doping concentration in the entire *n*-type GaN layer might cause an increase in the series resistance of the devices, so only those in the top portions of the *n*-type GaN layer, which are adjacent to the MQWs, were varied in our experiment. A standard LED fabrication process was used, i.e. the *p*-type GaN layer was partially etched to form mesas with an area of 450 × 450 μm^2 by using an inductively coupled plasma etching system after thermal activation of *p*-type GaN. Ti/Al and conductive ITO were deposited on the exposed *n*-type GaN, and the unetched *p*-type GaN surface for *n*-type and *p*-type ohmic contacts, respectively. Finally, a 0.2 μm-thick SiO$_2$ layer was deposited to protect the mesa sidewalls from unintentional leakage current. All of the LED samples had peak emission around 440 nm. Current-voltage (*I-V*) characteristics were measured using a four-point probe station combined with a parameter analyser (HP4155B) under ambient conditions in the dark. For the characteristics of the forward bias, the three samples show a similar *I-V* trend above the turn-on voltage of the LED. For example, the differences between the turn-on voltages are within 0.05 V and all three samples have almost identical series resistances.

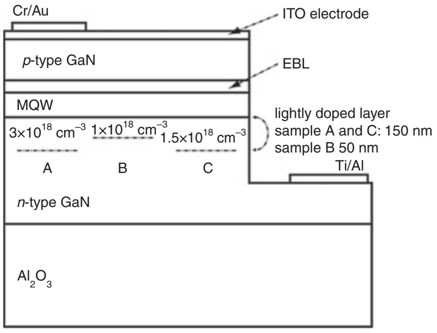

Fig. 1 *Schematic cross-section of GaInN/GaN light emitting diodes with distinctive features for samples A, B, C indicated*

Results: Fig. 2 shows typical reverse *I-V* characteristics for samples A, B, C. The reverse current gradually increases from picoamperes to microamperes as the bias is decreased from 0 to −10 V. Such large current variation with no apparent breakdown is not expected for the classical diffusion and generation-recombination current, but again may be attributed to tunnelling. For comparison, the reverse current is −50.5, −23.6, and −13.9 nA at a reverse voltage of −5 V for samples A, B, C, respectively. Moreover, for samples A and C, the reverse current of sample C becomes less than 20% of sample A when a bias voltage is decreased from −5 to −10 V. Since the epitaxial structures and fabrication processes are identical for all samples, except for the doping concentration in the top portion of the *n*-type GaN layer, the differences in reverse leakage current should be explained by the variance in the doping concentration in that layer.

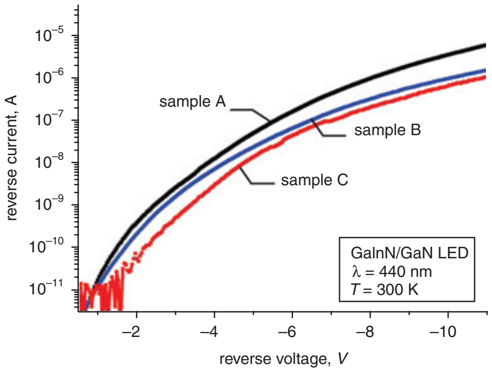

Fig. 2 *Reverse current-voltage characteristics for samples A, B, C at room temperature*

According to semiconductor *p-n* homojunction theory, the change in the tunnelling probability can be assumed with an electric field formed at the junction [7]. Specially, the change in depletion width (w_n and w_p) can be simply calculated from doping concentration of the *p*-type and the *n*-type semiconductor and built-in voltage [1]. For 3×10^{18} cm^{-3} of the *n*-type doping concentration and 5×10^{17} cm^{-3} of the *p*-type doping concentration for sample A, w_n and w_p are about 12.5 and 74.8 nm, respectively. The large discontinuity between the doping concentrations of the *n*-type and the *p*-type semiconductors results in an unbalanced depletion region and the narrow width declined to the *n*-type semiconductors. By reducing the concentration of the *n*-type GaN layer to half (sample C), w_n increases to 23.3 nm, almost the double value, and the total depletion width also increases from 87.3 to 93.1 nm. The increase in depletion width can weaken the internal electric field and also decrease the tunnelling probability of diodes, which appeared as a decrease of the reverse current. By comparing sample C with sample B, further decrease in the concentration from 1.5×10^{18} cm^{-3} to 1×10^{18} cm^{-3} does not result in additional increase of the tunnelling barrier. The reason is that the low-doped thickness for sample B might be too thin to cover the whole depletion width, w_n, and so the underlying layer, which has a high doping concentration

(5×10^{18} cm^{-3}), contributes to the formation of a high electric field in the junction.

To investigate quantitatively the reverse leakage current in our LEDs, the reverse *I-V* curves are analysed with (1), which is from the reverse-current tunnelling model for direct-gap semiconductors [8]:

$$I_{rev}(V) = a\,(V + V_b)^{3/2} \exp\,[b/(V + V_b)^{1/2}] \qquad (1)$$

where a, b, and V_b are fitting parameters. In Fig. 3, the fitted *I-V* curve (solid darker line) is shown along with the measured ones. It is remarkable that the entire curve can be very well approximated by a single set of parameters, especially for samples B and C. Extracted V_b for the three different LEDs shows a gradual increase from 1.4×10^{-4} of sample A to 0.72 and 1.37 of samples B and C, respectively. It is notable that V_b is inversely proportional to the reverse current in the LEDs. Although the value of V_b does not represent directly the physical energy barrier, it shows relative difficulty for the tunnelling of electrons into the conduction band.

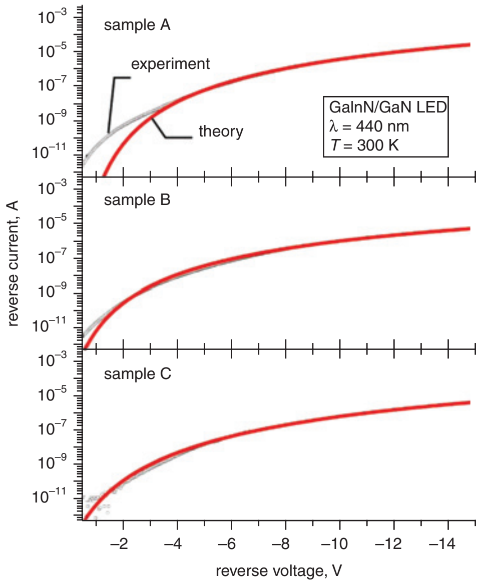

Fig. 3 *Reverse current-voltage characteristics and fitted solid line obtained from tunnelling current model applied to samples A, B, C*

It is meaningful to mention how the reverse current can be reduced in the LED structure from the viewpoint of the tunnelling probability. First, control of the doping concentration and control of band barrier height near the junction are effective methods. Another possible approach is to reduce the internal electric field induced by the spontaneous and the piezoelectric polarisation of nitride semiconductors. The polarisation-matched epitaxial structure [9] might be a good candidate and show improved electrical properties of the reverse leakage current.

Conclusion: The reverse leakage characteristics in nitride-based GaInN LEDs are analysed using a tunnelling current model. The experimental results show good agreement with the theoretical predictions for the change in the tunnelling probability caused by a change in the doping concentration of the *n*-type GaN layer. Approaches to reduce reverse leakage current are suggested and we especially note that the reduction of the internal field will be important for highly reliable devices at high power operation.

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