

# Analysis of Forward Tunnelling Current in GaN-based Blue LEDs

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**Abstract**—We present a systematic analysis of the forward tunnelling current in GaN-based blue light-emitting diodes by using the current-voltage ( $I$ - $V$ ) measurements from 100 K to 300 K. The semi-log forward  $I$ - $V$  curves in the above temperature range exhibit typical features of defect-assisted tunnelling mechanism, such as the temperature independent current slope and an ideality factor larger than 2. Exponential bias- and temperature-dependent characteristics of the tunnelling current have been observed, which are due to the bias-induced route change of the diagonal tunnelling and thermally-induced band gap shrinkage effect in the GaN materials, respectively.

**Keywords**- forward tunnelling current; GaN-based light-emitting diodes; defect-assisted tunnelling

## I. INTRODUCTION

The leakage current is one of the major factors that limit the electrical and optical performance of the GaN-based light-emitting diodes (LEDs), which can severely degrade the reliability and light emission efficiency of devices [1]. However, conventional GaN-based LEDs grown on foreign substrates usually suffer from the leakage current several orders of magnitude higher than the theoretical prediction based on the band gap of GaN. The excess leakage has been attributed to high density electrically active threading dislocations through the films, formed during the epitaxially growing process, which can provide additional pathways for excess electrons [2]. Previous studies on GaN-based LEDs usually focused on the leakage current in the reverse direction [3], while the forward current characteristics is seldom analyzed, which is nevertheless equally important and should be reduced considerably for practical applications of these devices. In this work, we study the forward tunnelling current in GaN-based blue LEDs by using the temperature-variable current-voltage ( $I$ - $V$ ) measurements, revealing the underlying physics of the bias- and temperature-dependence of the forward tunnelling current.

## II. EXPERIMENTAL

Samples used studied in this study work has have an InGaN/GaN multi-quantum-well (MQWs) structure grown on the  $c$ -plane sapphire substrates using by metal-organic chemical vapor deposition (MOCVD). The epistucture consists of a 2  $\mu\text{m}$  GaN:Si n-contact layer ( $N_D \sim 3\text{--}5 \times 10^{18} \text{ cm}^{-3}$ ), a ten-period of 3 nm undoped  $\text{In}_{0.2}\text{Ga}_{0.8}\text{N}$  and 7 nm GaN:Si MQW layers, a 70 nm p-AlGaIn electron blocking

layer (EBL) and a 0.2  $\mu\text{m}$  GaN:Mg ( $N_A > 1 \times 10^{19} \text{ cm}^{-3}$ ) p-contact layer. The LED chips having a mesa size of  $300 \times 300 \mu\text{m}^2$  were are fabricated using the standard photolithography and dry etching processes. Annealed Ti/Al/Ti/Au and Ni/Au (2.5 nm/2.5 nm) multi-layers deposited by e-beam evaporation were are employed as ohmic contact and semitransparent p-contact, respectively. The peak emission wavelength of the LEDs is about 466 nm with a full-width-at-half-maximum (FWHM) of 36 nm at 1 mA. The electrical characteristics of the LEDs were are measured by using the semiconductor parameter analyzer (Model Agilent 4156C). The constant temperature environments are obtained in a Lakeshore low-temperature probe station, which is stabilized within 0.05 K by using a temperature controller.

## III. RESULTS AND DISCUSSION

The forward  $I$ - $V$  curves measured from 100 K to 300 K are shown in Fig. 1. For low and medium biases, two close-to-linear segments with different slopes can be observed, indicating an exponentially dependent  $I$ - $V$  relationship. The corresponding current slopes are almost insensitive to the temperature, which can not be simply described by the traditional Shockley's equation, implying a non-diffusion recombination regime dominated in the diodes. In this case, the  $I$ - $V$  characteristics can be expressed by [4]

$$I = I_0 \exp\left(\frac{qV}{E_T}\right), \quad (1)$$

where  $I_0$  is the pre-exponential factor,  $E_T$  is the characteristic energy representing the transparency of related energy barrier, and  $q$  is the electron charge. In general, the  $I$ - $V$  characteristics of a p-n junction can be empirically expressed as  $I = I_0 \exp(qV/nkT)$ , where  $k$  is Boltzmann constant, and  $n$  is the ideality factor. The value of  $n$  can reflect the current transport mechanism in a diode. If  $n$  is between 1 and 2, the current flow is mainly in the diffusion-recombination regime, while if  $n$  is much larger than 2, the current should be dominated by the tunnelling mechanism. Consequently, by assuming  $E_T = nkT$ , the dominant carrier transport mechanism can be judged by the extracted value of  $n$ .

The values of  $E_{T1}$ ,  $E_{T2}$ ,  $n_1$  and  $n_2$  extracted at different temperatures are shown in Fig. 2. Both  $E_{T1}$  ( $\sim 120 \text{ meV}$ ) and  $E_{T2}$  ( $\sim 50 \text{ meV}$ ) are insensitive to the temperature, while  $n_1$  decreases continuously from 12.8 to 4.7, and  $n_2$  decreases from 6.2 to 1.9 with temperature increasing from 100 K to 300 K, respectively. A temperature independent  $E_T$ , an ideality factors larger than 2, and the exponential bias-

dependent relationship are the characteristics of a defect-assisted tunnelling current in a defective p-n junction. Therefore, the forward current of the diodes in low- and medium-bias regions should be governed by a defect-assisted tunnelling mechanism. At about 200 K  $n_2$  approaches 2, and decreases further with increasing temperature, suggesting that at high temperatures the current is dominated by diffusion and recombination processes. At higher injection current level ( $>10^{-3}$  A), the measured  $I$ - $V$  curves bend due to an increasing voltage drop on the series resistance of the diode as a function of the bias.

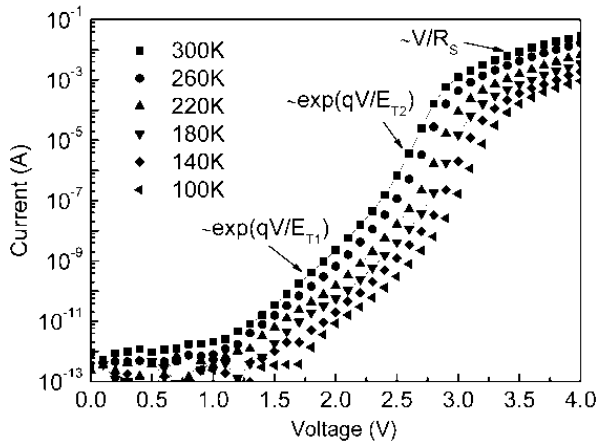


Figure 1.  $I$ - $V$  characteristics of a typical InGaN/GaN-MQW-based LED grown on sapphire.

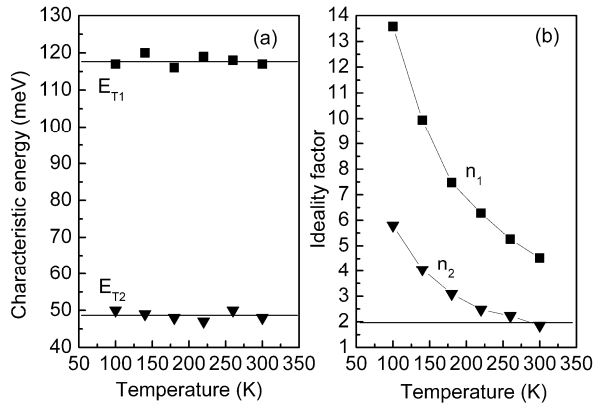


Figure 2. The extracted characteristic energy  $E_T$  and ideality factor  $n$  as a function of the temperature.

However, the expression of (1) does not explicitly reflect the physical nature of the bias- and temperature-dependent characteristics of the tunnelling current. It is most likely that, the defect-assisted tunnelling current arises from a complex multiple-step tunnelling process, similar to that occurred in a heavily doped Esaki pn junction[5]. If the concentration of the intermediate electrical active states in the band gap of the space charge region is sufficiently high, many electrons from the conduction band are able to “diagonally” tunnel down to

the valence band following a staircase route, and during that, the excess vertical energy was released. Since there exists a high-density of electrical active defect states extensively distributed in the band gap of (In)GaN, such a process could take place in the LEDs. The corresponding transport process was shown in Fig. 3, where an electron (hole) tunnels diagonally from the conduction (valence) band of n(p)-type side to the valence (conduction) band of p(n)-type side via intermediate defect states in the band gap of InGaN/GaN MQWs. For the case, the form of ET can be written as [4]

$$E_T \approx \frac{4eh}{\pi} \sqrt{\frac{N_I}{m^* \epsilon_r \epsilon_0}}, \quad (2)$$

where  $m^*$  is the tunnelling effective mass of specific type of carriers [6], and  $N_I$  is the reduced doping level at the SCR edge,  $\sim 2.5 \times 10^{17} \text{ cm}^{-3}$  determined by capacitance-voltage measurements. Physically,  $N_I$  links to the width of space charge region, which should be weakly dependent on temperature due to the deep-dopant effect of III-nitride semiconductors. Substituting  $N_I$ , the effective masses of electrons and heavy holes ( $0.2m_0$  and  $1.4m_0$ , respectively) [7], into (2), we can reproduce the experimental values of  $E_{T1}=110$  and  $E_{T2}=43.2$  meV, respectively. This means that, the low-bias voltage current component for  $E_{T1}$  can be explained by electrons tunnelling, while the medium-bias voltage current component for  $E_{T2}$  can be attributed to heavy holes tunnelling (see Fig. 3).

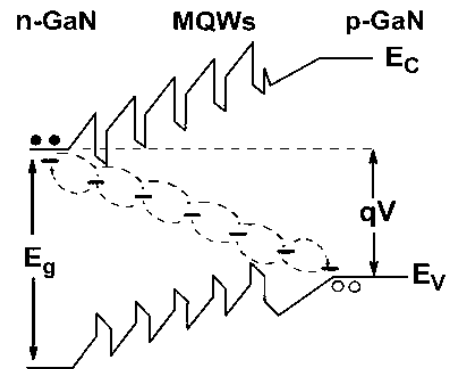


Figure 3. Schematic illustration of the proposed diagonal tunnelling process. The red solid dots represent electrons while the green open dots represent holes in GaN, respectively.

Then, it can be inferred from (1) that, the impacts of temperature on the forward tunnelling current could be included in the  $I_0$  term, which is balanced by the defect-assisted tunnelling current at extremely low forward bias. Due to the heavy doping levels at the n- and p-side of the LEDs, the built-in potential  $V_{bi}$  across the junction should be close to the band gap of GaN with zero bias voltage. Therefore, an electron could tunnel from the conduction band of n-side toward the valence band or acceptor impurity band of p-side almost horizontally, via the interface states distributed in the SCR with a negligible vertical energy loss.

This means that a horizontal tunnelling model is preferred to describing  $I_0$ ,

$$I_0 \propto P = \exp\left(-\frac{\alpha \varepsilon^{3/2}}{E}\right) \quad (3)$$

where  $\alpha = 8\pi(2m^*)^{1/2}/3eh$ ,  $h$  is the Planck's constant,  $\varepsilon$  is the tunnelling barrier, and  $E \approx E_g/eW$  is the effective electrical field,  $W \approx (2\varepsilon_0\varepsilon/e^2N_I)^{1/2}$  is the SCR width. Substituting  $E$  and  $\varepsilon \approx E_g$  into (3) gives the following tunnelling probability,  $P_0 \propto \exp(-\beta E_g)$ , where  $\beta = (8\pi/3h)(m^*\varepsilon_0/N_I)^{1/2}$ , indicating that the effect of temperature on the forward tunnelling current can be traced down to the thermally induced band gap shrinkage effect of GaN material, which would reduce both width and height of the tunnelling barrier.

From the above analysis, the bias- and temperature-dependent characteristics of the forward tunnelling current can be written as

$$I \propto \exp(-\beta E_g + \lambda V), \quad (4)$$

where  $\lambda = 1/E_T$ . This equation explicitly attributes the bias-induced route change of diagonal defect-assisted tunnelling and thermal induced band gap shrinkage effect as the primary causes for the bias and temperature dependent relationship regulated by two parameters  $\beta$  and  $\lambda$ , and predicts a constant ratio value of  $\beta/\lambda \sim 10.667$ , disregarding the bias condition, which can be deduced without knowing the exact value of  $m^*$  and  $N_I$ .

Fig. 4(a) and 4(b) show the experimentally measured tunnelling current versus band gap of GaN at different temperatures for the low- and medium-bias regions, respectively, where  $E_g$  was determined by  $E_g = 3.47 - (7.7 \times 10^{-4})T^2/(T+600)$  [6]. As can be seen, these data points could be nicely linearly fitted, and the corresponding lines appear to be parallel to each other, indicating constant value of  $\beta$  at different biases. Note that, only the data points below 200 K were fitted in the medium-bias region, because the diffusion-recombination mechanism gradually becomes dominant at higher temperatures. From the extracted slopes of the fitted lines, as shown in Figs. 4(a) and 4(b), the experimental  $\beta$  can be determined to be  $\sim 94$  and  $229.6 \text{ eV}^{-1}$ , respectively [here  $\beta = \ln(I_1/I_2)/\Delta E_g = 2.3 \times \log_{10}(I_1/I_2)/\Delta E_g$ , where subscripts 1 and 2 refer to data points at two different temperatures at a fixed bias]. Meanwhile, as the reciprocal of  $E_T$ , the values of  $\lambda$  for the low- and medium-bias region can be determined  $\sim 8.33$  and  $20 \text{ eV}^{-1}$ , respectively. Then, it allows us to obtain the experimental ratio of  $\beta/\lambda$  for  $E_{T1}$  and  $E_{T2}$ , which are calculated to be about 11, in consistent well with the theoretical result of 10.667, demonstrating the validity of (3).

Finally, a deeper question left here is: why does the forward tunnelling current of the GaN LED studied exhibit two bias regions with different characteristic energies of  $E_{T1}$  and  $E_{T2}$ ? A careful examination of (2) indicates that the evolution of  $E_T$  should be caused by a change in the effective mass  $m^*$  of tunnelling carriers as other parameters in (2) are constant in a given device. That is, the dominant tunnelling entities at low- and medium-bias regions are different. By taking the ratio of  $E_T$  in low- and medium-bias regions and comparing it to (2), one can obtain  $E_{T1}/E_{T2} = (m_2^*/m_1^*)$ , which associates the ratio of characteristic energies with the effective masses of the tunnelling entities. In GaN the

effective masses  $m^*$  for electrons, light holes, and heavy holes are  $0.2m_0$ ,  $0.3m_0$ , and  $1.4m_0$ , respectively. Substituting the experimental values of  $E_{T1}$  and  $E_{T2}$  into  $E_{T1}/E_{T2}$  yields  $\sim 2.4$ , which appears consistent with the ratio of the square root of the effective masses for heavy holes and electrons ( $\sim 2.65$ ). Thus, the tunnelling current in low-bias region might be dominated by electron tunnelling via intermediate states while heavy hole tunnelling prevails in medium-bias region. Similar suggestion has been made by Reynolds and Patel when studying GaN LEDs grown on sapphire substrates. As for why the tunnelling entities change from electrons to heavy holes with increasing bias, the underlying mechanism is still under investigation, which should be closely related to the layer structure and defect distribution within the LED.

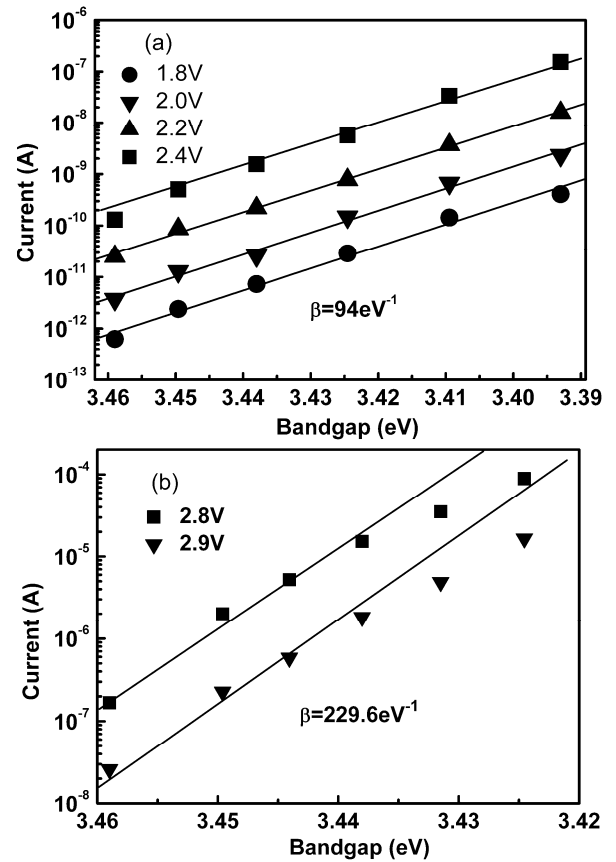


Figure 4. Temperature and band gap dependence of forward tunnelling current at different voltages: (a) for  $E_{T1}$  bias region and (b) for  $E_{T2}$  bias region.

For example, as Cao et al. reported, the forward tunnelling current (both electrons and holes) can be significantly suppressed when fabricating GaN-based LEDs on low-defect-density bulk GaN substrate [8]. Besides the special defect distribution in SCR of the LED which is still unknown in this study, another possible explanation is that the tunnelling barriers for electrons and holes across the LED junction are not symmetric due to the existence of

polarization field and the AlGa<sub>N</sub> electron blocking layer. Then the external electrical field should modify the tunnelling barriers for electrons and holes by a different degree, so that the current component with a heavy tunnelling mass could rise more rapidly with increasing bias due to its much larger reduced tunnelling barrier. In addition, this argument also suggests that depending on specific device structures, the dominant heavy hole tunnelling as revealed in this study might not happen or be apparent in the transport process of some GaN-based LEDs.

#### IV. SUMMARY

Forward tunnelling current in GaN-based blue LEDs grown on sapphire substrate was studied. It is identified that the current flow at the low- and medium- bias regions is dominated by defect-assisted tunnelling mechanism. We attribute the bias- and temperature-dependent characteristics of the forward tunnelling current to the bias-induced route change of diagonal tunnelling and thermally induced band gap shrinkage effect.

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