

The origin of the high diode-ideality factors in GaInN/GaN multiple quantum well light-emitting diodes

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We report on a significant decrease in the diode-ideality factor of GaInN/GaN multiple quantum well light-emitting diodes (LEDs), from 5.5 to 2.4, as Si-doping is applied to an increasing number of quantum barriers (QBs). The minimum ideality factor of 2.4 is obtained when all QBs are doped. It is shown that polarization-induced triangular band profiles of the undoped QBs are the major cause of the high ideality factors in GaInN/GaN LEDs. Numerical simulations show excellent agreement with the measured ideality factor value and its dependence on QB doping. © 2009 American Institute of Physics. [DOI: 10.1063/1.3089687]

In recent years, great progress has been made in developing high-efficiency, high-power GaN-based ultraviolet¹ and blue² light-emitting diodes (LEDs). In order to further improve the device performance, a number of material- and device-related problems must be resolved. As one of the commonly used parameters, the diode-ideality factor is directly related to carrier transport, recombination, and resistivity. A high diode-ideality factor results in a high forward voltage, and thus limits the power efficiency. However, it is well known that III-N-based *p-n* junctions with multiple quantum wells (MQWs) can have abnormally high diode-ideality factors ($n_{\text{ideality}} \approx 5 \sim 7$).³⁻⁸ This phenomenon has been a scientific “puzzle” for more than a decade, and the physical origin has not yet been fully identified.

Ideality factors between 1.0 and 2.0 are normally attributed to the competition between the carrier drift-diffusion process and the Sah–Noyce–Shockley generation-recombination process.⁹ Ideality factors exceeding 2.0 have been suggested to originate from the trap-assisted tunneling⁴⁻⁷ and carrier leakage.⁷ However, no quantitative attempts have been reported to connect these two mechanisms to the abnormally high ideality factors found experimentally in GaN-based LEDs.

Shah *et al.*³ proposed that GaN-based LEDs can be modeled as a series of rectifying unipolar heterojunctions and metal-semiconductor junctions, each having an associated ideality factor. The Shockley diode equation for $V > 3kT/q$ can then be rewritten as the summation of voltages dropping across individual rectifying junctions denoted by the subscript i .³

$$V = \sum_i V_i = \frac{kT}{q} \sum_i [n_{\text{ideality},i} (\ln I - \ln I_{S,i})], \quad (1)$$

where I_S is the reverse saturation current, q is the elementary charge, k is the Boltzmann constant, T is the absolute temperature, and n_{ideality} is the ideality factor. This dependence reveals that the ideality factors of individual rectifying junctions

add up to the total device ideality factor as $n_{\text{ideality}} = \sum_i n_{\text{ideality},i}$ which can lead to a high ideality factor of 5–7 when the *p-n* junction of the diode, a non-Ohmic metal-semiconductor junction and other rectifying junctions are considered. Shah *et al.*³ measured the ideality factor of a GaN-based *p-n* diode and a GaN-based *p-n* diode having a *p*-type AlGaIn/GaN superlattice on top of the *p-n* junction, and showed that the ideality factor decreases with the improved Ohmic behavior of metal-to-*p*-type-semiconductor contact. In this letter, we expand these considerations to the MQW active region of the LED and investigate the impact of unipolar heterojunctions formed in the MQW active region on the ideality factor. We report experimental results on the ideality factor of GaInN/GaN blue LEDs emitting at $\lambda = 450$ nm with a controlled number of doped QBs, and show that the high ideality factor is primarily caused by the GaN heterojunction QBs in the MQW active region.

Four GaInN/GaN MQW LEDs, each comprising five Ga_{0.85}In_{0.15}N QWs, were grown on sapphire substrates using metal-organic vapor-phase epitaxy. (0002) x-ray diffraction scans and dynamic diffraction fits were performed to obtain the QW and QB thicknesses and the QW In composition. The MQW consists of 2.5-nm-thick GaInN QWs and 8.2-nm-thick GaN QBs followed by a 20–30-nm-thick GaN spacer layer, an AlGaIn electron-blocking layer (EBL), and a *p*-type GaN cladding layer. The four LED heterostructures are distinguished by the number of QBs that are intentionally Si-doped, and we employ doping in 1, 2, 3, and 4 of the QBs, as depicted in the inset of Fig. 1(a). A barrier-doping level of $n \approx 3 \times 10^{18} \text{ cm}^{-3}$ is determined by the Hall-effect measurements of the thick reference GaN layers grown under the same conditions as the doped QBs. The four LED heterostructures are fabricated into $300 \times 300 \mu\text{m}^2$ LED devices and characterized in terms of their electrical characteristics.

The *I-V* characteristics of the LEDs are measured using a semiconductor parameter analyzer. A dependence of voltage V on injection current I from 0.01 to 10 mA is measured and displayed using a logarithmic current scale for the four LED structures as shown on the left-hand side in Fig. 1. The corresponding ideality factors are shown on the right-hand

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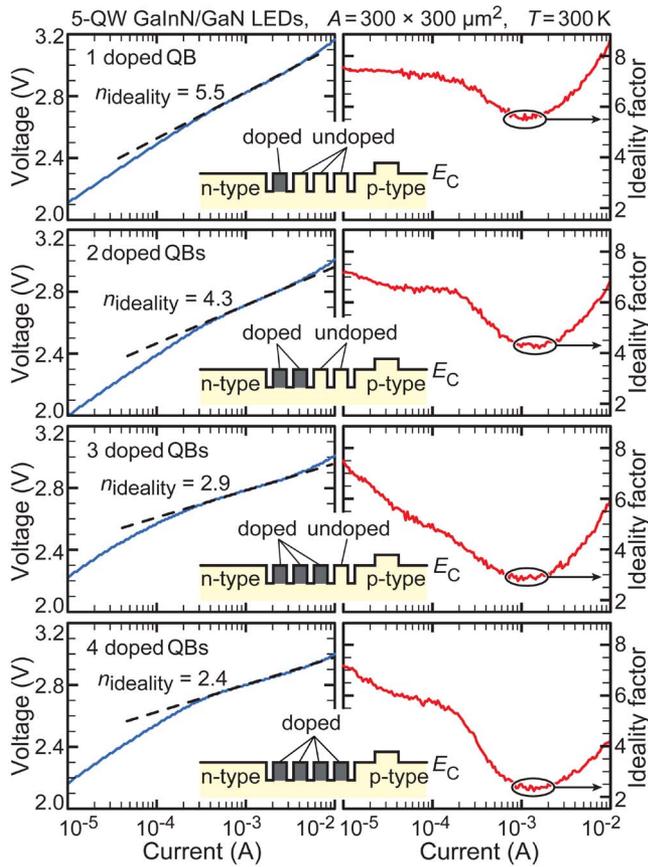


FIG. 1. (Color online) Left: semilogarithmic plot of the I - V characteristics of GaInN/GaN LEDs; Right: diode-ideality factor vs current for the LEDs. Ten data points around the minimum n_{ideality} value are used to determine the average n_{ideality} value and its standard deviation.

side in Fig. 1 and are inferred from the measurement using

$$n_{\text{ideality}} = \frac{q}{kT} \left(\frac{\partial \ln I}{\partial V} \right)^{-1}. \quad (2)$$

The measured ideality factor n_{ideality} depends on the junction current. There are generally three current ranges as can be seen from the right-hand results in Fig. 1. The ideality factor in the low current range is very high due to a shunt resistance R_{shunt} and decreases as the current increases. In the high current range, the series resistance R_{series} dominates and results in an increase in the ideality factor with increasing current. Both the R_{shunt} and R_{series} cause a significant deviation from the rectifying behavior of an ideal diode.¹⁰ The intermediate range, with a current level around 1 mA, is where the space charge region dominates the device I - V characteristics. Here, the I - V characteristic follows an exponential relation and has a local minimum value of the measured ideality factor (see right-hand side of Fig. 1). Therefore, the ideality factor is valid only in the linear region of the V versus $\ln I$ plot (dashed line on the left-hand side of Fig. 1), which corresponds to the minimum value of n_{ideality} .

The measured diode ideality factor is 5.5 for the one-QB-doped LED and decreases linearly as the number of doped QBs increases to a value as low as 2.4 for the all-QB-doped LED. This clear correlation indicates that the physical origin of the high ideality factors lies in the GaN QBs within the active region. In order to further investigate the mechanism responsible for the decrease in ideality factor, numeri-

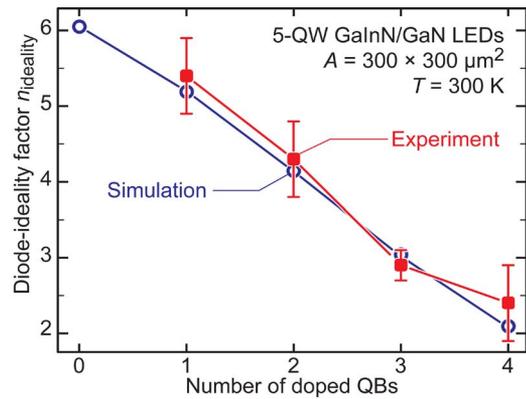


FIG. 2. (Color online) Calculated and simulated diode-ideality factors of GaInN/GaN LEDs as a function of the number of doped QBs. Measured structures have one to four QBs and simulated structures have zero to four QBs.

cal simulations of these LED structures with different numbers of doped QBs are performed using the APSYS modeling software. The actual geometry of the devices and commonly accepted material parameters^{11,12} are used in the simulations, including a Shockley-Read recombination lifetime of 1 ns in the EBL and p -type GaN, and spontaneous and piezoelectric polarization sheet-charge-carrier densities of 7.53×10^{12} and $2.75 \times 10^{12} \text{ cm}^{-2}$ at the GaInN/GaN and the GaN/EBL interfaces, respectively, which correspond to 50% of the theoretical prediction from Bernardini *et al.*¹³ and Bernardini.¹⁴

Figure 2 shows the measured and simulated ideality factors as a function of the number of doped QBs in the active region. Both the simulated and the measured ideality factors decrease with increasing number of doped QBs and they show excellent agreement.

Figure 3 plots the simulated band diagram of these structures under 3 V forward bias which corresponds to a current of about 1 mA. We see that the QBs in the conduction band show a large upward slope from the n -side of the device due to the spontaneous and piezoelectric polarization sheet charges at the interfaces.¹⁵ Each triangular QB functions like a forward-biased Schottky diode, impeding carrier transport and contributing a certain ideality factor. Thus, as an ex-

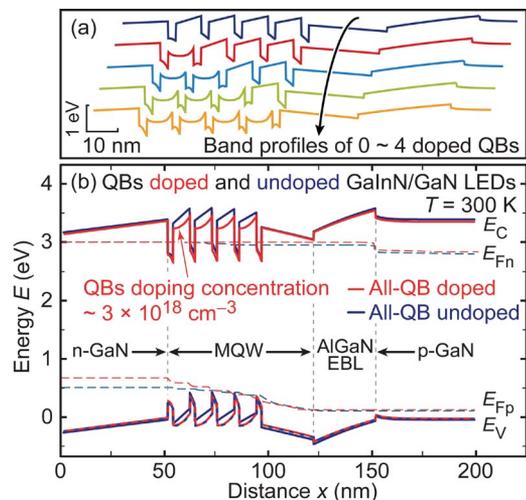


FIG. 3. (Color online) (a) Band profiles of GaInN/GaN LEDs for the different numbers of doped QBs. (b) Simulated band diagram of GaInN/GaN LEDs with all-QB-doped and zero-QB-doped under 3 V forward bias.

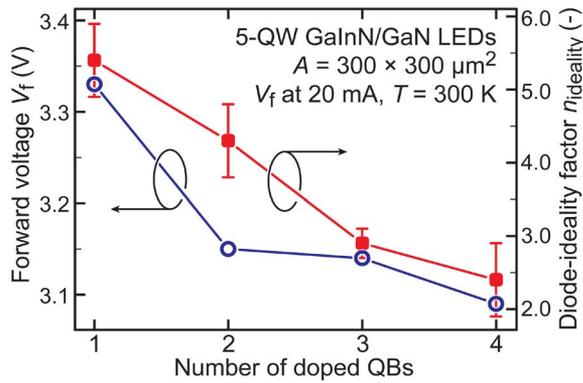


FIG. 4. (Color online) Correlation between diode-ideality factor and forward voltage of GaInN/GaN LEDs for the different numbers of doped QBs.

ample, three undoped QBs each having an ideality factor of $n_{ideality}$ together generate an ideality factor of $3n_{ideality}$. As a result of n -type doping in the QBs, significant barrier band-bending and barrier-height lowering are caused by ionized donors. Electrons can more easily overcome the doped QBs, such that the carrier transport through the doped QBs does not significantly contribute to the ideality factor. Therefore, the ideality factor of 2.4 for the all-QB-doped structure presumably comes mainly from the p - n junction diode. Note that the ideality factor is decreased by about 3 as the number of doped QBs increases from 1 to 4, consistent with the above explanation.

We further investigate the correlation between device forward voltage V_f and the ideality factor $n_{ideality}$ by comparing V_f at 20 mA for the four LEDs. As shown in Fig. 4, V_f decreases as the number of doped QBs increases. This observation is consistent with the dopant-induced lowering of the barrier height and improved current flow across the QB. Therefore, a clear dependence of both the ideality factor and the forward voltage on the number of doped QBs is established. The significant correlation between the ideality factor and the number of doped QBs indicates that heterojunctions in the MQW active region are the primary cause for the high ideality factor in the GaN-based MQW LEDs. QB doping, which changes the rectifying nature of the QBs, proves to be an effective way to reduce the high ideality factor. The correlation between V_f and $n_{ideality}$ verifies that low ideality factor generally results in a reduced forward voltage.

In conclusion, we have systematically investigated the ideality factors of four GaInN/GaN MQW LED structures with different numbers of doped QBs. Consistent with theory, a decrease in the ideality factor as well as a reduction in forward voltage is found with increasing number of doped

QB and is confirmed through simulation. The lowest ideality factor is found in the all-QB-doped MQW structure. These measurements indicate that the band profiles of QBs in the active region have a significant impact on the carrier transport mechanism, and the unipolar heterojunctions inside the active region play a major role in determining the ideality factor.

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