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Low Droop Nonpolar GaN/InGaN Light Emitting Diode Grown on *m*-Plane GaN Substrate

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The low droop nonpolar *m*-plane InGaN/GaN light emitting diode (LED) has been fabricated and investigated. The external quantum efficiency for a 300 × 300 μm square LED chip only drops about 18% from maximum at an operation current of 22 A/cm^2 (20 mA) to 330 A/cm^2 (300 mA) dc operations at room temperature. In addition, the internal quantum efficiency has been extracted by temperature-dependent photoluminescence measurements, and there is no droop observed as the carrier density increases. The small droop in efficiency of *m*-plane LEDs could be due to the lack of polarization effects that enhances the carrier confinement under high current density operation. The polarization anisotropy is clearly observed in the *m*-plane LED, and the degree of polarization is 68%.

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High efficiency light sources based on III-nitride light emitting diodes (LEDs) are required for the general illumination market, where the driving current of 1 A, corresponding to the current density of 100 A/cm^2 for a 1 mm^2 chip, is unavoidable to achieve high output power. However, for InGaN/GaN multiple-quantum-well (MQW) LEDs, a well-known fundamental problem needs to be overcome: the efficiency droop that describes the reduction in the external quantum efficiency (EQE) with the increased operation current density. Normally, the EQE of the InGaN MQW LED reaches its maximum at ~10 A/cm^2 and drops to half at ~100 A/cm^2. Many mechanisms have been suggested to account for the efficiency droop in InGaN LEDs.[1-5] To date, there still remains a debate about the main mechanism responsible for the significant efficiency drop at a high current in blue and green LEDs. Nonpolar GaN is one of the important approaches from preventing the efficiency droop that eliminates the quantum-confined Stark effect in the quantum wells (QWs).[6,7] In this study, we demonstrate a low droop nonpolar *m*-plane LED grown on the freestanding *m*-plane GaN substrate. For a 300 × 300 μm square LED chip, the EQE only drops about 18% from maximum at an operation current of 20–300 mA, corresponding to the current density of 330 A/cm^2. In addition, the electrical characteristics and polarization of the LED are presented and discussed.

The LEDs were grown by metallorganic chemical vapor deposition on freestanding bulk *m*-plane GaN substrates made by hydride vapor phase epitaxy. The exposed *m*-plane surface of these slices was prepared by chemical and mechanical surface treatment techniques. The threading dislocation density of the *m*-plane GaN substrate was less than 5×10^6 cm^2; the carrier concentration was about 1×10^{17} cm^3, and the root-mean-square value of the surface roughness was smaller than 1 nm. The growth conditions of the LEDs were very similar to those of the conventional *c*-plane LEDs. A GaN:Si layer was grown first on top of the substrate without a low temperature nucleation layer, followed by a four-period InGaN/GaN undoped QW active region. The X-ray diffraction ω/2θ measurement was performed to examine the well width and to identify the In composition. The thickness of the well and barrier were 2.5 and 10 nm, respectively, and the In composition was about 15% in the LED structure. After the active region was grown, a 20 nm thick p-AlGaN electron-blocking layer was grown on top of the last barrier, followed by a 200 nm thick p-GaN layer. An annealed SnO$_2$-doped In$_2$O$_3$ (indium tin oxide) p-type GaN contact was utilized as a transparent p-electrode. LED mesas were etched by reactive ion etching. Ti/Al/Ti/Au n-contacts were deposited by E-beam evaporation. The LED chip was diced into a 300 × 300 μm square with a planar type U-shaped n-contact. The n- and p-type GaN have no surface texturing for light extraction. The schematic of the LED structure is shown in Fig. 1.

The electrical and luminescence characteristics of the diode were measured by on-wafer probing of the devices, and the optical emission power was measured with a calibrated integrating sphere. All measurements were carried out under dc operations at room temperature. The dependence of power and EQE on the driving current density is shown in Fig. 2. The output power at 22 A/cm^2 was 2.4 mW, and the corresponding EQE was around 4.1%. Moreover, the output power was 29.6 mW, and the EQE was 3.3% at 330 A/cm^2. The inset in Fig. 2 shows the current–voltage (*I-V*) characteristic under the forward bias, and the forward voltage at 20 mA is about 4.24 V. The output power increased linearly as the current density increased, and a good linearity of the output power with increasing driving current density of up to about 330 A/cm^2 was obtained. The power rollover characteristic was not observed in our *m*-plane GaN LED. The EQE first increased as the increasing current density until the maximum value of 4.1% at 22 A/cm^2. The EQE appears to be constant during 22–66 A/cm^2 and shows a monotonous decrease to 3.3% at 330 A/cm^2. The EQE only drops about 18% from 22 to

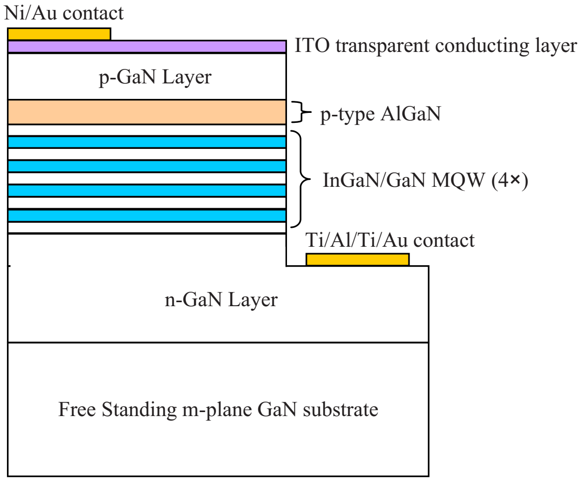

Figure 1. (Color online) Schematic cross section of the nonpolar *m*-plane InGaN/GaN LED structure.

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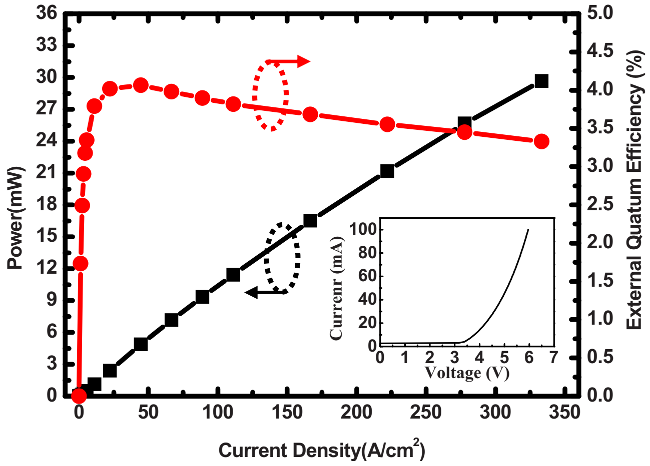

Figure 2. (Color online) The on-wafer optical output power and the EQE of the nonpolar *m*-plane LED vs the driving current. Inset shows *I*-*V* characteristic of the nonpolar *m*-plane LED.

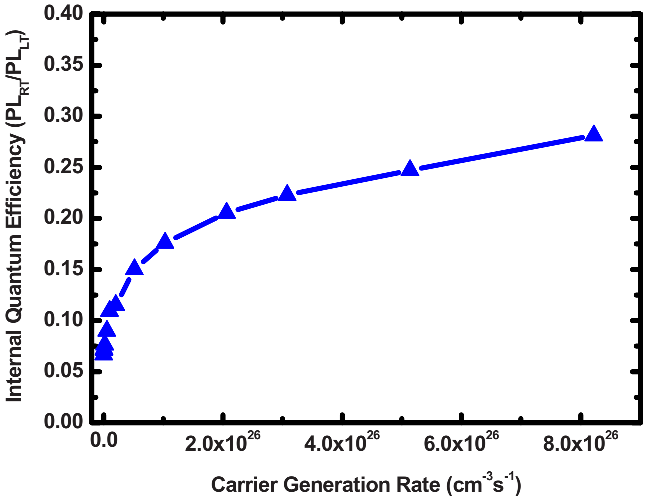

Figure 3. (Color online) The IQE of nonpolar *m*-LED vs carrier generation rate.

330 A/cm^2. It does not show a significant decrease in efficiency as seen in the typical *c*-plane LEDs operating at such a high current density,[4] showing the potential for high current operation for optical devices.

The temperature-dependent photoluminescence (PL) measurements with varying excitation power are performed to determine the radiative efficiency of *m*-plane LEDs. The excitation wavelength from the frequency doubled Ti:sapphire laser was set to 395 nm to generate electron–hole pairs only within the QWs. Figure 3 shows the dependence of the internal quantum efficiency (IQE) under a different excitation intensity. The IQE had been extracted out by dividing the PL integration intensity at room temperature by that at low temperature under various excitation densities where the IQE at low temperature (e.g., 15 K, in our case) was assumed to be 100%.[4,5] The carrier generation rates given in Fig. 3 correspond to an incident optical power density of 0.001–4.11 kW/cm^2. The IQE corresponding to the EQE maximum is about 18.5%, and there is no droop behavior observed. This could be due to the lack of polarization effects, which enhances the carrier confinement under high current density operation.[4,5]

In Fig. 4a, the electroluminescence (EL) spectra of the *m*-plane LED was measured for the dc driving current density ranging from 1.1 to 330 A/cm^2, and the emission peak and full width at half-maxima (fwhm) of EL are shown in Fig. 4b. The emission peak remains constant before suffering from excess heat at high current operation, indicating the absence of the polarization-induced electric fields in the *m*-plane QWs. The initial blueshift in the emission peak for driving current from 1.1 to 11 A/cm^2, also observed in other nonpolar InGaN/GaN LEDs, can be attributed to the band-filling of the localized states induced by alloy fluctuation in the InGaN QWs.[8] This may also originate from the variation in the In-incorporation efficiency due to the presence of inclined planes and defects, as is the case of *a*-plane InGaN QWs,[9] which was observed in the emission spectrum with a larger fwhm below 11 A/cm^2, as shown in Fig. 4. In the region from 22 to 165 A/cm^2, the emission peak remains the same. The peak wavelength starts to redshift, and the linewidth broadens when the current density is higher than 165 A/cm^2, as shown in Fig. 4. This could be attributed from the excess heat generated from the power dissipation that caused the obvious thermal effect and started to influence the recombination process.[10] The redshift of the peak wavelength from 165 to 330 A/cm^2 is about 3 nm, and the corresponding broadening of the spectrum width is about 2 nm. These small variations in the peak shift, spectral width broadening, and efficiency droop even under a high current density room temperature dc operations are comparable or better than the state-of-the-art *c*-plane LEDs operated at a pulsed condition.[11] One of the reasons comes from the good thermal conductivity of the GaN substrate compared to the sapphire substrate, which can also be responsible for the rapid transfer of heat out of the active regions. However, the intrinsic characteristics of nonpolar QW structures may play an important role. With the less polarization effects in the nonpolar QW structures, the holes can distribute more equally in MQWs due to the less negative polarization-induced sheet charge located at the bottom of the QW. This can effectively reduce the Auger recombination as the case in double heterostructure LEDs.[11] At the same time, less polarization could also effectively increase the potential height of the blocking layer to enhance

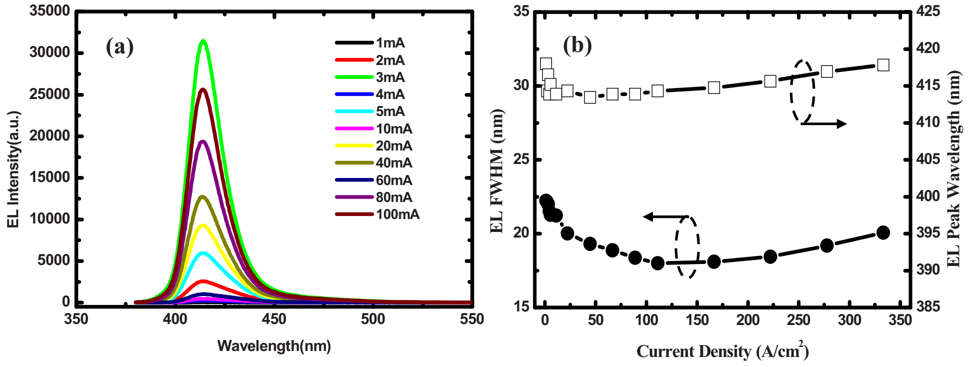

Figure 4. (Color online) (a) Room temperature EL spectra at different injection currents. (b) The peak wavelength and fwhm of EL spectra vs the driving current density.

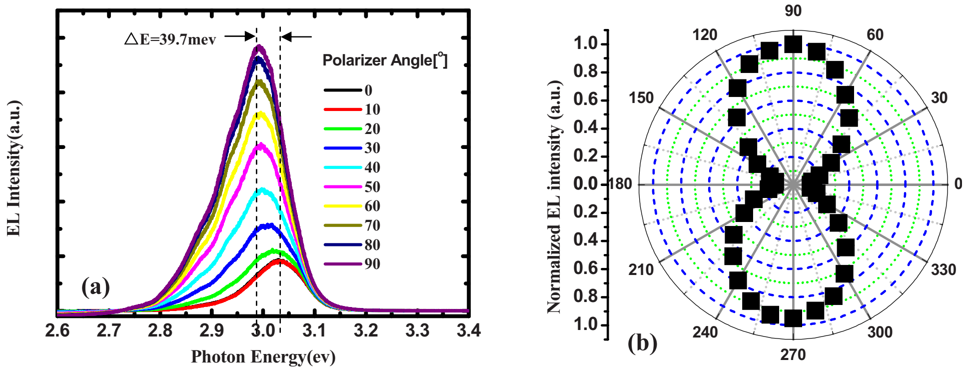

Figure 5. (Color online) (a) Room temperature EL spectra with different polarizer angle, the angle of 0° corresponds to a polarization parallel to *a*-axis. (b) Variation in EL intensity of peak wavelength with angular orientation of the polarizer at 20 mA operation current.

the carrier confinement, avoid the leakage current under high current operation,[4] and eliminate the heat generation from the nonradiative recombination.

The EL polarization anisotropy[12] was observed clearly in the *m*-plane LED, as shown in Fig. 5. The shift in the peak energy ΔE and the degree of polarization of the EL intensity of our device were analyzed by rotating a polarizer between the polarization angles 0 and 360°. In Fig. 5a, the ΔE is about 39.7 meV between the electric field perpendicular $(E\perp)$ to the *c*-axis component and parallel $(E\|)$ to the *c*-axis component. Our result is close to the theoretical calculation values reported by Kojima et al. using the $k \cdot p$ perturbation theory with similar active layer thickness and In composition.[13] The shift in the peak energy comes from the splitting of the valence bands caused by the in-plane compressive strain of the MQW, and the energy separation is proportional to the In composition of the active layer. Figure 5b shows the angular dependence of the polarization ratio under the operation current of 20 mA. The polarization ratio is defined as $\rho = (I\perp - I\|)/(I\perp + I\|)$, where $I\perp$ is the intensity of the $E\perp$ component and $I\|$ is the intensity of the $E\|$ component. In Fig. 5b, the degree of polarization was estimated to be about 68%, which was about 17% higher than the previous report by Koyama et al.[8] The degree of polarization in nonpolar LEDs gradually increases with a larger valance band splitting due to the higher In composition as well as higher compressive strain in the active material InGaN.[14] The large value of the degree of polarization in our *m*-plane LEDs could be contributed from the higher quality of InGaN epilayers in the MQW because the proper growth condition can prevent the InGaN from serious phase separation on the *m*-plane GaN surface and can result in higher compressive strain.

In conclusion, we have demonstrated low droop nonpolar m-plane LEDs grown on bulk *m*-plane GaN substrates and have investigated their EL characteristics. At 22 $\mathrm{A/cm^2}$ (20 mA) and 330 $\mathrm{A/cm^2}$ (300 mA) under dc operation, the output power and the EQE were 2.4 mW, 4.1% and 29.6 mW, 3.3%, respectively. The EQE only dropped about 18% from maximum at 22 $\mathrm{A/cm^2}$ to the operation current density of 330 $\mathrm{A/cm^2}$, and the broadening of the emission linewidth was only about 2 nm. In addition, no droop behavior was observed as increasing the carrier density in the temperature-dependent PL measurements. These results of low droop characteristics could be due to the lack of polarization effects that enhances the carrier confinement under a high current density operation. The EL polarization anisotropy was observed clearly in the *m*-plane LED and the degree of polarization was 68%. These results of low droop characteristics shall encourage the development of high performance and high efficiency nonpolar nitride-based semiconductors.

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