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Low efficiency droop in blue-green m-plane InGaN/GaN light emitting diodes

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We investigated the electroluminescence and relatively external quantum efficiency (EQE) of m-plane InGaN/GaN light emitting diodes (LEDs) emitting at 480 nm to elucidate the droop behaviors in nitride-based LEDs. With increasing the injection current density to 100 A/cm^2, the m-plane LEDs exhibit only 13% efficiency droop, whereas conventional c-plane LEDs suffer from efficiency droop at very low injection current density and the EQE of c-plane LEDs decrease to as little as 50% of its maximum value. Our simulation models show that in m-plane LEDs the absence of polarization fields manifest not only the hole distribution more uniform among the wells but also the reduction in electron overflow out of electron blocking layer. These results suggest that the nonuniform distribution of holes and electron leakage current due to strong polarization fields are responsible for the relatively significant efficiency droop of conventional c-plane LEDs. © *2010 American Institute of Physics*. [doi:10.1063/1.3449557]

In the state-of-art c-plane InGaN/GaN multiple-quantum-well (MQW) light-emitting diodes (LEDs), the quantum efficiency reaches its peak at very low current density, typically <10 A/cm^2, and monotonically decreases with further increasing drive current, which is the critical restriction for the usage of LEDs in high power application.[1,2] This phenomenon, well known as efficiency droop, becomes more severe while the peak emission wavelength of LEDs further increases from UV spectral range toward blue and green spectral range.[3] Even though driving the blue/green LEDs under short and low-duty cycle pulses to minimize the self-heating effect, the droop in quantum efficiency remains nearly identical.[3] Various methods are proposed to mitigate the efficiency droop, including quaternary AlInGaN barriers that eliminate electron overflow,[4,5] thick active region of double heterostructure that reduce Auger nonradiative recombination rate,[6,7] reduction in barrier thickness that makes hole distribution more uniform among the wells,[8] and so on. Nonpolar $[1\bar{1}00]$ m-plane epitaxial orientation has been demonstrated to increase internal quantum efficiency in LEDs because of the absence of polarization fields.[9–11] The usage of nonpolar orientation in LEDs is also expected to reduce the electron overflow and enhance holes transport throughout the active region, once again owing to the absence of polarization fields, and therefore mitigation of efficiency droop is predicted. Recently, Li *et al.*[11] reported that the near UV (~400 nm) m-plane LEDs can achieve efficiency retention even at high current injection level. Nevertheless, an overall physical explanation for efficiency retention of m-plane LEDs is still absent. Moreover, the behavior of efficiency droop of m-plane LEDs in blue-green emission wavelength range has not yet been reported, where the conventional c-plane LEDs suffer a more significant drop in quantum efficiency at high injection current density. In this paper, we present the comparison of efficiency droop in c-plane and m-plane LEDs with 480 nm emission wavelength and, for the exploration of origin of efficiency droop, the carrier injection and distribution in the polar c-plane and nonpolar m-plane active region are investigated numerically by the advanced physical models of semiconductor devices (APSYS) simulation program, which was developed by the Crosslight Software Inc.[12]

The respective c-plane and m-plane LED structures investigated are grown on c-plane GaN templates on sapphire

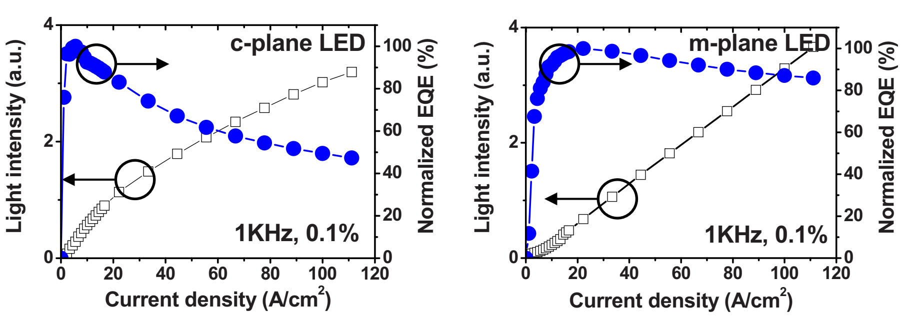

FIG. 1. (Color online) Integrated EL intensity and normalized EQE as a function of forward current density for c-plane LED and m-plane LED, respectively. Both samples have the same MQW active region and EBL structure.

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and on m-plane bulk substrates using the low pressure metalorganic chemical vapor deposition system. Both they comprises a 2-μm-thick undoped GaN layer, followed by a 2-μm-thick n-type GaN layer with an electron concentration of 3×10^{18} cm^{-3}. Then a six-period InGaN/GaN MQW active region is grown, consisting of 2.7-nm-thick $In_{0.22}Ga_{0.78}N$ wells and 11-nm-thick GaN barriers. On top of the active region is 20-nm-thick p-$Al_{0.1}Ga_{0.9}N$ electron blocking layer (EBL) and 0.2-μm-thick p-type GaN capping layer with a hole concentration of 1×10^{18} cm^{-3}. Subsequently, 300×300 μm^2 diode mesas are defined by chlorine-based reactive ion etching. Indium-tin-oxide (230 nm) layer is used as the transparent p-contact and finally Cr/Au (100/200 nm) are deposited to be the p-GaN and n-GaN contact pads. The EL measurements are performed in an unencapsulated wafer form, in which light output are collected primarily on-axis into the integrating sphere with a Si photodetector. Devices are tested in pulsed mode with 1 KHz frequency and 0.1% duty cycle to prevent self-heating effect. The EL spectra showed the center wavelength for both reference c-plane LEDs and m-plane LEDs is around 480 nm.

Figure 1 shows the light output intensity and normalized external quantum efficiency (EQE) as a function of forward current density for c-plane LED and m-plane LED, respectively. The light output-current curve of the reference c-plane LED is linear at low current density but becomes sublinear at high current density, indicating a reduced EQE. Its peak efficiency occurs at ~5 A/cm^2. Over this peak efficiency, the efficiency decreases rapidly. When the current density exceeds 100 A/cm^2, the EQE is reduced to just 50% of its maximum value. In contrast, the m-plane LED exhibits only 13% efficiency droop with increasing the injection current density to 100 A/cm^2, which shows almost negligible droop. It is also noticeable that the characteristic current density, which marks the peak efficiency, is extended to ~23 A/cm^2.

For the exploration of physical origin of efficiency droop in InGaN/GaN LEDs, we performed the simulation of aforementioned polar c-plane and nonpolar m-plane LED structure using the APSYS simulation software. Commonly accepted parameters are used in the simulations, including a Shockley–Read–Hall recombination lifetime of 1 ns, an Auger recombination coefficient of 2×10^{-30} cm^6 s^{-1}, and total polarization charge densities of 8.3×10^{12} cm^{-2} at the interfaces between the wells and barriers in the active region, respectively. Figure 2(a) shows the calculated energy band diagram of the reference c-plane and m-plane LED at a forward current of 20 mA. For the c-plane LED, as a result of the polarization charges, a severe situation of band bending, i.e., sloped triangular barriers and wells, is observed. Furthermore, the conduction band slopes upward while it approaches to the MQW active region from the n-GaN side and consequently the conduction band close to n-GaN is higher than the conduction band close to p-GaN, which results in a large electron leakage current. Even though an AlGaN EBL is introduced, the electron current overflows out of the MQW region even at a low current of 20 mA. With increasing the forward current to 100 mA, the electron leakage becomes more severe, as shown in Fig. 2(b). The electrons escaped from MQW active region are not contributed to radiative recombination and thereby lower the LED efficiency. This reveals the electron leakage current due to polarization fields is one of the dominated mechanisms that results in efficiency droop. In the m-plane LED, because of the absence of polarization fields, its GaN barriers do not exhibit triangular shape and the conduction band near p-GaN side is now higher than that near n-GaN side. As a result, the electron leakage current as well as efficiency droop is reduced significantly.

Figure 3 shows the carrier distribution in the whole InGaN/GaN MQWs structure at 20 mA forward current for the m-plane LED and the c-plane LED. It is obvious that in

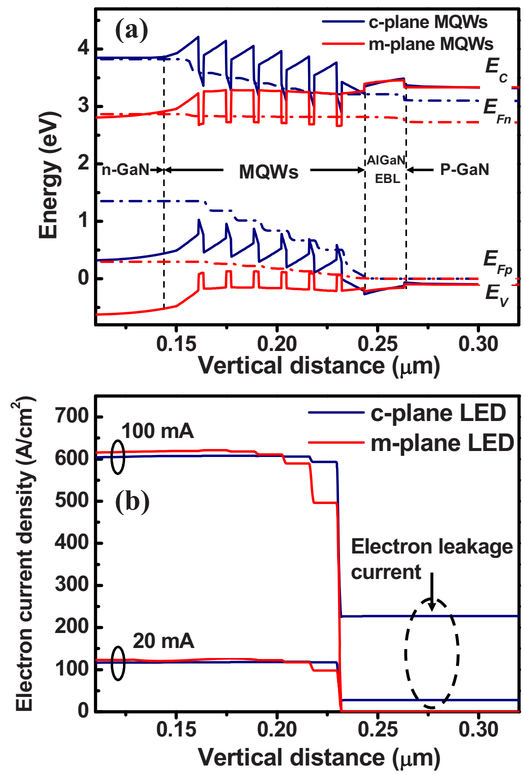

FIG. 2. (Color online) (a) Calculated band diagram of m-plane LED and reference c-plane LED under forward bias operation. (b) Simulated electron current density throughout the whole m-plane LED structure as well as c-plane LED structure at 20 and 100 mA forward current.

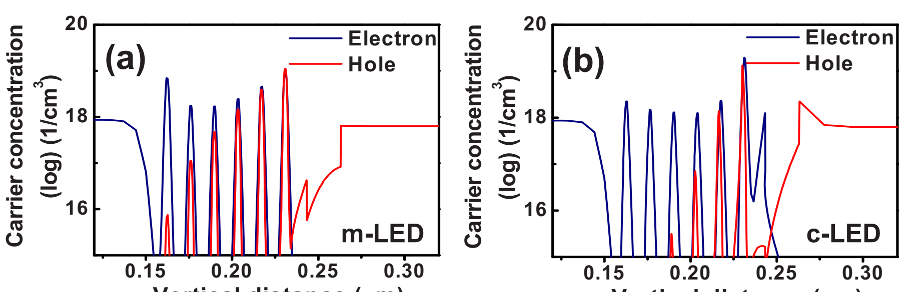

FIG. 3. (Color online) Distribution of carrier concentration of InGaN/GaN MQWs structure at 20 mA forward current density for (a) m-plane LED and (b) c-plane LED.

the c-plane LED both electrons and holes distributions are quite nonuniform among the quantum wells especially for holes. This is because holes have a relatively larger effective mass and therefore a very low mobility. Moreover, the triangular potential barriers which result from polarization fields hinder the holes transport throughout the active region as well. Under these circumstances, a large amount of minority carrier holes accumulate in the last well next to the p-GaN side, which means only the last quantum well next to p-GaN contributes to radiative recombination in the c-plane LED. It results in two circumstances. One is inefficient recombination with electrons in the other five wells increases the excess electron density and thus enhances the electron leakage. Second is the higher carrier density accumulated in the last well of c-plane LEDs, as compared with the m-plane LEDs, causes the greater radiative recombination rate relative to the nonradiative recombination rate, which is responsible for that the c-plane LEDs reach maximum efficiency at much lower current density than the m-plane LEDs do. In addition, in a recent paper, Shen and co-workers demonstrate that the Auger recombination coefficient is $\sim 2\times 10^{-30}$ cm^6 s^{-1} rather than a previous accepted value of 1×10^{-34} cm^6 s^{-1}.[6] which is large enough to significantly decrease the internal quantum efficiency of InGaN/GaN MQW LEDs at their standard operating currents. Since the carrier density accumulated in the c-plane MQWs is larger than that in the m-plane MQWs at the same forward current, it is expected that the Auger recombination rate in the c-plane LED is higher. The Auger coefficient in m-plane GaN has not yet been reported, we assume that Auger coefficient is also 2×10^{-30} cm^6 s^{-1} for m-plane orientation. In our calculation, at 20 mA forward current, the Auger recombination rate of the c-plane LED is 1.4×10^{27} cm^{-3} s^{-1}, which is approximately twice higher than that of m-plane LED ($\sim 8\times 10^{26}$ cm^{-3} s^{-1}) and thereby causes more severe efficiency droop.

After considering three aforementioned droop factors [including (1) electron leakage (2) hole transport and injection efficiency (3) Auger recombination], we simulated the EQE droop for c-plane LEDs and m-plane LEDs. The simulated and experimental EQE as a function of forward current density for c-plane LEDs and m-plane LEDs is plotted in Fig. 4, which shows good agreement between the experimental data and our simulation. It suggests that strongly inherent polarization fields are responsible for the significant efficiency droop of c-plane LEDs. Contrary to the c-plane LED, the m-plane LED exhibits the efficiency retention at high current injection as a result of the absence of polarization fields.

In conclusion, we have demonstrated relatively low efficiency droop in blue-green m-plane InGaN/GaN LEDs as compared with the c-plane LEDs. The EQE is nearly retained in m-plane LEDs even at a high forward current density of 100 A/cm^2 (only 13% droop), whereas c-plane LEDs exhibit as high as 50% efficiency droop under the same injection current density. Our theoretical simulations reveal that the strong polarization fields in the c-plane MQW active region enhance the electron leakage as well as the nonuniform distribution of holes, which are responsible for the severe efficiency droop. Therefore, the almost negligible droop in m-plane LEDs is a reasonable consequence of the absence of polarization fields.

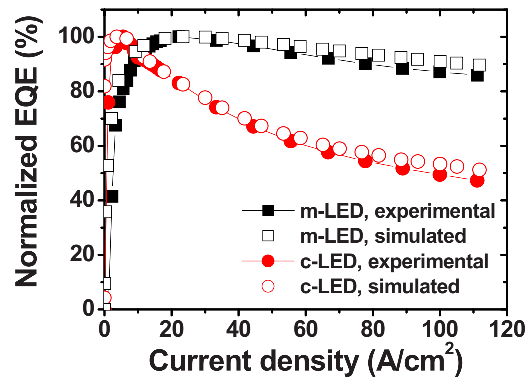

FIG. 4. (Color online) Experimental and simulated normalized EQE as a function of forward current density for c-plane LED and m-plane LED.

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