Effect of Back Diffusion of Mg Dopants on Optoelectronic Properties of InGaN-Based Green Light-Emitting Diodes *

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The effect of back-diffusion of Mg dopants on optoelectronic characteristics of InGaN-based green light-emitting diodes (LEDs) is investigated. The LEDs with less Mg back-diffusion show blue shifts of longer wavelengths and larger wavelengths with the increasing current, which results from the Mg-dopant-related polarization screening. The LEDs show enhanced efficiency with the decreasing Mg back-diffusion in the lower current region. Light outputs follow the power law $L \propto I^m$, with smaller parameter m in the LEDs with less Mg back-diffusion, indicating a lower density of trap states. The trap-assisted tunneling current is also suppressed by reducing Mg-defect-related nonradiative centers in the active region. Furthermore, the forward current–voltage characteristics are improved.

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High efficiency GaN-based light emitting diodes (LEDs) are in strong demand in display and solid state lighting, and will replace conventional fluorescent and incandescent lighting sources in some fields due to their lower energy consumption and longer lifetimes.[1,2] However, a problem of restricting the stability of LEDs is the Mg dopants back-diffusion from the p-layer into the active region.[3,4] The diffusion of Mg atoms in the GaN-based materials was achieved though the interstitial-substitutional mechanism with a high diffusivity.[5] In this diffusion process the Mg atom moves from interstitial site to vacant substitutional Ga site. In the hetero-epitaxial GaN layer grown on a foreign substrate, high concentration of defects, such as grain boundaries and dislocations, sometimes serve as the diffusion path, further facilitate the acceptor impurity diffusion. Moreover, higher Mg doping concentration and higher growth temperature for the p-layer of the LEDs required to enhance the hole concentration, increase the Mg diffusion coefficient and then the back-diffusing.[6,7] Thus the diffused Mg impurities introduce deep-level states in the active region and become increasingly problematic for the carrier transportation and recombination.[8] Furthermore, the ionized negative charges in the active region also lead to adjustment of the band structure and shifting of the p–n junction position, resulting in changes of the emission properties.[9] So far, only a few works have concentrated on the Mg atoms' back-diffusion and the research points focus on the prevention of the Mg back-diffusion to enhance the efficiency of LEDs,[2,10] whereas research about the influence of the back-diffusion on the emission properties and the electric characteristics is scarce. In this study, we try to control the back-diffusing Mg impurity profile in the active region and investigate its effects on the optoelectronic characteristics of the InGaN-based LEDs.

The LEDs with different last barrier thicknesses were grown along the (0001) orientation in a Veeco metal-organic chemical vapor deposition system. First, the sapphire substrate was cleaned in H_2 at 1015℃, followed by the growth of a 30-nm low temperature GaN buffer layer at 560℃. After high-temperature annealing of the buffer layer, 2 μm undoped GaN and Si-doped n-GaN layers were grown at a temperature of 1150℃, followed by two pairs of InGaN/GaN as pre-strained layers. Then, an InGaN/GaN MQWs sample consisting of ten pairs of 3.5 nm InGaN wells and 15 nm GaN barriers was grown. On top of the last QW was an undoped GaN layer as the last barrier, and a 30-nm thick p-type AlGaN and the 150-nm-thick Mg-doped GaN were deposited lastly. LEDs A and B were grown under the same growth condition, corresponding to 4 nm and 30 nm last undoped GaN barriers, respectively. LEDs with a size of $580 \times 250\,\mu m^2$ were fabricated by using a conventional mesa structure method. Indium tin oxide was used as a transparent conducting layer and Cr/Au was deposited as n-type and p-type electrodes. The electroluminescence and light output power (LOP) of packaged LEDs was measured in an integrating sphere at 300 K in a cw current mode. The electrical characteristics were measured by using a semiconductor parameter analyzer (Keithley 4200). Furthermore, the atomic concentration–depth profiles of two LEDs were recorded by using SIMS. Detailed information about the experimental process can be found in the early works of our team.[11,12]

The SIMS measurements performed for the two samples is shown in Fig. 1. The result reveals that the

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level of Mg atoms in the QWs close to the p-GaN for the LED B was lower than that in the LED A. It can be seen that the Mg atom concentrations in the last quantum well for LEDs A and B are 7.4×10^{18} and $2.8 \times 10^{18}\,\mathrm{cm}^{-3}$, respectively. The Mg atoms in the QWs have arisen from the diffusion from the p-AlGaN and p-GaN. The longer the diffusion distance for the Mg atoms in the LED B compared with those in the LED A is, the lower level of the Mg atoms in the QW is.

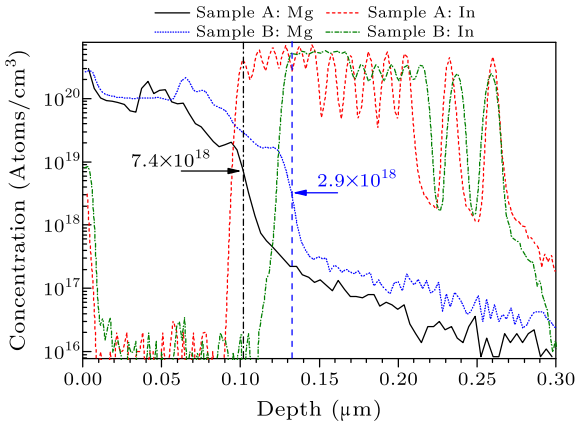

Fig. 1. The SIMS measurements performed for the two samples.

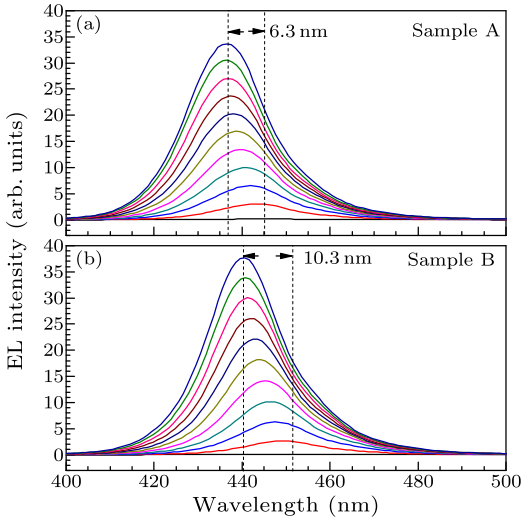

Fig. 2. The EL peak wavelengths with different injection currents for the two LEDs.

The electroluminescence (EL) properties of all the samples are compared and Fig. 2 displays changes of the EL peak wavelengths with different injection currents for the two LEDs. From Fig. 2, it can be seen that the peak emission energy position shifts to lower level with the decreasing Mg dopants back-diffusion. The EL peak wavelengths increase from 443.9 nm to 450.2 nm for the LED A to the LED B with an injection current of 20 mA. Moreover, the blue shift of EL peak wavelengths for the LED B is decreased with a thicker barrier under the injection level ranges from 2 mA to 100 mA. In the measured current region, the wavelengths shifts are 6.3 nm and 10.3 nm for LEDs A and B, respectively. It is known that the carriers from the ionized impurities in the active region screen partly the polarization fields in the QW, then reduce the band-gap narrowing.[13] Thus the reduction of the blue shift for the LED B with the increasing current can be attributed to the dopant screening effect. Shorter wavelength with the same current injection and the reduced blue shift of the EL peak with the increasing current intensity for the LED A further confirm the screening of polarization fields by the Mg atoms back-diffusing into the active region.

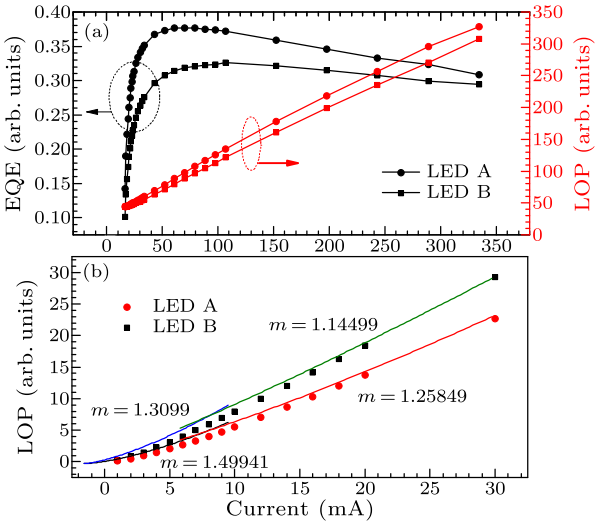

Fig. 3. (a) The light output power and external quantum efficiencies of LEDs A and B as a function of the current density. (b) The light output power versus current for the two LEDs with fitted curves by using the power law.

Figure 3(a) shows the light output power and external quantum efficiencies (EQEs) of LEDs A and B as a function of the current density. It can be seen that the light output power of the two LEDs increases sublinearly as the current density increases. The output power of the LED B is higher than that of the LED A in the measured current region. Furthermore, the difference of output powers becomes larger as the current density increases. The measured EQEs for both the LEDs show the maximum datum at low current density, then the EQEs drop rapidly with the current density. The droops are 21% and 11.6% at 350 mA for LEDs A and B, respectively. The EQE of the LED B is 5.5% higher than that of the LED A, at 350 mA. To comprehend different droop behaviors of the LEDs, the L–I curves for both the samples are fitted, as shown in Fig. 3(b), using the power law $L \propto I^m$, where the parameter m reflects the effect of the defect states on the recombination of carriers. The results exhibit that m of the LED A is 1.499 at relatively lower current values, while that of the LED B is 1.309, indicating a higher density of trap states in the LED A. Under high injection conditions, $L \propto I^m$ for both the samples show a sublinear variation, with P values of 1.259 and 1.145 for LEDs A and B, respec-

tively. It is known that m is attributed to the existence of trap states in the space charge region, which acts as a shortcut for the carrier transportation.[14] The larger m value in the LED A indicates that there is larger concentration of Mg impurity-related defects in the MQWs, originating from the back-diffusion, serving as deep-level traps and severely decreasing the radiative recombination, especially in the last QW, which contributes mostly to the light emission. This does explain why the LED B possesses a higher EQE compared with the LED A in the measured current region.

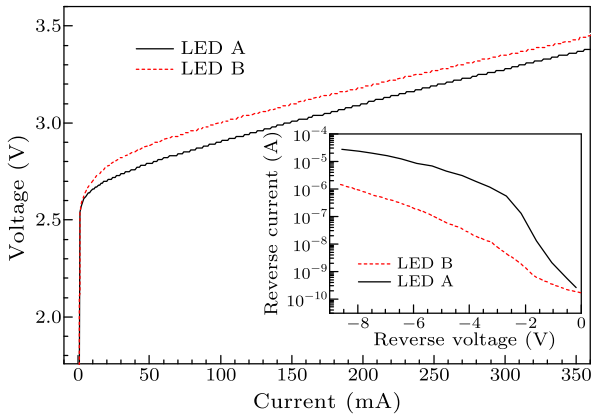

Fig. 4. The current–voltage characteristics for the two LEDs.

The current–voltage (I–V) characteristics for the two LEDs are shown in Fig. 4. It can be seen that the slopes of the I–V curves are different, which means that the series resistances of these two LEDs are different. Notably, the turn-on voltages of the LEDs are reduced with the increasing Mg back-diffusion, suggesting that the carrier transport characteristics for the two LEDs are different. Under the low forward bias, the carriers transport across the QWs mainly by tunneling though deep-levels rather than overcoming the GaN barrier. It is reported that the tunneling of carriers through defect states in QWs can reduce radiative recombination and then the IQE.[14] In our case, the LED A suffers from a larger tunneling leakage compared with the LED B, leading to an insufficiently radiative recombination under forward bias operation, meaning a poor EQE performance for the LED A with more Mg back-diffusion, which is consistent with the light-output result. To further understand the tunneling behavior, the reverse I–V curves are measured and are shown in the inset of Fig. 3. The leakage currents of the LED A are larger than that of the LED B by one of magnitude in the reverse voltage region of -2—8 V. It is known that the defect-assisted tunneling or band-to-band tunneling contributes to the reverse currents and a higher leakage current will lead to a lower turn-on voltage.[15] In this study, the growth conditions are the same for the two LEDs except the last GaN barrier thickness. Thus it is inferred that the differences in leakage currents through traps are likely the main reason for the differences of the turn-on voltages for the two LEDs. It is known that the defect-assisted tunneling located in the space-charge region contributed mainly to the reverse leakage current at low reverse voltage. Thus the larger leakage current in the LED A indicates a higher concentration of trap states stemming from the Mg-related defects. In the reverse voltages region, we could distinguish different slopes for the two LEDs. The reverse I–V curves show that the less the Mg diffusing is, the slower the exponential increasing is, revealing a lower degree of defect-assisted tunneling with the decreasing Mg back-diffusion.

In conclusion, we have investigated the effect of the Mg back-diffusion on the emission properties and electric characteristics in InGaN-based LEDs. The EL results show that the LEDs with less Mg back-diffusion show blue shifts of longer wavelengths and larger wavelengths with increasing the current. The fitted m values of the power law, $L \propto I^m$, for the two samples show that the Mg dopants diffused into the active region introduce deep-level trap states and the LEDs show reduced efficiency with the increasing Mg back-diffusion. Furthermore, reducing Mg back-diffusion-induced nonradiative centers in the active region can suppress the trap-assisted tunneling current to improve the forward current–voltage characteristics.

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