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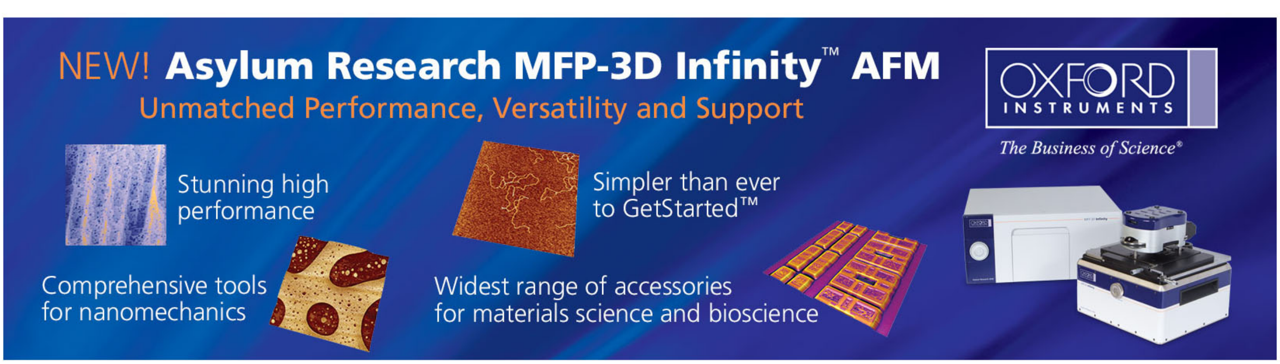

Characteristics of efficiency droop in GaN-based light emitting diodes with an insertion layer between the multiple quantum wells and *n*-GaN layer

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We have studied the characteristics of efficiency droop in GaN-based light emitting diodes (LEDs) with different kinds of insertion layers (ILs) between the multiple quantum wells (MQWs) layer and *n*-GaN layer. By using low-temperature (LT) (780 °C) *n*-GaN as IL, the efficiency droop behavior can be alleviated from 54% in reference LED to 36% from the maximum value at low injection current to 200 mA, which is much smaller than that of 49% in LED with InGaN/GaN short-period superlattices layer. The polarization field in MQWs is found to be smallest in LED with InGaN/GaN SPS layer. However, the V-shape defect density, about 5.3×10^8 cm^{-2}, in its MQWs region is much higher than that value of 2.9×10^8 cm^{-2} in LED with LT *n*-GaN layer, which will lead to higher defect-related tunneling leakage of carriers. Therefore, we can mainly assign this alleviation of efficiency droop to the reduction of dislocation density in MQWs region rather than the decrease of polarization field. © *2010 American Institute of Physics*. [doi:10.1063/1.3531957]

In recent years, great efforts have been made to improve the performance of GaN-based light emitting diodes (LEDs) due to their widespread application in solid-sate lighting, display technology, color printing, and optical storage.[1] One of the promising approaches is to introduce an additional layer, such as InGaN/GaN short-period superlattices (SPS),[2,3] InGaN layer,[4,5] or low-temperature (LT) *n*-GaN layer,[6] between the *n*-type GaN and the multiple quantum wells (MQWs) layers. Several studies have been revealed that such insertion layers (ILs) can release the residual strain in MQWs layer, reduce the V-pits density in MQWs, or improve the current spreading in LED.[2–6] As a result, the quantum efficiency and the output power of LED can be enhanced. However, as the efficiency of LEDs increases, the upcoming challenge is that the quantum efficiency substantially decreases with increasing drive current, so-called efficiency droop.[7] Over the past year, several different mechanisms for the efficiency droop have been suggested, including carrier leakage from the active region,[8] the effect of the polarization field in the MQWs,[9] nonuniform distribution of holes,[10] defect-related tunneling leakage of carriers,[11] Auger recombination,[12] and carrier delocalization.[13] Considering the advantages of using the ILs mentioned above, one can expect that the efficiency droop behavior can be alleviated in such LEDs with the ILs. But which kind of IL can reduce the efficiency droop more effectively? And what is the major mechanism for this reduction? More detailed investigations are necessary. In this work, we studied the characteristics of efficiency droop in GaN-based LEDs with different kinds of ILs by performing the electroluminescence, photoluminescence (PL), cathodoluminescence (CL), scanning electron microscope, and transmission electron microscopy (TEM) measurements.

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The samples in this study were grown on *c*-plane (0001) sapphire substrates by metalorganic chemical vapor deposition. After depositing a 20-nm-thick LT (550 °C) GaN nucleation layer on the sapphire substrate, a 2-μm undoped GaN and a 2-μm Si-doped (5×10^{19} cm^{-3}) *n*-type GaN were grown at 980 °C, followed by an IL and the MQWs active region. Two kinds of ILs were used in this study. One is InGaN/GaN SPS layer, which consisted of 10 pairs of $In_{0.06}Ga_{0.94}N$ layer (~0.9 nm) and GaN layer (~1.7 nm). The other is 60-nm LT *n*-GaN layer. Note that both of the ILs are doped with Si (5×10^{18} cm^{-3}) and deposited at 780 °C. The MQWs active region consisted of six pairs of GaN barrier (~14.2 nm, deposited at 860 °C) and unintentionally doped $In_{0.15}Ga_{0.85}N$ well (~3.9 nm, deposited at 780 °C). Finally, a 20-nm electron blocking layer with Mg-doped *p*-type $Al_{0.15}Ga_{0.85}N$ and a 200-nm Mg-doped *p*-type GaN layer were grown at 880 °C. The Mg-dopant concentration is about 1×10^{19} cm^{-3}. For comparison, the same LED structure without the IL was also prepared. After growth, the LED chips were fabricated by regular chip process with indium tin oxide current spreading layer and Ni/Au contact metal, and the size of mesa is 300×300 μm^2. Throughout this work, for convenience, we shall refer to LED structures without and with InGaN/GaN SPS and LT *n*-GaN ILs as reference, type I, and type II LEDs. In addition, in order to investigate the surface morphology of MQWs, three samples without the electron blocking layer and the *p*-type GaN layer were also grown, denoted as reference, type I, and type II MQWs.

The electrical and luminescence characteristics of the LEDs were measured at room temperature (RT) with a calibrated integrating sphere. To prevent the self-heating effect, the devices were driven in pulsed mode with 1 KHz frequency and 0.1% duty cycle. Figure 1(a) shows the output power of the three types of LEDs as a function of injection current. With 20-mA injection current, the output power of type I and type II LEDs are 18.0 and 17.0 mW, respectively,

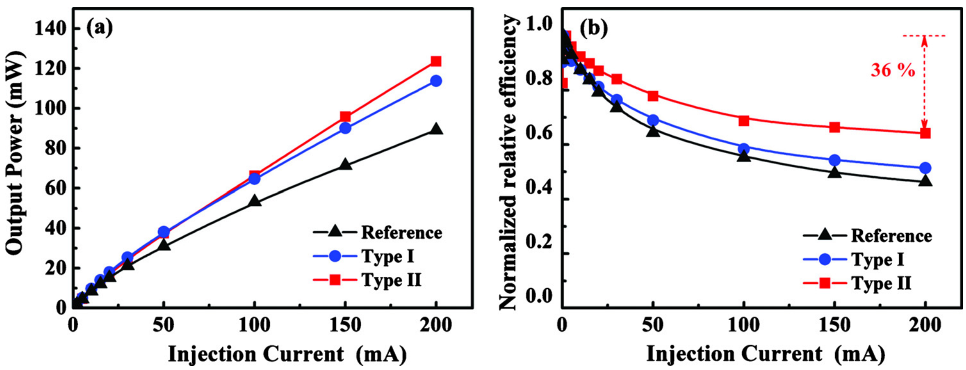

FIG. 1. (Color online) (a) The output powers and (b) the normalized relative efficiencies for the three types of LEDs as a function of injection current.

which are increased by 18% and 11%, as compared with the value of 15.3 mW for reference LED, while the enhancements at 200 mA are approximately 28% and 39% for type I and type II LEDs, respectively. These results indicate that not only the light output power has been improved but also the efficiency droop behavior has been changed by using the ILs. To illustrate the droop behavior more clearly, the normalized relative efficiencies of the three types of LEDs are plotted as a function of injection current in Fig. 1(b). Then, the efficiency droop can be defined as $(\eta_{peak} - \eta_{200\ mA})/\eta_{peak}$, where η_{peak} is the maximum efficiency at low injection current. It is interesting that the efficiency droop in type II LED is only about 36%, which is much smaller than that in type I LED (49%) and reference LED (54%). That is, the efficiency droop behavior can be alleviated more effectively by using the LT *n*-GaN IL.

To figure out the origins of the alleviation in efficiency droop for LEDs with ILs, the power-dependent PL measurements excited with a frequency-doubled Ti: sapphire laser at wavelength of 385 nm were first carried out at RT. The laser pulse width was 200 fs and the repetition rate was 76 MHz. The laser beam was focused to a spot with diameter of 50 μm. The luminescence spectrum was dispersed by a 0.5 m monochromator and detected by a photomultiplier tube. Figure 2 illustrates the emission energy and full width at half maximum (FWHM) as a function of excitation power. At an excitation power of 0.02 mW, the emission energies for type I and type II LEDs are 2.819 and 2.815 eV, respectively, which is much higher than that of 2.774 eV for reference LED. Meanwhile, the emission energies blueshift with increasing the excitation power in all of the three types of LEDs. Such blueshift can be attributed to two mechanisms: one is the photoinduced carriers screening effect of the polarization field accompanied by shrinkage of FWHM, the other is the band filling effect with a broadening of FWHM.[14,15] As can be seen from Fig. 2(b), the FWHM changes slightly in the low excitation power range (<10 mW), indicating the screening effect is dominated in this region. As the excitation power is further increased, the band filling effect becomes dominated because of the significant broadening of FWHM. Therefore, we analyzed semiquantitatively the polarization field by fitting the emission energy of PL spectrum $(h\upsilon)$ in the low excitation power range with a triangular well model[14]

$$h\upsilon = E_g(n) - dF(n) + \left[\left(\frac{1}{m_e}\right)^{1/3} + \left(\frac{1}{m_h}\right)^{1/3}\right] \times \left[\frac{9\pi\hbar}{8\sqrt{2}}F(n)\right]^{2/3}, \quad (1)$$

where the band-gap renormalization and the screening of the polarization field due to nonequilibrium carriers (n) are taken into account as $E_g(n)=E_g(0)-\beta n^{1/3}$, and $F(n)=F(0) - ned/\varepsilon\varepsilon_0$, respectively. Here, $E_g(0)$ and $F(0)$ are the energy band-gap and polarization field in the unexcited sample ($n=0$), respectively, while d, ε, and $m_{e,h}$ are the well width, dielectric constant, and electron- or hole-effective mass. In the calculation, the material parameters are obtained from the literature,[16] and the excitation power is converted into carrier density using the similar method in Ref. 14. The fitting results are illustrated in Fig. 2(a) by the dashed line. The F_0 in the reference LED is found to be about 1.21 MV/cm, which is lower than the value (1.87 MV/cm) obtained in similar MQW structure.[14] It can be attributed to that our MQWs were grown on thicker *n*-GaN layer with lower residual strain.[17] But for type I and type II LEDs, smaller values are obtained to be 0.62 and 0.66 MV/cm, respectively, implying both two kinds of ILs can release the residual strain for a certainty. The strain reduction effect by ILs has been studied and can be attributed to the suppression of the epiwafer bowing.[18] In addition, the InGaN/GaN SPS IL was demon-

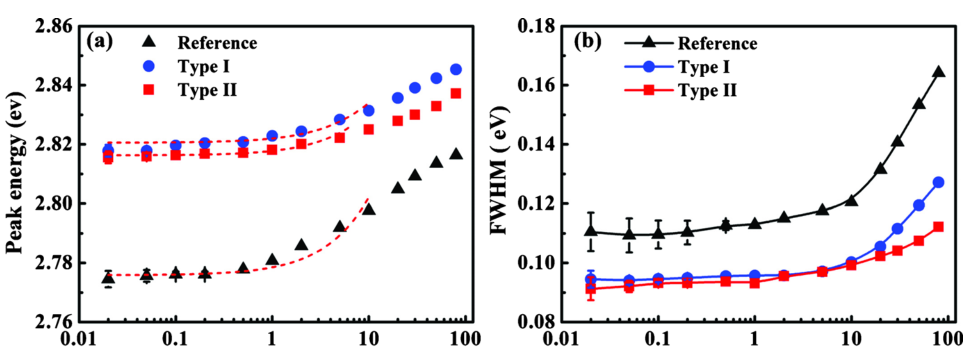

FIG. 2. (Color online) (a) The emission energy and (b) FWHM for the three types of LEDs as a function of excitation power.

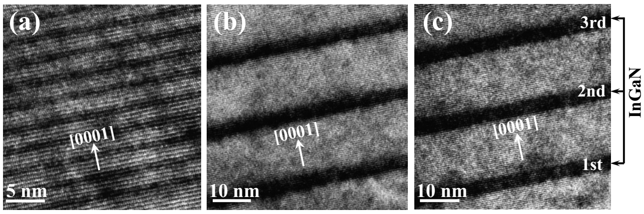

FIG. 3. Cross-section HRTEM images for (a) the SPS layer in type I LEDs, (b) MQWs structures in type I LEDs, and (c) MQWs structures in type II LEDs.

strated to decrease the epiwafer bowing more effectively, resulting in larger *a*-axis lattice constant of GaN and lower compressive strain in MQW. This agrees with our experimental results.

It is well known that the reduction of polarization field in InGaN/GaN MQWs causes less band bending, which in turn, results in higher emission energy, higher radiative recombination, and less electron leakage from the active region.[9,15,19] Therefore, it is reasonable that type I LED has the highest light output power at 20 mA and the largest emission energy, due to the smallest polarization field in it. However, it is still difficult to understand why the type II LED, instead of type I LED, does have a rather small efficiency droop.

Further insight investigations were performed by CL and TEM measurements. Although dark spots can be observed on the surface of all three samples from the monochromatic spatially resolved CL images (not shown here), the density is found to be decreased from 5.9 to 7.5×10^{8} cm^{-2} in reference MQWs to 5.3×10^{8} and 2.9×10^{8} cm^{-2}, for type I and type II MQWs, respectively. The fluctuation of the value for reference MQWs is due to that some of the dark spots overlap each other and difficult to figure out. Such dark spots are related to nonradiative centers in the V-defects confirmed by SEM morphology, which is commonly believed to consist of a threading dislocation terminated by a pit in the shape of an inverted hexagonal pyramid.[20,21] In this sense, the lower dark-spot density suggests the reduction of dislocation density in the MQWs region of both LEDs with ILs.

It has been reported that strain in the MQWs and In distribution inhomogeneities in the InGaN well are the main factors responsible for the V-defect occurrence and propagation.[20,21] As discussed above, for type I LED, the strain in the MQWs is relatively small. However, from the cross-section high resolution TEM (HRTEM) image in Fig. 3(a), one can clearly see slight well width and composition fluctuations in SPS layer. These may not only induce additional V-defects but also influence the subsequent growth of the MQWs layer. It is practical that type I MQWs exhibit rather rough interfaces and apparent nonuniformity of In distribution, as shown in Fig. 3(b). While for the type II MQWs [Fig. 3(c)], since the LT *n*-GaN IL dose not contain In, clear and sharp interfaces can be observed. In addition, the In distribution is more homogeneous especially for the first and the second wells. Therefore, the dislocation density is much lower in the MQWs region of type II LED. Accordingly, the tunneling leakage of carriers from the QW to defect states in barriers is expected to be much smaller in type II LED than that in type I LED, which is considered to be one of the major reasons for the efficiency droop.[11] As a result, the efficiency droop behavior is alleviated more effectively by inserting LT *n*-GaN layer.

In summary, the efficiency droop behaviors in two types of GaN-based LEDs with InGaN/GaN SPS and LT *n*-GaN ILs, respectively, were investigated in this work. The power-dependent PL reveals that the polarization field in MQWs is smallest in LED with InGaN/GaN SPS IL. Therefore, the output power at 20 mA (18.0 mW) is a little higher than that in LED with LT *n*-GaN IL (17.0 mW). However, the CL images indicate that the dislocation density in MQWs is much lower in the latter LED. This might be due to that the In distribution is more homogeneous and the interface in the MQWs is extremely sharp after inserting LT *n*-GaN layer, which is verified by the TEM image. Accordingly, the tunneling leakage of carriers from the QW to defect states in barriers is expected to be much smaller in LED with LT *n*-GaN IL. As a result, the efficiency only drops about 36% from the maximum value at low injection current to 200 mA, which is much smaller than that of 49% in LED with InGaN/GaN SPS IL and 54% in reference LED.

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