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The Efficiency Droop of InGaN-Based Green LEDs with Different Superlattice Growth Temperatures on Si Substrates via Temperature-Dependent Electroluminescence *

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InGaN-based green light-emitting diodes (LEDs) with different growth temperatures of superlattice grown on Si (111) substrates are investigated by temperature-dependent electroluminescence between 100 K and 350 K. It is observed that with the decrease of the growth temperature of the superlattice from 895°C to 855°C, the forward voltage decreases, especially at low temperature. We presume that this is due to the existence of the larger average size of V-shaped pits, which is determined by secondary ion mass spectrometer measurements. Meanwhile, the sample with higher growth temperature of superlattice shows a severer efficiency droop at cryogenic temperatures (about 100 K–150 K). Electron overflow into p-GaN is considered to be the cause of such phenomena, which is relevant to the poorer hole injection into multiple quantum wells and the more reduced effective active volume in the active region.

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Due to the high emission efficiency and energy conservation, InGaN-based multiple quantum well (MQW) light-emitting diodes (LEDs) are gradually replacing the traditional light sources such as halogen, incandescence and fluorescence, which can make us enter into the era of solid-state lighting. However, LEDs still have a serious problem that their internal quantum efficiency (IQE) appears a nonthermal reduction at high injection current density, known as efficiency droop.[1] Several physical mechanisms were proposed to explain the efficiency droop in InGaN-based LEDs, including carriers overflow, the Auger recombination,[2] nonradiative recombination and carriers delocalization.[3] Recently, the more pronounced efficiency droop in InGaN-based LEDs, experimentally observed at lower temperature, has been reported by several groups.[4–6] However, their explanations are quite different. For example, Kudryk *et al.*[4] suggested a more dramatic current crowd effect at lower temperature, which causes the substantial increase of the Auger recombination rate and thus makes a severer efficiency droop. Hammersley *et al.*[5] claimed the premature saturation of the available localization states within the quantum well at lower temperature leading to a fraction of excess carriers recombining non-radiatively. Shin *et al.*[6] proposed that a more striking efficiency droop at cryogenic temperatures is ascribed to the higher degree of saturation in the radiative recombination rate. Therefore, we regard that the origin of the more pronounced efficiency droop at low temperature still has no remarkable consensus and deserves further investigation. In this Letter, to elucidate the underlying mechanism of the more pronounced efficiency droop at low temperature, two InGaN-based green LEDs with different growth temperatures of superlattice grown on Si substrates are investigated by temperature-dependent electroluminescence (EL) between 100 K and 350 K.

InGaN-based green LEDs are grown on the 1.2 mm × 1.2 mm patterned 2-inch silicon (111) substrates by a Thomas Swan close-coupled showerhead (CCS) metal organic chemical vapor deposition (MOCVD) reactor. Details of the growth process can be found elsewhere.[7] To facilitate the comparison, two samples are grown under the identical parameters except the growth temperature of the superlattice, whose structure is shown in Fig. 1. The growth temperatures of the superlattice of two samples are 855℃ and 895℃, which are represented as samples A and B, respectively. After the epitaxial growth, two samples are fabricated into the vertical structure LED chips in size of 1.14 mm × 1.14 mm with the n-type GaN upwards and roughed. The specific chip manufacturing process has been described.[8] The temperature-dependent EL measurements are carried out utilizing the devices, which contain the integrating sphere and the CAS140CT spectrometer made by instrument systems, the temperature controlling unit made by MMR

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technologies, Inc., and the 2635 A sourcemeter made by Keithley instruments, Inc.

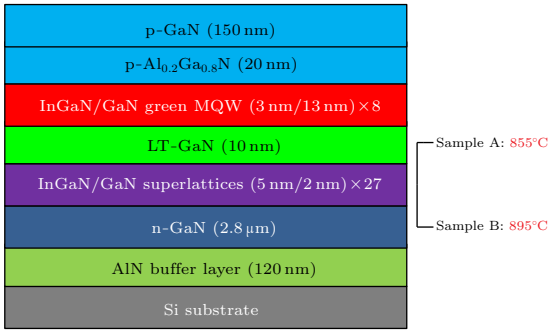

Fig. 1. Schematic epitaxial structure of two samples.

Figures 2(a) and 2(b) show the typical forward current-voltage (I–V) characteristic curves for samples A and B at different temperatures, respectively. It can be seen that the forward voltages of two samples increase with the decrease of the temperature. This result can mostly be attributed to the reduction in hole concentration due to the high ionization energy of the Mg acceptor in p-GaN.[9] To compare the I–V curves of these two samples conveniently, the results at 100 K, 120 K and 300 K are summarized in Fig. 2(c). It is found that sample A shows a lower forward voltage than sample B, especially at low temperature. For example, at the injection current of 75 mA, the forward voltage of sample A is 2.21 V at 300 K and 2.82 V at 100 K, and the forward voltage of sample B is 2.56 V at 300 K and 3.80 V at 100 K. The difference in forward voltage is attributed to the increased growth temperature of the superlattice. In previous studies, it has been reported that the size of V-shaped pits in MQW has a significant influence on the forward voltage and the sample with larger size of V-shaped pits has lower forward voltage on account of the V-shaped pits enhancing the hole injection into MQWs.[10] Therefore, to make clear the possible physical mechanisms of a lower forward voltage in sample A, it is essential to investigate the dependence of the size of V-shaped pits on the growth temperature of superlattice in these two samples.

It is noted that the extent of the Al element tailing in the secondary ion mass spectrometer (SIMS) profiles of GaN-based LEDs can be used to indirectly estimate the average size of V-shaped pits.[10] Thus to obtain the average size of V-shaped pits in two samples, the SIMS measurements are carried out utilizing a CAMECA IMS 7f instrument. The SIMS profiles of samples A and B are displayed in Fig. 2(d). The In profile of sample A is similar to that of sample B and thus not shown. It is revealed from Fig. 2(d) that there is a visible distinction in the Al profile between these two samples. Compared with sample B, sample A shows the deeper extent of the Al element tailing. It implies that sample A possesses a larger average size of V-shaped pits than sample B. Therefore, based on the above experimental data, the result that sample A has a lower forward voltage than sample B can be explained in terms of the existence of the larger average size of V-shaped pits.

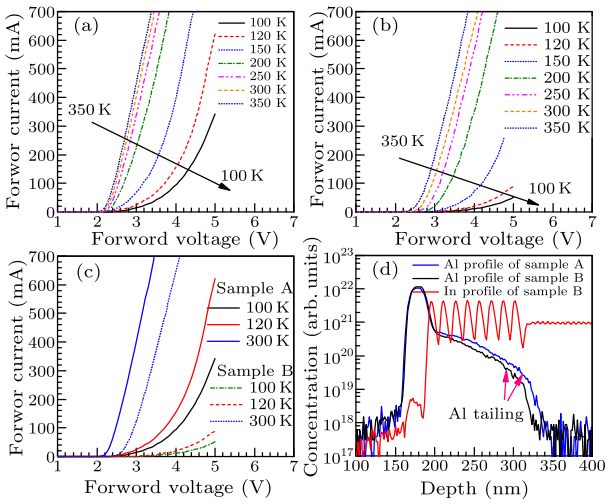

Fig. 2. Measured I–V curves at various temperatures for (a) sample A and (b) sample B. For comparison, I–V curves of two samples at 100 K, 120 K and 300 K are summarized in (c). (d) SIMS profiles of samples A and B.

The IQE as a function of the current density for two samples over a wide temperature range from 100 K to 350 K, plotted in semi-log scale, has been displayed in Fig. 3. The maximum IQEs of these two samples are normalized in Fig. 3. It can be clearly found that, as the temperature decreases from 350 K to 100 K, the IQE peak shifts toward lower current density and the IQE peak increases. This behavior denotes that defects (mainly point defects) in the MQW active region serving as nonradiative recombination centers are responsible for nonradiative recombination via the Shockley–Read–Hall (SRH) process, which is reduced rather monotonically with decreasing temperature due to the nature of the defects of freezing-out.[11] However, it is observed that when the operating temperature decreases to 150 K, the IQE curves for the two samples show an obvious difference. Compared with sample A, sample B appears to have a relatively severer efficiency droop as the current density increases. Also, this behavior becomes more significant with further temperature decreasing. In fact, it is practically common that many factors, such as SRH nonradiative recombination[3] and the Auger recombination,[2] may account for a more serious efficiency droop. However, since the nonradiative recombination via the SRH process is suppressed at low temperature, the server efficiency droop in sample B should not be relevant to the nonradiative recombination at defects. Additionally, because the difference in efficiency droop begins to appear at low current density (about 2 A/cm^2), the Auger recombination mechanism cannot also be the main factor in explaining the server efficiency droop

in sample B. Therefore, one can guess that there are other factors causing the IQE curves distinction between these two samples at low temperature.

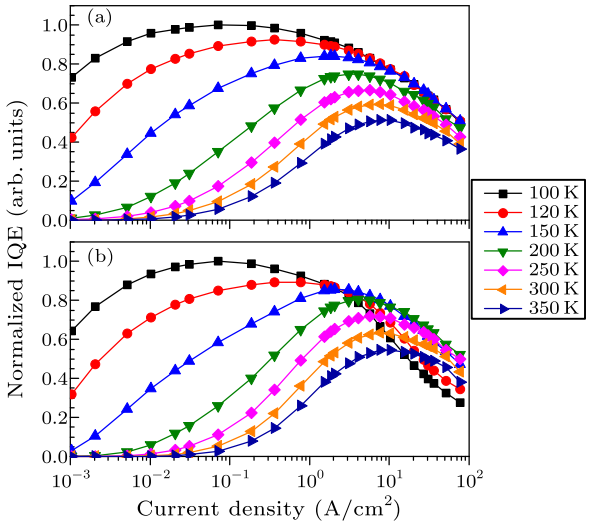

Fig. 3. Measured normalized IQE as a function of the current density at temperature between 100 K and 350 K, plotted in semi-log scale for (a) sample A and (b) sample B.

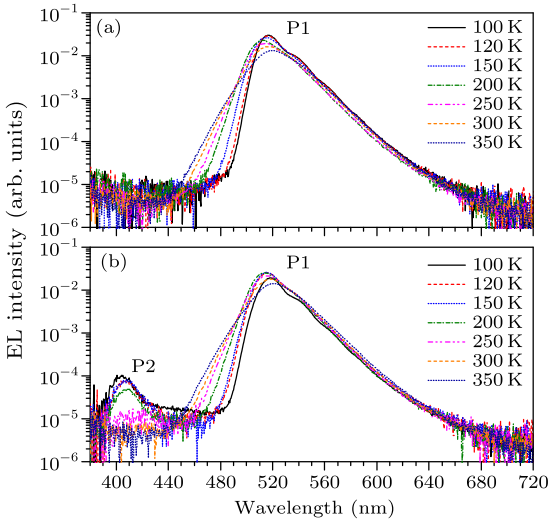

Fig. 4. Experimental results of EL spectra at 20 A/cm^2 for (a) sample A and (b) sample B measured at different temperatures and plotted in semi-log scale.

Figure 4 depicts the EL spectra measured at 20 A/cm^2 under different temperatures plotted in semi-log scale for two samples. As shown in Fig. 4, the phonon replicas become apparent at 120 K and 100 K, which indicates that these two samples are of high crystal quality. In sample A, only the main emission peak of c-plane MQW (P1) is observed as the temperature is lowered from 350 K. However in sample B, an extra short-wavelength emission peak (P2) emerges around 410 nm and its peak intensity increases with decreasing the temperature. The P2 is identified as originating from the Mg-related transitions in p-GaN caused by electron overflow from the InGaN/GaN active region to p-GaN.[12] Normally, it is believed that the P2 becomes more remarkable resulting in the severer efficiency droop.[6] Therefore, combining these EL spectra with the IQE curves, we can infer that the severer efficiency droop for sample B at low temperature demonstrated in Fig. 3 should be mainly attributed to the electron overflow to the p-GaN.

A remaining question is why sample B suffers the serious electron overflow at low temperature but not in sample A. We suggest that the electron overflow observed in sample B can principally be attributed to the following two reasons. Firstly, as mentioned above, with the growth temperature of the superlattice increasing from 855℃ to 895℃, the size of V-shaped pits decreases. Due to the V-shaped pits entirely being filled by p-GaN, sample B with smaller V-shaped pits has less spatial occupancy of p-GaN and thus leads to the smaller area of hole injection. On the other hand, since the resistance of p-AlGaN electron blocking layer (EBL) on the *c*-plane MQW is higher than that on the sidewall MQW at low temperature, the holes flow into MQW primarily via the sidewall of the V-shaped pit.[13] However, compared with sample A, sample B has a higher resistance of the EBL on the sidewall MQW because of a shorter length of the sidewall of the V-shaped pit causing the higher operating voltage demonstrated in Fig. 2(c), which may impact the hole injection into MQW via the sidewall of V-shaped pit negatively. Consequently, the hole injection into MQW in sample B is poorer than that in sample A, combined with a decreasing nonradiative recombination rate at low temperature, which result in the serious electron overflow to p-GaN. Secondly, with the higher growth temperature of the superlattice in sample B, the strain-induced piezoelectric field in the InGaN/GaN MQW active region becomes higher, which is confirmed by reciprocal space mapping (RSM) measurements. Figure 5 demonstrates the RSM of GaN (105) reflector for samples A and B, carried out by high resolution x-ray diffraction (HRXRD) produced by PANalytical. The black, pink and red solid dots represent the actual diffraction peak positions of GaN, superlattice and MQW, respectively. The vertical dashed line represents the fully strained axis. In RSM of GaN (105) reflector, the vertical distance between GaN peak and InGaN peak has been usually used to estimate the In composition of InGaN. It is normally acknowledged that the larger the vertical distance is, the higher the In composition is. In Fig. 5, the vertical distance between the GaN peak and the peak of superlattice of sample A is much larger than that of sample B, which implies the higher In composition of superlattice. However, the vertical distance between the GaN peak and the first peak of MQW of sample A is nearly identical to that of sample B, which indicates the same In composition of MQW in these two samples. On the other hand, it can be perceived

that the smaller horizontal shift of the peak of superlattice with respect to the GaN peak is observed in the sample B, indicating the lower strain relaxation. For example, the strain relaxations of superlattice are 16.06% and 8.53% for samples A and B, respectively. Based on this, the MQW of sample B grown on a superlattice with a lower strain relaxation will suffer a larger stress, which can result in a huger piezoelectric field. As a result of the huger piezoelectric field in sample B, the energy band bending is more serious and the spatial overlap of electron and hole wavefunctions is smaller,[14] causing the more reduced effective active volume than that in sample A. The radiative recombination rate in this poorer effective active volume is rapidly saturated at low injection current density, and the excess electrons not recombined in the QW tend to overflow into the p-GaN. Additionally, with the greater piezoelectric field in sample B, the restricted function of MQW on carriers becomes weaker,[14] which causes the tendency of the overflow to be reinforced. Also, due to the more serious energy band bending, sample B has a lower effective barrier height for electron injection from n-GaN to p-GaN causing electrons to overflow seriously. Therefore, for these reasons, sample B with 895℃ growth temperature of superlattice suffers a serious electron overflow at low temperature.

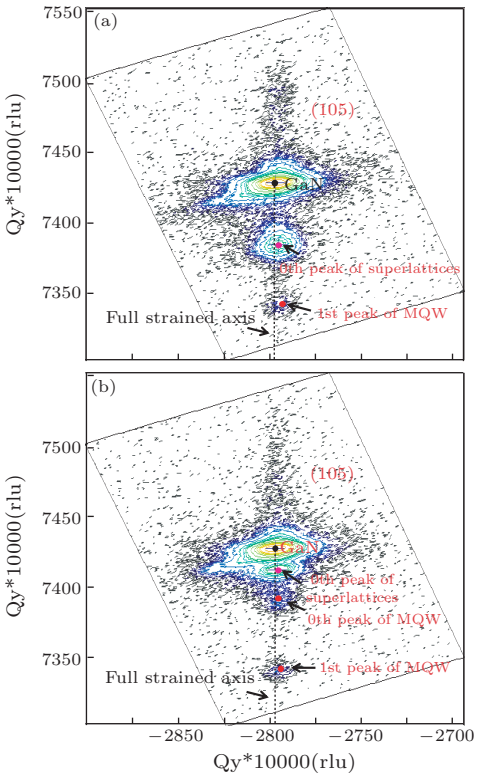

Fig. 5. RSM of the x-ray diffraction intensity around (105) reflector for (a) sample A and (b) sample B.

In summary, two InGaN-based green LEDs with different growth temperatures of superlattice grown on Si substrates have been designed and manufactured. The temperature-dependent EL measurements show that the sample with lower growth temperature of superlattice has a lower forward voltage, especially at low temperature, which should be attributed to the existence of the larger average size of V-shaped pits. Furthermore, as the temperature is decreased to the cryogenic region (about 100 K–150 K), the efficiency droop in the sample with higher growth temperature of superlattice is more serious than that in the sample with lower growth temperature of superlattice. In accordance with the EL spectra, we infer that this severer droop at low temperature can be ascribed to electron overflow, which is caused by the poorer hole injection into MQW and the smaller effective active volume in the active region. Hence, to reduce the efficiency droop, one should try to suppress the electron overflow from MQW into p-GaN. Suppression of the electron overflow requires the hole injection improvement and effective active volume enhancement by enlarging the size of V-shaped pits and reducing the piezoelectric field. The outcomes obtained in this study provide a feasible proposal on designing a more efficient LED structure with lower voltage and less droop.

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