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Research Article

Effect of Trapezoidal-Shaped Well on Efficiency Droop in InGaN-Based Double-Heterostructure Light-Emitting Diodes

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We investigated the effects of different well shapes on the external quantum efficiency (EQE) and the efficiency droop in wide-well InGaN/GaN double-heterostructure light-emitting diodes. For forward current densities in the measurement range of greater than 135 A/cm^2, the device featuring a trapezoidal well exhibited improved EQEs and alleviative efficiency droop, relative to those of the device featuring a rectangular well. The decreased Auger loss has been proposed as the main reason for the greater maximum efficiency that occurred at high current density (>50 A/cm^2). For the devices incorporating trapezoidal and rectangular wells, the EQEs at 200 A/cm^2 decreased by 14 and 40%, respectively, from their maximum values, resulting in the EQE at a current density of 200 A/cm^2 of the device featuring a trapezoidal well being 17.5% greater than that featuring a rectangular well. These results suggest that, in addition to the decreased Auger loss, the alleviation in efficiency droop at higher current densities might be due to higher internal quantum efficiency resulted from the improved carrier injection efficiency of the trapezoidal well.

1. Introduction

Research and development related to InGaN-based light-emitting diodes (LEDs) is currently of very high interest because of their applications as replacements for conventional lighting devices, including incandescent light bulbs, fluorescent lamps, and automotive head lamps. Many applications in the solid state general lighting industry require high light-output power, which can be achieved using a higher input current. Typical InGaN-based LEDs suffer, however, from a decrease in external quantum efficiency (EQE) at high injection current densities; this well-established phenomenon is known as "efficiency droop." To ensure that InGaN-based LEDs will be suitable for application in high-power solid state general lighting, it is imperative to overcome the efficiency droop phenomenon. Experimental and theoretical studies have suggested several different mechanisms to explain the phenomenon of efficiency droop, including carrier delocalization from In-rich clusters [1], junction heat [2], decreased injection efficiency [3], Auger loss [4, 5], polarization mismatches [6, 7], current rollover [8–10], defect-related tunneling [11], and interface states [12]. Although the Auger loss mechanism has been proposed to cause the efficiency droop in experiments using InGaN/GaN double-heterostructure (DH) active regions [4, 5], it is expected to be very small in semiconductors having wide band gaps, as has been verified using many-body models [13]. Nevertheless, according to the concept of carrier leakage from multiple quantum wells (MQWs), caused by the polarization field, the efficiency droop can be minimized when using AlInGaN, AlGaN, AlInN barriers or InGaN/GaN multilayer barriers [7, 14–16]. In addition, the efficiency droop can be improved by employing a trapezoidal well (TZW) in the MQWs active region to replace the conventional rectangular well [17]. The EQEs of these two differently shaped wells cross each other at 5 A/cm^2, which is a very low value when compared with previous results. It was suggested that the use of the trapezoidal well improved the internal quantum efficiency, with enhanced overlap of the electron and hole wave functions, due to a lower piezoelectric field at high current densities.

At present, most studies on the efficiency droops of LEDs have been made using InGaN/GaN MQWs as the active region; only a few examinations have been made into the mechanisms in InGaN-based DH structures. In this study, we investigated the impacts of trapezoidal and conventional rectangular wells on the efficiency droop phenomena when using a wide-well InGaN/GaN DH structure as the active region.

2. Experimental Procedure

The LED samples used in this study were grown on c-plane (0001) sapphire substrates through atmospheric-pressure metal, organic chemical vapor deposition (AP-MOCVD) in a Taiyo Nippon Sanso reactor system. Trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl), and ammonia (NH_3) were used as source materials for Ga, In, Al, and N atoms, respectively. Silane (SiH_4) and biscyclopentadienyl magnesium (CP_2Mg) were used as the n- and p-type doping sources, respectively. To avoid higher strain-induced piezoelectric fields in the LED structures, an active region having a lower In composition and the EBL of superlattice structure were used; prior to this growth, several calibration runs were carried out for the confirmation of the stoichiometrical ratio in the epilayers, and the estimated composition was determined by using high resolution X-ray diffraction for certifying the exact compositions. A 25 nm thick GaN nucleation layer was grown at 520°C, followed by a 1.3 μm thick undoped GaN layer at 1130°C. Ten-period n-type $Al_{0.2}Ga_{0.8}N$ (2.4 nm)/GaN (2.8 nm) structures were deposited and then a 3 μm thick Si-doped n-type GaN layer was deposited at 1130°C. An active region was grown on the Si-doped n-type GaN layer at 805°C and then 10-period p-type $Al_{0.1}Ga_{0.9}N$ (4 nm)/GaN (4 nm) superlattice structures were deposited as the EBL over the active region. Finally, a 100 nm thick heavily doped p-type GaN contact layer was deposited upon the EBL at 1030°C. Two types of DH active regions were grown, denoted herein as samples A and B. For a valid comparison, the thickness of the InGaN active region was selected to be 10 nm. Sample A (Figure 1(a)) had a DH active region consisting of GaN (2 nm)/$In_xGa_{1-x}N$ (with x ramping from 0 to 0.08) (1 nm)/$In_{0.08}Ga_{0.92}N$ (8 nm)/$In_xGa_{1-x}N$ (with x ramping from 0.08 to 0) (1 nm)/GaN (2 nm). For sample B (Figure 1(b)), the DH active region consisted of GaN (2 nm)/$In_{0.08}Ga_{0.92}N$ (10 nm)/GaN (2 nm). After growing the LED structures, a chip (1 × 1 mm^2) was fabricated through the standard process of lateral electrodes with interposed fingers. The fabricated chips were bonded on the ceramic lead frames of a surface mount-type and encapsulated with epoxy resin. Electroluminescence (EL) was measured using a Light Ports integrating sphere at room temperature in the dc pulse operation mode (pulse width: 100 μs; duty cycle: 1%) to eliminate the self-heating effect.

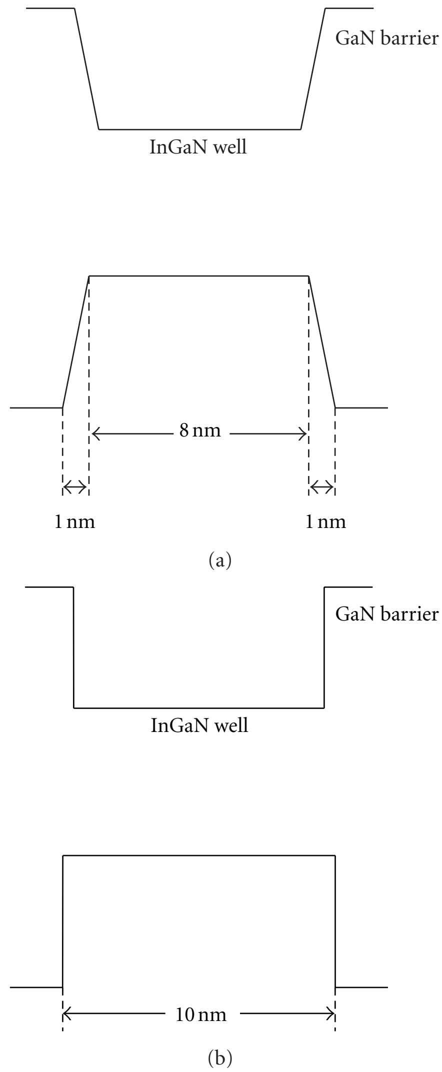

Figure 1: Schematic band diagrams for (a) sample A (trapezoidal well) and (b) sample B (rectangular well).

3. Results and Discussion

Figure 2(a) displays the light output power of samples A and B plotted with respect to the forward current density. The light output powers of both samples underwent sublinear increases upon increasing the current density. The light output power of sample B was greater than that of sample A in the measurement range from 5 to 135 A/cm^2, whereas the light output power of sample A surpassed that of sample B at current densities of greater than 135 A/cm^2. At a current density of 200 A/cm^2, the output power of sample A was 17% greater than that of sample B. Figure 2(b) presents the normalized EQEs of samples A and B plotted with respect to the forward current density. The normalized EQE of sample A increased monotonically from 5 to 100 A/cm^2 and then decreased slightly up to 200 A/cm^2. The normalized peak efficiency was 82%, decreasing to 70.5% at 200 A/cm^2. For sample B, the normalized EQE reached a maximum (100%) at 65 A/cm^2 and then decreased monotonically to 60% at a current density of 200 A/cm^2. Thus, the EQEs of samples A and B decreased from their peak values by 14 and 40%, respectively. Notably, however, sample A featuring a trapezoidal well, which exhibited an improved EQE and a significantly alleviated efficiency droop, relative to those of sample B, at forward current densities greater than 135 A/cm^2.

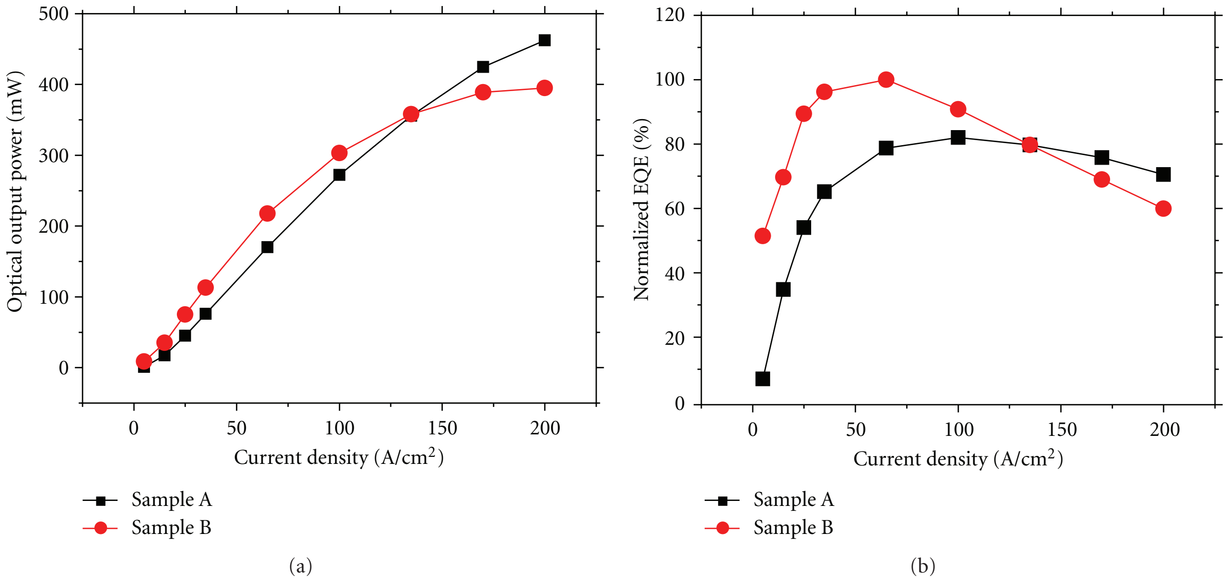

FIGURE 2: (a) Light output power and (b) normalized EQE of LED samples A and B, plotted with respect to the forward current density.

To delineate the efficiency droop phenomena occurring in this study, we explored the mechanisms other than decreased Auger loss resulted from a thicker InGaN active region. Although decreased Auger loss might have been mainly responsible for the improvement in maximum efficiency that occurred at a high current density ($>50\,\mathrm{A/cm^2}$) in both samples A and B, the relative efficiency droop of sample B was larger than that of sample A from the maximum value at $65\,\mathrm{A/cm^2}$ up to $200\,\mathrm{A/cm^2}$. Because the thickness of a trapezoidal well in the active region of sample A was 8 nm, narrower than that (10 nm) of a rectangular well in sample B, the Auger loss mechanism alone does not satisfactorily explain the difference in efficiency droop between samples A and B. However, according to calculated results for InGaN/GaN MQW LEDs, the separation of electron and hole wave functions in the active region is decreased significantly in trapezoidal wells [17]. Therefore, the alleviation in the efficiency droop might also be attributable to higher internal quantum efficiencies at higher current densities, that is due to the increased carrier injection efficiency at the graded interfaces in the active region of sample A.

Figures 3(a) and 3(b) present the EL spectra with the forward current density for samples A and B. Samples A and B exhibited blue shifts of their EL peak wavelengths when the forward current density was less than $35\,\mathrm{A/cm^2}$ and red-shifts when the current density was greater than $35\,\mathrm{A/cm^2}$. This blue-shift phenomenon was presumably caused by a decrease in the quantum-confined Stark effect (QCSE) and the band filling effect induced by the applied bias. It has been suggested that the red-shift phenomenon is caused by band gap renormalization at a lower current density for near-UV InGaN-based MQWs LEDs [18] and by a self-heating effect at higher current density [19]. Notably, however, the effect of the current density on the shift of the EL peak wavelength is inconsistent with the tendency of the peak EQE in Figure 2(b). Therefore, we suggest that the improvement of the peak EQE was not partially due to the reduction of the piezoelectric field and the renormalization of the band gap. Moreover, Figure 4 reveals that the forward voltage of sample A was slightly greater than that of sample B. This result violates the notion that using the trapezoidal well would induce a higher barrier to carrier flow than that obtained with a rectangular well; it is inconsistent with previous reports of an InGaN/GaN MQWs LED [17] and the use of an AlInGaN barrier to minimize the polarization mismatch [7]. Thus, we suggest that using the TZW structure would improve the carrier injection efficiency that not only increases the recombination rate, but also mitigates the piling up of unrecombined carriers, that could in turn increases the Auger effect. In other words, the joint effort of reduced Auger loss and improved carrier injection efficiency of structure featuring the active region with the smooth interface should affect the efficiency droop at higher current densities.

4. Conclusions

We have investigated efficiency droop phenomena in wide-well InGaN-based DH LEDs featuring trapezoidal and rectangular active regions. For the sample with trapezoidal well, it exhibited improved EQE and the efficiency droop was alleviated significantly, relative to those for the rectangular well, for current densities in the measurement range of greater than $135\,\mathrm{A/cm^2}$. It had been suggested that decreased Auger loss might be mainly responsible for the improvement in maximum efficiency that occurred at a high current density ($>50\,\mathrm{A/cm^2}$). The EQEs of the trapezoidal and rectangular wells decreased from their maximum values by 14 and 40%, respectively, upon increasing the current density to $200\,\mathrm{A/cm^2}$. Nevertheless, the relative maximum EQEs at

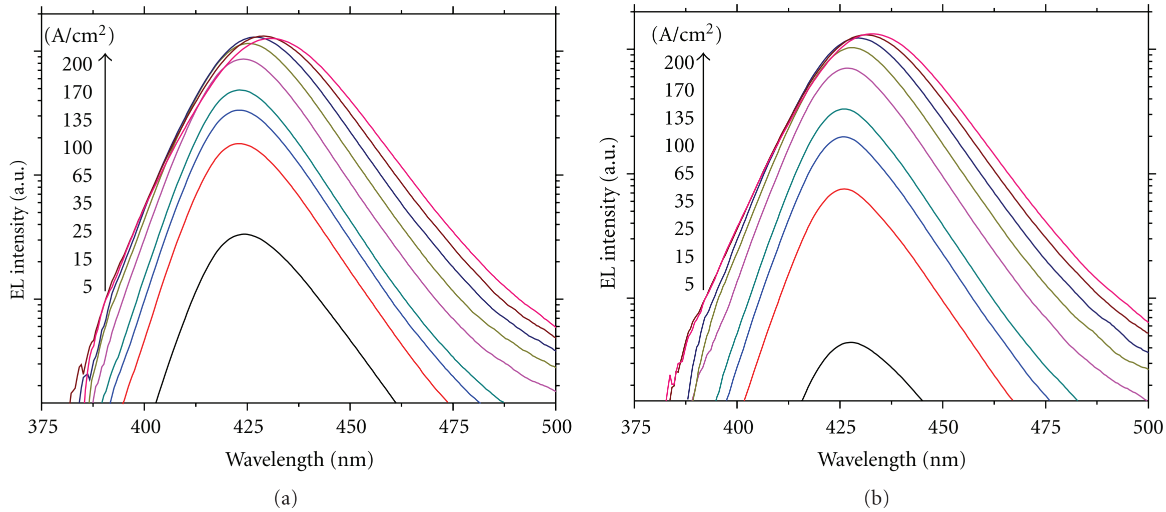

FIGURE 3: EL spectra of (a) sample A and (b) sample B at various forward current densities.

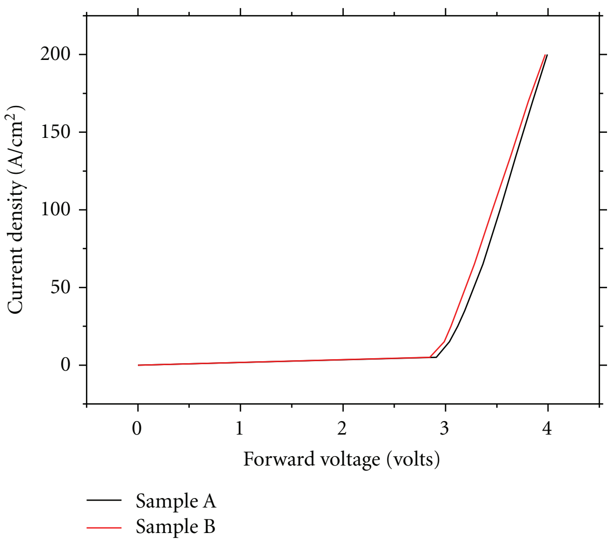

FIGURE 4: Current forward voltage curves of samples A and B.

a current density of 200 A/cm^2 for the DH active regions having trapezoidal and rectangular wells were 70.5 and 60%, respectively. In other words, the EQE for the device featuring a trapezoidal well was 17.5% greater than that featuring a rectangular well at a current density of 200 A/cm^2. We propose that, in addition to the decreased Auger loss, the alleviation in efficiency droop when using trapezoidal-well InGaN-based DH LEDs, at higher current density, might also be attributed to the higher internal quantum efficiency and/or the enhancement of carrier injection efficiency that in turn alleviates the carrier accumulation, wherein, lowers the Auger loss; in summary, both the reduction of the Auger effect and the improvement of the carrier injection efficiency should be as important for the effort of entirely solving the efficiency drooping problem of nitride LED at high current operation.

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