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Improvement of efficiency droop in InGaN/GaN multiple quantum well light-emitting diodes with trapezoidal wells

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Abstract
We investigated InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) with trapezoidal wells to improve the efficiency droop. MQW LEDs with trapezoidal wells showed a lower operating voltage and an improved efficiency droop with a low crossover current density of 5 A cm$^{-2}$, which was a significant improvement over conventional LEDs that use rectangular wells. The external quantum efficiency was increased by 20% at a current density of 70 A cm$^{-2}$. The improvement in efficiency droop of the MQWs with trapezoidal wells can be attributed to an increased internal quantum efficiency due to the enhanced overlap of the electron and hole wave functions at high current densities.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
In InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs), external quantum efficiency (EQE) decreases as injection current increases. This phenomenon is called efficiency droop [1]. Efficiency droop was not a significant issue during the early stages of InGaN/GaN LEDs due to its low operating current density of less than 10 A cm$^{-2}$. However, as the application of LEDs has expanded and their operating current density has increased, efficiency droop has become the main obstacle to achieving highly efficient LEDs operating at high current densities. There are many reports on the efficiency droop in InGaN/GaN LEDs. Electron overflow [1, 2], Auger nonradiative recombination [3], carrier delocalization [4, 5] and low hole injection efficiency [6] were suggested as the major causes of efficiency droop, and various solutions have been proposed to solve efficiency droop at high current densities. A polarization-matched quantum barrier [7] and a double heterostructure [8] were proposed to solve the electron overflow and Auger nonradiative recombination, respectively. In addition, Mg-doped quantum barriers and very thin barriers with a thickness of 3 nm have been suggested as ways to improve the low hole injection [9–11]. The suggestions for electron overflow and low hole injection efficiency are related to the reduced carrier injection efficiency and the Auger nonradiative recombination is related to the reduced internal quantum efficiency (IQE) at high current densities. Although there are many reports on the origin of efficiency droop, and on solutions for its improvement, the crossover current density of EQE between the reference LED and the improved LED was relatively large. The current densities of high power LEDs of size 1 × 1 mm$^2$ operating at currents of 350 mA (1 W level chip) and 700 mA (3 W level chip) are 35 A cm$^{-2}$ and 70 A cm$^{-2}$, respectively. In a previous report on the improvement of efficiency droop, the crossover current...
density was about 40 A cm\(^{-2}\), and the improvement of EQE was almost negligible at 35 A cm\(^{-2}\) and 9% at 70 A cm\(^{-2}\) [7]. In other reports, an improvement of EQE at 35 and 70 A cm\(^{-2}\) was negligible because crossover current density was almost 80 A cm\(^{-2}\) [8]. In this study, we have demonstrated InGaN/GaN MQW LEDs with trapezoidal wells that improved the efficiency droop showing a very low crossover current density of 5 A cm\(^{-2}\).

2. Experimental details

Metalorganic chemical vapour deposition (MOCVD) was used to grow InGaN/GaN MQW LEDs on a (0001) sapphire substrate. The sapphire substrate was cleaned in H\(_2\) at 1070 °C, followed by the growth of a 30 nm-thick low temperature GaN buffer layer at 570 °C. After high temperature annealing of the buffer layer, 5 \(\mu\)m-thick undoped GaN and Si-doped n-GaN layers were grown at a temperature of 1150 °C. InGaN/GaN MQWs with five pairs of undoped InGaN wells grown at 820 °C and undoped 7 nm-thick GaN barriers grown at 900 °C were grown on an n-GaN layer. For a comparative study, two types of LEDs were prepared. In LED A, the quantum well has a conventional rectangular-shaped well with a thickness of 2.5 nm, as shown in figure 1(a). In LED B, the quantum well has a trapezoidal-shaped well with a thickness of 1.5 nm/0.5 nm/1.5 nm composed of graded well/flat well/graded well, respectively. As shown in figure 1(b), the In composition in the well increases linearly and remains constant and decreases linearly. The In composition was controlled by the linear control of the flow rate of trimethylindium (TMIn). The TMIn flow rate was linearly increased from 20 to 900 sccm and maintained constant and linearly decreased again. During the change in the TMIn flow rate, the growth temperature was maintained at 820 °C. After the growth of a MQW, a p-AlGaN electron blocking layer with a thickness of 40 nm was grown, followed by a p-GaN layer. To fabricate the LEDs of size 550 \(\times\) 550 \(\mu\)m\(^2\), the p-GaN layer and MQW were etched using inductively coupled plasma until the n-GaN was exposed for n-contact. An indium tin oxide (ITO) layer was used as a transparent conducting layer on p-GaN. The dominant wavelength of electroluminescence of the LEDs was 440 nm at 20 mA. The light output power of the unencapsulated LEDs was measured in an integrating sphere at room temperature in pulse mode with a pulse duration time of 1 ms to minimize the heating effect.

3. Results and discussion

Figure 2(a) shows the current–voltage (\(I–V\)) curves of the LEDs. The forward voltages of LED A and LED B at 200 mA are 4.15 V and 4.07 V, respectively, and the calculated series resistances are 5.2 \(\Omega\) and 4.8 \(\Omega\), respectively. LED B shows a lower forward voltage and series resistance, indicating that the carrier transport in the MQW region is improved. The \(I–V\) curves are plotted in the semilogarithmic scale, as shown in figure 2(b), to examine the reverse current characteristic. At \(-10\) V, the reverse currents of LED A and LED B are 3.4 \(\mu\)A and 1.7 \(\mu\)A, respectively. Although both LEDs show good reverse current characteristics, LED B shows a lower reverse current than LED A at \(-10\) V. The lower series resistance is attributed to an improved carrier transport due to the graded In well layer. The graded In well layer is believed to decrease the heterojunction barrier between the well and the barrier compared with an abrupt junction [12].

Figure 3 shows the light output powers of LED A and LED B as a function of current density. In both LED A and LED B, output power increases sublinearly as current density increases. As shown in figure 3(a), LED A shows a higher output power than LED B at low current densities below 5 A cm\(^{-2}\), but the output power of LED B surpasses that of LED A at current densities above 5 A cm\(^{-2}\), as shown in figure 3(b). We calculated the EQE to compare the efficiency droop of the two LEDs. The EQEs of LED A and LED B are shown in figure 4. LED A shows a maximum EQE of 30.5% at a current density of 2 A cm\(^{-2}\) and LED B shows a maximum EQE of 30.6% at 12 A cm\(^{-2}\). At current densities...
of 35 A cm$^{-2}$ and 70 A cm$^{-2}$, which correspond to injection current levels of 350 mA and 700 mA, respectively, with LEDs of size 1 $\times$ 1 mm$^2$, the EQEs of LED A and LED B are calculated to be 23.9% and 28.4% at 35 A cm$^{-2}$ and 20.8% and 24.9% at 70 A cm$^{-2}$, respectively. In comparison with LED A, the EQE of LED B is improved by 19% at 35 A cm$^{-2}$ and by 20% at 70 A cm$^{-2}$. The EQEs drop by 32% and 19% for LED A and LED B at 70 A cm$^{-2}$ as compared with their maximum EQEs, and the current density of maximum EQE shifts to a higher value for LED B. The EQEs of LED A and LED B cross each other at 5 A cm$^{-2}$. The crossover current density of 5 A cm$^{-2}$ is a very low value when compared with the crossover current densities reported in previous studies [7, 8].

To explain the improved efficiency droop in LED B, the energy band diagrams of LED A and LED B were calculated, as shown in figures 5(a) and (b), and the electron and heavy hole wave functions in the well adjacent to p-GaN were also calculated at 70 A cm$^{-2}$, as shown in figures 5(c) and (d), using LED simulator SiLENSe 4.0. In LED A, the conduction and valence bands of the InGaN well layers are largely bent due to the piezoelectric fields in the well and barrier layers and the energy minimum of the conduction band and the energy maximum of the valence band are largely separated, as shown in figure 5(a). In LED B, the conduction and valence bands of the InGaN well layers are not seriously bent due to the trapezoidal shape of the wells, and the energy minimum of the conduction band and the energy maximum of the valence band are closer in LED B than those in LED A, as shown in figure 5(b). Consequently, the separation of electron and hole wave functions in the wells is much reduced in LED B. The calculated electron and heavy hole wave functions of LED A and LED B are shown in figures 5(c) and (d). The calculated overlaps of electron and heavy hole wave functions in the well adjacent to p-GaN in LED A and LED B are 37.2% and 41.6%, respectively, and the distances between the maxima of electron and hole wave functions are calculated to be 1.5 nm and 1.1 nm for LED A and LED B, respectively. This result indicates
that LED B has a higher IQE at high current densities due to the increased overlap of electron and hole wave functions, which is caused by the decreased piezoelectric field between the InGaN well layer and the GaN barrier layer. Interestingly, it has been reported that the increased volume of a well can improve efficiency droop [8, 13]. In our study, however, LED B with trapezoidal well showed an improved efficiency droop, although the volume of the well was decreased by 20% compared with that of LED A. This indicates that the decreased piezoelectric field in trapezoidal wells at high current densities has a more dominant effect on the improvement of efficiency droop compared with the nonradiative Auger effect. However, it was reported that nonpolar LEDs grown on m-plane GaN substrate, which have a better overlap of electron and hole wave functions due to the absence of polarization field in the MQW region, still show significant efficiency droop and this may be attributed to the large forward voltage of 6.4 V at 20 mA [14]. In the present study, the decreased volume of the well could enhance carrier confinement in the well layer and this result may also contribute to the improved efficiency droop. Although the effect of a trapezoidal well on efficiency droop has not been discussed, it was also reported that trapezoidal well could improve emission efficiency and this was attributed to the formation of denser and more uniform quantum dots in a trapezoidal well than in a rectangular well [15, 16]. Carrier localization in the quantum dot region may be advantageous for a higher efficiency at low current densities, but carriers will be delocalized over the quantum dot region at high current densities, and efficiency droop will not be improved by quantum dot formation in the trapezoidal wells. Therefore, it is believed that the increased IQE can be attributed to an enhanced overlap of electron and hole wave functions at high current densities, which resulted in an improvement in efficiency droop for LEDs with trapezoidal wells.

4. Conclusions

We have demonstrated MQW LEDs with trapezoidal wells to improve efficiency droop at high current densities. The MQW LEDs with trapezoidal wells showed a lower forward voltage and an improved EQE that was 20% higher when compared with MQW LEDs with rectangular well at a current density of 70 A cm$^{-2}$. In particular, a very low crossover current density of 5 A cm$^{-2}$ was observed for the MQW LEDs with trapezoidal wells. The improvement of efficiency droop in LEDs with trapezoidal wells is attributed to an IQE that was increased by an enhanced overlap of electron and heavy hole wave functions at high current densities.

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