Improved performance of GaN-based blue light emitting diodes with InGaN/GaN multilayer barriers

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Multi-layer barrier structure is suggested as an alternative approach to single-layer polarization matching barrier structure for the reduction of efficiency droop. Time resolved photoluminescence measurement showed that polarization field was reduced by 19% in the multilayer barrier light emitting diodes structures. Optical power measurements on packaged devices showed overall increase of external quantum efficiency for all currents up to the current density of 150 $\mathrm{A/cm^2}$. Increase of optical power is attributed to reduced polarization and decreased current overflow to *p*-side cladding layers. These results provide additional evidences that polarization is important in addressing the droop problem. © *2009 American Institute of Physics*. [doi:10.1063/1.3276066]

Recently, the application range of GaN-based light emitting diode (LED) is being greatly widened from mobile phone to general illumination.[1] Now, it becomes more important for LEDs to show high external quantum efficiency (EQE) at driving currents higher than 350 mA for 1 mm × 1 mm chip (35 $\mathrm{A/cm^2}$). The EQE of conventional GaN-based LED, however, is highest at low current density around 10 $\mathrm{A/cm^2}$ and decreases as current increases, which is called *efficiency droop*.[2] Various explanations on the mechanisms of the droop have been proposed, such as carrier leakage from the active region,[2–4] and Auger recombination.[5,6] The origin of the droop, however, is not clearly understood yet. It is necessary to find out which of the suggested mechanisms is the major cause of the droop phenomenon.

According to the authors of Ref. 2, polarization field across InGaN wells leads to band-bending, which makes it more likely that electrons jump across quantum wells and escape into *p*-type cladding layers. As the current increases, such carrier loss also increases and radiative recombination efficiency will decrease. Therefore, reduction of polarization field is a key to overcome the droop problem and polarization matching AlInGaN quaternary barriers or InGaN ternary barriers were suggested as a solution.[2] Generally, however, it is difficult to grow AlInGaN layers with high crystalline quality due to the differences between optimal incorporation conditions for Al and those for In. It was reported that the growth surface of InGaN was rough compared to that of GaN and GaN layers deposited on rough InGaN surface should provide a surface flat enough to maintain reasonably sharp interface and to suppress defect formation in the next deposited layer.[7] Because this procedure is inherently absent in LED structures with InGaN barriers, crystalline quality of active layers might be degraded as more InGaN barriers and wells are deposited repeatedly. Such issues of AlInGaN or InGaN quantum barrier layers have been an obstacle to realize high-efficiency LEDs with quaternary or ternary barriers.

The purpose of this letter is, first, to confirm that polarization is one of the major causes of the droop problem and, second, to describe an alternative approach to polarization matching barrier structure. This approach is designed to overcome crystalline quality issues of polarization matching barriers, to reduce polarization across wells and, as a result, to realize a high-efficiency LED structure.

The distinguishing feature of the alternative approach is the insertion of an undoped GaN layer in the middle of InGaN barrier. The structure is referred to as multi-layer barrier (MLB), since it has three-layer $\mathrm{In_{0.1}Ga_{0.9}N/GaN/In_{0.1}Ga_{0.9}N}$ structure. The additionally inserted GaN layer of MLB structure is expected to provide a better surface for the growth of the next quantum well, thus improving crystalline quality and higher barrier height for better carrier confinement with reduced polarization.

It is necessary to inspect the crystal quality of LED active layers with the MLB structure. Three LED structures with GaN barriers, bulk $\mathrm{In_{0.1}Ga_{0.9}N}$ barriers and MLBs, respectively, were grown without *p*-type cladding layers. Each has a five-pair multi-quantum well (MQW) structure. Upon the last InGaN quantum well, a 5 nm undoped GaN toplayers was deposited, the surface of which was inspected by Dimension 3100 AFM system in tapping mode.

After the deposition of 5 nm spacer GaN layer on top of five-pair MQW, the surface of the GaN top-layer should be flat enough for the deposition of *p*-type cladding layers. As shown in Fig. 1(a), the surface of the conventional MQW structure is filled with steps and dislocation-related black pits. However, Fig. 1(b) shows that there is no step structure visible on the surface of the MQW structures with five $\mathrm{In_{0.1}Ga_{0.9}N}$ barriers. Considering that step structure is essential to grow high quality epilayers in so-called step flow mode, such lack of step structure would lead to poor crystalline quality of *p*-type cladding layers. The large black pits

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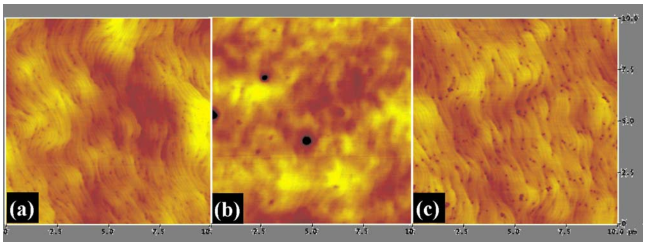

FIG. 1. (Color online) 10 μm × 10 μm AFM images of surface of a GaN layer deposited upon five-pair MQW structure with (a) only GaN barriers, (b) only $In_{0.1}Ga_{0.9}N$ bulk barriers, and (c) only MLBs.

shown in Fig. 1(b) were found everywhere in the wafer. The depth of those pits reached to 10 nm, indicating that those pits penetrate into active layers. It is clear that after the five-times repeated growth of InGaN barriers and wells, the surface of the last well is so rough that even 5 nm growth of a GaN layer failed to provide flat surface ready for the growth of *p*-type cladding layers. In Fig. 1(c), the surface of the MQW structures with five MLBs appears to be similar to that of the conventional MQW except for slightly larger black pits. Step structure of the GaN top-layer is clearly visible. The LEDs with the MLB structure appears to have good crystalline quality comparable to that of the conventional blue LED.

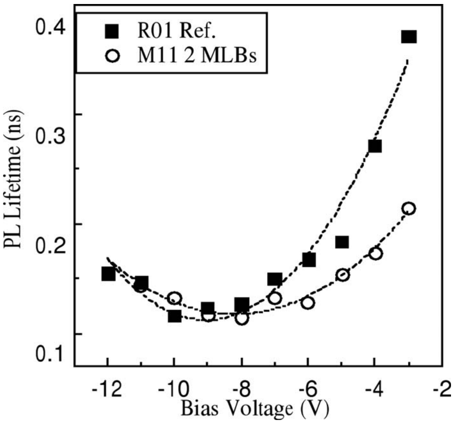

FIG. 2. PL lifetime as a function of bias voltage for the reference LED (R01) and the LED with two MLBs (M11).

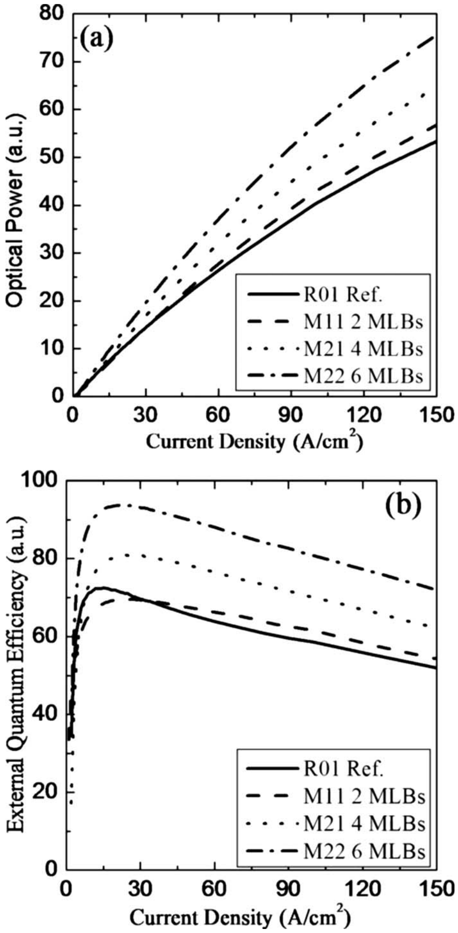

FIG. 3. (a) Optical power as a function of current density and (b) external quantum efficiency of the reference LED and the LEDs with the MLB structure.

As the next step, it is necessary to find out whether this MLB structures actually have reduced polarization, and show decreased efficiency droop. To confirm these, four LED structures (R01, M11, M21, and M22) were grown. All the four LEDs have seven-pair MQW structure. Reference R01 has six GaN quantum barriers, and M11 and M21 have two and four MLBs close to *p*-side, respectively, because it was reported that electron-hole recombination occurred mainly at the quantum well closest to *p*-side.[8] All the barriers of M22 were MLBs. Indium fraction of InGaN layers in MLBs was around 0.1 which was close to the value suggested in Ref. 2 for InGaN barrier. All the LED structures were grown on *c*-plane sapphires using metal-organic chemical vapor deposition method. For all the LED structures, the thickness of each quantum well and barrier was kept the same. Wavelength was tuned to be around 440 nm. Devices with 1 mm × 1 mm size were fabricated from each wafer and optical output power was measured by an integral sphere at current densities up to 150 A/cm^2 using continuous drive at room temperature with the integration time of 10 ms. To evaluate the change of polarization, time-resolved photoluminescence (TRPL) measurement was performed at room temperature using frequency-doubled beam of Ti:sapphire laser as pulsed excitation source.

To measure the polarization field of active layers, bias dependent TRPL analysis was performed on the reference LED (R01) and M11 structures. With the increase of reverse bias, PL lifetime values decreases initially, reaches minimum when band becomes flat and increases again. From the shortest lifetime values and corresponding reverse bias, values of polarization field can be estimated. As shown in Fig. 2, M11 shows the minimum lifetime values at lower reverse bias than those at which R01 shows the minimum lifetime values. This indicates that band-bending across M11 is less than that of R01, and polarization field of M11 is reduced. Thorough TRPL analysis showed that polarization field of an LED with MLBs was actually reduced compared to the reference LED by around 19%,[9] It is confirmed that the MLB structure actually reduces polarization field across wells.

Reduction of polarization across quantum wells will increase optical power in two ways. First, spatial separation between electron and holes in quantum wells will decrease and radiative recombination will increase. This has been confirmed by various approaches, such as an embedded AlGaN δ layer[10,11] or staggered quantum wells.[12–14] Second, according to the theory suggested by the authors of Ref. 2, electron overflow will decrease and efficiency increase. If, when polarization of the well closest to the *n*-side cladding layer decreases, optical power and efficiency increases, the decrease of separation between electrons and holes cannot be the sole reason for the increase of optical power, due to the fact that radiative recombination occurs little at the well closest to *n*-side due to limited hole transport.[8] One possible explanation is decreased electron overflow due to reduced band-bending.

Figure 3(a) shows the optical power from the packaged LED devices measured by an integral sphere as a function of current density. Optical power of M22 reaches to 137% of that of R01 at 35 $\mathrm{A/cm^2}$. Figure 3(b) shows EQE of the LED devices as a function of current density. Efficiency decrease from the peak point to the current density of 35 $\mathrm{A/cm^2}$ diminished from 5.2% of R01 to 1.6% of M22. Efficiency peak of M22 increases by 30% compared to that of R01. When the number of MLBs increased from two to four to six, optical output power and EQE increased. As discussed above, these results strongly indicate that polarization-induced band-bending contributes significantly to the efficiency droop problem. It should be noted that the droop problem does not completely disappear but appears to remain, although at a smaller magnitude. This can be due to the fact that the MLB structure does not eliminate polarization completely, and that the droop mechanism induced by the Auger recombination could be working. The increase of EQE, especially at low current density regime ($<20\ \mathrm{A/cm^2}$), also shows that the MLB structure does not suffer severely defect-related nonradiative recombination at low current regime,[3] indicating that the MLB structure suppressed the formation of nonradiative recombination centers.

In conclusion, the introduction of the MLB structure led to the increase of optical power and EQE in GaN-based blue LEDs. It was hypothesized that the additional GaN layer inserted into InGaN barrier would prevent the formation of additional defects in the active layers and the hypothesis was verified by showing enhanced EQE over the entire current range. Although it is inevitable that the MLBs will have a polarization matching effect that is less than that of bulk quaternary barriers, it was shown that the use of MLB structure increases optical power and decreases the efficiency droop, suggesting that polarization is important in addressing the efficiency droop problem.

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