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Band-edge luminescence in quaternary AlInGaN light-emitting diodes

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Operation of InGaN multiple-quantum-well (MQW) light-emitting diodes (LEDs) with quaternary AlInGaN barriers at room and elevated temperatures is reported. The devices outperform conventional GaN/InGaN MQW LEDs, especially at high pump currents. From the measurements of quantum efficiency and total emitted power under dc and pulsed pumping, we show the emission mechanism for quaternary barrier MQWs to be predominantly linked to band-to-band transitions. This is in contrast to localized state emission observed for conventional InGaN/InGaN and GaN/InGaN LEDs. The band-to-band recombination with an increased quantum-well depth improves the high-current performance of the quaternary barrier MQW LEDs, making them attractive for high-power solid-state lighting applications.
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Nearly all the high-efficiency and high-power purple-blue-green light-emitting diodes (LEDs) use InGaN quantum wells (QWs) with InGaN or GaN[1,2] barrier layers. The use of indium in the active region is shown[3,4] to increase the luminescence efficiency, possibly by partial screening of the piezoelectric field due to the formation of potential minima from the In concentration fluctuations and a carrier capture at the created localized states. The carrier capture at these localized minima is more efficient than nonradiative recombination when their spacing is less than the distance between threading dislocations.

However, high-power LEDs with emission in the ultraviolet region are needed for efficient pumping of phosphors for solid-state white-light applications. These devices require GaN or AlGaN quantum wells surrounded by AlGaN barrier layers with high Al content. To date, attempts to fabricate such multiple-quantum-well (MQW) structures with AlGaN barrier layers[5] have yielded devices with poor luminescence efficiency. In the past, we have shown[6] that this poor luminescence efficiency is caused by an inferior quality of the heterointerfaces and of the barrier AlGaN layers in the MQW region. This poor material quality primarily results from the growth of the AlGaN barrier layers at temperatures ranging from 750 to 850 °C. Exceeding this temperature range results in dissociation and, hence, in the degradation of the InGaN quantum-well quality. Recently, we have demonstrated an approach of using quaternary AlInGaN barrier layers to fabricate high optical quality AlInGaN/InGaN MQWs.[6] We now report on the fabrication of $p-n$ junction LEDs using these MQWs with quaternary barrier layers. We also present the results of a comparative study of optical emission in these as well as in the conventional GaN/InGaN MQW LEDs, both at room and at elevated temperatures. These results are used to establish the mechanism primarily responsible for the optical emission from these LEDs.

The device structure for this study was a $p-n$ junction LED with AlInGaN/InGaN MQW active region. It consisted of a 3-μm-thick Si-doped n^+-GaN layer ($n \sim 5 \times 10^{18}\,\mathrm{cm}^{-3}$) followed by four AlInGaN/InGaN MQWs capped with 200-Å-thick AlGaN layer. The indium composition in the well was about 15%. The Al and In compositions in the barrier layers were kept at 15% and 4%, respectively. Finally, a 0.25-μm-thick Mg-doped p-GaN($p \sim 5 \times 10^{17}\,\mathrm{cm}^{-3}$) layer was used as the hole injector. In addition, we grew three more epilayer structures. The first was identical to the quaternary MQW described above but with GaN layers replacing the quaternary AlInGaN barriers. The other two structures were also similar to the quaternary and the GaN barrier LEDs. However, these were grown without the top AlGaN electron blocking and the p-GaN layers. The MQW region of all the structures had the same layer thickness and the same In composition in the well. For all these cases, we used sapphire substrates and a conventional low-pressure metal–organic chemical-vapor deposition system. The growth details were identical to those described earlier[7] for similar structures used for photoluminescence (PL) studies.

In order to study the effect of quaternary AlInGaN barriers on the quality and on the interface roughness of the MQW layers, we measured the atomic-force microscopy (AFM) surface scans for the two structures without the top p-GaN and the AlGaN electron-blocking layers. These structures differed only in the barrier layer type, which was AlInGaN for the first structure and GaN for the second one. Figures 1(a) and 1(b) show the surface AFM scans for these structures. The use of the AlInGaN barrier layer results in a better surface morphology with the RMS roughness improving from 1.04 nm to only 0.55 nm.

LED structures with a 300 μm$\times$300 μm etched mesa geometry were then fabricated from the two epilayer types described above. We then compared the electrical and optical

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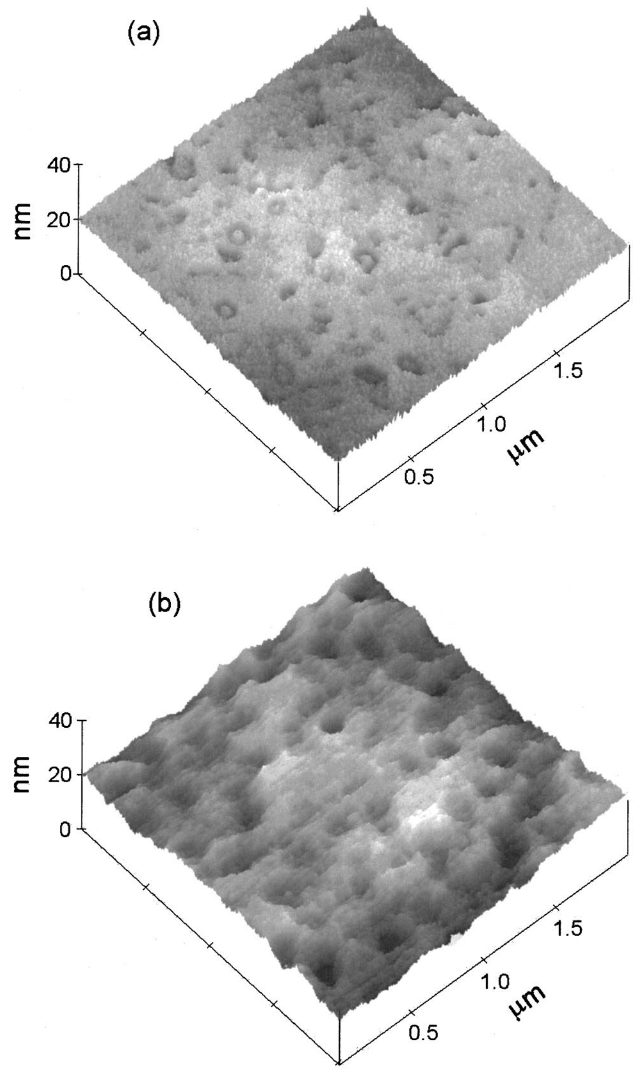

FIG. 1. AFM scans of (a) AlInGaN and the (b) GaN top surface.

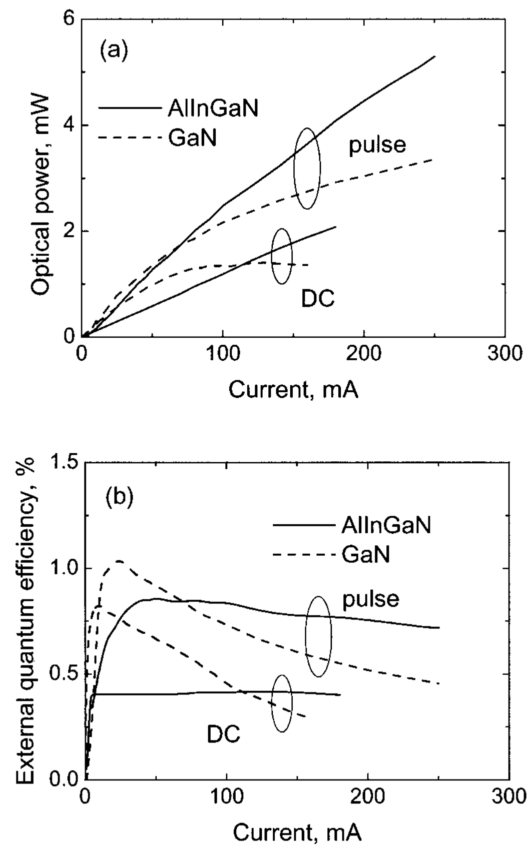

FIG. 2. (a) $L-I$ and (b) $\eta-I$ characteristics of AlInGaN/InGaN and GaN/InGaN MQW LEDs.

characteristics of the quaternary (AlInGaN) and binary (GaN) barrier MQW LEDs. These measurements included current–voltage ($I-V$), optical power versus current ($L-I$), and external quantum efficiency η versus current ($\eta-I$) characteristics. Measurements were made both in dc and the pulsed pumping regimes using pulses of 500 ns duration and a 0.5% duty cycle. The two structures showed very similar forward differential resistance ($\sim$35 Ω) and turn-on voltage ($\sim$3 V). The spectral emission characteristics were also very similar with both LEDs showing a full width at half maximum of 18 nm. Figures 2(a) and 2(b) show the LED $L-I$ and $\eta-I$ characteristics using on-wafer measurements with the light collection from the sapphire substrate side. As seen, for dc pump current above 50 mA, the output power for the GaN barrier LEDs saturates rapidly. This is in contrast to the quaternary barrier LEDs, where the output power increases linearly even up to pump currents as high as 250 mA. This saturation behavior, though less pronounced, still exists under pulsed pumping. The two LED types also exhibit a different dependence of their external quantum efficiency on the pump current. These observations of power saturation for the GaN/InGaN MQW LED cannot be explained by heating because the pulse width of 500 ns is much shorter than our measured characteristic device heating time of approximately 1 ms. The current leakage over the barrier[8] could be also ruled out as a cause for the optical power saturation and the quantum efficiency reduction. Such leakage at very high pump currents leads to carrier recombination in the regions outside the quantum wells. However, for our LED study the pump current density is only about 10 A/cm^2 at 10 mA pump current.

The quantum efficiency decrease shown in Fig. 2 can be understood if the emission mechanism for the GaN/InGaN MQW LED is the excitonic recombination from localized states formed by the indium variation in the QW. In this case, the carrier capture into localized states followed by emission is more efficient (faster) than the nonradiative recombination. However, since the density of these localized states is limited, at higher pumping levels, the nonradiative recombination (caused by the large number of defects) decreases the quantum efficiency.[9] It also saturates the total output power. We believe that this mechanism explains our data shown in Fig. 2.

In contrast, as can be seen from Fig. 2, the quantum efficiency for the quaternary barrier LED remains nearly constant at high pump currents after the initial increase. This behavior is similar to the behavior observed for other III–V semiconductors,[10] where the band-to-band recombination in the MQW region is the dominant emission mechanism. Thus, based on our data from Fig. 2 and on the results of our previous PL study,[7] we conclude that the dominant emission mechanism for LEDs with AlInGaN barrier layers is the band-to-band radiative recombination in the quantum-well layers.

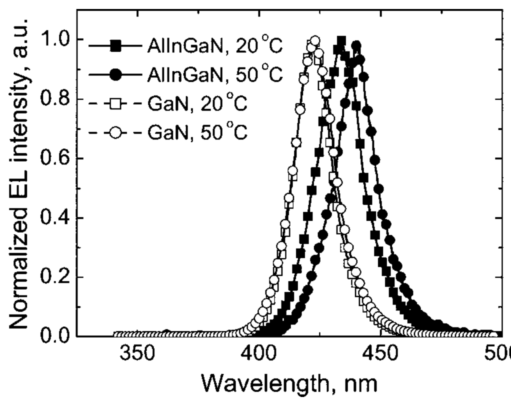

FIG. 3. Emission spectra of AlInGaN/InGaN and GaN/InGaN MQW LEDs.

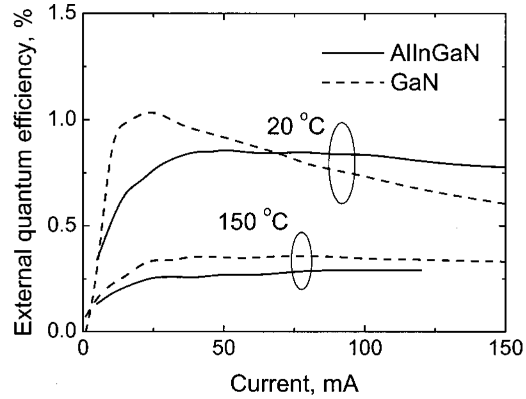

FIG. 4. $\eta - I$ characteristics of AlInGaN/InGaN and GaN/InGaN MQW LEDs.

In order to confirm the different emission mechanisms in the two LED types, we studied their spectral emission as a function of temperature. These spectra measured at room temperature and 50 °C using 100 mA current pulses are shown in Fig. 3. As can be seen, the peak emission wavelength is nearly constant for the GaN/InGaN MQW LED. However, the peak emission wavelength redshifts with temperature by about 6 nm for the AlInGaN/InGaN LEDs. Similar behavior of the luminescence properties of GaN/InGaN MQW LED structures as a function of temperature was observed for different In composition in the QW.[9] This behavior arises from a different emission mechanism for the LED with low- and high-indium composition. For the low-In MQWs, they suggested a band-to-band emission mechanism, since, in this case, the energy position of the states responsible for optical transitions redshifts with temperature (band-gap shrinkage). This results in a redshift of the peak emission wavelength. However, for the high-In MQW, the emission is dominated by carrier recombination through a large number of localized energy states caused by In-composition fluctuations in the (InGaN) quantum-well layer. At elevated temperatures, the carrier redistribution over high-energy states compensates for the band-gap shrinkage. Thus, the emission spectra are insensitive to a temperature rise. Using the same reasoning and based on the data shown Fig. 3, we conclude the dominant emission mechanism for our quaternary (AlInGaN) barrier LEDs to be band to band. This is in contrast to the GaN/InGaN MQW LEDs, which have the emission dominated by localized states.

Finally, we measured the $\eta - I$ characteristics of our LEDs at 150 °C using pulsed pumping. These data are presented in Fig. 4, along with the room-temperature $\eta - I$ data of Fig. 2(b). As can be seen, both samples show a nearly identical reduction in the external quantum efficiency with temperature. This, we believe, is caused by an increased carrier escape from the QWs and/or by the enhanced nonradiative recombination. At high temperature, the efficiency of the GaN barrier LED not only decreases but also becomes constant for high pump currents. This behavior is similar to that for the quaternary barrier samples. At elevated temperatures, a stronger carrier escape makes recombination through the localized states less efficient, thereby enhancing band-to-band transitions and making these transitions the dominant emission mechanism for both LED types.

In summary, we report the fabrication of $p - n$ junction LEDs using AlInGaN/InGaN MQWs and show their optical emission mechanism to primarily arise from band-to-band transitions. In contrast, for conventional GaN/InGaN MQW LEDs, optical transitions from recombination at localized states caused by indium composition fluctuations in the InGaN quantum well are dominant. We also show that the use of quaternary barriers significantly improves the MQW layer quality and interface roughness. These quaternary active layers are a prerequisite for the fabrication of high-efficiency ultraviolet light-emitting diodes for solid-state white lighting.

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