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Polarization-matched GaInN/AlGaInN multi-quantum-well light-emitting diodes with reduced efficiency droop

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Blue multi-quantum-well light-emitting diodes (LEDs) with GaInN quantum wells and polarization-matched AlGaInN barriers are grown by metal-organic chemical vapor deposition. The use of quaternary alloys enables an independent control over interface polarization charges and bandgap and has been suggested as a method to reduce electron leakage from the active region, a carrier loss mechanism that can reduce efficiency at high injection currents—an effect known as the efficiency droop. The GaInN/AlGaInN LEDs show reduced forward voltage, reduced efficiency droop, and improved light-output power at large currents compared to conventional GaInN/GaN LEDs. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2963029]

Typical GaInN light-emitting diodes (LEDs) are characterized by a substantial decrease in efficiency as injection current increases. This phenomenon—known as efficiency droop—is a severe limitation for high power devices that operate at high current densities and must be overcome to enable the LEDs needed for solid-state general illumination. The efficiency droop is caused by a nonradiative carrier loss mechanism, which is small at low currents but becomes significant for high injection currents. Competition between radiative recombination and this droop-causing mechanism results in the reduction in efficiency as current increases. The physical origin of efficiency droop remains controversial, and several different mechanisms have been suggested as explanations, including carrier leakage from the active region,[1–4] Auger recombination,[5,6] junction heating,[7] and carrier delocalization from In-rich low-defect-density regions at high carrier densities.[8,9]

Carrier leakage in GaInN LEDs generally refers to the escape of electrons from the active region to the *p*-type region. These leakage electrons may then recombine with holes either in the *p*-type region or at the contacts, dominantly by nonradiative processes. Necessarily, therefore, fewer holes than electrons are injected into the active region. These two phenomena—escape of electrons form the active region and reduced hole injection—are components of any carrier leakage explanation for droop. However, it is not clear which is cause and which is effect; both have been proposed. Hole injection into the active region may be the limiting factor, possibly due to the low *p*-type doping efficiency or the electron-blocking layer (EBL) acting as a potential barrier also for holes. As a result of the low hole injection, current across the device is dominated by electrons. Devices with *p*-type active regions—which should increase hole injection efficiency—have been proposed as a solution to this problem.[3,4] The alternative explanation is that the active region and EBL structure inadequately confine electrons to the active region and that the electrons escape to the *p*-type side where they recombine nonradiatively with holes before the holes ever have the chance to reach the active region.[1]

Previous studies have indicated that electron leakage from the active region is enhanced by sheet charges at heterointerfaces that result from polarization mismatch between layers in a conventional LED active region.[1] For example, at the interface between the GaN barrier and AlGaN EBL in the active region of a conventional LED, there exists a positive sheet charge, which is attractive to electrons. As a result, the conduction band of the EBL is pulled down, which reduces the effective barrier height for electrons. To reduce carrier leakage, active region designs, which include quaternary AlGaInN barriers in place of the conventional GaN barriers, have been proposed.[1]

Figure 1 shows constant-bandgap and constant-polarization-charge contours over a range of compositions for AlGaInN layers grown pseudomorphically on relaxed GaN. The bandgap and polarization charge for a given com-

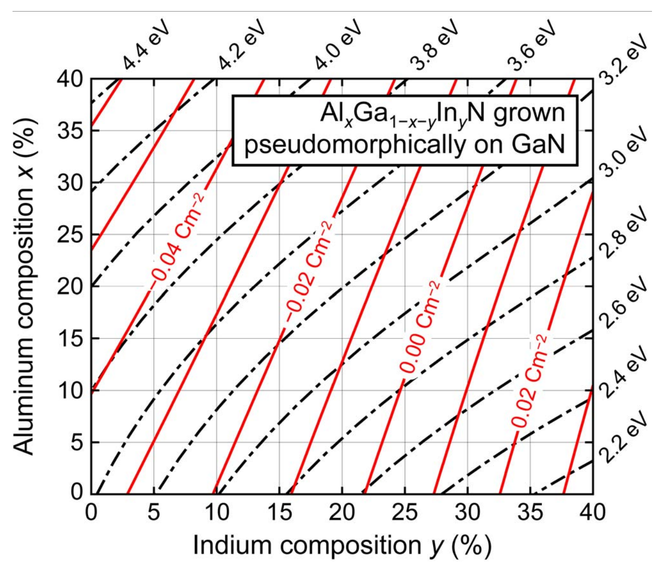

FIG. 1. (Color online) Ga-face polarization charge (red) and bandgap (black dashed) contours of quaternary $Al_xGa_{1-x-y}In_yN$ grown pseudomorphically on GaN substrates.

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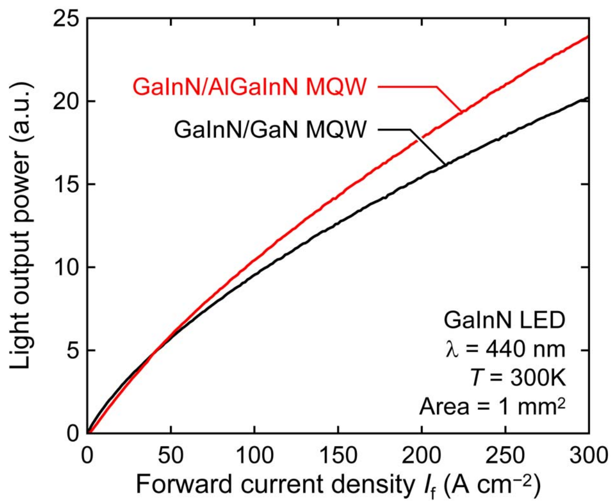

FIG. 2. (Color online) Light output power as a function of forward current density for GaInN/AlGaInN MQW LEDs and reference GaInN/GaN MQW LEDs.

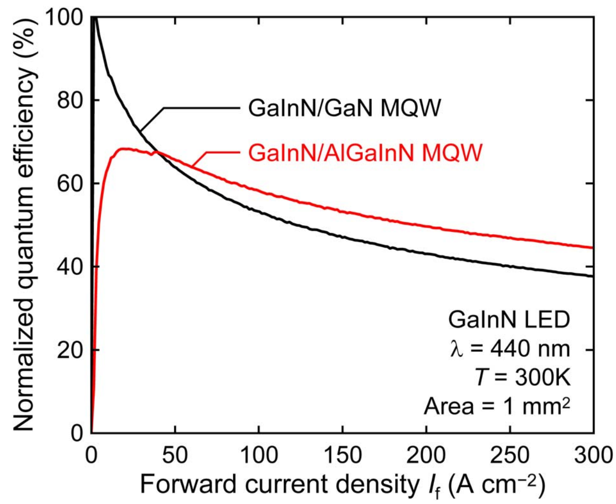

FIG. 3. (Color online) Normalized external quantum efficiency as a function of forward current density for GaInN/AlGaInN MQW LEDs and reference GaInN/GaN MQW LEDs.

position is calculated as described in Ref. 1. For layers composed of ternary AlGaN or GaInN, the polarization charge for a layer with a certain bandgap is fixed. Using quaternary AlGaInN instead introduces an additional degree of freedom, which allows the polarization charge to be tuned over a range of values while keeping the bandgap constant. Therefore, LEDs incorporating quaternary barriers can offer reduced polarization sheet charges at the interface between quantum well and barrier and, as a result, reduced carrier leakage from the active region and increased efficiency under high injection currents. In this work, we compare the light-output-power, efficiency, and forward voltage characteristics of LEDs with polarization-matched quaternary AlGaInN barriers with reduced polarization mismatch to those of LEDs with GaN barriers.

The structures under consideration are grown on a 0001-oriented sapphire by metal-organic chemical vapor deposition. Before growth, the sapphire substrate is exposed to H_2 at 1100 °C for 10 min. A 500 °C low temperature GaN buffer layer is deposited, followed by a 2 μm thick undoped GaN layer and a 3 μm thick Si-doped n-type GaN layer grown at 1010 °C. A five-period multi-quantum-well (MQW) active region is grown, consisting of 3 nm thick $Ga_{0.8}In_{0.2}N$ wells and AlGaInN barriers, with structures consistent with the design principles previously discussed.[1] The barriers are designed to significantly reduce the polarization mismatch between quantum well and barrier. Subsequently, a p-type $Al_{0.13}Ga_{0.87}N$:Mg EBL is grown at 930 °C, followed by a p-type GaN cladding layer. In addition to quaternary samples with GaInN wells and AlGaInN barriers, a reference sample with the conventional GaInN quantum well/GaN barrier active region is grown with the same structure as the quaternary samples. During the whole growth processes, H_2 has been used as an ambient gas and an alkyl carrier gas for GaN layers, but N_2 has been employed as an ambient gas for the growth of GaInN-based active regions. The center wavelength of electroluminescence for both reference and quaternary samples is around 440 nm. Wafers are processed into lateral LED structures 1×1 mm^2 in size and left unencapsulated in wafer form. Devices are tested at room temperature with currents up to 3 A. Testing is done in pulsed mode with 20 μs pulses and a 1% duty cycle to prevent self-heating.

Figure 2 shows the light-output power of the reference and quaternary LED samples as a function of the forward current density. The normalized external quantum efficiency for the two samples is shown in Fig. 3. The reference sample has a sharp peak in efficiency, which occurs at a current density below 5 A cm^{-2}. Following this efficiency peak, the efficiency rapidly decreases; when the current density reaches 300 A cm^{-2}, the efficiency is reduced to just 38% of its peak value. While the maximum efficiency for the quaternary sample is less than that of the reference sample, this maximum occurs at a higher forward current density,

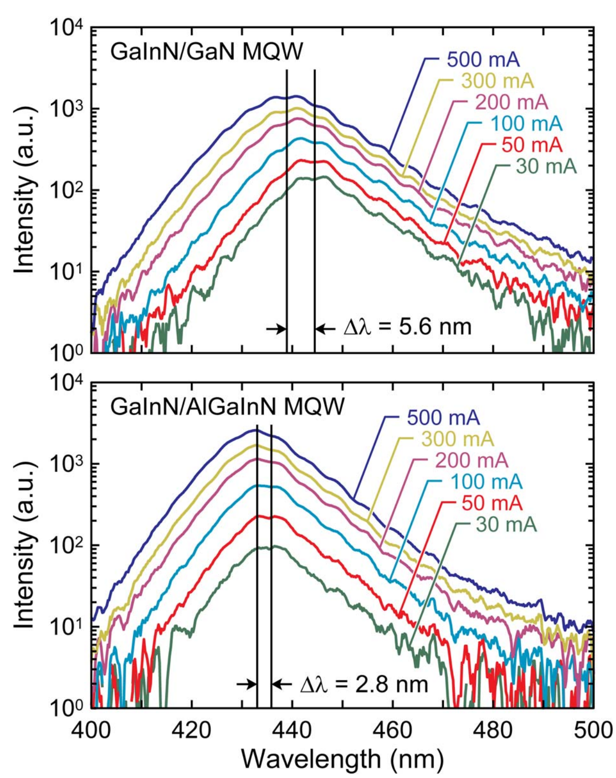

FIG. 4. (Color online) Electroluminescence spectra of GaInN/AlGaInN MQW LEDs and reference GaInN/GaN LEDs at various forward currents.

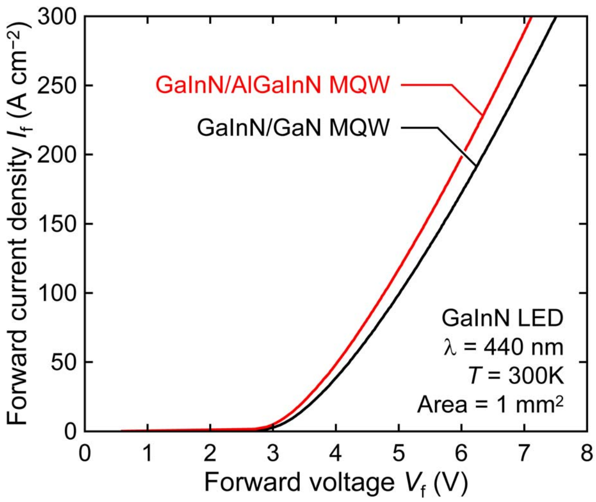

FIG. 5. (Color online) Forward current density as a function of forward voltage for GaInN/AlGaInN MQW LEDs and reference GaInN/GaN MQW LEDs.

22 A cm^{-2}. Additionally, the efficiency peak is less sharp. This is attributed to a shortened nonradiative lifetime, which acts to reduce the low-current efficiency peak.[4] As the forward current increases beyond the values at which peak efficiency occurs, the light-output power of both the reference and the quaternary sample increase sublinearly. However, the output power of the quaternary sample increases more rapidly and becomes greater than that of the reference sample once the forward current density reaches 40 A cm^{-2}. At this point, the efficiency of the two samples is equal; at larger currents, the quaternary sample has greater quantum efficiency. At the maximum tested forward current density of 300 A cm^{-2}, the light-output power of the quaternary sample is larger by 18.5%.

Figure 4 plots the electroluminescence spectra of the two samples at various injection current levels. Consistent with a reduction in the sheet charge magnitude, the shift in wavelength with increasing current is smaller for the GaInN/AlGaInN MQW sample. As the current is increased from 30 to 500 mA, the peak wavelength for the reference sample shifts by 5.6 nm; the peak wavelength for the GaInN/AlGaInN MQW sample shifts by 2.8 nm. In addition, the forward voltage of the quaternary sample is reduced, as shown in Fig. 5. Sheet charges in the active region, resulting from polarization mismatch, produce large triangular barriers that impede carrier flow, across which a bias must be applied for current to flow.[1] The use of AlGaInN barriers reduces the polarization mismatch and sheet charges and reduces the barriers to carrier flow. As a result, forward voltage is reduced and wall-plug efficiency is increased by 24.9%.

In conclusion, we have demonstrated GaN-based LEDs with GaInN quantum wells and polarization-matched quaternary AlGaInN barriers rather than the conventional GaN barriers. The use of quaternary AlGaInN in LED active regions has been proposed as a method for reducing efficiency droop. Consistent with theory, the LEDs show increased light-output power at high currents as well as reduced forward voltages, which results in increases in external quantum efficiency and wall-plug efficiency of 18.5% and 24.9%, respectively. These results indicate a reduction in the high-current loss mechanisms, which causes efficiency droop.

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