Origin of efficiency droop in GaN-based light-emitting diodes

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(Received 12 August 2007; accepted 27 September 2007; published online 30 October 2007)

The efficiency droop in GaInN/GaN multiple-quantum well (MQW) light-emitting diodes is investigated. Measurements show that the efficiency droop, occurring under high injection conditions, is unrelated to junction temperature. Furthermore, the photoluminescence output as a function of excitation power shows no droop, indicating that the droop is not related to MQW efficiency but rather to the recombination of carriers outside the MQW region. Simulations show that polarization fields in the MQW and electron blocking layer enable the escape of electrons from the MQW region and thus are the physical origin of the droop. It is shown that through the use of proper quaternary AlGaInN compositions, polarization effects are reduced, thereby minimizing droop and improving efficiency. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2800290]

Although significant progress in GaInN light-emitting diodes (LEDs) has been made, higher efficiencies and light output are necessary to penetrate the general illumination market, where drive currents larger than 350 mA are employed. However, the LED efficiency generally is highest at low currents—typically a few milliamperes—and as the injection current increases, the efficiency decreases gradually.[1–5] This well-known phenomenon, called *efficiency droop* must be solved for devices operating at high powers. A solution to the droop problem has not yet been provided, and, considering that different explanations were proposed,[1–5] its physical origin is not well understood. In this letter, we identify polarization fields as the physical origin of droop and show that employment of polarization-matched AlGaInN can reduce droop and enhance efficiency.

The GaInN LED structures investigated here are grown on *n*-type conducting *c*-plane GaN substrates by metal-organic vapor-phase epitaxy. After the pretreatment of GaN substrates in NH_3 and H_2 ambient at 1100 °C, a 3-μm-thick *n*-type GaN layer is deposited, followed by a 5 MQW active region. The MQW consists of 3-nm-thick $Ga_{0.8}In_{0.2}N$ wells and 18-nm-thick GaN:Si barriers. Subsequently, a *p*-type $Al_{0.13}Ga_{0.87}N$:Mg electron blocking layer (EBL) is grown, followed by a *p*-type GaN cladding layer. Vertical LED structures 1×1 mm^2 in size are fabricated; the unencapsulated devices emit at $\lambda = 450$ nm and have an output power of 250 mW at a current of 350 mA ($J = 35$ A/cm^2).

To establish the possible dependence of efficiency droop on junction temperature, temperature-dependent light-output-power-versus-current measurements are performed. The LED chips—mounted directly on a hot plate—are operated in pulsed current-injection mode to eliminate Joule heating. The relative output power is measured for heat-sink temperatures ranging from 25° to 150 °C using a Si photodetector. The absolute output power of the devices is measured by using an integrating sphere.

Figure 1(a) shows the measured external quantum efficiency (EQE) and light output power at different heat-sink temperatures as a function of forward current. The EQE at all currents decreases as the temperature rises, and the efficiency droop phenomenon is present at all temperatures. However, the peak efficiency decreases more rapidly with increasing temperature than the efficiency at high currents; thus the magnitude of the droop actually *decreases* with increasing temperature. Therefore, while an increasing temperature *decreases the overall efficiency*, temperature does not increase—*and thus, does not cause*—efficiency droop.

Room-temperature photoluminescence measurements with varying excitation power are performed on the GaInN LED wafer to determine the radiative efficiency of the MQW without an electrical bias. Using a 405 nm laser diode limits optical excitation to the quantum wells, and, due to the energy difference between the GaN bandgap and a 405 nm photon, photoexcited carriers remain inside the wells. Figure 1(b) shows the measured EQE and MQW radiative efficiency as a function of the carrier generation rate. For optical excitation, it is calculated by

$$G_{\text{optical}} = P_{\text{excitation}}\alpha/(Ah\nu), \tag{1}$$

where $P_{\text{excitation}}$ is the optical power of the 405 nm laser, A is the area of the laser spot, and α is the absorption coefficient at 405 nm of the $Ga_{0.8}In_{0.2}N$ well. The carrier injection rate is given by

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0003-6951/2007/91(18)/183507/3/$23.00

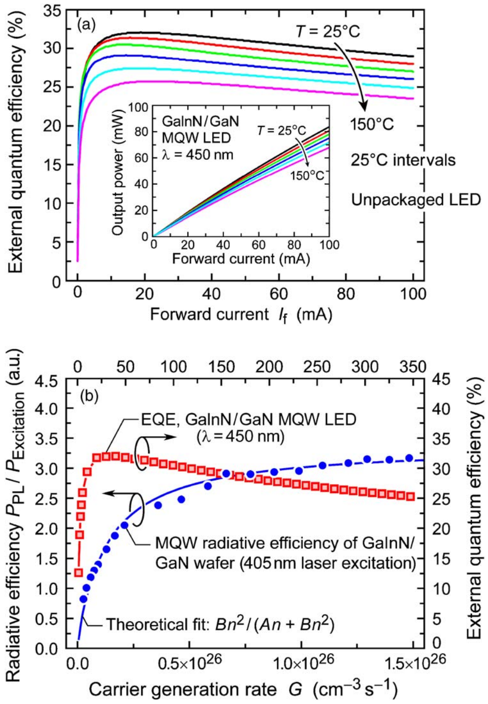

FIG. 1. (Color online) (a) EQE of GaInN MQW LED at heat-sink temperatures of 25–150 °C vs current. (b) EQE measured by integrating sphere and MQW radiative efficiency of GaInN wafer vs optical carrier generation rate.

$$G_{\text{electrical}} = I/(qV_{\text{active}}), \tag{2}$$

where q is the elementary charge and V_{active} is the active region volume. The carrier generation rates given in Fig. 1(b) correspond to an incident optical power density of 0.023–1.57 kW/cm^2 and an electrical current density of 0.01–35 A/cm^2. As seen in Fig. 1(b), the EQE increases steeply at very low injection currents and then starts to droop as the current increases further, as is typical for GaInN/GaN MQW LEDs. However, the MQW radiative efficiency as a function of the optical generation rate shows a fundamentally different behavior. At low generation rates, the MQW radiative efficiency increases rapidly and saturates at high generation rates; the MQW radiative efficiency *does not exhibit any droop*. The relation between MQW radiative efficiency and generation rate is in agreement with the expression

$$\eta_{\text{rad}} = Bn^2/(An + Bn^2), \tag{3}$$

where Bn^2 and An are the radiative and nonradiative recombination rates, respectively, and n is the free carrier concentration. The difference in the efficiency-versus-excitation characteristic for the electrical and optical case shows that the efficiency droop must be caused by carrier recombination outside the MQW under forward bias.

In order to investigate the physical origin of droop, simulations of the high-power blue LED structure described earlier are performed using APSYS modeling software. Commonly accepted parameters are used in the simulations, including a Shockley-Read lifetime of 1 ns in the EBL and p-type GaN, and spontaneous and piezoelectric polarization elementary charge densities of 1.04×10^{13} and 2.74×10^{12} cm^{-2} in the MQW and EBL, respectively.[6] The simulations fully agree with experimental LED data. Figure 2 shows the calculated LED band diagram at a forward current of 350 mA. As a result of the polarization charges, the conduction band slopes upward as it approaches the active region from the n side of the device; this shape is repeated in each of the quantum barriers. The sloped triangular barriers hinder the electron current thereby requiring a large bias to drive electrons through the MQW. For a current of 350 mA, the applied voltage is larger than the built-in voltage, as shown in Fig. 2. The conduction band on the n side is *higher* than the conduction band on the p side, which results in a large electron leakage current (as much as 60% of the total current, as will be discussed below).

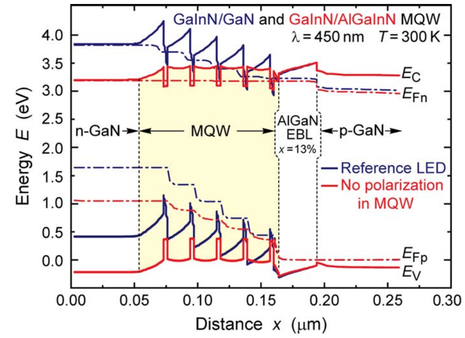

FIG. 2. (Color online) Calculated band diagram of reference GaInN/GaN LED as well as GaInN/AlGaInN LED structure with polarization-matched MQW under a forward bias condition.

Figure 2 also shows the calculated band diagram when the total spontaneous and piezoelectric polarization charges of the $Ga_{0.8}In_{0.2}N$ quantum wells are matched by equal polarization charges in AlGaInN quantum barriers and the remaining polarization charges at the bottom and top of the MQW are compensated by n- and p-type deltadopings, respectively. In the absence of the polarization charges, the triangular barriers disappear. Furthermore, the bias at 350 mA is reduced, and the conduction band on the p-side is now higher than on the n-side making it much more difficult for electrons to reach the p-side. As a result, the electron leakage current is virtually eliminated.

Figure 3 plots the internal quantum efficiency (IQE) and the electron leakage current across the EBL as a function of the forward current for the reference LED and LEDs in which the AlGaInN MQW quantum barriers and EBL are polarization matched to the QWs and to GaN, respectively. The efficiency droop, defined as $(\eta_{\text{peak}} - \eta_{350\text{ mA}})/\eta_{\text{peak}}$, is 25% for the reference LED. The decrease in efficiency is tied to the increase in electron leakage current, which is significant even at low currents and becomes larger as the forward current increases. This is partly attributed to the reduced effectiveness of the AlGaN EBL due to the effect of polariza-

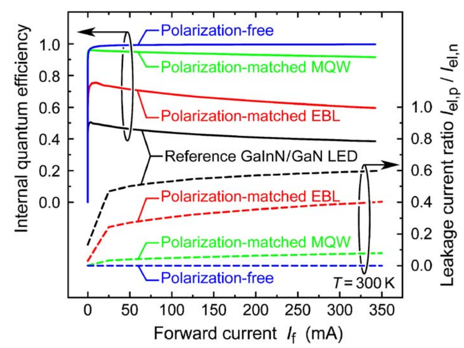

FIG. 3. (Color online) IQE and leakage current ratio of GaInN/GaN and GaInN/AlGaInN LEDs with and without polarization effect in the MQW and/or the EBL.

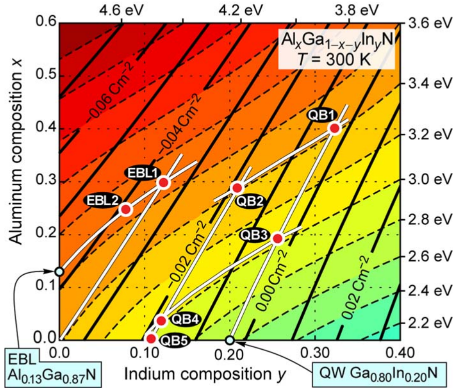

FIG. 4. (Color online) Bandgap (dashed-line contours) and total polarization charge (solid-line contours) of AlGaInN as a function of Al and In compositions.

tion charges. When an AlGaInN EBL is polarization matched to GaN, the light output increases by 49.5% at 350 mA and the droop decreases to 22%. However, electron leakage still constitutes more than 40% of the total injected current, due to the remaining polarization charges in the MQW. As shown in Fig. 3, when polarization-matched AlGaInN quantum barriers are used, the light output increases by 138% at 350 mA and the droop decreases to only 5%. Thus, polarization fields in the MQW active region and the EBL are the physical origin of the efficiency droop occurring in GaInN LEDs. Structures with polarization-free EBL and MQW show the highest light output power and virtually no efficiency droop.

Next we demonstrate that the polarization effect in the MQW and EBL can be reduced by the use of quaternary AlGaInN layers for the MQW barriers and the EBL. We have calculated the relationship between composition, bandgap, lattice constant, and the polarization charges of AlGaInN as follows. The polarization of the quaternary alloy layer is determined using the model given in Ref. 6. Vegard's law is used for the lattice constant of the quaternary alloy. The bandgaps of unstrained ternary alloys are calculated using the binary alloy bandgaps and associated bowing parameters.[7] To determine the bandgap of a quaternary alloy, three bandgap terms—based on AlN, GaN, and InN—are calculated. For the GaN, the bandgap term is determined from the line on a bandgap-versus-lattice-constant plot which connects the two ternary alloys with the same Ga composition as the desired quaternary alloy. Along this line, the lattice constant of the alloy composition varies linearly; the point where the lattice constant matches the lattice constant calculated for the quaternary alloy by Vegard's law is selected; the bandgap value can be expressed as

$$E_{g\text{-Ga}}^{\text{alloy}} = E_g^{\text{GaInN}} + (E_g^{\text{AlGaN}} - E_g^{\text{GaInN}})\frac{a^{\text{alloy}} - a^{\text{GaInN}}}{a^{\text{AlGaN}} - a^{\text{GaInN}}}. \qquad (4)$$

This process is repeated for AlN and InN; each term is then weighted by the Al, Ga, and In compositions of the quaternary alloy and added to determine its bandgap. Due to strain occurring when the quaternary alloy is grown pseudomorphically on relaxed GaN, the bandgap is modified by the term $E_\varepsilon = 15.4\varepsilon_{zz}$ eV, where ε_{zz} is the strain in the z direction.[8,9] The strain is calculated from the lattice constant mismatch and elastic constants, which are determined by linear interpolation from their binary alloy values.

Figure 4 plots contours of constant bandgap and constant polarization charge as a function of the Al and In compositions for quaternary AlGaInN grown on GaN templates. The compositions of the QW and EBL for the reference LED structure, which has GaN quantum barriers, are indicated. EBL1 lies on the constant-polarization contour starting at GaN, and on the constant-bandgap contour which crosses the reference EBL point. EBL2 maintains the bandgap of the reference EBL but reduces the polarization charge to 50% rather than eliminating it. Both EBL1 and EBL2 result in reduced droop compared with the reference EBL.

100% polarization matching of the quantum barrier to the QW is achieved for all compositions along the polarization contour that crosses the QW point (QB1 and QB3). 50% polarization matching to the QW is achieved for QB2 and QB4. QB1 and QB2 have the same bandgap as GaN, whereas QB3 and QB4 reduce the bandgap difference between the barrier and QW by half compared with the reference LED. As the polarization mismatch in the MQW is reduced, the electric field in the quantum wells is reduced and quantum confinement increases; this effect allows the use of barrier compositions with smaller bandgaps than GaN. Each of the four barrier compositions represents significant improvement over the reference structure; however, barrier compositions with high aluminum content would be difficult to realize experimentally. Note that the composition of QB4 has very little aluminum, yet provides improvement over the reference structure. Therefore, even aluminum-free barrier compositions, such as QB5, could provide an enhancement of efficiency and reduction of droop.

In conclusion, measurements show that efficiency droop, found in GaInN/GaN LEDs is unrelated to junction temperature. The radiative efficiency of GaInN LED wafers measured by using optical excitation does not show any droop while the external quantum efficiency of GaInN LEDs shows a strong droop as the carrier injection rate increases. Simulations reveal that polarization fields in the MQW active region and the EBL enhance the leakage of injected electrons into the p-type GaN cladding layer, and thus cause the efficiency droop. Theoretical considerations show that quaternary AlGaInN quantum barriers and EBL can be polarization matched to the QWs and GaN, respectively, to reduce carrier escape as well as efficiency droop while strongly enhancing the device efficiency at high current levels.

The authors gratefully acknowledge support by Samsung Electro-Mechanics Company, Sandia National Laboratories, Department of Energy, NSF, and Crystal IS.

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