Electroluminescence induced by photoluminescence excitation in GaInN/GaN light-emitting diodes

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Optical emission resulting from 405 nm selective photoexcitation of carriers in the GaInN/GaN quantum well (QW) active region of a light-emitting diode reveals two recombination channels. The first recombination channel is the recombination of photoexcited carriers in the GaInN QWs. The second recombination channel is formed by carriers that leak out of the GaInN QW active region, self-bias the device in forward direction, induce a forward current, and subsequently recombine in the GaInN active region in a spatially distributed manner. The results indicate dynamic carrier transport involving active, confinement, and contact regions of the device. © *2009 American Institute of Physics*. [doi:10.1063/1.3258488]

The recombination dynamics in GaInN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) is governed by various effects that include limited injection efficiency,[1] carrier leakage out of the active region,[2] compositional fluctuations and carrier localization,[3] Auger recombination,[1,4] polarization fields,[5,6] and the quantum-confined Stark effect (QCSE).[7] Understanding of excitation and recombination mechanisms is highly desirable, particularly at high current and carrier densities where high-power devices are operated. Photoexcitation using a 405 nm laser is suited to selectively generate carriers within only the quantum wells (QWs) of a GaInN MQW LED, ensuring uniform injection into each QW and providing additional insight compared to electrical excitation. However, despite carriers being generated exclusively within the QWs, leakage of carriers out of the wells has been reported.[8] Here we report on the recombination dynamics in GaInN/GaN MQW LEDs that are photoexcited using a 405 nm semiconductor laser diode. We show that the recombination includes two distinct mechanisms. The first is conventional photoluminescence created by carriers optically generated in the GaInN QWs. The second is photoexcitation-induced electroluminescence (EL) that occurs over the entire area of the LED chip.

The GaInN/GaN LEDs studied here were grown in the c-direction on a sapphire substrate by metal-organic chemical-vapor deposition and emit at approximately 460 nm. The LEDs have a 3 μm thick n-type GaN confinement layer and an indium tin oxide p-type contact. Both of these layers have a high conductivity allowing them to spread a current laterally over the entire LED chip area. The 405 nm laser instantaneous power is varied from 47 μW to 53 mW by controlling the laser diode current. The excitation spot size of the laser on the LED sample has a diameter of less than 25 μm. The LED chip size is 300×300 μm^2. Measurements are performed under a pulsed mode with a pulse duration long enough for measurement parameters, such as the open-circuit forward voltage, to reach steady state.

Photographs of the GaInN/GaN LED chip optically excited by the 405 nm laser are shown in Figs. 1(a) and 1(b) under short-circuit and open-circuit conditions, respectively. The 405 nm violet light of the laser is blocked by a long-wavelength-pass filter cutting off at 440 nm. Inspection of the photographs reveals that for the short-circuit condition, photoluminescence emanates only from the location of laser excitation. However, when the LED is in an open circuit, luminescence originates not only from the location of excitation, but from the entire LED chip. This light emission is uniform over the entire surface of the LED chip, and occurs even in areas that are distant from the excitation spot. Therefore, diffusion of electrons and holes within the QWs along the plane of the QWs can be ruled out as the cause. Figures 1(c) and 1(d), taken under electrical forward bias, suggest similarity between the blue emission found for optical excitation under open-circuit conditions and conventional EL.

To gain further insight into the mechanisms at work, we use a device simulator to model the GaInN/GaN LED with optical excitation. The simulator solves the Poisson equation and continuity equations for electrons and holes. The simulation is one dimensional, which corresponds to the case where optical excitation is uniform across the LED chip.

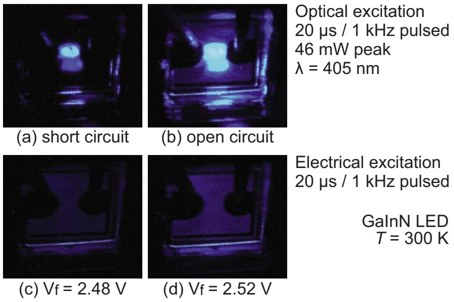

FIG. 1. (Color online) [(a) and (b)] Photographs of a GaInN/GaN LED chip under 405 nm optical excitation for open-circuit and short-circuit conditions. [(c) and (d)]: Photographs under external bias conditions without optical excitation.

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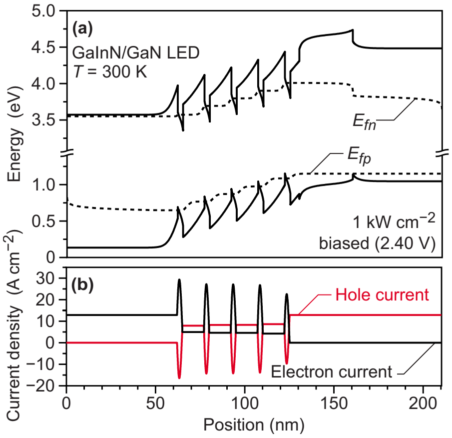

FIG. 2. (Color online) (a) Calculated band diagram for the GaInN/GaN LED with a 2.4 V forward bias and an absorbed optical power density of 1 kW cm^{-2}. (b) Calculated electron and hole current as a function of position.

However, the results will be used to provide insight into the workings of the present case where the optical excitation is confined to a small spot. Simulation results confirm that optical excitation of the LED does lead to carrier escape from the QWs and a photocurrent, as has been reported recently.[8] Figure 2(a) shows the band diagram of the LED forward-biased to 2.4 V with an absorbed optical power density of 1 kW cm^{-2}. Figure 2(b) shows the electron and hole current as a function of position. The current flowing in the device consists of electrons flowing toward the n-contact and holes flowing toward the p-contact. Within the QWs, due to the classical nature of the model, there is additional current as electrons and holes (which are uniformly generated in each QW) redistribute due to the strong polarization-induced electric fields. The model used considers only drift and diffusion current, and does not take into account quantum-mechanical tunneling through barriers or thermionic emission. Therefore, carrier escape from QWs and photocurrent should be somewhat underestimated.

When a uniformly excited LED is left in an open circuit, the voltage gradually increases as excess electrons and holes accumulate on the n-type and p-type sides, respectively, where their lifetimes are extremely long. As in a capacitor, this excess charge induces a voltage. Eventually the LED reaches the steady state open-circuit voltage, at which point the photocurrent caused by carrier escape and the forward current due to the forward bias exactly cancel at each location in the LED, and no net current flows. If the laser excites only a small area, however, excess carriers which escape into the n-type and p-type regions in the vicinity of the laser spot will distribute across the entire area of the LED chip due to the gradient in their concentration. The voltage induced across the junction is lesser; the ultimate voltage and the extent of carrier redistribution depend upon the conductivity of the n-type and p-type confinement and contact layers. These redistributed excess carriers are then injected across the junction. In steady state, then, the localized photocurrent is balanced by a forward current that is distributed across the entire LED chip. This distributed forward current is the origin of the chip-wide luminescence seen in Fig. 1.

The forward voltage of the LED under photoexcitation is assessed by measuring the open-circuit voltage using an oscilloscope with 1 MΩ input impedance. The laser pulse width is varied to ensure the open-circuit voltage reaches its steady state value. Figure 3 shows the measured open-circuit voltage of the device as a function of the 405 nm instantaneous optical power together with a schematic of the experimental setup. At a power of only a few 100 μW, the forward voltage exceeds the EL threshold, which is just above 2.2 V. As the laser power increases further, the forward voltage rises gradually, and at the highest excitation densities exceeds 2.48 V. The increase in EL corresponding to the increase voltage will be more significant due to the highly nonlinear current-voltage characteristic of the LED. It should be noted that the optical excitation induced EL corresponding to a given open-circuit voltage is not directly comparable to standard EL with an equivalent applied voltage, because in the former there is no current flowing through the contacts into the device. Therefore, the voltage drop in the contacts that occurs when the LED is electrically biased is absent, and the comparable voltage for standard EL is actually higher than the given open-circuit voltage. As shown in Fig. 1, the spatially distributed light emission for the open-circuit device closely resembles the EL with 2.52 V forward bias, although the measured open-circuit voltage from Fig. 3 is slightly lower.

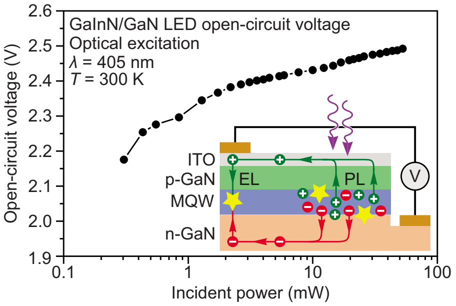

FIG. 3. (Color online) Measured open-circuit voltage of a GaInN/GaN LED chip for 405 nm optical excitation as a function of the optical excitation power and a schematic of the experimental setup. Recombination events resulting from EL and PL are indicated with the star.

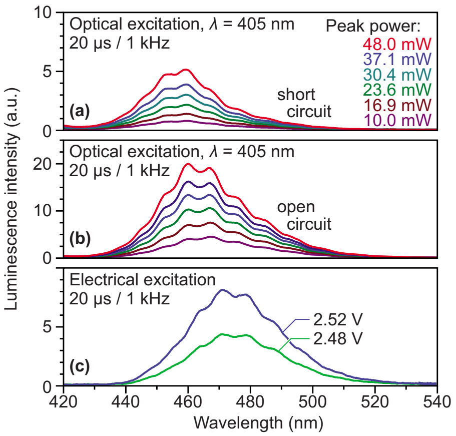

FIG. 4. (Color online) Luminescence spectra of GaInN/GaN LED chip for (a) 405 nm optical excitation and under short-circuit condition, (b) optical excitation under open-circuit condition, and (c) electrical excitation.

Figures 4(a) and 4(b) show the emission spectra of the GaInN/GaN LED for short-circuit and open-circuit conditions, respectively, for several values of the 405 nm instantaneous optical power. Figure 4(c) shows the spectrum in the case of electrical excitation. The relative shifts in peak lumi-

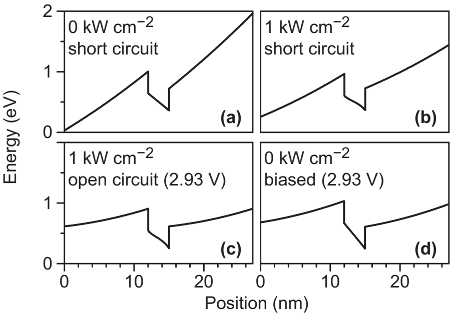

FIG. 5. Calculated conduction band edge of a GaInN/GaN QW (a) in equilibrium and (b)–(d) for the conditions shown in Fig. 4.

nescence wavelength are explained by the effect of carrier density and voltage across the junction upon the electric field in the QWs. Figure 5 shows the calculated conduction band edge of a QW in the LED for the conditions shown in Fig. 4. The shortest emission wavelength occurs for short-circuit photoexcitation; in the case of a short-circuit, the field due to the junction opposes the field due to polarization mismatch in the QW. In addition, optically generated carriers screen charges at the QW interface, further reducing the field in the well. Figure 5(b) shows the calculated QW conduction band profile for short-circuit photoexcitation, which clearly has minimum electric field of all the conditions considered. The reduced electric field minimizes the QCSE and results in a shorter emission wavelength. In the case of open-circuit photoexcitation, the LED self-biases itself, which decreases the field due to the junction. Although carrier density increases (along with luminescence intensity) compared to the short-circuit condition, the net effect is a larger electric field in the QW, as seen in Fig. 5(c). Therefore, due to increased QCSE, a longer emission wavelength is observed. Finally, in the case of electrical biasing to the open-circuit voltage, the QCSE is strongest, and emission wavelength is longest due to the small voltage across the junction and the absence of photogenerated carriers to screen the sheet charges at QW interfaces. Correspondingly, Fig. 5(d) shows the strongest electric field in the QW of all the cases considered.

In conclusion, selective photoexcitation of carriers in GaInN QWs using 405 nm laser excitation is performed for GaInN/GaN LEDs. The emission resulting from the photoexcitation consists of two recombination channels: the first recombination channel is the recombination of photoexcited carriers in the GaInN QWs. The second recombination channel is formed by carriers that leak out of the GaInN QW active region, self-bias the device in forward direction, cause a forward current, and ultimately recombine in the GaInN QW active region in a spatially distributed manner across the entire LED chip. This mechanism is revealed by examining the distribution of light emission across the LED chip for both short- and open-circuit configurations, and by measuring the forward voltage as a function of the excitation density. A shift of the luminescence peak energies toward lower energy under open-circuit conditions is attributed to the self-forward biasing of the device, the resulting increase of the electric field in the QW, and the associated enhancement of the quantum-confined Stark effect. The results suggest dynamic carrier redistribution under high excitation densities that allows for a deeper understanding of the carrier dynamics in LED structures under high optical excitation conditions.

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