Characteristics of dotlike green satellite emission in GaInN light emitting diodes

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An unwanted green satellite emission in blue GaInN light emitting diodes (LEDs) has been investigated under various electrical bias conditions and temperatures. The dot-shaped green satellite emission appears only under electrically biased conditions of the LED (but not under photoluminescence excitation) and contributes directly to a high subthreshold leakage current of the LED. A weak temperature dependency of the green satellite emission intensity is observed indicating that tunneling-assisted radiative recombination involving Mg acceptors is the origin of the green emission. © *2011 American Institute of Physics*. [doi:10.1063/1.3541880]

GaInN-based light emitting diodes (LEDs) have received much attention for display, automobile, and lighting applications. Rapid improvement of the power efficiency has been made by optimized crystal growth and refined chip fabrication techniques.[1,2] However, there still exist problematic characteristics in these LEDs such as the large reverse leakage current and low reverse breakdown voltage, both of which are very different from their theoretical expectations for GaN-based devices. Furthermore, an undesirable satellite emission with a much longer emission wavelength than the band-to-band emission wavelength has been found in blue GaInN LEDs.[3–6] Understanding these deviant characteristics is of importance for LEDs from the viewpoint of device reliability and also color purity.

The LEDs investigated in this study have an active region consisting of five pairs of GaInN/GaN multiple quantum wells (MQWs) grown on a *c*-axis sapphire substrate by metal-organic chemical vapor deposition. The wafer is processed into 1×1 mm^2 lateral-structure LED chips with a transparent *p*-type electrode.[7] The inset of Fig. 1 shows an optical micrograph with broad-area blue electroluminescence (EL) ($\lambda_P \approx 442$ nm) originating from the band-to-band recombination and dot-shaped green satellite emission ("green-dot") with $\lambda_P \approx 510$ nm under a 100 μA current injection. The size of the green dots ranges from 1 to 10 μm in diameter. In addition, we measured the photoluminescence (PL) of the same devices by using 266 and 405 nm laser sources to selectively excite either the GaInN QWs, or the GaN cladding layers and AlGaN electron-blocking layer (EBL). However, the green-dot emission is not observed in these PL measurements. Interestingly, we observe the green-dot emission only under EL injection conditions of the LEDs but not under PL excitation conditions. Kudryashov *et al.*[3] suggested that the green dots were caused by tunneling-assisted band-to-band recombination and developed a diagonal tunneling model to describe this phenomenon. Onushkin *et al.*[4] observed red-dot emission from green GaInN LEDs and suggested that the origin of the red-dot emission would be likely the same tunneling-assisted radiative recombination. However, the characteristics of the undesired satellite emission are not fully understood especially at high temperature. In this letter, we study the satellite emission of blue GaInN LEDs for various electrical biases and temperatures to understand the properties and origin of the green-dot emission.

First, we investigate the current–voltage (*I-V*) characteristics of two LEDs on the same wafer having two different green-dot densities, 100 and 900 mm^{-2}. As shown in Fig. 1, the two *I-V* curves are very similar in the low voltage region (<1.5 V) and also in the voltage region after turn-on (>2.5 V). However, in the subthreshold region (1.5–2.5 V), the LED with high density of green dots (900 mm^{-2}) shows a larger forward leakage current compared to the LED with a low density of green dots (100 mm^{-2}). We therefore conclude that the green-dot density has a close relationship with subthreshold carrier leakage in the LEDs.

Figure 2 shows the emission spectra of the LED with high density of green dots under different injection currents. The spectra show blue band-to-band recombination at around 442 nm (2.8 eV) and another emission peak with emission of around 509–525 nm (2.36–2.44 eV). A strong blueshift in the peak wavelength of the green-dot emission is found as the current increases from 10 to 90 μA; on the contrary, the peak emission wavelength for the blue emission is almost

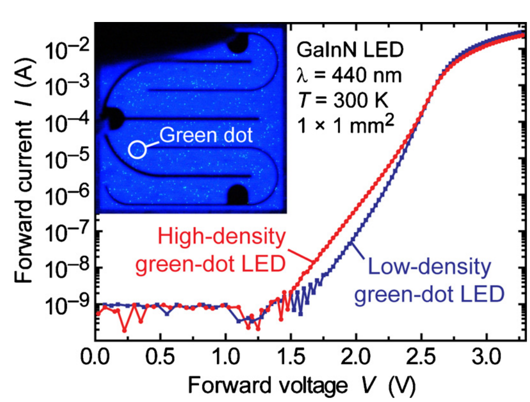

FIG. 1. (Color online) Current–voltage characteristic for a blue GaInN LED with high (900 mm^{-2}) and low (100 mm^{-2}) green-dot density. (The inset shows an EL micrograph of blue and green-dot emission from the high-green-dot-density LED injected with 100 μA. An example of a green dot is circled.)

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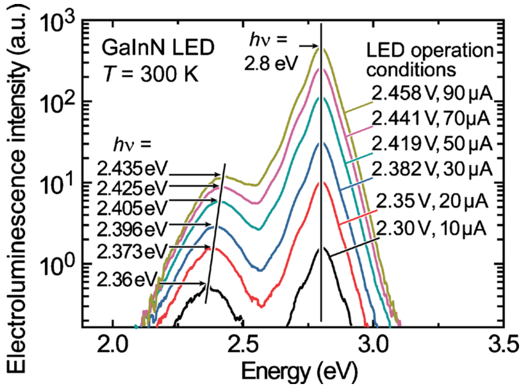

FIG. 2. (Color online) EL spectra of a blue GaInN LED under injection currents ranging from 10 to 90 μA showing a linear increase in the blue emission and a sublinear increase in the green-dot emission with injection current.

constant. For the blue emission, the injected current into the active region is too low to show the commonly found blueshift in the band-to-band recombination caused by a band-filling effect.[8] However, the green-dot emission, even though it is measured in the same current range, shows a large blueshift that has a strong dependency on the applied *voltage*. The photon energy ($\hbar\omega$) of the green-dot emission has a linear relationship with the applied voltage V, which is consistent with results reported in Ref. 3. We further note that the EL spectra of a blue GaInN LED show a linear increase in the blue emission and a sublinear increase in the green-dot emission as the injection current increases, which are typical dependences for band-to-band recombination and deep-level recombination, respectively. Given these results, we attribute the blueshift in the green-dot emission with increasing voltage to band flattening, which increases the energy difference between electrons in a QW of the conduction band and recombining holes occupying levels in the forbidden gap close to the valence band in the *p*-type region of the device.

Figure 3 shows temperature dependency of emission spectra of the LED for two following conditions: (a) a constant (fixed) injection current and (b) a constant (fixed) forward voltage. When a fixed current of 50 μA is applied to the LED, a redshift of 2.4 nm for the blue emission and a much larger redshift of 8.2 nm for the green-dot emission are observed when the temperature increases from 294 to 360 K [see Fig. 3(a)]. Comparatively, when a fixed forward voltage of 2.37 V is applied to the LED, the redshift for the blue emission is 3.1 nm when the temperature increases from 294 to 360 K; however, the peak wavelength of the green-dot emission is almost constant [see Fig. 3(b)]. That is, the magnitude of the redshift in the peak wavelength of the blue emission under both conditions is similar. However, the peak wavelength shift in the green-dot emission shows a distinct dependence on the operating methods. Though the redshift in the blue emission under both conditions is attributed to the band gap shrinkage with increasing temperature, the origin of the temperature characteristics of the green-dot emission still needs to be understood; (i) the redshift in the green-dot emission with increasing temperature is much stronger than the redshift in the blue emission at a fixed injection current; (ii) the redshift in the green-dot emission is almost nonexistent for a fixed forward voltage. The likely reason for these phenomena is the voltage dependent properties of the green-

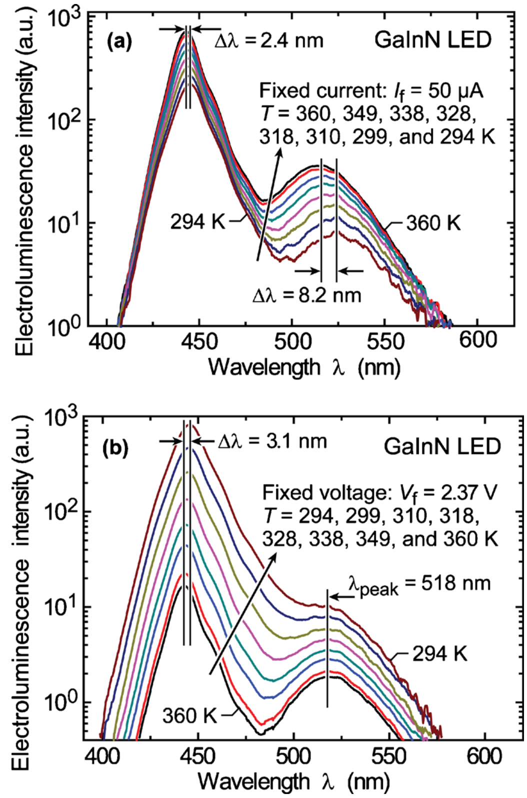

FIG. 3. (Color online) EL spectra of a blue GaInN LED with high green-dot density at (a) a constant injection current of 50 μA, (b) a constant forward voltage of 2.37 V for temperatures ranging from 294–360 K.

dot emission compared to the blue emission. At a fixed injection current, in addition to the "band gap shrinkage" by which the peak wavelength of green-dot emission naturally shifts to the red, it further experiences a redshift driven by the operating voltage reduction that is caused by the increasing temperature. On the other hand, when the applied forward voltage to the LED is fixed, the peak wavelength of the green-dot emission remains almost unchanged because of its dominant voltage dependence. These results clearly demonstrate that the green-dot emission has a different recombination mechanism than the blue emission. From the results shown in Fig. 3(b), the light-output intensities can be plotted as a function of temperature under a fixed voltage of 2.37 V (not shown here). The blue emission intensity increases much more rapidly than the green-dot emission intensity with increasing temperature. In other words, the green-dot emission intensity is much less dependent on temperature than the blue emission intensity.

We propose the following explanation for the fact that the green-dot emission is not observed in PL but is observed in EL; (i) PL uniformly probes MQWs except for the last-grown QW. The last-grown QW has lower light output compared to the other four QWs because electrons are likely to escape from the last QW due to the build-in electric field at the *pn* junction; (ii) EL mostly probes the last QW because of the low mobility of holes and high mobility of electrons. Accepting the fact that the two techniques, PL and EL, probe different QWs can thus explain the observation of the green dots exclusively by EL.

Finally, considering that the green emission has dot-shaped distribution on the LED's top emission surface, very different from a uniform areal distribution, a fluctuation must

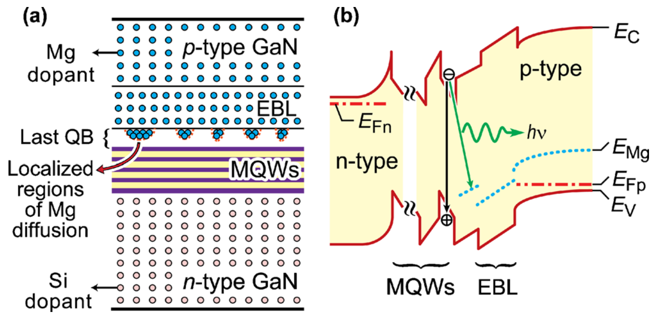

FIG. 4. (Color online) (a) Schematic LED structure and (b) band diagram showing locally enhanced diffusion of Mg doping atoms into the last QB layer.

exist across the LED wafer that causes the green-dot emission. There might be a thickness fluctuation of the last quantum barrier and/or AlGaN EBL; there could also be a Mg *p*-type doping concentration fluctuation.[9,10] So the tunneling probability initiating the green-dot emission could be influenced by these randomly distributed fluctuations. Above all, we strongly suspect that the green-dot emission comes from the Mg diffusion into the last barrier layer (spacer). The Mg diffusion may occur locally during the high-temperature growth of the LED's upper layers grown on top of the MQWs and/or during the post-growth high-temperature heat-treatment used for *p*-type acceptor activation. Microscopic defects (i.e., dislocations, pits, pipes, V-defects, particles, or other structural irregularities) could form a pathway for strongly enhanced Mg diffusion toward the active region. Figure 4 shows (a) a schematic LED structure and (b) a band diagram proposing Mg diffusion into the last quantum-barrier (QB) layer. This insight could motivate solutions on how to decrease the undesirable green satellite emission.

In summary, characteristics of the dot-shaped green emission in blue GaInN LEDs are investigated by EL and PL measurements in the temperature range of 294–360 K. We find that (i) green-dot emission is electrical bias-induced phenomenon and only found in EL measurements at low currents (not in PL); (ii) a higher density of the green dots contributes directly to the higher forward subthreshold leakage current; (iii) the temperature dependence of the green-dot emission intensity is much weaker than that of the blue emission intensity; (iv) the green-dot emission increases sublinearly with injection current. Tunneling-assisted radiative recombination by a locally enhanced Mg diffusion is proposed to be the origin for the green-dot emission.

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[1]E. F. Schubert, *Light-Emitting Diodes*, 2nd ed. (Cambridge University Press, Cambridge, UK, 2006).
[2]M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, J. Disp. Technol. **3**, 160 (2007).
[3]V. E. Kudryashov and A. É. Yunovich, J. Exp. Theor. Phys. **97**, 1015 (2003).
[4]G. Onushkin, J. Lee, J.-J. Yang, S.-E. Park, M.-H. Kim, and M. Koike, Phys. Status Solidi C **4**, 2793 (2007).
[5]K. X. Chen, Y. A. Xi, F. W. Mont, J. K. Kim, E. F. Schubert, W. Liu, X. Li, and J. A. Smart, J. Appl. Phys. **101**, 113102 (2007).
[6]E. F. Schubert, I. D. Goepfert, and J. M. Redwing, Appl. Phys. Lett. **71**, 3224 (1997).
[7]J. Cho, A. Mao, J. K. Kim, J. K. Son, Y. Park, and E. F. Schubert, Electron. Lett. **46**, 156 (2010).
[8]T. Mukai, M. Yamada, and S. Nakamura, Jpn. J. Appl. Phys., Part 1 **38**, 3976 (1999).
[9]G. A. Onushkin, S.-S. Hong, J.-H. Lee, J.-S. Park, J.-K. Son, M.-H. Kim, and Y. Park, Appl. Phys. Lett. **95**, 101904 (2009).
[10]O. Svensk, P. T. Törmä, S. Suihkonen, M. Ali, H. Lipsanen, M. Sopanen, M. A. Odnoblyudov, and V. E. Bougrov, J. Cryst. Growth **310**, 5154 (2008).