Junction Temperature-Controlled Spectrum in a Two-Color InGaN–GaN Quantum-Well Light-Emitting Diode

Chih-Feng Lu, Dong-Ming Yeh, Horng-Shyang Chen, Chi-Feng Huang, Jian-Jang Huang, and C. C. Yang

Abstract—We demonstrate the dependence of the output spectrum on the Ohmic-contact thickness in a blue/green two-color InGaN–GaN quantum-well (QW) light-emitting diode. By decreasing the metal thickness of the p-type Ohmic contact on the device, the contact resistance is increased and hence the junction temperature is raised. With the junction temperature raised, the probability for the hole to escape from the first QW (green emitting) and be captured by the next QWs is increased for more effective emission of blue light such that the blue/green intensity ratio can be adjusted. The conclusion of higher junction temperature in a sample of a thinner p-type metal layer is consistent with the measurement results of output power versus injection current and current versus applied voltage. The measurement based on the transmission-line method also shows the increasing trend of contact resistance in decreasing the p-type metal thickness.

Index Terms—Dual-color, InGaN–GaN quantum well (QW), junction temperature, light-emitting diode (LED).

I. INTRODUCTION

IN THE lighting application, the development of the semiconductor white-light light-emitting diode (LED) has become an important issue because of its advantages of high efficiency, long lifetime, and versatile geometry. Currently, in the commercial white-light LEDs, phosphors are used for converting UV or blue photons, generated from InGaN–GaN quantum wells (QWs), into longer-wavelength lights for color mixing. However, the use of phosphors has the disadvantages of Stokes-wave energy loss, short lifetime, and patent control. Therefore, single-chip, all-semiconductor white-light LED has been a topic of great interest. A single-chip, all-semiconductor white-light LED can be implemented by stacking InGaN–GaN QWs of different indium compositions and/or geometries on a wafer to simultaneously emit photons of different colors. All-InGaN two-color LEDs for blue/green and blue/yellow emissions have been fabricated [1], [2]. Also, all-InGaN three-color LEDs of blue/green/red emissions were reported [3], [4].

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The authors are with the Graduate Institute of Electro-Optical Engineering and Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C. (e-mail: ccy@cc.ee.ntu.edu.tw).

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However, in implementing such an LED of stacking different InGaN–GaN QWs, the short migration distance of the hole [5], relative to that of the electron, becomes a major problem of controlling the multicolor spectrum. Because of the short migration distance of the hole, the major emission contribution of such an LED is expected to originate from the QW closest to the p-type GaN layer. Therefore, the emission spectrum of a two-color LED is usually dominated by this QW. To improve the color contrast, i.e., enhance the emission intensity of a deeper QW, the hole migration distance must be increased or the physical separation between a QW and the p-type layer must be reduced. The reduction of the separation can be implemented by decreasing the barrier thickness near the p-type layer. However, a thin barrier may degrade the growth quality of a QW above it. Hence, enhancing the hole mobility is an important issue for controlling the color contrast of a multicolor LED.

In this letter, we demonstrate the variation of color contrast of a blue/green two-color InGaN–GaN QW LED by controlling the diode junction temperature. With different metal thicknesses of the p-type Ohmic contact on the LED, different contact resistance levels lead to different thermal effects, and hence, different junction temperatures. A sample of a higher junction temperature has a higher probability for the hole to escape from the first QW and be captured by the next QWs such that the holes can reach deeper QWs for the emission of another color.

The epi-structure of the blue/green two-wavelength LED was grown with metal–organic chemical vapor deposition (P75 system of Veeco, a turbo-disc reactor). After the growth of a 25-nm nucleation layer (grown at 535 °C), a 2- μm n-GaN was deposited at 1070 °C. Then, two QW growth conditions were considered: 1) temperature at 690 °C, wafer carrier rotation speed at 750 rpm, and gas flow rates at 3000 sccm for N₂ and 3000 sccm for NH₃, and 2) temperature at 710 °C, wafer carrier rotation speed at 1500 rpm, and gas flow rates at 1000 sccm for N₂ and 1500 sccm for NH₃. The first and second growth conditions were designed for the green- and blue-emission QWs, respectively. All the well thickness is about 3 nm. Under the different growth conditions, the indium compositions are different, leading to the emissions of different colors. Either purely blue or green LEDs have been fabricated based on the growth of five QWs under the same condition. In the mixed QW sample, we arrange the QW sequence as green/blue/blue/green in the four-QW structure. A green-emitting QW was placed at the top because such a QW usually has lower quantum efficiency than a blue-emitting one. The barrier thickness is normally 16 nm. However, the width of the last two barriers

Fig. 1. I - V curves of the three samples.

is only 6 nm such that the separation between a QW and the p-type layer can be reduced. After the growth of the four QWs, a 20-nm p- $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ layer, followed by a 120-nm p-GaN layer (both grown at 930 °C), was deposited. LEDs based on the mixed QW epi-structure were then fabricated with the standard procedure. Ti (15 nm)/Al (75 nm)/Ti (15 nm)/Au (150 nm) were used for the n-type Ohmic contacts. Three device samples were fabricated with different structures of p-type Ohmic contact. In Sample A, Ni (35 nm)/Au (100 nm) were used for the p-type Ohmic contacts. In Sample B, a structure of Ni (5 nm)/Au (5 nm)/Ni (5 nm)/Au (5 nm) was deposited. Then, in Sample C, the p-type Ohmic contact consists of the layers of Ni (5 nm)/Au (5 nm). Therefore, the different metal thicknesses of the three samples (135 nm in Sample A, 20 nm in Sample B, and 10 nm in Sample C) are expected to result in different contact resistance levels, and hence, different LED characteristics. In each sample, the mesa dimension is $300 \times 300 \mu\text{m}^2$ and the p-contact of $80 \times 80 \mu\text{m}^2$ in size was deposited with an electron-gun evaporator at a corner of the mesa.

Fig. 1 shows the curves of the injection current versus the applied voltage (I - V curves) of the three samples. One can see that all the turn-on voltages of the three samples are around 4 V. From the slopes of the I - V curves, we can easily see the lowest (highest) device resistance in Sample A (C). The differences in device resistance among the three samples are mainly attributed to the different p-contact thicknesses, which lead to the different contact resistance levels. To demonstrate the effect of metal thickness on contact resistance, we used the transmission-line method for evaluating the contact resistance levels of the three p-contact structures. The calibrated specific contact resistance levels of the three p-contact structures, corresponding to Samples A, B, and C, are 8.19×10^{-5} , 2.01×10^{-4} , and $1.31 \times 10^{-3} \Omega \cdot \text{cm}^2$, respectively. With the different device resistance levels, the junction temperatures of the three samples are expected to be different.

Fig. 2 shows the output spectra of the three device samples at several injection current levels. One can see that the emission of Sample A is mainly in the green range although tails in the blue range can be seen. The green spectral peak blue shifts by 2.5 nm in increasing the injection current from 1 through

Fig. 2. LED output spectra of Samples A, B, and C at various injection currents.

10 mA. In Sample B, besides the dominating green emission, the blue emission becomes more significant. In this sample, the green spectral peak blue shifts by 3.9 nm in the same current range. Then, in Sample C, the intensity of the blue emission becomes comparable to the green one. In particular, the blue/green contrast ratio is significantly increased. As the injection current increases from 3 through 10 mA, the blue and green spectral peaks blue shift by 4 and 9.9 nm, respectively. The blue shifts of the spectral peaks can be due to the band-filling effect and the thermalization of injected carriers (temperature increase) as the injection current increases. Also, the release of the quantum-confined Stark effect because of carrier screening can also contribute to the blue shifts [6].

Fig. 3 shows the comparison of the output spectra of the three samples when the injection current is fixed at 10 mA. One can clearly see the increasing blue intensity with decreasing metal thickness of the p-type Ohmic contact. Also, either green or blue feature in the LED output spectra blue shifts as the blue intensity becomes stronger. In other words, as the metal layer becomes thinner, the blue-emitting second and third QWs receive more holes for enhancing blue emission. As shown above, a thinner metal contact leads to a higher contact resistance level and hence a higher junction temperature. With a higher junction temperature, the probability for the hole to escape from the first QW (green emitting) and then be captured by the second and third QWs (blue-emitting) becomes higher. Therefore, the second and third QWs can receive sufficient holes for effective recombination. Hence, the relative blue intensity is the highest in Sample C, followed by Samples B and then A.

To further confirm the difference in junction temperature among the three samples, we plot the variations of the output power with the injection current in the three samples, as shown in Fig. 4. In all three samples, below 10 mA in injection current, the output power curves are quite linear. However, the output

Fig. 3. LED output spectra of the three samples with the fixed injection current at 10 mA.

Fig. 4. Output powers as functions of the injection current in the three samples.

power becomes saturated beyond 10 mA in Sample C, beyond 15 mA in Sample B, and beyond 25 mA in Sample A. Such differences in saturation current are related to the different junction temperatures. A higher device resistance level, and hence, a higher junction temperature in an LED results in a lower saturation current. The lowest and highest saturation currents in Samples C and A, respectively, are consistent with the expectations of the highest and lowest junction temperatures in the corresponding samples.

As discussed above, a higher resistance level results in a higher junction temperature. A higher junction temperature

will in turn lead to a higher diode resistance level because of the stronger lattice vibration. Therefore, the device resistance levels in Samples B and C are significantly higher than that of Sample A (see Fig. 1). Besides the factor of different contact resistance levels for different heating effects, the factor of heat radiation is another issue leading to the observed results. A thicker p-contact is expected to radiate the heat more effectively. Such an argument is also consistent with the conclusion of the highest junction temperature in Sample C. The green-emitting QW at the bottom was originally designed to absorb the downward-propagating blue photons for re-emitting green light and enhancing the green intensity. However, it is difficult to evaluate the effectiveness of the designed function.

In summary, we have demonstrated the dependence of the output spectrum on the junction temperature of a blue/green two-color InGaN–GaN QW LED. By decreasing the metal thickness of the p-type Ohmic contact on the device, the contact resistance was increased, and hence, the junction temperature was also increased. With the junction temperature increased, the probability for the deeper QWs to capture the holes became higher such that blue emission could be enhanced to compete with the dominating green emission from the first QW. The conclusion of a higher junction temperature in a sample of a thinner p-type metal layer was consistent with the measurements of the output power versus the injection current, the current versus the applied voltage, and the direct measurement of contact resistance.

REFERENCES

- [1] I. Ozden, E. Makarona, A. V. Nurmikko, T. Takeuchi, and M. Krames, "A dual-wavelength indium gallium nitride quantum well light emitting diode," *Appl. Phys. Lett.*, vol. 79, no. 16, pp. 2532–2534, Oct. 2001.
- [2] Y. D. Qi, H. Liang, W. Tang, Z. D. Lu, and K. M. Lau, "Dual wavelength InGaN/GaN multi-quantum well LEDs grown by metalorganic vapor phase epitaxy," *J. Cryst. Growth*, vol. 272, no. 1–4, pp. 333–340, 2004.
- [3] M. Yamada, Y. Narukawa, and T. Mukai, "Phosphor free high-luminous-efficiency white light-emitting diodes composed of InGaN multi-quantum well," *Jpn. J. Appl. Phys.*, vol. 41, no. 3A, pp. L246–L248, Mar. 2002.
- [4] B. Damilano, N. Grandjean, C. Pernot, and J. Massier, "Monolithic white light emitting diodes based on InGaN/GaN multiple-quantum wells," *Jpn. J. Appl. Phys. Part 2*, vol. 40, no. 9A/B, pp. L918–L920, Sep. 2001.
- [5] S. Fujita, M. Funato, D. C. Park, Y. Ikenaga, and S. Fujita, "Electrical characterization of MOVPE-grown p-type GaN:Mg against annealing temperature," *MRS Internet J. Nitride Semicond. Res.*, vol. 4S1, no. G6.31, 1999.
- [6] D. Xiao, K. W. Kim, S. M. Bedair, and J. M. Zavada, "Design of white light-emitting diodes using InGaN/AlInGa quantum-well structures," *Appl. Phys. Lett.*, vol. 84, no. 5, pp. 672–674, Feb. 2004.