Luminescence distribution and hole transport in asymmetric InGaN multiple-quantum well light-emitting diodes*

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Abstract: Asymmetric InGaN/GaN multiple-quantum well (MQW) light-emitting diodes were fabricated to expose the luminescence distribution and explore the hole transport. Under electrical injection, the sample with a wNQW active region in which the first QW nearest the p-side (QW1) is wider than the subsequent QWs shows a single long-wavelength light-emission peak arising from QW1. The inverse nWQW sample with a narrow QW1 shows one short-wavelength peak and one long-wavelength peak emitted separately from QW1 and the subsequent QWs. Increasing the barrier thickness between QW1 and the second QW (QWB1) in the nWQW structure, the long-wavelength peak is suppressed and the total light-emission intensity decreases. It was concluded that the nWQW and thin-QWB1 structure can improve the hole transport, and hence enhance the light-emission from the subsequent QWs and increase the internal quantum efficiency.

Key words: InGaN; asymmetric coupled multi-quantum-well; light-emitting diodes; luminescence distribution; hole transport

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1. Introduction

For multiple-quantum well (MQW) light-emitting diodes (LEDs), it was commonly considered that increasing the QW number could spread the carriers to more QWs and reduce the carrier density per QW. However, in GaN-based LEDs, it was found that only the first QW nearest the p-side (QW1) can emit light under electrical injection by angle-resolved and wavelength-resolved far-field measurements[1].Some other reports also revealed the dominant QW1 emission under electrical injection in GaN LEDs[2, 3]. This probably results from the inferior hole transport due to the holes' low concentration, large effective mass and small mobility relative to the electrons and thus dominant hole population in QW1. The luminescence distribution along with the related carrier transport and carrier distribution in MQW is an important issue for LED epitaxial structure design. If the holes are concentrated only in QW1, it may lead to Auger non-radiative recombination loss due to the high carrier density in QW1, and electron current leakage due to insufficient recombination with the holes, which are two probable origins of the efficiency droop under larger current injection. Two approaches were hence suggested to solve this problem: a double-heterostructure in place of the MQW active region was brought forward in order to reduce the carrier density and the Auger recombination loss under large current injection[4], and thin or p-doped barriers between QWs were brought forward to facilitate the hole transport[5, 6].In addition, the luminescence distribution in MQW has a direct effect on the color proportion in single-chip multi-color MQW LEDs[7].

Asymmetric (AS-) MQW structure can be utilized to expose the luminescence distribution by distinguishing the light-emission wavelength and also improve the hole transport by adjusting the valence band[8, 9].In this paper, InGaN/GaN AS-MQW LEDs, in which the thickness of QW1 is different from the subsequent QWs, were fabricated. The luminescence distribution was clearly exposed by the electroluminescence (EL) spectra. The hole distribution and hole transport, and their dependence on the QW sequence and the barrier width, were investigated.

2. Sample fabrication

A series of InGaN/GaN MQW LED wafers was grown on (0001) sapphire substrate by metalorganic chemical vapor deposition (MOCVD). Figure 1 shows the schematic sample structures. Each sample consists of 3 μm n-GaN with an electron concentration of 3×10^{18} cm^{-3}, an active region of eight InGaN/GaN QWs (labeled from the p-side as QW1, QW2, etc.), and 150 nm p-GaN with a hole concentration of about 3×10^{17} cm^{-3}. All samples were grown under the same conditions, except for some adjustment in the growth time for the wells or the barriers. Sample A consists of one 3.5 nm QW1 and seven 2.0 nm QWs (wNQW), while sample B consists of one 2.0 nm QW1 and seven 3.5 nm QWs (nWQW). The barrier between QW1 and QW2 (QWB1) is 5 nm and other barriers

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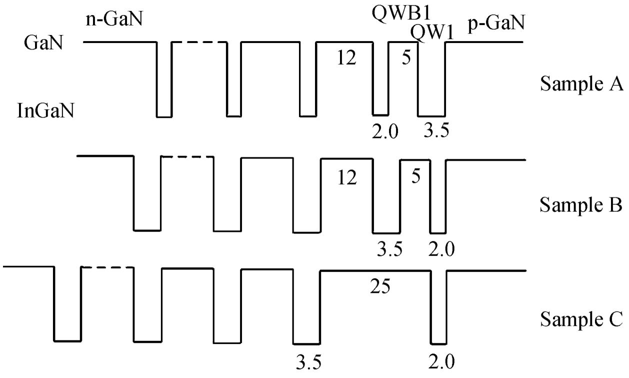

Fig. 1. Sketch drawing of the sample structures. The thickness of the wells and the barriers is labeled (unit: nm).

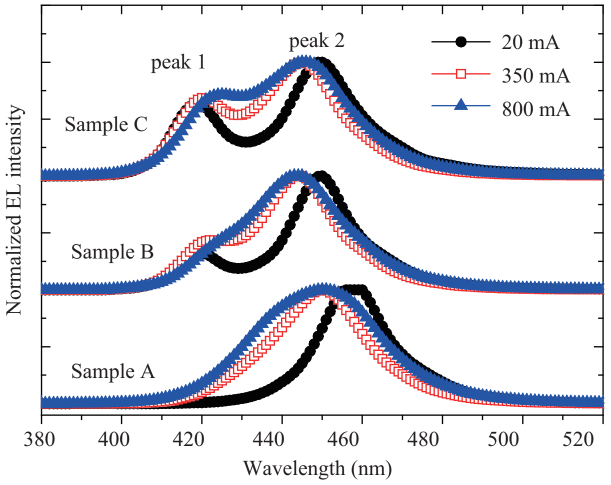

Fig. 2. (Color online) Normalized EL spectra measured under different injection currents. (Each spectrum is normalized to its peak intensity at about 450 nm.)

between QWs are all 12 nm in samples A and B. Sample C is the same as sample B, except the QWB1 is extended to 25 nm. The thickness of the wells and the barriers was derived from XRD measurement. Indium composition in the InGaN wells was estimated to be about 17% according to XRD analysis of a single-layer InGaN reference sample. The epitaxial wafers were processed to form 1 × 1 mm^2 lateral LED chips and then encapsulated.

3. Measurements and analysis

EL spectra of the encapsulated samples were measured using an integrating sphere. Figure 2 shows the normalized EL spectra of the three samples. Sample A shows a single peak at about 450 nm. Both samples B and C exhibit two peaks, one short-wavelength peak located at about 420 nm and one long-wavelength peak at about 450 nm, labeled as peak 1 and peak 2, respectively. The light-emission at about 420 nm and 450 nm should separately come from the 2.0 nm well and the 3.5 nm well according to our previous experiments and simulation.

In sample A, no obvious short-wavelength light-emitting peak arising from the subsequent narrow QWs was observed, even under large injection current. The inferior hole-injection and uneven hole-distribution in MQW under electrical injection can be easily anticipated due to the holes' low concentration, large effective mass and small mobility relative to the electrons in the InGaN material. The larger effective mass of holes will lead to much smaller tunneling probabilities than electrons. The smaller mobility of holes will lead to a smaller diffusion coefficient, while diffusion and tunneling, mainly trap-assisted tunneling, is the major carrier transport mechanism in this type of InGaN/GaN MQW LED[10]. Thermionic field emission should be minor since the GaN potential barrier is rather high. This suggests that most holes were injected into QW1 and few holes were injected into the subsequent QWs in this sample.

To investigate the hole transport, the effect of the QW sequence and the QWB thickness was analyzed. Compared with sample A, sample B shows significant light-emission from the subsequent wide QWs (peak 2). It may benefit from the increased hole population in the subsequent QWs due to the energy-level difference and well-width difference. The ground-state energy level in one wide QW is lower than one narrow QW due to the weaker quantum confinement, which will lead to larger carrier occupation probabilities according to the Fermi distribution function. In addition, one wide QW has a larger density of states than one narrow QW. Increasing the injection current, peak 1and peak 2 are both blue-shifted and broadened. The blue-shift was caused by the screening of the polarization field and the energy-band filling. The broadening was mainly caused by the energy-band filling effect. The integrated intensity ratio of peak 2 to peak 1, deduced from Gaussian fitting and separate integration, is 3.3, 4.4, and 13.1 under 20 mA, 350 mA and 800 mA, respectively. The ratio increases with the injection current, although the two-peak fitting might be uncertain and the ratio derived from it might be overestimated. The increased ratio under larger current can be attributed to more hole transport into the subsequent QWs, because of the high carrier density and the reduced potential-barrier height due to the screening of the polarization charge, and also the enhanced thermionic field emission at high bias level.

The EL spectra of sample C also show two peaks, but the integrated intensity ratio of peak 2 to peak 1 is significantly smaller than sample B. The ratio is 2.2, 2.7, and 3.7 under 20 mA, 350 mA and 800 mA, respectively. The smaller and more slowly increasing ratio can be mainly attributed to the reduced hole tunneling probabilities due to the thick QWB1.

EL spectra of samples A, B, C are further compared in Fig. 3. It is obvious that sample B has stronger light-emission than samples C and A. Both samples B and C have two peaks; however, in sample B, the long-wavelength peak is significantly higher, and hence the total light-emission intensity of the two peaks is stronger. The total light-emission intensity of samples A, B, C as a function of the injection current is compared in Fig. 4. At 350 mA, the total light-emission intensity of sample B is 33% higher than sample C, and 42% higher than sample A. Compared with sample C or sample A, the stronger light-emission from the subsequent QWs in sample B can be mainly attributed to the increased hole tunneling probabilities. The increased total light-emission intensity may be attributed to the reduced electron density in QW1 and hence reduced electron current leakage or Auger recombination loss.

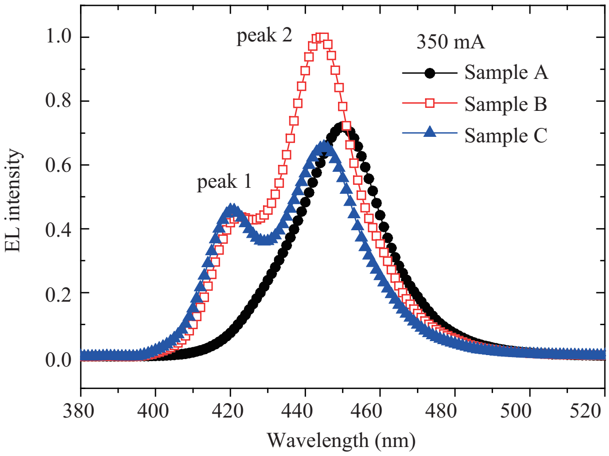

Fig. 3. (Color online) EL spectra of samples B and C measured under the injection current of 350 mA (normalized to the peak intensity at about 450 nm of sample B).

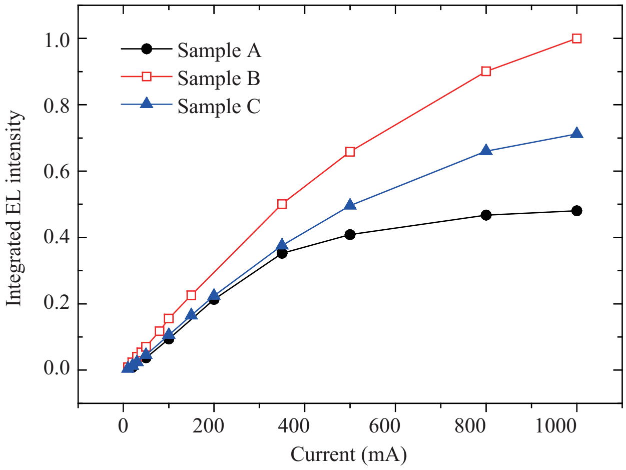

Fig. 4. (Color online) Integrated EL intensity of samples B and C as a function of the injection current (normalized to the integrated EL intensity at 1 A of sample B).

On the other hand, it should be noted that the wide QWs can be excited by the high-energy light emitted from the narrow QWs, referred to as the secondary excitation. It can affect the spectral distribution of luminescence, reducing the short-wavelength peak and increasing the long-wavelength peak, but it cannot increase the total light output power. In sample A, if holes can be injected into the subsequent QWs, recombine with electrons and emit light, the emitted light can excite the QW1. But it is impossible that no short-wavelength light remains after secondary excitation. Maybe the detection instrument is not sensitive enough, but, at least, the light-emission from the subsequent QWs is very weak. The suggested few-hole injection into the subsequent QWs still sounds reasonable. In samples B and C, the narrow QW1 emission can excite the subsequent QWs. In sample C, considerable long-wavelength light-emission might arise from the secondary excitation effect, since the hole transport though the thick QWB1 may be difficult. However, the increased long-wavelength light-emission in sample B compared with sample C, especially under larger injection current, should contain little contributed by the secondary excitation effect, since it should be little affected by the barrier thickness and cannot increase the total light-emission intensity.

The stronger light-emission from the subsequent QWs in sample B than in samples A and C can be well explained by the facilitated hole transport, including the increased hole distribution probabilities and the increased tunneling probabilities induced by the ground-state energy-level difference, the well-width difference, and the thin QWB1[5, 8, 9]. So it suggests some effective approaches to facilitate the hole transport by introducing an energy-level difference or reducing the QWB thickness. The energy-level difference can be formed by gradually reducing the thickness or cutting the indium composition of the wells, or gradually reducing the silicon doping or increasing the magnesium doping of the barriers, in MQW growth from the n-side to the p-side. MQWs separated with thin barriers are referred to as coupled quantum wells or superlattices. Besides facilitating the hole transport, the nWQW structure could also block electron tunneling to fill a higher energy level[8], and hence balance the electron injection and the hole injection to some extent. It could help to suppress the electron density in QWs and alleviate the electron current leakage or Auger recombination loss, and eventually increase the internal quantum efficiency of LEDs.

4. Conclusion

A series of InGaN/GaN MQW LED structures in which the QW1 emits light at a wavelength different from the subsequent QWs was fabricated. The EL spectra were investigated. The wNQW structure shows no obvious light-emission from the subsequent QWs. The nWQW structure exhibits significant light-emission from the subsequent QWs. Increasing the thickness of QWB1 in the nWQW structure, the light-emission from the subsequent QWs is significantly suppressed and the total light-emission intensity decreases. The hole distribution and hole transport were analyzed. It was concluded that the nWQW structure and the thin QWBs can increase the hole distribution probabilities and tunneling probabilities, and hence enhance the light-emission from the subsequent QWs and increase the internal quantum efficiency of LEDs.

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