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ABSTRACT

GaN/GaInN asymmetric multiple quantum well light-emitting diodes with varying potential barrier thicknesses (5 and 15 nm) are grown by using metal organic chemical vapor deposition. The narrow barrier structure improves the performance of the device, including the super-linear increase of electroluminescence integral intensity, the mitigation of efficiency droop at high current density, the reduction of wavelength drift, the reduction of forward voltage, and the improvement of wall-plug efficiency. This is due to the narrowing of the thickness of the quantum barrier, which results in the smaller electric field among the quantum well, the weakening of the quantum confinement Stark effect, the more uniform distribution of carriers across the active region of the device, and the suppression of electron leakage.

I. INTRODUCTION

III-nitrides light-emitting devices are a subject of active research because of their increasingly wide utilization such as solid-state lighting, automotive lighting, back lighting in liquid-crystal displays, outdoor displays, and traffic lights.[1–3] Although enormous development has been made in these fields, there is still more effort required in order to make these nitrides devices operate with higher efficiency and reliability. GaN/InGaN MQWs must be paid special attention because they act as the active layer in most III-nitride light-emitting diode (LED) and Laser Diodes (LDs) structures.[4–6] However, the effective mechanism of efficiency droop in multiple quantum wells remains an open question, and various origins behind the droop have been under discussion.[7,8] The inhomogeneous distribution of holes in the MQWs and the resulting electron leakage from the active region were judged to have been a possible mechanism resulting in the efficiency droop.[3,7] The holes in InGaN MQW have large effective mass and small mobility relative to electrons, which leads to poor injection and transport capacity through the barrier.[9] Therefore, the injected holes always concentrate at the quantum well (QW) neighboring the p-side GaN resulting in lower hole concentration in other quantum wells and serious electron leakage, which leads to reduced efficiency.[10] To enhance the uniformity of hole distribution and reduce the carrier leakage, many strategies including the effect of the barrier doping, height and width, and the well thickness and shape on GaN/GaInN conventional symmetric multiple quantum wells to improve the properties have been explored, such as different barrier thickness,[11] triangular-shaped quantum well,[12] InGaN quantum well (QW) with n-doped quantum barriers,[13] quaternary devices,[14–16] graded quantum well structure,[17,18] zigzag-shaped quantum well,[19,20] and asymmetric multiple quantum wells.[21] The asymmetric InGaN quantum well structure is one of the effective approaches to improve the carrier distribution among the active region and suppress electron leakage from the wells. Zhang *et al.* experimented and compared the light emission intensity of asymmetric quantum wells with that of traditional symmetric quantum wells.[22] Usman *et al.* theoretically studied and compared the internal quantum efficiency of LEDs with multiple asymmetric quantum wells and potential barriers with traditional LEDs with uniform multiple quantum wells.[23] These previous studies show that the asymmetric quantum well structure has better photoelectric characteristics than the traditional quantum well structure. The light-emitting diode (LED) with the asymmetric quantum wells seems to be important and worth researching. In addition, the polarization field of quantum wells is strongly affected by well thickness and barrier thickness. It has been revealed that the employ of conventional quantum wells with thin barriers could be conducive to the uniformity of hole distribution among the InGaN wells, thereby improving the efficiency degradation at high current density.[11] Nevertheless, the effect of barrier layer thickness on asymmetric multiple quantum wells is not detailed. In this letter, two asymmetric InGaN/GaN quantum wells LEDs with different barrier thicknesses are fabricated by using a metal organic chemical vapor deposition system, and the asymmetric InGaN/GaN QWs are experimentally characterized. Furthermore, the effects of barrier thickness on relative external quantum efficiency (EQE), electroluminescence (EL) spectrum, and IV characteristics are studied, and the reasons for the improvement of device performance are analyzed.

II. MATERIALS AND STRUCTURES

The two epitaxial structures under investigation are deposited by low pressure metal organic chemical vapor deposition upon 0001-oriented sapphire substrates. The epitaxial wafer is epitaxially grown by the research group of Professor Zhang Bao-ping of Xiamen University according to the predetermined quantum well structure. The growth conditions and structural parameters are the same as in our previous study.[22] After depositing a GaN nucleation layer, a 1.8 μm thick n-type GaN:Si layer on the substrate, followed by an active region composed of $In_{0.2}Ga_{0.8}N$/GaN multiple quantum wells. A Mg-doped layer stack composed of an 80 nm GaN:Mg cladding layer on top of a 15 nm $Al_{0.2}Ga_{0.8}N$:Mg electron blocking layer is grown on the active region. Both samples are asymmetric stretch (AS)-QWs active region structures. The two samples are constructed by two series of three asymmetric $In_{0.2}Ga_{0.8}N$ quantum wells, which are separated by a 17 nm GaN Insert layer. The quantum well thickness of each series is 3, 2.5, and 2 nm, respectively. As is well known, the hole concentration is higher in the well near the p side, and the narrower well has a larger recombination rate due to the better quantum confinement effect and the weaker quantum-confined Stark effect (QCSE); therefore, the well width near the p side is designed to be the thinnest. The differences in the two

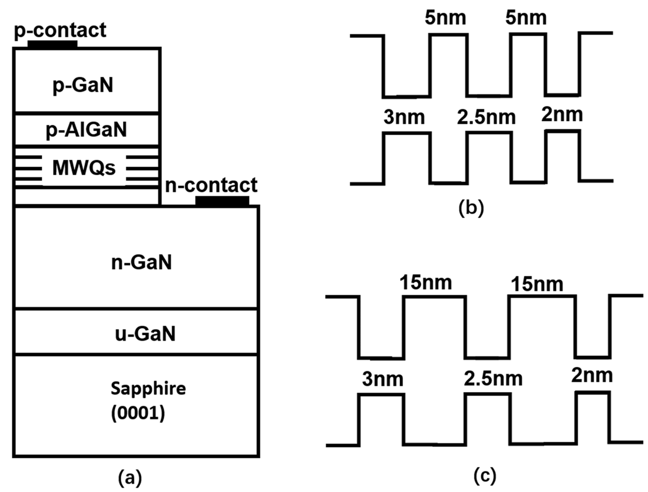

FIG. 1. Schematic diagram of the LED structures investigated (a) and detailed parameters of multiple quantum wells for QB-1 (b) and QB-2 (c).

LED structures are only barrier thickness. In the first (marked as QB-1) and second structures (marked as QB-2), the barrier layer thicknesses are 5 and 15 nm, respectively. The epitaxial wafers are processed into LED structure and are not encapsulated (the LED structure was prepared by the research group of Professor Zhang Bao-ping of Xiamen University). The LED structures are schematically shown in Fig. 1. When the injection current density is 5 mA/cm^2, the electroluminescent center wavelengths of the two samples are 446 and 449 nm, respectively.

The wafer surface morphology was characterized by Seiko spa400 atomic force microscope (AFM). Devices are tested in wafer form at room temperature. The pulsed current is adopted in 1 kHz frequency with a duty cycle of 1% up to 500 mA/cm^2. Light out is primarily collected from the vertical direction of the surface into a spectrometer with a resolution of 0.1 nm, which is based on a cooled charge coupled device (CCD).

III. RESULTS AND DISCUSSION

The typical AFM scanning morphology on a 2 μm square area is exhibited in Figs. 2(a) and 2(b) for the two different epitaxial structures. The surface clearly exhibits the growth terraces, which is a typical step flow growth mode of nitrides. The AFM scanned results show the root mean square (rms) surface roughness of 0.24 and 0.25 nm for the wafer with 5 nm and 15 nm thick barriers, respectively. It is obvious that the two samples are almost the same surface roughness.

To make the LED dissipate heat in time (considering the influence of the temperature), the electroluminescence (EL) spectrum of LED was obtained by adopting a 1 kHz frequency pulse current source with a duty cycle of 10%. The integral electroluminescence (EL) intensity and the relative external quantum efficiency (EQE) as functions of the injection current density for the LEDs of 5 and 15 nm thick GaN barrier are revealed in Figs. 3(a) and 3(b). In the whole measurement range of Fig. 3(a), the intensity of integrated

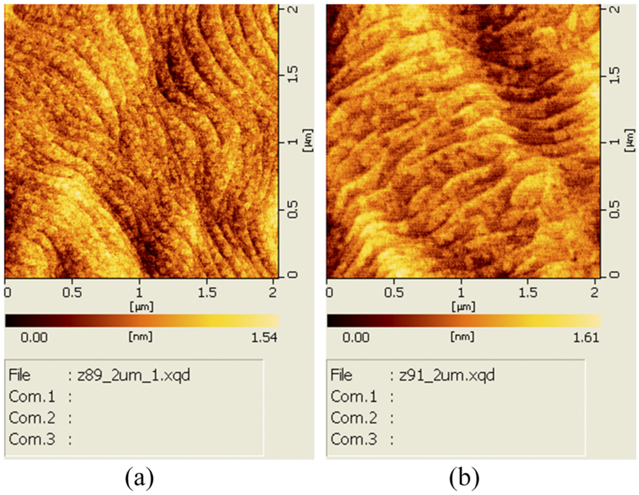

FIG. 2. AFM images of 2 × 2 μm^2 areas for the epitaxial wafer with 5 nm barriers (a) and 15 nm barriers (b), respectively.

electroluminescence enhances with the increase of injection current density. When the current density is less than 380 mA/cm^2, the integrated EL intensity of the QB-2 structure with the thicker barrier is stronger than that of the QB-1 structure with a 5 nm barrier. With the further enhancement of the injection current, nevertheless, the integrated EL intensity of the structure with 15 nm barrier is weaker than that from the structure with a thinner barrier. The integrated electroluminescence intensity from the QB-2 structure is observed a sublinear behavior over the whole current density range, 0–500 A/cm^2. By contrast, as presented in Fig. 3(a), the intensity of integrated electroluminescence for the QB-1 structure increases relatively quickly with current density and shows super-linear characteristics within the measuring range. A typical current density dependence is also noted where the relative EQE from QB-2 initially increases with current density, before reaching a maximum at 40 A/cm^2, and then decreases significantly with subsequent increases in injection current. The efficiency droop is ~32% at the injection current density of 500 A/cm^2. However, with the increase of injection current density, the relative EQE from QB-1 structure remains monotonically increased, as exhibited in Fig. 3(b). No decrease in LED efficiency is observed in the measurement range, which corresponds with the results reported by Ni *et al.*[11] It can be noted that the integrated electroluminescence intensity and the EQE efficiency from the QB-1 are less than that of the QB-2 at lower current density. This is an obvious consequence of the higher carrier density among the multiple quantum wells with 15 nm thick barriers.[24] Because of the tunneling effect, the carrier distribution in QB-1 structure with the thin barrier is relatively uniform, and the carrier density of a single well is relatively small. For the QB-1 structure with a 5 nm thick barrier, the integral EL intensity and EQE increase faster. At higher current, the sample with a 5 nm thick barrier has higher the integral EL intensity and external quantum efficiency. The phenomenon may be due to the fact that the QB-2 structure with a 15 nm thick barrier suffers from electron leakage through AlGaN current blocking layer from the active region due to poor holes tunneling through the thick barrier. In the case of the multiple quantum wells region with a 5 nm thick barrier, where the hole diffusion and tunneling are better, it is possible to realize a more uniform hole distribution and a lower carrier density at a higher injected current density. Therefore, the intensity of integral electroluminescence and the relative external quantum efficiency of the QB-1 structure with 5 nm thick barriers exceed that of the QB-2 structure with 15 nm thick barriers at high injection levels.

The normalized EL spectra from the two structures under injected current densities of 10 and 100 mA/cm^2 are plotted in Fig. 4. In the case of the QB-1 structure, the peak of the electroluminescence spectrum only reveals a little blue shift under two different current densities, whereas the peak wavelength of the QB-2 with 15 nm thick barriers shows a larger blueshift. As shown in Fig. 4(a), generally, the total strain in the MQWs would be increased due to the increase in the total thickness of the MQWs as the GaN barrier thickness is increased. Accordingly, the larger blueshift of the QB-2 structure with 15 nm thick barriers is attributed to the stronger QCSE in the wider barriers.[25] In addition, as can be seen From Fig. 4, the broadening of electroluminescence spectrum mainly occurs in the direction of a shorter wavelength. In general, the phenomenon is the band-filling effect.[5] Therefore, the EL spectrum of structure QB-1 with a 5 nm thick barrier exhibits a smaller broadening, indicating that the carrier density in the wells is relatively lower, and illustrating that the hole distribution across all quantum wells is relatively uniform. As a result, the hole can recombine efficiently

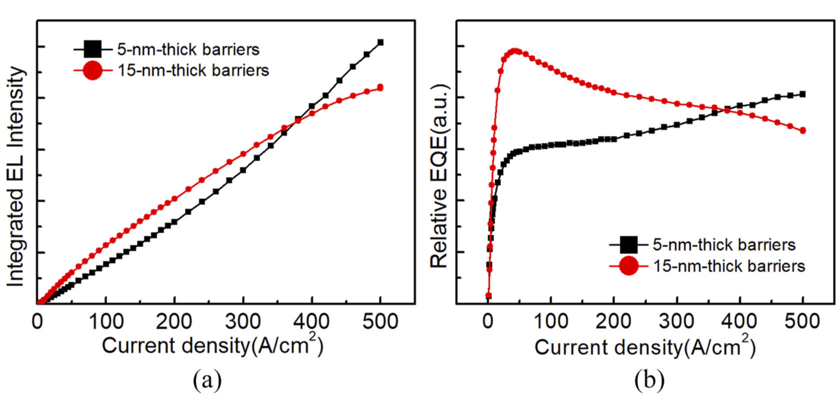

FIG. 3. Variation of integrated electroluminescence (EL) intensity characteristics (a) and normalized relative external quantum efficiency (EQE) (b) for epitaxial structures.

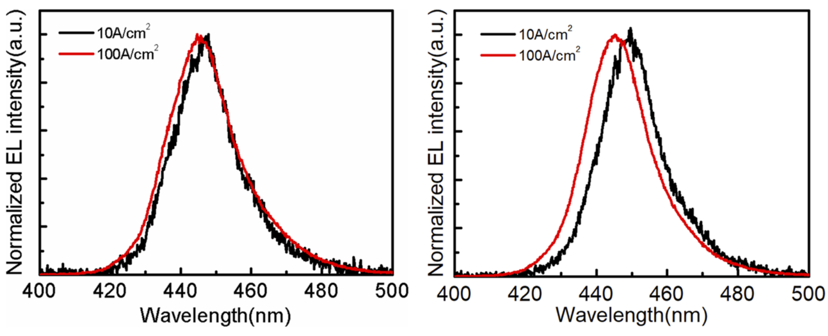

FIG. 4. The normalized EL spectrum of the (a) QB-1 and (b) QB-2 structures at a current density of 5 and 100 A/cm^2, respectively.

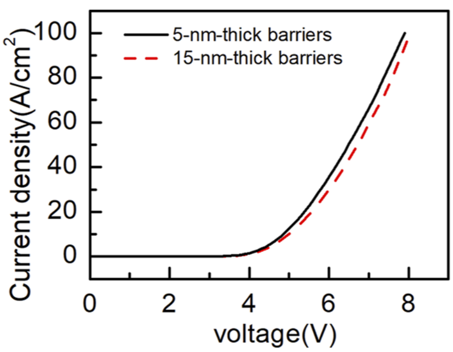

FIG. 5. I–V curves of the QB-1 and QB-2 structures.

with electrons in all quantum wells, thereby reducing the excess hole concentration within the first quantum well close to the p-type side.

The electrical properties of the two structures are exhibited in Fig. 5. Compared with the LED with a 15 nm thick barrier, the LED with a 5 nm thick barrier has lower forward voltage, which may be due to the more uniform and more carrier concentration in all quantum wells, leading to higher conductivity and lower series resistance. Lower forward voltage results in an increase in the EL intensity at fixed current and indicates higher wall-plug efficiency.

IV. CONCLUSION

In conclusion, our work has demonstrated the influence of quantum barrier thickness on the optical and electrical characteristics of the AS-MQWs LEDs. The GaN barrier thickness in the AS-MQWs was found to play an important role in determining the optical and electrical characteristics of the AS-MQWs. Experimental results show that the structure with narrower barriers improves device performances, including enhancing integrated electroluminescence (EL) intensity at high current density, improving efficiency droop, reducing wavelength shift, diminishing forward voltage, and improving the wall-plug efficiency. This is the result of the narrowing of the quantum barrier thickness, the weakening of the quantum confinement Stark effect (QCSE), and the more uniform carrier distribution among the multiple quantum wells of the device. The results show that the thinner QB thickness provides an effective and practical method to improve the performance of GaInN/GaN asymmetric quantum well light-emitting diodes.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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