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Characteristics of μ-Slice InGaN/GaN Light Emitting Diodes Formed by Focused Ion Beam Process

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1. Introduction

GaN-based light-emitting diodes (LEDs) grown on the c-plane sapphire substrate have attracted a great of interests in the application of solid-state lighting and backlight modules for liquid crystal displays. [1-3] The electro-beam writer and dual-beam focused ion beam system (DB-FIB) had been frequently used to achieve nano devices. The ion damage induces structure defects to degrade device performance. As a result, the single nano devices exhibited low device performance when their scale were down to hundreds nanometers. [4] In addition to the ion damage, such single nano devices also encountered great difficulties in the formation of electrical contact. [5-6] Therefore, the devices can exhibit ordinary photoluminescence (PL) characteristics, but they generally lack good electroluminescence (EL) characteristics. [6] There are few publications which have revealed the electrical and optical properties of GaN-based emitters with nano scale formed by FIB. [6] In this work, we report the fabrication of sliced GaN/InGaN multi-quantum well (MQW) LEDs with dimension of few micrometers formed by FIB technique. Electrical and optical characterizations of the experimental LEDs were also characterized in detail.

2. Experiment

The GaN/InGaN MQW LEDs used in this study were grown on (0001) sapphire substrates by metal-organic chemical vapor deposition (MOCVD) system. Similar layer structure and growth procedure were described in previous publications. [7] Regarding to the process procedures, the p-GaN and GaN/InGaN MQW layers were first etched away to explore the n^+-GaN underlying layer. A 200 nm-thick indium tin oxide (ITO)film was deposited on p-GaN contact layer to serve as a high-transparency p-type Ohmic contact. Next, a bilayer metal of Cr/Au (50/100 nm) was deposited on the ITO layer and the n-GaN underlying layer to serves as the p-type and n-type electrode pads, respectively. Process for fabricating the thin slice LEDs was began with the formation of rectangular mesa (40 μm × 25 μm) by conventional photolithography and dry etching techniques. The rectangular mesa LEDs were then sliced by FIB down to 4.0 μm × 1.4 μm. It should be noted that a 245 nm-thick SiO_2 layer prepared by plasma-enhanced chemical vapor deposition was selectively deposited on the LED samples to restrict the current path within the slice. These slice LEDs were labeled as μ-slice LED. Fig.1 schematically depicts a side view of the μ-slice LED. For comparison, conventional LEDs with dimension of 340 μm × 340 μm were also characterized and labeled as “broad-area LED”.

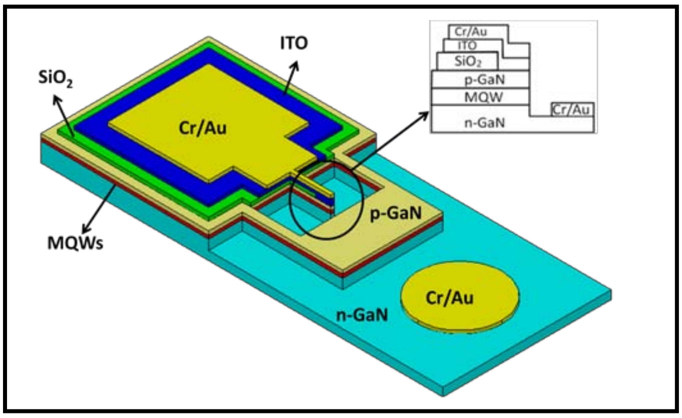

Fig.1 schematically depicts the structure of μ-slice LED.

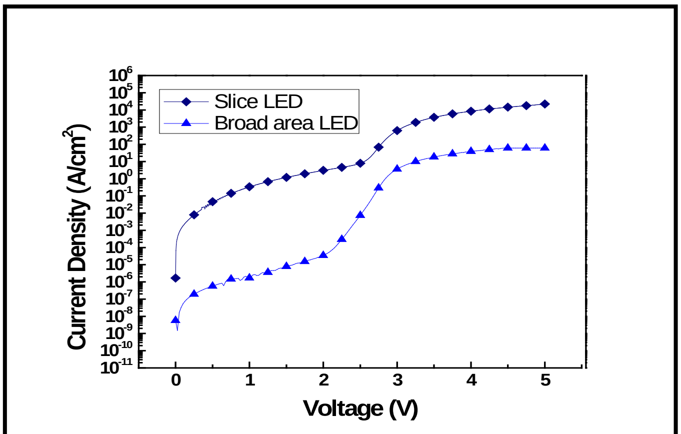

Fig.2 Typical forward current density-voltage (J-V) characteristics of the fabricated LEDs in semi-logarithm scale

3 .Result and Discussion

Fig.2 shows the typical current density-voltage (J-V) characteristics taken from the μ-slice and broad-area LEDs. With the same current density, the turn-on voltage of μ-slice LEDs was far lower than those of broad-area LEDs. It is well known that GaN-based LEDs' turn-on voltage is strong dependent on current spreading effect. [8] Therefore, there may be due to the fact that the broad-area LEDs with larger area lead to a poor current spreading effect compared with the μ-slice LEDs. On the other hand, a very high electric field was induced directly on the p-n junction beneath the Cr/Au contact due to the small device area of μ-slice LED acting like the point contact junction diodes. [9] As a result, potential barrier thickness decreases markedly with an increase of forward voltage and, hence, resulting in easy electron tunneling across p-n junction. In fact, projected straggle of ion beam may lead to amorphous layer around the slice, and thereby results in the practical slice width smaller than its exterior dimension. As a result, the practical electric field should be higher that the estimated number.

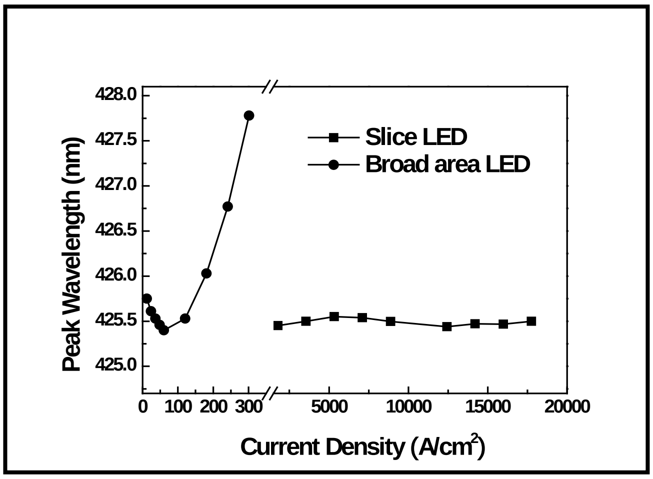

Fig.3 Peak wavelengths spectra taken from the slice and broad-area LEDs as a function of forward current density

Fig.3 shows peak wavelength (λ_p) versus forward current density (J_f) taken from the fabricated LEDs. The broad-area LEDs showed a typical behavior that the λ_p exhibited blue shift first and then showed a red shift with an increase of J_f. The blue shift is well known to be due to the quantum confinement stark effect (QCSE) [10-11], and the red shift is mainly due to the band gap narrowing caused by Joule heating effect. Since we could not observed reliable and stable EL spectra from the μ-slice LEDs when J_f was lower than ~1700 A/cm^2, we could not further comment the difference of λ_p shift between the broad-area and μ-slice LEDs when the J_f was lower than 1700 A/cm^2. However, it is worth to note that the μ-slice LEDs exhibited a different optical property from the broad-area LEDs when J_f was higher than ~1700 A/cm^2. First, the blue or red shift of λ_p with an increase of J_f could not be observed in the μ-slice LEDs. They exhibited a near constant λ_p unlike the broad-area LEDs had a marked bias-dependent λ_p. This phenomenon could be attributed to the fact that the effects of joule heating (i.e., band gap narrowing) and band filling on shift of λ_p compete with each other to lead to a nearly constant λ_p, as shown in Fig.3. On the other hand, the absence of blue shift of λ_p with increasing the J_f of μ-slice LEDs might be also due to the fact that strain release after the ion milling process could result in reduction of piezoelectric field in the quantum wells of the μ-slice LEDs and thereby lead to a mitigation of the effect of QCSE.

4. Conclusion

In conclusion, we have demonstrated the μ-slice GaN-based LEDs formed by focused ion beam system. In the light of the aforesaid results, one would like to suggest that the GaN-based single nano LEDs formed by FIB process and operated under low power with high performance might be potentially able to serve as a single photon sources.

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