Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp95-96

Nearly Wavelength-shift Free (20-21) Semipolar Micro Light-emitting Diodes with Improved Performance via Atomic Layer Deposition

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Abstract

In this work, the (20-21) semipolar micro-LEDs with nearly wavelength-shift free performance have been demonstrated. The semipolar epitaxial process reduced the impact of quantum confined Stark effect on the active region. Furthermore, a high-quality atomic layer deposited passivation layer reduced the leakage current by a few order, further improved the micro-LEDs performance and reliability.

1. Introduction

The gallium nitride-based (GaN) light-emitting diodes (LED) have been widely used in solid-state lighting, optical communication, and display technology [1]. The commercial available GaN-based LEDs are normally grown on the conventional (0001) *c*-plane sapphire substrates, the epitaxial technology of *c*-plane GaN-based LED has been quite mature in the past decades. However, the LED fabricated by *c*-plane substrates were suffer from the quantum confined Stark effect (QCSE) and the efficiency droop that resulting in emission wavelength-shift and the efficiency reduction [2]. The micro-LED display will face the color-shift problem due to the driving conditions have to modulate according to the variation of ambient light brightness, such as the display of the mobile phone under indoor or outdoor environment. The generation of QCSE is because of the built-in electrical field caused by the polarization field. The natural structure of GaN is a hexagonal crystal with wurtzite structure that the existence of spontaneous polarization and piezoelectric polarization due to the highest symmetry compatible [3]. Furthermore, a large piezoelectric field in the order of MV/cm can be induced in the multiple quantum wells with the strained layers in LED structure [4]. These internal polarization fields along *c*-plane (z-axis) result in the accumulation of charge at heterojunction of quantum barrier (QB) and quantum well (QW) further tilt the energy bandgap of QB and QW, also caused the spatial separation between the wave-function distribution of holes and electrons. This will cause a red shift of emission wavelength and decrease of the transition probability. Thus, the *c*-plane-grown GaN materials are subject to strong built-in electric fields because of spontaneous and piezoelectric polarization. The LEDs based on the *c*-plane epitaxial wafer can only operate at low current densities due to the significant decrease of efficiency as the current density increases which means serious droop phenomenon. The common approach to address the QCSE in *c*-plane epitaxy process is to insert the strain relief layer before multiple quantum well during the epitaxial process. Reduced the influence of piezoelectric polarization through the release of stress. But this method can only eliminate a small proportion of QCSE.

The promising technology to improve these phenomena is to replace the conventional *c*-plane LED epitaxial wafer with a nonpolar or semipolar epitaxial wafer. Growth of optical devices on nonpolar or semipolar orientations of InGaN/GaN represents an additional approach to droop reduction and circumvents the issues associated with polarization-related electric fields in conventional *c*-plane structure.

In this work, a $50\ \mu m \times 50\ \mu m$ chip size, (20-21) semipolar micro-LED with great performance improvement by polarization reduced and defects control during epitaxial process. Compared with the *c*-plane LED by similar multiple quantum wells (MQWs) design, (20-21) semipolar micro-LED shows only 3.7 nm emission peak wavelength shift which better than 12.0 nm shift of *c*-plane LED. The droop phenomenon was also greatly improved because the carrier recombination rate increased and the lower level of the electron overflow. This micro-LED shows just 10% droop under 200 A/cm^2 current density. Moreover, the sidewall passivation using atomic layer deposition (ALD) has been demonstrated. The ALD passivation provides excellent film quality and uniformity that significantly reduced leakage current by 10^2 A/cm^2 at -4 V and shows very low leakage current density that lower than 10^{-6} A/cm^2. This great improvement was contributed by lower sidewall defects and surface recombination through ALD passivation.

2. Results and discussion

Figure 1 shows the schematic diagram of the crystal plane of (20-21) semipolar and the scanning electron microscope (SEM) image of (20-21) semipolar GaN bulk layer is grown on the specific patterned sapphire substrates. The SEM image clearly shows that the (20-21) orientation bulk GaN layer was successfully merged together by epitaxial layer overgrowth process.

Figure 2 presents the power-dependent electroluminescent spectrum of semipolar micro-LED and the device lighting image. The peak wavelength of the semipolar micro-LED only changes 3.7 nm with a blue shift under 200 A/cm^2. Compared with the *c*-plane micro-LED of wavelength shift issue, semipolar micro-LED shows good color stability which benefit to apply into display applications, as shown in figure 2(b).

Semipolar micro-LED characteristic between w/ and w/o ALD passivation of leakage current density and output power as shown in figure 3. Because of the effective passivation ability, the reduced leakage current was contributed by reduced the sidewall defects and surface recombination. The leakage current has been reduced by 2-order under -4 V with the excellent passivation in semipolar micro-LED device. Furthermore, the related output power also increasing by 35% with ALD passivation layer due to increasing inject current caused by the reduction of leakage current, and total internal reflection reduced. This results also helps to improve the reliability of the micro-LED device.

Figure 4 shows the normalized external quantum efficiency (EQE) of semipolar and *c*-plane micro-LED. The semipolar micro-LED shows only 10% droop under 200 A/cm^2 current density which much better than 55% droop of the *c*-plane sample. It's because of the improved of the QCSE and high carrier recombination rate and low electron overflow.

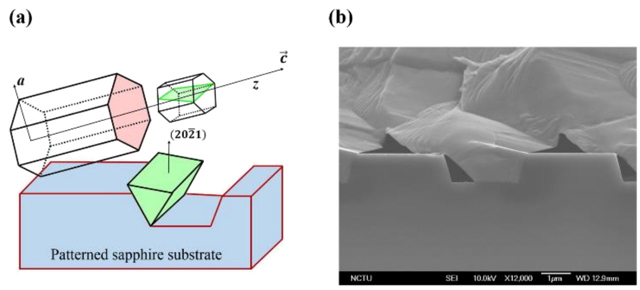

Fig. 1. (a) The schematic diagram of the crystal plane of (20$\bar{2}$1) semipolar GaN (b) The SEM image of (20$\bar{2}$1) semipolar GaN bulk layer.

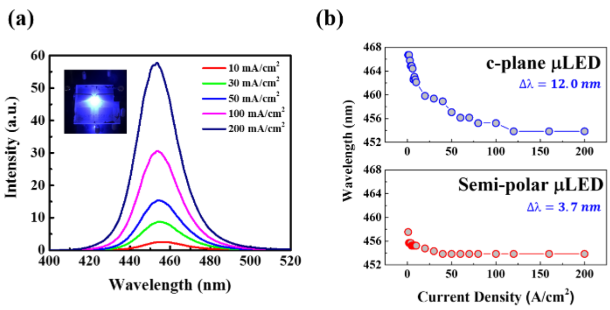

Fig. 2. (a) The power-dependent electroluminescent spectrum of semipolar micro-LED (b) Wavelength-shift comparisons between *c*-plane and semipolar micro-LED.

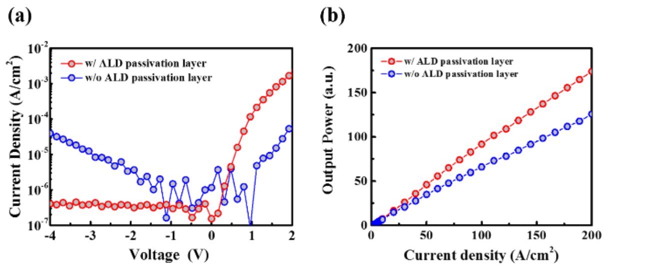

Fig. 3. Semipolar micro-LED characteristic between w/ and w/o ALD passivation of (a) leakage current density and (b) output power.

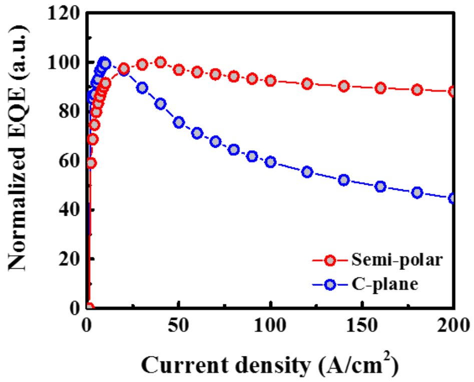

Fig. 4. The normalized EQE of *c*-plane and semipolar micro-LED.

3. Conclusions

A nearly wavelength-shift free micro-LED fabricated by (20-21) semipolar epitaxial wafer has been demonstrated. With the excellent passivation layer deposited by ALD, the output power increased by 35% and leakage current density reduced by 2-order. Compared with the *c*-plane sample, semipolar micro-LED provided much better emission color stability and efficiency performance.

Acknowledgements

The authors express their gratitude to PICOSUN^{TM} for provided the ALD technical support. This work is funded by the ministry of science and technology of Taiwan under grant number MOST 106-2622-E-009 -005 -CC2

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