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InGaN-based Blue Light-Emitting Diodes with Electron Blocking Layer Fabricated on Patterned Sapphire Substrates

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1. Introduction

Nitride-based blue light-emitting diodes (LEDs) grown by metalorganic chemical vapor deposition (MOCVD) are already commercially available [1,2]. However, one important issue of LED is how to increase output power for achieving high-brightness LED applications. In general, GaN films are usually grown on the sapphire substrate. Due to the large differences in the lattice-mismatch and thermal expansion between GaN films and sapphire substrate, a large number of threading dislocations (~10^{10}cm^{-2}) are induced in the GaN films which can result in a significant degradation in brightness and anti-electrostatic properties of LEDs [3,4]. By epitaxial lateral overgrowth (ELOG) with SiN or SiO mask patterned on as-grown GaN seed crystal, threading dislocations can be significantly decreased [5,6]. Although this overgrowth technique can dramatically improve crystalline quality, the requirement of two-step growth procedure is time-consuming and easily introduced contamination. Recently, the single-step growth using patterned sapphire substrate (PSS) without mask has been proposed to overcome the problems of threading dislocation [7-9]. Besides, geometrical shape of the sapphire patterns can also effectively enhance light scattering at GaN/PSS interface. On the other hand, carries tend to escape from the active layer of LED into the confinement layers and reducing the luminescence efficiency for the structure of conventional LEDs because of a low barrier height at the active-confinement interface. Furthermore, high temperatures promote carrier loss out of the active region resulting in reverse leakage current. To reduce carrier leakage out of the active region, carrier blocking layer are used in LED structures.

In this study, InGaN-based high-brightness blue LEDs with electron blocking layer (EBL) fabricated on PSS using metalorganic chemical vapor deposition (MOCVD) has been investigated. A more detailed study on electrical and optical properties of the InGaN-based blue LEDs will be reported.

2. Experiments

The PSS used in this study is fabricated by standard photolithography and subsequent inductive couple plasma (ICP) etching in which Cl_2/BCl_3 gases are used. The PSS contains a periodically trapezoid column-shaped pattern with a depth of 1.6µm and the slanted sidewall angle of 70°. The dimensions of the structure are as follows: the top and bottom diameters are 2.8 and 4.6 µm, respectively, which are separated from each other in an interval of 1.4µm. Figure 1 shows cross-sectional scanning-electron-microscopy (SEM) micrograph of PSS structure. The LED samples are grown on c-face 2-inch PSS by MOCVD. Ttrimethylgallium (TMGa), trimethylindium (TMIn), and ammonia (NH_3) are used as Ga, In, and N sources, respectively. Silane (SiH_4) and biscyclopentadienyl magnesium (CP_2Mg) are used as n- and p-type dopants, respectively. Prior to the growth, the substrate is initially heated to 1100 °C in hydrogen (H_2) ambient for cleaning the surface of substrate. The structure consists of a 30-nm-thick low-temperature GaN buffer layer grown at 550 °C, a 1.5-µm-thick undoped GaN layer grown at 1100 °C, a 1-µm-thick Si-doped GaN layer, an $In_{0.3}Ga_{0.7}N$/GaN multiple-quantum well (MQW) active layer grown at 780 °C, a 10-nm-thick $Al_{0.15}Ga_{0.85}N$ EBL grown at 1100 °C, and finally, a 0.2-µm-thick Mg-doped GaN layer grown at 940 °C. The MQW active layer consists of six periods of 3-nm-thick $In_{0.3}Ga_{0.7}N$ well layers and 20-nm-thick GaN barrier layers.

The LEDs are fabricated using standard chip-processing techniques. First, the surface of the p-type GaN layer is partially etched until the n-type GaN layer is revealed. Indium tin oxide (ITO) is then deposited on the p-type GaN surface as the transparent contact layer. Next, a p-type Ni/Au electrode is deposited on the p-type GaN surface. Ti/Al/Ti/Au is deposited on the n-GaN-revealed surface for ohmic contact. The LED size is 365 × 350 µm^2. Afterward, the wafer is lapped and polished down to about 100 µm. The wafer is cut into a small square shape. The cutted wafer is then mounted (p-side up) on a lead frame without molded by epoxy resin (PSS-EBL LED). For comparison, the LED without EBL fabricated on a conventional sapphire substrate (CSS) is also prepared under the same growth and fabrication conditions (CSS LED).

3. Results and discussion

The dislocation densities of GaN grown the PSS and CSS measured by SEM are estimated to be 3×10^8 and 1×10^9 cm^{-2}, respectively. Figure 2 shows the reverse-bias current and voltage (*I–V*) characteristics of PSS-EBL and CSS LEDs. Leakage current is significantly suppressed for PSS-EBL LED. The result can be attributed to the PSS-EBL LED have a lower dislocation density and a better electron confinement, which resulting in the reduction of leakage current. In addition, the forward voltages measured at 20 mA are 3.64 and 3.75 V for the PSS-EBL and CSS LEDs, respectively. Figure 3 shows the room temperature (RT) electroluminescence (EL) spectra of both LED samples measured at 20 mA. It is found that the EL intensity of PSS-EBL LED is obviously increased compared with CSS LED. Besides, the peak wavelengths of PSS-EBL and CSS LEDs appear at 442 and 456 nm, respectively. The blue-shift phenomenon is due to the reduction of indium mole ratio in the active region for PSS-EBL LED, which is proven by simulations using simulative datum of X-ray diffraction (XRD).

Figure 4 shows the light output power versus injection current (*L*-*I*) characteristics of both LED samples. It can be observed that the output power of these LEDs is linearly increased until saturated and then decreased with increase of the injection forward current owing to the thermal heating effect. Under a 20 mA forward injection current, the output powers of PSS-EBL and CSS LEDs without molded by epoxy resin are estimated to be 6.5 and 2.1 mW, respectively. A 209% enhancement in output power can be achieved in PSS-EBL LED as compared with that of PSS LED. We attributed the improved EL intensity and output power to a combination of enhanced light scattering at GaN/PSS interface, the reduction in dislocation density (by PSS) and the better carrier confinement which leads to a larger number of electrons come back MQW and then increased the recombination between electrons and holes (by EBL).

4. Conclusions

InGaN-based high-brightness blue LEDs have been fabricated using a combination of PSS and EBL techniques. Experimental results indicate that PSS-EBL LED have a smaller forward voltage and reverse leakage current, a stronger EL intensity, and a 209% enhancement in light output power as compared with that of the CSS LED. The improvement can be attributed to the reduction in dislocation density, the enhancement of light scattering at GaN/PSS interface and the better carrier confinement from EBL.

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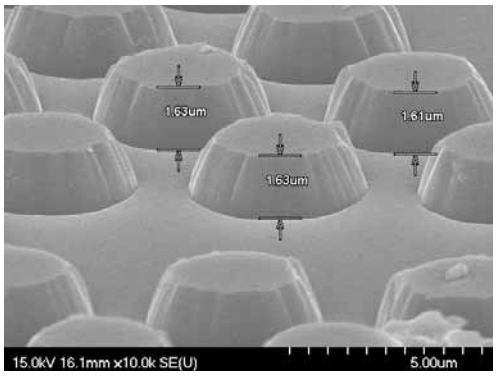

Fig. 1 SEM micrograph of PSS structure.

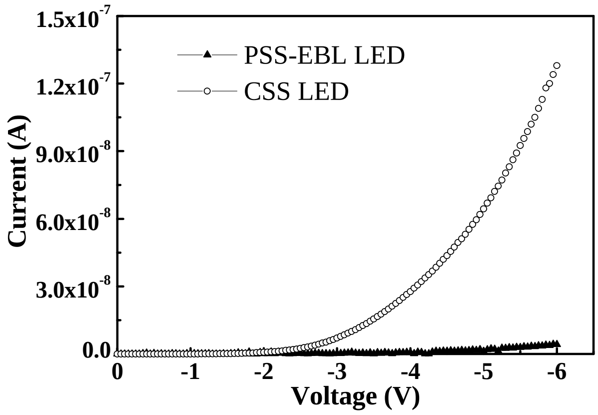

Fig. 2 Reverse-bias *I*–*V* characteristics of PSS-EBL and CSS LEDs.

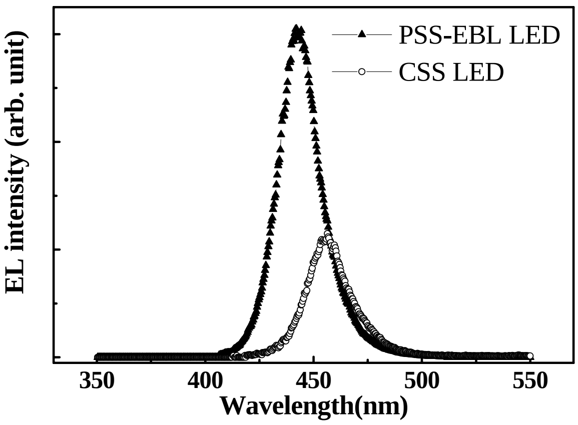

Fig. 3 RT EL spectra of PSS-EBL and CSS LEDs.

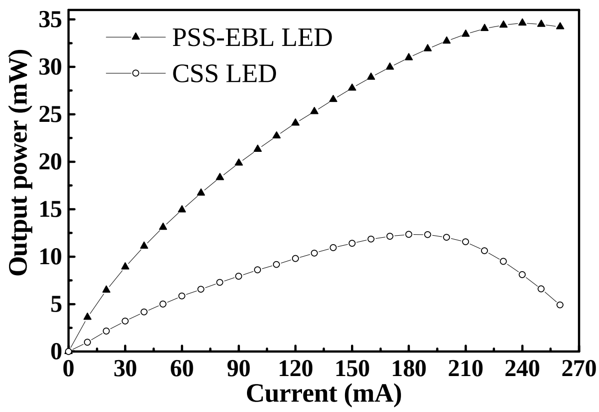

Fig. 4 *L*–*I* characteristics of PSS-EBL and CSS LEDs.