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Enhanced Extraction and Efficiency of Blue Light Emitting Diodes Prepared Using Two-Step–Etched Patterned Sapphire Substrates

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1. Introduction

In this study, we prepared PSSs having two types of surface morphology—a pyramidal patterned sapphire substrate (PPSS) and a flat-top patterned sapphire substrate (FTPSS)—and grew InGaN-based LEDs on top of them. We measured the electrical and optical properties to verify the output enhancement effects of the PPSS and FTPSS and determined the internal residual strain effect.

2. Experimental

After forming the patterned SiO2 mask, the samples were dipped into a mixture of 98 wt% H2SO4 and 68 wt% H3PO4 (3:1, v/v) at 280 °C to create the convex FTPSS. A two-step wet etching method, which had not been widely studied, was sequentially used to make the PPSS: (i) the FTPSS sample created in first step was again immersed in BOE solution to remove all SiO2 mask; (ii) the FTPSS sample without SiO2 cap was dipped into the hot acid mixture again to remove flat surfaces which were previously covered with SiO2 and, thus, form the pyramidal grains on sapphire. The grain diameter was 3 μm; the spacing between grains was 1 μm.

For comparison, an LED sample grown on conventional sapphire was also prepared. The LED structure comprised a 25-nm-thick GaN nucleation layer grown at 500 °C, a 1.4-μm-thick unintentional GaN buffer layer grown at 1130 °C, a 3-μm-thick Si-doped n-type GaN layer grown at 1130 °C, a five-pair multiple quantum well (MQW) layer of $In_{0.25}Ga_{0.75}N$/GaN having a thickness of 3/12 nm grown at 795 °C, a Mg-doped $Al_{0.17}Ga_{0.83}N$/GaN superlattice grown at 980 °C as the electron blocking layer, and a 100-nm-thick Mg-doped p-type GaN layer. After epitaxial growth, the samples were heated at 750 °C in N_2 ambient for 20 min. to activate the Mg dopants in the p-GaN. In this paper, the LEDs grown on the conventional sapphire, PPSS, and FTPSS samples are given the descriptors CS-LED, PPSS-LED, and FTPSS-LED, respectively.

3. Results and Discussion

Fig. 1(b) presents an SEM image of the grains of the PPSS after performing the wet-etching process. The nature of the sapphire crystal makes the etching rate depend on the facet orientation, following the order {0001} (C-plane) > {1-102} (R-plane) > {10-10} (M-plane) > {11-20} (A-plane) [1]. Fig. 1(d) reveals a flat surface on top of an FTPSS grain having a diameter of 1 μm; this flat plane was produced while using the two-step wet-etching method described in the experimental section. The grains of FTPSS, which formed a trapezoid-like shape, featured the same combination of {11-2k} facets as those in the PPSS grains and the flat-top surface.

Fig. 2 displays the I–V characteristic of the LEDs grown on the various substrates. When we applied a –10 V reverse bias to the samples, the leakage currents of the conventional sapphire sample, PPSS, and FTPSS were 557, 76.7, and 28.9 nA, respectively. For the PPSS and FTPSS, the leakage current decreased, such that we consider the TDDs within these two samples to be restrained. The X-ray diffraction spectra in Fig. 3 confirm the improved crystal quality. The full-widths at half-maximum (FWHMs) in the (102) ω-scans of the PPSS and FTPSS are very close (360 and 356.4 arcsec, respectively) and much lower than that in the conventional sapphire sample (479 arcsec). These values are consistent with our hypothesis of a dislocation suppression effect in the PPSS and FTPSS.

Fig. 4 displays the electroluminescence (L–I) behavior of each of the samples at injection currents varying from 1 to 600 mA. For each sample, the output intensity increased rapidly upon increasing the injection current from 1 to 200 mA, but increased at a much lower rate thereafter, finally declining when the injection current reached 460, 500, and 520 mA for the CS-LED, PPSS-LED, and FTPSS-LED, respectively. When the injection current increases, the junction temperature also rises, and nonradiative recombination becomes stronger because of a phonon effect. The CS-LED, PPSS-LED, and FTPSS-LED samples had output powers of 5.03, 5.93, and 5.97 mW, respectively, at 20 mA; i.e., relative to that of the CS-LED, the power improved by 17.9 and 18.7% when using the PPSS-LED and FTPSS-LED structures, respectively. In addition to their improved crystal quality, we believe that the enhanced output was due mainly to the higher degrees of interfacial roughness in the patterned samples.

To further investigate strain characteristics in each sample, a power-dependent photoluminescence spectroscopy was performed at 40 K. Fig. 5 displays the emission peak shift of different samples versus pumping power density. Inset of Fig. 3 reveals that the indium contents of these samples were almost identical. In addition, the satellite peak positions are quite similar, indicating a strong structural similarity for all three samples, so we induce that the difference in blue-shift mainly originated from the nature of substrates. For CS-LED, the value of peak shift was -5.5 nm while pumping power density raise from 1 W/cm^2 to 80 W/cm^2, which is larger than -3.46 and -4.46 nm of PPSS-LED and FTPSS-LED, respectively. Since CS-LED has largest power-dependent blue shift among all samples, we inferred that QCSE is also strongest in it. In consideration of surface morphology, the epilayer of CS-LED almost fully contacted to sapphire substrate, which leaves strong residual strain within quantum wells. Similar to CS-LED, since FTPSS-LED has a flat surface on top, the contact area is also larger than PPSS-LED, thus the emission peak shifts slightly faster as pumping power went up.

4. Conclusion

The output powers of LEDs incorporating the PPSS and FTPSS were up to 17.9 and 18.7% higher, respectively, relative to that of the corresponding LED featuring conventional sapphire. Emission blue-shifts for all samples revealed the existence of screening and band-filling effects. Furthermore, longer emission wavelengths were obtained from the patterned samples, further evidence of their lower residual strain.

Figures and Captions

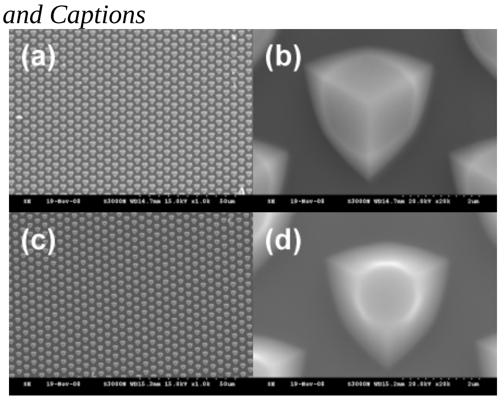

Fig. 1 SEM images of (a, b) PPSS and (c, d) FTPSS prior to performing epitaxy.

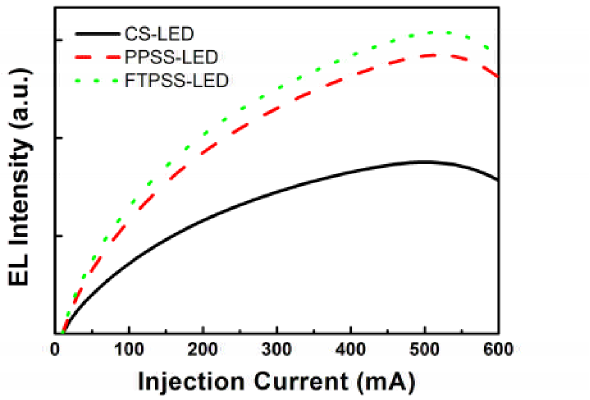

Fig. 2 I–V curves of CS-LED, PPSS-LED, and FTPSS-LED, recorded at room temperature under both forward and reverse biases.

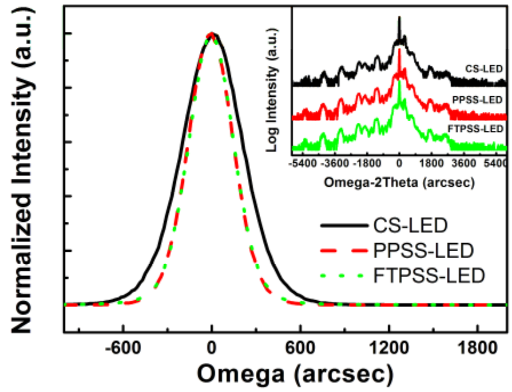

Fig. 3 HRXRD (102) ω scans of CS-LED, PPSS-LED, and FTPSS-LED. Inset: Corresponding (002) ω-2θ scans.

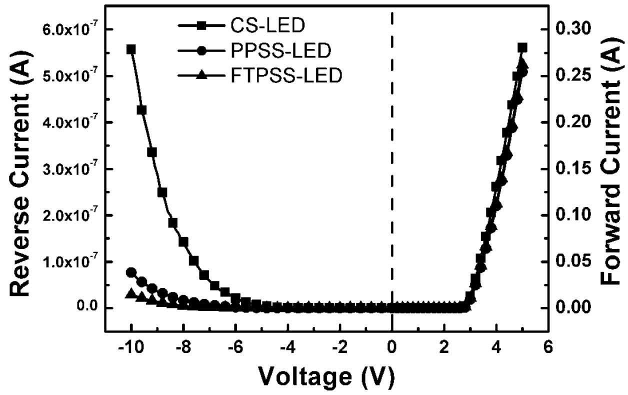

Fig. 4 Room-temperature EL profiles of CS-LED, PPSS-LED, and FTPSS-LED.

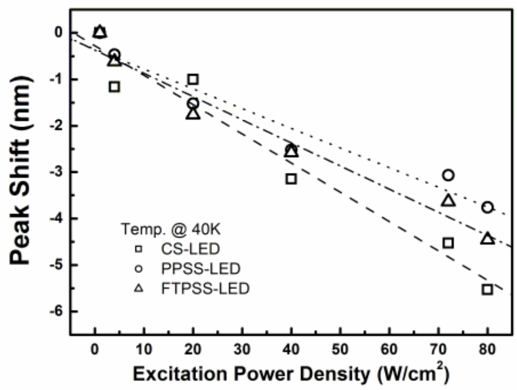

Fig. 5 Emission peak shifts versus pumping power density for CS-LED, PPSS-LED, and FTPSS-LED. Dashed, dotted, and dash-dotted lines correspond to their peak-shifting ratio.

References

[1] S.J. Kim, Jpn. J. App. Phys. 44, 2921 (2005)