High-Performance Green and Yellow LEDs Grown on SiO_2 Nanorod Patterned GaN/Si Templates

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***Abstract*— High-performance GaN-based green and yellow light-emitting diodes (LEDs) are grown on SiO_2 nanorod patterned GaN/Si templates by metalorganic chemical vapor deposition. The high-density SiO_2 nanorods are prepared by nonlithographic HCl-treated indium tin oxide and dry etching. The dislocation density of GaN is significantly reduced by nanoscale epitaxial lateral overgrowth. In addition to the much improved green LED (505 and 530 nm) results, the fabricated yellow (565 nm) InGaN/GaN-based multiquantum well (MQW) LEDs on Si substrates are demonstrated for the first time. High-quality GaN buffer and localized states in MQWs are correlated to obtaining high-efficiency long-wavelength emission in our devices.**

***Index Terms*— InGaN/GaN, light-emitting diode (LED), nanotechnology, SiO_2 nanorods.**

I. Introduction

GREEN and yellow (500–575 nm) InGaN/GaN light-emitting diodes (LEDs) are important devices in generating multicolor-based white light with high color rendering index [1]. However, compared with the widely reported GaN-based blue LEDs, efficiencies of yellow and green LEDs are relatively low [2]. This is because extending wavelength from blue to green and yellow normally requires higher indium composition with lower InGaN growth temperature, which tends to worsen the crystalline quality of the InGaN. Also, it has been reported that green and yellow LEDs are more sensitive to threading dislocations (TDs) [3]. For GaN-based LEDs grown on Si substrates, due to the existence of a large amount of TDs in the GaN buffer, the longest wavelength of fabricated InGaN/GaN multiquantum well (MQW) LEDs on Si was 518 nm measured at 0.5-mA current injection, reported by Egawa *et al.* [4].

It is well known that one of the methods to reduce TDs and enhance the internal quantum efficiency of GaN-based LEDs is epitaxial lateral overgrowth (ELO). Light output enhancement of GaN-based LEDs through microscale or nanoscale ELO (NELO) have been reported for sapphire substrates [5], [6]. However, there are few reported device results for LEDs on Si substrates through the NELO method [7], especially for green and yellow LEDs due to the difficulties of growing full coalesced, low-TD, and crack-free ELO-GaN on Si. In this letter, we demonstrate the device results of green and yellow LEDs on Si through NELO of GaN on SiO_2 nanorod patterned GaN/Si templates. The structural, electrical, and optical properties of the green and yellow LEDs on Si are discussed.

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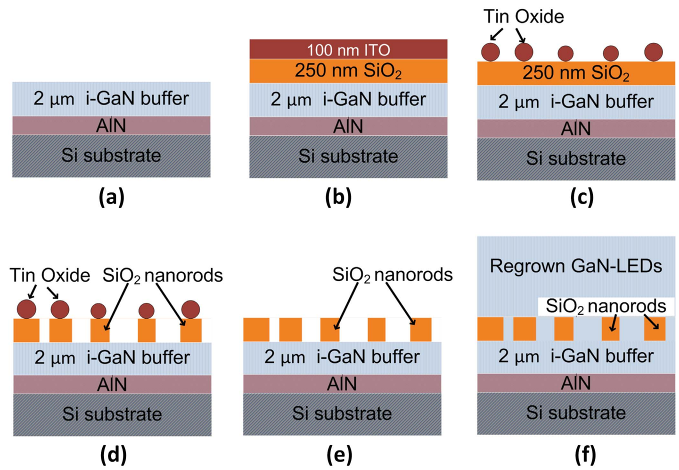

Fig. 1. Schematic diagram of the preparation procedure of GaN-based LEDs with embedded SiO_2 nanorods (a) 2-μm GaN deposition on Si. (b) SiO_2 and ITO deposition. (c) ITO patterning in HCl. (d) SiO_2 dry etching. (e) Dry etching mask removal. (f) Regrowth of GaN-based LEDs.

II. Experiment

The preparation process of the yellow LED sample with embedded SiO_2 nanorods is schematically illustrated in Fig. 1. The LEDs were grown on a 2-in. Si (111) substrate by metal–organic chemical vapor deposition (MOCVD). After growing a 30-nm-thick AlN nucleation layer at 1160 °C, a 2-μm-thick undoped GaN layer was grown using eight pairs of AlN/GaN superlattices (SLs) as an interlayer for stress balancing [Fig. 1(a)][8]. Then, 250-nm-thick SiO_2 and 100-nm-thick indium tin oxide (ITO) were deposited onto the GaN surface [Fig. 1(b)]. Next, the sample was dipped into a 2% HCl solution at room temperature (RT) for 30 s to etch away the indium oxide, leaving the nanoscale-sized tin oxide on the SiO_2 surface as the dry etching masks [9] [Fig. 1(c)]. The SiO_2 was etched by inductively coupled plasma etching to expose the GaN for regrowth [Fig. 1(d)]. After the removal of the tin oxide masks, the SiO_2 nanorod patterned GaN/Si template was ready for regrowth [Fig. 1(e)]. Following an 800-nm undoped GaN regrowth, AlN/GaN SLs were inserted as an interlayer, and then a full LED structure, consisting of 2-μm n-GaN, five pairs of MQWs, and 200-nm p-GaN, was grown [Fig. 1(f)]. Besides the LED sample emitting yellow light, green LED

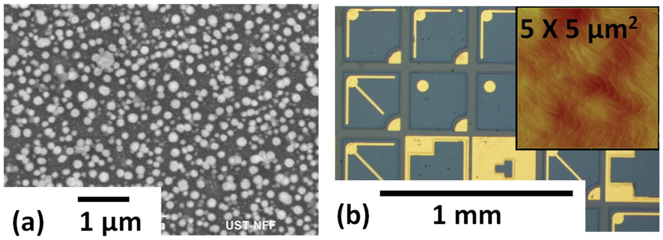

Fig. 2. (a) Planar view SEM image of SiO_2 nanorods on the GaN surface. (b) Microscopic image of the fabricated yellow LEDs (5×5 μm^2 AFM image of the regrown yellow LED surface).

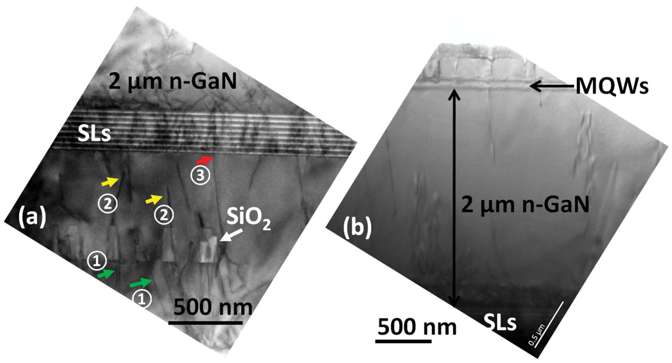

Fig. 3. Cross-sectional TEM images of the yellow LED sample (a) in the vicinity of SiO_2 and (b) in the 2-μm n-GaN and MQWs.

samples emitting from 505 to 530 nm were also prepared using the same SiO_2 nanorod preparation method. The LED samples were processed into 300×300 μm^2 LED chips, as shown in Fig. 2(b).

III. Results and Discussion

Fig. 2(a) shows the planar view SEM image of an SiO_2 nanorod patterned GaN/Si template. With diameters ranging from 100 to 200 nm, the SiO_2 nanorods were uniformly distributed on the GaN surface with a density of $2 \times 10^9 cm^{-2}$ and a surface coverage of 35%. After regrowth, atomic force microscopy image shows a smooth LED surface obtained, with a root mean square roughness of 0.49 nm in the 5×5 μm^2 scan [Fig. 2(b)].

Fig. 3(a) is a cross-sectional transmission electron microscopy (TEM) image showing how the dislocation lines evolved in the vicinity of the SiO_2 nanorods for the yellow LED sample. There were three types of dislocations: 1) those terminated by the SiO_2 nanorods; 2) those annihilated above the SiO_2 nanorods after around 500-nm i-GaN regrowth; and 3) those developing along the GaN growth in the area without SiO_2 nanorods coverage, as pointed out by markers ① ② ③, respectively. Due to their high density and coverage, the SiO_2 nanorods worked efficiently as growth masks in reducing dislocation density and improving the crystalline quality. Fig. 3(b) shows that in the top region of the 2-μm n-GaN, the dislocation density was reduced to 8×10^8 cm^{-2}, for the growth of high-quality MQWs on top. The TD density is one of the lowest values reported for GaN on Si substrates, as determined by TEM.

Fig. 4(a) shows the light output power (LOP)-current–voltage (L–I–V) characteristics of the LEDs after packaging. The LOP of the 300×300 μm^2 LEDs decreased as

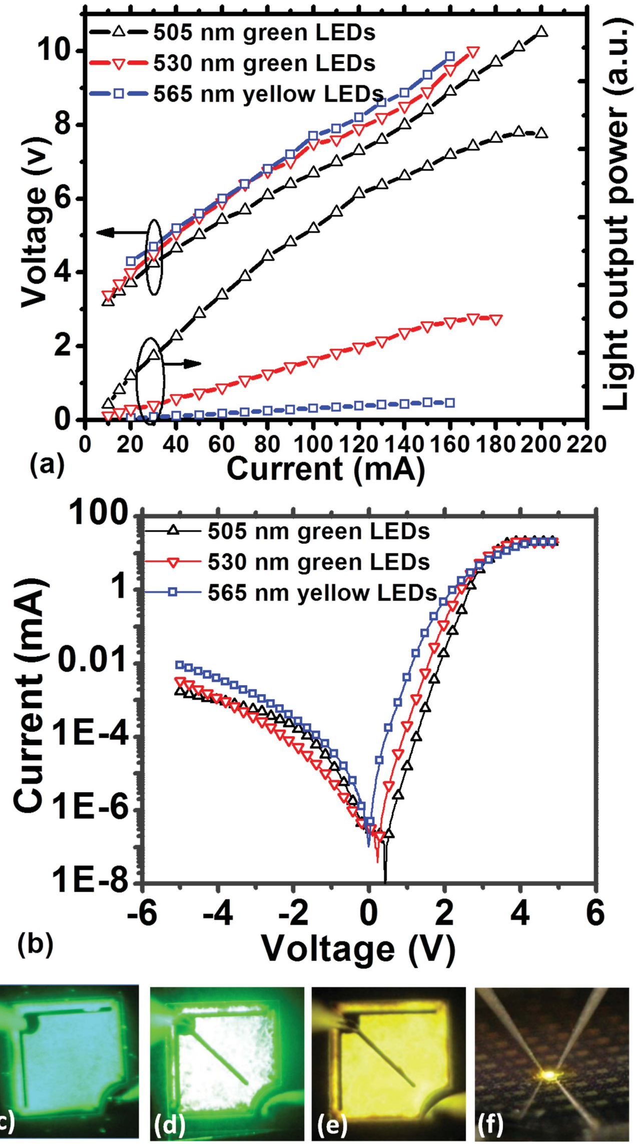

Fig. 4. (a) L–I–V characteristics of green and yellow LEDs encapsulated with silicone domes. (b) I–V characteristics. Light-emitting images of (c) 505-nm LEDs, (d) 530-nm LEDs, and (e), (f) 565-nm LEDs.

the wavelength was extended from green to yellow. After encapsulation with silicone domes, the LOP of 505-, 530-, and 565-nm LEDs measured in an integrating sphere were 1.18 mW, 0.30 mW, and 74 μW at 20 mA, respectively. The corresponding saturated LOP values were 7.60, 2.72, and 0.52 mW, at drive currents of 200, 180, and 160 mA, respectively [Fig. 4(a)]. This is the first report of fabricated 565-nm yellow InGaN/GaN MQW LEDs on a silicon substrate, and the LOP of the 505-nm LEDs was much higher than that for the LEDs on Si reported in the past. The high performance of the green LEDs is attributed to: 1) the good crystalline quality of the NELO-GaN buffer over the SiO_2 nanorods and 2) the light scattering effects of the SiO_2 nanorods to redirect light and enhance the light extraction efficiency.

Fig. 4(b) shows the I–V characteristics of the LEDs before packaging. At 20 mA, the forward voltages of the LEDs increased from 3.8 to 4.3 V as the wavelength red-shifted from 505 to 565 nm. Correspondingly, a larger series resistance of 82 Ω at 20 mA and a higher reverse leakage current of 8.8 μA

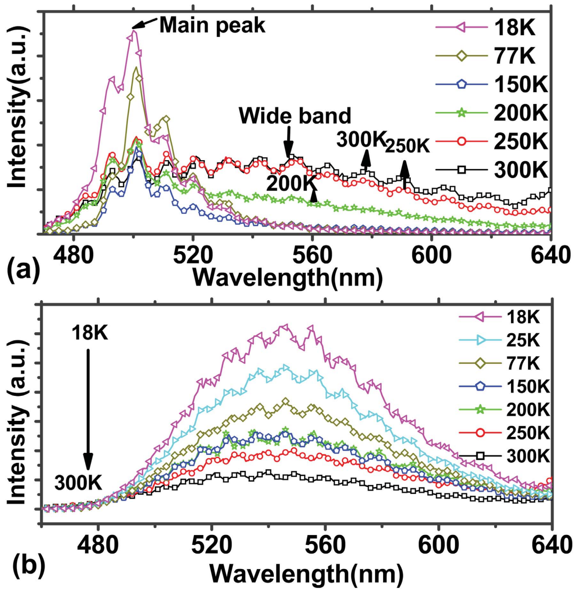

Fig. 5. Temperature-dependent PL spectra of (a) 505-nm green LEDs and (b) 565-nm yellow LEDs.

at −5 V were extracted from the 565-nm LEDs compared with 57 Ω and 1.7 μA from the 505-nm LEDs. During the yellow LED growth, the InGaN and p-GaN layers were both grown at relatively lower temperatures compared with shorter wavelength LEDs. Somewhat inferior p-GaN quality induced by the lower growth temperature and the lattice mismatch introduced by the high indium content quantum wells are two primary reasons for the higher operating voltage and larger reverse current in the yellow LEDs [10].

Fig. 5 shows the temperature-dependent photoluminescence (PL) spectra of the 505-nm green and 565-nm yellow LEDs. For the green LEDs, when the temperature was higher than 200 K, together with quenching of the main peak at around 500 nm, a wide band showed up at the longer wavelength side [Fig. 5(a)]. Moreover, in 77-K electroluminescence (EL) measurements, the 505-nm green LEDs lost 80% of LOP compared with those at RT under the same current injection 20 mA. These low-temperature (LT) PL and EL data suggest that the wide yellow band in the green LEDs was caused by the In composition fluctuation in the MQWs [11] that contributed to the radiative emission. As the temperature increased, carriers were transferred to localized states induced by In-rich clusters with thermal assistance [12]. With more carriers successfully injected into the localized states, the LOP was enhanced as the temperature increased from 77 K to RT. Whereas for the yellow LEDs, only one main yellow band at around 550 nm was observed for temperatures from 18 to 300 K [Fig. 5(b)]. It suggests that carriers could be transferred into localized states at very low temperature, that is, 18 K. In the 77-K EL measurements, the LOP of the 565-nm LEDs was improved by 34% compared with that at RT. The LOP improvement is attributed to the suppression of defect effect at LT [13] and keeping the high carrier transfer efficiency at 77 K, so that radiative recombination efficiency was improved. It is concluded that In-rich clusters induced localized states in the MQWs, and effective carrier injection into the localized states played a key role in the highly efficient "green gap" spectrum emission.

IV. Conclusion

We demonstrated a nonlithographic, low-cost, and fast patterning technique to achieve NELO of InGaN/GaN-based green and yellow LEDs on Si substrates. For $300 \times 300\ \mu m^2$ 505-nm green LEDs with silicone domes, the saturated LOP reached 7.60 mW at 200 mA. Moreover, fabricated 565-nm yellow LEDs were demonstrated for the first time for MQW LEDs on Si. The LT PL and EL results suggested that effective carrier transfer to localized states in the MQWs is necessary in high-efficiency light emission for green and yellow LEDs.

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