Current Spreading Improvement in GaN-Based Light-Emitting Diode Grown on Nano-Rod GaN Template

Cheng-Huang Kuo, Li-Chuan Chang, and Hsiu-Mei Chou

***Abstract*— In this letter, we demonstrate GaN-based light-emitting diodes (LEDs) with high-quality heavily-Si-doped n-GaN prepared on a nano-rod GaN (NR-GaN) template. With 20-mA current injection, it was found that light output power (LOP) can be enhanced 29.0%, as compared to the conventional LED. Enhancement of the LOP can be attributed to the improvement of the current spreading and the increase of light extraction efficiency by using the heavily-Si-doped n-GaN prepared on the NR-GaN template.**

***Index Terms*— Current spreading, InGaN/GaN, light-emitting diode (LED), nano.**

I. Introduction

RECENTLY, tremendous progress has been achieved in GaN-based light emitting diodes (LEDs) [1,2]. These LEDs have already been extensively used in full-color displays and high efficient light source for traffic light lamps. Nitride-based LEDs are also potentially useful for solid-state lighting. The most commercial GaN-based LEDs are now heteroepitaxially grown on insulated sapphire substrate due to the lake of native GaN substrate. The GaN-based LED devices grown on sapphire are normally fabricated in lateral device configuration, which means both p-side and n-side electrodes are located on the same side. The current crowding near the n-side electrode of LED became severe at high current density due to the non-uniform current spreading [3,4].

Previously, X. Guo et al. and Hyunsoo Kim et al. have both theoretically and experimentally shown the equivalent LED circuit model [3-6]. Appling the assumption reported by X. Guo et al. and Hyunsoo Kim et al. [3-6] , the equivalent LED structure circuit in the present experimental LEDs could be plotted, as shown in inset of figure 4. The ρ_t and t_t are the resistivity and thickness of the transparent contact layer (TCL). The ρ_c is the specific contact resistance between TCL and p-GaN. The ρ_p, $\rho_{p-AlGaN}$, and ρ_n(t_p , $t_{p-AlGaN}$, and t_n) are the electrical resistivity (thickness) of p-GaN, p-AlGaN and n-GaN. The V_j is the junction voltage drop. The current spreading length (L_S) is given by

$$L_S = \sqrt{(\rho_c + \rho_p t_p + \rho_{AlGaN} t_{AlGaN}) \left| \frac{\rho_n}{t_n} - \frac{\rho_t}{t_t} \right|^{-1}} \quad (1)$$

The equation shows that the current distribution depends on the properties and thickness of materials. To achieve uniform current spreading and reduce the series resistance in LED device, one can reduce the resistivity of Si-doped n-GaN to increase the current spreading length (L_S) [3,6]. Typically, to increased SiH_4 flow during growing Si-doped n-GaN could reduce the resistivity and increase the carrier concentration of n-GaN. However, the number of threading dislocations (TDs) in n-GaN layer increase as increasing the carrier concentration of Si-doped n-GaN [7,8]. The TDs could degrade the performance of LED device. Very recently, we have demonstrated that heavy Si-doped n-GaN could directly grown on NR-GaN template with high crystalline quality [9]. In this letter, we report the fabrication of GaN-based LEDs with the heavily Si-doped n-GaN prepared on NR-GaN template. Detailed fabrication process and the electro-optical properties of the fabricated LEDs will also be discussed.

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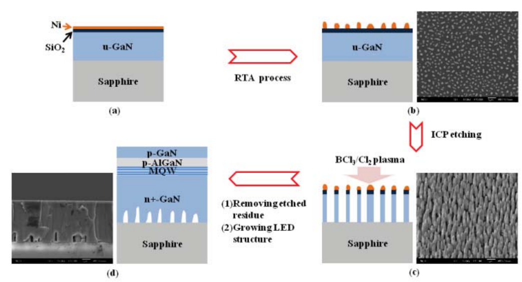

Fig. 1. Schematic fabrication process of GaN-based LED on NR GaN template. (a) Ni film on GaN. (b) Ni nano-mask on GaN. (c) NR GaN template formed by ICP etching. (d) GaN-based LED grown on the NR GaN template.

II. Experiment

The NR-GaN templates and GaN-based LED samples used in this letter were all prepared by metalorganic chemical vapor deposition (MOCVD).

Figure 1 schematically illustrates the proposed process of fabricating NR-GaN template. Details of the NR-GaN template processing procedures can be found elsewhere [9]. Figure 1(c)

TABLE I

SiH_4 DOPING FLOW, R.T. CARRIER CONCENTRATION, MOBILITY, RESISTIVITY, ROOT MEAN SQUARE (RMS) ROUGHNESS, AND EPD OF THESE nGaN SAMPLES

Sample	SiH_4 flow (sccm)	n (cm^{-3})	μ (cm^2/V-s)	ρ_n (Ω-cm)	RMS (nm)	EPD (cm^{-2})
C-nGaN I	1.25	5.0×10^{18}	209	5.14×10^{-3}	0.3	6.7×10^8
NR-nGaN I	1.25	5.0×10^{18}	210	5.33×10^{-3}	0.4	3.6×10^8
NR-nGaN II	3.75	1.5×10^{19}	157	2.55×10^{-3}	0.4	3.9×10^8
NR-nGaN III	4.25	1.7×10^{19}	-	-	crack	-

shows SEM image of the etched sample (i.e., NR-GaN template). It can be seen clearly that vertical GaN nanorods with an average diameter of about 250 nm to 500 nm were formed. It was also found that GaN nanorods density was around $3.0 \times 10^8 cm^{-2}$.

We subsequently deposited a heavily Si-doped n-GaN on top of the NR GaN template (i.e., NR-nGaN). We prepared NR-nGaN I, NR-nGaN II and NR-nGaN III with SiH_4 doping flow of 1.25 sccm, 3.75 sccm and 4.25 sccm, respectively. The thickness of NR-nGaN was 4 μm. For comparison, a conventional heavily Si-doped n-GaN without the NR structure was also prepared (i.e., C-nGaN I). The SiH_4 doping flow of C-nGaN I was 1.25 sccm. The C-nGaN consists of a 4-μm-thick Si-doped n-GaN and a 2-μm-thick u-GaN.

III. RESULTS AND DISCUSSION

Table I shows the room temperature carrier concentration, mobility, resistivity, root mean square (RMS) roughness and etching pit density (EPD) of those nGaN samples. It was found that EPD of the these n-GaN prepared on NR GaN template was smaller than those observed from conventional n-GaN epitaxial layer. It was also found that we can reduce EPD in heavily Si-doped n-GaN (i.e., NR-nGaN II) epitaxial layer by a factor of 1.72 using the NR GaN template, as compared to C-nGaN I. Such a result indicates that we could reduce the TDs of n-GaN layer by using NR GaN template. It should be noted that the crack surface of NR-nGaN III is due to the high SiH_4 doping flow. It could be attributed that the tensile stress and TDs in Si-doped n-GaN increases as increasing the Si concentration in Si-doped nGaN [8].

Blue GaN-based LED with the NR GaN template (i.e., NR-LED) was also prepared. The epitaxial structure of the LED can be found elsewhere [9,10]. We prepared NR-LED I and NR-LED II with carrier concentration of Si-doped n-GaN were $5.0 \times 10^{18} cm^{-3}$ and $1.5 \times 10^{19} cm^{-3}$, respectively. For comparison, a conventional LED without NR-GaN template was also prepared (i.e., C-LED I). The structure of C-LED I without NR-GaN template consisted of a 2-μm-thick u-GaN layer, a 4-μm-thick Si-doped n-GaN layer with $5.0 \times 10^{18} cm^{-3}$ carrier concentration. Details of the LED fabrication procedures can be found elsewhere [10]. The size of the fabricated LEDs was kept at 300 μm $\times$ 300 μm.

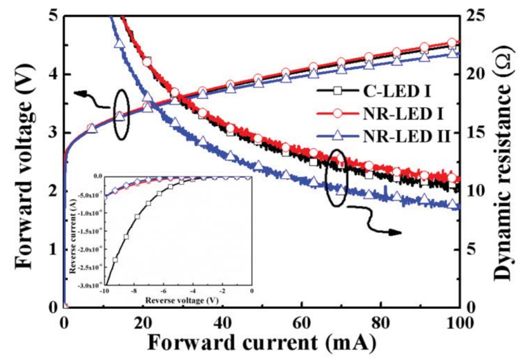

Fig. 2. Forward I–V characteristics and dynamic resistances of the three fabricated LEDs. Inset: Reverse I–V characteristics of the three fabricated LEDs.

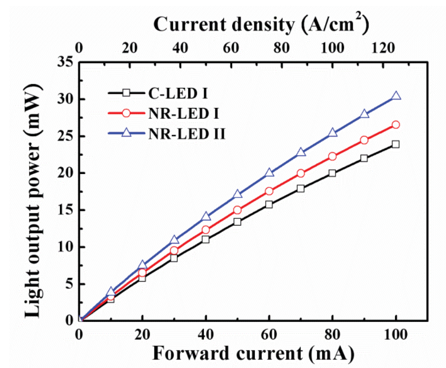

Fig. 3. L–I characteristics of the fabricated LEDs.

Figure 2 shows forward I-V characteristics and dynamic resistances of the three fabricated LEDs measured at room temperature. With 20mA current injection, it was found that forward voltages were 3.41, 3.42, and 3.39 V for C-LED I, NR-LED I, and NR-LED II, respectively. It was also found that series resistance measured from NR-LEDII was lower than C-LED I and NR-LED I. As shown in the table I, it was found that we also can reduce resistivity in heavily Si-doped n-GaN (i.e., NR-nGaN II) epitaxial layer by a factor of 2.02 using the NR GaN template, as compared to C-nGaN I. Therefore, the lower series resistance observed from the NR-LED II could be attributed the smaller resistivity of in the heavily Si-doped n-GaN (i.e., n+−GaN: $1.5 \times 10^{19} cm^{-3}$), as compared to the resistivity of the Si-doped n-GaN (i.e., n-GaN: $5 \times 10^{18} cm^{-3}$) in C-LED I and NR-LED I. Inset of figure 2 shows the reverse I-V characteristics of the three fabricated LEDs. With a 10 reverse bias, it was found the leakage current of the C-LED I, NR-LED I, and NR-LED II were 3.2×10^{-6}, 5.5×10^{-7}, and 5.7×10^{-7} A, respectively. The smaller leakage current observed from NR-LED I and NR-LED II could be attributed to its better crystal quality by using NR-GaN template.

The relationship between light output power and injected forward current (L-I) was also measured. Figure 3 shows measured light output power (LOP) as functions of injection current for the fabricated LEDs. It can be seen that LOP of these LEDs increase as increasing the injection current. Under the same injection current, it was found that we achieved the largest LOP from NR-LED II, followed by NR-LED I while

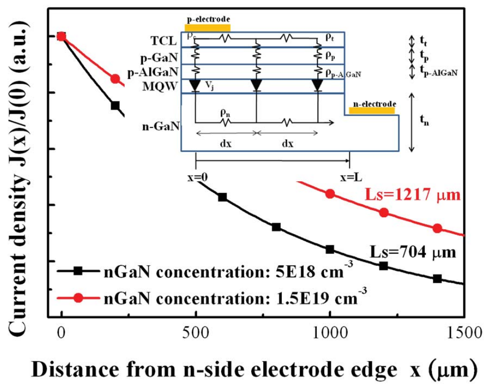

Fig. 4. Theoretically calculated current distribution versus the lateral length in LED structure. The inset shows schematic equivalent LED circuit.

output power observed from conventional C-LED I was the weakest. With 20 mA current injection, it was found that LOP were 5.82 mW, 6.54 mW, and 7.51 mW for C-LED I, NR-LED I, and NR-LED II, respectively.

When comparing with C-LED I, the 12.4% enhancement in output power of NR-LED I should be attributed to the NR-GaN template induced light scattering and reduced the dislocaion density. It was found that air voids in the GaN/sapphire interface can enhance the light extraction efficiency (LEE) compared with conventional planar LED (i.e. C-LED I), as shown in figure 1(d). Another, improving the crystalline quality of GaN by using NR-GaN template could enhance the internal quantum efficiency (IQE). Such mechanisms of improving LEE and IQE of LED with nano structure have been reported [10].

Compare NR-LED II with NR-LED I, it was found that we can further enhance the output power by 14.8%. The NR-LEDs were all prepared on the same NR-GaN template. In other word, the LEE and IQE of NR-LED I and NR-LED II were almost the same. The much output power from NR-LED II could be attributed to the better current spreading due to the lower resistivity of heavily Si-doped n-GaN. To clarify the origins of the LOP enhancements, the theoretically calculated current spreading length (L_s) and near-field emission images photographed from the fabricated LEDs were analyzed.

Figure 4 shows the theoretically calculated current distribution of GaN-based LED. The parameters of GaN-based LED used in the equation (1) are as follows : Thickness of TCL, p-GaN, p-AlGaN, n-GaN are $t_t = 0.25\ \mu m$, $t_p = 0.30\ \mu m$, $t_{p-AlGaN} = 0.10\ \mu m$, and $t_n = 4.00\ \mu m$. The electrical resistivity of TCL, p-GaN, p-AlGaN are $\rho_t = 2.00 \times 10^{-4}\Omega$-cm, $\rho_p = 1.17\ \Omega$-cm, $\rho_{p-AlGaN} = 4.00\ \Omega$-cm. The electrical resistivity (ρ_n) of n-GaN:5.0 $\times\ 10^{18}$ cm^{-3} and n+−GaN:1.5 $\times\ 10^{19}$ cm^{-3} are 5.14 $\times 10^{-3}$, 2.55 $\times\ 10^{-3}\Omega$-cm. The specific contact resistance (ρ_c) is $2.4 \times 10^{-2}\Omega$-cm^2. The current lengths (L_S) of NR-LED was calculated from equation (1). The L_s of NR-LED I (n-GaN:5.0 $\times\ 10^{18}$ cm^{-3}) and NR-LED II (n+-GaN:1.5 $\times\ 10^{19}$ cm^{-3}) are 704 μm and 1217 μm, respectively. The calculation indicates that low resistivity of heavily Si-doped n-GaN could effectively improve the current spreading length in LED.

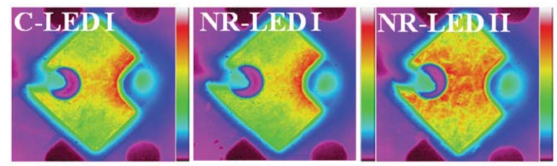

Fig. 5. Near-field emission images of the fabricated LEDs photographed at 100-mA current injection.

Figure 5 shows the images measured from C-LED I, NR-LED I, and NR-LED II, as we injected 100 mA current (i.e., current density : 125A/cm^2) into the LEDs. It should be noted that in order to clarify the current spreading in LEDs, the emission intensity of each LED was independent. The emission intensities were indicated by the color bar as shown in the right-hand of near-field emission images. For the NR-LED II, it can be seen clearly that the output light was emitted uniformly across the chips since current spread uniformly in the LEDs. The much output power from NR-LED II might be attributed to the better current spreading due to the lower resistivity of heavily Si-doped n-GaN.

IV. Conclusion

In summary, GaN-based LED with heavily Si-doped n-GaN prepared on NR-GaN template is proposed and fabricated. It was found that we could reduce the series resistance and leakage current from the NR-LED with heavily Si-doped n-GaN by using NR-GaN template. With 20 mA current injection, the present experimental LED (NR-LED II) exhibit a 29.0% improvement in LOP due to the enhancement of LEE and current spreading, as compared with the conventional LED (C-LED I).

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