GaN-based Light Emitting Diode with Embedded SiO2 Pattern for Enhanced Light Extraction

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Abstract—The n-GaN layer of c-plane GaInN/GaN light emitting diodes (LEDs) on sapphire was modified to contain a pattern of SiO2 nanorods. This embedded pattern of 300 nm long rods and diameter of 200 - 400 nm was created by thermal agglomeration of a Ni mask layer and subsequent dry-etching. The light output power (LOP) and external quantum efficiency (EQE) of the resulting LEDs increased both by some 25% to 40% depending on current density over the unpatterned structure. The increase is thought to be primarily the result of enhanced light extraction efficiency induced by enhanced scattering at the substrate-side interface.

Index Terms—green light emitting diode, light extraction efficiency, nano-pattern n-GaN substrate, Ni self assembly.

I. INTRODUCTION

Group-III nitride compound semiconductors are the leading material system for consumer and utility scale energy savings in lighting by help of light-emitting diodes (LEDs) [1,2], laser diodes [3,4], and rapidly expand into utility scale power generation by help of solar cells [5]. While GaInN/GaN materials have been extensively used, the output power in particular of longer wavelength LEDs needs to be improved. The external quantum efficiency (EQE) is the product of internal quantum efficiency (IQE) and light extraction efficiency (LEE). Within state-of-the-art LEDs, IQE is limited by high threading dislocation (TD) densities in GaN junction layers, generally induced by the lattice mismatch with sapphire substrate. Light extraction, in turn is governed by the optical refractive index of GaN ($n_{\text{GaN}} \approx 2.5$) which induces total internal reflection (TIR) beyond an extraction cone of $\theta_{\text{c}}=23^\circ$ opening angle. This results in a first path LEE of only 4%. Unless light scatters internally to fall into an extraction cone, the remainder must be lost in absorption.

It has been reported that patterned sapphire substrate (PSS) on a length scale of a few micrometers can both, reduce the TD density [6] and improve the LEE [7]. It was found that TDs initiated at the bottom of an etched substrate can mostly be stopped by open voids while TDs originating from inclined facets of the pattern can change direction to propagate only within the growth plane and annihilate. Primarily TDs originating in the un-etched portions of the substrate seem to propagate up with growth towards the ensuing active region [8]. LEE improvement can be attributed to light scattering at the patterned GaN/sapphire interface. Consequently, the use of micrometer-sized PSS has widely been adopted in the LED industry. Furthermore, with patterning on the nanometer length scale, we recently demonstrated 3.4 times enhanced efficiency of green LEDs, which by detailed quantitative analysis could be attributed to about equal enhancement of IQE (2.24-fold) and LEE (1.58-fold) [8].

Patterning of a template for homoepitaxial overgrowth by SiO2 patterns was applied by T. Zheleva et al to GaN and showed substantial reduction in dislocation densities on SiC [9]. In turn, patterning of the substrate itself, e.g. by a pattern aiming at a photonic crystal by J. Park et al showed an enhanced LOP of some 20% [10]. K. Kwon et al showed blue LEDs with a patterned n-GaN substrate with SiO2 nano sized patterns, and found 33% improvement in LOP [11].

In this paper, we present our work in GaN-based LEDs with embedded SiO2 pattern in n-GaN.

II. EXPERIMENTS

Epitaxial layers of GaN were grown on c-plane sapphire substrate by metal organic vapor phase epitaxy (MOVPE). After growth of a low temperature GaN buffer layer, a 5 µm thick u-GaN/n-GaN layer was grown successively by MOVPE. The n-GaN sample was then taken to undergo the nanorod fabrication process. A layer of 300 nm SiO2 was deposited on the top surface of n-GaN by plasma enhanced chemical vapor deposition (PECVD), followed by a 20 nm Ni layer by electron beam evaporation (Fig. 1(a)). The Ni-coated sample was subsequently subjected to rapid temperature annealing (RTA) in nitrogen ambient at 850 °C for 1 min to form self-assembled Ni metal clusters [12] (Fig. 1(b)). The nano-pattern generated by the Ni mask is then transferred into the SiO2 layer by etching. The SiO2 layer was etched down to the n-type GaN layer by inductively coupled plasma-reactive ion etching (ICP-RIE) to form nanorods. Then the sample was dipped into a heated nitric acid solution (HNO3) for 10 min to remove the Ni nanomask (Fig. 1(c)).

Figure 2(a) shows a scanning electron microscopy (SEM) image of the SiO2 patterns on the n-type GaN layer. The diameters of the SiO2 pattern columns range from 200 nm to 400 nm, and the height is 300 nm. After the SiO2 nano sized columns were formed on the surface of the n-type GaN layer, the full LED structure was regrown (Fig. 1(d)) including n-GaN, MQW, and p-GaN. The cross-section SEM image of the LED structure is shown in Fig. 2(b). The regrown n-GaN layer was 3.5 µm thick, which covers the SiO2 patterns to become a smooth layer (Fig. 2(c)). The active layers were grown on the
smooth n-GaN, which consisted of ten periods of GaInN quantum well and GaN barrier with a period of about 17.5 nm (Fig. 2(d)). A reference LED with the same structure without embedded SiO2 pattern was prepared for comparison.

III. RESULTS AND DISCUSSION

In an x-ray diffraction analysis of the two samples, no significant difference was found between the samples. The line width of the rocking curve along 002 direction showed 323 and 351 arcsec (full width at half maximum, FWHM) for the reference LED and LED with embedded SiO2 pattern (patterned), respectively. The linewidth of the rocking curve along 102 direction showed 319 and 415 arcsec for the reference LED and patterned LED, respectively. These indicated that the embedded SiO2 layer does not change the crystal quality of the GaN layer.

The samples were inspected in the microscope under UV illumination (Fig. 3). The reference LED showed uniform light across the sample with some dark spots attributed to dislocation bunches (Fig. 3(a)). The patterned LED showed bright spots under UV illumination (Fig. 3(b)). Analysis of these bright spots showed that they had similar size to the SiO2 nanopatterns (Fig. 3(b) insert). We can deduce from the comparison that the bright spots came from the scattering from the SiO2 pattern. This indicated an improvement in light extraction due to the increase in scattering.

Electroluminescence measurement was performed at room temperature (RT) using Indium contacts with about 1 mm2 in size from the substrate side. Both LEDs show a single green emission line. The LOP, EQE, voltage, and wavelength as a function of current are shown in Figure 4. The LOP clearly increased in the patterned LED (Fig. 4(a)). The overall L–I curve for the patterned LED was a smooth curve with no abrupt slope change, indicating the absence of anomalies such as instability. An improvement of 38% was obtained from the patterned LED under a current of 20 mA (2.5 A/cm2), and 25% at 100 mA (12.7 A/cm2). EQE maximum was achieved at 5 mA (0.6 A/cm2) for both LEDs, which was 8.8% for the patterned LED, and 5.8% for the reference LED. A significant EQE enhancement of 52% was achieved at 5 mA, 39% at 20 mA, and 26% at 100 mA. The wavelength for the LED with embedded SiO2 is 517 nm at 20 mA, and 511 nm at 100 mA, slightly higher than the reference LED. The voltage for the patterned LED is higher, 11 V at 100 mA compared to 7 V for the reference LEDs.

It is likely that the embedded SiO2 layer in the n-GaN substrate affects both, the wavelength and the I-V characteristics through a variation of thermal properties during both, growth and operation of the LED. The layer is likely to cause an increase of series resistance within the n-GaN layer and lead to a higher voltage drop during operation, which in turn could lead to a larger junction temperature increase with current in comparison to the unpatterned structure. This
resulted in a red shift of wavelength and rapid decrease in EQE under high current injection for the patterned LED.

For an upper limit estimate of IQE, the photoluminescence (PL) efficiency as a function of excitation power density was measured at RT and at 4.2 K [13]. IQE at RT was determined by scaling to the point of highest PL efficiency at low temperature (Fig. 5). By choosing an excitation wavelength of 408 nm, within the bandgap of GaN, photo carriers are generated directly within the QWs.

IQE varies strongly with excitation power density. The patterned LED showed a maximum of 30% at 2.3 kW/cm², while the reference LED reached 35% at 0.9 kW/cm². Under low and moderate laser excitation power below 10 kW/cm², IQE of the patterned LED is lower than that of the LED on regular n-GaN. IQE of the patterned LED surpass that of the reference LED for high laser excitation power over 10 kW/cm².

While EQE for the patterned LED is higher, IQE is lower than the reference LED for low and moderate laser intensity. This indicates the improvement in EQE is mostly due to the improvement of LEE. The improvement of LEE can be contributed to the improvement in light-escape due to the scattering of light caused by the SiO₂ nano sized columns inside the n-type GaN. Further optimization of the growth condition can be optimized and has the potential to decrease the dislocation density in the LED with embedded SiO₂, and improve IQE as well.

**IV. CONCLUSION**

In conclusion, we demonstrate green GaInN LEDs using a patterned n-GaN substrate with nano sized SiO₂ columns fabricated by Ni self assembly process. The LEDs with embedded SiO₂ pattern were compared to reference LEDs on planar n-GaN. Both, the LOP and EQE of the LEDs with embedded SiO₂ pattern increase about 40% at 2.5 A/cm², and about 25% at 13 A/cm² over the unpatterned structure. The increase is primarily attributed to enhanced light extraction, by increased light scattering at the nano sized SiO₂ pattern integrated inside n-GaN in the LED structure.

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