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Effect of nano-patterning of p-GaN cladding layer on photon extraction efficiency

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ABSTRACT

Various sized nano-patterns, ranging from 0.8 μm × 0.4 μm to 2.0 μm × 1.0 μm were formed on the p-GaN top cladding layer of green LED, in order to increase photon extraction efficiency by suppressing total internal reflection. Fabrication of nano-patterns was done by UV nanoimprint lithography and reactive ion etching of p-GaN using $SiCl_4$ and Ar gases using SiO_2 as an etch mask. The effect of various nano-patterns on top p-GaN layer was investigated by photoluminescence. Compared to LED structure without nano-patterns on top cladding layer, the LED structures with sub-micron sized nano-patterns exhibit up to four times stronger emission intensity. This implies that the photon extraction efficiency of LED structures was increased by nano-patterns on top p-GaN layer. However, the luminescence intensity of LED structures with patterns greater than a micron, was less increased.

1. Introduction

Group III nitride based light-emitting diodes are applying to various fields such as backlight unit for LCD display, outdoor full color display, traffic signal light, light source for mobile electronics and general illumination due to their high energy conversion efficiency, longer lifetime and eco-friendly nature. However, further improvement in Group III nitride based LEDs are required to be used in light source for general illumination.

In order to make the LEDs brighter, both internal and external quantum efficiency of Group III nitride based LEDs needs to be improved. Internal quantum efficiency can be improved by growth of better quality GaN crystal, higher doping in p-GaN, and more ohmic contact for both p- and n-GaN. External quantum efficiency is directly related with photon extraction efficiency. External quantum efficiency can be increased by suppressing total internal reflection. The photons generated inside the GaN crystal need to be extracted to outer space. However, only the fraction of them can be escaped from the GaN crystal and the rest of them are trapped and absorbed by GaN crystal due to total internal reflection at the surface. Total internal reflection can be reduced by roughening the GaN surface [1–3], inserting the photonic crystal patterns on GaN layer [4–8] and top conducting electrode layer [9] and using the patterned sapphire substrate [10–12]. By interacting between photons and micro to nano-sized features on the surface, photons are scattered on the surface and consequently total internal reflection is suppressed and more number of photons can escape from the GaN crystal. To given wavelength of photons, the size of features will affect the interaction to photons and thus the size of features need to be optimized for maximizing the external quantum efficiency [13]. In this study, periodic hole array pattern with various sizes ranging from 0.8 μm to 2 μm was inserted to p-GaN top cladding layer using nanoimprint lithography and photon extraction efficiency was measured by photoluminescence from the multi-quantum well structure inside GaN, in order to verify the size of patterns on the suppression of total internal reflection.

2. Experiments

InGaN based green light-emitting diode structure, used in this study, was grown on (0 0 0 1) sapphire substrate by metal organic chemical vapor deposition. As shown in Fig. 1, the green LED structure contains 30 nm thick low temperature grown GaN buffer layer, 0.5 μm thick un-doped GaN layer, 3 μm thick Si doped

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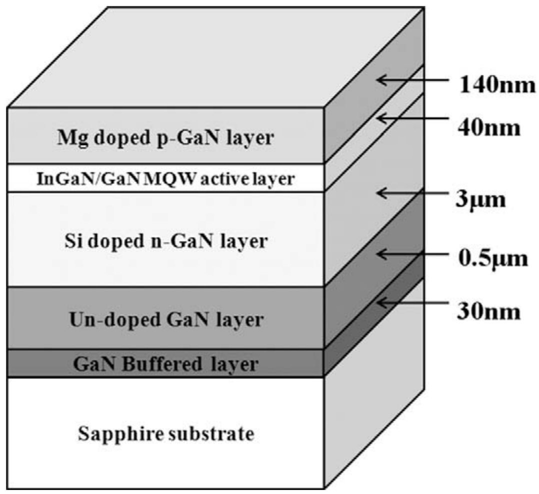

Fig. 1. A schematic diagram of GaN based green LED substrate.

n-GaN layer and InGaN/GaN multi-quantum well active layer and 140 nm thick Mg doped p-GaN cladding layer. The composition and thickness of InGaN/GaN multi-quantum well active layer was optimized for emission of green light at 525 nm. A 20 mm × 20 mm sized quartz stamp, diced from 6 in. diameter quartz wafer was used as a master template for nanoimprint lithography. Master template contained 0.4–2.0 μm sized surface protrusion patterns and they were made using conventional DUV photolithography and CF_4 based reactive ion etching processes. Prior to imprinting, the surface of quartz master template was coated with silane based hydrophobic self assembled monolayer for easier detachment of template [14].

Overall process flow was explained in Fig. 2. As a first step, 50 nm thick SiO_2 layer, which will be used as an etch mask, was deposited on p-GaN surface by RF sputtering. Then, 0.3 μl of UV curable monomer based imprint resin was dispensed on SiO_2 layer over LED structure. UV nanoimprint process was then followed under 30 atm of imprint pressure for 10 min, in order to obtain the residual layer free imprinted patterns. Since imprinted resist pattern has poor etch resistance and etching of GaN requires highly energetic ions to break interatomic bonding between Ga and N, use of hard mask layer is inevitable in order to obtain high fidelity GaN patterns. For uniform and effective delivery of imprinting force, imprinting system used isobaric pressing method, described elsewhere [15]. After imprinting process, SiO_2 layer was etched using CF_4/CHF_3 based plasma. GaN layer was then etched with SiO_2 pattern as an etch mask. Fifteen sccm of $SiCl_4$ gas and 5 sccm of Ar gas mixture were used to etch GaN at a pressure of 3 mTorr, bias power of 50 W, and ICP power of 300 W. A 1 min of etch was conducted using the mentioned recipe with ICP etcher made by Oxford™ and the etch rate was approximately 50 nm/min. After GaN etching, remaining imprinted resin and SiO_2 layer was removed by DMF (dimethylformarnide) and BOE (buffered oxide etcher) solutions, respectively. Finally, 0.8–2 μm sized hole array patterns were formed on the p-GaN top cladding layer.

3. Results and discussion

SEM micrographs of quartz master template were shown in Fig. 3a-1 to a-6. Patterns of master template contain the rectangular array of oval shaped pillars ranging from 0.8 μm × 0.4 μm to 2.0 μm × 1.0 μm. Pattern height was about 300 nm and pillars have near vertical profile. SEM micrographs of imprinted resin patterns on SiO_2/LED substrate were shown in Fig. 3b-1 to b-6. As shown in Fig. 3b-1 to b-6, pillar patterns of master template was reversed to hole patterns and transferred to the imprinted resin with high fidelity. The dimensions of patterns on imprinted resin have nearly identical to those of master template and any defect related with detachment was not observed in the imprinted patterns. Using imprinted resist patterns as an etch mask, 50 nm thin SiO_2 layer was patterned and then used as an etch mask for p-GaN layer. Since the imprinted resin has poor etch resistance and etching of GaN requires highly energetic ions to break bonding between Ga and N, GaN cannot be etched directly with imprinted resin patterns as an etch mask. In order to obtain vertically etched profiles of GaN, hard mask layer needs to be used. The p-GaN layer was then etched using mixture of $SiCl_4$ and Ar gases with Oxford™ ICP etching system. For preventing the plasma etch damage on InGaN multi-quantum well layer beneath p-GaN cladding layer, etch depth of p-GaN was limited to 50 nm. After reactive ion etching of p-GaN layer, remaining SiO_2 layer was removed by BOE solution. SEM micrographs of patterned p-GaN layer with various sizes ranging from 0.8 μm × 0.4 μm to 2.0 μm × 1.0 μm are shown in Fig. 3c-1 to c-6. Surface protrusion patterns of master template was reversed and faithfully transferred to p-GaN layer with vertical etch profile and smooth surface was maintained.

In order to verify the effect of micro to nano-sized patterns on the p-GaN layer on photon extraction efficiency, photoluminescence study was done. The schematic of photoluminescence measurement system used in this study can be found elsewhere [4]. The 325 nm wavelength He–Cd laser illuminated the LED sample with an incident angle of 45° in order to pump the photons from the InGaN/GaN multi-quantum well active layer. The emitted photons from the LED sample was collected by the series of lenses and finally sent to photomultiplier tube and photo-detector. The photoluminescence spectrum of green LED sample without any pattern on p-GaN surface and green LED samples patterned with various sizes are shown in Fig. 4. According to Fig. 4, patterning of p-GaN layer enhances the photon extraction from multi-quantum well layer to outer space, regardless of pattern sizes. All green LED samples with patterned p-GaN cladding layer, ranging from 0.8 μm × 0.4 μm to 2.0 μm × 1.0 μm, exhibit the increased luminescence intensity, compared to un-patterned reference green LED sample. Samples patterned with (a) 0.8 μm × 0.4 μm, (b) 0.9 μm × 0.7 μm, (c) 1 μm × 0.6 μm sized holes shows much

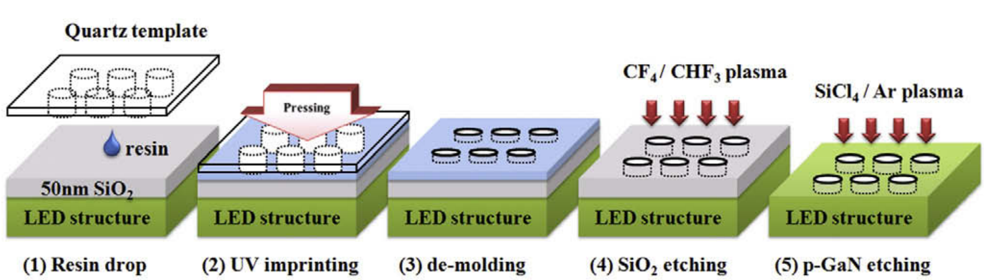

Fig. 2. Schematic illustration of overall processes flow for patterning of p-GaN top cladding layer of LED using nanoimprint lithography.