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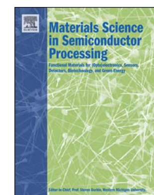

# III-nitride ultraviolet, blue and green LEDs with $SiO_2$ photonic crystals fabricated by UV-nanoimprint lithography

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ABSTRACT

In this paper, we report the effect of the $SiO_2$ photonic crystals (PhCs) on the enhancement of light-output power (LOP) in the UV, blue and green InGaN light-emitting diodes (LEDs). The $SiO_2$ PhCs were fabricated by an UV-nanoimprint lithography technique. It is found that the LOP of the LEDs is effectively enhanced by the utilization of the $SiO_2$ PhCs, and the enhancement of the LOP is strongly dependent on the emission wavelength of the active region. As compared to the LEDs without PhC structure, the LOP of the UV, blue and green LEDs with the $SiO_2$ PhCs were enhanced by 27.7%, 14.6% and 40.5%, respectively. Moreover, the dependence of the light extraction efficiency on the emission wavelength was conducted through three-dimensional finite-difference time-domain (FDTD) simulation. The experimental observations were qualitatively consistent with the tendency of the FDTD simulation results.

## 1. Introduction

III-nitride light-emitting diodes (LEDs) are widely used in the field of traffic lights, full color display, printers and general illumination due to their low power consumption, long life and environmentally-friendly [1–4]. Nevertheless, a large part of the emitted light from the active region of the LED chip is lost to the guide modes because of the large refractive index contrasts between the semiconductor materials and the outer medium [4,5]. Therefore, the low light-extraction efficiency (LEE) of the InGaN-based LEDs is left as one of the critical issues hindering further improving the light-emission efficiency [6,7]. Recently, several design schemes including surface roughening [8–10], resonant cavity [11–13], and photonic crystals (PhCs) [14–16] had been proposed to solve this problem. Among them, the PhCs are a kind of micro-/nano-structures in which dielectric constant varies periodically. The photonic bandgap (PBG) of the PhCs are useful for extracting the guided modes to different extents and offering better control over the directionality of light emission [4]. To achieve an appropriate PBG at the required wavelength, the lattice constant of the PhCs should be in the order of magnitude with the wavelength of the light entering the PhCs structure, which means nano-fabrication techniques should be employed to attain a periodic nano-structure acting on the visible (or ultraviolet) light region. Electron beam lithography is a usual method for the fabrication of periodic nano-structure [17,18], however, it cannot be used for actual commercial production of the nitride LEDs due to its low throughput and high cost. On the other hand, nanoimprint lithography can be an alternative for the fabrication of the LEDs with the nano-structure, possessing great precision, simple process and short manufacturing cycle time [19–21]. Chen et al. fabricated sapphire nano-pillars with highest reported sidewall angle of 80° by $SiO_2$ masking, nanoimprint lithography and inductively coupled plasma (ICP) etching, which provided large volume manufacturing for future GaN LEDs light extraction applications [19]. Zhou *et al.* reported a nano-patterned p-GaN realized by UV nanoimprint lithography for GaN blue LEDs. The Ohmic contact of the p-GaN was not destructed and up to 11% enhancement in light output power (LOP) was observed in the nano-patterned blue LEDs [14]. Park et al. employed a nano-patterned current blocking layer (CBL) to enhance the LOP of the GaN blue LEDs, yielding 12% higher LOP than the LEDs with conventional CBL [15]. Byeon et al. fabricated $SiN_x$-based PhCs on the indium tin oxide (ITO) electrode layer of GaN blue LEDs by UV-nanoimprint lithography. The patterned LED devices showed 19% increase electroluminescence intensity compared with the unpatterned LED devices [20]. In this work, an UV nanoimprint lithography technique is employed to fabricate surface $SiO_2$ PhCs for InGaN-based UV, blue and green LEDs. As compared to the LEDs without $SiO_2$ PhCs, the LOP of the UV blue and green LEDs with the $SiO_2$ PhCs were enhanced by 27.7%, 14.6% and 40.5%, respectively. Furthermore, the effects of emission wavelength on the

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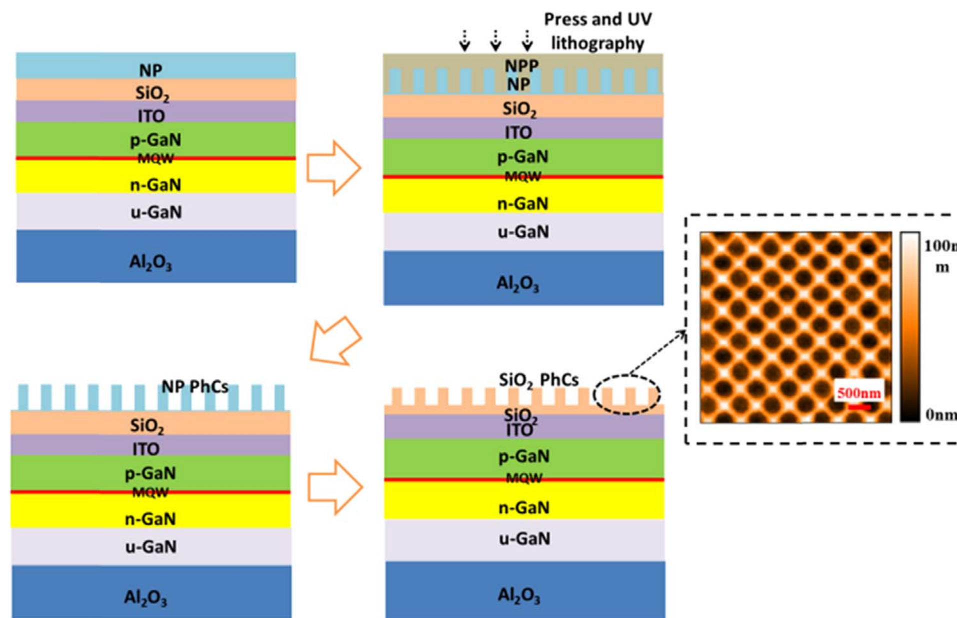


**Fig. 1.** Fabrication processes of surface $SiO_2$ PhCs on transparent ITO layer. The inset is the AFM image of the $SiO_2$ square-lattice PhCs.

LOP of the LEDs with the $SiO_2$ PhCs were investigated, and the dependence of the LEE on the emission wavelength was conducted through a three-dimensional (3D) finite-difference time-domain (FDTD) simulation.

## 2. Experiments

### *2.1. Fabrication of the surface $SiO_2$ PhCs*

The nitride epitaxial layers for this experiment were grown on c-plane (0001) 2-in. sapphire substrates by using a metal-organic chemical vapor deposition system. The multilayer structure consisted of a 2-μm-thick undoped GaN layer, a 4-μm-thick Si-doped n-GaN layer, a ten periods InGaN/GaN multiple-quantum-well (MQW) active region, a 30-nm Mg-doped p-AlGaN electron-blocking layer, and a 200-nm-thick Mg-doped p-GaN layer. Fig. 1 illustrates the fabrication processes of the $SiO_2$ PhCs. Prior to define the PhC patterns, a 120 nm transparent ITO was first deposited on the p-GaN layer by electron beam evaporation. A 900 nm-$SiO_2$ layer was then deposited on top of the ITO layer by plasma enhanced chemical vapor deposition (PECVD) at 300 °C for 20 min. Afterwards, the nano-imprinting photoresist (NIP) was spin-coated on the $SiO_2$ layer at 1000 rpm for 40 s and subsequently baked on a hot plate at 120 °C for 30 s. Next, 2-in. square array patterns with a 300 nm cylindrical pillar in the center of a 4-in. nano-pressure plate (NPP) were adhered to the NIP layer, followed by a UV-curing process utilize an EVG 610 machine (EVG Group, Austria). After the removal of the NPP, the square-lattice PhC structure was formed in the NIP layer as an etching mask. Finally, the $SiO_2$ PhCs were obtained by ICP dry etching of the NIP mask into the $SiO_2$ layer with a gas mixture of $CHF_3$/$CF_4$ (10/20 sccm) at a chamber temperature of − 10 °C. The parameters of the $SiO_2$ PhCs were quantified using an atomic force microscope (AFM) operated in the tapping mode. The inset of the Fig. 1 shows the AFM image of the $SiO_2$ PhCs, the lattice constant, the height and the hole diameter of the $SiO_2$ PhCs are approximately 600 nm, 100 nm and 420 nm, respectively.

### *2.2. Fabrication of UV, blue and green LEDs with $SiO_2$ PhCs*

The epitaxial structure of the 2-in. LED wafers was described above, and the indium contents of the InGaN/GaN MQWs emitted in UV, blue and green light were controlled for different LED wafers. To fabricate the LED chips with $SiO_2$ PhCs, the LED wafers were first cleaned in mixed solution of vitriol and hydrogen peroxide (3:1) at 60 °C for 10 min. A 120-nm-thick ITO film was then deposited as a transparent current-spreading layer, and the samples are annealed in a mixture of $N_2/O_2$ (40:7) ambient at 550 °C for 3 min in a lamp-heated rapid thermal processor. Subsequently, a mesa was etched down to the n-doped GaN layer by using ICP dry etching with a mixture of $BCl_3/Cl_2$ to define a chip size of 250 μm × 575 μm. The 900-nm-thick $SiO_2$ layer was deposited by the PECVD. The $SiO_2$ PhCs were formed by using the same fabrication processes as we described above. Afterwards, the partial $SiO_2$ were removed by buffered oxide etchant to expose the n-GaN and ITO for n-type and p-type contact, respectively. Finally, a Cr/Al/Ti/Au (50/800/100/200 nm) multilayer was deposited as n- and p-electrodes. Schematic diagram and SEM image of the LED chip with the $SiO_2$ PhCs are shown in Fig. 2. Current-voltage characteristics, LOP vs current and electroluminescence (EL) spectra were performed using the Wenmin LED-2627V400 LED chip/wafer probing and testing system. An integrating sphere with an opening diameter of 20 mm at the bottom and a perpendicular distance of 10 mm (corresponding to a collection angle of 120°) is on the right above the LED chip.

## 3. Results and discussion

The current-voltage (I-V) characteristics of the UV, blue and green LEDs with and without $SiO_2$ PhCs are shown in Fig. 3. The forward voltages of the UV, blue and green LEDs are 2.94 V, 2.47 V and 2.02 V at an injected current of 1 mA, respectively. The lower voltage of the green LEDs could be attributed to the higher indium content in the MQW active region [22]. In addition, the forward voltages of the UV, blue and green LED chips are decreased from 3.61 V, 3.28 V and 3.05–3.42 V, 3.13 V and 2.91 V at 20 mA by introducing the $SiO_2$ PhCs, respectively. The n-type contact between n-GaN and Cr/Al/Ti/Au for the LED chips with and without $SiO_2$ PhCs were almost the same, thus the improved electrical performance was deduced to the enhanced current spreading capability of the ITO layer promoted by the $CF_4$ plasma during the $SiO_2$ ICP dry etching processes [23].

The EL spectra of UV, blue and green LEDs with and without $SiO_2$ PhCs at an injected current of 20 mA are shown in Fig. 4(a). It is found that the EL intensities of the UV, blue and green LEDs with $SiO_2$ PhCs are stronger than that of UV, blue and green LEDs without $SiO_2$ PhCs, respectively. The emission peak wavelength movements of the UV, blue

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