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Electroluminescence comparison of photonic crystal light-emitting diodes with random and periodic hole structure

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Abstract
We compare the characteristics of photonic crystal (PC) light-emitting diodes (LEDs) with the same hole pattern density of 12 ea μm^{-2}. The PC LED with periodic hole structure demonstrated an increased output power, improved external efficiency at high current operation and uniform radiation owing to the periodic nanoscale features generating a photonic band gap (PBG), when compared with those of the random hole (RH) LED. The electroluminescence images obtained by confocal scanning electroluminescence microscopy (CSEM) show the difference of light emission propagation from the random and periodic structures.

(Some figures in this article are in colour only in the electronic version)

GaN-based materials have attracted considerable attention since the demonstration of their application in solid state light-emitting diodes (LEDs). Recently, highly efficient GaN-based blue LEDs, which produce white light with yellow phosphors, have generated much interest because of their potential to replace fluorescent lamps. For the white LEDs to compete with the traditional lamps, high efficiency and high luminous flux are major requirements. Therefore, several approaches have been proposed to enhance the light extraction efficiency: surface roughening [1], GaN epilayer growth on a patterned sapphire substrate (PSS) [2], integration of two dimensional (2D) photonic crystal (PC) structures [3] and utilization of surface plasmon resonance [4]. In particular, rapid progresses have been reported in the past several years to increase the light extraction from the LEDs by roughing or incorporating the PC structures into the emitting surface with the help of nanoscale patterning technology such as porous anodic aluminium [5], laser holographic lithography [6], e-beam lithography [3], nanoimprint lithography [7] and colloidal lithography [8]. However, most results with the PC structures focused on the enhancement of light output power, which was not clear to prove that the improvement came from the PC effect or from just random scattering.

In this paper, we fabricated the GaN-based RH LED and the PC LED with the same pattern density and performed direct comparison between the two different devices. Far-field and near field images of electroluminescence from the LEDs were obtained to trace the light propagation through the modified surface.

For the comparison of the optical and electrical characteristics, two different surface features were made using the same batch LED wafer. Conventional InGaN/GaN multiple quantum well (MQW) blue LED structures were grown by a metalorganic chemical vapour deposition (MOCVD) system. The LED structure consisted of a 30 nm thick GaN nucleation

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layer grown on the PSS having a periodic lens pattern (3 μm diameter with 2 μm space) with a 1.5 μm etching depth, a 3 μm thick unintentionally doped GaN layer, a 2.5 μm thick Si-doped GaN n-cladding layer (n-GaN), a region with five periods of InGaN/GaN MQWs and a 0.14 μm thick Mg-doped GaN (p-GaN) from the bottom to the top.

To fabricate the random patterns for the RH LED, colloidal lithography was utilized, and the details were previously reported [8]. Figure 1(*a*) shows the colloidal lithography process. Chromium (20 nm thickness) was evaporated on the polystylene (PS) spheres arranged substrate, and the sample was subsequently immersed into CH_2Cl_2 solvent for the lift-off the PS spheres from the substrate. The process resulted in a chromium film with holes approximately around 200 nm in diameter. The p-GaN surface was etched using inductively coupled plasma (ICP) to a depth of 90 nm. Finally, the chromium etching mask was removed with a $H_2O_2 : HCl_4(3:1)$ solution. Figures 2(*a*) and (*b*) show a top view and a tilted scanning electron microscopy (SEM) image of the p-GaN layer of the RH LED. It shows holes with somewhat different diameters in hexagonal formation (density: 12 ea μm^{-2}) and variant centre-to-centre distance between neighbouring holes since the colloidal lithography is based on spontaneous assembly between spheres which are difficult to be arranged in a controlled manner.

Laser holographic lithography (figure 1(*b*)) was used to make a periodic hole pattern for the PC LED. The period of pattern was given by $\Lambda = \lambda/(2\sin\theta)$, where λ and θ indicate the wavelength of the UV laser and incident angle, respectively. To have same pattern density as the RH LED, the incident angle was set to 31.8°. The sample was spin coated with a diluted AZ®6612 positive photoresist at 5000 rpm for 40 s to have a thickness of 150 nm and then baked at 90 °C for 90 s. Two beams, one directly from a 325 nm He–Cd laser and the other reflected from a Lloyd mirror, met coherently and constructive and destructive interference between the two beams occurred on the resist surface. After the first exposure with a 1.4 mJ cm^{-2} energy dose was performed for 20 s for one dimensional (1D) line patterns with a pitch of 300 nm, the sample was rotated by 90°. Another exposure was then executed for the two dimensional (2D) features. After the development process using MIF 500 solution for 40 s, two dimensional resist pillars were obtained. Then, chromium (Cr) was then deposited on the periodic photoresist pillar pattern, and the subsequent lift-off process was performed with acetone. 2D hole PC structures in the p-GaN surface

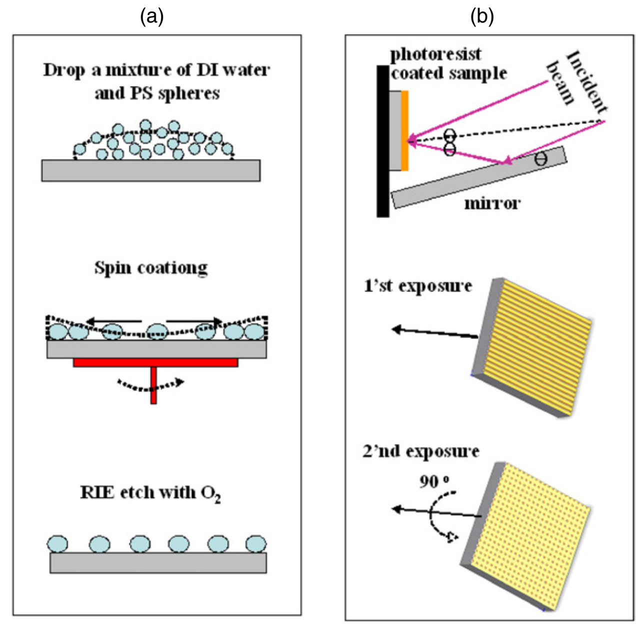

Figure 1. Schematic illustration of the fabrication of (*a*) random structure by colloidal lithography and (*b*) periodic structure by laser holographic lithography.

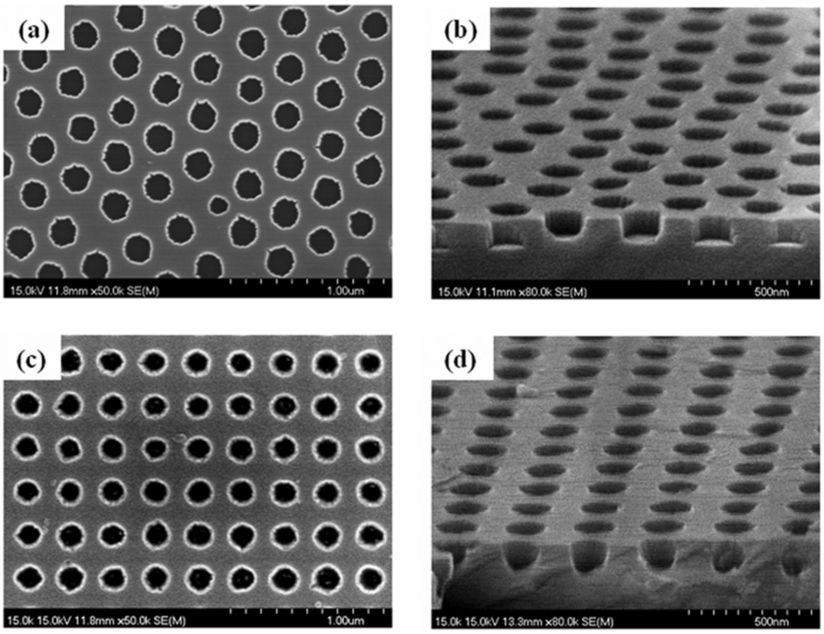

Figure 2. (*a*) A top and (*b*) a tilted scanning electron microscopy (SEM) images of the p-GaN layer with the RH structure. (*c*) A top and (d) a tilted SEM image of the p-GaN layer with the PC structure.

were fabricated by ICP etching and subsequent removal of the chromium mask. Figures 2(*c*) and (*d*) show a top view and a tilted SEM image of p-GaN surface of the PC LED. This figure illustrates the well ordered holes in square formation. Finally, the two surface modified LEDs (300 × 300 μm^2) and a conventional LED surface (C LED) without any features on the p-GaN were fabricated for the comparison of optical and electrical characteristics. Photolithography and subsequent ICP etching to the n-GaN layer were used to define the contact area. Cr/Ni/Au (20/30/500 nm) was deposited as ohmic bonding pads to both the exposed n-GaN layer and the surface modified p-GaN layer. The fabricated LEDs were packaged on transistor outline (TO) without epoxy encapsulation prior to measurements.

Figure 3(*a*) shows the forward current–voltage (I–V) characteristics from C LED, RH LED and PC LED. The forward voltages of both RH LED and PC LED at a current of 20 mA were slightly higher than that of the C LED. This was due to the increased contact resistance between the roughened surface and the p-ohmic bonding pad, which was ascribed to the plasma damage during the p-GaN etching process [6]. The etched p-GaN layer of PC LED induced a slight curve shift towards higher voltage without changing the slope. Meanwhile, the I–V curve of the RH LED exhibited a leakage current at low voltage region due to the lager hole size than that of the PC LED. The inset in figure 3(*a*) displays the emission spectra from the LEDs taken at an injection current of 20 mA, showing no difference in emission wavelength peak and full width at half maximum (FWHM) among the three different structures. Figure 3(*b*) shows the output power (mW) and external quantum efficiency (%) characteristics of the LEDs versus injection current (mA). The output power of the RH LED and the PC LED was enhanced by as much as 9.23% and 21.92%, respectively, when compared with that of the C LED at an injection current of 20 mA. The PC LED demonstrates, particularly, an improved external efficiency at high current operation. Figure 3(*c*) shows far-field radiation patterns from the three LEDs. The PC affected the light propagation from the emitting surface, which resulted in the change in the observed radiation pattern. Both the C LED and the RH LED have light emission patterns that peaked at normal to the emitting surface. Meanwhile, the PC LED had lobes at 60° that distributed more lights to the lateral direction, which is advantageous to excite a yellow phosphor layer sitting on the LED and release white light.

In order to confirm the photonic band diagram of PC LED, we calculated the photonic band gap (PBG) using the plane-wave expansion method [9, 10]. The PC structure, which had the periodic hole patterns in square lattice formation with a frequency of $a/\lambda = 0.62$, a depth of 90 nm and a ratio (r/a) of 0.26, was simulated to locate within the PBG (data not shown). To compare the light propagation directly, confocal scanning electroluminescence microscopy (CSEM) was utilized; known as an effective experimental tool for optical characterization to image light propagation from the three LEDs [11]. CSEM images were obtained with spatial resolution of 200 nm at an injection current of 0.1 mA. A monochromator and a photomultiplier tube detector were

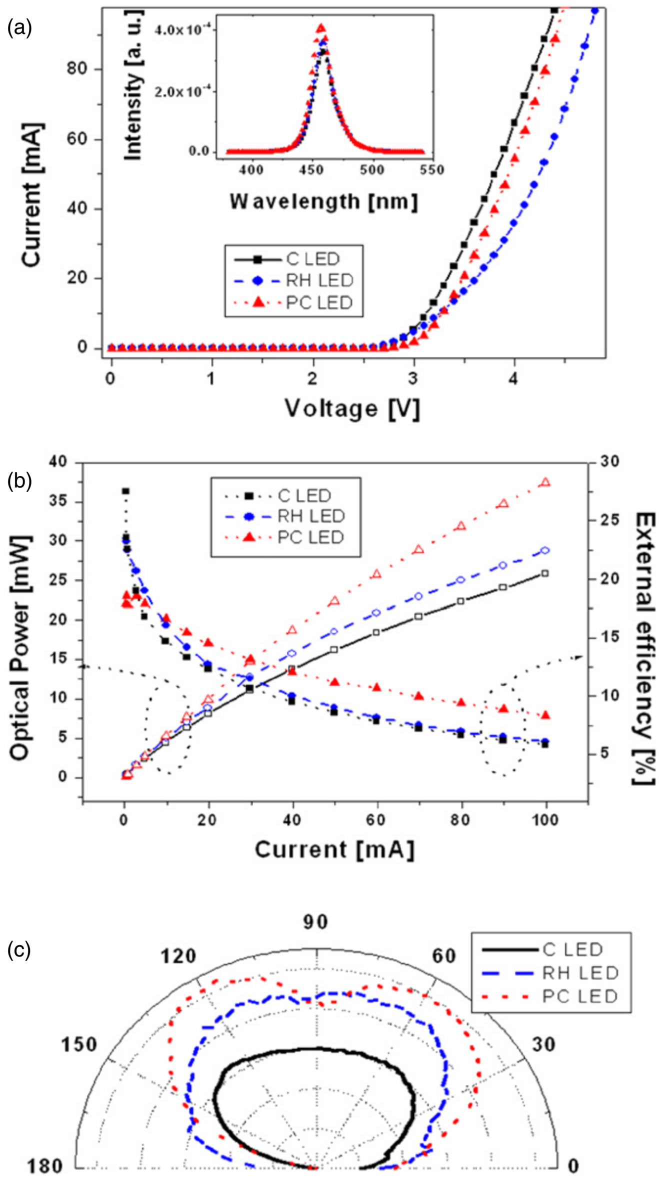

Figure 3. (*a*) I–V characteristics and (*b*) the light output power (mW) and external quantum efficiency (%) versus injection current (mA) from the C LED [■], the RH LED [●] and the PC LED [▲]. The inset in (*a*) shows the emission spectra from each device. (*c*) Far-field radiation pattern from the C LED, the RH LED and the PC LED.

used to achieve an EL spectrum. The light emission was collected from the top surface of the LEDs by an objective lens with a numerical aperture of 0.9. Figure 4 indicates the electroluminescence images of (a) C LED, (b) RH LED and (c) PC LED measured by CSEM. The bright spots are generated by reflection from the 3 μm diameter lens patterns on the sapphire substrate. Figures 4(*a*) and (*b*) show the lateral propagation of photons generated in the bright spot. Meanwhile, the lateral propagation is not shown in figure 4(*c*). This phenomenon is caused by blocking of the lateral propagation owing to the periodic features fabricated on the PC LED surface [9, 12].

In summary, we have fabricated the RH LEDs and the PC LEDs with the same pattern density and compared their device

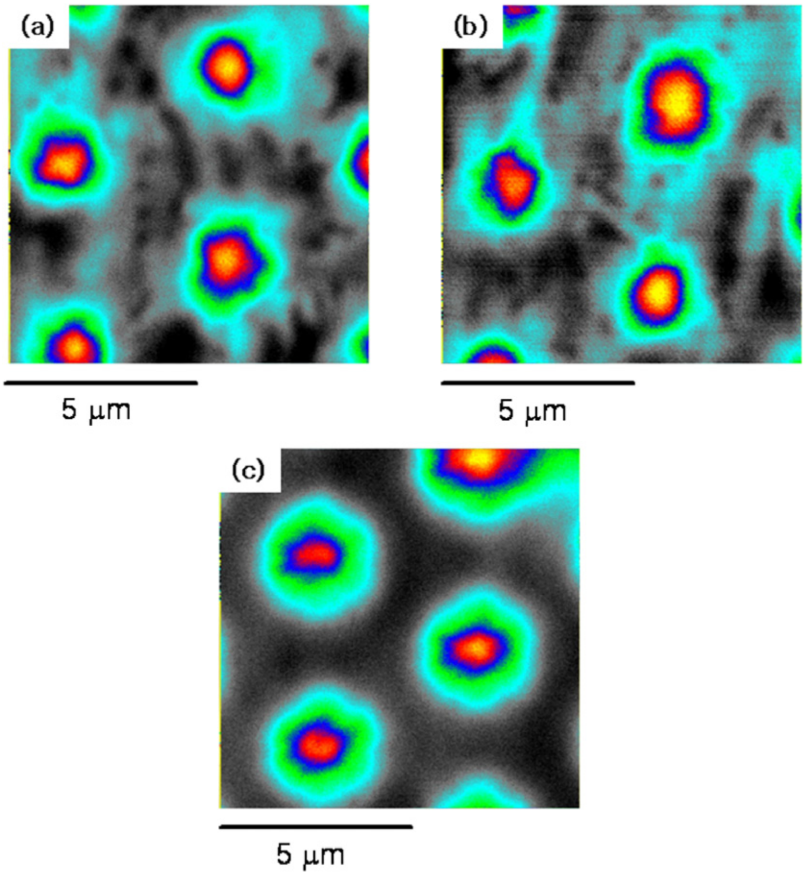

Figure 4. Electroluminescence images of (*a*) C LED, (*b*) RH LED and (*c*) PC LED measured by confocal scanning optical microscopy with 200 nm resolution and photon counting photomultiplier tube detector.

characteristics. The PC LED shows the increased output power, improved external efficiency at high current operation and uniform radiation due to the periodic nanoscale features located within the PBG, when compared with the RH LED. The CSEM results illustrated the PC effect in which the lateral light propagation was inhibited by the periodic structure.

Acknowledgments

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