Enhancement in external quantum efficiency of blue light-emitting diode by photonic crystal surface grating

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Blue photonic crystal light-emitting diodes were evaluated with photonic crystal hole patterns. The diameter of the holes, lattice constant, and emission wavelength were selected to be 110, 220 and 450 nm, respectively, to attain a maximum enhancement in the wall-plug efficiency. The improvement in external quantum efficiency was 30–50%. Changes in voltage characteristics caused by the etched holes were found to be correlated with increased leakage current.

Introduction: The high brightness (HB) light-emitting diode (LED) has drawn more attention recently for a variety of applications in mobile electronics, flat panel displays, automobiles, traffic signals, large outdoor displays, and general lighting [1]. The development of blue and green GaN HB LEDs with an efficiency of 150 lm/W has been limited owing to the low internal quantum efficiency caused by defects in epitaxy, device parasitics such as large p-ohmic contact resistance, and poor external quantum efficiency [2–4]. Among these issues, the external quantum efficiency has been considered to be the most critical. The critical angle needed to avoid total internal reflection is about 23°, so only a small fraction of light generated in the active region of the LED can escape to the surrounding air. Therefore, the external quantum efficiency would be reduced to a few per cent even if the internal quantum efficiency were close to 100%.

There have been several approaches to maintain the angle of the emitted light from the active region within the critical angle, such as changing the LED chip shape, reducing the thickness of the film, and roughening the surface [5]. A 60% improvement in wall-plug efficiency has been reported with use of a micro-roughened top surface [5]. However, the roughened surface morphology was irregular and uncontrolled. The approach using photonic crystal (PC) patterning in an LED has also drawn attention [6]. A six-fold enhancement in an infrared PC light-emitting slab with the lattice distance (a) to wavelength (λ) ratio, hereafter referred to as the lattice parameter (a/λ), of 0.36 inside the photonic bandgap (PBG) was observed using optical pumping [7]. The external quantum efficiency could be improved by factors of 10–15 through an optical pumping experiment of an infrared PC light-emitting slab with a lattice parameter of 0.47 [8]. A blue PC light-emitting slab was also shown through optical pumping to exhibit a sixfold increase in external quantum efficiency with a lattice parameter of 0.34 inside the PBG [9]. The enhancement occurs through a combination of spontaneous emission enhancement from a photonic crystal effect and Bragg scattering, which reduces parasitic absorption.

Although improvement in light extraction of slab emitters through photopumping has been shown, this structure is not amenable to electrical injection. Without a slab-like structure or significant vertical confinement by other means, the photonic crystal is unable to offer spontaneous emission enhancement in more conventional devices and the only benefit from surface-etched holes is improved photon extraction through Bragg scattering. Nonetheless this improvement is expected to exceed that yielded by the random surface roughening technique [8] and has been shown in theory and experiment to yield promising results for conventional diodes [10–12]. It was argued that the increase in the external quantum efficiency was due to coherent Bragg scattering that allows photon escape at a rate higher than that of random surface roughness. In particular, an enhancement factor of over 3 has been observed at infrared wavelengths [11].

In this Letter, an experiment to measure the enhancement of the external quantum efficiency due to photonic crystal holes with lattice parameter chosen to be 0.49 was performed. To avoid complication due to current spreading issues, three experimental aspects were considered. First, the size of the LED was chosen to be 40×40 μm with a ring pattern electrode compared to a conventional LED which typically has a larger size (~300×300 μm) with top and bottom pads. Secondly, the PC pattern was etched into the conventional LED after both top and bottom electrodes had been evaporated. The only difference between the conventional and PC LED was the presence of the holes of the PC pattern. Thirdly, no transparent electrode was deposited.

Fabrication: A conventional LED was made by a common fabrication procedure on a typical blue GaN wafer. It was composed of Si-doped n-GaN/InGaN multiple quantum well/Mg-doped p-GaN epitaxial layers (3000/50/200 nm) on a sapphire substrate. A top ring Ni/Au electrode (20/200 nm) was deposited first and annealed by rapid thermal annealing (RTA) at 500°C for 1 min. Then, SiO_2 was deposited by plasma enhanced chemical vapour deposition (PECVD) at 300°C and used as a mask for defining a mesa structure. The mesa was etched by inductively coupled plasma (ICP) etching with Cl_2 and Ar gases at an etch rate of 100 nm/min. A bottom ring electrode was deposited with Ti/Al (20/200 nm) and RTA was followed at 300°C for 1 min. Electrical characteristics and the emission spectra of the samples were measured. SiO_2 was deposited again as a mask for defining a PC pattern at 270°C to avoid any harmful effect on the Al electrode. A triangular photonic crystal lattice pattern defined with electron beam lithography was etched into the top p-doped GaN layer using ICP etching. The depth of the holes was measured to be approximately 150 nm.

Results: Electrical characteristics and emission spectra of the conventional and PC LED were measured at room temperature operated continuous wave. A photodetector was placed close to the top of the LED to collect as much light output as possible. Although much of the light from the sides and back of the LEDs was lost, it was expected that this method was accurate enough to compare the relative light output intensities between the conventional and PC LED. It was assumed that no specific enhancement would be attained from the side and backside of a PC LED. This assumption was tested over a 120° topside emission cone (60° from the vertical axis) by far-field measurement of conventional and PC LEDs. Results indicated that the fraction of output power within 120°, 50° and 20° cones showed no significant differences between the two device types.

Fig. 1*a* shows pictures of the conventional LED emitting blue light. The size of the mesa is 40×40 μm and actual lighting area is 20×20 μm. An electron microscope image of the PC pattern on a PC LED with 220 nm lattice distance is shown in Fig. 1*b*. Electrical characteristics and light output are shown in Figs. 2*a* and *b*, respectively. The maximum light output over light emitting area is $\sim 3.75 \times 10^{-4}$ mW/μm^2, which is larger than that in a previous report [10], confirming a reasonable fabrication process in the present study. The external wall-plug efficiency of a PC LED was increased by about 35% compared to the conventional LED at the highest powers shown. The current–voltage characteristic of the PC LED was also improved by about 30% compared to the conventional LED, which is similar to a prior result [10].

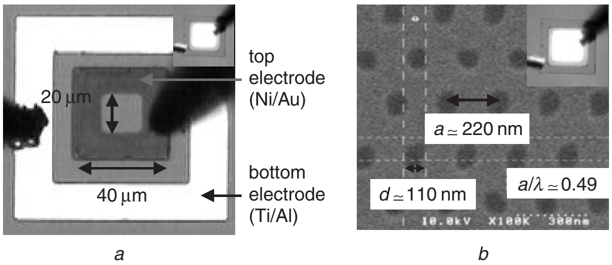

Fig. 1 *Conventional LED and electron microscope image of PC pattern*

a Conventional LED
b Electron microscope image of PC pattern

Because the voltage decrease in the present work cannot be caused by an improved ohmic contact, it is likely that non-radiative carrier leakage paths are created from damage caused during dry etching of the holes. This hypothesis was tested by measuring reverse leakage current at a fixed reverse bias of −5 V. Conventional LEDs showed a consistent reverse leakage of −0.2 nA, but PC LEDs fabricated in this study showed much larger leakage currents ranging from −1.1 nA to 75 μA (−74 μA for the optimum device described in this Letter), always more than five times higher than in the conventional LED. Forward current leakage through non-radiative mechanisms leading to the drop in the operating voltage at fixed current is consistent with the present study and prior reports [10]. In spite of this carrier loss to non-radiative recombination, an increase of 35–50% in wall-plug efficiency improvement due to the Bragg scattering effect is introduced by the photonic crystal. If the leakage paths were eliminated, a much greater improvement is expected. The emission characteristics of the PC LED and conventional LED were nearly identical.

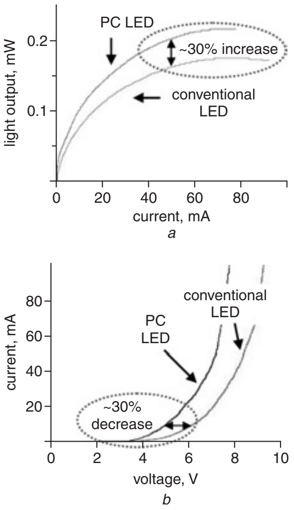

Fig. 2 *Electrical characteristics of PC and conventional LED; light output; V–I*

a Light output
b V–I

Conclusion: A PC LED with lattice parameter (a/λ) of 0.49 was evaluated to discern the enhancement in the external quantum efficiency attributable to PC patterning. The external wall-plug efficiency of PC LED was improved by about 35%, with an additional enhancement of I–V characteristics due to non-radiative carrier leakage. Further improvements are expected from improved epitaxial material quality and optimised PC designs.

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