Enhanced light extraction in III-nitride ultraviolet photonic crystal light-emitting diodes

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III-nitride photonic crystal (PC) ultraviolet (UV) light-emitting diodes (LEDs) were fabricated. Triangular arrays of the PCs with different diameters/periodicities were patterned using electron-beam lithography and inductively coupled plasma dry etching. The optical power output of LEDs was enhanced by a factor of 2.5 due to PC formation. It was observed that the optical enhancement factor depends strongly on the lattice constant and hole size of the PCs. The achievement of nitride PCs is expected to benefit many applications of III-nitride optoelectronics, particularly for the improvement of extraction efficiency in III-nitride deep-UV emitters ($\lambda < 340$ nm), which are crucial for many important applications, but presently have a very low quantum efficiency. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1768297]

High-power ultraviolet (UV) light-emitting diodes (LEDs) are sought for many applications, such as compact chemical and biological detection system, medical and health research, and solid-state lighting. Improvement of the efficiency is one of the biggest challenges for nitride LEDs, especially for deep ultraviolet (UV) LEDs ($\lambda < 340$ nm), which currently have very low internal quantum efficiency (QE). In addition to the low internal QE, UV LEDs suffer inherent loss due to parasitic absorption of lateral guided modes in the semiconductor material. Only about $1/(4n^2)$ of light generated in the active region radiates through the top and bottom,[1] which amounts less than 4% for deep-UV light in nitride materials with refractive index $n \sim 2.6$. Many different schemes have been reported to improve the QE of LED, such as modifying spontaneous emission by resonant cavity,[2] utilizing geometries to enlarge escape cones of generated light by random surface texturing,[3] interconnected microdisk LED architecture,[4] or two-dimensional (2D) photonic crystals (PCs).[5–9]

Periodic arrays of holes are typically etched in semiconductors to realize 2D PCs that forbid certain electromagnetic radiation in the lateral direction creating so called "photonic band gaps" (PBGs) in the plane. 2D PCs enhance the light output from LEDs by extracting lateral guided modes of light in the vertical direction. Very little work in PCs involving III-nitride materials have been reported due in part to the difficulty in fabrication associated with the required nanometer scale periodicity. We have obtained a maximum 20-fold enhancement of light extraction by PCs using optical pumping in the nitride materials at 475 nm.[8] Recently, we also reported optical power enhancement under current injection by 63% and 95% in blue (460 nm) and UV (340 nm) PC-LEDs, respectively.[9] In our previous PC-LED work, 2D PCs were formed everywhere including metal transparent layer, except the contact pads, on $300 \times 300\ \mu m^2$ square-shaped LEDs, which does not consider the difference in the symmetry of LEDs with that of PCs and has no distinction between the light generation region and extraction region. In this letter, we report a design geometry of LED and PCs as well as the lattice constant and hole size dependence of the optical power enhancement factor in III-nitride UV LEDs. The design is guided by the optical pumping configuration that provides a maximum 20-fold enhancement of light extraction by PCs. In the optimized optical pumping configuration, the light generation region (pump spot) was separated from the light extraction region (PCs) and the extraction efficiency was strongly dependent on the angle between the propagation direction of emission light and the PCs lattice.[8]

The III-nitride LEDs structure used were grown by metalorganic chemical vapor deposition on sapphire substrates. Figure 1(a) shows the schematic diagrams of our 333 nm UV

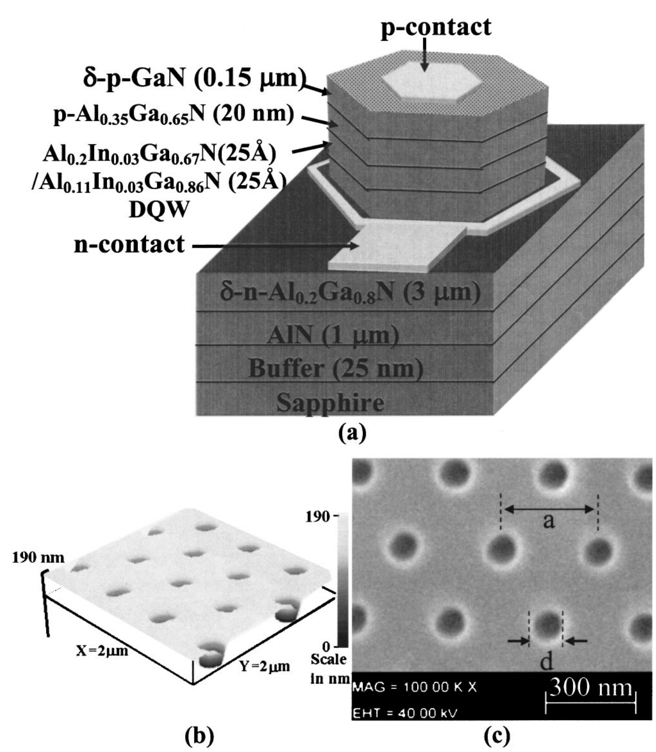

FIG. 1. (a) Schematic diagram of 333 nm UV LED structure showing mesa and contact pads. (b) AFM image of the PCs on UV LED with $a = 600$ nm and $d = 200$ nm. The etch depth is around 190 nm. (c) The SEM image of the PCs on UV LED with lattice constant $a = 300$ nm and hole diameter $d = 100$ nm.

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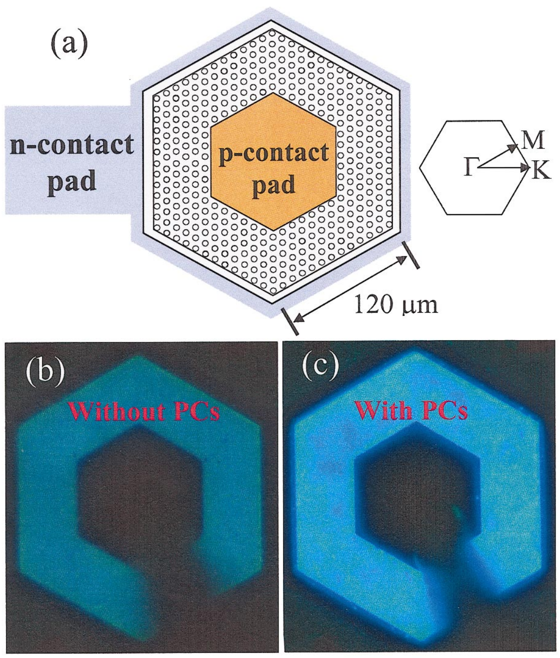

FIG. 2. (Color) (a) Schematic top view diagram of the hexagonal mesa. The *p*-contact pad side length is 60 μm. Triangular array of holes were etched on top of mesa all around *p*-contact pad with $\Gamma-K$ direction of PCs perpendicular to the side of mesa. The change coupled device images of UV LEDs at 20 mA current injections (b) without PCs and (c) with PCs (a=600 nm, d=200 nm). The darker area in the right bottom side of both of the images is due to the light obstruction by the *p*-contact probe.

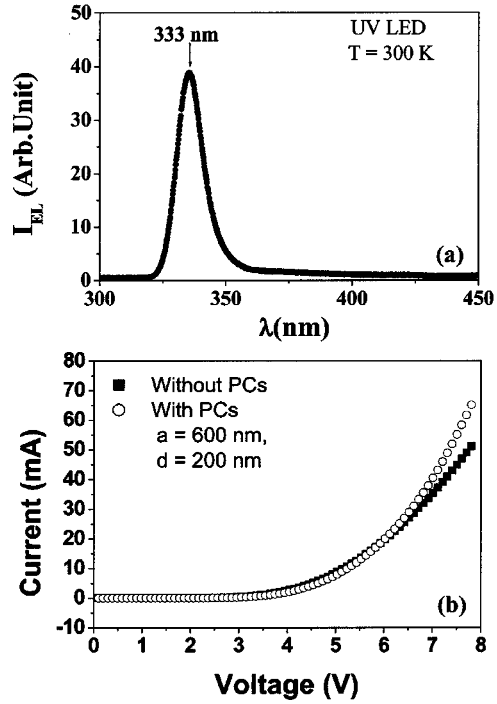

FIG. 3. (a) Typical EL spectrum of the 333 nm UV LEDs. (b) The I–V characteristics of UV LEDs with PCs (a=600 nm, d=200 nm) and without PCs.

LED structure with LED mesa and contact pads. The metal-organic sources used were trimethylgallium for Ga, trimethylaluminum for A1, trimethylindium for In, and ammonia for nitrogen. For Mg doping, bis-cyclopentadienyl-magnesium was transported into the growth chamber during growth while SiH_4 was used for Si doping. The active region for the LEDs was an $Al_{0.11}In_{0.03}Ga_{0.86}N/Al_{0.2}In_{0.03}Ga_{0.77}N$ double quantum wells. The hexagonal mesa of side length 120 μm, as shown in Fig. 2(a), was defined by electron-beam (e-beam) lithography and etched by inductively coupled plasma (ICP) dry etching. A hexagonal *p*-contact pad with 60 μm side length was deposited at the center of the LED mesa. To improve the electrical transport, a 10 μm wide *n*-type ohmic contact was deposited around the mesa along with a 100×100 μm^2 *n*-contact pad. More details of the LED fabrication procedures have been described elsewhere.[10] The PCs with triangular lattice patterns of circular holes with varying diameter d=100 nm to d=200 nm and periodicity a=300 nm to a=600 nm were fabricated using e-beam lithography and ICP dry etching as described previously.[8,9] Extraction of guided light traveling along $\Gamma-K$ direction can be as much as three times more than the light traveling along $\Gamma-M$ direction of the PCs in the nitride quantum well.[8] For efficient extraction of the guided light, $\Gamma-K$ direction of the PCs was set perpendicular to the sides of the mesa. An atomic force microscopy (AFM) image of the PCs on UV LED with a=600 nm and d=200 nm is shown in Fig 1(b). The targeted etching depth of the holes was 200 nm. The AFM image revealed that the depth of the etched holes varied from 175 nm to 190 nm and that the holes with a larger diameter were etched relatively deeper. This indicates that most of the holes were etched through to the active layers. Figure 1(c) shows the (SEM) image of the PCs with a=300 nm and d=100 nm etched on UV LED.

Figures 2(b) and 2(c) show the optical microscopy images of UV LEDs in action at 20 mA current injections. The less bright image in Fig 2(b) is the LED without PCs. The LED with PCs (a=600 nm, d=200 nm) is shown in Fig. 2(c), which clearly shows a significant enhancement of light output compared with the LED without PCs. The current was injected by probing with a needle hence, the darker area in the right bottom side of both of the images is due to the light obstruction by the probe tip. Typical electroluminescence (EL) spectrum of the 333 nm UV LEDs is shown in Fig. 3(a). No change was noticed in the peak position as well as the linewidth of the EL spectrum due to PC formation indicating that the spontaneous emission is not significantly altered by the formation of PCs. Even though the holes were etched through the active layers, the PC formation was unlikely to modify the spectra as the lattice constant of the PCs is larger than the normally required value ($\sim\lambda/2$) (Ref. 11) to tune into the PBG of spontaneous emission regions. Figure 3(b) shows the current–voltage (I–V) characteristics of UV LEDs with PCs (a=600 nm, d=200 nm) and without PCs. While the operating voltages at 20 mA (V_f) for both LEDs are the same around 5.7 V, the forward current increases faster in the LED with PCs. The turn-on voltage for the LED with PCs is slightly higher than that of without PCs, which can be attributed to the reduced area of the *p*-type material due to the formation of PC. The faster increase of the forward current for the LED with PCs may be due to the following two reasons. First, the formation of PCs enhances the spontaneous emission rate in the LED due to microcavity effect or Purcell effect, which increases the carrier injection or current. The second and more probable reason for the increase in the current is the increase in the surface recom-

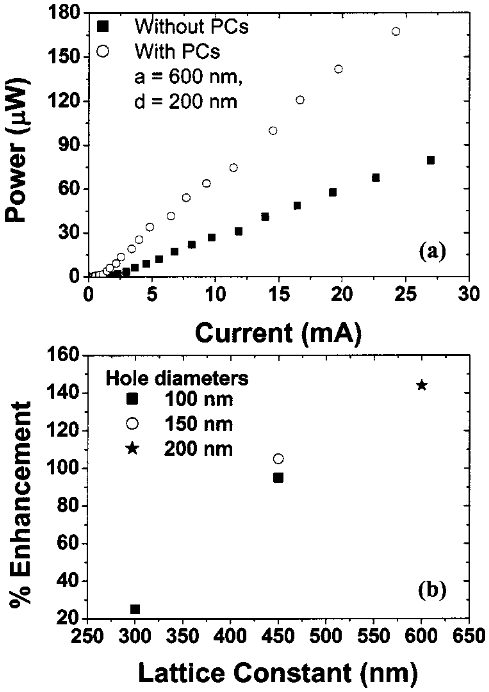

FIG. 4. (a) The *L–I* characteristics of LEDs without PCs and with PCs, measured using an integrating sphere. At 20 mA, the output power was enhanced by a factor of 2.5 in the PC-LED. (b) The PC lattice constant and the air hole diameter dependence of the enhancement factor in the UV LEDs. While the optical power level is still low for the UV LEDs studied here, comparison is being made on the overall intensity enhancement using PCs. We expect that the power enhancement due to PC formation will translate into our LED materials that provide an optical power exceeding 1 mW at 300 nm.

bination of the injected electrons and holes as a result of increased surface around etched holes.

The output power versus injection current $(L\text{–}I)$ characteristics of LEDs without and with PCs $(a=600\text{ nm}, d=200\text{ nm})$ are shown in Fig. 4(a). Output power was measured using an optical integrating sphere. At $I=20$ mA, the output power of UV LEDs with /without PCs are 147 μW/60 μW, respectively, giving an enhancement by a factor of about 2.5 with PCs. While the optical power level is still low for the UV LEDs studied here, a comparison is being made on the overall intensity enhancement using PCs. Our most recent experiments have yielded UV LED materials that offer outputs of more than 1 mW of 300 nm radiation at 120 mA. We expect that the overall power enhancement due to PC formation will translate into those LEDs. There are two possible ways for the enhancement of extraction efficiency of LEDs by the 2D PCs. First, the creation of 2D PBG forbids the lateral guided modes in the bandgap region thus forcing the emitted power to couple to free space modes and radiate out of plane.[11,12] The midgap frequency of the PBG of triangular PCs of air hole in GaN with dielectric constant $\varepsilon=8.9$ is estimated to be around the normalized frequency of 0.5.[11,12] A periodicity of less than 165 nm is required to tune the PBG to the emission wavelength of the UV LED. Second, the PC periodicity folds the higher momentum guided modes, which lie below the air light line defined by $\omega=c|k_o|$ with k_o being in-plane wave vector in air, to the first Brillouin zone. The folded guided mode that lie above the air light line can phase match to the radiation mode and leak out as Bragg scattered light.[5,11] For the triangular lattice of air hole, all of the modes above normalized frequency $a/\lambda=0.66$ (i.e., all $\lambda<1.51\ a$) will be Bragg scattered.

Figure 4(b) shows the PCs lattice constant and the air hole diameter dependence of the power output enhancement factor in the UV LEDs. In contrast to the expectations, we got surprisingly higher enhancement for larger dimensions of lattices. This implies that the light extraction was dominated by the process of Bragg scattering instead of the effect of the PBG creation. For the same air-filling factor $f=0.1(a/d=3)$, the enhancement increases with the lattice dimension. However, a decrease in the enhancement factor was observed for $a>600$ nm. For the same value of $a=450$ nm, the enhancement is larger for a larger hole diameter. This may be due partly to the fact that the etching is not perfectly vertical and the actual hole size near the active layer is smaller than the targeted. In any case, the bigger targeted holes seem to perform better than the smaller holes in terms of light extraction. We believe that further enhancement can be achieved by improving vertical etching as well as increasing the air-filling factor.

In summary, we have achieved a power enhancement by a factor of about 2.5 for 333 nm III-nitride UV LEDs under current injection using 2D PCs. Triangular lattice 2D PCs with various diameters and periodicities of holes were patterned on specifically designed hexagonal mesa UV LEDs using e-beam lithography and ICP dry etching. Our results show that the PC-LED mesa design aimed at separating the light generation and extraction area, as guided by optical pumping, yields higher enhancement. Also, the lattice constant around 600 nm and larger filling factor of PCs provide higher optical power enhancement.

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