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]
LED structure with LED mesa and contact pads. The metal-organic sources used were trimethylgallium for Ga, trimethylaluminum for Al, trimethylindium for In, and ammonia for nitrogen. For Mg doping, bis-cyclopentadienyl-magnesium was transported into the growth chamber during growth while SiH4 was used for Si doping. The active region for the LEDs was an Al0.11In0.03Ga0.86N/Al0.2In0.03Ga0.77N 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 μm2 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 δ = 100 nm to δ = 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 Γ–K direction can be as much as three times more than the light traveling along Γ–M direction of the PCs in the nitride quantum well.8 For efficient extraction of the guided light, Γ–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 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 (≈λ/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 (Vf) 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-
s
teristics of LEDs without and with PCs = 200 nm
d
The midgap frequency of UV LED. Second, the PC periodicity folds the higher mo-
mentum guided modes, which lie below the air light line above the air light line can phase match to the radiation mode and leak out as Bragg scattered light.\textsuperscript{5,11} For the triangular lattice of air hole, all of the modes above normalized frequency \(\alpha/a=0.66\) (i.e., all \(\lambda<1.51\)) 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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\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure4.png}
\caption{(a) The \(L-I\) characteristics of LEDs without and with PCs \((a=600\) nm, \(d=200\) 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 without PCs is 147 \(\mu\)W and that with PCs is 200 \(\mu\)W, 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, 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. (b) The output power versus injection current \((L-I)\) characteristics of LEDs without and with PCs \((a=600\) nm, \(d=200\) nm) are shown in Fig. 4(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.}
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\includegraphics[width=\textwidth]{figure5.png}
\caption{The output power versus injection current \((L-I)\) characteristics of LEDs without and with PCs \((a=600\) nm, \(d=200\) 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 without PCs is 147 \(\mu\)W and that with PCs is 200 \(\mu\)W, 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, 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.}
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\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure6.png}
\caption{The midgap frequency of PBG is estimated to be around the normalized frequency \(\alpha/a=0.66\) for the triangular lattice of air hole. The folded guided mode that lie above the first Brillouin zone. The folded guided mode that lie above the first Brillouin zone.}
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\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure7.png}
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\includegraphics[width=\textwidth]{figure8.png}
\caption{The midgap frequency of PBG is estimated to be around the normalized frequency \(\alpha/a=0.66\) for the triangular lattice of air hole. The folded guided mode that lie above the first Brillouin zone.}
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\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure9.png}
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\includegraphics[width=\textwidth]{figure10.png}
\caption{The midgap frequency of PBG is estimated to be around the normalized frequency \(\alpha/a=0.66\) for the triangular lattice of air hole. The folded guided mode that lie above the first Brillouin zone.}
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