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Double embedded photonic crystals for extraction of guided light in light-emitting diodes

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Light-emitting diodes (LEDs) were fabricated in gallium nitride with two embedded photonic crystals (PhCs), creating a waveguide with a highly confined, strongly excited, and well-extracted fundamental mode. This structure improves upon previous PhC LED designs by reducing the extraction length of the fundamental mode and establishing a path to designs with very low absorption losses. Optical output was measured with angular-resolved electroluminescence. The extraction length of the fundamental mode was measured to be 21–39 μm along the PhCs’ Γ-M directions, which is much shorter than values reported for single-PhC devices. This structure opens the way to more efficient LEDs and lasers. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4705735]

Photonic crystals (PhCs) have been explored as a means to extract light from light-emitting diodes (LEDs) for many years. In addition to increasing the extraction efficiency of these devices, periodic gratings have the ability to enhance their directionality.¹–⁴ While surface roughening is the most commonly utilized method for improving the extraction efficiency of devices, the extraction efficiency by this method is ~80%,⁵ and the angle of extraction of guided light is random, leading to a Lambertian emission pattern.

Extraction efficiencies as high as 94% have been reported for encapsulated indium-gallium nitride (InGaN) LEDs with embedded PhCs.⁶ This is due to the ability of embedded PhC LEDs to guide a large amount of the emitted light in optical modes which are strongly extracted to air by diffraction. Extraction efficiency, in this case, depends on the competition between absorption losses and diffraction by the PhC. Through design of PhC waveguides, absorption losses can be reduced while diffraction to air increases. The PhC LED mentioned, however, used an n-side embedded PhC guiding a majority of the light between the PhC and the p-side surface of the device. In this geometry, the device was limited to a small p-contact area to minimize metal absorption, and therefore total device power was limited by current density.

Current-spreading layers on the p-side of an LED are typically used to increase the useful current injection area, but a semitransparent metal or transparent conductive oxide introduces absorption losses. To reduce the absorption on the p side of a PhC LED, a PhC can be used to reduce the interaction of the guided modes with the p-side contact and current spreading layers. Recent advances in metalorganic chemical vapor deposition (MOCVD) methods for lateral epitaxial overgrowth (LEO) over air-gaps have now made it possible to embed air-gap PhCs on the p-side.⁷ The p-side PhC still performs the function of a light extractor while guiding light away from absorbing p-contact materials.

In this letter, we therefore demonstrate a LED with two PhCs embedded by MOCVD: one below the active region (n-side) and one above the active region (p-side). The planar embedded 2-D PhCs are composed of GaN (n = 2.48) and air (n = 1.0). These layers have an effectively lower refractive index than the surrounding material and thus behave as low refractive index layers similar to cladding layers in a semiconductor laser. The 2-D nature of the PhCs allows light propagating in all in-plane directions to be extracted. The advantages of this device design are confinement of most of the guided light away from absorbing layers and an increased interaction between guided light and the PhCs, leading to shorter extraction lengths which, in turn, lead to an even further reduction in the absorbed fraction of guided light. The exact design of this LED was not based on any extensive modeling but was an educated guess based on previous work found in the references. This letter is a proof of concept; modeling will be done for future work.

Fabrication of two layers of air-gap embedded PhC requires three stages of MOCVD growth separated by patterning processes outside of the reactor. For the devices in this paper, four separate growths in two different MOCVD reactors were used based on reactor availability and suitability.

An unintentionally doped (uid) GaN buffer layer followed by n-GaN:Si was grown on a c-plane sapphire substrate to a thickness of approximately 4 μm in an atmospheric pressure MOCVD reactor. At that point, the sample was removed from the reactor for patterning of the n-side PhC. A 180-nm-thick SiO₂ hard mask was deposited by plasma-enhanced chemical vapor deposition (PECVD), and nano-imprint resist was spun onto the sample to a thickness of 200 nm. The pattern was formed by means of a wide-area imprint stamp. The pattern was then transferred into the SiO₂ hard mask with a CHF₃-based inductively coupled plasma (ICP) etch. A second ICP etch in an atmosphere of N₂ and CCl₄ created a pattern of 500-nm-deep holes in the n-GaN. The remaining SiO₂ hard mask was then removed with buffered hydrofluoric acid. To embed the PhC air-gaps, the

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sample was loaded into a Thomas Swan MOCVD reactor, where it was annealed at 1180 °C for 30 s in an atmosphere of NH₃ and N₂. During the anneal, a very thin (< 40 nm), smooth coalescence layer was formed over the top of the air-gaps by mass-transport. For growth of the active region, the sample was transferred to the atmospheric pressure MOCVD reactor, where an InGaN/GaN superlattice, four 2.5-nm In₀.₁₈Ga₀.₈₂N quantum wells (QWs) with 20-nm barriers, an electron blocking layer, and thick (~500 nm) p-GaN:Mg were grown. The sample was removed from the reactor for patterning another PhC—this time etched to a depth of 350 nm in the p-GaN. The final re-growth occurred in the Thomas Swan MOCVD, where the sample was annealed at 1100 °C for 30 s in an atmosphere of NH₃ and N₂ to coalesce a thin GaN layer over the air-gaps. After complete coalescence, 100 nm of p-GaN were grown under normal growth conditions. Devices were fabricated from this epitaxial structure by etching a mesa and depositing metal contacts as shown in Fig. 1(c). The mesa was 280 μm × 280 μm, and the p-contact had an area of 0.012 mm². There was no current spreading layer on the p-side.

The dimensions of the embedded air gap features in the final devices were characterized by scanning electron microscopy (SEM) using samples that were carefully prepared by focused-ion-beam (FIB) etching to reveal the PhCs in a fully processed LED. The top view (Fig. 1(a)) shows the p-side PhC on the bottom and left and the n-side PhC on the top-right. One can see that the PhCs have good hexagonal symmetry and are rotated in plane by 22° relative to one another. The two PhCs were intentionally misaligned to clearly observe and differentiate diffraction by each lattice—where 22° is an arbitrary value. The planes made visible by FIB etching in Fig. 1(a) pass roughly through the center of each PhC air-gap, but some of the air-gaps are covered by gallium metal. This is simply a result of the ion-beam etching, which is composed of gallium ions. The cross-section (Fig. 1(b)) shows the consistency in size and location of the air-gaps.

The cross-section surface is aligned parallel to the Γ-K direction of the p-side PhC, and the n-side PhC is seen along a plane 22° from Γ-K. The periodicity of both PhCs is 230 nm. The heights of the PhCs are 345 nm (n-side) and 245 nm (p-side), and the areal fill factors are estimated to be 27% (n-side) and 15% (p-side). The height of the waveguide between the PhCs is 495 nm.

Output from the LED through the sapphire substrate was measured before the addition of the p-side PhC. A quick test using soldered indium-dot contacts and a photodetector with a numerical aperture of 0.75 produced ~0.8 mW at 20 mA with only the n-side PhC present. The current density was 20 A/cm², based on a contact area of roughly 0.1 mm². After device fabrication was completed, output power was measured to be 1.13 mW at 20 mA. Based on the contact area of 0.012 mm², the current density was 170 A/cm², assuming no current spreading. This was a significant improvement in output power even though the current density was much higher (implying a decrease in the internal quantum efficiency (IQE)—the universally observed efficiency droop at high current densities). This means that the double-embedded PhC device had significantly improved extraction efficiency compared to the device with only the n-side PhC. Since it is very difficult to accurately measure IQE, we can only make conservative comparisons: At constant IQE, extraction efficiency improved by ~40% due to the addition of the p-side PhC, but the improvement should be significantly higher due to droop.

Electroluminescence of the LED was measured as a function of angle in order to probe the guided modes present in the device as well as to characterize their extraction. Each guided mode in the structure has a characteristic in-plane k-vector (kᵦ) which can be calculated if the periodicity of the PhC and kᵦ of the extracted mode are known. Fig. 2 shows the far-field optical power density emitted out the top surface of the LED as a function of kᵦ and kᵦ. The measurement was taken over 90° in θ and only 60° in φ, but the six-fold symmetry allows for a re-creation of the full hemisphere. The primary features of the far-field emission pattern are:

1. There are two identical patterns with hexagonal symmetry rotated 22° relative to each other, indicating that the two PhCs are both extracting light independently.
2. One of the two patterns shows stronger light extraction than the other. Based on the orientation of the sample during the measurement, the source of the stronger extraction is the p-side PhC.
3. Diffraction from nearest PhC reciprocal lattice points gives a single strong line, indicating that a large fraction
of the guided light is carried by one mode, which is, in this case, the fundamental mode (TE₀) between the two PhCs.

4. In addition to the peak from the TE₀ mode, two peaks appear stronger and broader than the higher-order modes, which are also labeled and highlighted with a dotted line in the figure. These three modes are diffraction lines from the modes overlapping most with the QWs.

5. There are faint lines of light diffracted at large θ angles which are not parallel to the first-order diffraction lines. These can be shown to originate from light guided in the fundamental mode which is preferentially diffracted by each PhC in different directions. Two of these lines are labeled “2-PhC diffractions” and highlighted with a dotted line in the figure—each has six-fold symmetry.

We also measured the modal decay length (L_decay) of TE guided modes through the full-width half maximum (FWHM) of their corresponding extracted peaks using the method described in Ref. 9, where L_decay = 2/(α_eff Δk₀), with Δk₀ being the wave vector linewidth observed on a mode. L_decay values for the fundamental TE mode were measured to be 25 ± 4 μm and 31 ± 8 μm in the Γ-M direction of the p-side and n-side PhCs, respectively. The measurement error is estimated from the angular aperture of the optical fiber and the effective sample size as well as broadening effects from the slit size of the spectrometer. Due to the low signal-to-noise ratio and high concentration of higher-order modes, only values for the fundamental mode could be calculated. However, this mode is of the most interest since it carries a majority of the light and is the most difficult to extract. Higher order modes have a larger overlap with the PhCs and are therefore better extracted.16

Peaks from extracted modes were found to be well-approximated by a Lorentzian lineshape, leading us to believe there is very little inhomogeneous broadening and the PhCs are uniform with low scattering losses. Scattering losses arise due to defects and random fluctuations in the periodic PhC lattice. These deviations from the ideal periodicity create scattering centers that scatter light out of the guided PhC propagating modes. The image of the PhCs in Fig. 1(b) supports the evidence that the PhCs are uniform. On the other hand, the homogeneous broadening component contains contributions from absorption losses as well as extraction to air by the PhCs. Absorption losses can be neglected here, however, because they are relatively very weak. The Stokes shift observed for InGaN QWs with these dimensions is very large (∼15 nm),11 so QW absorption is minimal, and free carrier absorption is also low. In a previous study, a guided mode with a similar profile in a 450-nm LED had a measured absorption length of 600 μm at λ = 433 nm and longer absorption lengths at longer wavelengths.9 All measurements in the current study were taken between 445 nm and 455 nm, so the effect of absorption on the decay length is much less than the measurement error. We can then say that L_decay is a good approximation of the modal extraction length (L_extraction), or L_decay = L_extraction.

The L_extraction values for this device are very short compared to previously reported values for embedded PhC LEDs, which have been around 80 μm for single-PhC devices.10 Since there are two PhCs in this device, the effect on light extraction is understandably about twice as strong. A further cause is the increase in overlap between the electric field of the guided mode and the PhCs. In this case, the optical confinement factor with the two PhCs (Γ_Phc) is 2.27%. In the aforementioned single-PhC devices, the average Γ_Phc was less than 1%. The change in extraction length correlates very well with the inverse of Γ_Phc. More precisely, 2.27:1 = 80 μm:35 μm and L_extraction for this device is near 35 μm.

The observation of one dominant mode in the angular-resolved electroluminescence measurements is a peculiar feature that requires additional attention. Further insight can be gained by simulating the mode profile of the TE modes guided near the QWs based on the accurate dimensions obtained by the SEM characterization (Fig. 3). The optical confinement factor (Γ, overlap of the mode with the QWs) for the fundamental TE mode is 3.49%, or 0.87% per quantum well, which is similar to lasing modes in c-plane lasers.12 This mode is strongly excited and only weakly absorbed by the GaN, so it is very prevalent in the angular measurement. The second-order mode (Γ = 0.34%) is weakly excited, so it is only slightly visible in Fig. 2. The third-order (Γ = 0.29%) mode is weakly excited and strongly absorbed by the p-contact, so its diffraction peak is not observed. And the fourth-order mode (Γ = 1.63%) is only slightly visible because it is moderately excited and strongly absorbed. The waveguide in this device is not optimized, which is why the lossy fourth-order mode has such a high optical confinement factor. In optimized structures, Γ for modes absorbed by the metal contact can be significantly reduced by increasing the fill factor and/or the depth of the p-side PhC while decreasing the fill factor of the n-side PhC.

Ideally, the distance between the PhCs should also be as small as possible to increase Γ for the fundamental mode as
well as the interactions between the PhCs and the fundamental mode. The major limitations to the waveguide height are the shrinkage of the p-side PhC during LEO of the etched void and the etch damage that is caused to the QWs if the p-side PhC is etched too close to the active region.

Comparing the dimensions of the embedded PhC air-gaps to those of the as-processed holes, the n-side PhC is now 155 nm shallower, and the p-side PhC is 105 nm shallower. Some of the loss of height (50 nm) occurs at the top of the etched hole during mass transport, but most of it is due to filling in at the bottom of the hole, causing the bottom to rise up. The p-side PhC was etched to within 150 nm of the active region, so in the final device, the p-side PhC is 205 nm from the active region. This distance can likely be reduced with the use of an etch-stop layer and refinement of the LEO step.

The filling factors are also slightly smaller after regrowth, but most of the difference between the two PhCs here is due to the fact that the longer etch for the n-side PhC created holes which were deeper as well as wider than on the p-side.

The limits on fill factor are likely not a limitation for light extraction. As the PhC fill factor is increased, the Fourier coefficient for diffraction increases due to the refractive index contrast between GaN and air, but the low-index layer pushes the optical mode profile away, decreasing $\Gamma_{\text{PhC}}$. The net result is that increasing the fill factor decreases modal extraction for most of the possible range of values.\(^1\)\(^0\) In a previous study, the optimal embedded PhC fill factor for a 540-nm waveguide was found to be 14%.\(^6\) And, in fact, in this work, we observe that the p-side PhC (fill factor = 15%) has a larger $\Gamma_{\text{PhC}}$ (1.21% compared to 1.06% for the n-side PhC) and extracts light more strongly than the n-side PhC.

In conclusion, we have demonstrated an LED with two embedded PhCs which enhance light extraction while exhibiting no significant deleterious effects on the device. A majority of the guided light is confined in the fundamental mode by the PhC waveguide, which very quickly extracts the light to air. $L_{\text{extraction}}$ values of 21–39 $\mu$m were measured for the fundamental TE mode, which are much lower than any previously reported values for PhC LEDs. This device architecture will enable future LEDs with exceedingly high extraction efficiencies, including in the green and UV wavelength ranges, where there is more room for improvement. There are also applications for lasers, since the confinement provided by the PhC waveguide can enhance the optical confinement factor of the lasing mode.

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