Interplay of Cavity Thickness and Metal Absorption in Thin-film InGaN Photonic Crystal Light-emitting Diodes

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Thin-film InGaN photonic crystal (PhC) light-emitting diodes (LEDs) with a total semiconductor thickness of either 800 nm or 3.45 μm were fabricated and characterized. Increased directional radiance relative to Lambertian emission was observed for both cases. The 800-nm-thick PhC LEDs yielded only a slight improvement in total light output over the 3.45-μm-thick PhC LEDs. Simulations indicate that, except for ultrathin devices well below 800 nm, the balance between PhC extraction and metal absorption at the backside mirror results in modal extraction efficiencies that are almost independent of device thickness, but highly dependent on mirror reflectivity. © *2010 American Institute of Physics*. [doi:10.1063/1.3480421]

Photonic crystals (PhCs) are now well recognized as a means to enhance the light extraction and emission directionality of InGaN light-emitting diodes (LEDs). However, several key design parameters for high-efficiency PhC LEDs remain to be fully characterized. One of the critical considerations for surface-patterned PhC LEDs is the thickness of the underlying semiconductor. In general, reduction of the semiconductor thickness will improve the overlap between the guided optical modes and the PhC layer. This is especially important for low-order modes, whose interaction with a shallow-etched PhC can be very weak.[1] More specifically, simulations have shown[2] that the extraction length of low-order modes—the $1/e$ in-plane decay length as the modes are diffracted to air by the PhC—scales as t^3, where t is the thickness of the unetched semiconductor below the PhC, as shown in Fig. 1(a). Thus, holding all else constant, higher extraction efficiency is expected for thinner devices. In addition, it has been suggested that thinner PhC LEDs may afford more directional far-field patterns, since their emission is concentrated into a smaller number of guided modes.[3,4]

While the epitaxial thickness of conventional InGaN LEDs on sapphire is generally fixed by growth constraints to several microns or more, thin-film LEDs offer greater flexibility since the *n*-GaN can be thinned down after removal of the sapphire substrate. Several thin-film InGaN PhC LEDs with submicron thickness have now been reported,[3–6] including a 700-nm-thick device with an unencapsulated extraction efficiency of 73%.[5] However, the impact of thickness on the directionality and extraction efficiency has not been studied in detail. In particular, while the importance of metal absorption in these devices has been highlighted,[3] the magnitude of this absorption loss as a function of cavity thickness has not been quantified.

In this letter, we report on an experimental comparison between thin (800 nm) and thick (3.45 μm) vertically injected thin-film InGaN PhC LEDs. Despite a large difference in the number of guided modes supported by the two structures, the wavelength-integrated far-field patterns were remarkably similar. In addition, the thin PhC LEDs exhibited only a small improvement in total output power over the thick PhC LEDs. This result is explained by simulated extraction and absorption lengths for low-order modes, which indicate that the balance between extraction and absorption is maintained as the structure is thinned to 800 nm, resulting in an extraction efficiency that is largely independent of device thickness.

The epitaxial material was grown by metal-organic chemical vapor deposition on *c*-plane sapphire substrates. The structure consisted of an unintentionally doped GaN buffer, several microns of *n*-GaN, a 115-nm-thick InGaN/GaN 8× MQW active region emitting at $\lambda=450$ nm, a 15-nm-thick AlGaN electron blocking layer, and a 265-nm-thick *p*-GaN layer. After deposition of a Ni/Ag mirror as the *p*-contact, thin-film LEDs were fabricated by flip-chip bonding and laser lift off. The *n*-GaN was then thinned down by dry etching and mechanically polished to obtain a smooth surface. The remaining III-nitride thickness was 800 nm (3.45 μm) for the thin (thick) structures. Hexagonal PhCs with an air fill factor of 30% and lattice constant of $a=448$ nm were patterned by e-beam lithography and dry etched into the *n*-GaN to a depth of 240 nm. Finally, an Al-based *n*-contact was deposited outside the PhC pattern. The side length of the LED mesa was 330 μm. An image of one of the PhC LEDs operating at 2 mA is shown in Fig. 1(b). The PhC is patterned in the four quadrants outside the cross-shaped *n*-contact, and recessed from the *n*-contact by 10 μm. The areas containing the PhC are visibly brighter

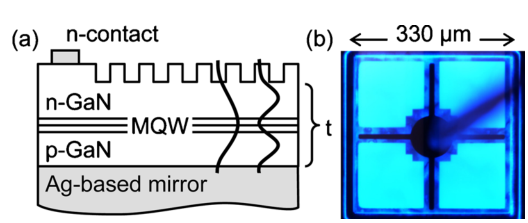

FIG. 1. (Color online) (a) Schematic cross section of the thin-film PhC LED structure, illustrating the TE_0 and TE_1 modes. (b) Top lit view of the thin-film PhC LED.

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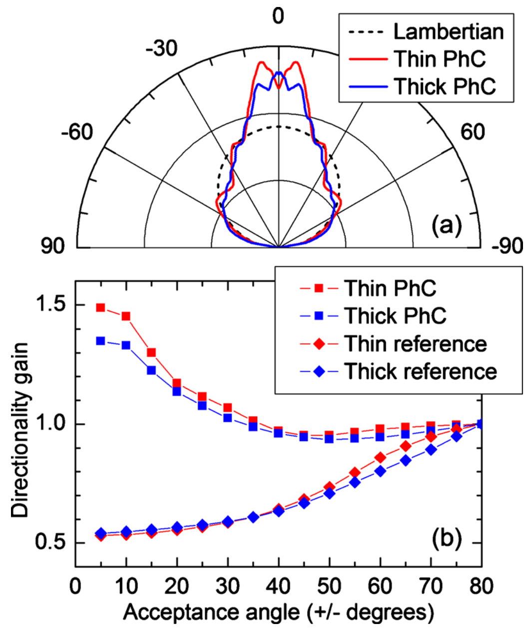

FIG. 2. (Color online) (a) Normalized far-field emission of 800-nm-thick and 3.45-μm-thick PhC LEDs. (b) Directionality gain relative to Lambertian emission as a function of acceptance angle.

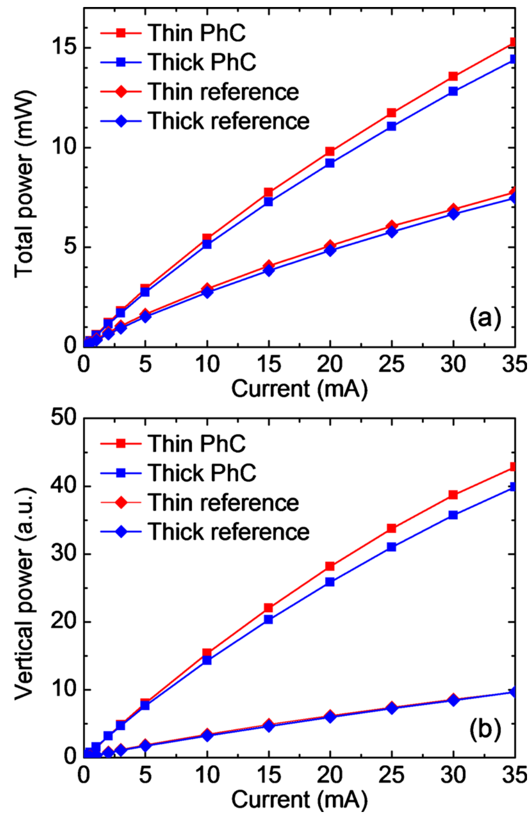

FIG. 3. (Color online) (a) Average total power vs current for the unencapsulated PhC and non-PhC LEDs. (b) Average power vs current collected with a limited acceptance angle of $\pm 20°$. Same devices as in (a).

than the unpatterned regions between the PhC and *n*-contact.

Far-field patterns were measured by wavelength- and angle-resolved electroluminescence at 20 mA. As expected, the large disparity in the number of guided modes supported by the thin and thick PhC LEDs—roughly eight TE modes in the thin LED compared to 34 in the thick LED—was reflected in the much richer PhC band structure measured for the thicker device (not shown). However, the overall shape of the wavelength-integrated far-field patterns was almost independent of the device thickness, as shown in Fig. 2(a). The data here has been averaged over a set of 120 measured in-plane angles in order to account for the azimuthal asymmetry of the PhC, and normalized such that the total integrated power is the same for both devices. The resultant patterns deviate substantially from one another only at small angles near the surface normal. At wider angles, where the intensity is determined by a larger number of guided modes and averaging effects prevail, the two curves are nearly identical.

The directionality of the far-field patterns can be quantified by comparison with a theoretical Lambertian emitter having the same total power as the PhC LEDs, as illustrated by the dashed curve in Fig. 2(a). The directionality gain is then defined as the power emitted into a given acceptance angle by the PhC LED, divided by the power emitted into the same aperture by the Lambertian emitter.[4] As shown in Fig. 2(b), both the thin and thick PhC LEDs yielded a substantial directionality gain for small acceptance angles. This vertical directionality arises from the diffraction of highly excited, closely spaced low-order guided modes to the center of the air cone via second and third order diffraction at the chosen lattice constant. The similarity between the thin and thick PhC LEDs is a product of the fact that the guided modes in the thin structure, though more sparsely distributed, span nearly the same range in *k*-space as the guided modes in the thick structure. For comparison, the directionality gain of unpatterned reference LEDs on the thin and thick samples is also shown. Here the gain is less than unity due to the contribution of sidewall emission at large angles and the detuned half-cavity[7] formed by the mirror and first quantum well. We note the excellent agreement between our results and those of Bergenek *et al.*,[4] who observed similar directionality gain for 850-nm-thick PhC LEDs with an a/λ ratio close to ours. It is also worth noting that the directionality gain will of course depend on what fraction of the total emission is due to PhC extraction.

The output power of the unencapsulated LEDs was measured under DC operation in an integrating sphere on TO-56 headers. The results are shown in Fig. 3(a), where the data have been averaged over all measured devices of each type. We note that no significant difference was observed between the unpatterned thin and thick LEDs. We attribute the absence of a microcavity enhancement[8] (or suppression) of the extraction efficiency in the thin LEDs to a thickness variation in the order of ± 40 nm across the mesa, arising from the thinning and polishing process, which simulations indicate would be sufficient to average out any microcavity effects.[9] More surprisingly, the efficiency of the PhC extraction also exhibited little dependence on the nominal device thickness. The average power of the thin PhC LEDs was just 6% higher than that of the thick PhC LEDs, barely higher than the standard deviation of 4% within each set of devices.

The output power was also measured using a photodetector mounted above the sample with an acceptance angle of about $\pm 20°$. As shown in Fig. 3(b), the thin PhC LEDs yielded an average enhancement over the unpatterned LEDs of 4.5 times—much higher than the enhancement in total power (1.9 times)—as a result of the vertical directionality of the PhC emission. However, the thickness of the devices still

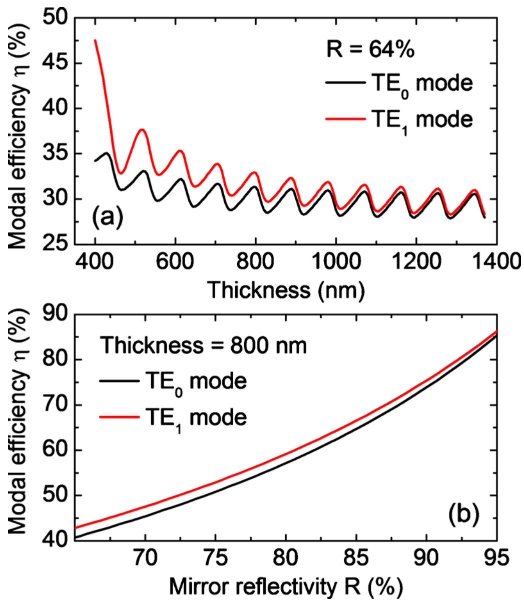

FIG. 4. (Color online) (a) Simulated modal extraction efficiency for the TE_0 and TE_1 modes as a function of the total PhC LED thickness. (b) Simulated modal extraction efficiency for the TE_0 and TE_1 modes in an 800-nm-thick PhC LED as a function of the mirror reflectivity.

had little impact; with the vertical power of the thin PhC LEDs just 9% higher than that of the thick PhC LEDs.

As discussed above, the advantage of a very thin PhC LED is the improved overlap between low-order guided modes and the PhC layer. However, the thin nature of the structure also increases the overlap of these modes with the lossy metal mirror. To quantify the magnitude of these competing effects, we calculated the $1/e$ decay lengths corresponding to absorption by the metal mirror and extraction to air by the PhC—denoted by L_{abs} and L_{ext}—using a three-dimensional scattering matrix formalism.[10] The simulated device had a hexagonal PhC with a lattice constant of $a=200$ nm and etch depth of 170 nm. To approximate the unoptimized Ag-based mirrors used in this study, the complex refractive index of the mirror was taken to be $n=0.54+2.47i$, which yields a normal-incidence GaN-to-metal reflectivity of $R=64\%$ at $\lambda=450$ nm.

Neglecting sidewall emission, the extraction efficiency of a single guided mode is given by

$$\eta = \frac{1/L_{ext}}{1/L_{ext} + 1/L_{abs}}. \tag{1}$$

This modal efficiency is plotted in Fig. 4(a) for the TE_0 and TE_1 modes as a function of the device thickness. Raw simulations were convoluted with a thickness variation of ± 40 nm to account for the nonuniformity in the real devices. Aside from periodic oscillations corresponding to vertical resonances with the PhC, the modal extraction efficiency exhibits a weak downward trend as the thickness is increased from 400 nm, with almost no dependence on thickness above 800 nm. This is a result of the fact that any increase in L_{ext} is compensated by a corresponding increase in L_{abs}. Notably, repeating the simulation for higher mirror reflectivities yielded the same trend, simply shifting the two curves upwards in efficiency.

To further explore the role of metal absorption in our thin PhC LEDs, the thickness of the simulated device was fixed at 800 nm and the normal-incidence mirror reflectivity in GaN was varied from $R=65\%$ to 95% by varying the real component of the mirror's refractive index from $n=0.54$ to 0.01, keeping the imaginary component fixed at $k=2.47$. As shown in Fig. 4(b), relatively small degradations in mirror reflectivity were found to correspond to large decreases in modal efficiency, due to large increases in modal absorption. For $R=89\%$, corresponding to an ideal Ag mirror with a refractive index of $0.15+2.47i$,[11] the extraction efficiency of the TE_0 mode is only 71%. For $R=80\%$, the extraction efficiency of the TE_0 mode drops to 57%. Given that low-order modes carry a substantial fraction of the total quantum well emission, these results highlight the critical importance of mirror quality in high extraction efficiency thin-film PhC LEDs.

In summary, we have fabricated and characterized thin-film InGaN PhC LEDs with total semiconductor thickness of either 800 nm or 3.45 μm. Vertically directional light emission was observed in both cases. The output power of the PhC LEDs was found to be almost independent of the device thickness. These results are in good agreement with simulations, which indicate that the improvement in PhC extraction obtained by thinning the devices to 800 nm is largely negated by a corresponding increase in metal absorption. We conclude that except for extremely thin devices well below 800 nm, the thickness of the PhC LED has little importance for either the directionality or the total extraction efficiency. In addition, we find that the extraction efficiency is strongly dependent on the optical properties of the metal mirror.

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