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Photonic-crystal GaN light-emitting diodes with tailored guided modes distribution

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We relate the currently limited efficiency of photonic crystal (PhC)-assisted gallium nitride light-emitting diodes (LEDs) to the existence of unextracted guided modes. To remedy this, we introduce epitaxial structures which modify the distribution of guided modes. LEDs are fabricated according to this concept, and the tailored band structure is determined experimentally. We investigate theoretically the consequences of this improvement, which significantly enhances the potential for efficient light extraction by PhCs. © 2006 American Institute of Physics.

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Gallium nitride (GaN) based materials, which emit in the UV and blue-green wavelengths, represent a promising but challenging solution towards efficient solid-state lighting. Conventional GaN-based light-emitting diodes (LEDs) still suffer from limited light extraction, due to total internal reflection (TIR) of the emitted light at the interface between semiconductor and air. Efficient solutions, such as flip-chip1 or surface-roughened2 LEDs, unfortunately require complex fabrication procedures. On the other hand, photonic crystal (PhC) were studied extensively in a variety of materials in the last decade, as an efficient means to enhance light extraction in LEDs, while keeping a full planar device fabrication. More recently, another strategy was also explored: light extraction by coupling to the surface plasmons of Ag films.3–5

Two schemes can be considered for PhC-assisted LEDs: formation of band gaps to prevent emission into guided modes,6 or PhCs acting as diffraction gratings to extract guided light.7–11 While good results have been reported regarding the former scheme for low-temperature photoluminescence experiments,12 extension to room temperature may finally, 66% is trapped in the GaN layer by TIR at the air and sapphire interfaces. We label this light as guided light.

Substrate light has negligible interaction with the PhC region, as it propagates for long distances in the thick (~500 μm) transparent sapphire wafer, and impinges on the PhC no more than once before exiting the LED region. Therefore, the PhC only aims at extracting guided light.

We showed recently that, even though for good material quality the GaN layer needs to be thick (~3–5 μm), it can still be studied as a (strongly multimode) waveguide,

[FIG. 1. (a) Possible paths for emitted light in a GaN structure. (b) Various guided modes in presence of a confining low-index layer.]
High-order modes need not be altered, but one has to modify low-order modes. To this effect, let us consider a structure formed of a GaN buffer, a lower-index layer—for instance an Al$_{x}$Ga$_{1-x}$N layer—and a GaN cap layer containing the $p$-$n$ junction and active InGaN quantum wells (QW) region. The modes supported by the new structure are depicted in Fig. 1(b). Of course, the former low-order modes localized in the buffer still exist, but very little light is emitted into these modes due to their poor overlap with the QW region. On the other hand, if the GaN cap layer on top of the AlGaN is thick enough, it supports a mode of high $n_{\text{eff}}$ ($n_{\text{GaN}} > n_{\text{eff}} > n_{\text{AlGaN}}$). This cap layer mode (CLM) receives most of the light emitted at glancing angles as it is intense in the QW region, and interacts strongly with the PhC, with which it has a good vertical overlap. Finally, high-order ($n_{\text{eff}} < n_{\text{AlGaN}}$) modes are hardly affected by this slight change of index.

This approach is supported by a frequency-domain three-dimensional modeling of the PhC structure, which gives access to the extraction length $L_{\text{dec}}$ for each mode (characterizing the exponential decay of modes along propagation in the PhC). We obtain, respectively, for the ground state mode (lowest-order mode), the CLM, and a typical high-order mode: $L_{\text{ground}} \sim \infty$, $L_{\text{CLM}} \sim 100$ μm, $L_{\text{high-order}} \sim 60$–200 μm depending on the mode and frequency.

Such a structure was grown by metalorganic chemical vapor deposition. The epitaxial structure consisted of a 3-μm-thick GaN buffer, a 800-nm-thick Al$_{0.1}$Ga$_{0.9}$N layer, and a 600-nm-thick GaN cap layer with a multi-QW region embedded at its center. LEDs were formed on the material, with a $p$-contact injection area of 100×100 μm. The area surrounding the $p$ contact was patterned with photonic crystals using electron-beam lithography and a SiO$_{2}$ hard mask. The PhCs were then etched by reactive ion etching. We used angular-resolved measurements as in our previous work. Electroluminescence was collected at all angles (−90° to 90°) by a rotating arm and analyzed in a spectrometer.
collected both the direct emission of the LED, and the diffraction of the surrounding PhC. Collection angles were then converted to in-plane wave vectors $k$ and wavelengths to frequencies $a/\lambda$, yielding the band structure (Fig. 2). In contrast to previous measurements, the direct emission from the LED could not be isolated and subtracted here, since the PhC diffracted in all directions. Therefore, the direct emission is present as a gray background (modulated by Fabry-Pérot interferences of the GaN layer) on the spectra of Fig. 2.

On the sample presented here, the lattice constant is $a = 215$ nm so that emission is tuned around the second Bragg order of the PhC. The filling factor is $f = 0.3$. As in previously measured PhCs samples, we observe sets of bands stemming from the high-order modes. However, in contrast to previous results, a new, intense band now appears at lower frequency. This band corresponds to the CLM. A simple fit by a line of dispersion $\omega = k c n_{\text{eff}}$ [green line on Fig. 2(c)] yields the effective index of this mode: $n_{\text{eff}} = n_{\text{GaAlN}} - 0.045$, midway between the indices of GaN and AlGaN layers, confirming that it is guided in the cap layer. The intensity of this mode—notice the log scale of Figs. 2(c) and 2(d)—is evidence of the large fraction of light it receives from the QWs.

In order to measure the extraction efficiency of the LEDs, we placed a mirror under the sapphire layer, thus mimicking a realistic device where light extracted downwards is redirected upwards. We compared the PhC-LEDs to classic LEDs (simultaneously formed on the same wafer with no surrounding PhCs). The extraction enhancement, measured by a photodiode with a numerical aperture 0.5, was only +70% at an injection current of 10 mA dc (100 A/cm$^2$). This modest enhancement is not surprising owing to the lack of optimization in these LEDs. Indeed, in our epitaxial layers, the placement of the QWs with respect to the AlGaN layer is so far not optimized. Moreover, in these test structures, the length of the PhC surrounding the injection area is only 80 $\mu$m, clearly not sufficient to extract all the guided light. It is also possible to extrapolate the extraction enhancement from angular measurements, but this should be carried out with care as light emission is quite dependent on the azimuthal angle and polarization of collected light—see the difference between band structures of Figs. 2(c) and 2(d). By carefully fitting the angular measurements with a simple ray-tracing model for extraction, we deduced an extraction enhancement of +100%. From these two figures, we estimate the total light extraction efficiency to be between 20% and 24%. It should also be noted that this is obtained at no compromise of the $I$-$V$ characteristics of the LEDs, which are similar for patterned and unpatterned LEDs, mainly because the contact area is free of patterning.

To estimate further the potential of our approach, we calculated the QW radiation pattern in our structure, using the transfer matrix method with a dipole source. It turns out that if a QW is located at the antinode of the CLM, coupling between the QW and the CLM is maximal. In an optimized structure (consisting of a 300-nm-thick cap layer with a QW placed in its middle, and a 1-$\mu$m-thick Al$_0.1$Ga$_0.9$N layer) this mode can receive up to 30% of the total emission of the QW, even though the index contrast between GaN and AlGaN is only 0.1. Figure 3 depicts the dipole emission pattern without AlGaN and with the optimized AlGaN layer. In the optimized structure, nearly no light is emitted in the low-order modes. Only the CLM and the high-order modes carry light, so that practically all of the guided light is prone to interaction with the PhC.

At this point, the limitation in PhC extraction is no longer governed by the "vertical" direction, but by in-plane phenomena. One is the azimuthal anisotropy of the PhC (e.g., which crystal directions can extract light) and another is parasitic diffraction to the substrate, as additional diffraction orders can couple guided light to substrate light. We believe that future efforts addressing these points are the path to ultraefficient PhC LEDs.

In conclusion, we have clarified the purpose of PhC diffraction gratings in extracting light in GaN-based LEDs. After pointing out some issues due to the multiple modes in thick GaN layers, we have studied and characterized a solution based on tailoring the structure of guided modes, which enables nearly all of the guided light to be prone to interaction with the PhC. The fabricated LEDs, while still far from an optimal design, confirm the validity of the approach of modes tailoring. This improvement comes at no cost or additional fabrication steps, and could easily be combined with future optimization of the intrinsic PhC properties, bringing us closer to ultraefficient PhC-assisted LEDs.

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18. The index dispersion of GaN is given by Ref. 19, and the index of AlGaN is assumed to follow the dispersion of GaN, shifted by the change in band gap.