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We report on the fabrication and study of laser lift-off GaN-based light-emitting diodes, thinned down to the microcavity regime, incorporating two-dimensional photonic crystal diffraction gratings. Angle-resolved measurements reveal the photonic behavior of the devices, which strongly depends on the GaN thickness. Data point out the detrimental role of metal absorption. We explore theoretically the possibility to limit this loss channel. © *2006 American Institute of Physics*.
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Gallium nitride (GaN) is currently considered as the prominent semiconductor for UV to blue-green solid-state lighting. However, as is the case for any light-emitting diode (LED), light tends to be trapped in the high-index semiconductor by total internal refraction, thus raising the issue of light extraction. Several strategies have been considered to improve the efficiency of GaN-based LEDs.

On the one hand, photonic crystals (PhCs) have attracted much attention in the context of light extraction,[1–4] most recently as outcoupling gratings integrated to GaN LEDs.[5–8] However, all current studies focus on GaN-on-sapphire LEDs, where the photonic crystals are formed on top of the GaN epitaxial layer, and where it is best to separate the contact and PhC regions. Therefore, this approach is challenging for high-power LEDs which need broad injection areas.

On the other hand, efficient high-power LED structures have been demonstrated using wafer bonding to a new substrate.[9] Such structures combine high injection areas with efficient thermal dissipation. Sapphire substrate removal by laser lift-off[10] (LLO) promises even higher efficiencies, as it enables supplemental schemes to increase light extraction, such as surface roughening[11] or microcavity effects.[12]

In this Letter, we combine both approaches and report on the first laser lift-off GaN LEDs with photonic-crystal-assisted light extraction. LEDs with various thicknesses are fabricated and characterized by angle-resolved angular spectroscopy, evidencing different photonic regimes. Metal absorption appears to strongly limit the efficiency of the fabricated devices. We then explore theoretically how this limitation can be solved by appropriate structure design.

To fabricate the PhC-LLO LEDs, we use the same process as in Ref. 12. The epitaxial layer, grown on a sapphire substrate, consists of a 2-μm-thick GaN buffer, a 2-μm-thick *n*-doped GaN layer, five InGaN quantum wells (QWs) with emission wavelength of $\lambda \sim 430$ nm, and a 300- nm-thick *p*-GaN layer. A $RuO_2/Ni/Ag$ electrode surrounded by a 200-nm-thick SiO_2 layer is formed on the top of the *p*-type GaN, the current injection area being defined by the SiO_2 region. The sample is then covered with Au, flipped and bonded onto an AlN ceramic substrate. The sapphire substrate is removed by LLO. The GaN layer is then thinned down by Cl_2-based reactive ion etching (RIE), flattened by chemical-mechanical polishing, and another RIE etch is used to define mesas. Thanks to a nonuniform polishing, several mesa thicknesses could be obtained on the same sample, ranging from 1 μm to 400 nm. PhC patterns are then formed by electron-beam lithography on top of some mesas, and etched by RIE, using a SiO_2 hard mask, to a depth of ~250 nm. The PhCs have a triangular lattice with a lattice constant of 215 nm, close to the second Bragg order, and filling factor of 0.38. Figure 1 sketches the structure of the samples, and shows images of a device and of the PhC.

Due to accidental damage induced by the PhC formation process, the LEDs (both those with and without PhC patterning) were partially shorted and had a strong leakage current and poor *I-V* characteristics. They are therefore not representative of the high theoretical potential of such structures. However, angle-resolved electroluminescence spectroscopy[7] clearly reveals their relevant properties.

Figure 2 shows angle-resolved spectra obtained on two devices of different thicknesses (ΓM direction, TE polarization). The spectra display the direct emission of the LED, together with diffraction of the guided modes by the PhC (those are barely visible on the raw spectrum of the second device). In order to determine the thicknesses of the devices, the intensity I is normalized by the intrinsic emission line shape of the QWs $L(\lambda)$, and by its theoretical angular depen-

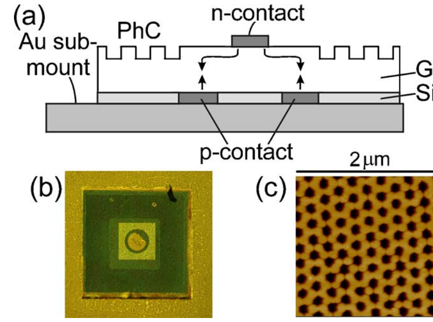

FIG. 1. (Color online) (a) Sketch of the devices. The arrows represent current flow (with current spreading in the *n*-GaN region). (b) Microscope image of a device (c). Atomic force microscope image of a PhC region.

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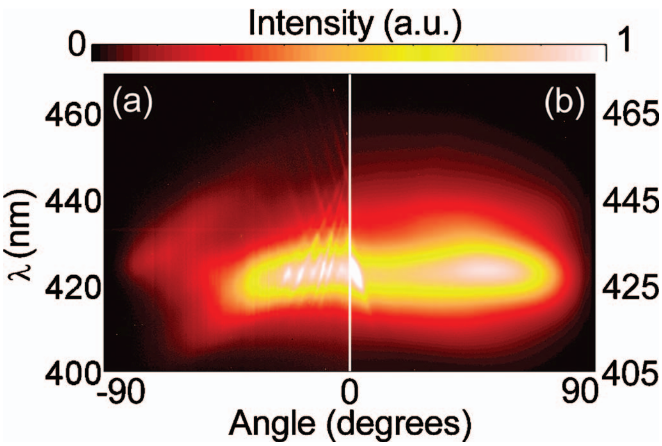

FIG. 2. (Color) Angle-resolved spectra of two devices: (a) device 1, ~1000 nm thick and (b) device 2, ~400 nm thick. There is a slight shift in wavelength between both devices.

dence: $I(\lambda,\theta) \sim L(\lambda)F(\theta)\cos(\theta)$, where F is the Fresnel transmission coefficient and the cos term a correction to the solid angle dependence. The Fabry-Pérot fringes of the direct emission—corresponding to the GaN cavity between metal and air—are thus restored, and can be fitted [taking into account the index dispersion $n(\lambda)$ of GaN][13] in order to obtain the thickness of each device. For the devices of Fig. 2, ~1000 and ~400 nm are obtained, respectively. Device 2 is hence clearly in the microcavity regime.[12]

Figure 3 shows the experimental band structure of both devices. The band structures are obtained from the angular spectra by the same method as in Refs. 7 and 8—here however, direct emission from the LED cannot be easily subtracted so that Fabry-Pérot fringes appear in addition to the photonic bands. The photonic bands are not very intense with respect to the direct emission of the LED; this is probably due to absorption of the guided modes in the metallic layers before they reach the PhC. The number of guided modes supported in the structure increases with the GaN layer thickness. Accordingly, numerous diffraction bands can be observed on device 1, while only a few are visible on device 2. Moreover, as the device gets thinner, the Bloch modes are expected to become more lossy, because of both stronger PhC diffraction and metal absorption. Indeed, the full width at half maximum of the fundamental mode of device 1 is 2.3 nm, and that of device 2 is 5 nm (at a normalized frequency $a/\lambda=0.47$), corresponding to exponential decay lengths of ~10 and ~5 μm, respectively. This should be compared with the extraction length of shallow GaN-on-sapphire PhCs, on the order of 50–100 μm:[7,8] LLO-PhC LEDs offer stronger interaction with guided modes, and could thus constitute more compact and brighter light sources. In addition to these trends, strong variations in the intensity along a given PhC band are visible, especially for device 2.

The theoretical band structures of both devices, obtained by full three-dimensional spectral modeling, are superimposed on the measured band structures. Most of the features of the spectra are well reproduced by modeling.[14] The nonobservation of some calculated bands of low effective index may be due to the bad coupling of incoming guided modes with Bloch modes which penetrate the PhC (for clarity, these nonobserved bands of low effective index are not plotted). Modeling confirms that device 1 supports approximately six

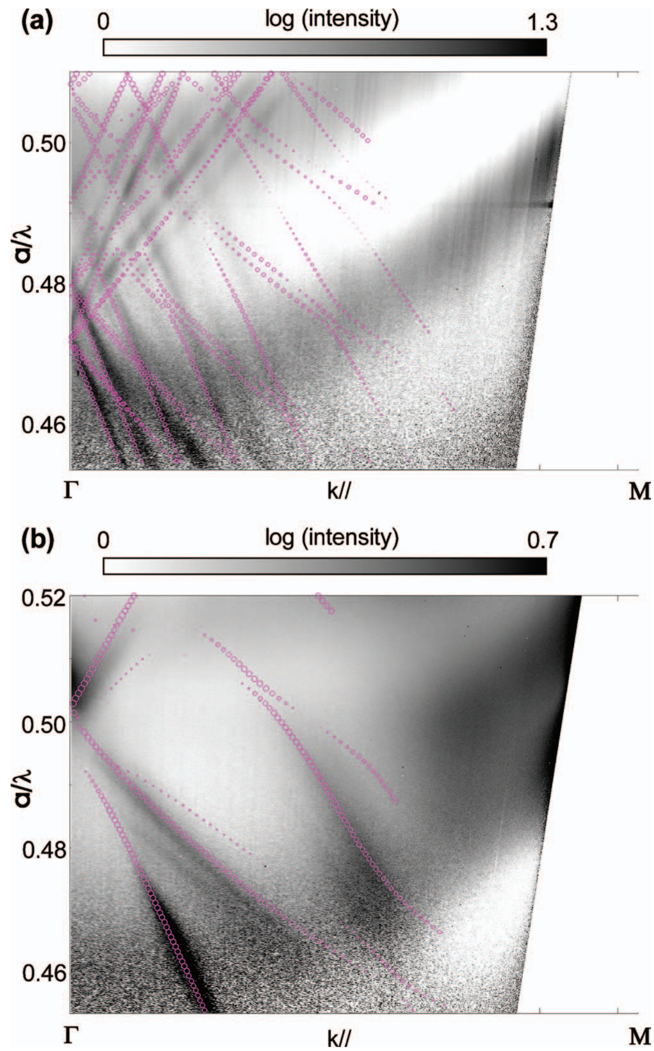

FIG. 3. (Color) Band structures corresponding to the spectra of Fig. 2: (a) device 1 and (b) device 2. Calculated band structures are superimposed (the radius of the points being proportional to the ratio of power emitted to air).

guided modes, whose dispersion is still quite close to that of free photons because the PhC grating only has a perturbative effect on dispersion. Device 2 supports approximately two modes, whose dispersion is more strongly affected as the PhC is etched deeply and leaves little unetched GaN. The photonic behavior of this last device, combining strong PhC and microcavity effects, differs significantly from that of GaN-on-sapphire structures which support dozens of modes, thus hindering optimization of optical properties.[7]

Because of the presence of a gold layer under the GaN, absorption of guided modes along their propagation is expected: this absorption competes with extraction to air. In Fig. 3, the radius of the calculated points of the band structure is proportional to the ratio $\eta = P_{air}/P_{in}$, where P_{air} is the power flow radiated to air and P_{in} the incoming power flow of a Bloch mode. At some frequencies this ratio is seen to become weak: most of the guided power is then lost to the gold layer (or partially reflected back, close to the band gaps). The oscillations in intensity of the computed bands are in good agreement with the variations observed experimentally. Modeling also reveals the existence of several bands which are not observed at all, due to their low value of η.

Thus, it appears that loss in the metal carries away a large fraction of guided light. This is also evidenced by direct

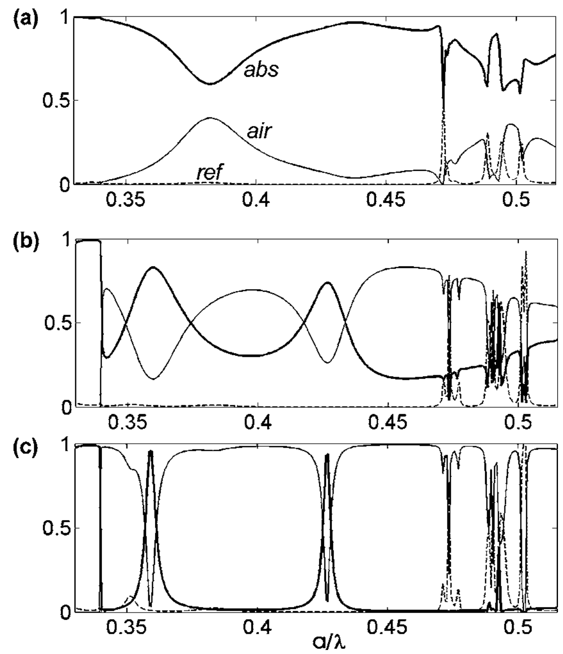

FIG. 4. Power flows of the fundamental Bloch mode. Thin: P_{air}/P_{in}; thick: P_{abs}/P_{in}; Dashed: P_{ref}/P_{in} (P_{in}, incoming power of the Bloch mode; P_{air}, power radiated to air; P_{abs}, power absorbed in the mirror; and P_{ref}, power reflected backwards). (a), (b), and (c), respectively, correspond to the following structures: thin SiO_2 layer, thick SiO_2 layer, and thick SiO_2 layer and Ag mirror. For $a/\lambda < 0.34$ the mode is under the light cone and $P_{air}=0$. For $a/\lambda \sim 0.48-0.5$ the mode reaches the edge of the Brillouin zone and undergoes minigaps and anticrossing with other modes.

observation of the LEDs: under injection, the PhC region is quite dim. No measurement of the light extraction enhancement was attempted in view of the poor *I-V* characteristic of the LEDs, which would make comparison between patterned and unpatterned devices unreliable. However, it is quite clear that metal absorption is a major issue for such devices.

To explore how better design could solve this limitation, we now consider several model structures: (a) A structure made of a Au mirror, a thin (20 nm) SiO_2 layer, and a 600 -nm-thick GaN layer etched halfway by a PhC (triangular lattice, filling factor of 0.3, lattice constant of 200 nm); (b) same as (a) but with 200 nm of SiO_2; and (c) same as (b) but with a Ag mirror. For each structure, we compute the ratio η for the lowest-order Bloch mode in the ΓM direction as a function of frequency (Fig. 4). For structure (a), the loss in the mirror is very strong at all frequencies, because the thin SiO_2 layer does not isolate the Bloch mode, which penetrates strongly in the Au layer.[15] For structure (b), direct loss in the mirror is limited by the thicker SiO_2 layer. η oscillates due to vertical interferences of the radiated component of the Bloch mode: these oscillations are comparable to those we observed in Ref. 7 for a GaN-on-sapphire PhC. However, the loss remains rather high. For structure (c), loss is very small, thanks to the better reflective properties of silver: apart from some sharp absorption dips, η exceeds 90%. The fabricated LEDs are in the regime of structure (b), where a significant fraction of the guided power is still lost in the metal.

Therefore, radiative loss in the lower mirror could be efficiently quenched by using a better mirror, and designing the photonic bands so that most of the bands have a high η in a wide enough frequency range. Such LLO-PhC LEDs could then provide a suitable alternative to other high-power, high brightness nitride-based LEDs. They could also offer a much better control on the directionality and far-field pattern, as fine tuning of the microcavity effect and of the photonic bands can favor emission at any desired angle,[16] especially in the case of thin GaN layers. Finally, LLO-PhC LEDs present an additional advantage over usual microcavity LEDs: their efficiency is not critically dependent on the GaN thickness, because light is extracted either through direct emission or by guided mode diffraction.

In conclusion, we fabricated and characterized lift-off and thinned down GaN LEDs incorporating photonic crystals. Angle-resolved measurements lead to the band structure of the photonic crystals, and reveal different photonic regimes with varying cavity thicknesses. Photonic effects are strongest in the thinnest devices, and could lead to much stronger extraction rates than for conventional GaN-on-sapphire LEDs. Metal absorption strongly limits the efficiency of the current devices which are far from optimal, but appropriate and careful design may solve this issue. This could lead to promising LEDs, offering high efficiency and brightness together with unusual directionality properties.

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[14]We use a spectral method where the field is decomposed on a plane-wave basis in the horizontal direction, and by finite differences in the vertical direction.
[15]More precisely, the main harmonic of the Bloch mode leaks through the SiO_2 into the Au layer, leading to strong loss at all frequencies.
[16]This should be compared with "usual" PhCs in strongly multimode GaN waveguides, which only provide directionality toward the vertical direction.