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GaN light-emitting diodes with Archimedean lattice photonic crystals

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We study GaN-based light emitting diodes incorporating an omnidirectional photonic crystal with Archimedean lattice. Photonic bands are observed over several Brillouin zones, revealing reciprocal space symmetries and evidencing the omnidirectionality of the photonic crystal. Intensities of the diffracted bands are found to agree with the Fourier transform of the crystal lattice, and confirm its Archimedean nature. © 2006 American Institute of Physics. [DOI: 10.1063/1.2168673]

Photonic crystals (PhCs) have been repeatedly considered as potential candidates for light extraction from light-emitting diodes (LEDs), as they could extract the emitted light otherwise trapped inside the semiconductor due to its index contrast with air.1–4 Recently, PhCs were used as out-coupling gratings in GaN-based LEDs, operating at blue and UV wavelengths.5–10 While some enhancements in light extractions was obtained by basic lattices, the huge parameter space of PhCs is far from being explored and could lead to highly efficient light-extracting structures.

Among other desirable properties, a PhC outcoupler should be omnidirectional; that is, be able to diffract guided light incoming at any azimuthal angle. In typical second-order gratings (with a lattice constant \( a \approx \lambda/n \), where \( \lambda \) is the wavelength and \( n \) the index of the material), diffraction is due to the nearest neighbors of the reciprocal lattice (RL), and this property cannot be fulfilled: even with a triangular lattice, the number of nearest neighbors in the RL is only 6. As the extraction occurs over an angular range \( \pm \pi/n_{\text{eff}} \) around each of these points, only 80% of all azimuthal angles are addressed in the case of GaN where \( n_{\text{eff}} \approx 2.4 \).11 High-order gratings (\( a \ll \lambda/n \)) have the opposite property because many points of the RL lay in the air cone, whatever the direction of the mode. However, they generally present two drawbacks: the extraction length scales as \( a \) so that an extended PhC is needed to extract all light, decreasing the brightness; and the number of reciprocal points in the substrate cone grows faster than in the air cone, so that more light is diffracted in the substrate.

On the other hand, omnidirectionality has also been sought as a desirable property for other PhC applications, especially as concerns band gaps. A number of alternative crystal lattices have been suggested, essentially to obtain band gaps of similar magnitude in all directions: Archimedean tilings,12 Penrose lattices,13–15 or other quasicrystals.16–19 It is expected that such isotropic behaviors can be transposed to light-diffracting PhCs. In this letter, following the suggestion of Ref. 20, we study the use of A7-type Archimedean tilings in GaN-based LEDs.

The epitaxial structure used for LEDs fabrication is as follows: a 3 \( \mu \)m thick GaN buffer, a 800 nm thick Al0.1Ga0.9N layer, and a 600 nm thick GaN cap layer with a multi-quantum-well region emitting at \( \lambda \approx 450 \) nm embedded at its center. LEDs are formed on the material, with a p-contact injection area of 100 by 100 \( \mu \)m. The AlGaN layer acts as a lower-index cladding layer, so that the GaN cap layer on top of it forms a monomode waveguide. Its presence is expected to increase the efficiency of the PhC grating.10

A7 patterns are then formed on top of some LEDs by electron-beam lithography, and transferred to the GaN by reactive ion etching using a SiO2 hard mask, with a depth \( \approx 250 \) nm. Figure 1 presents an atomic force microscope (AFM) image of the A7 pattern and displays the corresponding Fourier coefficients of the dielectric map \( \varepsilon(\mathbf{G}) \) (which gives the coupling strength between two RL points separated by a reciprocal vector \( \mathbf{G} \)). An A7 is actually a triangular lattice with a more complex basis made of 7 “atoms” (holes here) per unit cell, all holes being separated by a distance \( a \). LEDs were fabricated, incorporating PhCs with \( a=190, 200 \), and 215 nm. The crystal lattice is \( b=a(1+\sqrt{3}) \); this is indeed a high-order crystal, where the second to seventh-nearest RL neighbors cause diffraction to air. However, due to the complex basis of the A7, a few of these RL points have the largest “photonic strength” [the largest \( \varepsilon(\mathbf{G}) \) value], while other RL points carry little strength. Thus, the two drawbacks usually associated with high-order lattices are circumvented: the RL points responsible for diffraction to air are strong, inducing a short extraction length, while the other points are weak, diffracting little power to the substrate.

![AFM image of an A7 PhC](https://example.com/afm_image.png)

![Fourier transform of the dielectric map](https://example.com/ft_image.png)

FIG. 1. (a) AFM image of an A7 PhC (full white line: unit cell of the crystal). (b) Fourier transform of the dielectric map \( \varepsilon(G) \) (in arbitrary units) for a filling factor \( f=0.3 \). The RL points are indexed by their distance from the center.

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In order to characterize the band structure of the PhCs, the LEDs’ emission patterns \( I(\lambda, \theta) \) were measured by angle-resolved electroluminescence, as in Refs. 9 and 10. The angular spectra were then converted to band structures after normalization of the wavelength and angle dependence as in Ref. 9 [and using \( k_0 = \frac{2\pi \sin(\theta)}{\lambda} \)]. In the band diagrams, the direct emission from the radiative modes of the LED and the photonic bands diffracted by the PhC are superimposed. Figures 2 and 3, respectively, show an original angular spectrum and band structures of LEDs measured with various periods, polarizations, and crystal directions.

The basic features of the band structure are comparable to those of Refs. 9 and 10: the GaN waveguide is strongly multimode, and each mode is folded by periodicity, giving rise to photonic bands that can be measured when they are above the light line of air. As we are observing the band structure at high frequency, the guided modes give rise to photonic bands that can be measured when they are multimode, and each mode is folded by periodicity, giving rise to photonic bands that can be measured when they are above the light line of air. We are observing the band structure at high frequency, the guided modes give rise to photonic bands that can be measured when they are above the light line of air. As we are observing the band structure at high frequency, the guided modes give rise to photonic bands that can be measured when they are above the light line of air.

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served through the intensities of the diffracted photonic
the Brillouin zones are well verified experimentally. More-
over several Brillouin zones, and the symmetry properties of
the atoms of the unit cell redistribute most photonic strength
to these RL points. In Fig. 3, the RL points responsible for
diffraction are indicated for each of the calculated bands.
Quite clearly, the expected trend is observed: the bands cor-
responding to the fourth-nearest neighbors are the most in-
tense in the measured spectra, while some bands (bands 2
and 7) are not visible. An additional proof is brought by the
overall light extraction enhancement due to the PhC. We use
the same method as in Ref. 10, where the light extraction
enhancement due to an LED with second-order triangular
lattice PhC (fabricated simultaneously on the same sample)
was estimated to be $\sim 70\%$—in a numerical aperture 0.5 and
at a direct current of 10 mA. With the Archimedean lattice, the
enhancement is $\sim 50\%$. The two values are of the same
order of magnitude, which indicates that the photonic
strength is similar for the nearest neighbors in the triangular
lattice, and the fourth-nearest neighbors in the A7 lattice.

From these elements, the collective coherent behavior of
the atoms of the unit cell is quite clear: this constitutes a
direct observation of the Archimedean nature of the lattice.
The total extraction enhancement measured on the A7
sample is slightly lower than that obtained with the second-
order PhC with a triangular lattice. A possible reason for this
is the small numerical aperture of our power collection setup,
which does not collect the modes diffracted at glancing
angles—those are numerous for A7 lattices, according to the
angular measurements. Another reason is the lack of optimi-
zedation of the PhC parameters, which is a challenging task
here due to the multiple photonic bands. Further optimization
is clearly required, and preliminary theoretical results
suggest that a distributed Bragg reflector should be inserted
in the epitaxial structure in order to quench the remaining
diffraction in the substrate by fourth-nearest neighbors of
the RL.

In summary, we have fabricated and studied GaN-based
LEDs with Archimedean lattice light-diffracting photonic
crystal. Measurements confirm that diffraction occurs
over several Brillouin zones, and the symmetry properties of
the Brillouin zones are well verified experimentally. More-
over, direct proof of the Archimedean lattice behavior is ob-
served through the intensities of the diffracted photonic
bands. This approach brings complementary information to
most experimental studies of nonconventional crystal lattices
which focus on the band gap properties and are somehow
indirect. While high-efficiency devices still call for thorough
optimization, the present observations are encouraging as re-
gards the future use of Archimedean lattices for light-
diffracting PhCs.

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