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Transmission measurement of the photonic band gap of GaN photonic crystal slabs

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A high-contrast-ratio (30 dB) photonic band gap in the near-infrared transmission of hole-type GaN two-dimensional photonic crystals (PhCs) is reported. These crystals are deeply etched in a 650 nm thick GaN layer grown on sapphire. A comparison of the measured spectrum with finite difference time domain simulations gives quantitative agreement for the dielectric band and qualitative agreement for the air band. The particular behavior of the air band arises from the relatively low index contrast between the GaN layer and the sapphire substrate. Our results call for extension of the operation of GaN PhCs to the visible range. © *2008 American Institute of Physics*.
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Because of their special and applicable properties, photonic crystals (PhCs) are expected to play an important role in upcoming photonic applications.[1] The most prominent property is the photonic band gap, a range of wavelengths for which the crystal is opaque. In view of envisioned integration of PhCs into photonic circuits, they are mainly studied as two-dimensional (2D) slabs. Si, InP, and GaAs are the main dielectrics for these slabs, while the wide band gap semiconductor GaN received less attention. Recently, however, PhCs etched into the top layer of blue emitting GaN light emitting diodes started to play an important role in enhancement of light extraction from these devices.[2–4] Further, 2D GaN PhCs were studied with photoluminescence,[5] while very recently GaN PhCs led to a new approach to GaN-based surface-emitting lasers.[6] In spite of this progress, a band gap measured in the transmission of guided modes in a 2D GaN PhC so far has not been reported.

In this letter we present near-infrared transmission measurements on hole-type GaN PhCs, discuss the properties of the observed spectrum, including the photonic band gap, and make a comparison with simulation data.

The material for the PhCs is a 650 nm thick GaN layer grown on a sapphire substrate, giving a slab with sapphire/air cladding. The GaN layer is grown by low-pressure organometallic vapor phase epitaxy. After thermal substrate cleaning about 25 nm GaN is grown at 550 °C. Then, GaN is epitaxially grown at 1100 °C up to the total required thickness. This GaN/sapphire system is rather special in the sense that the refractive index of GaN is relatively low ($n_{\mathrm{GaN}}=2.31$) for a core layer, while the index of sapphire is relatively high for a cladding layer ($n_{\mathrm{sapph}}=1.77$). Consequently, vertical confinement of PhC modes in this system is rather weak. In low-index-contrast systems such as GaAs/AlGaAs and InP/InGaAsP proper guiding of PhC modes is obtained by deep etching of the claddings, yielding distinct and deep band gaps. In another low-index-contrast system of a polymer ($n=1.54$) on Teflon ($n=1.30$) a shallow etched or unetched substrate was used,[7] but this only yielded a weak band gap, which is contrast limited. For the present GaN/sapphire system it is technologically not feasible to also etch the sapphire. A completely GaN-based stack with low index contrast, i.e., a GaN core layer sandwiched between AlGaN cladding layers, requires etching with extremely high aspect ratio, which is technologically beyond reach as well.

The GaN thickness of 650 nm was chosen to accommodate only the lowest mode in the vertical direction for near-infrared wavelengths. Working on this wavelength range relaxes the requirements for dry etching of the GaN, which is a hard-to-etch material, especially in view of the required deep etching of nanometer-scale lateral dimensions.

The PhCs are fabricated with e-beam lithography and dry etching. A 550 nm thick SiN_x layer is grown with chemical vapor deposition on the GaN, to serve as a hard mask. On top of this 500 nm ZEP520A resist is spin coated. The pattern is written with a Leica 5000+ e-beam system. After resist development, the pattern is transferred to the hard mask by reactive-ion etching in a CHF_3/Ar plasma. The final pattern transfer to the GaN is performed by inductively coupled plasma etching, using a Cl_2/N_2 plasma. We optimized this plasma for etching of high quality holes with diameters down to 140 nm,[8] corresponding to an aspect ratio of 3.8. After etching of GaN, a 150 nm thick residual SiN_x layer is left on top of the structure ($n_{\mathrm{SiN}}=1.93$). In the scanning electron micrographs (SEMs) of Fig. 1 impressions are given of etched PhCs, both in cross section and top view, the former being obtained by focused ion beam (FIB) milling. As seen, circular holes, with very smooth and steep sidewalls are obtained.

We use hole-type PhCs with a triangular lattice, with r/a ratio of 0.25. The lattice parameter a is varied between 406 and 764 nm across 13 lithographically tuned[9] PhCs on a chip, to cover the complete band gap with a laser tunable between 1440 and 1630 nm (Santec TSL-210VF). Each of the PhCs, which are oriented for light propagation in the ΓM direction, has two opposite 2.5 μm wide GaN waveguides attached to it, for in- and outcoupling of the laser light, and

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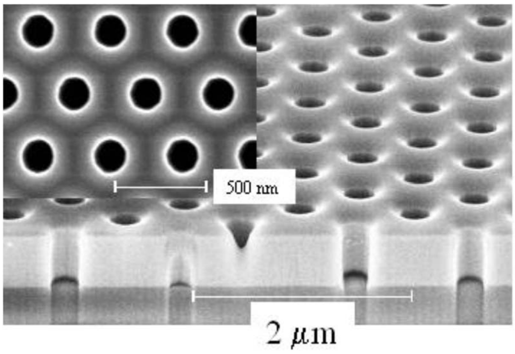

FIG. 1. SEM of a FIB-cut cleave plane, with smooth and close to vertical 240 nm diameter holes. In the cleave plane the transition between light and dark marks the interface between GaN and sapphire. Some holes are cut by the cleave plane at a distance from their axis so that a slight deviation from perfect anisotropy of the etch is reflected in an exaggerated way. Inset: top view of 170 nm diameter hole pattern.

11 rows of holes perpendicular to the direction of light propagation. The chip also includes plain waveguides for reference measurements. The final step is manual cleaving of the chip perpendicular to the waveguides on either side of the PhCs. This yields flat and high quality waveguide facets, which define end-to-end lengths of a few millimeters. The transmission of the PhCs was measured with the end-fire technique, using a setup as described before,[10] the only difference being a wider tuning range of the laser. The polarization of the *E* field of the light is in plane so that TE modes are excited in the PhCs.

Several sets of lithotuned PhCs were measured. A resulting transmission spectrum of one of these sets is logarithmically plotted in Fig. 2. As can be seen, at $a/\lambda=0.25$ the transmission starts with a clear dielectric band, then decreases by three orders of magnitude to reach a bottom around $a/\lambda=0.32$, and finally climbs back to about the original level, thus reaching the air band. This measurement of a region of strongly suppressed transmission (contrast ratio 30 dB) between two regions of high transmission should be interpreted as the observation of the photonic band gap in these GaN PhCs on sapphire. This interpretation is supported by the simulations presented below. The strong signal variations in the spectrum are Fabry–Pérot (FP) fringes arising from cavities delimited by the waveguide facets and the PhC mirrors. Such fringes are common for PhC geometries with highly coherent round tripping waves.[9]

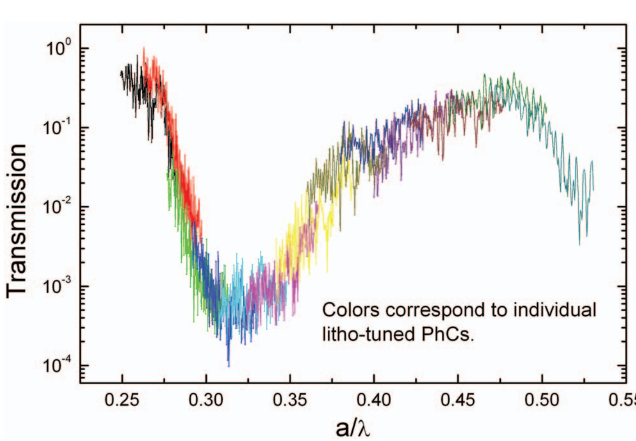

FIG. 2. (Color) Measured transmission spectrum of lithotuned GaN PhC slabs. The spectrum is normalized with respect to the average transmission of three reference waveguides on the same chip.

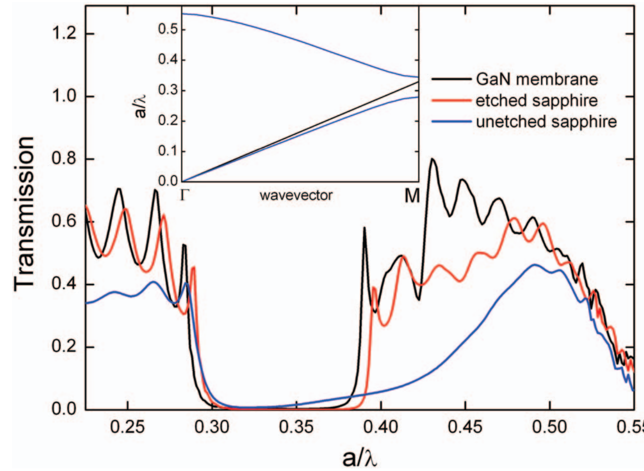

FIG. 3. (Color) 3D FDTD simulations for three types of GaN PhCs, for hole diameter $2r=334$ nm and for GaN thickness=650 nm ($r/a=0.30$). The inset shows the 2D simulated dispersion of the dielectric and air band for unetched sapphire ($r/a=0.25$) in the ΓM direction, and the sapphire light line. To simulate the dispersions an effective index $n=2.14$ was used.

For a more detailed discussion, three dimensional (3D) finite difference time domain (FDTD) simulations are performed. Three types of GaN PhCs are simulated for $r/a=0.30$, viz., a PhC in an air-clad GaN membrane, a PhC deeply etched through into the sapphire substrate, and a PhC with unetched sapphire, as in the experiment. For a general discussion of properties of such interrelated PhCs, irrespective the material system, we refer to Ref. 11. Our simulation results are shown in Fig. 3.

For the membrane case clear bands exist separated by a band gap with steep edges on either side, which are characteristics of a PhC with well guided modes both in the dielectric and the air band. For holes etched into the sapphire, the result is very close to that of the membrane, much in the spirit of our previous remark on etched claddings of low contrast stacks. The situation is completely different when the sapphire cladding is not etched. In that case a dramatic weakening of the air-band edge is seen, accompanied by a seemingly upward shift in frequency and reduced transmission of the air band. Such a change between a membrane or holes etched through into the substrate and an unetched substrate is a characteristic of a low-vertical-index-contrast system.[7] The details of the change in Fig. 3 are determined by the specific system studied here, i.e., 650 nm GaN on sapphire. The simulation for unetched sapphire suggests losses due to leaky air-band modes to the sapphire. This agrees with the position of the air band[12] in the ΓM direction in the vicinity of the *M*-point of the Brillouin-zone boundary (inset of Fig. 3). At the zone boundary the simulated air band is situated above the light line of sapphire. Thus, the modes in the air band will be leaky, resulting in a weaker edge and a weaker transmission of the air band compared to those of the dielectric band. Both features are observed in the experiment, which is more clearly seen when the same data are plotted on a linear scale, as in Fig. 4. Actually, the value of r/a for which the air band coincides with the light line at the zone boundary is about equal to our experimental r/a value of 0.25. Therefore, in experiments the position of the air band with respect to the light line in vicinity of the zone

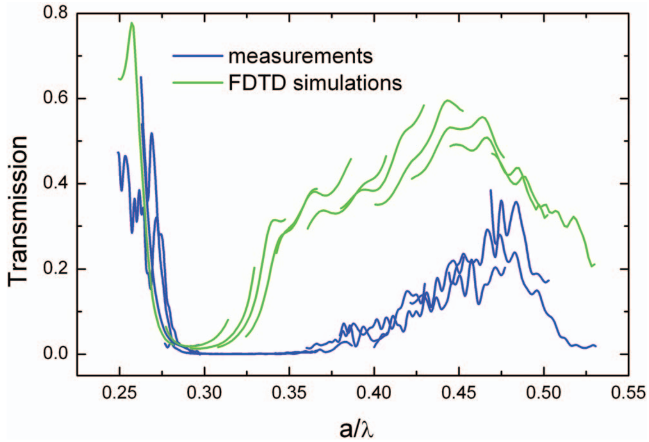

FIG. 4. (Color) Comparison of the Fourier-smoothed measured spectrum with 3D FDTD simulations of the set of PhCs.

boundary depends critically on the r/a value.

After observation of these trends, the measured spectrum is simulated as closely as possible. The whole set of lithotuned PhCs is used as input, simulating for each PhC the same frequency range as in the experiment. A fair comparison requires this since each PhC has its own t/a ratio (t=GaN thickness). In Fig. 4 the experimental spectrum, Fourier smoothed to take out the FP fringes, is compared to the 3D simulations. For the edge of the dielectric band there is excellent quantitative agreement, its position in both curves occurring at $a/\lambda \approx 0.27$. The measured air-band edge is shifted upward and less pronounced compared to the simulated result, while the measured transmission in the air band is about one-third of the simulated value. Thus, indeed the measured spectrum qualitatively fits the trend shown in Fig. 3, which is for fixed a, but some discrepancy with the most detailed simulations of Fig. 4 remains. Actually, the simulation in Fig. 3 for unetched sapphire (r/a=0.30) is closest to the measurement (r/a=0.25). It was verified that such a resemblance with the measurement still occurs when the simulation for r/a=0.30 is performed for lithotuned PhCs, i.e., with changing t/a ratio. We speculate that the remaining discrepancy in Fig. 4 is due to experimental parameters not properly or not taken into account in the simulations, e.g., nonroundness and residual tapering of the holes. Such nonidealities may further suppress the air band.

In summary, we fabricated hole-type 2D GaN PhCs in a 650 nm thick GaN layer on sapphire. The holes of the PhCs are of high quality in terms of verticality and smoothness. These PhCs yield a high-contrast-ratio band gap (30 dB) in the near-infrared transmission. FDTD simulations confirm this observation. The somewhat weak and seemingly blueshifted air-band edge and the reduced transmission in the air band originate from the low contrast properties of the GaN/sapphire system and the PhC parameters used. These results call for extension of the operation of these PhCs to the visible part of the spectrum, to provide for PhC building blocks for various applications, e.g., for monolithic edge-emitting GaN-based PhC lasers or GaN-based chemical sensors.

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