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Observations of band structure and reduced group velocity in epitaxial GaN–sapphire 2D photonic crystals

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ABSTRACT We report experimental results for the band structure of 2-dimensional triangular photonic crystals of air holes in an epitaxial group III–nitride waveguide film. Surface coupling techniques enable the observation of sharp resonance dips in the transmission spectra due to a resonance phenomenon between the incident light and Bloch modes of the photonic crystal. The position of the dips has been measured as a function of angle of incidence and the photonic band structure has been successfully constructed by the measurement. Corresponding Bloch-mode group velocities have also been obtained.

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1 Introduction

Group III–nitride semiconductor epitaxial heterostructures are now widely used in blue LEDs and lasers. In-plane confined or modified optical propagation is often a feature of such device structures, whether as an intrinsically required feature of the design or as an undesired parasitic effect in vertical emission devices. One- or two-dimensional photonic crystal structures etched into appropriate parts of a light emitting device can be used to modify the in-plane propagation of light – leading, for example, to enhanced in-plane feedback or vertical out-coupling – or to combinations of the two, depending on the choice of crystal parameters. We report here new results for the band structure and related properties of photonic crystals realised as two-dimensional triangular lattices of holes etched deeply into an epitaxial III–nitride film. Mapping the band structure of photonic crystals is important because of phenomena such as superprism effects [1, 2] and reduced group velocity [3–5], as well as the modification of emission via photonic bandgap effects. We have previously reported on band structure measurements for a particular GaN:sapphire sample with a two-dimensional photonic crystal hole structure fabricated in it by electron beam lithography and reactive ion etching [6], with strong vertical confinement resulting from the large film-substrate refractive index difference (contrast $\approx 2.35 : 1.7$). Measurements [7] of the photoluminescence properties of such etched photonic crystal structures have shown that the luminescence of the quasi-bulk gallium nitride is not greatly diminished by the damage introduced locally by the fabrication processes used, although there is evidence of peak-position shifting, probably due to strain relaxation in the highly-stressed epitaxial structure.

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2 Experimental

The multi-stage RIE pattern transfer process used to produce relatively deep holes with nearly vertical side walls has been described in some detail elsewhere [6, 8]. The scanning electron micrograph of Fig. 1a shows a typical local region of the etched photonic crystal in a 1.6-μm-thick-GaN epilayer grown on (0001) sapphire. The sample consisted of a number of triangular lattices of holes with different lattice constants (a) and with different air-filling factors (f). We have focused our study on three lattices of holes with the periodicity $a = 1$ μm and with various hole diameters, so that $f = 0.19$, 0.21 and 0.22. The side wall verticality of the holes is quite good, as shown in the height profile obtained by atomic microscopy measurements in resonant mode (Fig. 1b). The hole penetration depth into the epilayer was estimated to be at least 1.1 μm.

We have taken a similar approach for measurements to that of Astratov et al. [3], but have exploited substrate transparency to observe transmission spectra for collimated broad-spectrum light incident on the surface of the 2D photonic crystal over a range of angles with respect to the surface normal, within a Fourier transform infrared spectrometer. Sharp resonances observed in the transmission spectra could be attributed to the Bloch modes launched in the photonic crystal when both the photon energy and in-plane wave-vector matched those of the photonic crystal structure. We were able to determine the position of several different resonances, with selected polarization, by scanning the angle of incidence θ from 0° to 50°, with an accuracy of ±1°. If the sample is defined to lie in the (x,y) plane, rotating the sample around the y axis in 2° steps up to 50° allows the study of the dispersion relation in the k_x direction. The transmission spectra were measured at frequencies ranging from 4000 cm^{-1} to 12 000 cm^{-1} (wavelengths from 2.5 μm to 0.833 μm) for both s- and p-polarized light (s when the electric field is perpendicular to the plane of incidence, p when the electric field is parallel) and the

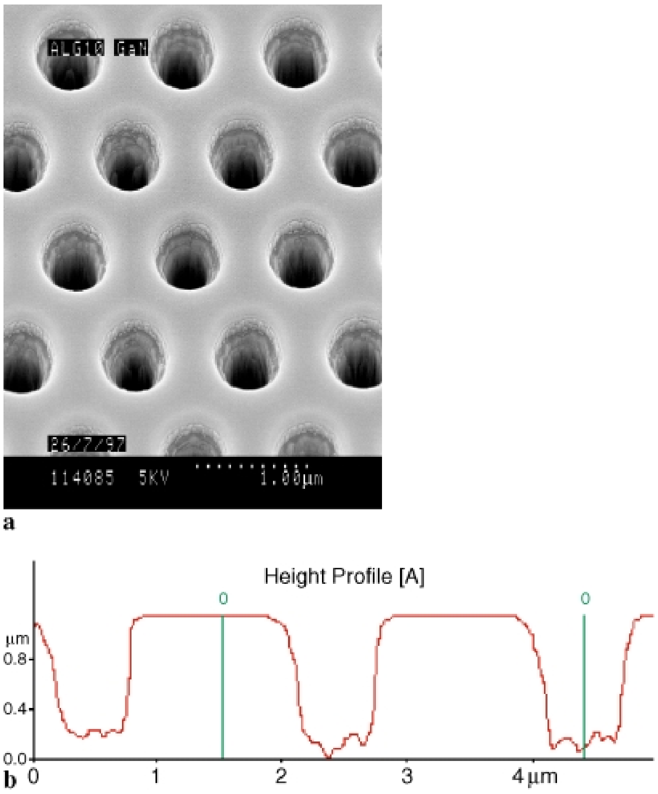

FIGURE 1 **a** Electron microscopy image of a photonic crystal with a triangular arrangement of air holes etched in GaN:sapphire. The holes are 490 nm in diameter and the spacing a between the axes of nearest holes is 1.0 µm, so that $f = 0.22$; **b** AFM scan of a lattice with a periodicity $a = 2$ µm showing the hole penetration depth

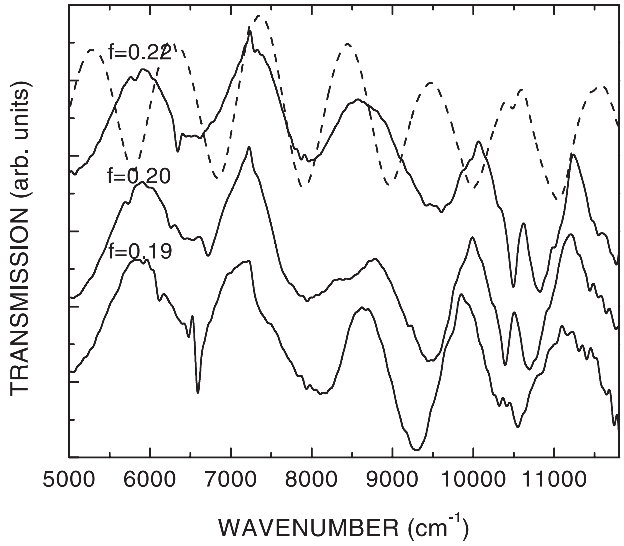

FIGURE 2 Transmission spectra at normal incidence $\theta = 0°$ from an unetched area (*dashed line*); transmission spectrum from the photonic crystals with filling factor of 0.19, 0.21, and 0.22 (*solid lines*)

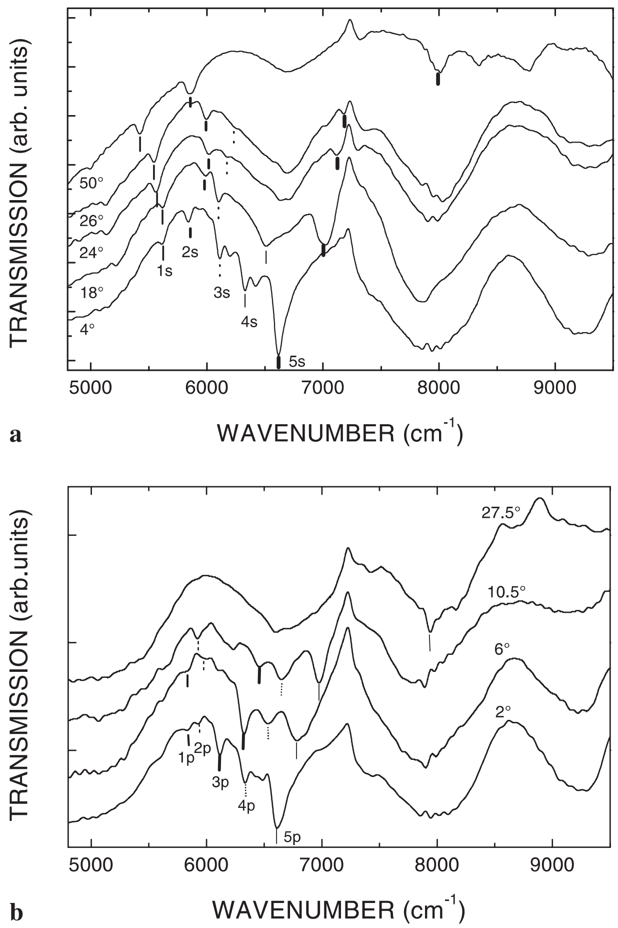

FIGURE 3 Transmission spectra for different angles of incidence θ: **a** for s polarization; and **b** for p polarization from the lattice with $f = 0.19$. Light was incident along the Γ–M direction

Γ–M orientation was chosen for k_x. The extension of the angular measurement range now reported is significant because it goes fully to the edge of the Brillouin zone – which was not achieved in measurements reported previously [6].

3 Results and discussion

Measurements were made over a range of angles of incidence, including normal incidence, i.e. $\theta = 0°$, in photonic crystal regions with all three filling factors and, for comparison, in plain film regions (Fig. 2). This enabled the resonant absorption dips corresponding to the photonic crystal Bloch modes at the zone center to be distinguished from the nearly periodic, broader variations in transmission produced by the plain film alone. With increasing filling factor, the resonance dips shifted to higher energy.

Figure 3a and 3b show the typical results for s- and p-polarized incident light along the Γ–M direction of the reciprocal space for the hole lattice with $f = 0.19$. When θ was increased from zero up to 50°, a remarkable difference between s- and p-polarization behaviour appeared. The modes from different bands were excited either by s- or by p-polarized light and the resonances were found to shift with the angle of incidence.

The experimental results in Fig. 4 represent the spectral position of the resonances plotted as $\omega a/2\pi c$ versus the in-plane wavevector $k_x = k \sin\theta = \omega/c \sin\theta$ for both s and p polarizations. The complex dispersive behaviour is attributable to photonic crystal band structure effects. Figure 4 illustrates the comparison between the experimental dispersion in the 2D photonic crystal etched in a planar waveguide and the theoretical 2D simulation for an infinite photonic crystal obtained

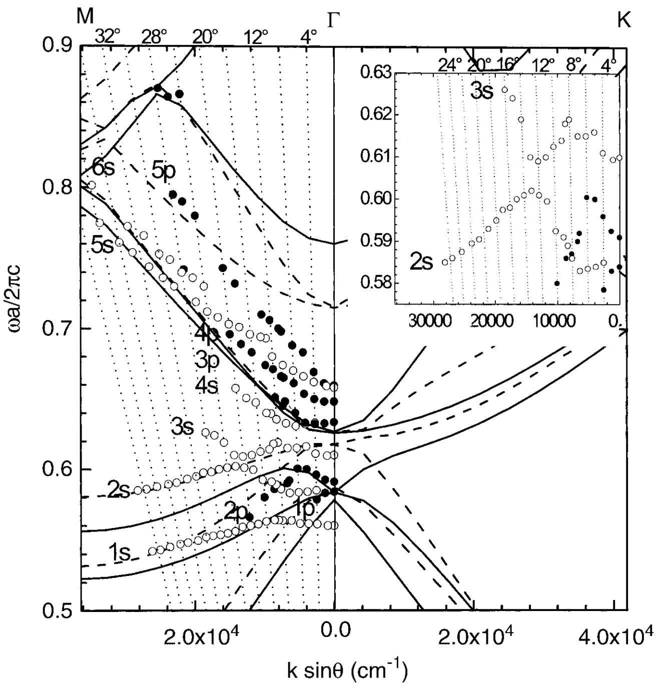

FIGURE 4 The *open* (*full*) *circles* are the measured data for s (p) polarization from the 1-μm-period photonic crystal with an air-filling factor of 0.19. The photonic band structure is calculated for a refractive index of 2.0, for E (*solid line*) and H polarization (*dashed line*). Oblique dotted lines correspond to light incident on the lattice at angles of incidence from 4° to 50° in 2° steps. The *inset* represents an expanded scale near the experimental anticrossing between photonic bands 2s and 3s for s polarization

using the plane wave expansion method, with a basis of 1024 plane waves and a refractive index of 2.0. This 2D calculation provides a useful guidance for the understanding of the complex behaviour of the bands with varying group velocities and demonstrates that the experimental curves result from a photonic band effect. The differences which occur between the experimental and theoretical results can be qualitatively explained. Firstly, the strong vertical confinement introduces additional higher order modes not found in the 2D simulation. Secondly, the dissymmetry due to the presence of the sapphire substrate, ignored in the 2D simulation, gives rise to a mixing between differently polarized modes, which manifests itself by additional increase in degeneracy at the crossing points between bands. Such remarkable features can be observed in the experimental band structure: An anticrossing between the bands labeled 2s and 3s for s polarization occurs away from the zone center at $\theta \approx 20°$ ($k \sin\theta \approx 14\,000\ \mathrm{cm}^{-1}$). The inset in Fig. 4 shows this region on an expanded scale. The width of the anticrossing gap is about 10 meV, leading to a bending of the bands.

In Fig. 5, we show group velocity values obtained using experimental data points to estimate the local slope of the 1s band and of the 2s bent band of Fig. 4. Remembering the enhanced impact of errors in estimating derivatives from experimental data, it is noteworthy that the group velocity data show clear trends with modest levels of scatter. It is also evident that, with estimated group velocity values which go consistently from positive to negative, points of nominally zero energy transport can be identified with precision.

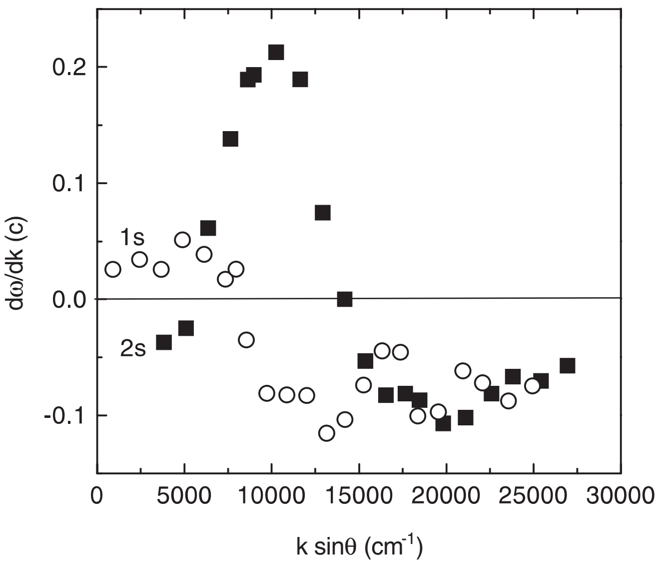

FIGURE 5 Measurements of normalised group velocity in units of the light velocity in vacuum versus $k \sin\theta$ for the bands 1s and 2s of the GaN: sapphire photonic crystal

4 Conclusions

We have demonstrated experimentally a significant part of the band structure characteristics of epitaxial GaN:sapphire photonic crystals and have obtained moderately good agreement with strictly 2D computations based on an effective index approximation. Clearly, full computational characterization requires a properly three-dimensional and vectorial approach. We have also demonstrated that the band structure measurements are sufficiently accurate to give plausible data for the group velocity at values very much less than the material or modal phase velocities. The experimental method used can be extended to cover all in-plane propagation directions and, via prism coupling, to access the band structure below the free-space light line. Such measurements will be useful in the design of both luminescent and passive photonic crystal device structures down to the shortest visible wavelengths, particularly where enhanced and variable delay is of interest.

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