Band Structure Measurements and Calculations of Epitaxially Grown GaN Based Photonic Crystal Slabs with Semipolar Quantum Wells

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We report on the large area realization of GaN photonic crystal slabs with semipolar InGaN quantum wells (QWs) using laser interference lithography and selective area metalorganic vapour phase epitaxy (MOVPE). Directional extraction of guided modes was observed in angle-resolved photoluminescence spectroscopy (ARPL), and the photonic crystal slab dispersion relation was measured. A comparison of the observed band structure to theory was made using the finite difference time domain method (FDTD).

1. Introduction

Currently available GaN based green light emitting diodes (LEDs) and laser diodes (LDs) still suffer from a reduced device performance due to strong internal electrical fields. These fields especially appear in *c*-direction of the hexagonal wurtzite crystal, inducing a tilt in the band structure [1]. A separation of the electron and hole wave functions occurs, leading to a reduced overlap integral and, finally, causing a lowered radiative recombination rate. In contrast, devices grown in semipolar crystal directions reveal a reduced piezoelectric field and hence promise a more efficient way of light generation [2].

Today lots of efforts are made in order to overcome the so-called "green gap", with many groups working on semipolar GaN based optoelectronics. Nevertheless light extraction still plays an important role in device fabrication [3]. Due to high contrast in index of refraction most of the emitted light is typically trapped in the crystal by total internal reflection [3,4]. Only light emitted within a narrow light cone can directly escape into space, whereas most light gives rise to guided modes propagating in the high index dielectric similarly like in a waveguide [4, 5].

Extraction of guided modes can be done by integrating photonic crystals in a dielectric slab. Photonic crystals are periodically modulated dielectric structures with a periodicity comparable to the considered wavelength regime [6]. This periodicity introduces so-called Bloch modes which can be folded into the light cone by a photonic crystal reciprocal lattice vector $\vec{G}$, and thus couple to radiative modes. So-called photonic crystal LEDs [7] and LDs [8] have already been realized providing efficient and directional guided mode extraction without using additional optics [5]. Furthermore beam profile engineering becomes possible [9–12] using theoretical calculations of photonic crystal band structures.

In this work photonic crystal structures have been realized which combine both features, offering a directional light extraction and using semipolar QWs for highly efficient light generation. Far field measurements of extracted Bloch modes have been performed using angle-resolved photoluminescence spectroscopy (ARPL). Subsequently the dispersion relation was determined and a comparison to simulation was made with the finite difference time domain method (FDTD) [13], using the freely available software package MEEP [14].

2. Fabrication Procedure

Realizing photonic crystals for the visible spectrum of light requires sub-µm-patterning. Here laser interference lithography, using a Lloyd's mirror [15–18], and conventional e-beam lithography have been used to structure periodically resist stripe and point structures on GaN templates, grown on sapphire substrates. These structures were subsequently transfered to epitaxial masks using a lift-off technique. Selective area overgrowth in MOVPE was applied to realize three-dimensional GaN-structures with semipolar side facets including InGaN-QWs (see annual report R.A.R. Leute).

3. Optical Characteristics

As described by E. Matioli and C. Weisbuch [19], directional light extraction of a GaN photonic crystal slab can be explained by considering guided modes as a finite sum of plane waves

$$\vec{E}^n(\vec{r}) = \vec{E}_0^n \mathrm{e}^{i\vec{k}_n \cdot \vec{r}}, \tag{1}$$

where each mode has been labeled by its own index n. For planar symmetry, wave vectors $\vec{k}_n$ can be separated into components parallel ($\vec{k}_{\parallel,n}$) and perpendicular ($\vec{k}_{z,n}$) to the waveguide

$$\vec{k}_n = \vec{k}_{\parallel,n} + \vec{k}_{z,n}. \tag{2}$$

The parallel component of a guided mode propagating in a dielectric slab can now be written as

$$k_{\parallel,n} = \frac{2\pi}{\lambda} n_{\mathrm{GaN}} \sin(\theta_n) \tag{3}$$

with propagation angle θ_n and index of refraction n_{GaN} for GaN [7]. Introducing a photonic crystal with reciprocal lattice vector $\vec{G}$, the parallel component of the wavevector can be changed following the equation

$$\vec{k}_{\parallel,m} = \vec{k}_{\parallel} + \vec{G} = \vec{k}_{\parallel} + m\vec{G}_0, \tag{4}$$

with scattered wavevector $\vec{k}_{\parallel,m}$, and new Bloch index m (index n was neglected for simplification) [19, 21]. For a 1D-photonic crystal the fundamental reciprocal lattice vector with lattice constant a can be considered as $G_0 \equiv \left|\vec{G}_0\right| = 2\pi/a$ [7]. The infinite sum of harmonics now introduces one Bloch mode [19, 22] described by

$$\vec{E}(\vec{r}) = \sum_m \vec{E}_m \mathrm{e}^{i(\vec{k}_{\parallel,m} \cdot \vec{r}_{\parallel} + k_z z)}. \tag{5}$$

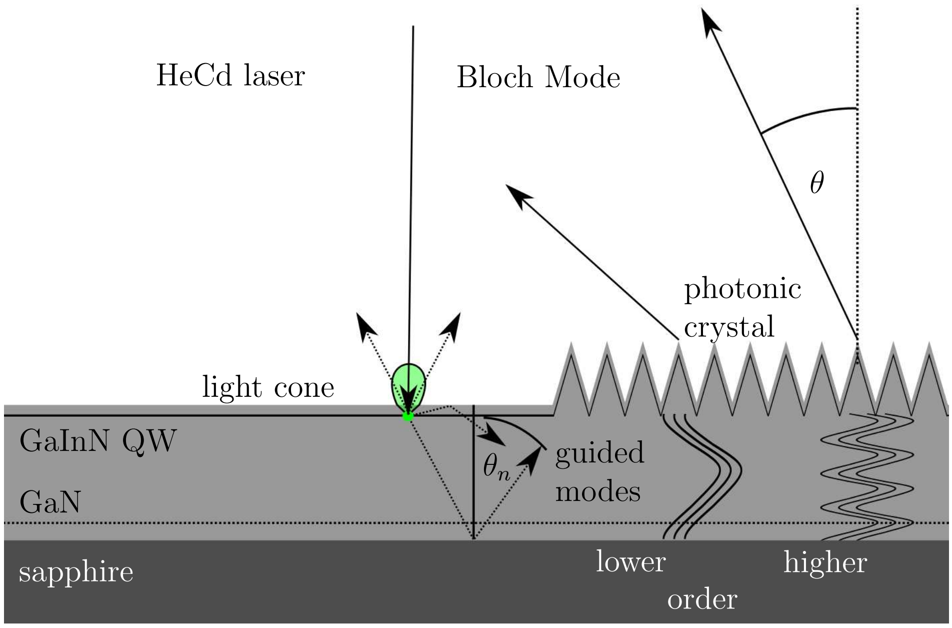

Fig. 1: Extraction of guided modes in a GaN slab by a photonic crystal made of Ga(In)N stripes. Excitation can be arranged by moving the focus point into or out of the structured area for investigation of semipolar or polar QWs, respectively [20, 23].

Bloch modes are periodic in $\vec{G}_0$ (see Eqn. 4 and 5) and by modifying $\vec{k}_\parallel$ total internal reflection can be avoided. Guided modes n with $\left|\vec{k}_{\parallel,m}\right| < k_0$ lie within the light cone and can couple to radiative modes [19]. Propagation and outcoupling of guided modes is schematically indicated in Fig. 1. Extracted guided modes are typically referred to as leaky modes and can be observed in angle-resolved photoluminescence spectroscopy. Excitation of semipolar and polar QWs could be achieved by moving the focus point of the HeCd-laser beam into or out of the structured area, respectively.

First one-dimensional photonic crystal stripe structures with period $a \approx 240\,\mathrm{nm}$ have been investigated. The emission spectrum $I(\lambda)$ for TM modes was spectrally and directionally resolved with varying emission angle θ and presented in a colour map (Fig. 2). At $\lambda \approx 480\,\mathrm{nm}$, semipolar QW emission could be observed, while longer wavelength contributions can be explained by yellow defect luminescence.

In addition, two folded GaN Bloch modes could be observed, corresponding to $m = \pm 1$ reciprocal lattice vectors $\vec{G}_0$, intersecting with each other. Both Bloch modes consist of several lines, each corresponding to a higher order guided mode in the GaN layer (order increases from top to bottom). At the intersection point of higher order guided modes (coming from left) with the QW emission, an increased light extraction was observed, while lower order modes (coming from right) show reduced light extraction. Compared to lower order modes, higher order guided modes in GaN have a higher overlap with the photonic crystal in longitudinal direction (compare Fig. 1 and [19]), hence show an improved light extraction.

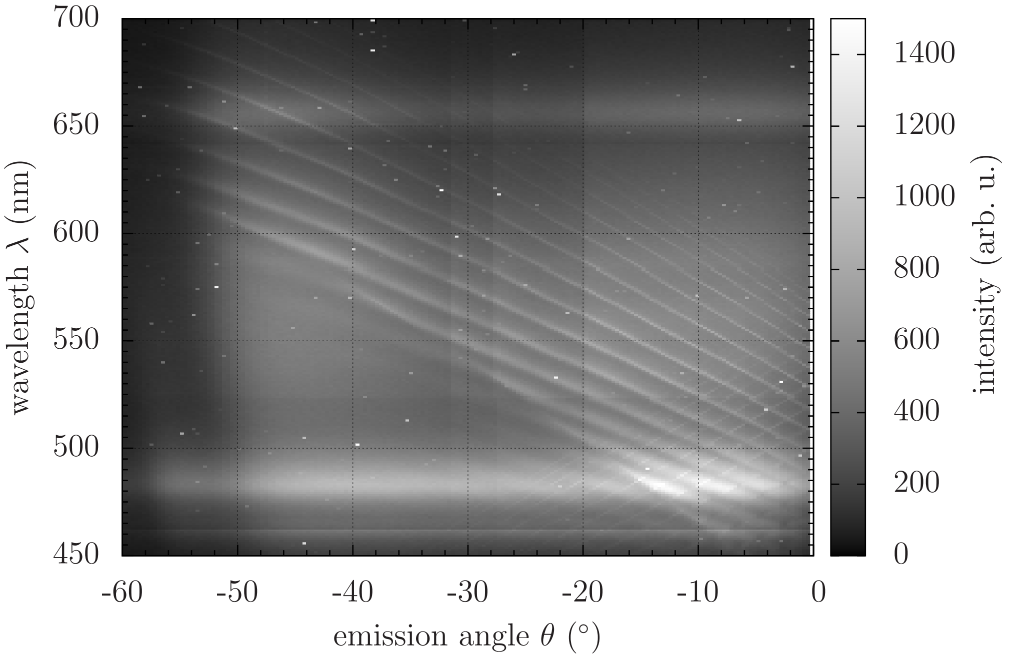

Fig. 2: Angle-resolved photoluminescence spectrum of a Ga(In)N stripe sample for TM modes (polarization set perpendicular to the stripes). Beside QW emission at $\lambda \approx 480\,\text{nm}$, guided mode extraction was observed for the longer wavelength regime, excited by yellow defect luminescence. Both Bloch modes (corresponding to $m = \pm 1$ reciprocal lattice vectors $\vec{G}_0$) intersect in the QW region, showing an improved light extraction.

4. Dispersion Relation of a Photonic Crystal Slab

By performing an axis transformation from (λ, θ) to $\left(\frac{a}{\lambda}, \frac{a}{\lambda}\sin(\theta)\right)$ [20], the dispersion relation of a stripe photonic crystal slab could be derived (Fig. 3). Only the first Brillouin zone was plotted, and both axes are scaled using the photonic crystal period $a = 240\,\text{nm}$ (Fig. 3). Additional lines have been plotted using the corresponding index of refraction for air ($n \approx 1$), GaN ($n \approx 2.45$) and sapphire ($n \approx 1.75$) using the relation

$$n \equiv \frac{k_\parallel}{k_0} = \frac{a\left(\frac{2\pi}{\lambda}\sin(\theta)\right)}{a\frac{2\pi}{\lambda}} \tag{6}$$

and folding them at the zone edges [19].

Bloch modes can only be observed inside the light cone, which is indicated by the light line in Fig. 3, and are limited to the region between the sapphire- and GaN-line. Regarding their slope, observed modes can clearly be correlated to guided modes in GaN. For a more detailed description, we calculated the dispersion relation and photonic band structure using the finite difference time domain [13] and filter diagonalization method [24] for an estimated thickness of the GaN layer of $d \approx 2.5\,\mu\text{m}$. A broad Gauss-pulse was assumed for excitation with center frequency at $\frac{a}{\lambda} = 0.488$ and spectral width $\Delta = 0.3$. Simulated values are indicated in the overlay of Fig. 3 as points, with the field amplitude shown in grayscale. Calculated modes are in very good agreement with experiment, while some

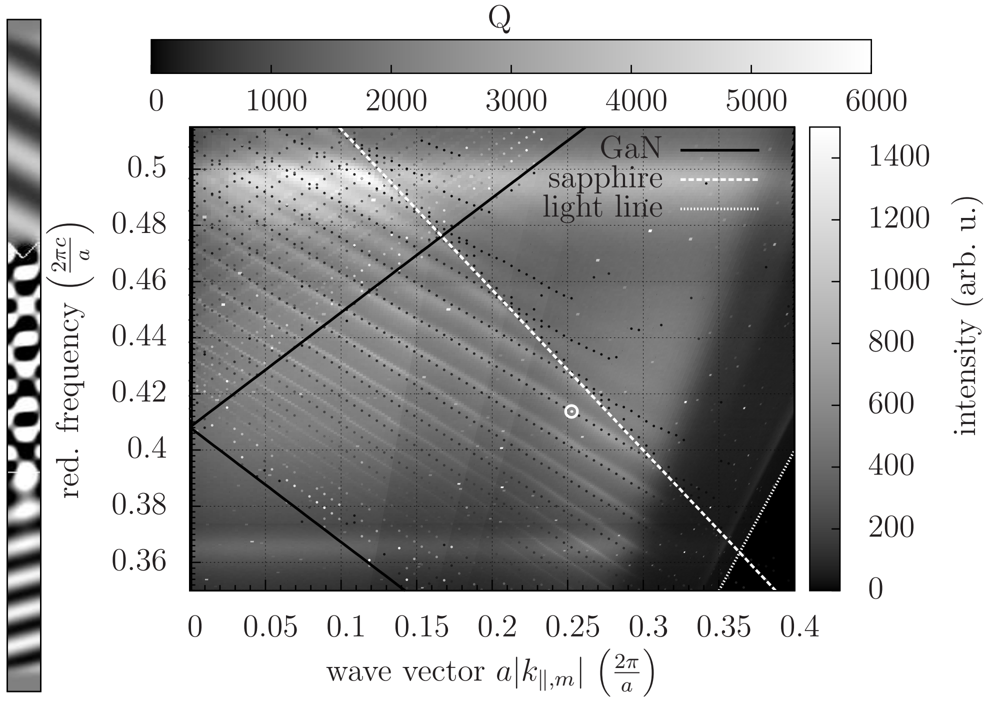

Fig. 3: Measured dispersion relation of a stripe (1D-)photonic crystal slab with corresponding intensity in gray scale (right). FDTD simulation is presented in the overlay with quality factor Q in gray scale (top). Extracted modes were folded into the light cone between GaN and sapphire line. Calculated field distribution for a certain leaky mode in the dispersion relation (white circle) can be seen on the left hand side with indicated unit cell. Observed modes clearly correspond to higher order guided modes in GaN (middle), which radiate to air (top) and sapphire (bottom).

minor discrepancy can be explained by the neglected material dispersion in this model. Calculations of the quality factor show highest Q values for lower order modes, which corresponds to the experimentally observed linewidth. Due to the reduced overlap with the photonic crystal, lower order modes stay longer confined in the crystal. This longer confinement corresponds to a smaller line width observed in the spectrum, because more stripes interfere. The higher order modes are coupled out faster (their extraction length is shorter), what results in broader linewidth of these modes.

Using a pulse with small spectral width and defined $|k_{\parallel,m}|$, corresponding field distributions have been calculated. On the left hand side of Fig. 3, the unit cell for calculation is presented (cross section) with the overlayed field distribution for an arbitrarily chosen frequency and wavevector (see corresponding white circle in dispersion relation). The investigated guided mode is obviously confined into the GaN-layer (middle) and radiates to air (top) and sapphire (bottom) directionally. Its order can be estimated to approximately 14 by counting the number of nodes.

If "forbidden" points above the sapphire and below the GaN-line are chosen, no total internal reflection at the interface GaN/sapphire occurs. Hence no extracted guided modes can be observed in this region.

5. Conclusion

In this work photonic crystal slabs with semipolar QWs have been realized. This approach based on selective area overgrowth allows structuring without using etching methods and could provide very high crystal quality. Directional extraction of Bloch modes could be observed in angle-resolved photoluminescence spectroscopy, as a characteristic feature of photonic crystals. Measurements of the dispersion relation show very good agreement with theoretical calculations done by FDTD method. Similar structures shall be applied in photonic crystal LEDs providing efficient and directional light extraction.

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