Photonic Band Structure Mapping in Mid-Infrared Photodetectors

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A periodic array of holes is etched through the light sensitive region of mid-infrared photodetectors, which therefore forms a two dimensional photonic crystal slab. This enables sensitivity to light coupled in via the surface. Moreover, since the deep etched structure provides a strong coupling between the optical mode and the photonic lattice, the detector response is enhanced whenever the incoming light matches a photonic crystal mode. This effect is visible through distinct peaks of enhancement in the spectral photocurrent. Via an angular dependent characterization it is possible to map the photonic bandstructure by tracing the energetic position of these peaks.

Introduction

Quantum well infrared photodetectors (QWIPs) are photoconductive detectors that rely on intersubband transitions in a heterostructure [1]. By means of band structure engineering the spectral response can be tailored within the mid-infrared (MIR) region and up to the THz regime [2]. Due to intersubband selection rules n-type QWIPs are only sensitive for radiation with the electric field component polarized normal to the detecting layers. To circumvent the standard detecting geometry, which couples the light via a 45° polished facet, a cavity is needed that can couple surface incident light to detectable TM modes. Surface gratings and random corrugations have been extensively studied in the past [3]. Photonic crystals (PhC) in contrast have only been used so far in combination with a quantum dot infrared detector (QDIP) [4]. The three dimensional electron confinement in a quantum dot makes QDIPs sensitive to surface incident light and the PhC was used to increase the quantum efficiency. Recently we presented a combination of a QWIP with a hexagonal PhC structure [5].

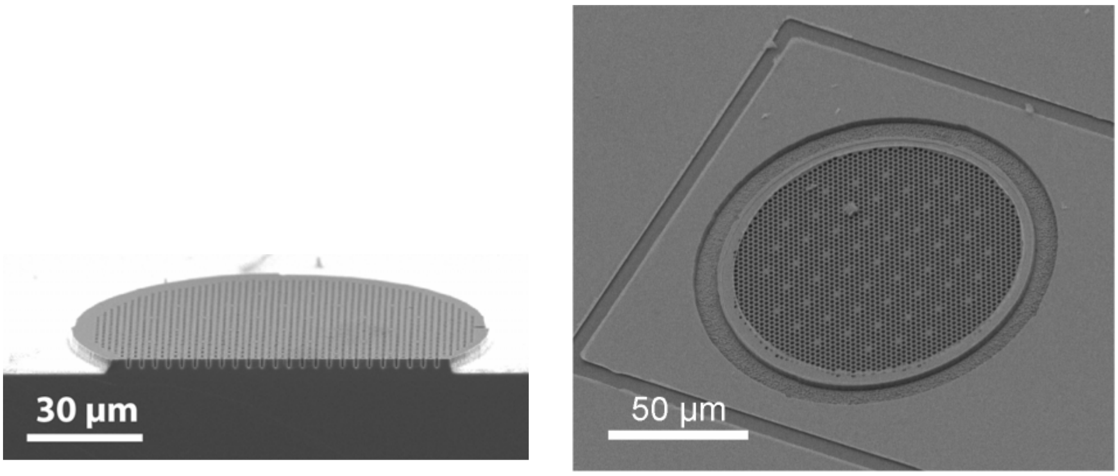
Theory

Aside from the usability as a detector (e.g. one pixel of a focal plane array) it is an ideal test object for slab PhCs. Out of the whole frequency spectrum of an incident beam from a broad band MIR source only a few frequencies are coupled into the waveguide. This happens whenever a pair of in-plane wave vector and frequency matches a mode of the photonic band structure. These modes get absorbed in the quantum wells and contribute to the photocurrent. Each mode can therefore be identified with a peak in the spectral photocurrent. With this method it is possible to map out the whole photonic band structure within the response of the QWIP by simply illuminating at different angles of incidence and crystallographic directions. A similar technique was presented earlier by Astratov *et al.* where resonant features in the reflection from a PhC slab (illuminated in the same geometry) could be related to PhC modes [6].

Experimental

Fabrication

The samples are fabricated in a mix and match processing using direct electron beam lithography for the PhC pattern and standard UV contact lithography to define the insulation openings as well as the extended contact pads for electric connections. After exposure and development of the PMMA resist the pattern is transferred into a SiN_x hard mask and subsequently into the underlying Ge/Au/NiAu contact metal. The deep etching step is performed by reactive ion etching in iCl_4/N_2 [7], which allows to fabricate ~5 µm deep air holes with the required high aspect ratio as well as smoothness of the sidewalls. Figure 1(a) shows a scanning electron picture taken from a cleaved sample directly after the deep etching process. SiN_x insulation and Ti/Au contact pads are finishing the processing (Fig. 1(b)).



(a) (b)

Fig. 1: Scanning electron pictures taken after the deep etching process (a) and of a finished device (b).

Measurements

Band Structure Measurements

The unpolarized light of a glow bar was directed through a fourier-transform infrared spectrometer and either directly aimed on the sample or polarization filtered in order to achieve a σ (TE) or π (TM) incident wave. By tilting the cryostat around its vertical axis it is possible to collect the response spectra at varying angles of incident. The device was mounted so that either the ΓK or the ΓM direction coincided with the rotation axis. Knowing the angle θ_i and the crystallographic direction of the PhC all positions ω_i of the spectral peaks can be assigned to certain points $(\omega_i/c \cdot \sin(\theta_i), \omega_i)$ in the reduced zone scheme, and the band structure can be recorded by this method. The measurement range is limited at the low frequency end by the air light cone and at the high frequency end by the response function of QWIP used for the experiment. Figure 2(b) shows the mapping of the whole data onto the photonic band structure. The band structure was calculated with the plain wave expansion method (PWEM). Considering the uncertainty in determination of the air fill factor and the absence of the vertical waveguide in the PWEM calculation of the band structure we get very good agreement with the experimental data.

Polarization Mixing

Figure 1(a) shows a typical detector response for unpolarized, TM, and TE polarized light. Apart from the peak at ~920 cm^{-1} (which is congruent with the peak responsivity of the QWIP) there are 6 clearly displayed maxima in the spectrum taken without a polarizer. Some of the resonant peaks disappear for a TM like excitation. In Fig. 2(a) all points originating from a measurement with TM polarized light are marked as a + and can be identified as even cavity modes. This effect has been reported earlier for microwaves [8] and can be explained as free space TM wave is naturally even and can therefore not couple to odd TM PhC modes. An excitation under TE polarization in contrast leads to a detector response for the odd modes. This (even) TE to (odd) TM conversion is basically enabled through the PhC lattice and the vertical surface-plasmon waveguide which allows for polarization mixing as there is a sufficient overlap of the in plane electric fields of both polarizations [9].

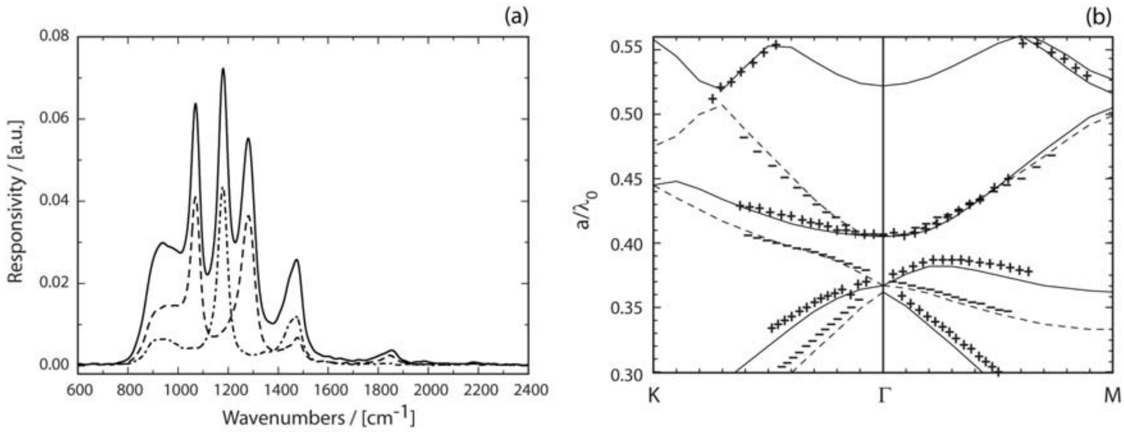


Fig. 2: (a) The response spectra were collected at 50° angle of incident and along ΓM direction. The solid line was measured without a polarizer while the dashed line refers to TM polarized excitation and the chain dotted line refers to TE polarized excitation. (b) Collecting the data points for several angles of incident adds up to the photonic band structure. The underlying lines are a 2D PWEM calculated band structure for TM like modes. The solid lines refer to modes with even symmetry, whereas the dashed lines refer to modes with odd symmetry. The measured data points are marked as + if they originate from TM excitation and are marked as – for TE excitation. Note that TM polarized light couples to even TM modes while TE polarized light couples to odd TM modes

Conclusion

The implementation of a QWIP in a planar PhC cavity makes the sensor capable to detect surface incident radiation. The angular dependence of the response spectra are a direct image of the photonic band structure above the light line and as the measurement principle directly relays on the intracavity absorption of TM polarized photonic crystal modes it represents a very realistic test object for intersubband devices. With this method we performed a polarization dependent band structure mapping which showed a strong polarization mixing for the surface-plasmon waveguide used. The detection for the bands with odd parity is realized via conversion from an incident TE polarized wave to a detectable TM polarized cavity mode.

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