

Photonic Crystal Slabs for Resonant Photodetection in Quantum Wells

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Abstract

We present a photonic crystal slab (PCS) photodetector, designed for resonant absorption of infrared light in quantum wells. With the PCS it is possible to enhance the absorption efficiency by increasing photon lifetime in the detector active region. To design the optical properties of the device we simulate the PCS photonic band structure with the two-dimensional (2D) revised plane wave expansion method. Compared to an ideal 2D photonic crystal, the photonic bands in a PCS exhibit a blue-shift, caused by the finite slab thickness. This effect is modeled by introducing a slab effective refractive index. With this detector design, we are able to extend the usable temperature range by at least 30K compared to a standard quantum well photodetector.

1. Introduction

The properties of photonic crystals (PCs) offer unique ways for the control of light [1]. Most existing devices are realized as two-dimensional (2D) PC structures, as they are compatible to standard semiconductor processing. An important class of 2D-PCs is the photonic crystal slab (PCS), which confines photons in the out-of-plane direction with a dielectric slab wave guide.

We present a PCS photodetector, designed for resonant absorption of infrared light in quantum wells. Quantum well infrared photodetectors (QWIPs) are reliable and sensitive detectors for the mid-infrared region [2]. However, the performance of QWIPs at higher temperatures is limited by thermally generated noise. By using a PCS for resonant in-coupling of the external radiation it is possible to exceed this limitation [3]. Further, a QWIP is insensitive to surface normal incidence light, caused by quantum mechanical selection rules. With a PCS fabricated from QWIP material it is possible to achieve efficient coupling of surface incidence light, increased absorption in the detector active region and improved temperature performance.

2. Fabrication

The QWIPs are grown by molecular beam epitaxy and designed to operate at a wavelength of 8 μm . The active region consists of 26 doped GaAs quantum wells ($N_D = 4 \times 10^{11} \text{ cm}^{-2}$), each with a well width of 4.5 nm separated by 45nm thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barriers. The layer sequence is a GaAs substrate, followed by a 2 μm thick AlGaAs sacrificial layer, a 500-nm thick GaAs bottom contact layer, the 1.4 μm thick active region, and a 100 nm GaAs top contact layer.

From the QWIP material the PCS photodetectors and, for comparison, standard mesa photodetectors are fabricated. The PC structures are defined by laser direct writing followed by anisotropic SiCl_4 reactive ion etching. To create free standing PCSs the sacrificial AlGaAs layer is selectively etched with a 24% HCl solution. A schematic illustration of the finished device is shown in Fig. 1a.

3. Simulation

The optical properties of PCs are represented by the photonic band structure. To simulate the PCS band structure we use the 2D revised plane wave expansion method (RPWEM) [4]. Compared to an ideal 2D-PC, which extends to infinity in the out-of-plane direction, the photonic bands in a PCS exhibit a blue-shift. The modes leak out of the slab into the surrounding air and “feel” a lower refractive index (inset Fig. 1b). To model this effect an effective refractive index of a uniform slab is introduced and entered into the RPWEM algorithm as frequency dependent permittivity. The equations describing the uniform slab wave guide can be solved analytically. To approximate the quantum well heterostructure an average refractive index of $n_s = 3.12$ is used. Fig. 1b shows a simulated photonic band structure of a PCS with lattice constant $a = 3.1 \mu\text{m}$, hole radius $r/a = 0.2$ and slab thickness $d = 2 \mu\text{m}$.

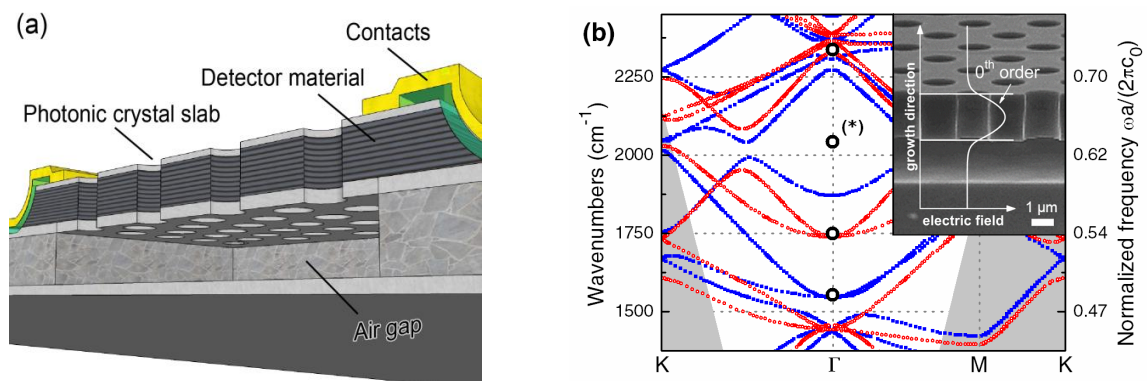


Fig. 1: PCS-QWIP design. (a) Cross section through the PCS-QWIP structure. (b) Photonic band structure of a PCS. The modes have odd (blue squares) or even (open red circles) symmetry. The resonance peaks from Fig. 2a are marked as large open circles. Inset: SEM image of the PCS, overlaid with the slab mode profile.

4. Measurements

The processed PCS-QWIPs are illuminated at surface normal incidence. Standard QWIPs are measured at a 45° angle of illumination as they are insensitive to surface normal incidence light. The photocurrent spectrum of the standard QWIP has one broad absorption peak at 1250 cm^{-1} (Fig. 2a, dashed line). Photons below this frequency do not have sufficient energy to excite electrons from the bound state into the continuum. For photons above this frequency an electronic transition becomes less probable, hence the absorption is reduced. The spectral response of the PCS-QWIP (Fig. 2a, solid line) shows pronounced resonance peaks, which can be explained with the simulated photonic band structure (Fig. 1b) [5]. At surface normal incidence the in-plane wave vector is zero, so the resonances are at the Γ -point of the photonic bands structure. The frequencies of the first and second resonance coincide very well with the simulated TM and TE photonic bands, respectively. The third resonance falls right between the photonic bands, it most likely corresponds to a first order slab mode. In this simulation only the zeroth order slab modes were calculated. All further resonance peaks correspond to higher photonic bands. The fact that some PCS modes are not seen as resonance peaks while others are visible can be explained by symmetry arguments. A pronounced resonance peak is only visible when the PCS mode is in-plane symmetry-matched to an incident wave [6].

The performance of standard QWIPs is usually limited by a thermally generated dark current, as it grows exponentially with temperature. In the PCS-QWIP the photocurrent is resonantly enhanced without creating additional dark current. The increased photon lifetime leads to absorption enhancement in the detector active region. Designing the PCS such, that a resonance coincides with the QWIP absorption peak results in a significantly higher photocurrent and signal-to-noise ratio (Fig. 2b). The standard QWIP signal vanishes in the noise around 140K while the PCS-QWIP resonance peak is still visible at 170K (Fig. 2c).

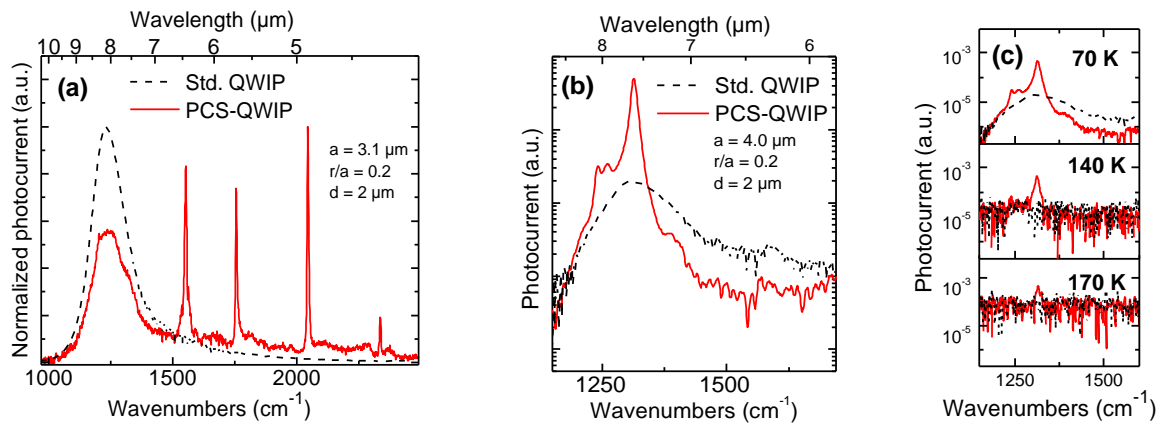


Fig. 2: Photocurrent response of a PCS-QWIP (solid line) and a standard QWIP (dashed line). **(a)** The spectral response of the PCS-QWIP shows pronounced resonance peaks, which correspond to the photonic bands at the Γ -point. **(b)** The PCS is designed to have a resonance at the QWIP peak absorption. At the resonance frequency the photocurrent is 24x enhanced. PC parameters are: lattice constant $a = 4.0 \mu\text{m}$, $r/a = 0.2$ and slab thickness $d = 0.65 a$. **(c)** Temperature dependent photocurrent spectra. At temperatures above 140 K, the standard QWIP signal disappears in the noise, while the PCS-QWIP signal is still visible.

5. Conclusion

In conclusion, we presented a PCS photodetector, designed for resonant absorption of infrared light in quantum wells. The PCS photonic band structure was simulated with the 2D-RPWEM by using a slab effective refractive index. The PCS enhances the absorption efficiency by increasing photon lifetime in the detector active region. With this detector design, we were able to extend the usable temperature range by at least 30K compared to a standard quantum well photodetector.

Future research on this topic will include optimization of the PCS design to further increase resonant absorption enhancement. We envision that this approach will enable improved infrared photodetectors, finally operating at or close to room temperature, for applications including thermal imaging or high speed data transmission.

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