Resonant Absorption Enhancement in Photonic Crystal Slab Quantum Well Photodetectors

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Introduction

Photonic crystals (PCs) are structures with a periodic modulation of the refractive index, which exhibit fascinating properties for the control of light [1]. Most devices are fabricated as two-dimensional (2D) PC structures, as they are compatible to standard semiconductor processing. To confine the light in the out-of-plane direction the PC is often fabricated as a photonic crystal slab (PCS).

Here we present a photodetector, designed as a PCS for resonant absorption of infrared light and fabricated from a quantum well infrared photodetectors (QWIPs). Research on QWIPs has yielded 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].

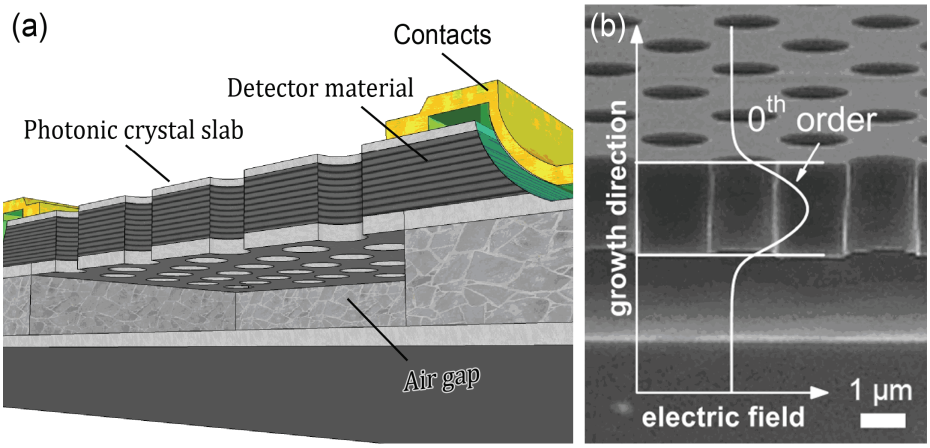

Fig. 1: PCS-QWIP design. (a) Cross section through the PCS-QWIP structure. (b) SEM image of the PCS, overlaid with the slab mode profile.

Experimental

The QWIPs are grown by molecular beam epitaxy and designed to operate at a wavelength of 8 µm. The detailed device structure can be found in [3]. From the QWIP material the PCS photodetectors and, for comparison, standard mesa photodetectors are fabricated. A schematic illustration of the finished device is shown in Fig. 1.

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. 2, 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. 2, solid line) shows pronounced resonance peaks, which correspond to the photonic bands at the Γ-point [4].

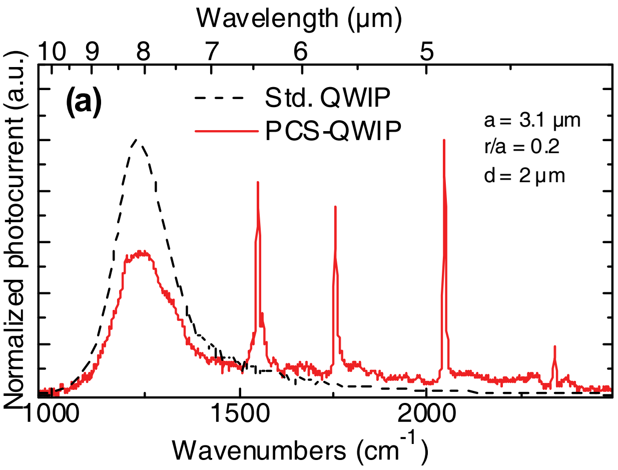

Fig. 2: Photocurrent response of a PCS-QWIP (solid line) and a standard QWIP (dashed line). The spectral response of the PCS-QWIP shows pronounced resonance peaks, which correspond to the photonic bands at the Γ-point.

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) [5], [6]. 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 (Fig. 1 (b)). To model this effect an effective refractive index of a uniform slab is introduced and entered into the RPWEM algorithm as frequency dependent permittivity (Fig. 3 (a)). 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. Figure 3 (b) shows a simulated photonic band structure of a PCS with lattice constant a = 3.1 µm, hole radius r/a = 0.2 and slab thickness d = 2 µm.

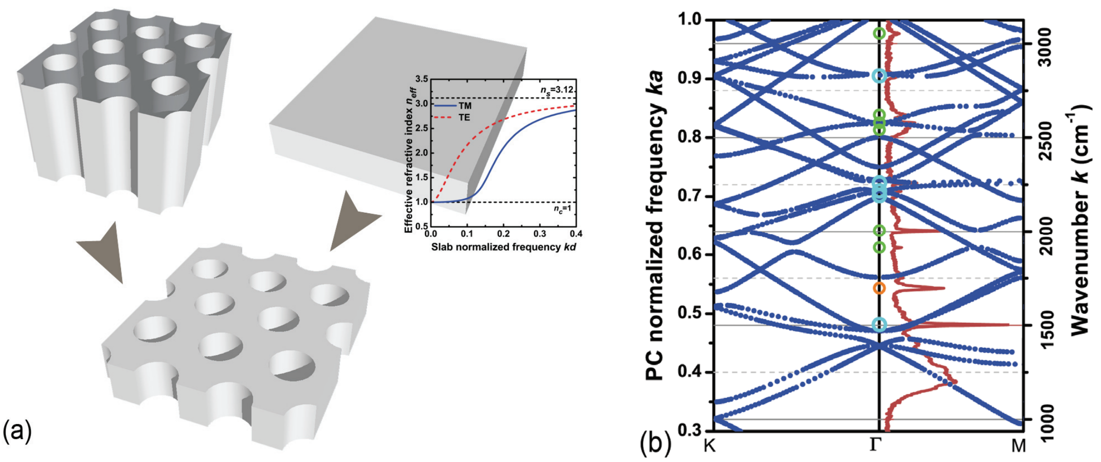

Fig. 3: RPWEM simulation of the PCS band structure. (a) The PCS is treated as a combination of a uniform slab wave guide and an ideal 2D-PC. (b) Comparison of the measured spectrum for surface normal incident light (Γ -Point) and the simulated band structure for TM-like modes. Blue circles indicate peaks that fit with the shown TM-like band structure. The orange circle fits in the not shown band structure for TE-like modes. Green circles correspond to higher order slab modes, as described in [6].

Results

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.

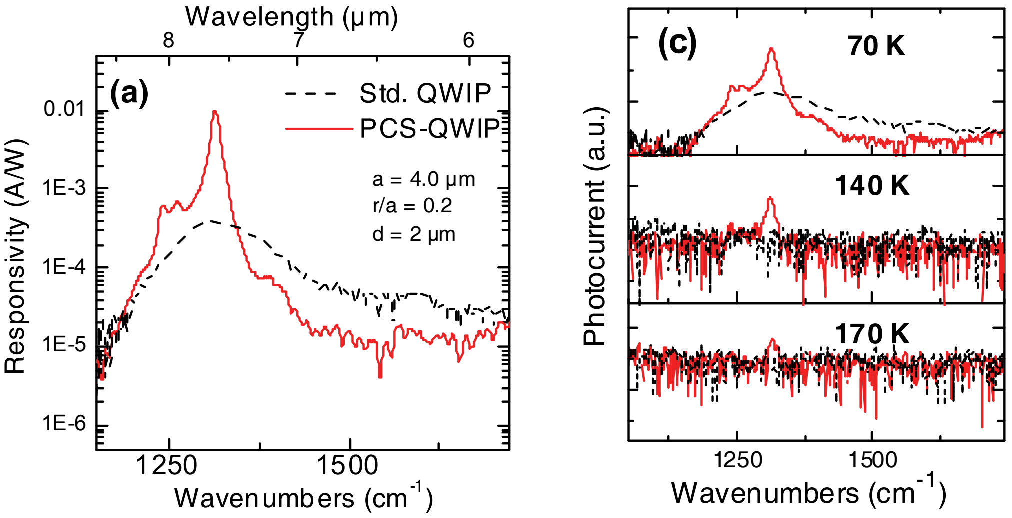

Fig. 4: Resonant absorption enhancement (a) The PCS is designed to have a resonance at the QWIP peak absorption. At the resonance frequency the responsivity is 24x larger compared to the standard QWIP. (c) Temperature dependent photocurrent spectra. At temperatures above 140 K, the standard QWIP signal disappears in the noise, while the PCS-QWIP signal is still visible.

Designing the PCS in a way that a strong resonance coincidences with the QWIP absorption peak results in a significantly higher responsivity and signal-to-noise ratio (Fig. 4 (a)). The standard QWIP signal vanishes in the noise around 140K while the PCS-QWIP resonance peak is still visible at 170K (Fig. 4 (c)).

Further, a standard QWIP is insensitive to surface normal incident light, caused by quantum mechanically forbidden electron transitions. With the PCS it is possible to achieve efficient coupling of surface normal incident light.

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 improve the responsivity up to 24x, 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 with superior detectivity compared to standard QWIPs, for applications including thermal imaging or high speed data transmission.

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References

[1] Y. Kurosaka, S. Iwahashi, Y. Liang, K. Sakai, E. Miyai, W. Kunishi, D. Ohnishi and S. Noda, On-chip beam-steering photonic-crystal lasers, Nature Photonics **4**, 447-450 (2010)

[2] H. Schneider and H. C. Liu, Quantum Well Infrared Photodetectors, Berlin Heidelberg New York, Springer (2007).

[3] S. Kalchmair, H. Detz, G. D. Cole, A. M. Andrews, P. Klang, M. Nobile, R. Gansch, C. Ostermaier, W. Schrenk and G. Strasser, Photonic crystal slab quantum well infrared photodetector, Appl. Phys. Lett. **98**, 011105 (2011).

[4] S. Schartner, S. Golka, C. Pflügl, W. Schrenk, A. M. Andrews, T. Roch, and G. Strasser, Band structure mapping of photonic crystal intersubband detectors, Appl. Phys. Lett. **89**, 151107 (2006).

[5] S. Shi, C. Chen and D.W. Prather, Revised plane wave method for dispersive material and its application to band structure calculations of photonic crystal slabs, Appl. Phys. Lett., vol. **86**, p. 043104 (2005).

[6] R. Gansch, S. Kalchmair, H. Detz, A. M. Andrews, P. Klang, W. Schrenk, and G. Strasser, Direct measurement of higher order slab modes in Photonic Crystal Slab Quantum Well Infrared Photodetectors, submitted to Optic Express.