Si/SiGe Cascade Injector QWIPs for Resonator Enhanced, Voltage Tuneable Two-Band Detection

T. Fromherz, P. Rauter, M. Grydlik and G. Bauer
Institut for Semiconductor and Solid State Physics, University of Linz
Altenbergerstraße 69, A-4040 Linz, Austria

Photocurrent spectroscopy has been performed on doped Si/SiGe valence band cascade injector structures in the mid-infrared spectral region. A large tunability of the photoresponse peak wavelength (from 5.2 µm to 3.2 µm) by an externally applied electric field is observed. The tunability of the photoresponse is a consequence of an electric field induced transfer of holes from the deepest to the shallowest quantum well of the injector sequence. Depending on the bias voltage, dark current limited peak detectivities in excess of $D^* = 1 \times 10^9$ cm $Hz^{0.5}$ W^{-1} were obtained at a temperature of 77 K.

Introduction

Infrared detection employing optical transitions in quantum wells has attracted a lot of research interest in the past several years. Due to the design freedom a variety of detector figures like for example the spectral region of sensitivity, the response time, the detector noise etc. can be adjusted over a large parameter range [1], [2] and optimized detector performance can be achieved for several areas of applications. In this work, we demonstrate that for quantum well infrared photo-detectors (QWIPs) in addition a large wavelength tunability can be achieved by employing the injector concept originally developed for quantum cascade electroluminescence and laser structures. In these structures, the large tunability results from the charge transfer from a deep to shallower wells. The charge transfer becomes possible by the alignment of the ground-states of adjacent quantum wells in an externally applied electric field.

Experimental

Photocurrent spectroscopy in the mid-infrared (MIR) spectral region has been performed on p-type Si/SiGe quantum cascade injector structures. The samples were grown by molecular beam epitaxy (MBE) at a low nominal growth temperature (350 °C) pseudomorphicaly on a Si substrate. The active region of the samples contains 5 SiGe valence band quantum wells (widths: 39, 26, 24, 23, and 35 Å; Ge content x: 0.42, 0.42, 0.40, 0.37, and 0.28, respectively) separated by Si barriers (thickness: 30, 25, 25, and 25 Å). These wells will be denoted w1, w2, w3, w4 and w5 in the following. The set of quantum wells w1 – w5 and barriers is p-type doped (2.5×10^{17} cm^{-3}) and repeated 10 times with an undoped 500 Å Si barrier between the subsequent quantum well sets. The 10 periods were sandwiched between 300 nm (100 nm) p-type (2×10^{18} cm^{-3}) bottom (top) contact layers.

For an externally applied bias of 1 V, the valence band edges and the wavefunctions as contour plots centred at the corresponding eigenenergies of a period of a typical sample are shown in Fig. 1 (a) for 1 V externally applied bias. The details of the calculations are given in Ref. [3]. For the photocurrent measurements, the samples were processed into 300 x 300 μm^2 mesas and contacted by Al:Si metallization.

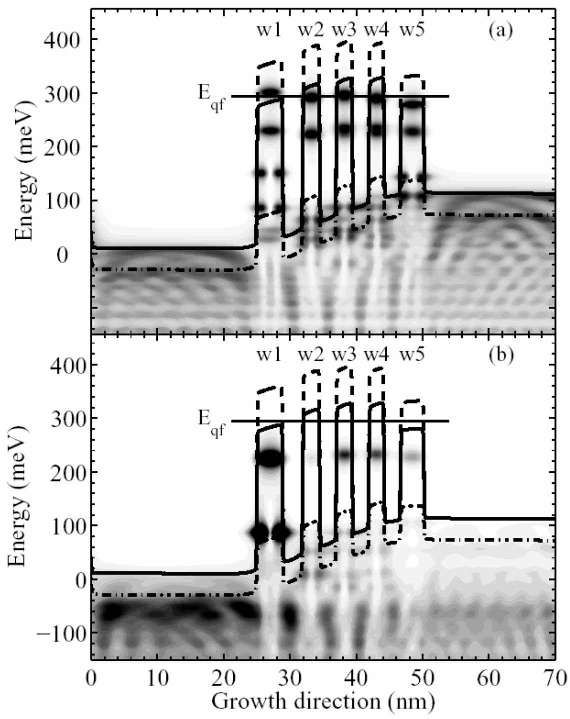

Fig. 1: (a) Contour plot of the wavefunctions and band edge profiles for the HH (dashed), LH (full) and SO (dashed dotted) valence bands for an externally applied bias of –1V. (b) For the same situation as in (a), contour plot of excited state wavefunctions integrated over the in-plane dispersion and weighted by their contribution to the absorption of normal incident radiation.

Figure 2 shows photocurrent spectra measured at T = 77 K for various bias voltages. The spectra were measured for MIR radiation propagating perpendicular to the sample surface. Since the quantum wells are formed in the *valence band* of the SiGe quantum wells, intersubband transitions are allowed for this polarization. The bias voltages indicated in the plot were applied to the top contact with respect to the bottom contact. A huge tuneability of the responsivity is observed for our samples: Depending on the bias voltage, the photoresponse of the cascade samples can be shifted between two MIR detection bands with maxima at 240 meV (5.2 µm) and 370 meV (3.4 µm). Both detection bands are slightly asymmetric showing a high-energy tail, the full widths at half maximum (FWHM) are 140 meV and 110 meV for the low- and high-energy band, respectively. For detection in the low-energy band, the ground states of the five coupled quantum wells are tuned into resonance by the applied negative bias voltage and a hole transfer from w1 to w5 occurs. For this bias, the photocurrent spectra are determined by bound to continuum transitions of the shallowest quantum well. For positive bias, most of the holes populate the ground state of w1 and consequently, photocurrent spectra due to bound to continuum transitions of the deepest quantum well with peaks around 370 meV are observed. At –1 V bias, a reversal of the sign of the photocurrent is observed for energies above and below 340 meV. From the simulations shown in Fig. 1 (b) it becomes clear that the sign reversal is due to resonances of the wavefunctions above the barriers: The final states of the transitions at higher energies are localized above the thick barriers separating the quantum well sequences. Due to the doping profile and the charge redistribution in the ground states, the thick barriers are virtually field free at this bias, and therefore, the direction of the photocurrent is determined by the center of gravity of the final state wavefunction, since on average, a transition from the ground state to this state implies a shift of the hole in the direction opposite to the applied electric field.

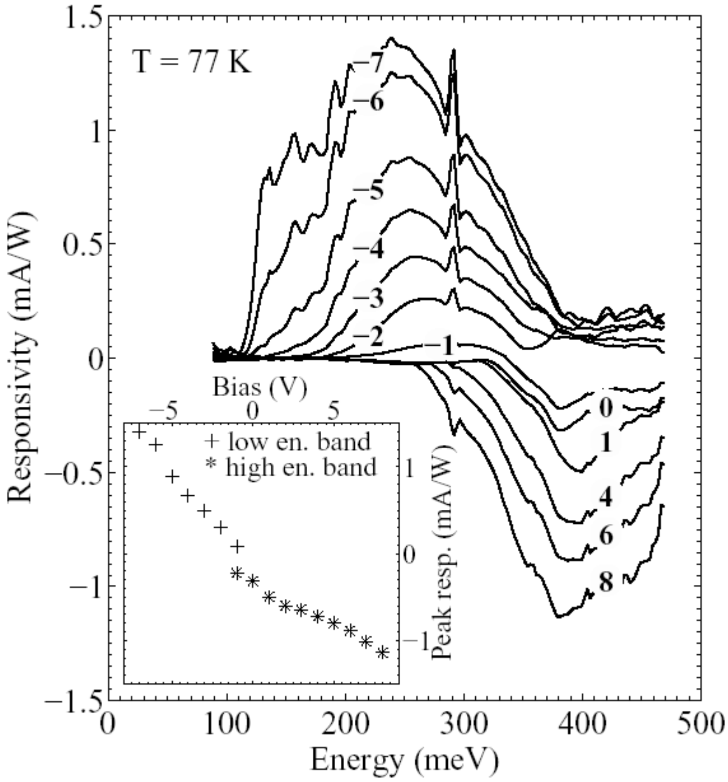

Fig. 2: Photocurrent spectra of Si/SiGe quantum cascade injector structures measured at the bias voltages indicated in the plot. At –1V, a different sign of the photocurrent is observed for MIR radiation with energy below and above 340 meV.

The final states of the transitions at around 270 meV are localized in the region above w2 in which a strong electrical field is present that determines the direction of the photocurrent.

Depending on the applied bias, in both detection bands, the detectivity D* of the QWIPs is approx. 1.5 $x10^9$ $cmHz^{0.5}/W$. In order to enhance the detectivity and eliminate the spectral overlap of the high and low energy detection bands, the QWIP structures will be integrated in a vertical cavity. QWIP samples grown on SOI substrates show similar spectral response as shown in Fig. 2. With these samples, an integration of the QWIP structure in a resonator appears to be feasible by etching from the wafer backside to the buried oxide layer and by subsequent mirror deposition. Since the photoresponse of the QWIPs can be tuned for example from an energy to twice that energy (for example, 200 meV to 400 meV as shown in Fig. 2), both detection bands can be tuned into resonance with the cavity

Conclusions

In conclusion, we have demonstrated a QWIP based on a doped cascade injector structure that can be tuned over a large spectral region. The tunability of the device allows detection in two broad bands in the MIR that can be selected by the applied bias voltage. Up to now detectivities approximately 1 order of magnitude smaller than those of standard normal incidence QWIPs [4] compatible with standard Si technology could be demonstrated. However, the additional feature of the large tunability broadens the window of possible application significantly and makes these structures interesting for applications where high detectivity is not an absolute demand.

Acknowledgements

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