Resonator Fabrication for Cavity Enhanced, Tunable Si/Ge Quantum Cascade Detectors

M. Grydlik[1], P. Rauter[1], T. Fromherz[1], G. Bauer[1], L. Diehl[2], C. Falub[2], G. Dehlinger[2], H. Sigg[2], D. Grützmacher[2]

[1] Institute for Semiconductor and Solid State Physics, University of Linz, Altenbergerstraße 69, A-4040 Linz

[2] Laboratory for Micro- and Nanotechnology, Paul-Scherrer Institute, CH-5232 Villigen PSI

A process for integrating SiGe quantum well infrared photodetectors (QWIPs) grown on SOI substrates into a vertical cavity resonator has been developed. The process is based on a low temperature (T < 250°C) etch mask deposition and, therefore, is applicable for novel QWIP structures grown by low temperature Si MBE.

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 a recent work on Si/Ge QWIPs, we have demonstrated that in addition a large wavelength tunability can be achieved by employing the injector concept originally developed for quantum cascade electro-luminescence and laser structures [3]. The detectivity of these tunable SiGe QWIPs at 77K is approximately 1.5 x 10^9 $\mathrm{cmHz^{0.5}/W}$, typically 1 – 2 orders of magnitude smaller than the detectivity of group III-V based devices. One concept to increase the detectivity of SiGe QWIPs in a narrow detection bandwidth consists of integrating the QWIP into a resonator. In Si/Ge QWIPs, typically the absorption of valence band quantum wells (QWs) is the basis for photocurrent generation. Since for valence band QWs, absorption is also allowed for radiation propagating parallel to the growth direction, vertical cavities can be used to enhance the absorption efficiency of these devices. Moreover, since for QWIPs based on SiGe cascade structures, an extremely large tuning range from for example 200 meV to 400 meV was demonstrated [3], the integration of this novel detectors into a properly designed vertical cavity will allow resonator enhanced detection for 2 narrow bands at wavelengths λ and 2λ that can be addressed by the externally applied voltage.

Experimental

For integrating a tunable QWIP into a vertical cavity resonator, 15 periods of nominally the same QW sequence as described in Ref. [3] (5 SiGe valence band quantum wells with 39, 26, 24, 23, and 35 Å well width and 0.42, 0.42, 0.40, 0.37, and 0.28 Ge concentration, respectively, separated by 30, 25, 25, and 25 Å Si barriers) have been grown on a SOI substrate by low temperature (T = 300 °C) solid source MBE. Detector mesas (typically 300 x 300 μm^2) with bottom and top contacts were formed by reactive ion etching and Al:Si metallization. A schematic sketch of the detector structure is shown in the inset of Fig.1. The photocurrent spectra shown in Fig. 1 clearly demonstrate that the detectors grown on SOI substrate show a similar tunability as reported previously [3] for detectors grown on Si substrate.

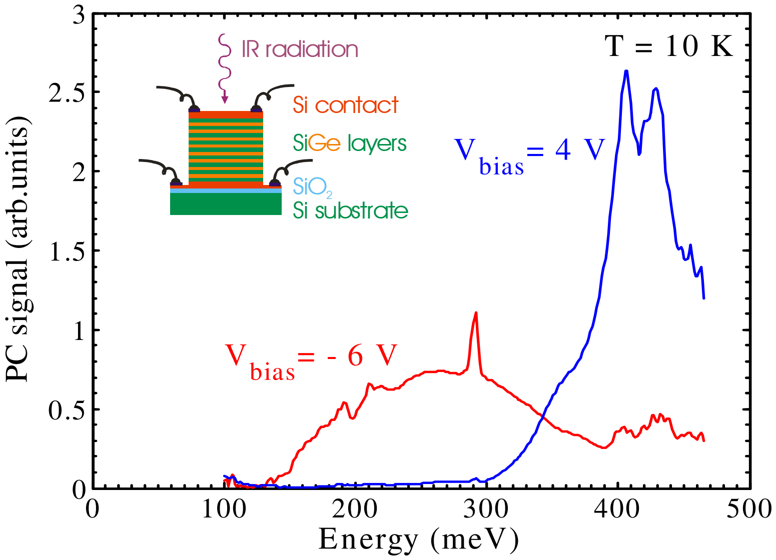

Fig. 1: Photocurrent spectra of SiGe cascade QWIPs measured at the bias voltages indicated in the plot.

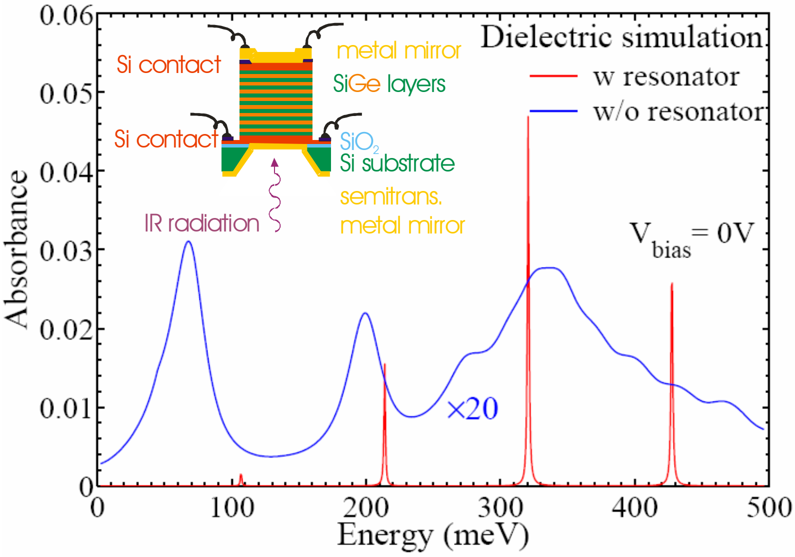

Fig. 2: Simulation of the QWIP absorbance with (red line) and without (blue line) resonator mirrors. Note that the result obtained for the case without mirrors is multiplied by 20.

In Fig. 2 a simulation of the effect of a resonator on the absorption efficiency is shown. Using the absorption spectrum calculated for the QWIP structure by k.p band structure simulations [3], the sample transmission, reflection and absorption including multireflections at all interfaces in the sample was calculated for radiation propagating perpendicular to the sample surface by the transfer matrix method [4]. The intensity absorbed by the QWIP layer sequences is shown by the blue line in Fig. 2. Using the same band stucture for the QWIP and assuming a free standing membrane consisting of the QWIP layers coated with a thick gold layer on top of the membrane and a thin (for example 20 nm), semitransparent gold layer at the opposite side of the membrane through that radiation can be coupled into the QWIP (for a sketch, see inset of Fig. 2), the QWIP absorption was simulated by the transfer-matrix method [4] for comparison. In this simulation, the dielectric function of the gold was described by a Drude dispersion according to [5]. The simulated QWIP absorbance is shown by the red line in Fig. 2. It is evident from this plot that at the resonance wavelengths the QWIP absorption is enhanced by at least an order of magnitude.

For fabricating vertical cavity resonator as sketched in the inset of Fig. 2, openings aligned to the detector mesas have to be etched from the backside of the sample through the substrate. The buried oxide layer of the SOI substrate is used as an etch-stop. After removing the remaining SiO_2 layer by an HF etch, a free standing film consisting of the detector QW sequences results. On the top and bottom side of this detector film, broadband, high-reflectivity metal or Bragg mirrors will be deposited that finally form the resonator.

From the previous paragraph it is clear that the choice of a proper etchant is crucial for successful resonator fabrication. In our work, TMAH (Tetramethylammonium Hydroxide) at 90 °C was used as etchant for the following reasons: (a) TMAH has reasonably large etch rate (30 µm/h) for the Si (001) lattice plane that allows to etch free the buried oxide layer of a thinned SOI substrate (200 µm) in approximately 7 h. (b) In addition, the TMAH etch rate for Si (111) lattice planes is approximately an order of magnitude smaller than in (001) direction. Therefore, TMAH etch grooves are bound by (111) planes and negligible underetching of the etch mask occurs. (c) The etch rate of TMAH for thermally grown oxide is virtually vanishing. Therefore the etching process is effectively stopped by the 200 nm thick buried oxide of the SOI substrate. Even after a 2 h long over-etching the exposed SiO_2 layer showed no indication of an etch attack and remained optically flat. (d) TMAH is compatible with the standard Si technology as it is contained in most of the photoresist developers.

For the long etch times required to etch from the wafer backside to the buried SiO_2, an etch mask with high resistance against TMAH is required. In standard Si MEM technology, a structured Si_3N_4 layer deposited by LPCVD at approximately 900 °C is commonly used as mask for long TMAH etches. However, due to the high deposition temperature necessary for the LPCVD process, this mask material can not be used for samples with QWIP structures grown on the wafer front side. On the other hand, a 300 nm thick Si_3N_4 deposited at lower temperatures (250 °C) in a plasma enhanced CVD (PECVD) process was destroyed by the TMAH etch after approximately 100 nm etch depth. Increasing the thickness of the Si_3N_4 to 400 nm and 500 nm did not improve the results most probably due to increased number of strain induced cracks in the thicker Si_3N_4 layers.

The best results were obtained by a mask consisting of a double layer of Si_3N_4 (200 nm) and the spin-on polymer BCB (Bencocyclobutene, Dow Chemicals brand name: “Cyclotene” [6]) with a thickness of 6 – 8 µm. BCB can be structured by reactive ion etching in a mixed O_2 and CF_4 plasma. The Si_3N_4 layer acts as an adhesion promoter for the BCB film. With this mask and a 10 h long TMAH etch, free standing Si membranes could be produced on a test wafer consisting of a Si layer grown on an SOI substrate instead of the Si/Ge QWIP structure. Electron and optical microscope pictures of the membrane are shown in Figs. 3 (a) – (d). In the optical microscope (Figs. 3 (a), (b)) no surface roughness of the membrane and the (111) sidewalls are visible. The sample shown in Figs. 3 (a), (b) was illuminated from the backside resulting in a bright appearance of the Si membranes, indicating that the membranes are transparent in the visible spectral region due to their small thicknesses. Also the electron microscope pictures (Figs. 3 (c), (d)) do not show significant surface roughness of the membranes and the sidewalls. The etch mask shown in Fig. 3 (d) is evidently not attacked by the TMAH etch and only a small underetching due to the non-vanishing etch rate in (111) direction is shown. Infrared transmission through a Si membrane was measured with an infrared microscope. The transmission spectrum plotted in Fig. 3 (e) shows strong Fabry-Perot oscillations with a periodicity corresponding to a membrane thickness of 1.42 µm. In future work, the line width of these oscillations will be decreased by increasing the cavity Q-factor with high-reflectivity broadband mirrors deposited on the membrane surfaces.

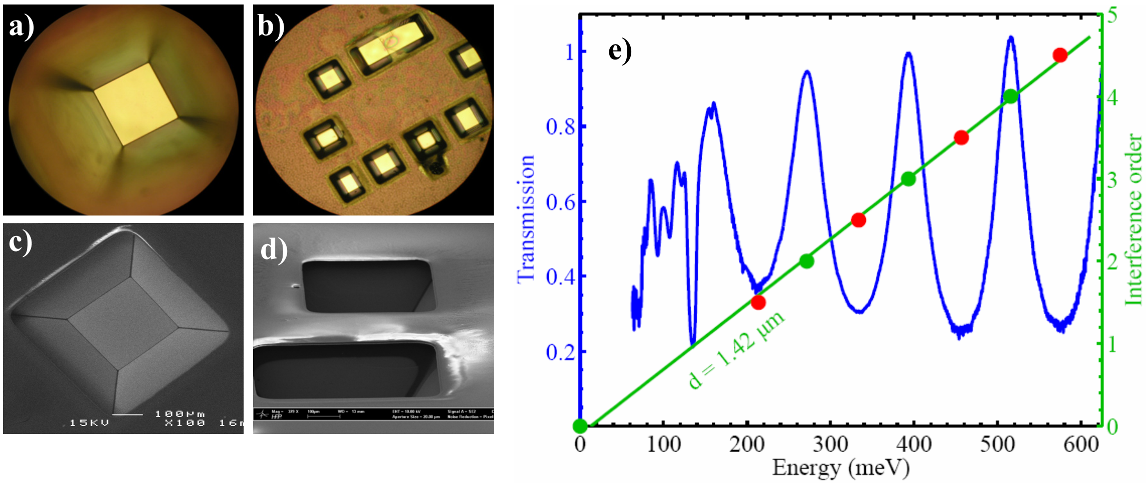

Fig. 3: Results obtained by visible ((a), (b)), electron ((c), (d)) and infrared microscope (e) experiments revealing an optically flat Si membrane with thickness of 1.42 µm fabricated by the process described in the text.

Conclusions

A process for fabricating a thin, free standing Si membrane by etching grooves from the backside of an SOI wafer has been developed, where the buried SiO_2 layer acts as an effective etch stop. Since only low temperature (T< 250°C) process steps are involved, the process is perfectly suited for integrating Si/Ge based QWIPs grown on SOI substrates into vertical cavity resonators.

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