Structural and optical characterization of hole-doped Ge/SiGe multiple quantum wells for mid-infrared photonics

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Abstract. The structural and optical properties of p-doped Ge quantum wells separated by SiGe barriers are presented. The composition profile was determined by atom probe tomography and X-ray diffraction measurements. The energy and broadening of the fundamental intersubband transition were studied by Fourier transform infrared spectroscopy which revealed a strong absorption peak around 8.5 μm making this or similar heterostructures suitable for the realization of optoelectronic devices working in the fingerprint region.

1 Introduction

The capability of generating, manipulating and detecting mid-infrared light is of crucial importance in countless applications such as material recognition, sensing and imaging. However, most of nowadays available optoelectronic devices rely on III-V semiconductors which suffer from a less mature technology than silicon also making the integration with standard Si-based electronic circuits challenging. In this respect, group-IV semiconductors are promising candidates for the realization of cheap and compact Si-compatible devices working in the fingerprint region, which find application for the identification of chemical and biological substances in diagnostics and industrial monitoring. Indeed, graded-index SiGe photonic integrated circuits (PICs) show remarkable properties such as their transparency over a wide spectral range [1].

The implementation of PICs still faces several challenges, including the availability of integrated photodetectors and high-speed optical modulators. In this context, Ge/SiGe quantum wells integrated on silicon substrates represent a viable solution to address these challenges. Indeed, intersubband (ISB) transitions in such heterostructures can be exploited to realize quantum well infrared photodetectors as well as optical modulators relying on the quantum confined Stark effect.

As a preliminary investigation, we report here the characterization of the structural and optical properties of p-doped Ge/SiGe multiple quantum wells (MQWs) designed to have an ISB transition in the mid-infrared.

2 Structural and optical characterization

The heterostructure was designed by means of an advanced semi-empirical first-neighbour $sp^3d^5\sigma^*$ tight-binding Hamiltonian model which also includes the spin-orbit coupling [2]. The germanium content and the width of wells and barriers were chosen in such a way that only two confined energy levels exist in the heavy-hole (HH) subband and thus only one major ISB transition between these two occurs: in particular, the heterostructure contains 3 nm-thick Ge quantum wells enclosed between 8 nm-thick $Si_{0.3}Ge_{0.7}$ barriers, as depicted in Figure 1(a), and has been designed to have a TM-polarized ISB transition around 8.5 μm. The potential energy profiles of the HH and light-hole (LH) subbands and the wavefunctions of the electronic states calculated starting from the experimental germanium profile are shown in Figure 1(b).

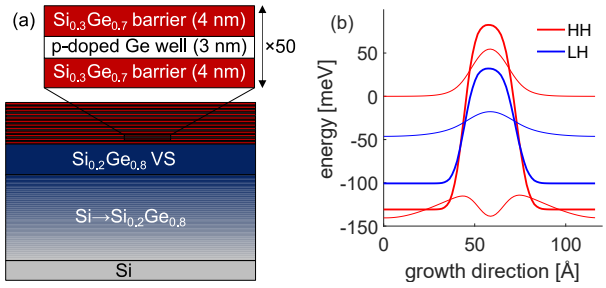

Figure 1. (a) Nominal structure of the sample. (b) HH and LH potential profiles and confined electronic states.

The samples were grown by low-energy-plasma-enhanced chemical vapor deposition (LEPECVD) [3] on a fully relaxed 2 μm-thick $Si_{0.2}Ge_{0.8}$ virtual substrate to ensure strain compensation. B_2H_6 was added during the growth, varying the diborane flux to obtain structurally identical samples with different hole density inside the wells.

The structure of the grown samples was investigated by means of atom probe tomography (APT) and high-

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resolution X-ray diffraction (HR-XRD) measurements. Since silicon and germanium are miscible, the interfaces between the layers are not abrupt; besides, due to the growth dynamics, the well profiles are also expected to be asymmetric. For these reasons, the variation of the germanium concentration along the growth direction was measured by APT and then used to reproduce the XRD scan obtaining a good agreement as shown in Figure 2.

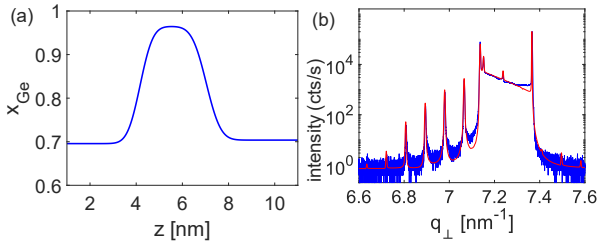

Figure 2. (a) Germanium content profile retrieved from APT measurements. (b) Experimental XRD scan and Darwin model simulation based on the APT profile.

Fourier-transform infrared (FTIR) spectroscopy was employed to study the optical properties of the heterostructures. The samples were prepared in the single-pass prism-like waveguide geometry and the dichroic transmission spectra were obtained by dividing the transmission spectra acquired for TM-polarized light by those acquired for TE-polarized light. In doing so, any feature which can be excited by both polarizations cancels out leaving only purely-TM and purely-TE features appearing as dips and peaks, respectively. The FTIR dichroic spectra of two samples having two different doping concentrations are reported in Figure 3(a) and (b). At low temperature, the less doped sample shows a Lorentzian dip centred around 145 meV; the most doped sample, instead, reveals a more complex spectral lineshape, possibly due to the non-parabolicity induced by the high doping level.

Figure 3(c) shows the two-dimensional absorption coefficient at 10 K derived from the corresponding dichroic spectrum of Figure 3(a) compared to the theoretical absorption coefficient. It is worth noting that, though having the same linewidth of around 25 meV, the main peak in the two curves occurs at different energy. This can be understood considering that the simulations do not take collective effects such as the depolarization shift into account and strongly depend on the doping and valence band offset which are free parameters at this stage. Hall bar measurements are currently ongoing and might provide us with an estimate of the two-dimensional hole density in the wells to be used to refine the numerical calculations.

3 Conclusions and perspectives

In this work we presented a systematic characterization of the structural and optical properties of boron-doped Ge/SiGe MQWs. The Ge-content profile was retrieved from APT and confirmed by the results of XRD measurements. The FTIR dichroic transmission spectra showed that, for low enough doping levels, a single Lorentzian absorption peak is observed in the mid-infrared at 8.55 μm corresponding to the transition between the fundamental and the first excited state of the HH subband.

The same heterostructure studied here is now being employed for advanced applications such as the investigation of enhanced light-matter interaction in Ge/SiGe MQWs [4] or the realization of a waveguide-integrated quantum well infrared photodetector in graded-index SiGe photonic circuits.

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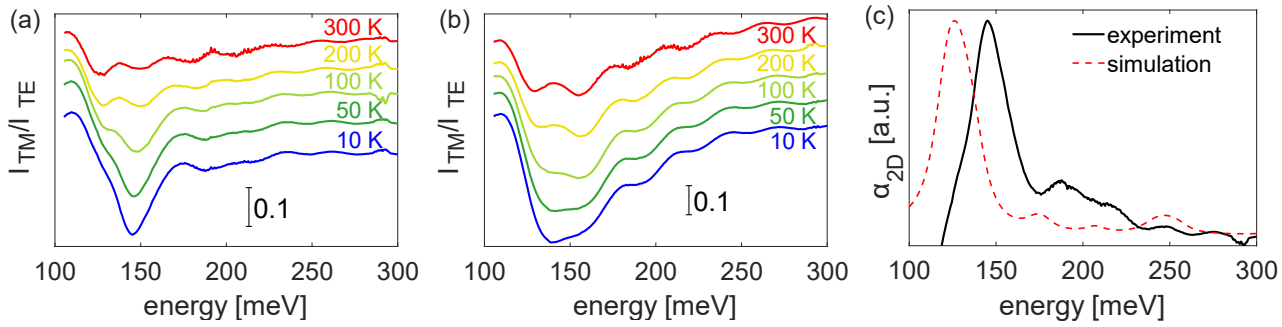

Figure 3. (a) Dichroic transmission spectra of the less doped sample as a function of the temperature. (b) Dichroic transmission spectra of the most doped sample as a function of the temperature. (c) Experimental two-dimensional absorption coefficient compared to the one calculated from the simulated bandstructure.