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Strong coupling between photonic modes of stripe microcavities and intersubband transitions in Ge/SiGe multiple quantum wells

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Abstract. In this work, we assessed by means of numerical simulations the observability of mid-infrared intersubband polaritons in hole-doped Ge/SiGe multiple quantum wells embedded into stripe microcavities consisting of an upper gold grating and a bottom highly n-doped SiGe mirror.

1 Introduction

The capability of engineering the electrical and optical properties of semiconducting materials paved the way to the development of many electronic and optoelectronic devices. In this context, intersubband (ISB) transitions in semiconductor quantum wells have been thoroughly investigated and eventually employed for the realization of devices such as quantum cascade lasers, quantum well infrared photodetectors and quantum cascade detectors.

When a multiple quantum well (MQW) structure is put into a photonic microcavity and the ISB transition is resonant with one of the cavity modes, the system might enter the strong coupling regime where the degeneracy is lifted and two new quasi-particles called ISB polaritons appear which could possibly enhance the optoelectronic properties of the aforementioned ISB-based devices.

Since the first demonstration [1], many theoretical and experimental investigations were devoted to ISB strong coupling which however focused exclusively on III-V semiconductors. Nonetheless, silicon, germanium and their alloys would allow for the implementation of optoelectronic devices which might be monolithically integrated with classical Si-based read-out circuits and could benefit from the strong coupling regime as well. As a first step towards the realization of such devices, we thus studied the interaction between ISB transitions in hole-doped Ge/SiGe MQWs and the photonic modes of patch [2] and stripe microcavities, these latter being the focus of this report, with the aim of assessing the observability of ISB polaritons in the SiGe material platform.

2 Methods and results

The heterostructure which was considered in this work contains 3 nm-thick Ge quantum wells sandwiched between 8 nm-thick $Si_{0.3}Ge_{0.7}$ barriers and has been designed to have a TM-polarized ISB transition in the mid-infrared occurring between the fundamental and the first excited state of the heavy-hole subband. To experimentally characterize the optical transition, the sample was 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 as shown in Figure 1(a). The heterostructure was doped by adding boron atoms to the wells during the growth. The potential profile and the confined energy levels plotted in Figure 1(b) were calculated with the 8-band k·p modelling as implemented in the nextnano software [4].

From the dichroic transmission spectra of Figure 1(c), acquired by FTIR spectroscopy in the so-called single-pass waveguide geometry, the ISB transition energy, the linewidth and the two-dimensional hole density in the wells were determined to be 1180 cm^{-1}, 200 cm^{-1} and 7×10^{11} cm^{-2}, respectively, at 10 K.

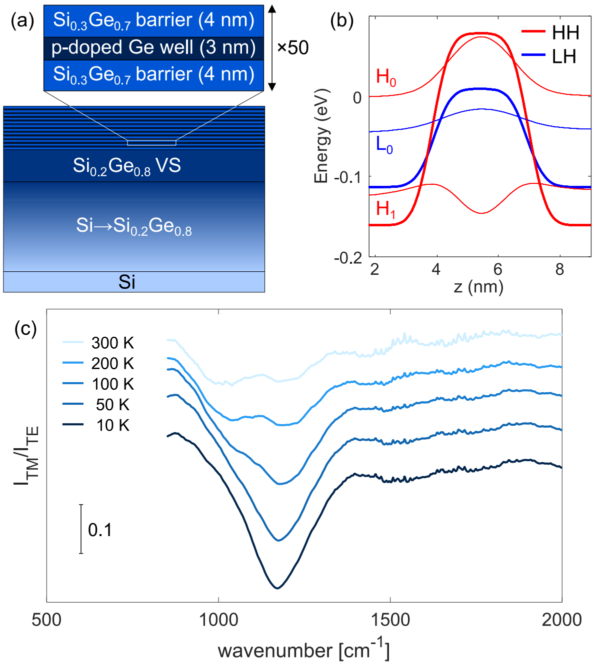

Figure 1. (a) Nominal structure of the sample. (b) Potential energy profile and confined states of the heavy- and light-hole subbands. (c) Temperature-dependent FTIR dichroic transmission spectra showing at 10 K a Lorentzian dip around 1180 cm^{-1} corresponding to the main ISB transition.

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In order to enter the strong coupling regime, MQWs are usually enclosed between a gold film and an array of gold antennas. However, this approach would require the removal of the substrate and we therefore explored the possibility of using a heavily-doped SiGe layer both as the virtual substrate for the growth of the heterostructure and as the mirror for the stripe microcavities.

The simulations were carried out with the finite-difference time-domain (FDTD) method as implemented in the Lumerical software and focused on the spectral region between 500 and 2000 cm^{-1}. The dielectric function of the n-doped SiGe mirror was modelled according to the Drude dispersion relation with a free carrier concentration of 2×10^{20} cm^{-3}. The MQWs were instead described as an effective layer with an anisotropic dielectric function accounting for the selection rule on the polarization of the light which can be absorbed by ISB transitions [5].

Before considering doped MQWs, we analysed the dependence of the photonic mode of bare microcavities, appearing as dips in the reflection spectrum of the SiGe mirror, on the width *s* of the stripes which was varied to make the photonic mode span the whole spectral region around the ISB transition. When considering doped samples, instead, the photonic mode split into two dips, as shown in Figure 2(a), corresponding to the upper and lower ISB polaritons. Following the spectral shift of these two dips as a function of the width of the stripes, we can appreciate the avoided-crossing behaviour typical of the strong coupling regime [6] shown in Figure 2(b). Moreover, by fitting the dispersion of the two polaritonic branches with the width of the stripes according to the secular equation [7], we managed to determine a Rabi splitting of about 150 cm^{-1}.

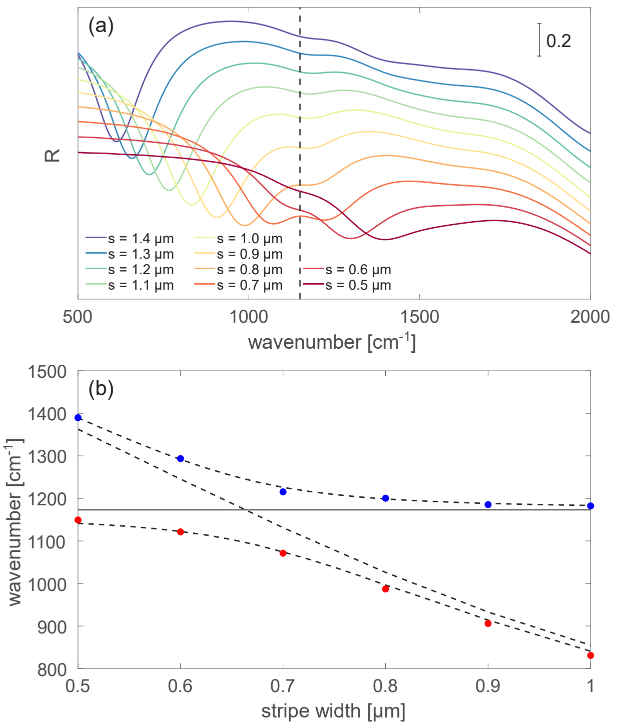

Figure 2. (a) Reflectivity spectra as a function of the width *s* of the stripes in the strong coupling regime. (b) Dispersion relation of the ISB polariton peaks with the width of the stripes.

3 Conclusions and perspectives

In this work, we investigated with FDTD simulations the interaction between ISB transitions in p-doped Ge/SiGe MQWs and the photonic modes of hybrid metal-semiconductor stripe microcavities relying on a heavily-doped semiconducting mirror. We demonstrate that such a system can enter the strong coupling regime with a splitting which, however, does not allow to reach the ultra-strong coupling regime.

In perspective, highly-reflective SiGe mirrors such as the one employed for this numerical investigation can be realized by a combination of ultra-high doping and pulsed laser melting to fully activate the dopants.

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