Electron-doped SiGe Quantum Well Terahertz Emitters pumped by FEL pulses

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***Abstract* — We explore saturable absorption and terahertz photoluminescence emission in a set of n-doped Ge/SiGe asymmetric coupled quantum wells, designed as three-level systems (*i.e.* quantum fountain emitter). We generate a non-equilibrium population by optical pumping at the 1→3 transition energy using picosecond pulses from a free-electron laser and characterize this effect by measuring absorption as a function of the pump intensity. In the emission experiment we observe weak emission peaks in the 14-25 meV range (3-6 THz) corresponding to the two intermediate intersubband transition energies. The results represent a step towards silicon-based integrated terahertz emitters.**

I. INTRODUCTION

QUANTUM well THz-emitters, such as the THz-quantum cascade lasers (QCLs), are presently made of group III-V compounds, whose polar crystal lattice prevents their operation between 5 and 10 THz due to radiation absorption by optical phonons. The non-polar lattice of Si and Ge could thus help fill this THz-frequency gap; furthermore, it has been predicted theoretically [1] that, among group IV materials, *n*-type (electron-doped) Ge/SiGe multi-quantum well systems are the most promising structures for the realization of a room-temperature THz-QCL. Non-equilibrium Green's Function simulations have assessed the potential of Ge/SiGe QCLs to achieve THz emission at room temperature through a detailed comparison with an equivalent GaAs/AlGaAs design. In the Ge/SiGe case, the gain is found to be much more robust to temperature, which is clearly attributed to the weaker electron–phonon interaction [2]. Moreover, SiGe-based emitters could be grown epitaxially on silicon substrates and are thus potentially integrable with silicon microelectronic foundry processes.

The realization of an electrically pumped SiGe emitter (QCL or electroluminescent device), which requires multi-micron-thick quantum wells stack is, however, very challenging, especially due to the high lattice constant mismatch between Si and SiGe alloys, which introduces inherent strain. Therefore, here we start by characterizing, in simpler optically pumped three-level systems, the population dynamics and the electron scattering by interface roughness and phonons, all important parameters influencing the THz emission efficiency [3].

II. RESULTS

N-doped Ge/SiGe asymmetric-coupled quantum well structures, ACQWs, consisting in a narrow well and a wide well separated by a thin barrier, have been designed as three-level systems (quantum fountain) with energy separation in the 14 to 45 meV (3 to 12 THz) range. Samples have been grown on Si(001) substrates, by means of ultra-high vacuum chemical vapor deposition (UHV-CVD), providing sharp interfaces down to the ultrathin barrier limit (see Fig. 1b), and then characterized by FTIR spectroscopy, confirming a good reliability with the design model, which is based on Schrodinger-Poisson solutions [4].

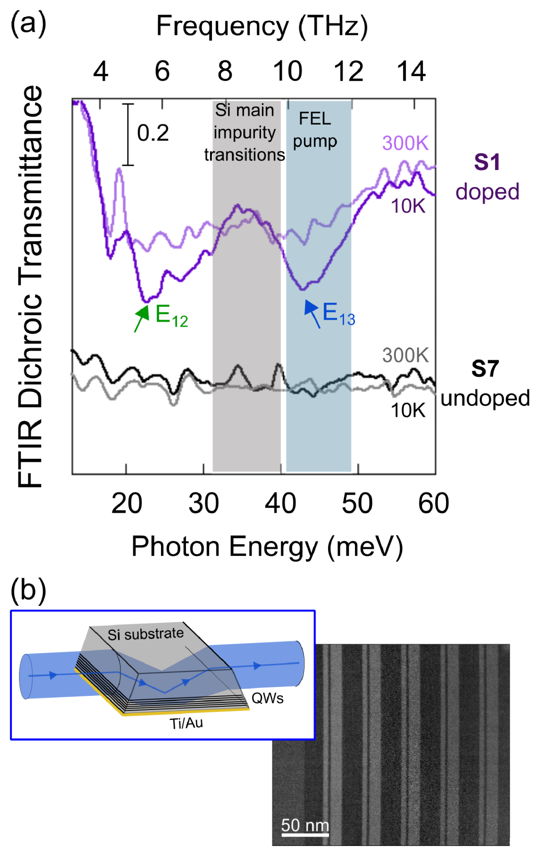

Fig. 1. a) Dichroic spectra (TM signal/TE signal) recorded by FTIR for samples characterization. Transmittance dips corresponding to 1→2 and 1→3 ISBTs appear for the doped sample (S1), while the undoped reference (S7) is completely flat. The pump photon energies, close to the E_{13} (blue shaded area) have been selected to avoid the main transitions of the Si wafer impurities (grey shaded area). b) Sample waveguide geometry for optical experiments and TEM image showing very sharp interfaces.

Here we present optically pumped experiments to directly measure photon emission at the intersubband transition (ISBT) energies under optical pumping. The free-electron laser (FEL) FELBE (Dresden, Germany) has been used to pump electrons from the ground state to the second excited level (1→3 ISBT), paying attention to avoid the main transitions of the Si wafer impurities (grey shaded area in Fig. 1a).

We searched for photoluminescence (PL) emission at the 3→2 ISBT and from level 2 indirectly populated from level 3 through both radiative emission and non-radiative scattering. Therefore, in order to observe any ISBT-PL signals, level 3 must be heavily populated by the FEL pulse. To test pump efficiency, a saturable absorption (SA) experiment has been performed as a function of the FEL pump intensity for three different photon energies close to the E_{13}. From the variation of the power-dependent transmittance, normalized to the measured FTIR value T_0, *i.e.* the transmittance at zero pump intensity (upper panel of Fig. 2b), we obtain a relative ISBT bleaching of up to 30% at resonance. This result has been also confirmed by a theoretical model based on energy-balance equations that provides the crucial information on the population dynamics, as it considers all the elastic and inelastic non-radiative scattering channels affecting electrons pumped at the level 3. By simulations, indeed, an excited-state peak population n_3 of almost the 10% of the total ground state population n_0 (Fig. 2c) has been obtained. The SA experiment also demonstrates the potential of SiGe ACQWs as THz saturable absorber devices in the 5-10 THz range, if appropriate band-structure engineering is carried out [5]. Having shown that FEL pump brings electrons to the upper level, ISBT emission could be explored. The intensity of the observed weak ISBT-PL signals is compatible with the population values determined from the SA data.

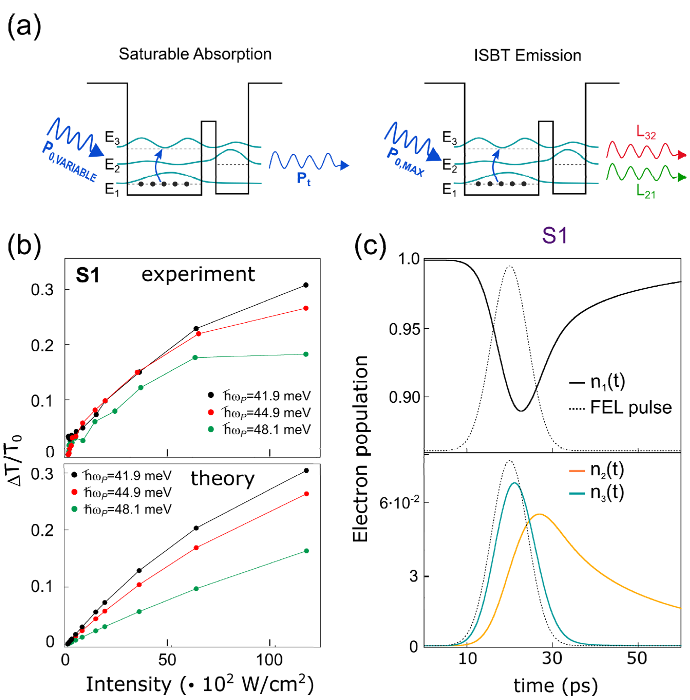

Fig. 2. a) A sketch of the SA and PL experiments performed on Ge/SiGe ACQWs doped in the conduction band. b) The variation of the power dependent transmittance in the SA experimental data (upper panel) and comparison with simulations (lower panel). Data, normalized at zero input power to the FTIR value T_0, are reported for three different pump photon energies. c) The simulated population dynamics for the three levels obtained with the energy-balance rate equation model. The FEL pulse is also reported as black-dashed line.

In order to discriminate the role of the different scattering channels, we also studied ISBT lifetimes in different Ge/SiGe QW structures. All the THz time-resolved pump-probe spectroscopy data obtained at FELBE have been compared with the theoretical model based on Schrödinger-Poisson and energy-balance equations. The experimental relaxation times have been employed to calibrate the out-of-equilibrium ISB energy balance model, with which we calculate the population dynamics under optics pumping (see Fig. 2c).

III. Acknowledgments

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