Germanium quantum wells for mid-infrared integrated photonics

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Ge/SiGe quantum wells grown on Si substrates can be used to explore new functionalities in mid-infrared integrated photonics. In such structures, intersubband optical transitions in the valence band can be leveraged to realize wavelength converters.

Keywords: *mid-infrared photonics, quantum wells, nonlinear optics*

INTRODUCTION

In recent years, mid-infrared integrated photonics has raised an increasing interest due to the envisioned applications in molecular sensing, environmental monitoring and security [1]. The Silicon-on-insulator (SOI) based technology ,operating at wavelengths $\lambda < 3.2$ µm has already reached a significant technology readiness level. By leveraging the maturity of the SOI technology, and taking advantage of the high index contrast between Si and SiO_2 many functionalities such as low-loss waveguiding, modulation and frequency comb generation have already been demonstrated. [1] Nevertheless, extending the operational wavelengths toward the long-wave infrared region (LWIR) (8 µm – 12 µm) present many challenges. First of all, the SOI technology cannot be used above 3.2 µm because of the strong absorption inSiO_2 . In order to address these challenges, many material platforms including III-V semiconductors, halides, chalchogenides have been investigated. In this framework, the SiGe-on-Si material platform seems particularly promising. First of all, by taking advantage of the wide transparency range of Ge, low-loss waveguides operating up to λ =11 µm have been recently demonstrated, as well as a whole set of passive photonic components including Mach-Zehnder interferometers, resonators and spectrometers [2] . Also electro-optic modulation based on the plasma effect has been recently reported [3]. Nevertheless, key functionalities such as wavelength conversion, photodetection and high speed optical modulation are still missing. In this framework, Ge/SiGe quantum wells (QW) could be exploited to fill this gap. Intersubband optical transitions in the valence band of such heterostructures can be used for light detection, for high-speed modulation through the quantum confined Stark effect (QCSE), and for wavelength conversion through second harmonic generation. Ge/SiGe QWs can be easily grown on top of SiGe buffers, making them fully compatible with the existing SiGe-on-Si material platform. In this work, we show an experimental demonstration of second harmonic generation at mid-infrared frequencies [4,5] and a preliminary study for waveguide integration of the QW stack.

MID-INFRARED SECOND HARMONIC GENERATION

Group IV semiconductors, such as Si and Ge, feature a vanishing second-order optical linearity $\chi^{(2)}$ due to their centrosymmetric crystal structure. Nevertheless, such symmetry can be broken by creating an asymmetric potential profile for carriers, a condition that can be easily achieved in asymmetric coupled quantum wells (ACQW). Interestingly, the $\chi^{(2)}$ arising from intersubband dipole moments in ACQWs can reach values of 10^4-10^5 pV/cm, orders of magnitudes higher with respect to the best nonlinear crystals. Such giant optical nonlinearities have been investigated in III-V semiconductors, but only in recent years the SiGe epitaxial technology has reached a sufficient level of maturity for growing these heterostructures. The bandstructure of the sample has been designed with a semi-empirical first-neighbor $sp^3d^5s^*$ tight-binding Hamiltonian which includes spin-orbit interaction (fig 1a) and it has been used to calculate the absorption spectrum (fig 1b) and the second order nonlinear susceptibilty (fig 1c).

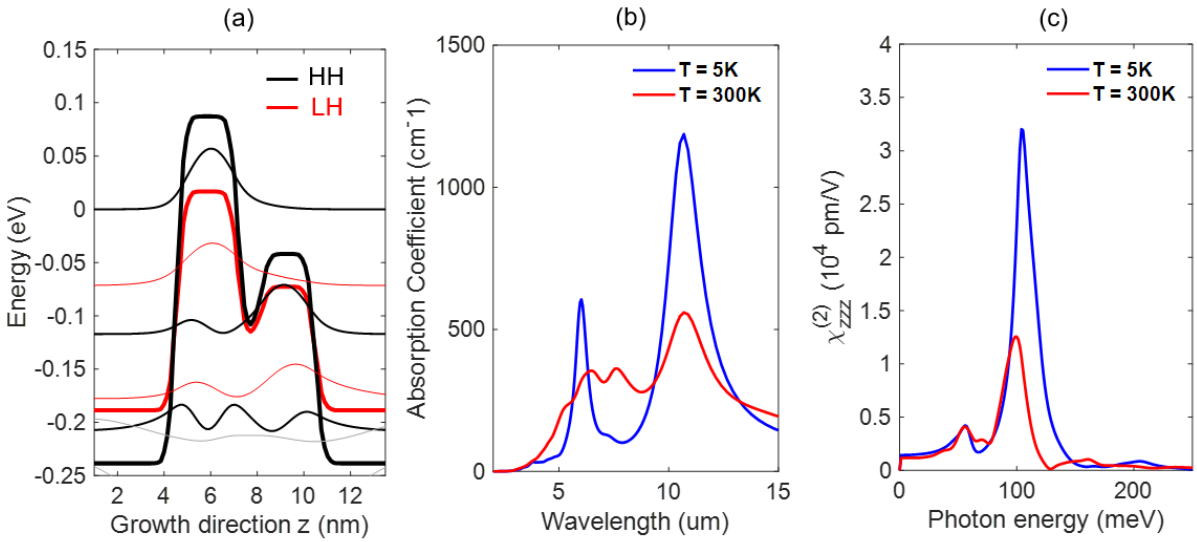

Figure 1: Valence band profile and wavefunctions (a), calculated absorption spectrum (b) and second order nonlinear susceptibility of the ACQW for TM polarization at T = 5 K (blue) and at room temperature (red).

The sample (see fig. 2a) has been grown by low-energy plasma enhanced chemical vapor deposition (LEPECVD) on a (100) Si-substrate. The first part of the structure consists in a 1 µm thick $Si_{0.8}Ge_{0.2}$ buffer followed by a 1 µm thick $Si_{0.3}Ge_{0.7}$ virtual substrate. Then 20 periods of the ACQW (**well**/barrier thickness **2.4**/1.0/**2.7**/3.9 nm, and Ge content x_{Ge} = **0.96**/0.67/**0.93**/0.52) have been deposited at a rate of 0.1 nm/s at a growth temperature of T = 350°C. The main well has been p-doped with a 2D concentration of 4.1×10^{11} cm^{-2}. The sample has been structurally characterized by high-resolution X-Ray diffraction (HR-XRD). The reciprocal space map (RSM) relative to the (224) Si reflection is reported in Fig. 2b. From the RSM it is possible to notice the very high quality of the ACQW stack and its coherence with respect to the virtual substrate.

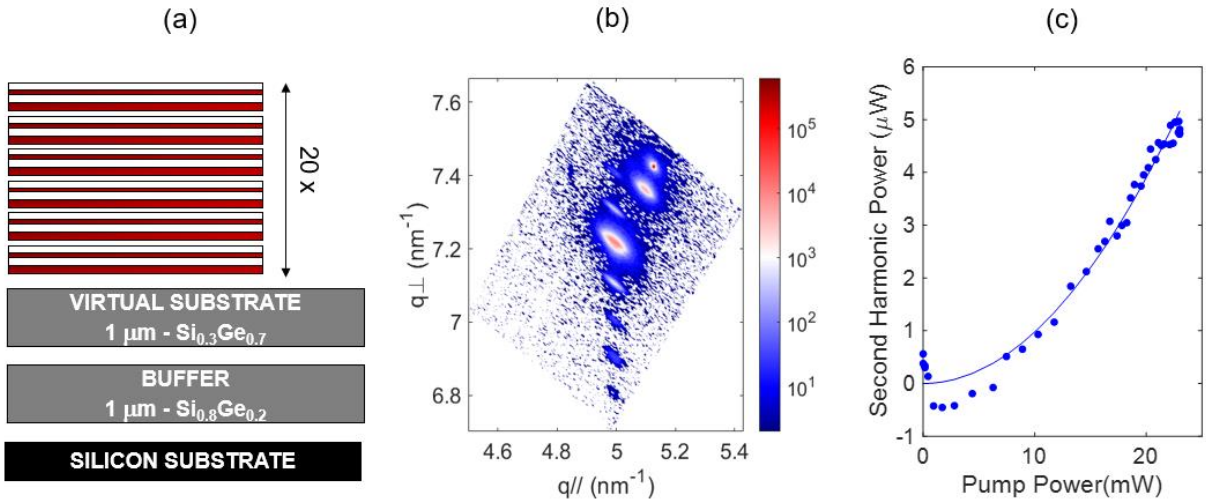

Figure 2: Schematic of the ACQW stack (a), 224 RSM of the sample (b). Second harmonic emission as a function of the pump power (c).

For the optical measurements, samples were cut in a 2 mm single-pass surface-plasmon waveguide with the side facets shaped to 70° with respect to the growth plane and the top facet close to the ACQWs region coated by a Ti/Au layer. Then the samples (cooled at 10 K) have been pumped with a CW quantum cascade laser emitting at λ =10.3 µm. The light coming out from the samples have been then filtered and collected by an MCT detector. The second harmonic emission has been recorded as a function of the input power (see fig. 2c). A $\chi^{(2)} = 6 \times 10^4$ pm/V has been extracted from the measurement.

Finally, we have theoretically investigated the possibility to integrate the ACQW in waveguides. Since these "artificial nonlinearities" involve real quantum states, as opposite to the virtual quantum states employed in standard nonlinear crystals, optical absorption at the pump and second harmonic wavelengths must be taken into account. Some studies [6,7], by solving the coupled wave equations in presence of absorption, show that the second harmonic emission has a peak for an optimal wavelength length (assuming perfect phase matching), and then decays for the combined effect of pump depletion and second harmonic re-absorption. Preliminary calculations show that such optimal length, in the case of Ge/SiGe ACQW, is of a few hundreds of µm. For this reason, we are considering the design sketched in fig. 3a for ACQW integration. In this concept, the light coming from a $Si_{0.3}Ge_{0.7}$ waveguide is injected in a second waveguide, integrating the ACQW stack, through an adiabatic taper. The pump and the second harmonic mode are fairly overlapped in the ACQW region, as shown in fig 3a and 3b, where we calculated the distribution of the first TM mode by the Lumerical software package. The waveguide integrating the ACQW is periodically etched to achieve phase matching.

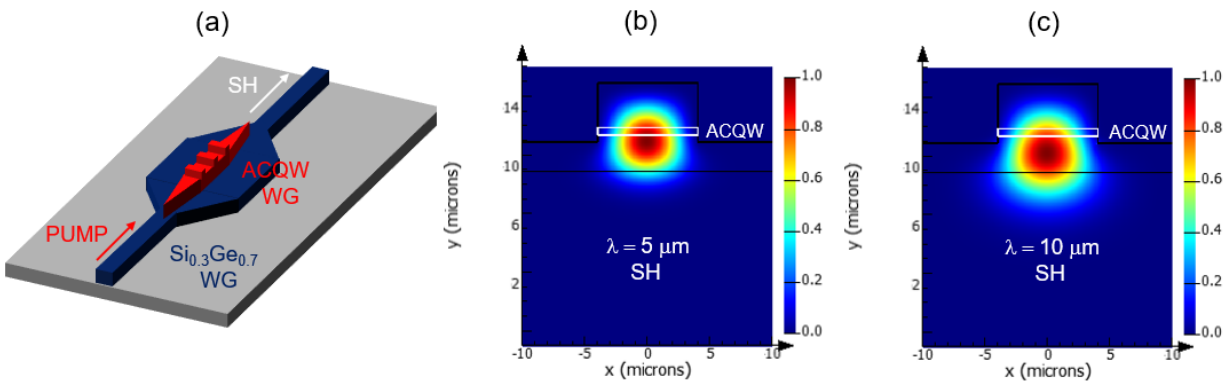

Figure 3: Sketch of the envisioned waveguide integrated wavelength converter (a), First TM mode at λ = 5 µm (SH) (b) and at λ = 10 µm (PUMP) (c) in the ACQW waveguide.

In conclusion, Ge/SiGe ACQW are very promising to expand the functionalities available in MIR integrated photonic circuits, especially in the important LWIR spectral region. In particular, the experimental data obtained from the material characterization, as well as the preliminary studies of waveguide integration show that Ge/SiGe ACQW has the potential to realize integrated wavelength converters.

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