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Citation for the original published paper (version of record):
Frigerio, J., Ciano, C., Ballabio, A. et al (2020). Mid-infrared second harmonic generation in Ge/SiGe coupled quantum wells. 2020 IEEE Photonics Conference, IPC 2020 - Proceedings, September 2020.
http://dx.doi.org/10.1109/IRMMW-THz50926.2021.9567195

Mid-infrared second harmonic generation in Ge/SiGe coupled quantum wells

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Abstract— **We present the theoretical investigation and the experimental demonstration of second harmonic generation in the mid-infrared by hole-doped Ge/SiGe asymmetric quantum wells.**

I. Introduction

Mid-infrared (MIR) photonics is receiving considerable attention due to the variety of envisaged applications in medical diagnostics, biochemistry studies, chemical analytics, and environmental monitoring for safety and security [1]. Nowadays, commercially available MIR spectroscopic systems are based on bulky and expensive instruments and, as a consequence, there is an increasing demand for compact sensing solutions. In this framework, group IV photonics is emerging as a promising option to realize portable MIR spectroscopic systems. Since broadband MIR light sources integrated on silicon are still not available, wavelength conversion through nonlinear effects is under investigation. Second-order nonlinear effects are forbidden in bulk Si and Ge for their centrosymmetric crystalline structure, but this limitation can be overcome by creating asymmetric potential profiles through quantum confinement and by exploiting intersubband optical transitions (ISBT). In this work we present the theoretical investigation and the experimental demonstration of mid-infrared second harmonic generation (SHG) in hole-doped Ge/SiGe asymmetric quantum wells (ACQW).

II. Theory

The Ge/SiGe quantum well used in this work has been designed by using a semi-empirical first-neighbor $sp^3d^5s^*$ tight-binding Hamiltonian which includes spin-orbit interaction in order to calculate the electronic band structure. The results have been then used to calculate the second-order nonlinear optical susceptibilities as a function of the temperature, doping, pump wavelength and polarization. The model predicts second-order non-linear susceptibilities as high as 12×10^4 pm/V at T = 10 K for TM polarization [2]. The calculated wavefunctions are reported in figure 1.

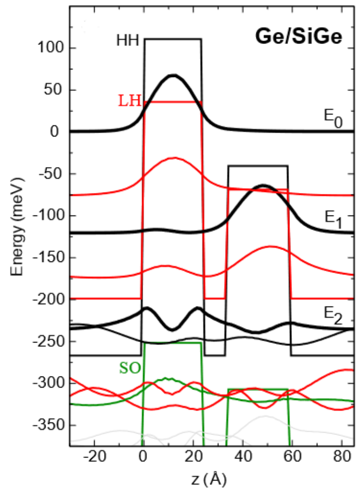

Figure 1: Calculated wavefunctions. The energy levels involved in the SHG process are highlighted as E_0,E_1,E_2.

III. Material growth and characterization

We have grown four samples by Low-Energy Plasma-Enhanced chemical vapor deposition (LEPECVD) [3] and they consist of 20 Ge/SiGe ACQWs (the epitaxial schemes are reported in Fig. 1) grown on top of a $Si_{0.3}Ge_{0.7}$ virtual substrate deposited on silicon. The larger wells of samples A,B and C have been p-doped (B) in-situ. The doping densities are $N_A \approx 4\times10^{11}$ cm^{-2} for samples A and C, $N_A \approx$

$4x10^{11}$ cm^{-2} for sample B. Sample D is nominally undoped. The epitaxial structure of the samples is reported in Fig. 2 (a) and (b). The samples have been structurally characterized by means of high-resolution X-Ray diffraction (HRXRD) and scanning transmission electron microscopy (STEM). The HRXRD reciprocal space map with respect to the (224) Si reflection (Fig. 2(c)) shows that the ACQW stack is coherent with the virtual substrate and the STEM image reported in Fig. 2(d) shows that the ACQW layers are well defined and separated by sharp interfaces.

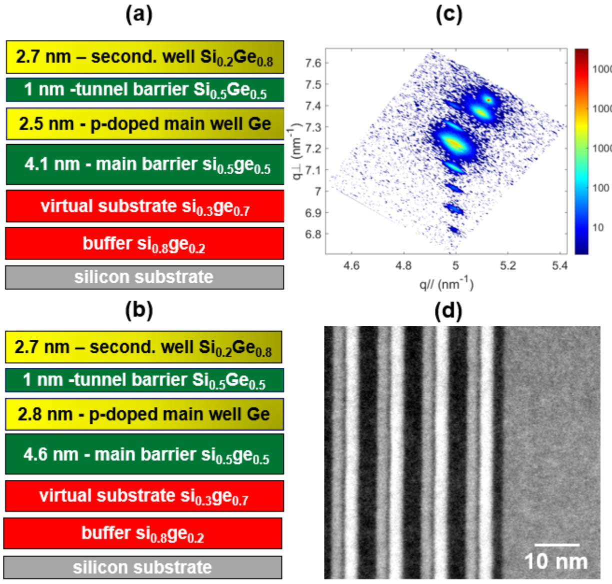

Figure 2: Epitaxial structure of the samples A,B, D (a) and C (b). Reciprocal space map with respect to the (224) Si reflection (c) and STEM image (d) of the sample A.

IV. OPTICAL CHARACTERIZATION

For 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 Pt/Au layer. SHG has been demonstrated in two configurations. In the first one, the samples (cooled at 10 K) have been pumped with a CW quantum cascade laser emitting at λ =10.3 µm.

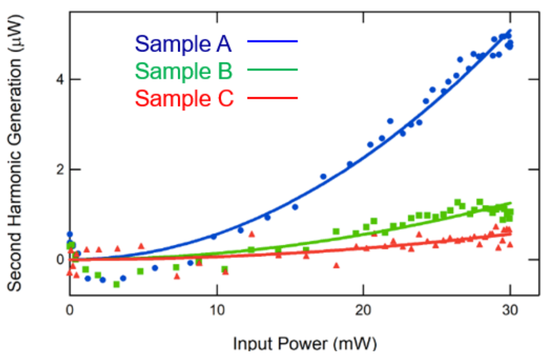

Figure 3: SHG emission power recorded at 10 K as a function of the input power for samples A B and C.

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 for the three samples (see fig. 3). The sample A shows the higher conversion efficiency. A $\chi^{(2)}$ = $6x10^4$ pm/V has been extracted from the measurement for sample A, in good agreement with the theoretical prediction [2]. No SHG has been observed for sample D, confirming that the SHG is due to the intersubband transitions and not to the multiple interfaces of the sample. In order to investigate the spectral dependence of the second harmonic emission, we have performed a second experiment where the samples have been pumped with non-monochromatic pulses centered at λ_0 = 10.4 µm and the output has been spectrally resolved with a grating spectrometer. The pulses were obtained from a nonlinear optical parametric amplifier (NOPA). A clear second harmonic emission has been observed at λ = 5.2 µm at room temperature, as shown in Fig. 4.

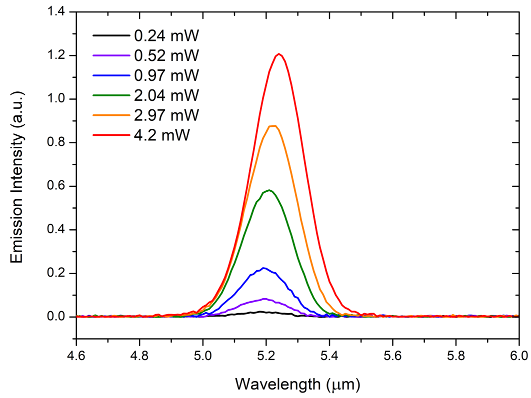

Figure 4: Second harmonic emission of sample A as a function of the wavelength for different input powers .

V. CONCLUSIONS

In conclusion we have investigated second harmonic emission from Ge/SiGe ACQWs in the mid-infrared. A clear second harmonic emission has been measured in CW and pulsed configurations. This result paves the way toward the exploitation of second-order nonlinear effect in group-IV materials.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 823717 – ESTEEM3.

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