Perspectives on electrically pumped Ge/SiGe QW emitters at THz frequencies

C. Ciano[1], M. Montanari[1], L. Persichetti[1], D. Stark[2], G. Scalari[2], J. Faist[2], L. Di Gaspare[1], G. Capellini[1,3], C. Corley[3], T. Grange[4], S. Birner[4], M. Virgilio[5], L. Baldassarre[6], M. Ortolani[6], and M. De Seta[1]

[1]University of Roma Tre, Rome, 00154 Italy
[2]Institute of Quantum Electronics ETH Zurich, Zurich, 8093 Switzerland
[3]IHP-Leibniz-Institut für innovative Mikroelektronik, Im Technologiepark 25, D-15236 Frankfurt (Oder), Germany
[4]nextnano GmbH, Garching b. München, 85748 Germany
[5]Università di Pisa, Pisa, 56127, Italy
[6]Sapienza University of Rome, Rome, 00185 Italy

***Abstract* — The realization of a Ge/SiGe THz emitter is of great interest since it can help to reach room-temperature operation due to the peculiar electron-phonon interaction in nonpolar crystals. Here we present Ge/SiGe quantum-well building blocks epitaxially grown on silicon wafers in order to understand limitations of this material platform in the perspective of realizing a Si-based laser.**

I. INTRODUCTION

EMITTERS exploiting the intersubband transitions (ISBTs) in quantum wells (QWs) are still under the spotlight thanks to the easiness of selecting by design the emission photon energy in the entire spectral range from THz to IR. III-V Quantum Cascade Lasers (QCL), Quantum Fountain Lasers (QFL) and Parabolic Quantum Wells (PQW) are now commercially exploited in the mid-IR and widely employed also as THz sources [1]. Nevertheless, the polar nature of the crystal structure of III-V semiconductors prevents both room-T operation and emission throughout their Reststrahlen band (5-10 THz). Conversely, the nonpolar group-IV semiconductors (Ge, Si and alloys) in principle allow for the realization of room temperature QW devices emitting over the entire THz range. Moreover, SiGe emitters could be eventually integrated in photonics integrated circuits since they can be epitaxially grown on Si substrates.

Among different structures, *n*-type Ge/SiGe QCLs have been predicted to be the most promising structures for reaching such goal [2]. Many heterostructure growth challenges must be addressed to realize an electrically pumped SiGe QCL, but the easier growth of QW building blocks can provide important information in the path towards Si-based QCLs. Optically pumped Ge/SiGe QFL have recently been investigated experimentally, but they suffer from low efficiencies [3]. PQWs are very interesting structures both from the fundamental and the technological point of view [4]. Indeed, PQWs feature ISBTs among equally spaced subbands providing a single absorption (and therefore emission) peak at both low and high temperatures, as the energy is independent of the electron distribution and concentration in the well [5]. This particular property makes them suitable for several applications leveraging on strong light-matter coupling at room-T in the THz range [6]. Here we report the structural and optical characterization of $Ge/Si_{1-x}Ge_x$ PQWs grown by ultra-high vacuum chemical vapor deposition realizing continuously-graded interfaces [7, 8] and compare their optical properties with those of QW building blocks having a different geometry (square and asymmetric-coupled QWs), with the perspective of an electrically driven semiconductor source emitting at THz frequencies.

II. RESULTS

Multiple-period $Ge/Si_{1-x}Ge_x$ PQW samples were epitaxially grown on a reverse-graded $Si_{0.09}Ge_{0.91}$ buffer. The period is composed by a 45 nm-thick parabolic well: this has been obtained with a Ge content continuously increased from 0.83 to 1 with a quadratic dependence on the distance from the center of the well, sandwiched between two 13 nm-thick $Si_{0.17}Ge_{0.83}$ barriers. The corresponding potential profile and wavefunctions, simulated by the Nextnano software, is reported in Fig. 1a. The secondary ion mass spectrometry (SIMS) measurement performed on four periods of the heterostructure (orange curve in Fig. 1b) reveals a Ge compositional profile that perfectly follows a parabola (blue curve). We remark that, from the growth standpoint, obtaining such perfect match is a nontrivial task that requires a fine control over the flux of precursors. The high structural and crystalline quality of the samples is further confirmed by high-resolution rocking curve obtained around the (004) Si Bragg peak by X-ray diffraction (XRD) where several-order sharp satellite fringes associated to the superlattice periodicity are visible (Fig. 1c).

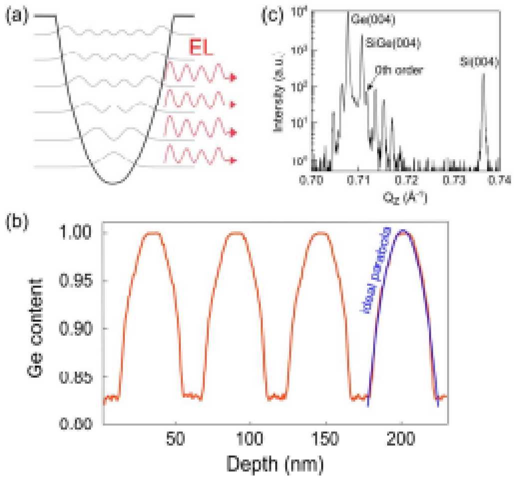

Fig. 1. a) Sketch of the electroluminescence (EL) principle: in-plane current excites electrons on the equally spaced parabolic well levels that subsequently relax emitting photons. PQW wavefunctions have been simulated by the nextnano software. b) SIMS measurement on four-periods of a PQW (orange curve) confirming the parabolic profile (blue curve). c) XRD rocking curve around the (004) reflection.

Samples were *n*-doped to intentional sheet carrier density values between $5 \cdot 10^{10}$ cm^{-2} and $5 \cdot 10^{11}$ cm^{-2}, high enough to guarantee strong absorption lines in far-infrared spectroscopy experiments. The required doping level has been achieved by phosphine co-deposition, at the well center. Fourier Transform Infrared (FTIR) spectroscopy is employed for the measurement of the intersubband absorption spectrum of the PQW samples. The chips have been shaped in a single-pass waveguide with a metal coating on top of the quantum well layers for a proper coupling of the light to the QW region (upper panel of Fig. 2). Measurements have been performed both at low and room temperature to study the effects of the carrier distribution on the intersubband absorption energy. Narrow absorption lines (FWHM~4 meV, centered around 15 meV) have been observed, as shown in Fig.2, where the dichroic FTIR spectrum of a PQW sample (green line) is compared with those acquired on square and asymmetric-coupled multi-QW structure (red and blue lines, respectively). The measured ISBT absorption energies of the samples investigated are in good agreement with preliminary theoretical estimations. A close comparison with the theoretical calculations and sample structure analysis is ongoing.

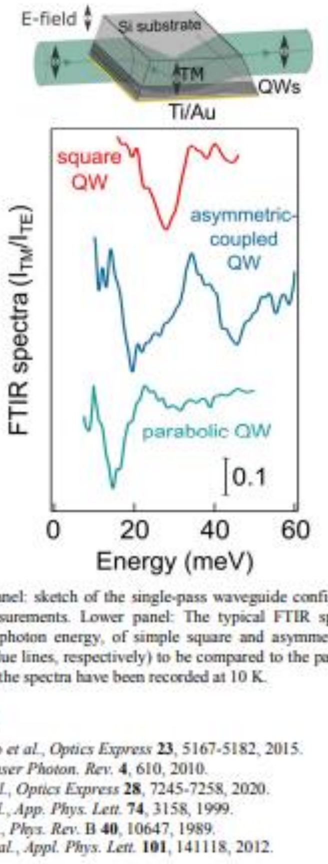

Fig. 2. Upper panel: sketch of the single-pass waveguide configuration for the optical measurements. Lower panel: The typical FTIR spectra, as a function of the photon energy, of simple square and asymmetric-coupled QWs (red and blue lines, respectively) to be compared to the parabolic QW (green line). All the spectra have been recorded at 10 K.

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