Silicon Photonics Based on Ge/SiGe Quantum Well Structures

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D. Marris-Morini[1], P. Chaisakul[1,3], J. Frigerio[2], M-S. Rouifed[1], V. Vakarin[1], D. Chrastina[2], X. Le Roux[1], G. Isella[2], L. Vivien[1]

1 Institut d'Electronique Fondamentale, Univ. Paris-Sud, CNRS UMR 8622, Orsay, France
2 L-NESS, Politecnico di Milano, Polo di Como, Italy
3 Department of Materials Engineering, The University of Tokyo, Japan

delphine.morini@u-psud.fr

Abstract: Ge/SiGe Quantum well structures have a strong potential to revolutionize silicon photonics. This paper reviews recent works including high speed modulator and photodetector, QW engineering to tune the wavelength and waveguide integration.
OCIS codes: (130.3120) Integrated optics devices; (230.4205) Multiple quantum well (MQW) modulators; (130.0250) Optoelectronics.

1. Introduction

The interest in silicon photonics is continuously growing as it is now considered to have potential applications in telecommunication and data communications. In this context, Ge has been proposed by a few research groups as the material of choice for the realization of a complete photonic circuit. Despite being an indirect band gap material, its absorption is "direct gap like" thanks to the small energy difference between the direct and indirect bandgaps. Moreover, it is a group IV material, compatible with fabrication in CMOS foundries. Among Ge-based structures, Ge rich-Ge/SiGe quantum wells (QW) have received a growing interest, as the quantum confinement in Ge wells allow additional features with respect to the bulk materials, such as more abrupt band-edge absorption, the presence of excitonic features as well as the possibility of band structure engineering.

The first demonstration of a direct gap-related optical property in Ge/SiGe QW was the observation of the quantum-confined Stark effect (QCSE) [1,2]. These results paved the way to a number of exciting works addressing not only the electro-absorption but also the electro-refraction [3] mechanisms in Ge/SiGe QW structures and tackling the realization of innovative optoelectronic devices.

Recent advances in the theoretical and experimental studies of Ge/SiGe quantum wells structures will be presented with a focus on optical telecommunication applications. Firstly, high-speed stand-alone Ge/SiGe QW electro-absorption modulators and photodetectors will be reported. It will be followed by the presentation of different methods for engineering Ge/SiGe QW to tune the operating wavelength to 1.3 µm. Finally it will be shown that these active devices can be combined with advanced passive structures using Ge-rich SiGe virtual substrate on graded buffer as a waveguide.

2. High speed modulator and photodetector

QCSE leads to a strong variation of absorption coefficient around the absorption band-edge of Ge/SiGe QW structures. This effect has first been used to demonstrate high speed modulation. The stand-alone modulator is reported in Fig 1. It is based on a 3 µm-wide, 90 µm-long waveguide made of Ge/$Si_{0.15}Ge_{0.85}$ QW inserted in a PIN diode. The QW are grown on a $Si_{0.1}Ge_{0.9}$ relaxed buffer using a strain compensated design, and a 13 µm-thick graded buffer between Si and $Si_{0.1}Ge_{0.9}$ is used to manage the lattice mismatch between Si and $Si_{0.1}Ge_{0.9}$ and to minimize the threading dislocations density [4].

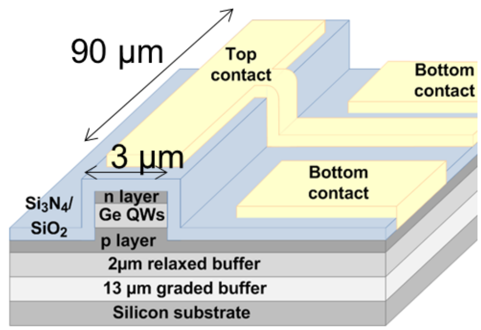

Fig. 1. Schematic view of a Ge/SiGe QW structure in a waveguide configuration that can be used as a modulator or as photodetector.

A high extinction ratio up to more than 10 dB is obtained while an extinction ratio larger than 6 dB is reported in a 20 nm wavelength range. The electro-optic bandwidth is measured larger than 20 GHz, while the power consumption is less than 100 fJ/bit. Interestingly, as the modulator is based on electro-absorption, the same active region can be used for photodetection. Responsivity between 0.5 and 0.8 A/W is obtained in a 80 µm-long waveguide. 10 Gbit/s operation was demonstrated [5].

3. Ge/SiGe quantum well engineering

As a main advantage, QW can be engineered to obtain significant QCSE around the telecommunication wavelength of 1.3 µm. In the first demonstrations, $Ge/Si_{0.15}Ge_{0.85}$ QW grown on $Si_{0.1}Ge_{0.9}$ virtual substrate lead to QCSE at 1.42 µm. Different methods can be used to decrease the operating wavelength. Firstly, knowing that a higher level of compressive strain on Ge allows increasing its bandgap energy, a design has been proposed based on $Ge/Si_{0.35}Ge_{0.65}$ QW grown on $Si_{0.21}Ge_{0.79}$. As predicted, a strong absorption variation has been obtained at 1.3 µm [6]. A second way to decrease the operating wavelength of the widely-used $Ge/Si_{0.15}Ge_{0.85}$ QW grown on $Si_{0.1}Ge_{0.9}$ is to increase QW confinement energy by varying the quantum well thickness. As an example, the absorption spectra of a structure made of 6.5 nm-thick Ge well is reported in Figure 2, showing a strong QCSE within the O-band telecommunication wavelength, verifying the potential to use this structure for high extinction ratio and moderate absorption loss modulator over 30-nm-wide spectral range from 1330 to 1360 nm.

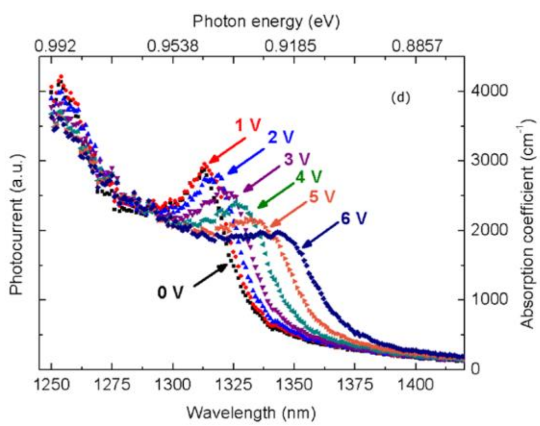

Fig. 2. QCSE in the O-band telecommunication wavelength, using 6.5 nm-thick $Ge/Si_{0.15}Ge_{0.85}$ QW grown on $Si_{0.1}Ge_{0.9}$

4. Combination with advanced passive structures

The main challenging point of Ge/SiGe QW-based devices is their integration with silicon on insulator (SOI) waveguides because of the need of a virtual substrate between Si and Ge-rich structures. We proposed to integrate Ge/SiGe QW devices with SiGe waveguides using the linear index increasing in the graded buffer. Light can then be coupled in the QW using tapered waveguides for the active devices as illustrated in Fig 3. As a main challenge the Ge concentration in the SiGe waveguide should allow simultaneously a low loss waveguide and a good crystalline quality of the Ge/SiGe QW active region. Using this approach, an optical link based on a passive $Si_{0.16}Ge_{0.84}$ waveguide and optoelectronic Ge/$Si_{0.16}Ge_{0.84}$ QWs devices including an optical modulator and a photodetector has been demonstrated. [8]

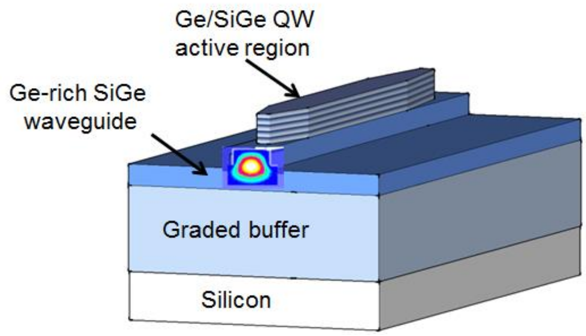

Fig. 3. Integration of Ge/SiGe QW devices with Ge-rich SiGe waveguide on graded SiGe buffer.

In addition we recently demonstrated the possibility to use this new Ge-rich SiGe on graded buffer waveguide as a competitive platform for photonic integration: sharp bends and an integrated Mach-Zehnder interferometer including SiGe waveguides and a relatively compact beam splitter were demonstrated from Ge-rich SiGe waveguide on graded buffer on silicon substrate. These results pave the way toward the monolithic integration of Ge-based active devices with efficient and compact passive Ge-rich SiGe optical circuitry on bulk silicon wafers.

5. Acknowledment

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