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Silicon photonics based on Ge/SiGe quantum well structures

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Abstract—Ge/SiGe Quantum well structures have a strong potential to revolutionize silicon photonics. This paper review recent works including high speed modulator and photodetector, electro-refraction, QW engineering to tune the wavelength and waveguide integration.

Keywords—Quantum well, quantum confined Stark Effect, silicon, germanium, modulation, photodetection

I. 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. Demonstrations of electro-refraction in Ge/SiGe quantum well will then be shown, followed by the presentation of different methods for engineering Ge/SiGe QW to tune the operating wavelength to 1.3 μm . Finally different solutions to integrate Ge/SiGe QW devices with low-loss waveguides will be presented.

II. 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 -width, 90 μm -long waveguide embedded 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].

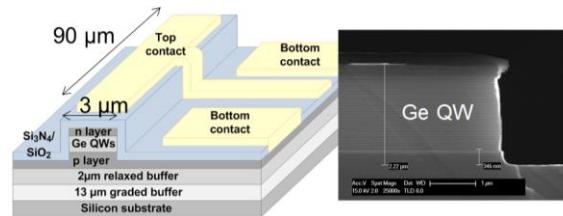


Fig. 1. Schematic view of a Ge/SiGe QW structure in a waveguide configuration that can be used as a modulator or as photodetector.

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 has been demonstrated [5].

III. ELECTRO-REFRACTION IN GE/SiGE QUANTUM WELL

QCSE causes strong variations in the absorption spectrum, which also lead to changes of the refractive index, as stated by Kramers-Krönig relations. Electro-refraction based on QCSE can make Ge/SiGe QW attractive for the realization of electro-optic devices requiring phase shifters. We investigated such electro-refractive effect by experimentally characterizing the shift of Fabry-Perot fringes in the transmission spectra of a Ge/SiGe QW waveguide [3]. A refractive index variation up

to 1.3×10^{-3} was measured with an applied electric field of 88 kV/cm for photon energy located 50 meV below the excitonic resonance. The $V_{\pi}L_{\pi}$ figure of merit is deduced to 0.46 V \times cm which makes Ge/SiGe QW phase shifter competitive with silicon phase shifter.

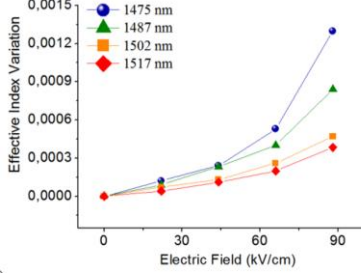


Fig. 2. Effective index variation in Ge/SiGe QW as a function of the electric field for different wavelengths over the band-edge wavelength.

IV. GE/SiGE QUANTUM WELL ENGINEERING

As a main advantage, QW can be engineered to obtain significant QCSE around the telecommunication wavelength of 1.3 μ m. 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 μ m. 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 μ m [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 3, 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.

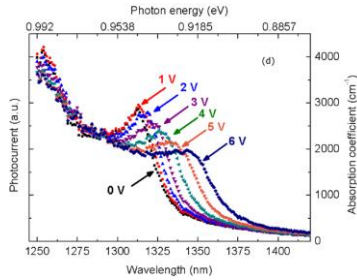


Fig. 3. QCSE in the O-band telecommunication wavelength, using 6.5 nm-thick Ge/Si_{0.15}Ge_{0.85} QW grown on Si_{0.1}Ge_{0.9}

V. WAVEGUIDE INTEGRATION

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 are currently considering two possible integration schemes.

In a first approach we proposed a new strategy of integrating Ge/SiGe QW devices with silicon wafers, based on the use of 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 4. 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]

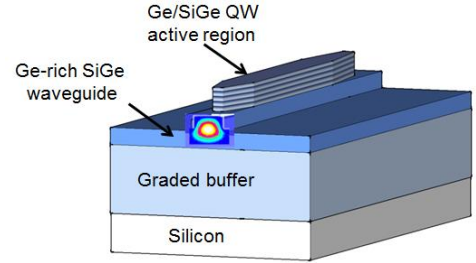


Fig. 4. Integration of Ge/SiGe QW devices with Ge-rich SiGe waveguide on graded SiGe buffer.

When considering high data rate communications based on polarization and wavelength multiplexing, the integration of Ge/SiGe QW structures with SOI waveguide would allow benefiting from both compact and low power consumption active devices and efficient and compact passive building blocks such as AWG. Such integration requires a reduction of the thickness of the buffer layer between Ge/SiGe QW and silicon wafer. To this purpose, we developed a relaxed buffer with 360nm thickness that would practically allow the optical coupling between a SOI waveguide and the Ge/SiGe QW active region [9]. We then theoretically investigated properties of a QW modulator integrated on SOI waveguides. 8 dB ER were predicted with only 4 dB optical insertion loss.

VI. CONCLUSION

The recent reports of high speed modulator and photodetector, electro-refraction, wavelength tuning by engineering Ge/SiGe QW and waveguide integration has demonstrated the strong potential of these structures for silicon photonics.

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