Electro-absorption and electro-refraction in Ge/SiGe coupled quantum wells

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ABSTRACT

Electro-absorption and electro-refraction in Ge/SiGe coupled quantum wells (CQW) grown on Si have been investigated by means of optical transmission measurements. The separate confinement of electrons and holes in the heterostructure gives rise to an anomalous Quantum Confined Stark Effect (QCSE) that can be exploited to strongly enhance the electro-refractive effect with respect to uncoupled quantum wells. A refractive index variation up to 2.3 x 10^{-3} has been measured at 1.5 V, with an VπLπ of 0.046 V cm. This result is very promising for the realization of an efficient and compact phase modulator based on the Ge/SiGe material system.

Keywords: Germanium, quantum wells, silicon photonics, modulators

1. INTRODUCTION

In the last decade, optical devices based on QCSE in Ge/SiGe multiple quantum wells (MQW) grown on Si[1] have undergone an impressive development. QCSE causes a red-shift of the absorption spectrum and a significative reduction of the excitonic absorption peak[2], features that can be exploited to realize compact and efficient intensity modulators. The optical properties of Ge/SiGe MQW have been widely studied, and modulators working at 1490 nm[3-6] and at 1550 nm[7-8], as well as high-speed operation[9] have been demonstrated. The most interesting feature of intensity modulators based on QCSE, thanks to their efficiency, is the possibility to reach power consumption levels as low as 10 fJ/bit [9], thus meeting the aggressive requirements for on-chip optical interconnects[10]. Composition and thicknesses of Ge/SiGe MQW can be finely tailored in order to engineer the material bandgap and to consequently address a very wide range of modulation wavelengths. This approach has been exploited to demonstrate intensity modulation at 1300 nm by increasing the compressive strain in the Ge layers in Ge/$Si_{0.35}Ge_{0.65}$ grown on a $Si_{0.3}Ge_{0.7}$ buffer [11-12] or simply by reducing the well thickness in Ge/$Si_{0.15}Ge_{0.85}$ MQW[13]. All the aforementioned modulators works by exploiting QCSE of the first excitonic transition (cΓ1-HH1), nevertheless, also the second excitonic transition (cΓ1-LH1) was investigated[14]. Very recently, an integrated optical interconnection made by a Ge/SiGe MQW modulator and photodetector connected through a low- loss SiGe waveguide was demonstrated[15]. Remarkably, all the devices were monolithically integrated on silicon by a single epitaxial growth, paving the way for the integration of Ge/SiGe MQW devices with passive optical circuitry. All the aforementioned modulators work by exploiting the electro-absorption based on QCSE. In contrast, much less efforts have been made in order to investigate the electro-refractive effect in Ge/SiGe MQW. QCSE causes strong variations in the absorption spectrum, leading to a significant change in the refractive index as stated by Kramers-Kronig relations. Recently an effective refractive index variation up to 1.3x10^{-3} at -8V bias, with a figure merit $V_\pi L_\pi$ of 0.46 V cm was reported for Ge/$Si_{0.15}Ge_{0.85}$ MQW [16]. It has been theoretically predicted that in symmetrically coupled Ge/SiGe MQW (CQW) the electro-refractive (ER) effect should be even stronger, thanks to the tendency of electron and hole envelope functions to be confined in different QWs under bias [17]. Symmetrically and asymmetrically CQW exhibit a peculiar physical behavior due to the coupling of the wavefunctions through the barrier[18]. For this reason, they were widely investigated in III-V semiconductors for many purposes including non-linear optics[19], photodetection[20] and optical modulation[21]. In this work, electro-absorption (EA) and ER have been investigated in Ge/$Si_{0.15}Ge_{0.85}$ CQWs by means of optical transmission measurements.

2. SAMPLE GROWTH

The CQW heterostructure was grown by Low Energy Plasma enhanced chemical vapor deposition (LEPECVD) [22] on a 100 mm n-Si(001) substrate with a resistivity of 1-10 Ω cm. Before the heteroepitaxial growth, the substrate was dipped in an aqueous hydrofluoric acid solution for 30 seconds to remove the native oxide. The first part of the structure consists of a $Si_{1-y}Ge_y$ graded buffer, with a total thickness of 13 μm, where the Ge concentration y was linearly raised from 0% to 90% with a grading rate of 7%/μm. The growth rate was 5-10 nm/s, while the substrate temperature was linearly decreased from 740°C to 525°C. The graded buffer was then capped with a 2 µm thick p-doped ($5x10^{18}$ cm^{-3}) $Si_{0.1}Ge_{0.9}$ layer to form a fully relaxed virtual substrate (VS) and the p-type contact of the p-i-n structure embedding the CQWs. The threading dislocation density was 6 x 10^6 cm^2 as measured by chemical defect etching[23]. The MQW consists of seven repetitions of the following period (10 nm Ge well + 3 nm $Si_{0.15}Ge_{0.85}$ inner barrier + 10 nm Ge well + 37 nm $Si_{0.15}Ge_{0.85}$ outer barrier). Individual layer thicknesses and compositions were designed to realize a strain-symmetrized structure. The outer barrier is thick enough to avoid coupling between adjacent periods. This part of the structure was grown at rate of 1 nm/s and the temperature was lowered at 475°C to avoid the inter-diffusion at the barrier/well interface. Finally a 200 nm phosphorous doped (1 x 10^{19} cm^{-3}) $Si_{0.1}Ge_{0.9}$ n-type contact layer was deposited. A cross section of the structure is shown in Fig.1a. Layer compositions and strain states were measured by high-resolution x-ray diffraction (HR-XRD) by using a PANalytical X'Pert PRO MRD diffractometer. Out-of-plane and in-plane lattice parameters, were measured (relative to the Si reflection) for the VS peak and the superlattice satellites. Ge content and strain were then obtained using the known lattice parameters for relaxed SiGe alloys[24] and interpolated elastic constants of Si and Ge[25]. The final composition of the VS was found to be 90% (with a residual in-plane strain of 0.12%). The in-plane lattice parameter of the MQW stack is the same as that of the VS, meaning that the MQW stack is coherently matched to the VS. In Fig. 1b the omega-2theta scan (measured with respect to the 004 Si reflection) is reported. The reciprocal space maps are reported in Fig. 1(a and b).

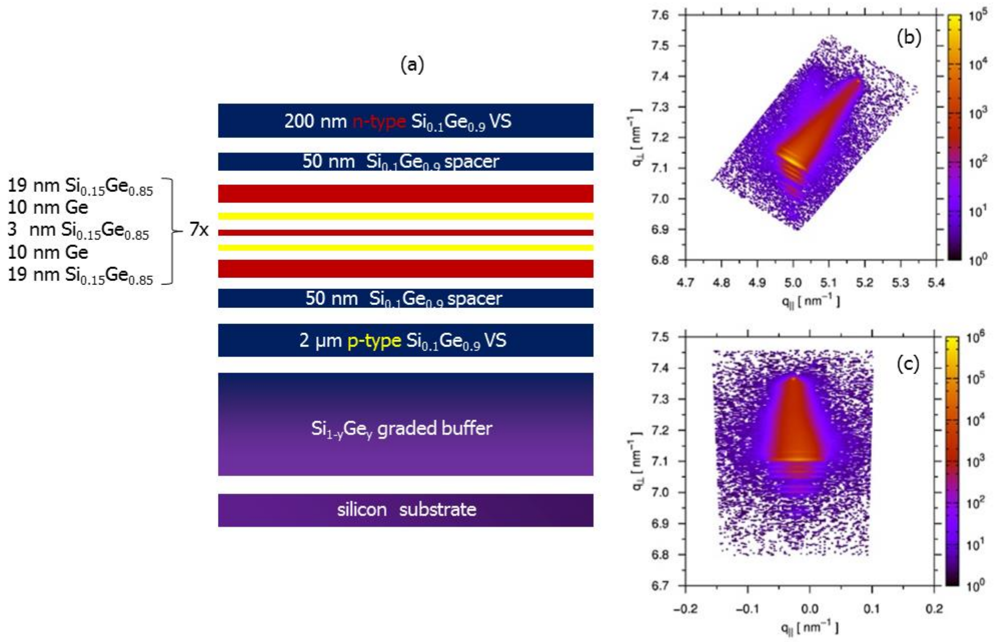

Figure 1: Schematic of the sample with detailed growth steps (a). Reciprocal space maps with respect to the 224 Si reflection (b) and to the 004 Si reflection.

3. DEVICE FABRICATION AND MEASUREMENT SET-UP

In order to investigate the EA and ER effects in Ge/SiGe CQWs, 64 µm long, 100 µm wide planar waveguides have been fabricated. The waveguides were patterned by optical litography and then dry etched to the p-doped Si0.1Ge0.9 layer. The sidewall roughness of the etched mesa was smoothened by hydrogen peroxide (H2O2) solution. 100 nm of silicon dioxide were deposited as passivation layer on the left and right walls of the waveguide by plasma-enhanced chemical vapor deposition (PECVD). For n and p contacts 10 nm of Ti and 300 nm of Au was evaporated and lifted off. The I-V characteristic of the device is shown in Fig. 2. The measurements have been performed at room temperature with a spectral resolution of 0.1 nm. A tunable laser emitting light from 1250 to 1450 nm with a power of 1 mW has been used. Light from the laser has been butt coupled into the planar waveguide using a taper-lensed fiber, which has been positioned to inject light in the waveguide region not covered by the top metal contact to reduce optical losses. An objective has been used to couple the output light into a photodetector. A schematic of the measurement set-up is shown in Fig. 3.

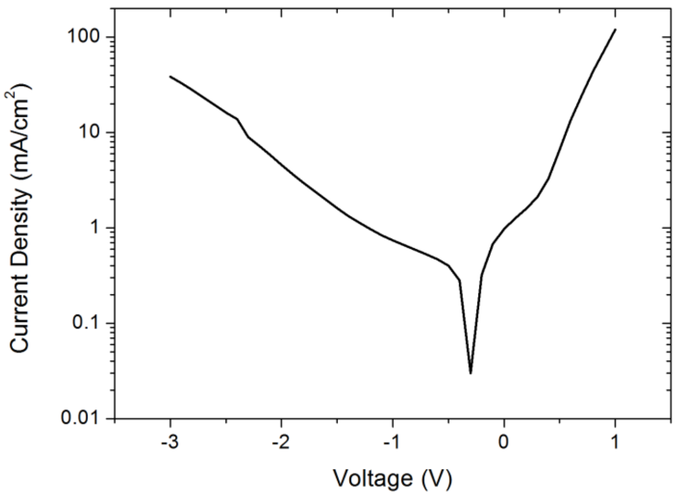

Figure 2: Dark current density as a function of voltage of the processed device.

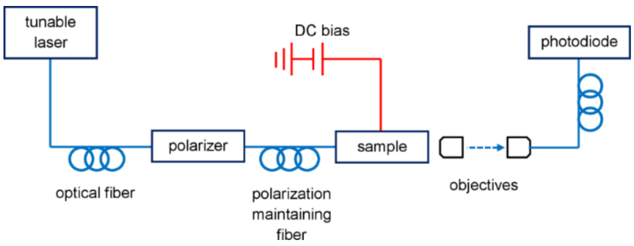

Figure 3: Schematic of the experimental set-up used for the transmission measurements.

4. ELECTRO-ABSORPTION

The absorption spectra of the device at different electric field obtained from optical transmission measurements are reported in Fig. 4 for light with TE polarization. The baseline of each curve has been shifted of 200 cm^{-1} to better highlight the spectral features. In a standard uncoupled quantum well, cΓ1-HH1 and cΓ2-HH2 transitions would be separated by a few tens of meV , but in the case of a CQW, the cΓ1 and cΓ2 states represents the “bonding” (zero-node wavefunction) and “anti-bonding” (one-node wavefunction) forming due to QW coupling and are separated only by ≈ 10 meV. A few meV energy also separates the HH1 and HH2 states. When a small electric field is applied to the structure, the bonding and antibonding states become more localized in two different wells. A detailed explanation of the evolution of the absorption spectrum as a function of the electric field can be found in[18].

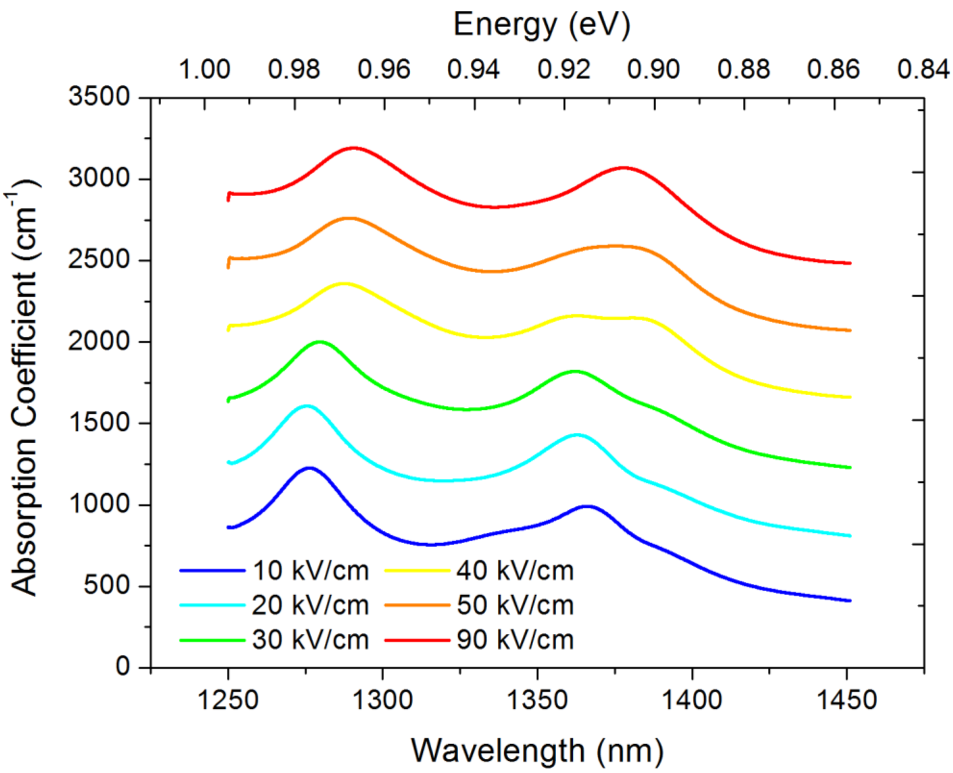

Figure 4: Absorption spectra at different electric field.

5. ELECTRO-REFRACTION

The effective index variation was experimentally characterized by the shift of the Fabry-Perot (FP) fringes in the absorption spectra of the planar waveguide as a function of the applied bias. FP fringes experience a spectral shift when a voltage is applied to the device. In a cavity, the resonance condition determines the wavelength of the maxima (λ_p) in the transmission spectra according to the equation (1):

$$2n_{eff}(\lambda)L = p\lambda_p \tag{1}$$

where L is the device length, n_{eff} is the effective index of the guided mode and p is an integer number representing the order of the transmission peak. Taking into account the dispersion properties of the medium, a spectral shift $\Delta\lambda$ (see fig. 5) is related to the effective index variation by:

$$\Delta n_{eff}(\lambda) = \frac{\Delta\lambda}{\lambda} n_g(\lambda) \tag{2}$$

Finally the group index $n_g(\lambda)$ can be experimentally deduced from the longitudinal mode spacing $\Delta\lambda_p$ by using:

$$n_g(\lambda_p) = \frac{\lambda_p^2}{2L\Delta\lambda_p} \tag{3}$$

The effective index variation Δn_{eff} was thus obtained from Eq. 2 using the measured values of $\Delta\lambda$ and $n_g(\lambda)$, and is reported in Fig. 6 for different wavelengths from 1420 to 1440 nm. Strikingly, the refractive index variation shows a local maximum at an electric field of 40 kV/cm (1.5 V) for all the considered wavelengths. In order to evaluate the viability of the device as a phase shifter, the device length necessary to achieve a p phase shift L_π was calculated as:

$$L_\pi = \frac{\lambda}{2\Delta n_{eff}} \tag{4}$$

For λ = 1420 nm, where the electro-refractive effect is stronger, $L\pi$ is 300 μm for an electric field of 40 kV/cm (1.5 V bias) with a $V\pi L\pi$ figure of merit of 0.046 V cm according to eq. 4. This value is one order of magnitude lower with respect to uncoupled Ge/SiGe QWs[16] and competitive with respect to pure Si[26].

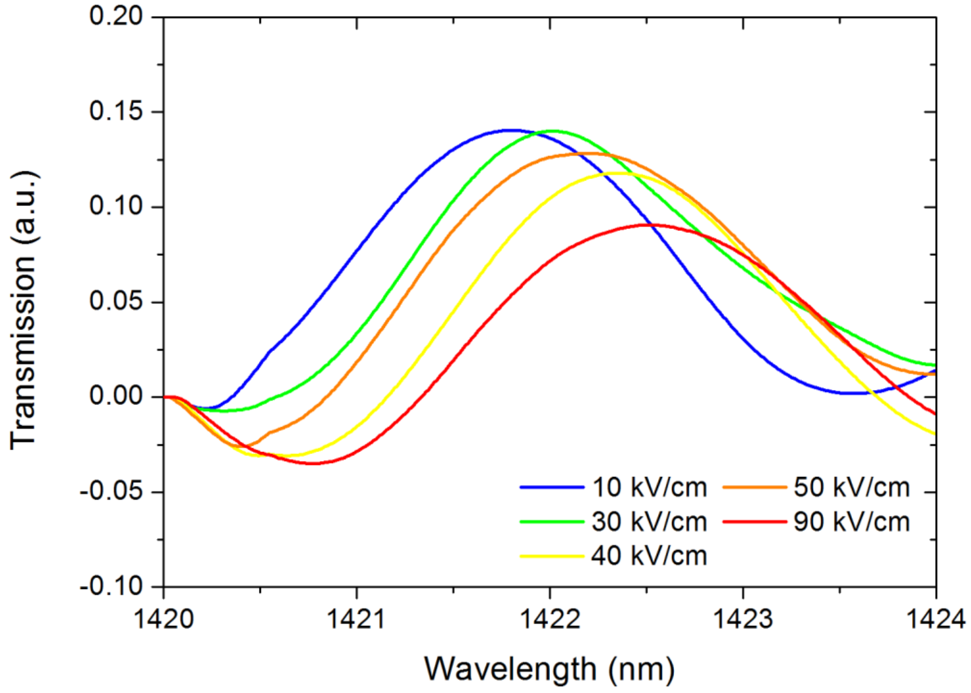

Figure 5: Shift of the Fabry-Perot fringes as a function of the electric field.

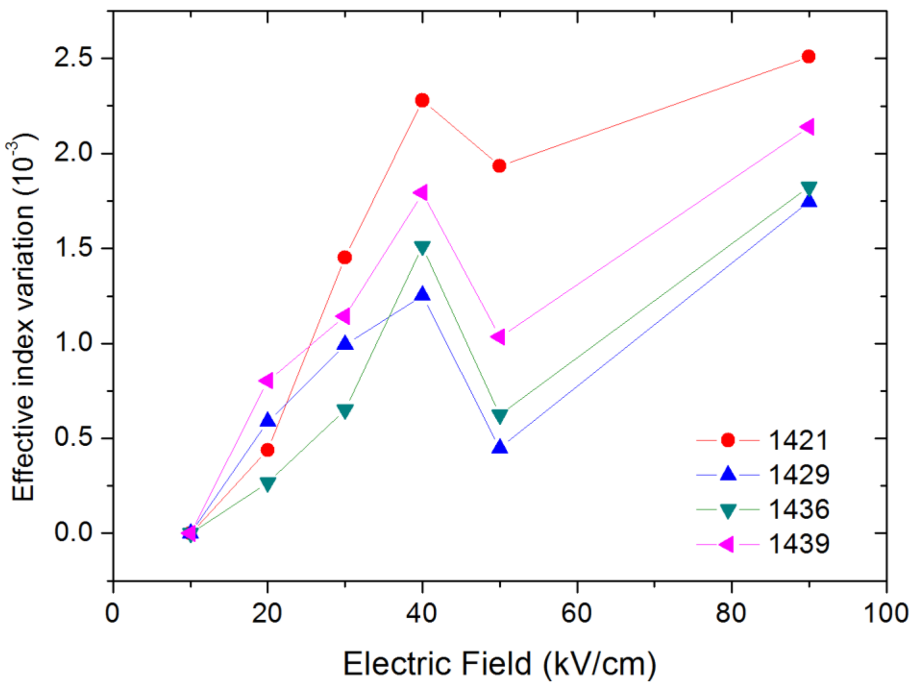

Figure 6: Effective index variation as a function of the applied electric field for different wavelengths.

6. CONCLUSIONS

To summarize, we have investigated the electro-absorption and electro-refraction in Ge/SiGe symmetrically coupled quantum wells. The evolution of the absorption spectra of the device as a function of the applied electric field is very different with respect to standard quantum wells thanks to the coupling, leading to an enhanced electro-refractive effect with effective index variation higher than $2x10^{-3}$ under moderate electric field. In order to exploit the potentiality of Ge/SiGe CQW as compact, high speed and low power consumption optical modulators, the active region will have to be integrated into an interferometric structure such as a Mach– Zehnder interferometer. The integration of QW active regions with low-loss SiGe waveguides on top of graded buffer is a promising approach, as sharp bends and Mach-Zehnder interferometers[27] as well as the integration of a passive SiGe waveguide with an electro-absorption modulator and a photodetector[15] were demonstrated recently.

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