Quantum-confined Stark effect at 1.3 µm in Ge/SiGe quantum-well structures

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***Abstract*—We demonstrate a room-temperature strong quantum confinement Stark effect (QCSE) in Ge/SiGe multiple quantum wells (MQW) heterostructures, embedded in PIN diode. The device is designed to operate at 1.3µm, and QCSE is shown by photocurrent measurement in a surface illuminated device.**

Keywords : electroabsorption; Quantum Confined Stark Effect, Ge/SiGe MQW; optical interconnects.

I. Introduction

Optical interconnects in chip-scale distance have been considered as an efficient alternative to electrical interconnects [1]. To integrate both electrical and optical devices on the same chips, the fabrication of the latter with processes compatible with Silicon CMOS (Complementary Metal-Oxide Semiconductor) is highly desirable [1]. Ge-based photonics has shown recently impressive results with demonstrations of light source [2], modulator [3], waveguides [4] and photodetectors [5-6]. Electroabsorption modulator based on Quantum Confined Stark Effet (QCSE) was formerly demonstrated with group III-V material [7], and recently in group IV material like Ge/SiGe multiple quantum well structures (MQW) [8-9]. Among the advantages of MQW structures in comparison to bulk materials, MQW structures can be engineered to shift the operating wavelength of QCSE. In this work we demonstrate room-temperature QCSE in Ge/SiGe MQWs working at 1.3µm.

II. Device Design and Fabrication

To work at 1.3µm, a blue shift of the absorption edge from 0.8eV for bulk Ge to 0.95eV is needed. Different methods can be used to achieve this wavelength shift, among them are the increase of the confinement in the quantum wells by, for example, using very narrow quantum well, or the use of SiGe material as the quantum well or the use of strain engineering to increase the band gap energy in Ge quantum well [10].

We designed Ge/SiGe QW structure by strain engineering in order to work at 1.3 µm. In comparison with our first demonstration [9] working at 1.4 µm Ge concentration is now decreased in the barriers and in the relaxed buffer (a strain compensated structure is used). Therefore, Ge well is more compressively strained relative to the relaxed buffer and its band gap energy is increased. In the fabricated device, 21% of Si is used in the relaxed buffer and 35 % in SiGe barriers while the wells are made of pure Ge.

The Ge/$Si_{0.35}Ge_{0.65}$ MQW structure is embedded in a PIN diode, allowing large electrical field to be applied across the active region. The structure is grown by low energy plasma-enhanced chemical vapor deposition (LEPECVD) [11]. On a 100mm Si(001) substrate, a 11µm $Si_{1-y}Ge_y$ graded buffer was linearly grown from y=0 to y=0.79 of germanium concentration with rate of 7%/µm. This graded buffer allows achieving very high quality QW structures despite the large lattice mismatch between Si and Ge, which is very useful to study material properties. After this graded buffer, 2µm of $Si_{0.21}Ge_{0.79}$ is added forming a fully relaxed virtual substrate (VS) on where PIN diode can be grow. P region was then deposed, which consists a 500nm boron-doped $Si_{0.21}Ge_{0.79}$ layer, followed by 50nm $Si_{0.21}Ge_{0.79}$ spacer. The MQW region is formed by 10 nm of Ge (well) and 15nm $Si_{0.35}Ge_{0.65}$ (barrier) which are repeated 20 times to achieve 20 QW's. This thick structure is possible thanks to the average Ge concentration in Ge/SiGe MQW layers equal that of the buffer layer. Finally, a 50nm $Si_{0.21}Ge_{0.79}$ cap layer and 100nm phosphorus-doped $Si_{0.21}Ge_{0.79}$ n-type layer are added to form the top contact.

A square surface 100µmx114µm illuminated PIN diode was fabricated for the photocurrent measurement. UV lithography and dry etching were used to pattern the mesa. For metallic contacts, 20nm of Ti and 300nm of Au are evaporated and lifted-off for both n and p contacts. The schematic view and optical microscope image of the fabricated device are show in figure (1).

III. Experimental Results

Photocurrent measurements of the Ge/SiGe MQWs at several reverse bias voltages were performed at room temperature. The incident light, normal to the surface of diode, was randomly polarized from tunable laser from 1245nm to 1350nm with step of 1nm. A chopper was used to modulate the input light at 0.5 kHz and a lock-in amplifier permits to measure precisely the photocurrent spectra, provided that a reference photocurrent measurement at a given wavelength is used for normalization.

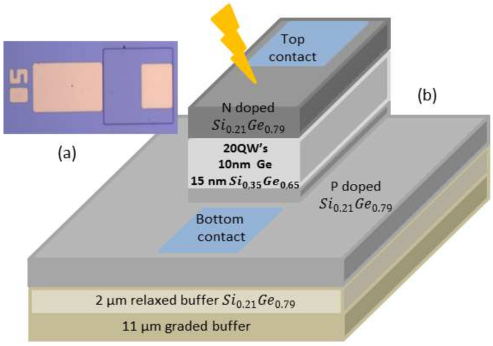

Figure 1. (a). Optical microscopic top view of device. (b), Cross section showing the differents layers.

To estimate the strength of band-to-band absorption for light incident perpendicular to QW structures, the fraction of light absorbed per well γ_{well}, can be calculated by the following equation in case of $\gamma_{well} << 1$ [12]:

$$N \times \gamma_{well} = \frac{\Delta P}{P_0} \quad (1)$$

Where ΔP the optical power absorbed in the MQW's and P_0 is the incident power. N is the number of wells in the intrinsic region. To calculate the fraction of light absorbed per well from the photocurrent measurements, the following relation is used [9]:

$$I_{ph} = \frac{eP_0 N\gamma_{well}(\lambda)\lambda}{hc} \quad (2)$$

Where P_0 is the incident optical power, taking into account the reflection at the surface of device, h is Planck constant, e is electron charge, c is the speed of light and λ is wavelength.

The absorption spectra obtained from this method is reported in figure (2). As a consequence of the confinement effect in the MQW and the strain between Ge in QW and the VS, a shift of absorption edge from 0.8eV for bulk Ge to 0.96eV is clearly observed. At low reverse bias (-1V is used in order to have electric field applied across the entire PIN diode, in order to collect all photogenerated carriers), clear exciton peak is seen in the spectra at 1.277 µm which can be attributed to the transition between heavy hole level and electronic state at Γ point. It can be noted that at higher wavelength (1.34µm), the residual fraction of light absorbed, attributed to the indirect absorption in the quantum wells is rather small in comparison with direct gap absorption.

When the reverse bias is increased, the two mean characteristics of QCSE are observed in the measured spectra: the absorption edge is shifted toward larger wavelength, and the excitonic peak absorption is decreased. From those two effects, absorption per well at 1.3 µm goes from 1.5×10^{-3} to 3.5×10^{-3} when bias varies from 1 to 5V.

IV. Conclusion

In this work, we demonstrate the possibility to engineer Ge/SiGe MQW structures. Strong quantum confined Stark effect was demonstrated at 1.3 µm, which will enable reliable

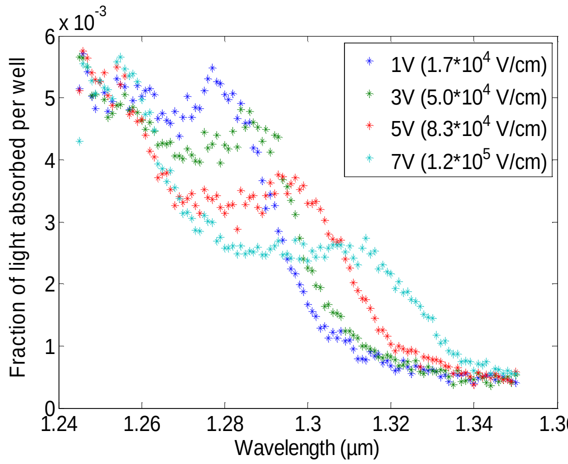

Figure 2. Absorption spectra for different applied electrical field from photocurrent measurement.

design of integrated photonic devices based on Ge/SiGe MQW structures.

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