Quantum-confined Stark effect in Ge/SiGe multiple quantum well planar waveguides

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Résumé

Room-temperature quantum-confined Stark effect (QCSE) in Ge/SiGe multiple quantum wells (MQWs) with light propagating parallel to the plane of the Ge/SiGe MQWs is reported. The absorption spectra at different reverse bias voltages are obtained from optical transmission measurements of planar waveguides embedded in a p-i-n diode. Polarization dependence of the absorption spectra of the Ge/SiGe MQWs is clearly observed. The planar waveguides exhibit a high extinction ratio and low insertion loss over a wide spectral range for TE polarization. The results indicate the potentiality of using the heterostructures as high performance optical modulator integrated directly on silicon electronic chips for optical interconnect application.

1. Introduction

Group-IV photonic devices are considered as promising and cost effective solutions to the interconnect bottleneck caused by metallic interconnection [1, 2]. Active building blocks such as silicon optical modulators, Ge photodetectors, hybrid silicon lasers, and a Ge-on-Si laser have been demonstrated [3-6]. Nevertheless, complete CMOS-compatible monolithic integration between optics and electronics for chip-scale optical interconnects remains a challenging task due to the different materials and technologies used. Using direct-gap transitions in group IV indirect-gap semiconductors such as Ge/SiGe heterostructures or bulk GeSi [7-9] provides a new path towards the monolithic integration of light sources, optical modulators, and photodetectors. For modulation, the quantum-confined Stark effect (QCSE) in Ge/SiGe multiple quantum wells (MQWs) has been demonstrated with light incident perpendicular to the plane of the MQWs [7, 9]. However, for applications in integrated photonics, propagation of light parallel to the plane of the Ge/SiGe MQWs has to be investigated. In this case, theoretical calculations show strong polarization dependence of the absorption coefficient [10]. In this work, we report absorption spectra of Ge/SiGe MQW planar waveguides embedded in p-i-n diode structure for TE and TM light polarizations. Polarization dependence of the absorption as well as QCSE at different reverse bias voltages is clearly demonstrated and the optical modulation characteristics of Ge/SiGe MQWs are also investigated from the experiments.

2. Ge/SiGe heterostructures and p-i-n diode fabrication

Figure 1. (a) Schematic view of the fabricated Ge/SiGe MQWs planar waveguides. (b) Optical microscope view of the device with the input fiber injecting light into the waveguide.
In this work, Ge/SiGe MQWs are grown by low-energy plasma-enhanced chemical vapor deposition (LEPECVD) [11]. On a 100 mm Si(001) substrate, Si$_{1-y}$Ge$_y$ graded buffer is deposited from Si to Si$_{0.1}$Ge$_{0.9}$. Later, 2 µm of Si$_{0.1}$Ge$_{0.9}$ are grown on top of the graded layer, forming a fully relaxed virtual substrate (VS). Subsequently, a 500 nm boron-doped Si$_{0.1}$Ge$_{0.9}$ layer is grown for p-type contact. The MQWs consist of twenty 10 nm Ge quantum wells (QWs) sandwiched between 15 nm Si$_{0.1}$Ge$_{0.85}$ barriers. Finally, a 100 nm phosphorus-doped Si$_{0.1}$Ge$_{0.9}$ n-type contact is added.

To investigate absorption spectra of Ge/SiGe MQWs waveguides at different reverse bias voltages, 100 µm wide planar waveguides, embedded in a p-i-n diode, are fabricated allowing an electric field to be applied across the plane of MQWs as in Fig 1(a). The waveguides are patterned by standard UV lithography and dry etched to the p-doped Si$_{0.1}$Ge$_{0.9}$ layer. A few tens of nanometers of silicon dioxide are deposited to serve as a passivation layer on the left and right walls of the waveguide, to reduce leakage current. For metallization, 600 nm of Al are evaporated and lifted-off for both p and n contacts. The top contact covers only part of the waveguide ridge so as to minimize optical loss due to absorption from the metal. For device characterization, an input fiber is positioned to inject light where there is no top contact metal in order to avoid optical loss as shown in Fig. 1(b). The waveguide lengths are 64 µm. Therefore, a deep etch of 90 µm is performed in order to bring the input fiber and output objective to the input and output facets of the waveguide. Absorption spectra are obtained via direct optical transmission measurements.

3. Measurement results: electro-optic properties of Ge/SiGe quantum wells

Transmission measurements of the Ge/SiGe MQW waveguides at several reverse bias voltages are performed at room temperature with a tunable laser emitting light from 1390 to 1540 nm, covering the spectral range exhibiting efficient electroabsorption effect with limited insertion loss.

The absorption spectra of a waveguide with 64 µm length at different reverse bias voltages are reported in Fig. 2a for light with TE polarization, for which both HH$_{1-c\Gamma_1}$ and LH$_{1-c\Gamma_1}$ transitions are allowed [10]. The absorption edge is shifted from the 0.8 eV of bulk Ge due to both the confinement effect in the QWs and the strain between the Ge QWs and the VS. Without bias voltage, a clear exciton peak at room temperature is observed around 1400 nm (0.88 eV) which can be attributed to the HH$_{1-c\Gamma_1}$ transition. The exciton peak associated with the LH$_{1-c\Gamma_1}$ transition has a higher energy, which is beyond the spectral range of the experiment. With increasing reverse bias voltages, two main characteristics of the QCSE are observed: the Stark (red) shift of the absorption spectra and the reduction of the exciton related absorption peak due to the reduction of the overlap between the electron and hole wavefunctions.

For light with TM polarization, the HH$_{1-c\Gamma_1}$ transition is forbidden and only the LH$_{1-c\Gamma_1}$ transition is allowed [10]. The absorption spectra at different reverse bias voltages experimentally obtained from the transmission measurements are reported in Fig. 2b. Evidently, the exciton peak due to the HH$_{1-c\Gamma_1}$ transition disappears thanks to the aforementioned selection rules. Moreover, although the exciton peak of LH$_{1-c\Gamma_1}$ transition is beyond the spectral range of the experiment at zero bias, the overall absorption characteristics of light with TM polarization at each bias voltage from 1390 to 1480 nm are consistent with the simulation results in Ref. 10.

To be effectively used as a waveguide electroabsorption modulator, the Ge/SiGe MQW waveguide structures must demonstrate the ability to operate with high extinction ratio and low insertion loss [13]. The extinction ratio can be increased with the use of longer Ge/SiGe MQW waveguides; nevertheless, a higher insertion loss can be expected since indirect gap absorption is becoming more and more relevant in longer devices.
Figure 3. The extinction ratio between 0 V and 6 V reverse bias and the absorption loss at 0 V of the fabricated Ge/SiGe MQWs planar waveguides for (a) TE polarization (b) TM polarization.

In Fig. 3a, the extinction ratio between 0 and 6 V reverse bias and the insertion loss at 0 V reverse bias are presented for TE polarization. The waveguide has an extinction ratio larger than 5 dB for a wide spectral range between 1414 and 1437 nm, and a maximal value of 9.5 dB at 1423 nm. In addition 5 dB extinction ratio is achieved simultaneously with insertion loss lower than 3 dB for the 14 nm wide spectral range between 1423 and 1437 nm. For the 34 µm device, an extinction ratio larger than 5 dB is obtained for wavelength from 1415 to 1431 nm. 5 dB extinction ratio is achieved simultaneously with insertion loss lower than 3 dB for the 8 nm wide spectral range between 1423 and 1431 nm.

For TM polarization, as shown in Fig. 3b, a high extinction ratio can be observed between 0 and 8 V reverse bias. The waveguide has an extinction ratio larger than 5 dB with insertion loss lower than 3 dB for an approximately 4 nm wide spectral range from 1409 to 1405 nm.

4. Conclusions

In conclusion, Room-temperature QCSE in Ge/SiGe MQWs with light propagating parallel to the plane of the Ge/SiGe MQWs waveguide is investigated. The device exhibits strong polarization dependence. A wide working regime can be identified for both TE and TM polarizations for the given heterostructures. High extinction ratio of 9 dB with low absorption loss of 2 dB is experimentally obtained from the fabricated device at 1426 nm for TE polarization. The results clearly indicate the potentiality of using the heterostructures as high performance optical modulator integrated directly on silicon electronic chips for optical interconnect application.

Références