High performance Ge/SiGe quantum well electro-absorption modulator

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***Abstract*— A 23 GHz Ge/SiGe multiple quantum well electro-absorption waveguide modulator is demonstrated with 10 dB extinction ratio (ER). 9 dB ER is achieved with 1V swing with energy consumption limited to 108 fJ per bit.**

Keywords-component; Quantum-confined Stark effect, Ge/SiGe, multiple quantum well modulators

I. INTRODUCTION

To be a viable replacement of copper wires at the chip scale, optical interconnects have to meet aggressive requirements in terms of power consumption, data density, and preferably monolithic integration with silicon. The devices should operate over a wide spectral range with an energy consumption of less than 100 fJ/bit [1]. Such low power consumption and wideband devices are unlikely with conventional silicon modulators based on a Mach–Zehnder interferometer (MZI) or a resonator [1, 2]. In this aspect, the electro-absorption (EA) modulator is one of the best approaches to obtain low energy consumption and high speed modulation due to its small footprint and sub-picosecond operation time for a wide spectral range [3]. Ge, a group IV material like Si, has been successfully monolithically integrated into CMOS fabrication processes by semiconductor companies [4, 5]. Interestingly, Ge quantum wells (QWs) [6, 7] have demonstrated a QCSE as strong as that of III-V semiconductor QWs. So far, high speed modulation using Ge/SiGe MQWs has been demonstrated up to 3.5 GHz using a surface illuminated p-i-n diode structure [8] and a transmission at 7 Gbps has also been demonstrated in waveguide configuration based on butt-coupling between the MQW structure and a Silicon-on-Insulator (SOI) waveguide [9]. In this paper, we demonstrate a modulator with a modulation bandwidth of 23 GHz obtained from a Ge/SiGe MQW waveguide. The modulator also exhibits high extinction ratio over a wide spectral range with an estimated energy consumption of as low as 108 fJ per bit. The schematic view of the fabricated device is shown in Fig. 1.

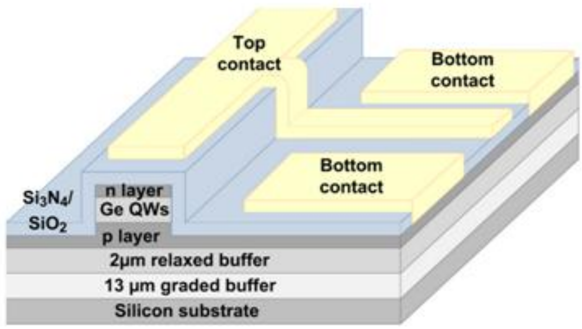

Figure 1. Schematic view of the 3 µm × 90 µm Ge/SiGe MQW modulator; Ge/SiGe MQWs were grown by low-energy plasma-enhanced chemical vapor deposition [10] and detailed epitaxial layers can be found in Ref 7.

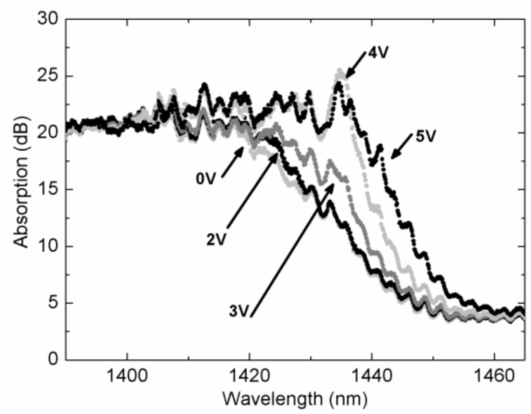

Figure 2. Absorption spectra of the 3 µm wide 90 µm long Ge/SiGe MQW waveguide as a function of wavelength and photon energy for reverse bias voltages of 0, 1, 2, 3, 4, and 5 V.

II. EXPERIMENTAL RESULTS

Transmission spectra of the Ge/SiGe MQW waveguides at several reverse bias voltages are shown in Fig 2. By increasing the reverse bias voltages, the red shift of the absorption spectra, which is a characteristic of the QCSE, is observed. Extinction ratio achieved using different bias can be deduced by substracting transmission spectra, and are reported in Fig 3 and 4. From Fig 3. an extinction ratio (ER) higher than 6 dB for a wide spectral range between 1425 and 1446 nm is obtained, with a maximal ER value of around 10 dB achieved between 1433 and 1442 nm for a reverse bias of 5 V and between 1433 and 1437 nm for a reverse bias of 4 V. From Fig 4. with a voltage swing of only 1 V between 3 and 4 V and of only 2 V between 3 and 5 V, ER higher than 6 dB is obtained from 1433 to 1437 nm and from 1433 to 1444 nm respectively. As seen in Fig 2., the absorption loss at 0 V of the Ge/SiGe waveguide used in this work is around 5.5 – 12 dB at the wavelength region between 1433 and 1444 nm. This absorption loss could be decreased by optimizing the light confinement in the MQW region. Indeed the overlap of the first optical mode with the MQW region is only 12 % and part of the optical loss also comes from the overlap between the optical mode and the 2 µm thick $Si_{0.1}Ge_{0.9}$ relaxed buffer and the doped regions. The frequency response of the modulator was evaluated at 1448 nm using an opto-RF vector network analyzer (Agilent 86030A). The normalized optical response at the dc reverse bias of - 4.5 V as a function of frequency is given in Fig. 5. The 3 dB cut-off frequency of 23 GHz was experimentally obtained. For energy consumption, the junction capacitance of the waveguide device with a size of 3 µm × 90 µm and 20 Ge QWs is calculated to be 62 fF, which is also consistent with the values extracted from S_{11} parameter measurement. From energy/bit = 1/4 $(CV_{off}^2\text{-}CV_{on}^2)$, the energy consumption per bit of the EA modulator in this paper can estimated to be 108 fJ/bit for a voltage swing of 1 V between 3 and 4 V biases.

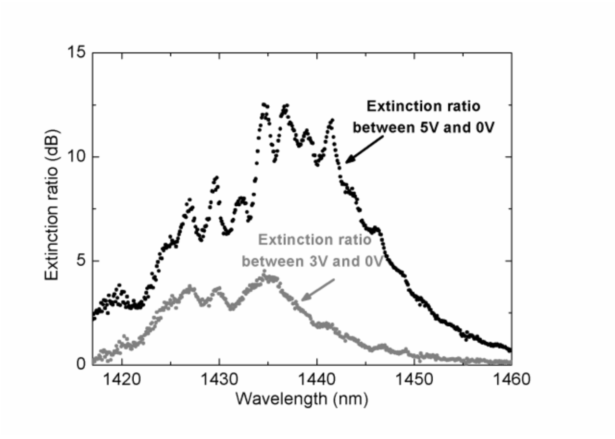

Figure 3. Extinction ratio of the waveguide between 0 and 3, 5 V

The research has received funding from the French ANR under project GOSPEL (Direct Gap related Optical Properties of Ge/SiGe Multiple Quantum Wells). Financial support for the epitaxial growth was provided by the Cariplo foundation through NANOGAP project.

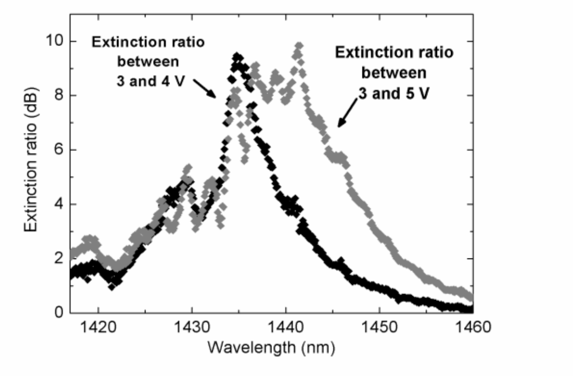

Figure 4. Extinction ratio of the waveguide for a voltage swing of 1 V between 3 and 4 V and of 2 V between 3 and 5 V

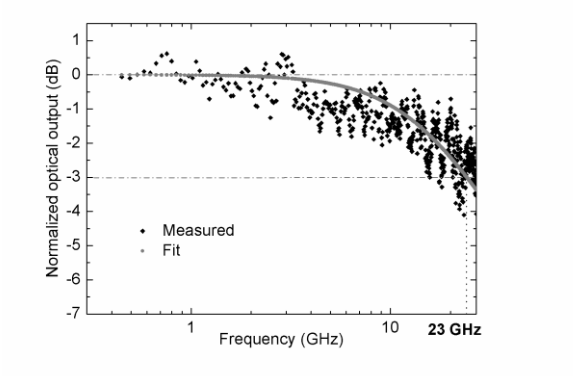

Figure 5. Normalized optical response at the dc reverse bias of - 4.5 V.

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