Solid-State Electronics 83 (2013) 92–98

Contents lists available at SciVerse ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Ge quantum well optoelectronic devices for light modulation, detection, and emission

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ARTICLE INFO

Article history:
Available online 28 February 2013

Keywords:
Ge/SiGe
Multiple quantum wells
Electro-absorption modulator
Photodetector
Light emitting diode
Waveguide

ABSTRACT

We report on light modulation, detection, and emission characteristics of Ge/SiGe multiple quantum well waveguides using the same epitaxial growth and fabrication steps. As an electro-absorption modulator, the device exhibits the capability to achieve high extinction ratio with low swing bias voltages and high modulation bandwidth. As a photodetector, dark currents, optical responsivities, and high speed performance have been studied. High speed light detection up to 10 Gb/s has been obtained simultaneously with good values of optical responsivity. As a light emitting diode, direct gap electroluminescence (EL) from the Ge/SiGe MQW waveguides has been experimentally demonstrated at room temperature within the spectral range of light modulation and detection.

1. Introduction

Ge has been identified as a promising material to cost-effectively enhance the performance of Si electronic and photonic integrated circuits (ICs) [1–6]. For optics, despite being an indirect-gap semiconductor, Ge has been expected to play a key role in enabling future chip scale optical interconnects to meet aggressive requirements in terms of power consumption, data density, and monolithic integration with silicon [7]. Strong light detection, modulation, and emission capabilities around C and L telecommunication wavelength bands were shown [8–12] using Ge direct-gap transitions of bulk Ge on Si. The ongoing investigations of integrating crystalline bulk Ge at the front-end-of-line and back-end-of-line of a CMOS chip for photonic applications have shown several significant developments recently [13–16]. On the other hand, Ge quantum wells (QWs) were shown to further enhance light modulation based on quantum-confined Stark effect (QCSE) using the direct-gap transition of Ge multiple quantum wells (MQWs) embedded in a vertical p–i–n diode [17,18]. For light detection and emission, high speed Ge MQW p–i–n surface-illuminated photodiodes [19] and room temperature (RT) photoluminescence (PL) from similar Ge MQWs [20,21] were experimentally shown. The ability to work at the telecommunication wavelengths of 1.3 and 1.55 μm was theoretically and experimentally discussed [22–25]. Moreover, in order to be practically employed in photonic integrated circuits, light modulation and detection from Ge/SiGe MQW waveguides were also investigated. Light modulation at 7 Gbps was demonstrated based on butt-coupling between the MQW structure and a Silicon-on-Insulator (SOI) waveguide [26]. For light detection, Ge/SiGe MQW waveguide detectors were reported with a data transmission rate up to 2.5 Gb/s at −8 V reverse bias and responsivity as high as 0.3 A/W [27]. For both demonstrations, Ge/SiGe MQWs were grown on Si substrate through a direct 400–800 nm thick $Si_{0.1}Ge_{0.9}$ relaxed buffer obtained via relatively high temperature (800–850 °C) annealing using reduced-pressure chemical vapor deposition.

In this article, the Ge/SiGe heterostructures were grown on Si substrate using a buffer graded from Si to $Si_{0.1}Ge_{0.9}$ using low-energy plasma-enhanced chemical vapor deposition (LEPECVD) technique [28]. With the use of a low energy plasma to enhance and control the deposition, a fast growth rate as high as 10 nm s^{-1} of Si_xGe_{1-x} graded buffer with low surface roughness and dislocation density can be obtained at substrate temperatures down to 400 °C. Then, at the same temperature a high quality Ge/SiGe MQW structures can be deposited with lower deposition rate of 0.3 nm s^{-1}. This allows us to investigate the properties of the MQW structures with very good material quality. Through LEPECVD deposition technique, these works report light modulation, detection, and emission characteristics of Ge/SiGe MQW waveguides. It aims to comprehensively study the potential to simultaneously employ the same Ge/SiGe MQW epitaxial growth and fabrication process for different photonic functionalities on photonic integrated circuits. 3 μm wide and 80–90 μm long Ge/SiGe MQW waveguides embedded in a coplanar electrode were fabricated. The electro-absorption characteristics of the Ge/SiGe MQWs were assessed by both DC and RF measurements. The

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http://dx.doi.org/10.1016/j.sse.2013.01.024

modulator exhibited the capability to achieve high extinction ratio with low swing bias voltages and high modulation bandwidth of 23 GHz. For light detection, dark currents, optical responsivities, and high speed performance were studied from the same device configuration. High speed operation up to 10 Gb/s was obtained simultaneously with high values of optical responsivity. Finally, the same devices were investigated as light emitting p–i–n diodes to study emission properties of the Ge/SiGe MQWs at room temperature and within the spectral range of light modulation and detection. Direct gap electroluminescence (EL) from the Ge/SiGe MQW waveguides was experimentally demonstrated. The dependence of the EL intensity on the injection current and temperature was measured. The direct gap EL from Ge/SiGe MQWs was shown to be transverse-electric (TE) polarized, confirming that the EL originated from recombination with a HH state.

2. Epitaxial growth and device fabrication

Ge/SiGe MQWs structures were grown on 4 inch Si wafers. A 13 μm $Si_{1-y}Ge_y$ graded buffer was deposited with linearly increasing Ge concentration y at a rate of 7%/μm from Si to $Si_{0.1}Ge_{0.9}$. Then, 2 μm of $Si_{0.1}Ge_{0.9}$ was grown on the top of the graded layer, forming a fully relaxed virtual substrate (VS) on which high quality Ge rich heterostructures can be grown. Subsequently, a 500 nm boron-doped $Si_{0.1}Ge_{0.9}$ layer was grown to serve as a *p*-type contact. The epitaxial steps from the graded buffer to the *p*-type layer were conducted with a high growth rate of 5–10 nm s^{-1} for maximum efficiency. Next for optimum layer and interface control, a low growth rate of ~0.3 nm s^{-1} was used to deposit a 50 nm $Si_{0.1}Ge_{0.9}$ spacer, the MQW stack, and a 50 nm $Si_{0.1}Ge_{0.9}$ cap layer. The MQW stack itself consisted of twenty 10 nm Ge quantum wells (QWs) sandwiched between 15 nm $Si_{0.15}Ge_{0.85}$ barriers. The average Ge concentration in the Ge/SiGe MQW stack was designed to be equal to that of the $Si_{0.1}Ge_{0.9}$ VS, allowing the growth of strain compensated thick structures. Finally, a 100 nm phosphorus-doped $Si_{0.1}Ge_{0.9}$ *n*-type contact was grown in an alternative reactor to avoid cross-contamination. Schematic cross section of the epitaxial steps for the Ge/SiGe MQWs, and scanning electron microscopy (SEM) image of the Ge/SiGe MQWs with 20 Ge QWs are shown in Fig. 1a and b respectively.

The 3 μm wide and 80–90 μm long waveguide p–i–n diodes embedded in a coplanar electrode were fabricated. four main lithography steps for (1) mesa etching, (2) mesa isolation etching, (3) Si_3N_4/SiO_2 insulation layer deposition and patterning, and (4) metallization were used as summarized in Fig. 2a. The fifth lithography step for 90 μm deep etching was also done to allow the input fiber to be brought to the input facet of the waveguide. The schematic and SEM views of the fabricated devices of a 3 μm wide waveguide with a coplanar electrode are shown in Fig. 2b and c respectively. Dark current characteristics of the fabricated diode are presented in Fig. 3. Under −1 V, relatively low current densities of around 200 mA/cm^2 (500 nA) were obtained with good rectifying characteristics. No breakdown behavior was observed up to a reverse bias voltage of −6 V.

3. Characterization

Light modulation, detection, and emission characteristics of the fabricated Ge/SiGe MQW waveguide embedded in a p–i–n diode were investigated at room temperature. Firstly, as an electro-absorption modulator Section 3.1 reports on DC and high speed modulation characteristics of the waveguide device. Then, as a waveguide photodetector Section 3.2 demonstrates its light detection performance. Lastly, as a light emitting diode, electroluminescence measurement of the Ge/SiGe MQW waveguide is reported at room temperature in Section 3.3.

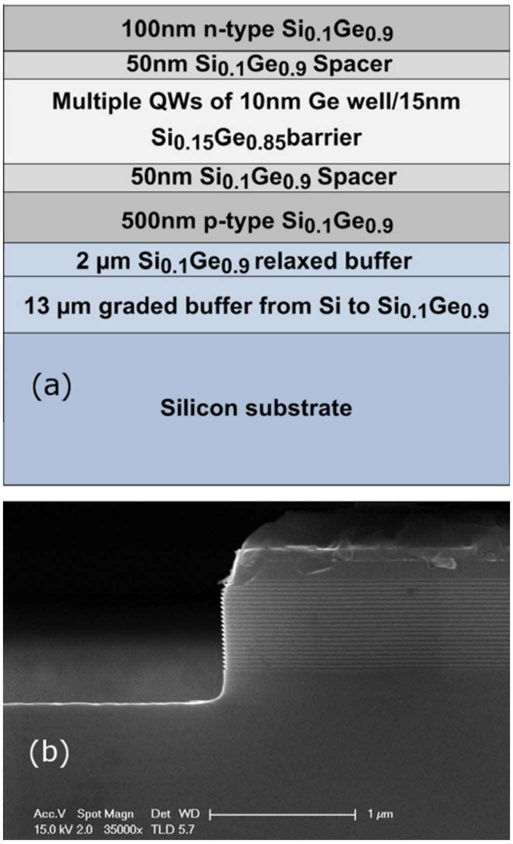

Fig. 1. (a) Cross section of epitaxy steps used for the Ge/SiGe MQWs in this work. (b) SEM image of the Ge/SiGe MQWs with 20 Ge quantum wells.

3.1. Light modulation by QCSE from Ge/SiGe MQW waveguide

Transmission measurements of the Ge/SiGe MQW waveguides at several reverse bias voltages were performed within the absorption edge of the $Ge/Si_{0.15}Ge_{0.85}$ MQWs from 1390 to 1465 nm. Laser light with transverse-electric (TE) polarization was butt coupled into the input facet indicated in Fig. 2b by a taper-lensed fiber. Output light was coupled into a digital photodetector recording the output power. The coupling loss was subtracted from the spectra using a cut-back technique. Transmission measurements of the Ge/SiGe MQW waveguides with different lengths were conducted, and the coupling losses were then estimated by extrapolating the data to a waveguide length of zero.

The measured transmission spectra of the waveguide at reverse bias voltages of 0, −2, −3, −4, and −5 V are reported in Fig. 4a. Wavelength separation between transmission peaks of around 3 nm was due to the Fabry-Perot resonance between the input and the output facets of the waveguide. The absorption edge was shifted from 1550 nm of bulk Ge to around 1420 nm due to both the quantum confinement in Ge QWs and the strain between Ge QWs and the VS. At increasing reverse bias voltages, red shift of the spectra, which is a characteristic of the QCSE, was observed. However, the reduction of absorption at the excitonic transition wavelength when increasing the reverse bias voltages could not be observed, as previously seen in our works with surface-illuminated [17] or shorter waveguide [29] devices, due to the long absorption length of the waveguide configuration [30]. From Fig. 4b, with a voltage swing of 2 V between −2 and −4 V and