Tensile Strained $Ge_{0.99}$ $Si_{0.01}$ EA Modulator Arrays for Integrated Broadband Modulation

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ABSTRACT

Electronic and photonic integrated circuits serve as a promising platform for telecommunications and sensing applications. A one-for-all tensile strained $Ge_{0.99}$ $Si_{0.01}$ modulator array design is proposed to cover a broad telecommunication band with multiple modulators designed and fabricated simultaneously in a single lithography and patterning flow. Modulators with the width from 0.5µm to 3µm demonstrated the absorption edge shift from 1533nm to 1566nm, relating to an array wavelength operation from 1526nm to 1575 nm, with an extinction ratio of 4.5dB at 3V reverse bias. This strain engineering innovation can be applied not only to Ge and GeSi materials, but also to III-V materials for light-emitting, photodetecting, wavelength filtering, and sensing applications. This approach allows electronic - photonic integrated systems to be developed with a simpler device layout, higher device yield, and lower fabrication cost.

Keywords: strain, germanium, waveguide device, modulator, integrated photonics, low-cost fabrication

1. INTRODUCTION

Electronic and photonic integrated circuits serve as a promising platform for telecommunications and sensing applications [1]. Electroabsorption modulators utilize the field-induced Franz-Keldysh effect, which allows fast modulation, small device footprint, and low power consumption [2-3]. Epitaxially grown GeSi films on Si substrates are a suitable materials platform for integrated modulator applications because of the Si CMOS compatibility and distinctive optoelectronic materials properties [3]. A modulator's operation wavelength adjustment and its system integration for broadband modulation are two major challenges of fabricating on-chip modulator arrays for telecommunication. In the case of an electro-absorption modulator, the optimization of the modulator material for a specific wavelength can be achieved by tuning the material composition or applying strain to the material since modulation is achieved near the direct bandedge.

The conventional strategy of inserting a modulator for a specific modulation wavelength involves specific materials engineering and device fabrication for each individual modulator [4-5]. In order to realize an integrated system with broadband modulation, multiple modulators have to be fabricated individually and assembled onto a chip. Each fabrication step adds cost to design and processing. Integrating more modulators for multiple operation wavelengths gives broader band coverage and higher optoelectronic data processing capacity. In this work, a one-for-all tensile strained $Ge_{0.99}Si_{0.01}$ modulator array design is proposed and demonstrated to cover a broad telecommunication band with multiple modulators designed and fabricated simultaneously in a single lithography and patterning flow [6]. A stressor layer applies a homogeneous strain to the modulator structures. By changing the modulator width, the strain in the modulator changes, tuning the $Ge_{0.99}Si_{0.01}$ bandgap and, therefore, the modulation operation wavelength. Thus, modulators made of the same material can operate at various wavelengths with the same stressor layer by simply changing in the dimension of the modulators.

2. MODULATORS ARRAY DESIGN WITH STRAIN ENGINEERING

The waveguide-integrated modulator contains three major optical parts, as shown in Fig 1a. The $Ge_{0.99}Si_{0.01}$ waveguide is placed on top of the Si waveguide with GeSi optical tapers on both ends for the light coupling in and out of the waveguide modulator. The electro-absorption optical modulation occurs in the $Ge_{0.99}Si_{0.01}$ waveguide. The height of Si and $Ge_{0.99}$ $Si_{0.01}$ waveguides are 250nm and 300 nm, respectively. The width of the modulator waveguide is a unique design parameter to vary the modulator materials bandgap as a response of the external stressor layer. The 0.6GPa tensile stressor layer is designed to be on the sides of the modulator waveguides in order to apply uniform and sufficient tensile stress across the short axis of the modulator waveguide. The electrical contacts are on top and bottom of the modulator with ground-signal-ground pads for high-speed modulation measurements, as shown in Fig 1b. As a demonstration of the concept, the $Ge_{0.99}Si_{0.01}$ modulators with waveguide widths of 500nm, 1µm, and 3µm are fabricated and tested.

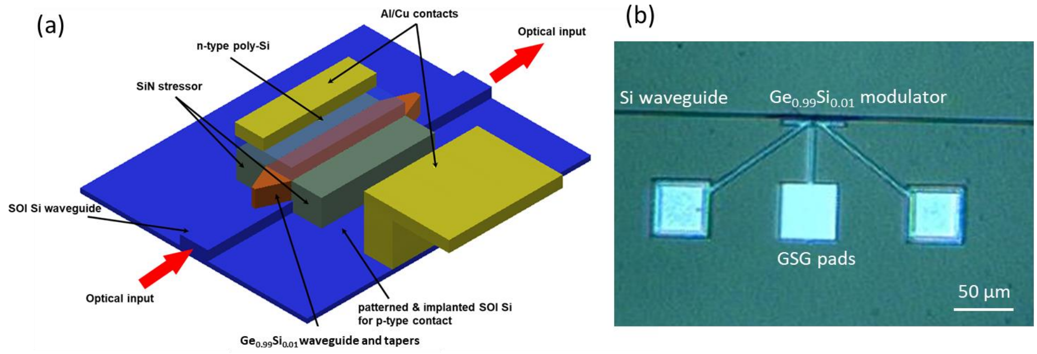

Figure 1. (a) individual $Ge_{0.99}Si_{0.01}$ waveguide modulator schematic, and (b) optical image of the modulator

A finite element model was developed to investigate the strain distribution in $Ge_{0.99}Si_{0.01}$ modulators array for broadband modulation. The simulation was based on solid mechanics theory. The stressor layer is made from silicon nitride with a tensile stress of 0.6 GPa. The strain distribution in 500nm, 1µm, and 3µm wide $Ge_{0.99}Si_{0.01}$ waveguide modulators are plotted in Fig 2. Uniform tensile strain of 0.39%, 0.33%, and 0.18% is obtained in waveguides with widths of 500nm, 1µm, and 3µm, respectively. A deformation potential theory based on quantum mechanics was applied to derive the effect of strain on the band structure of semiconductor materials. The electro-absorption modulator operation wavelength is related to its material band structure. Therefore, the correlation between the operation wavelength and modulator waveguide strain is established and plotted in Fig 2. The $Ge_{0.99}Si_{0.01}$ waveguide modulators with widths of 500nm, 1µm, and 3µm are simulated to have absorption edge at 1572 nm, 1563 nm, and 1542 nm, respectively.

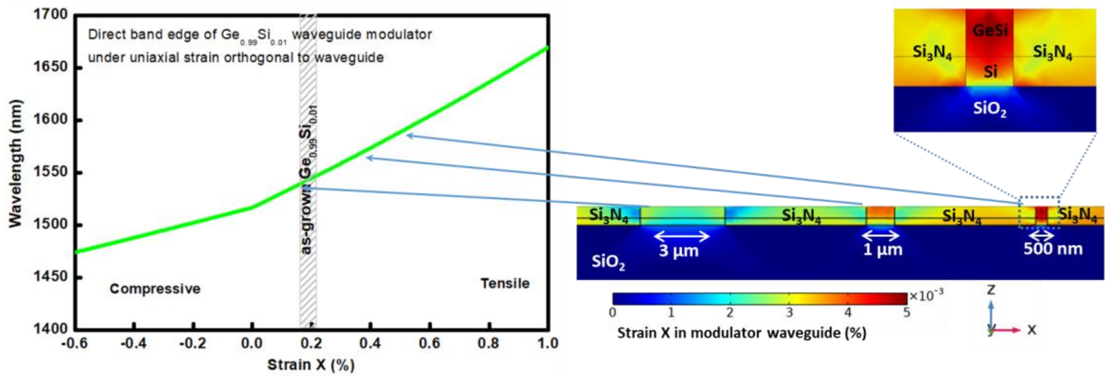

Figure 2. modulator absorption edge as a function of strain in $Ge_{0.99}$ $Si_{0.01}$ waveguide, along with strain distribution in the waveguides under 0.6GPa stressor layer

3. DEVICE FABRICATION AND EXPERIMENTAL RESULTS

The strained modulators array was fabricated in MIT Nano and the Substrate Engineering Lab Cleanroom Facilities. We started with 250nm Si on 3µm SiO_2 insulator wafers. The boron implantation was performed on patterned Si on the SOI wafer. $Ge_{0.99}Si_{0.01}$ was grown epitaxially and annealed cyclically on the p-type Si layer, followed by a poly Si layer growth on top of the $Ge_{0.99}Si_{0.01}$ layer. Phosphorous was implantated with subsequent thermal annealing to provide an n-type Si contact layer. $Ge_{0.99}Si_{0.01}$ waveguides of various dimensions were patterned and etched. A Si_3N_4 stressor layer was then deposited via multi-frequency plasma-enhanced chemical vapor deposition. Finally, trenches were opened for the metal contacts. Multiple waveguides are simultaneously fabricated in the same process flow to achieve the modulators array. The fabrication steps are CMOS-compatible and can be readily implemented into a foundry fabrication.

Optical transmission measurements with and without DC bias were performed to evaluate the device operation wavelength and modulator performance, as shown in Figure 3. The optical transmission spectra of three waveguide modulators with various widths show a shift of the absorption band-edge. A generalized Franz-Keldysh model was applied to fit the optical transition and exacted the direct band structure parameters. The direct bandgaps derived from the fitting are 0.792 eV, 0.797 eV, and 0.809 eV for 500nm, 1µm, and 3µm wide $Ge_{0.99}$ $Si_{0.01}$ waveguide modulators with the 0.6GPa tensile stressor layer. That corresponds to the wavelength of the absorption edge at 1566nm, 1555nm, and 1533nm, which are consistent with the values simulated from the device design. Since the modulation width of a single GeSi EA modulator is around 15 nm [3], the demonstrated wavelength range for our modulator array ranges from 1526nm to 1575 nm. The optical transmission under reverse bias shows a device extinction ratio of 4.5dB at –3V. The modulators show an increase in insertion loss with waveguide width, that is believed to be due to the optical loss during the light coupling through the tapers, and optical absorption induced from the contacts. The device design can be further improved to reduce insertion loss and increase the extinction ratio.

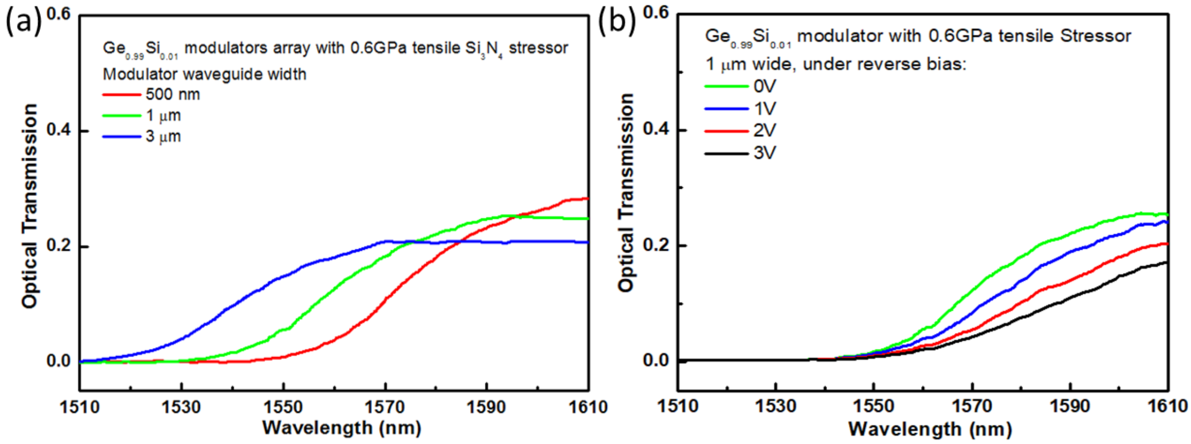

Figure 3. Optical transmission measurement of modulators array (a) without and (b) with reverse bias voltage.

4. CONCLUSIONS

In summary, a one-for-all tensile strained $Ge_{0.99}$ $Si_{0.01}$ modulator array design is proposed to cover a broad telecommunication band with multiple modulators designed and fabricated simultaneously in a single lithography and patterning flow. Modulator arrays with waveguide widths from 0.5µm to 3µm, show an wavelength operation from 1526nm to 1575 nm, with an extinction ratio of 4.5 dB at operation wavelength and 3V reverse bias. Variation in composition and strain can extend the operation range of the array significantly. This strain engineering innovation can be applied not only to Ge and GeSi materials, but also to III-V materials for light-emitting, photodetecting, wavelength filtering, and sensing applications. That allows the electronic and photonic integrated system be developed with a simpler device layout, higher device yield, and lower fabrication cost.

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