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Ge-rich silicon germanium as a new platform for optical interconnects on silicon

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ABSTRACT

We propose germanium-rich silicon-germanium (SiGe) as a new platform for optical interconnects. The platform viability is experimentally and theoretically investigated through the realization of main building blocks of passive circuitry. Germanium-rich $\text{Si}_{1-x}\text{Ge}_x$ guiding layer on a graded SiGe layer is used to experimentally show $12\mu\text{m}$ radius bends by light confinement tuning at a wavelength of 1550nm . As a next step, Mach Zehnder interferometer with 10 dB extinction ratio is demonstrated. High Ge content of the proposed platform allows the coupling with Ge-based active devices, relying on a high quality epitaxial growth. Hence, the integration on Silicon of high speed and low power consumption Ge-rich active components is possible, despite the high lattice mismatch between silicon and germanium.

Keywords: Silicon photonics, Germanium, Waveguide, Bends, Mach-Zehnder interferometer

I. INTRODUCTION

Data consumption is increasing every day and electronic integrated circuits are reaching their limits. To follow the trend, new technical solutions have to be proposed to overpass high power consumption and bandwidth limitations. Optical interconnects are probably the most viable solution. However, the choice of material for the photonic platform is crucial as it must be compatible with actual silicon based CMOS technology. Germanium is identified as a very promising option for Si compatible optical interconnects. Using Ge pseudo direct gap properties, Ge based devices have shown efficient optical modulation¹⁻⁴ and photodetection⁵⁻⁹ within the telecommunication wavelength range. These devices are remarkable for their high speed and low power consumption properties. Moreover according to recent results on electrorefraction in germanium quantum wells, Ge based compact phase shifters can be targeted¹⁰⁻¹¹. Additionally, germanium laser sources are under development¹²⁻¹³. However, the integration on bulk silicon and with passive circuitry of these components is challenging from material point of view because of a huge lattice mismatch between Si and Ge. The use of a graded buffer layer is an efficient strategy that allows growing high quality active devices on silicon thanks to low dislocation rate. It was recently shown that light can be confined in a Ge-rich SiGe virtual substrate grown on such graded layer. Hence, the integration of Ge based active devices becomes possible: germanium quantum well (QW) active region embedded in a PIN diode is grown on $\text{Si}_{1-y}\text{Ge}_y$ (with y higher than 0.8 to guarantee high quality of active region) virtual substrate that acts also as a guiding layer. Thus, an optical link composed of a Ge/SiGe quantum well photodetector and modulator linked by $\text{Si}_{0.16}\text{Ge}_{0.84}$ virtual substrate waveguide was successfully demonstrated¹⁴. With this approach only straight waveguides were shown. Due to low index contrast in these waveguides, low footprint passive structures were still a challenge. In the following, sharp bends and Mach Zehnder interferometers are demonstrated. By playing on light confinement compact passive structures were obtained. Ge rich SiGe on graded buffer waveguides are experimentally shown to be a promising platform for optical interconnects on silicon. This work paves the way for the monolithic integration of Ge based active devices on silicon.

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II. EPITAXIAL GROWTH, DESIGN AND FABRICATION

2.1 SIGE GROWTH

The structure composed of $2\mu\text{m}$ thick relaxed $\text{Si}_{0.2}\text{Ge}_{0.8}$ guiding layer on top of a graded buffer was grown by low energy plasma enhanced chemical vapor deposition (LEPECVD). The $\text{Si}_{1-y}\text{Ge}_y$ graded buffer is grown on a 100mm silicon wafer with a deposition rate of 5-10 nm/s. Ge concentration y is linearly increased from 0 to 0.79 during the growth over $11\mu\text{m}$ thickness. Thus the refractive index varied from 3.477 to 4.112 at 1550nm wavelength. Then, $2\mu\text{m}$ thick relaxed $\text{Si}_{0.2}\text{Ge}_{0.8}$ guiding layer is grown on the top of the graded buffer. Ge concentration of 0.8 in the guiding layer places indirect absorption band edge below $1.55\mu\text{m}$ wavelength. A better vertical light confinement is achieved by 1% difference in Ge concentration between the top of the graded buffer and the guiding layer. A cross section of sample layers is shown in Fig.1(a). The terminal Ge concentration of the graded buffer is inspected and confirmed by X-ray diffraction measurement after the growth (Fig.1(b)). Passive circuitry fabrication can be performed using this structure and its germanium concentration is high enough to use the guiding layer as a virtual substrate for further growth of Ge-rich layers for active components.

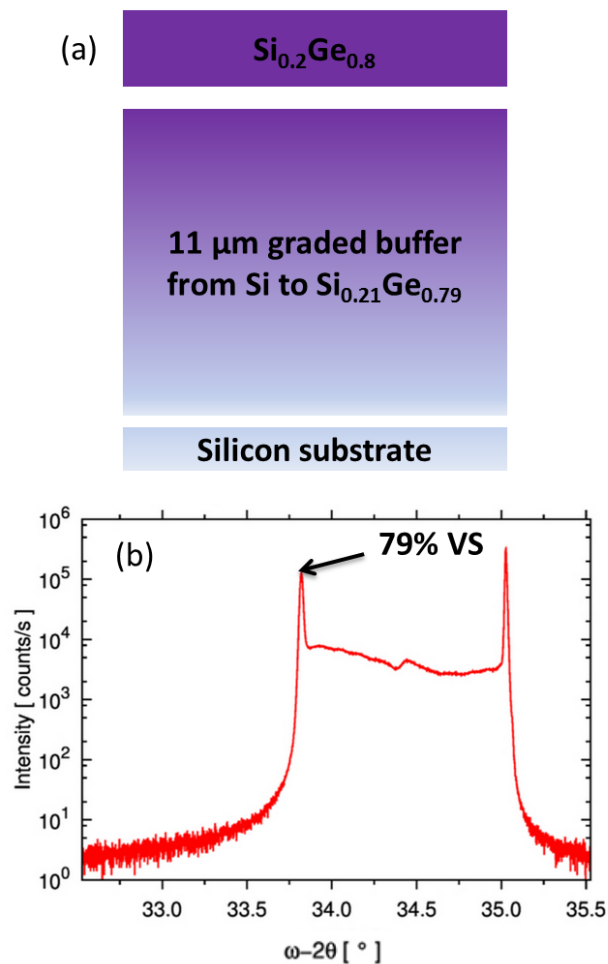


Figure 1. (a) Schematic diagram of Ge-rich SiGe waveguide. (b) X-ray diffraction ω - 2θ scan

2.2 PASSIVE DEVICES DESIGN AND FABRICATION

Slightly etched waveguides (Fig. 2(a)) have low propagation losses. However because of their low confinement (Fig. 2(b)) low bend radii (below $100\mu\text{m}$) cannot be reached using only this kind of waveguides.

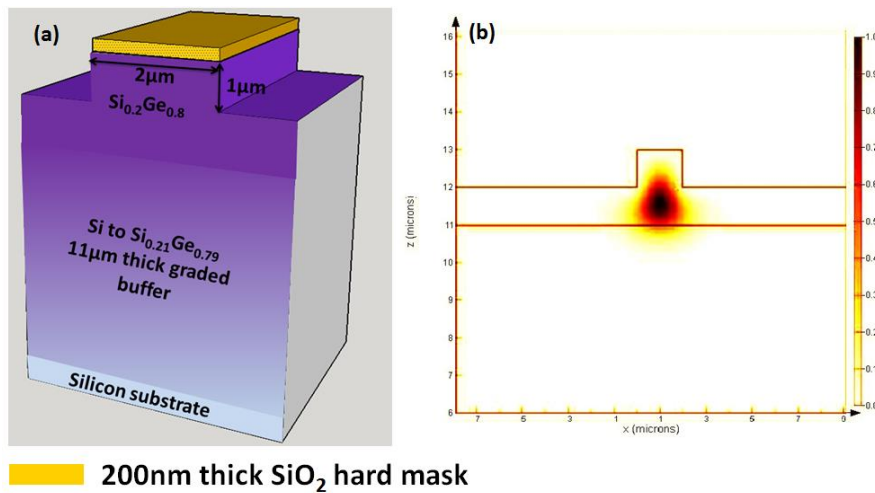


Figure 2. (a) Slightly etched waveguide for straight waveguide portions. (b) Field intensity profile in TE polarization

To obtain compact and sharp 90° turns slightly etched waveguides are combined with deeply etched ones (Fig. 3(a)). $2\mu\text{m}$ wide and $2.5\mu\text{m}$ deeply etched waveguides have better light confinement (Fig. 3(b)) and consequently lower radiation losses¹⁵. Hence, sharper turns with acceptable losses for telecom wavelengths can be attained by slight etching straight portions and deep etching bent regions.

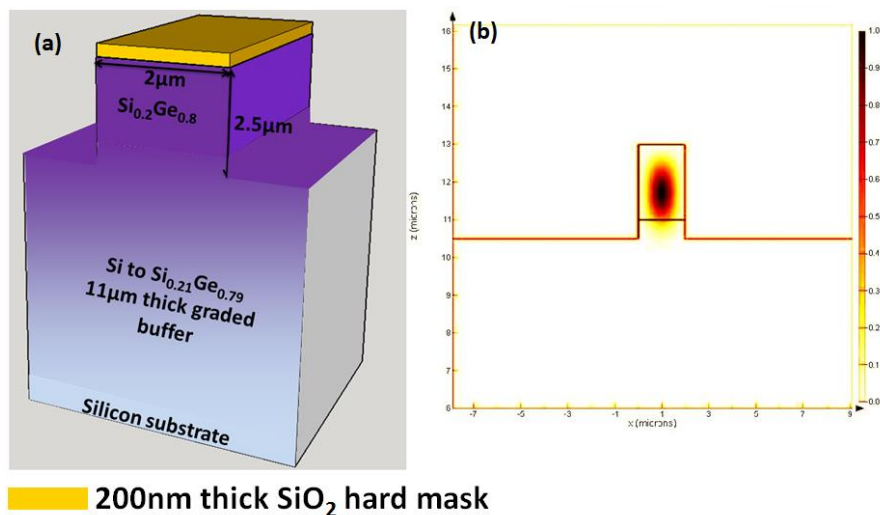


Figure 3. (a) Deeply etched waveguide for bent portions. (b) Field intensity profile in TE polarization

Based on the growth reported on Figure 1.(a), sharp bends and asymmetric Mach-Zehnder interferometers were fabricated. First, 200nm silicon dioxide (SiO_2) was deposited by plasma enhanced chemical vapor deposition (PECVD) on the waveguide layer. Then, with deep UV lithography followed by inductively coupled plasma etching (ICP), SiO_2 hard mask is fabricated. Slightly etched rib waveguides are then defined by ICP etching (Fig2. (a)) and treated with hydrogen peroxide solution to smooth sidewall roughness (H_2O_2). At the end 90° bends and bent portions of Mach Zehnder interferometers were deeply etched using 200nm SiO_2 hard mask (Fig4.(a) and (b)). SiO_2 hard mask is thus used for the self-alignment of consecutive slight and deep etch steps in the bent portions. Finally, H_2O_2 treatment is done again.

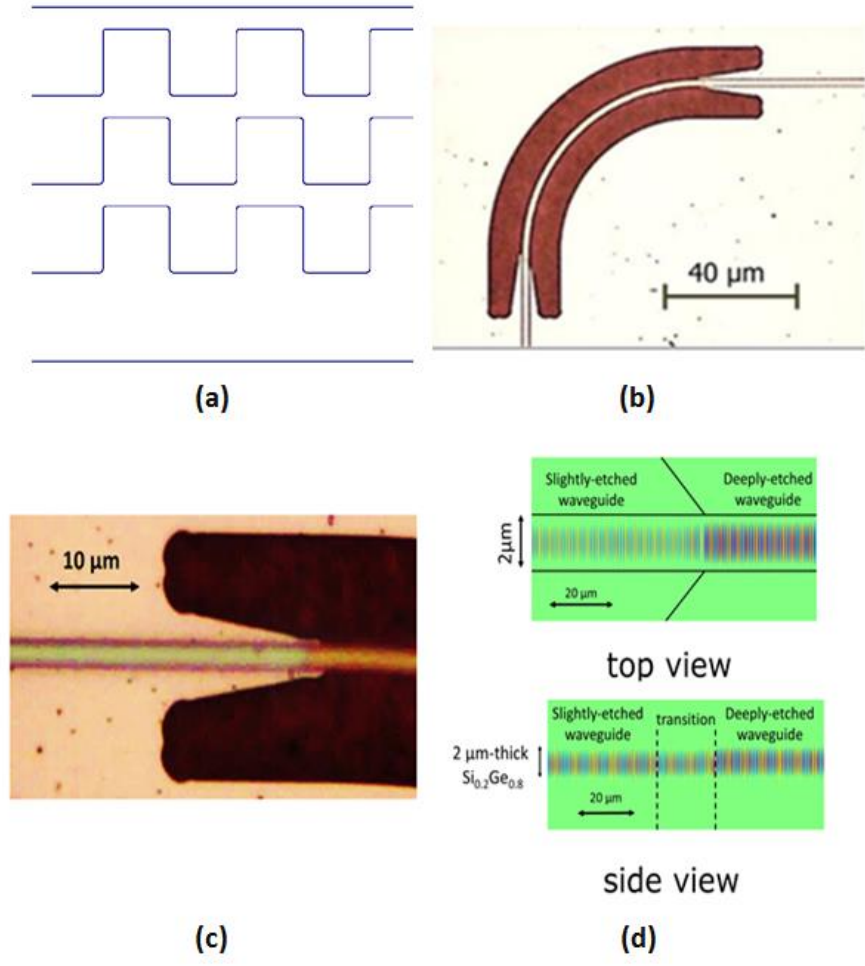


Figure 4. (a) schematic view of fabricated 90° turns. (b) Zoom on a 90° bend, deeply etched region appear darker. (c) Zoom on the transition between differently etched regions (d) propagation simulation for the transition section calculated in TE polarization with eigen mode expansion solver

An abrupt change in the effective index occurs when the light passes by the junction between differently etched waveguides generating additional optical losses. Consequently, to minimize transition losses a $20\mu\text{m}$ tapered transition was designed (Fig. 4(c)) using numerical simulations (Fig. 4(d)). For the side view, a slice located $1\mu\text{m}$ below the top surface of the waveguide is considered for the calculation while a simulation is performed on the slice located in the middle of the waveguide for the side view. From this simulations no radiation losses is seen which indicates the good design of the tapered transition.

Phase tuning is a criterion that should be considered to evaluate the validity of a photonic platform. Ge-rich asymmetric Mach-Zehnder interferometers on graded buffer were studied to demonstrate the viability of the new Ge-rich photonic platform. Using slightly etched rib waveguide (Fig. 2(a)) Multi-Mode beam splitters (MMI) have been designed. Optimal performances are obtained for the following geometry: $187\mu\text{m}$ long, $11\mu\text{m}$ wide beam splitter with a $2\mu\text{m}$ width input waveguide and $3.5\mu\text{m}$ width output waveguides separated by $2.3\mu\text{m}$ as reported on the schematic view of the beam splitter Fig. 5 (a). The propagation simulation is shown in Fig.5 (b). Using this type of beam splitter, an asymmetric Mach-Zehnder was designed as shown on the layout general view on Fig.5 (c). Zooms on slightly etched MMI beam splitter and deeply etched Y junction of the fabricated interferometers are shown in Fig.5 (d) and (e).

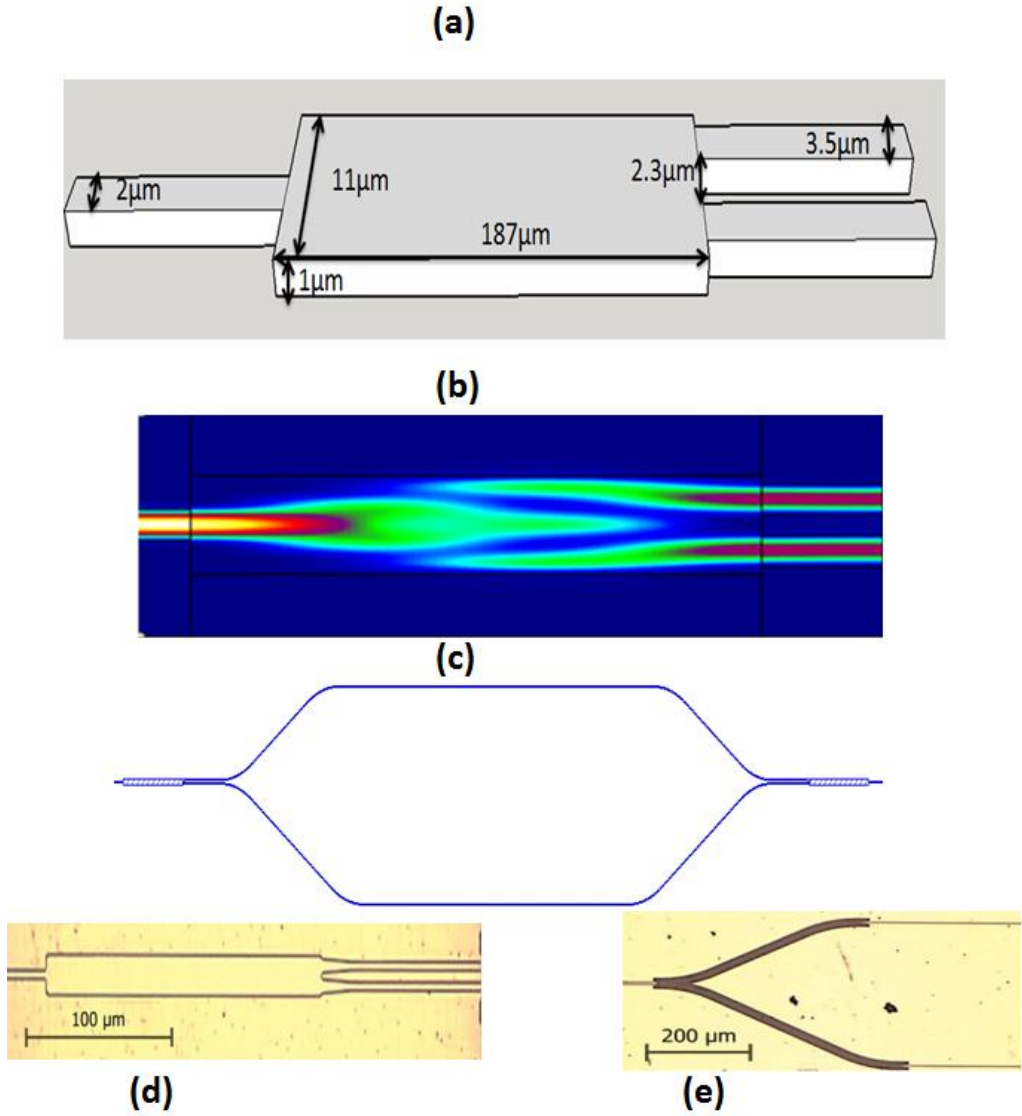


Figure 5. (a) 1x2 MMI beam splitter design. (b) Electric field's component propagation simulation. (c) asymmetric Mach Zehnder interferometer general layout view. (d) Zoom on fabricated beam splitter under optical microscope. (e) Deeply etched bent region of the fabricated Mach-Zehnder interferometer, deeply etched regions appear darker.

III.PASSIVE STRUCTURE CHARACTERISATION AND DISCUSSION

3.1 BENDS CHARACTERISATION

Butt coupling technique was used to measure losses of the fabricated 90° turns. Using a tunable laser TE polarized light was injected in the waveguide with a lensed fiber. An objective was used to inject output light to a photodetector. By comparing the transmission of a straight waveguide with the waveguide including 32 consecutive 90° turns bend losses were evaluated. 12, 25, 50 and $100\mu\text{m}$ radii were considered. Measurements were performed at $1.55\mu\text{m}$ i.e above the indirect optical absorption band-edge for $\text{Si}_{0.2}\text{Ge}_{0.8}$

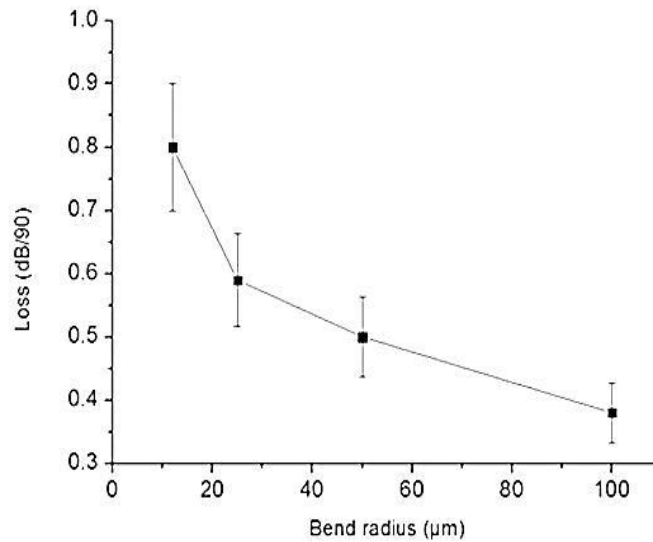


Figure 6. 90° bend losses as function of bend radius

Straight waveguide propagation losses are evaluated to be 1dB/mm . These losses can be minimized by appropriate surface passivation and etching process optimization for low sidewall roughness. Characterization results are reported in Fig.6 which represents bend losses as a function different bend radii. For $50\mu\text{m}$ bend radius, $0.5\text{dB}/90^\circ$ losses were obtained. From simulations arises that the modal mismatch between straight and bent waveguide of a 90° bend structure is the main contribution to the optical losses. $0.1\text{dB}/90^\circ$ can further be achieved by using an offset technique¹⁵ or by continuously varying bend curvature¹⁶.

3.2 ASYMMETRIC MACH ZEHNDER INTERFEROMETERS

Butt coupling method was used as well for the characterization of asymmetric Mach Zehnder interferometers. An extinction ratio of more than 10dB is obtained as reported in Fig. 7. An experimental free spectral range of 24.4nm is in good agreement with 24 μ m length difference between the arms of the interferometer.

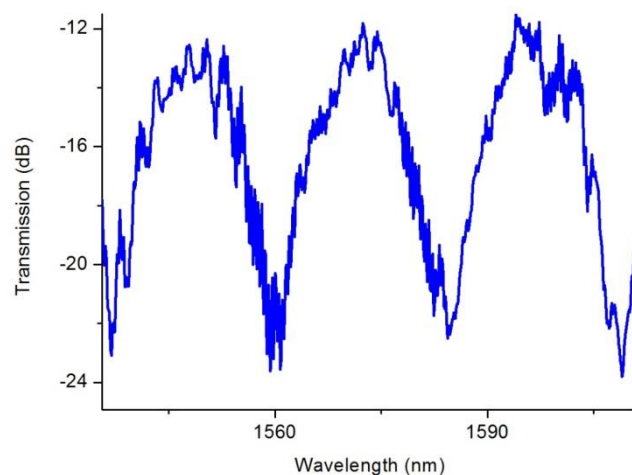


Figure7. Optical transmission of the fabricated asymmetric Mach-Zehnder interferometer

12 dB losses are obtained between the input and output of the chip. This includes: 8 dB losses for 8mm total length of access waveguides i.e input and output, 2dB loss in Mach-Zehnder arms and 2dB losses for the couplers. The use of short access waveguide will dramatically reduce the total losses.

CONCLUSIONS

The viability of a new Ge-rich silicon-germanium on graded buffer platform was evaluated. Main components of passive circuitry such as sharp and compact footprint 90° bends and Mach-Zehnder interferometers were designed, fabricated and experimentally validated. Light confinement tuning made possible to obtain bends with radius as small as 12 μ m and Mach-Zehnder interferometers with good extinction ratio. The use of a hard mask is a key point to obtain perfect alignment during the fabrication process and combine slightly and deeply etched regions in the same device. This work paves the way for the demonstration of wavelength division multiplexing devices on silicon substrate. By incorporating Ge based light sources, modulators, photodetectors on a unified Ge-rich SiGe photonic platform we can obtain in the future efficient Ge based photonic integrated transceivers on silicon.

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