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Si Optical Modulator with Strained SiGe Layer and Ge Photodetector with Lateral PIN Junction for 56 Gbaud Optical Transceiver

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Abstract: We developed a high speed and high efficiency of a depletion type Si optical modulator (Si-MOD) with PN junction by applying a p-type-doped strained SiGe layer which was stacked on the lateral PN junction type Si-MOD. We designed the optimum Si-MOD structure and demonstrated a high modulation efficiency of 0.6 to 1.0 Vcm, which is about 50% more efficient than that of a Si-MOD with a lateral PN junction. We also demonstrated a high speed operation of 56 Gbps for the Si-MOD and the integrated high-performance Ge photodetector (Ge-PD) of 50 GHz bandwidth and 80% quantum efficiency (Q.E.) at around 1.3 μm wavelength.

1. Introduction

Silicon photonics has recently attracted much attention because it offers low cost, low power consumption, and high bandwidth for optoelectronic solutions for applications ranging from telecommunications to chip-to-chip interconnects [1]. To realize an effective photonics-electronics convergence system, it is very important to achieve a high-speed and high-efficiency Si-MOD.

Among various Si optical modulators demonstrated so far, the Si Mach-Zehnder optical modulators based on the plasma dispersion effect have been mostly reported for high-speed modulation and broad-wavelength operation. However, the carrier-depletion Si modulators need relatively long phase-shifter or high driving voltage because of the weak plasma dispersion effect in Si, which are not favorable for large-scale integration. For further improvement in modulation efficiency, it has been proposed that strained SiGe modulators to enhance the plasma dispersion effect by reducing effective mass of holes in SiGe because the effect is inversely proportional to the effective carrier mass [2,3].

In this paper, we design the optimum Si-MOD structure with applying a strained SiGe and demonstrate a high modulation efficiency of 0.6 to 1.0 Vcm, which is about 50% more efficient than that of Si-MODs with just a lateral PN junction. We also demonstrate a high speed operation of 56 Gbps for the Si-MOD at around 1.3 μm wavelengths and also demonstrate a 50GHz bandwidth and 80% Q.E. of an integrated waveguide-type Ge-PD on the lateral PIN junction of a silicon-on-insulator (SOI) layer.

2. Experiment and Design

Figure 1 shows a schematic diagram of depletion type Si-MOD with a strained SiGe layer. The Si-MOD consisted of an asymmetric Mach-Zehnder Interferometer (MZI) structure to evaluate the modulation efficiency and in the optical transceiver chip, a symmetric MZI structure with 4 divided electrode elements was integrated with a waveguide Ge-PD. The fabrication process started with 300mm-diameter of SOI wafers, of which SOI thickness was 200 nm for the 1.3 μm wavelength. After ion implantation of boron and phosphorus, the Si waveguides (Si-WGs)

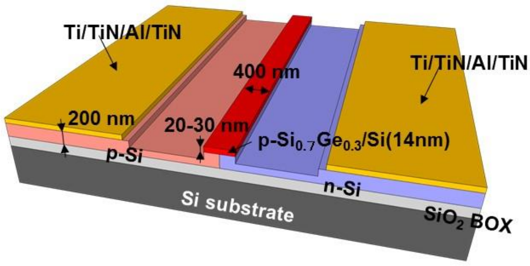

Fig. 1 Schematic diagram of depletion type Si- MOD with strained SiGe layer.

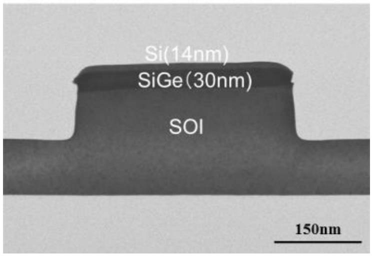

Fig. 2 TEM image of selective grown $Si_{0.7}Ge_{0.3}$ layer on SOI.

were patterned by ArF immersion lithography and dry etching. After SiO_2 layer deposition, SiGe-selective-growth windows were formed on the phase sifter of the Si-MOD with a lateral PN junction. Then a 30 nm-thick strained-SiGe layer and a 14nm-thick Si-capping layer were selectively grown by LP-CVD method and boron-doped by ion-implantation. Next, a SiO_2 open-window was formed on the SOI, and 500nm-thick Ge layer with a Si-capping layer was selectively grown on the lateral PIN junction of a patterned SOI layer. Finally, the upper clad layer and contact-hole were formed, and the stacked electrodes of the Ti/TiN/Al layers were deposited and patterned. The doping densities of p-Si, n-Si, and p-SiGe were 0.5-1x10^{18}/cm^3, respectively for the Si-MOD. In the experiment, phase shifter length was 200. Figure 2 shows a TEM image of a selective grown $Si_{0.7}Ge_{0.3}$ layer on the SOI. With optimizing the growth temperature, very smooth surface of a $Si_{0.7}Ge_{0.3}$ layer was obtained.

Design of the Si-MOD with a p-type-doped strained Si-

Ge was performed by linked simulation of carrier transport and optical mode analyses.

3. Results and discussion

3-1 Simulation and experiment for $V_\pi L$ and Loss

Figure 3 shows simulation results of (a) $V_\pi L$ and (b) optical loss dependence on applied voltage for the Si-MOD with and without a $Si_{0.7}Ge_{0.3}$ layer. By applying the strained $Si_{70}Ge_{30}$ layer, about twice larger optical modulation efficiency in $V_\pi L$ can be obtained. In case of a relaxed $Si_{0.7}Ge_{0.3}$ layer, enhancement factor in $V_\pi L$ decrease to about 50%, but optical loss is comparable to that without a SiGe layer.

From the Raman spectra and SIMS analyses, Ge composition in SiGe was estimated to be 30%. Crystalline strain of SiGe was estimated to be 1.7% on the 0.04 mm^2 square pattern, which is comparable to the theoretical value.

The Si-MOD showed about 30 GHz bandwidth at -4 V_{dc} with 200μm-long phase-shifter. Figure 4 shows a measured NRZ (non-return-to-zero) eye diagram at 56 Gbps of 2^{31}-1 PRBS at 1.3 μm wavelength, applying 5 V_{pp} with -4V_{dc}. Modulation efficiency was 0.6 to 1.0 Vcm, which could be improved by PN junction offset.

3-2 High-speed characteristics of Ge-PD

Figure 5 shows a schematic diagram of a Ge photodetector on the lateral pin junction of an SOI layer. Figure 6 shows frequency response of a Ge-PD with 0.6 μm-width Ge mesa on a lateral PIN junction of SOI. The Ge-PD showed 50 GHz bandwidth at -3 V_{dc} for 40 μm-length. Electrical capacitance of the device was estimated to be around 10 fF, which is small enough for high-speed operation. Therefore, photocarrier transit time limits the frequency response.

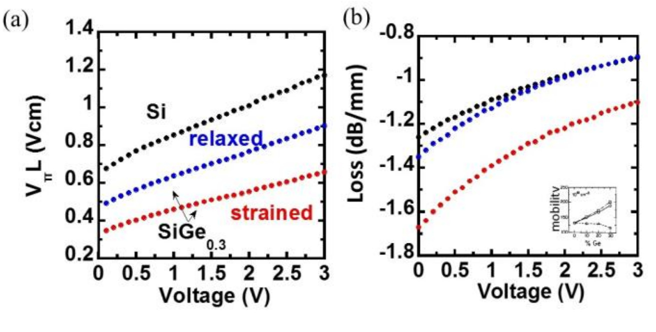

Fig. 3 Simulation result of (a) $V_\pi L$ and (b) propagation loss dependence on applied voltage for Si-MOD with p-type-doped Si and strained SiGe layers.

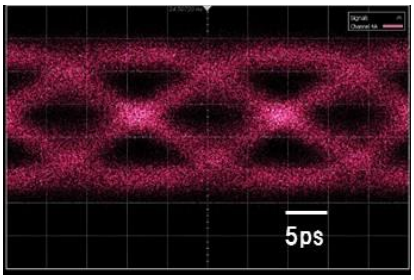

Fig. 4 Measured eye diagram at 56 Gbps of 2^{31}-1 PRBS at 1.3 μm wavelength.

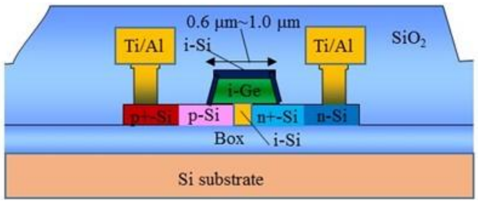

Fig. 5 Schematic diagram of Ge photodetector on lateral pin junction of SOI.

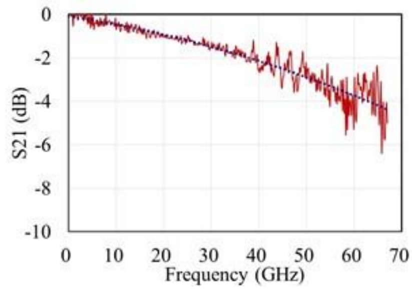

Fig. 6. Frequency response of Ge photodetector with 0.6 μm-width of Ge mesa on lateral PIN junction.

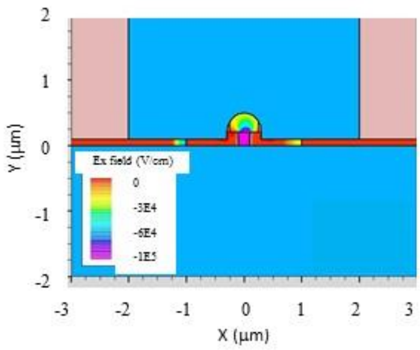

Fig. 7. Contour map of electric field intensity in case of 0 dBm optical power input.

The fabricated Ge-PD showed about 80% Q.E. at 1.26 to 1.36 μm wavelengths, which was estimated by omitting a Si waveguide (Si-WG) loss and coupling loss between a lensed fiber and a Si-WG. Figure 7 shows a simulated electric field intensity contour map in case of 0 dBm optical power input. With increase in input optical power, internal electric field intensity decreased, which affected the frequency response of the Ge-PD.

4. Conclusion

We studied the Si-MOD with applying a strained SiGe layer. We demonstrated a high modulation efficiency of 0.6-1.0 Vcm and a high speed operation of 56 Gbps at 1.3 μm wavelength. An integrated Ge-PD showed high responsivity of 80% Q.E. and high speed of 50 GHz bandwidth.

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References

[1] G. T. Reed et al., Nat. Photon. 4, 518–526 (2010).
[2] M. Takenaka et al., IEEE J. Quantum Electron. 48, p.8–15 (2012).
[3] J. Fujikata et al., Proc. GFP2017, WD3 (2017).