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MOS Capacitor Type Si Optical Modulator Integrated with Ge Photodetector, and its High Speed Operation with CMOS Driver

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Abstract

We developed a high speed and high efficiency MOS (metal-oxide-semiconductor)-capacitor type Si optical modulator (Si-MOD). We designed the optimum Si-MOD structure and demonstrated a very high modulation efficiency of 0.28-0.30 Vcm, which is one of the most efficient in Si-MODs with MOS junctions. We also demonstrated a high speed of 25 Gbps for the Si-MOD integrated with a Ge photodetector (Ge-PD), and also high-speed operation of 15 Gbps with 65nm CMOS driver at 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. To realize an effective photonics-electronics convergence system, it is very important to achieve a high-speed and high-efficiency Si-MOD with low power consumption.

For MOS capacitor type Si-MODs, high efficiency has been achieved by accumulating free-carriers at the gate-oxide/silicon interface [1], [2]. However, a MOS type Si-MOD integrated with a Ge-PD is a challenge, because the poly-Si gate fabrication in the MOS-capacitor would affect the quality of a selective epitaxial growth of a Ge layer on a SOI (silicon-on-insulator) layer.

In this paper, we present a high-speed and high-efficiency Si-MOD with a MOS junction, and demonstrate a MOS-capacitor type Si-MOD integrated with a Ge PD at 1.3 μm wavelength. We also demonstrate high-speed operation with CMOS driver at 1.3 μm wavelength.

2. Experiment and Analysis

Figure 1 shows (a) schematic diagram the Si-MOD with a MOS junction and (b) cross-sectional TEM image for the Si-MOD for 1.3 μm wavelength. The Si-MOD consisted of a symmetric Mach-Zehnder Interferometer (MZI) structure. The fabrication process started with 4-inch SOI wafers with a SOI thickness of 180 nm for the 1.3 μm wavelength. After a 5-nm-thickness of gate-oxide was grown by thermal oxidation, an amorphous-silicon layer was deposited by low-pressure chemical vapor deposition (LP-CVD) and recrystallized by two-step annealing [3]. Then, Si waveguides (Si-WGs) and poly-Si gates were patterned by electron beam lithography and dry etching. After SiO_2 upper-clad layer deposition, contact-holes were formed. Finally, the stacked electrodes of the Ti/TiN/Al layers were deposited and patterned. The doping densities of p-Si and n-poly-Si were 1-2 $x10^{18}/cm^3$, respectively. In the experiment, phase shifter lengths were 120-200 μm for the segment unit.

Figure 2 shows a schematic diagram of MZI structure of MOS-capacitor type Si-MOD integrated with Ge-PD. The Si-MOD consists of a MZI structure, in which operation point is controlled by p-i-n diode-type optical phase-shifter. It has two output ports, and one is connected with a Ge-PD, and the other is an inverse-taper structure in order to couple the lensed fiber.

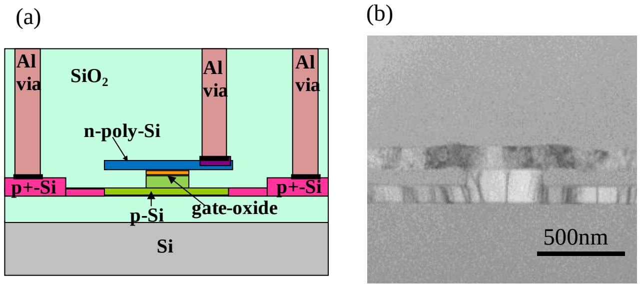

Fig. 1 (a) Schematic diagram of MOS capacitor type Si- MOD and (b) cross-sectional TEM image.

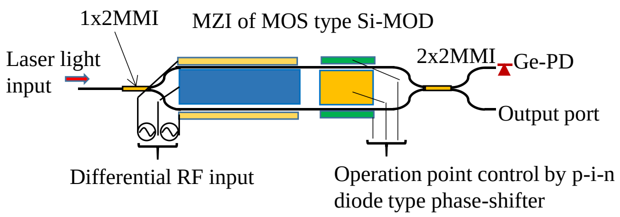

Fig. 2 Schematic diagram of MZI structure of MOS type Si-MOD integrated with Ge-PD.

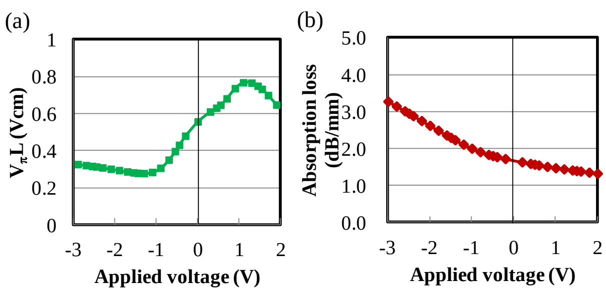

Fig. 3 Simulation results of Si-MOD for (a) $V_{\pi}L$ and (b) absorption loss dependence on applied voltage [4].

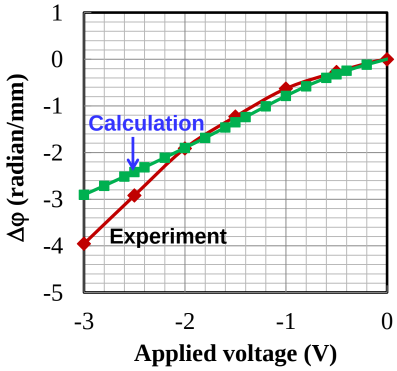

Fig. 4 Simulation and experimental results of optical phase change dependence on applied voltage.

3. Results and discussion

3-1 MOS Capacitor Type Si-MOD at 1.3 μm wavelength

Figure 3 shows (a) the effective refractive index (n_{eff}) and (b) optical propagation loss of the Si-MOD with MOS junction dependence on the applied voltage to the gate poly-Si electrode (V_G) in the simulation. When the applied was negative, free carrier accumulation occurred around the gate-oxide/Si interfaces. In this case, the largest modulation efficiency ($V_\pi L$) of 0.28 Vcm could be obtained.

Figure 4 shows optical phase change dependence on applied voltage for calculation and experimental results. Calculation and experimental results agree well, and modulation efficiency of 0.28 to 0.4 Vcm could be experimentally obtained.

3-2 Si-MOD integrated with Ge-PD

Figure 5 shows (a) Ge-PD photoresponsivity integrated with a MOS type Si-MOD and (b) 25 Gbps with 2^7-1 PRBS output waveform from the Si-MOD. Dark current of Ge-PD is 70 nA at 1 V, which is very low, and dislocation density of a Ge-mesa was very low by TEM analysis. The Si-MOD integrated with Ge-PD operated at high speed of 25 Gbps with 2^7-1 PRBS.

3-3 High-speed operation with 65nm CMOS driver

Finally, we studied the Si-MOD with 65nm CMOS

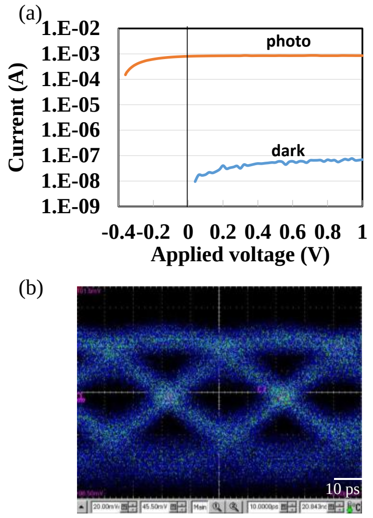

Fig. 5 (a) Ge-PD photoresponsivity integrated with MOS type Si-MOD and (b) 25 Gbps with 2^7-1 PRBS (psuedorandom sequence) output waveform from the Si-MOD.

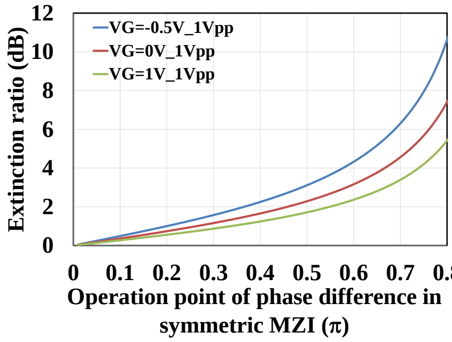

Fig. 6 Extinction ratio (ER) dependence on V_G and MZI operation point.

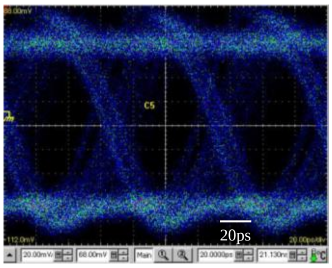

Fig. 7 Output waveform at 15 Gbps with 2^7-1 PRBS at 1.3 μm wavelength for MOS type Si-MOD with 65nm CMOS driver.

driver, which consists of a CMOS inverter circuit. The Si-MOD has a multi-segment structure and total phase -shifter length was 480 μm.

Figure 6 shows calculated ER dependence on V_G and MZI operation point. In case of 0.5 π in operation point, ER of 3 dB can be obtained with 1.0 V_{pp} and -0.5 V_G. Figure 7 shows experimental output waveform at 15 Gbps with 2^7-1 PRBS at 1.3 μm wavelength for the MOS type Si-MOD with 65nm CMOS driver. A clear eye-pattern was obtained and consumption power of CMOS driver LSI was 2-3 mW/Gbps. Therefore, the MOS-capacitor type Si-MOD with a CMOS driver is expected to contribute to low power and high-speed for the optical interconnection. In addition, higher speed and lower consumption power can be expected with more advanced technology node of CMOS driver.

4. Conclusions

We developed a high speed and high efficiency MOS -capacitor type Si-MOD. We designed the optimum Si-MOD structure and demonstrated a very high modulation efficiency of 0.28 Vcm. We also demonstrated a high speed of 25 Gbps for the Si-MOD integrated with a Ge photodetector (Ge-PD), and also high-speed operation of 15Gbps with 65nm CMOS driver at 1.3 μm wavelength.

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