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High-Performance MOS Capacitor Type Si Optical Modulator, and Surface Illumination-type Ge Photodetector for Optical Interconnection

Junichi Fujikata[1], Shigeki Takahashi[1], Masashi Takahashi[2], Masataka Noguchi[1], Makoto Miura[1], Takahiro Nakamura[1], and Yasuhiko Arakawa[3]

[1] Photonics Electronics Technology Research Association (PETRA), Tsukuba, Ibaraki 305-8569, Japan
[2] National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8569, Japan
[3] The University of Tokyo, Meguro, Tokyo 153-8505, Japan
Phone: +81-29-868-6520 E-mail: j-fujikata@petra-jp.org

Abstract

We developed a high speed and high efficiency MOS (metal-oxide-semiconductor)-capacitor type Si optical modulator (Si-MOD). We demonstrated a high modulation efficiency of 0.16 Vcm, using carrier accumulation mode, which is the most efficient in Si-MODs with MOS junctions. We demonstrated a high speed operation of 25 Gbps for the Si-MOD with a short phase shifter of 60 μm length at 1.3 μm wavelength. We also demonstrated a vertically-illuminated p-i-n Ge photodetector (Ge-PD), which shows both high bandwidth of 24 GHz and high-efficiency of 0.8-0.9 A/W.

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 more efficient MOS type Si-MOD is a challenge to realize low power optical interconnect.

In addition, in order to achieve a high optical-coupling efficiency with a multimode optical fiber, a vertically-illuminated Ge-PD is promising. However, there has been trade-off relationship between bandwidth and efficiency. Therefore, design of a vertically-illuminated Ge-PD structure which satisfy high efficiency and high speed is very important to achieve high bandwidth and low power optical interconnect.

In this paper, we present a high-speed and high-efficiency Si-MOD with a MOS junction, and demonstrate high modulation-efficiency of 0.16 Vcm and high-speed of 25Gbps with 60μm phase-shifter at 1.3 μm wavelength, using carrier accumulation mode. We also demonstrate a vertically-illuminated p-i-n Ge-PD, which shows both high bandwidth of 24 GHz and high-efficiency of 0.8-0.9 A/W.

2. Experiment

Figure 1 (a) and (b) show a schematic diagram the Si-MOD with a MOS junction and a 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 silicon-on-insulator (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 60-120 μm.

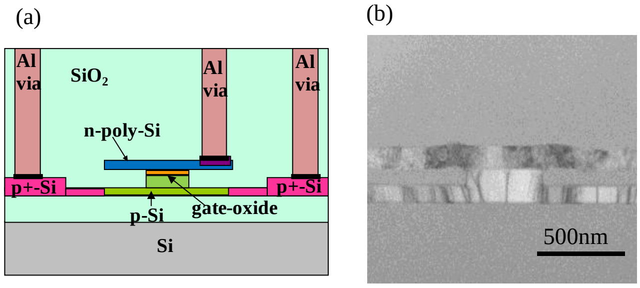

Fig. 1 (a) Schematic diagram of MOS capacitor type Si- MOD and (b) cross-sectional TEM image.

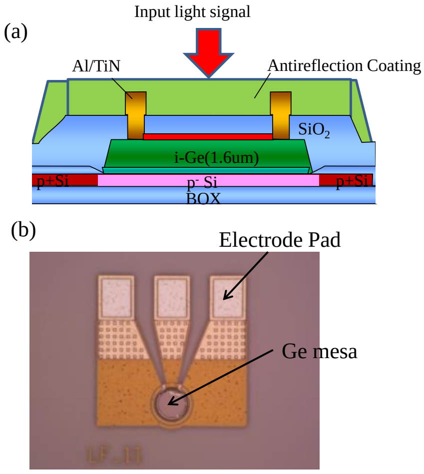

Fig. 2 (a) Schematic diagram surface-illumination type Ge-PD and (b) micrograph of the fabricated device.

Figure 2 (a) and (b) show a schematic diagram surface-illumination type Ge-PD and a micrograph of the fabricated device. The fabrication process started from 4-inch SOI wafers, of which SOI thickness was 220 nm. A Si pedestal was patterned by electron beam lithography and dry etching. Then, B ions were implanted and the wafers were annealed

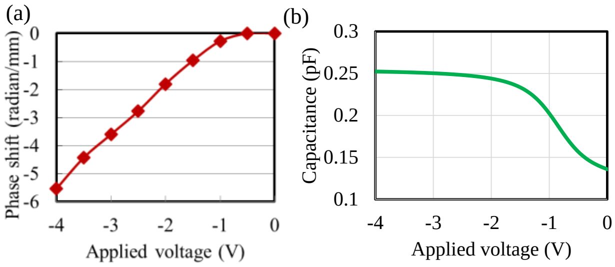

Fig. 3 (a) Experimental result of Si-MOD for phase shift dependence on applied voltage and (b) simulation result of capacitance for 60μm-length of phase shifter.

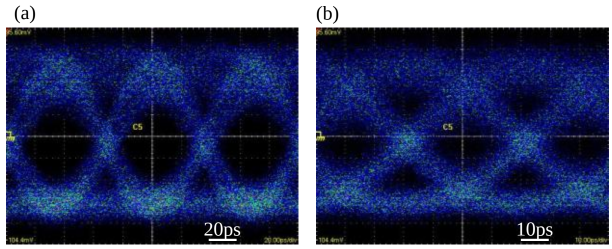

Fig. 4 Output waveforms at (a) 15 Gbps and (b) 25 Gbpswith 2^{31}-1 PRBS at 1.3 μm wavelength for MOS type Si-MOD.

to form p^+-Si of the bottom electrode. The 1.8μm-thickness of epitaxial germanium mesas were selectively grown on the Si pedestal by reduced-pressure chemical vapor deposition method. A 20nm-thick SiGe cap layer was deposited on a Ge layer to passivate the Ge surface and P ion implantation was performed. Then a SiO_2 upper-clad layer was deposited, and contact-holes were formed by UV lithography and dry-etching process. Next, metal electrodes of Ti/TiN/Al layers were deposited and patterned. Finally, a SiN_x/SiO_2 multi-stacked layer was deposited as an anti-reflection coating, and electrode pads were opened.

3. Results and discussion

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

Figure 3 (a) and (b) show an experimental result of Si-MOD for optical phase shift dependence on applied bias voltage (V_{bias}) and simulation result of capacitance dependence on V_{bias} for 60μm-length of phase shifter. When V_{bias} was negative, free carrier accumulation occurred around the gate-oxide/Si interfaces. Optical phase shift dependency on V_{bias} is consistent with capacitance. That is, optical phase shift depends on accumulated carrier charge, and the largest modulation efficiency ($V_\pi L$) of 0.16 Vcm could be obtained in case of more than 1.5 V_{bias} which is comparable to the flat band voltage.

Figure 4 (a) and (b) show output waveforms at 15 Gbps and 25 Gbps with 2^{31}-1 PRBS (psuedorandom sequence) at 1.3 μm wavelength for MOS type Si-MOD with a 60μm phase shifter in case of 2.0 V_{pp} differential RF drive voltage and 2.5 V_{bias}.

3-2 Surface-Illumination type Ge-PD

Figure 5 (a) and (b) show Ge-PD photoresponsivity and dark current and their temperature dependence. Photoresponsivity was insensitive to temperature, and high efficiency of 0.8-0.9A/W was obtained. On the other hand, dark current increased from 39 nA to 569 nA with increasing temperature at 1 V_{dc}. The photo-to-dark current ratiowas higher than 30 dB up to 373K.

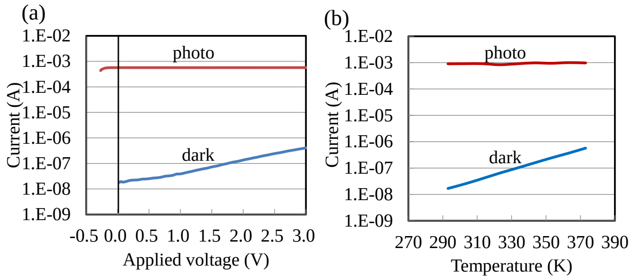

Fig. 5 (a) Ge-PD photocurrent and dark current dependence on dc applied voltage (Vdc) and (b) their temperature dependence

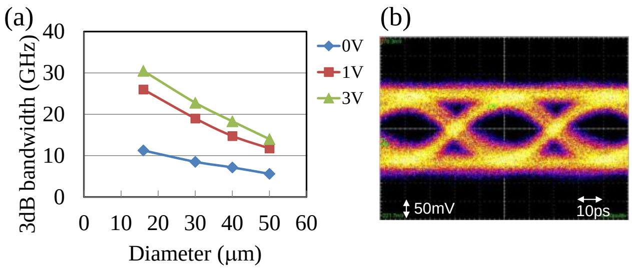

Fig. 6 (a) 3dB bandwidth dependence on Ge-mesa diameter and output waveform at 25 Gbps with 2^7-1 PRBS at 1.3 μm wavelength.

Figure 6 (a) and (b) show 3dB bandwidth dependence on Ge-mesa diameter and output waveform at 25 Gbps with 2^7-1 PRBS at 1.3 μm wavelength. 3dB bandwidth increased with decreasing Ge-mesa diameter, but carrier drift time mainly contribute to the 3dB bandwidth in case of 1.6μm-thick Ge. 24 GHz bandwidth was achieved in case of 30 μm diameter with 3 V_{dc}.

4. Conclusions

We developed a high speed and high efficiency MOS -capacitor type Si-MOD. We demonstrated a high modulation efficiency of 0.16 Vcm, using carrier accumulation mode, which is the most efficient in Si-MODs with MOS junctions. We demonstrated a high speed operation of 25 Gbps for the Si-MOD with a short phase shifter of 60 μm length at 1.3 μm wavelength. We also demonstrated a vertically-illuminated p-i-n Ge photodetector (Ge-PD), which shows both high bandwidth of 24 GHz and high-efficiency of 0.8-0.9 A/W. These results would contribute to low power optical interconnect [5].

Acknowledgements

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