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45 GHz Bandwidth of Si Waveguide-Integrated PIN Ge Photodiode, and its Zero-Bias Voltage Operation

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1. Introduction

Silicon photonics has recently become a subject of intense interest because it offers an opportunity for low cost, low power consumption, and high bandwidth of optoelectronic solutions for applications ranging from telecommunications down to chip-to-chip interconnects [1]. By the integration of germanium into silicon photonics circuit, very efficient photodetection has been demonstrated for the past several years [2], [3].

Although developments of high speed and high efficiency Ge photodiodes (Ge-PDs) have been reported, higher performance with low dark current density has not been achieved by practical fabrication process. In addition, low-applied-bias-voltage operation is expected to contribute to low-power receiver circuit.

In this paper, we present a Si waveguide-integrated PIN-type Ge-PD, which shows very low dark current density with high efficiency and high speed. We also report on its zero-bias voltage operation.

2. Experiment

Figure 1 (a) and (b) show a schematic diagram and SEM image of the Si-waveguide integrated PIN Ge-PD. The fabrication process started from 4-inch silicon-on-insulator (SOI) wafers, of which SOI thickness was 220 nm. The Si waveguides (Si-WGs) were patterned by electron beam lithography and dry etching. Then, B ions were implanted and the wafers were annealed to form p$^+$-Si of the bottom electrode. The 1.0μm-thickness of epitaxial germanium mesas were selectively grown on the Si-WGs by reduced-pressure chemical vapor deposition method.

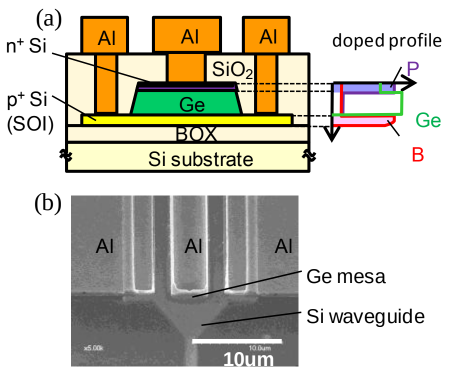

Fig. 1 (a) Schematic diagram and (b) SEM image of the Si waveguide integrated PIN Ge-PD.

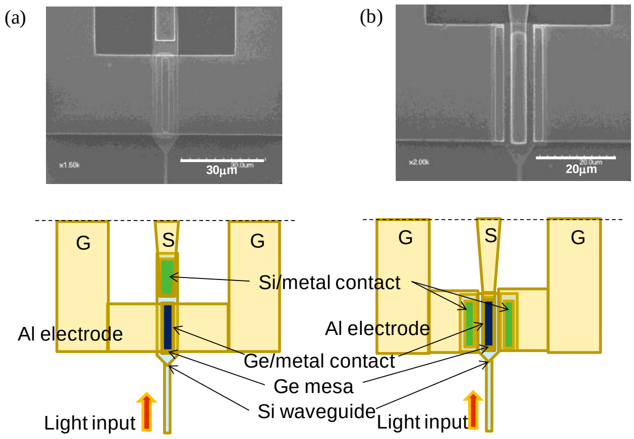

Fig. 2 SEM images and schematic diagrams of Si waveguide-integrated PIN Ge-PDs of (a) back-contact and (b) side-contact structures for Si and metal contact.

A Si cap layer was deposited on a Ge layer to passivate the Ge surface. After P ion implantation and 1μm-thick SiO_2 upper-clad layer deposition, contact-holes were formed by UV lithography and dry-etching process. Finally, metal electrodes of Ti/TiN/Al layers were deposited and patterned.

We studied two types of Si-waveguide-integrated PIN Ge-PD structures (Fig. 2). One has a back-contact structure for p$^+$-Si and metal contact, and the other has a side-contact structure. The back-contact structure enables higher optical coupling efficiency between a Si waveguide and a Ge mesa. The side-contact structure enables a smaller series resistance for extending p$^+$-Si layer between a Ge mesa and a Si/metal contact area.

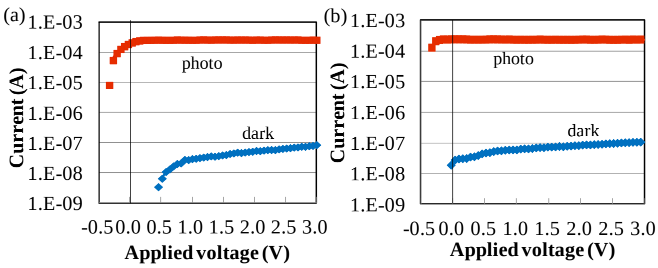

Fig. 3 Photoresponsivity of the fabricated PIN Ge-PD for (a) back-contact and (b) side-contact structures.

3. Results and discussion

Figure 3 shows the photoresponsivity of the fabricated PIN Ge-PDs for (a) back-contact and (b) side-contact structures. In this experiment, laser diode light of 0.3 mW power and 1.55 μm wavelength was introduced into the Si-WG. Photoresponsivity of the back-contact structure was 0.9 A/W, while 0.8 A/W was obtained with lower dc bias voltage (V_{dc}) of -0.3 V for the side-contact structure. Both structures showed low dark current density of 0.8 nA/μm^2.

Figure 4 (a) shows dependence of 3dB bandwidth for PIN Ge-PDs of the back-contact and the side-contact structures on V_{dc}. The side-contact structure showed 45 GHz bandwidth at V_{dc} more than 2 V, and also 23 GHz at 0 V_{dc}. On the other hand, the back-contact structure showed 8 GHz at V_{dc} more than 2 V. Figure 4 (b) shows details of additional resistance for three different PIN Ge-PDs of the conventional PD [4], the back-contact, and the side-contact structures. In this study, contact resistance between a metal electrode of Ti/TiN/Al and n^+-Si was successfully reduced to $1x10^{-5}\Omega/cm^2$, and about 10 Ω contact resistance was achieved, which is more than 10 times lower than that of the conventional PD. A sheet resistance of p^+-Si was about 282 Ω/□, and the back-contact structure showed a larger p^+-Si series resistance. Therefore, differences in 3dB-bandwidths among three types of the PIN Ge-PDs are explained by CR time constant limit.

Figure 5 shows measured eye diagrams for the PIN Ge-PD of side-contact structure in case of (a) 25 Gbps at 0 V_{dc} and (b) 40 Gbps at 3V_{dc} with 2^{15}-1 PRBS. In this experiment, light from a 1.55-μm-wavelength laser was modulated with an external 30 GHz $LiNbO_3$ optical modulator by applying the RF signal at 25 Gbps and 40 Gbps with

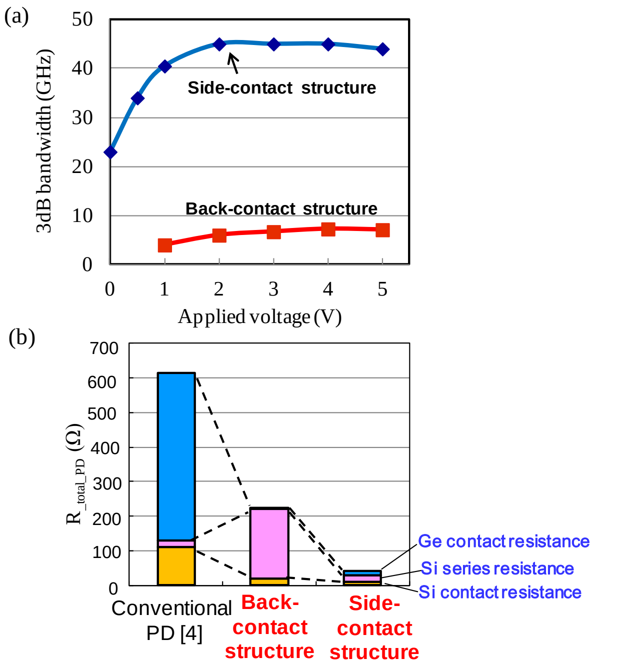

Fig. 4 (a) Dependence of 3dB bandwidth for PIN Ge-PDs of back-contact and side-contact structures on dc bias voltage. (b) Details of additional resistance for three different PIN Ge-PDs of conventional PD, back-contact, and side-contact structures.

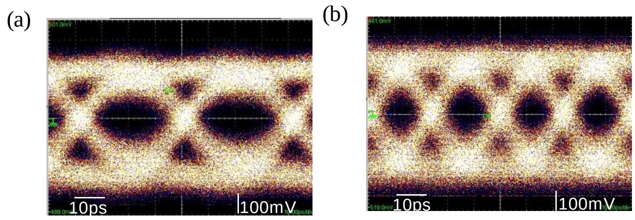

Fig. 5 Measured eye diagrams for the PIN Ge-PD of side-contact structure in case of (a) 25 Gbps at 0 V_{dc} and (b) 40 Gbps at 3V_{dc} with 2^{15}-1 PRBS.

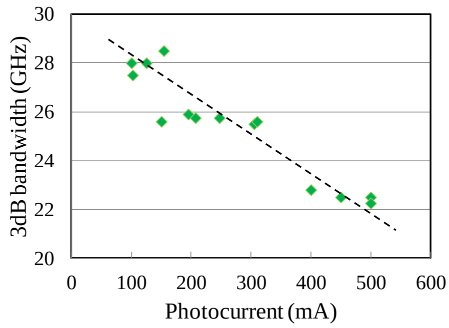

Fig. 6 Dependence of 3dB bandwidth for the PIN Ge-PD of side-contact structure on photocurent.

2^{15}-1 non-return-to zero (NRZ) pseudo random binary sequence (PRBS). V_{dc} was applied to the PIN Ge-PD via a bias-tee, and the RF output from the photocurrent was amplified with 40 GHz amplifier and measured with a 65 GHz sampling oscilloscope. The clear open eyes suggest that the optical links are capable of 25 Gbps and 40 Gbps data transmission. Therefore, the PIN Ge-PD expected to be promising for high-bit-rate data transmission.

Finally, we analyzed zero-bias voltage operation of the PIN Ge-PD of the side-contact structure. Figure 6 shows dependence of 3dB bandwidth for the PIN Ge-PD of side-contact structure on photocurrent. 3dB bandwidth decreased gradually from 28GHz to 22GHz with increase of photocurrent. It shows that photocarriers have screening effect on the built-in electric field in the Ge absorption layer.

4. Conclusions

Si waveguide-integrated PIN Ge-PD was studied. By applying a side-contact structure for metal and Si, 45 GHz bandwidth was obtained with low dark current density of 0.8nA/μm^2, and also more than 20 GHz bandwidth was achieved with zero-bias voltage. In case of zero-bias voltage operation, 3dB-bandwidth was a little affected by input power, which would originate from photocarriers' screening effect on built-in electric field.

Acknowledgements

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