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Si Waveguide-Integrated MSM Ge Photodiode

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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, smaller footprint and higher performance have not been achieved by practical fabrication process. Metal-semiconductor-metal (MSM) Ge-PD is one of the candidates for the future high-density optical interconnects.

In this paper, we present a Si waveguide-integrated MSM Ge-PD, which shows low dark current density with high efficiency and high speed. We also report a smaller footprint of Ge-PD by surface plasmon effect [4], [5].

2. Experiment

Figure 1(a) shows a schematic diagram of the Si-waveguide integrated MSM 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. The epitaxial germanium mesas for the 0.8-1.0μm-thickness of Ge-PDs were selectively grown on the Si-WGs by ultra-high vacuum chemical vapor deposition or reduced-pressure chemical vapor deposition. The 10-20nm thickness of a Si cap layer was deposited on a Ge layer to enhance the Schottky barrier and reduce the dark current. After 500nm-thick SiO_2 upper-clad layer deposition, contact-hole array of 1.0 μm width and 2.5-3.0 μm period were formed by UV lithography and dry-etching process. Finally, Schottky-metal electrodes of Ti/TiN/Al layers were deposited and patterned to form an MSM junction (Fig. 1(b)).

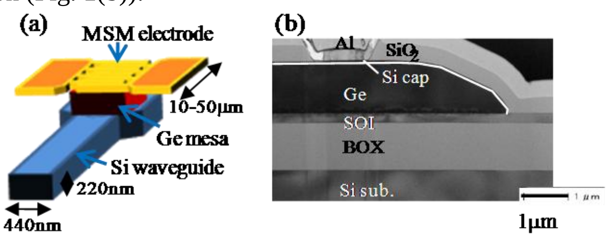

Fig. 1 (a) Schematic diagram and (b) cross-sectional TEM image of Si waveguide integrated MSM Ge-PD.

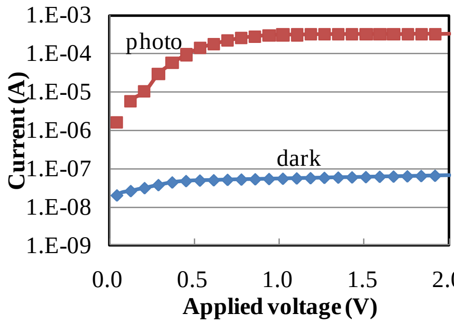

Fig. 2 Photoresponsivity of the fabricated MSM Ge-PD.

3. Results and discussion

First, photoresponsivity and dark current properties were studied. Figure 2 shows the photoresponsivity of the fabricated MSM Ge-PD. Laser diode light of 0.4 mW power and 1.55 μm wavelength was vertically-illuminated in this experiment. Photoresponsivity of about 0.8 A/W was obtained and very low dark-current density of around 0.4 nA/μm^2 was achieved by applying the Si cap layer.

To evaluate Schottky barrier height of an MSM junction, temperature dependence of dark current was investi-

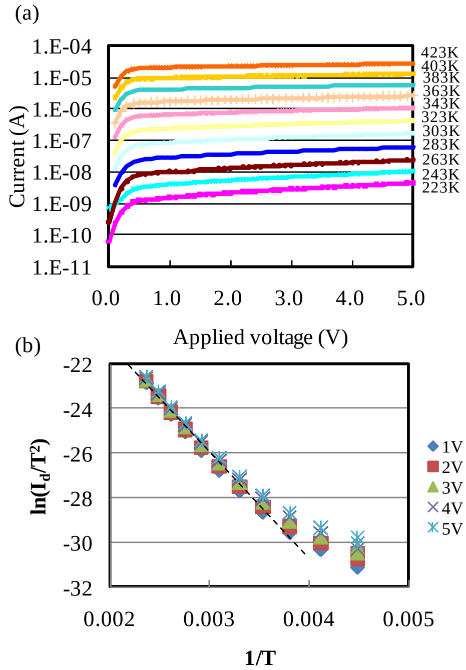

Fig. 3(a) Temperature dependence of dark current and (b) plotted data of $\ln(I_d/T^2)$ vs. (1/T) with various bias voltages.

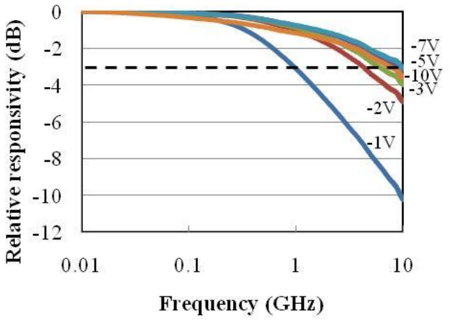

Fig. 4 Dependence of frequency response of MSM Ge-PD on dc bias voltage.

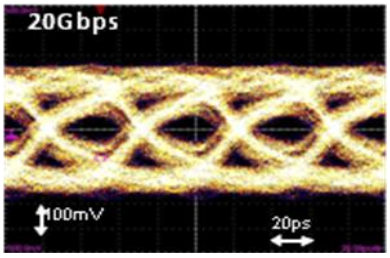

Fig. 5 Measured eye diagram at 20 Gbps with 2^{15}-1 PRBS.

gated at 223-423 K. Figure 3(a) and (b) show temperature dependence of dark current and plotted data of $ln(I_d/T^2)$ vs. (1/T) with various dc bias voltages (V_{dc}). Here, I_d and T represent dark current and temperature respectively. From the linear fit of the slope in $ln(I_d/T^2)$ vs. (1/T), Schottky barrier height was estimated to be about 0.44 V, which is not very dependent on V_{dc}. For lower temperature below 263 K, the experimental data is weakly dependent on temperature and deviates from the linear fit, because thermoionic emission or Schockley-Read-Hall generation mechanism plays a minor role at low temperature [3].

Next, frequency response was measured for high bandwidth of data transmission. Figure 4 shows dependence of frequency response of the MSM Ge-PD with 50- μm optical coupling length and 1-μm electrode spacing on V_{dc}. With increase of V_{dc}, bandwidth increased and saturated at 10 GHz with 5-7 V_{dc}. Bandwidth was also affected by electrode spacing, and shorter spacing contributed to higher bandwidth, because carrier transit time between MSM electrodes mainly determined the frequency response.

Figure 5 shows the measured eye diagram when 1.55 μm wavelength of optical signal was input by a lensed optical fiber. In this experiment, light from a 1.55-μm-wavelength laser was modulated with an external 40 GHz $LiNbO_3$ optical modulator by applying the RF signal at 20 Gbps with 2^{15}-1 non-return-to zero (NRZ) pseudo random binary sequence (PRBS). 5 V_{dc} was applied to the MSM 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 20 Gbps data transmission. Therefore, the MSM Ge-PD expected to be promising for high-bit-rate data transmission.

Finally, smaller footprint of Ge-PD with surface plas-

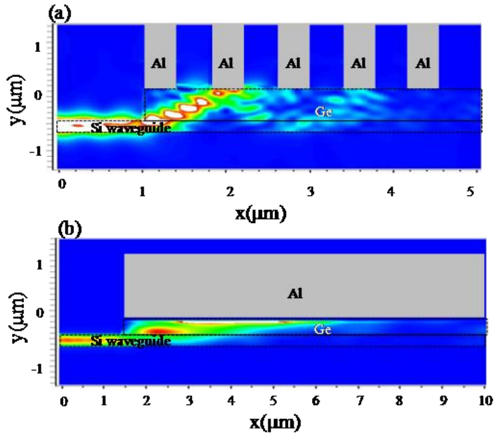

Fig. 6 Electric field density contour map of Si-waveguide coupled Ge-PD with Al electrode structure by 3D-FDTD method in case of (a) TM and (b) TE polarization light input.

mon effect was analyzed by three-dimensional finite difference time domain (3D-FDTD) method simulation. Figure 6 shows electric field density contour map of Si-waveguide coupled Ge-PD with upper Al electrode structures in case of (a) transverse magnetic (TM) and (b) transverse electric (TE) polarization light input. In case of TM polarization light, MSM electrodes period was designed to be satisfied with the momentum conservation law [4]. When MSM electrode period was 800 nm, TM polarization light was efficiently absorbed by surface plasmon resonance at the interface of Ge/Si and Al layers. On the other hand, in case of TE polarization light, surface plasmon effect was enhanced by the Al strip electrode structure, which excited the dipole resonance between edges of it. By surface plasmon effect, less than 10 μm length of Si waveguide coupled Ge-PD expected to be realized.

4. Conclusions

Si waveguide-integrated MSM Ge-PD was studied. By applying 10-20 nm of a Si-cap layer, Schottky barrier height was enhanced up to 0.44V, and very low dark current density of around 0.4 nA/μm^2 was achieved with high responsivity of 0.8 A/W. In addition, small electrode spacing of 1μm realized high speed photodetection of 20 Gbps. To realize smaller footprint for the future high-density optical interconnect, surface plasmon effect was analyzed and less than 10 μm optical coupling length of Ge-PD with the upper Al electrode structure was designed.

Acknowledgements

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