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 0.8–1.0 μm-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\textsubscript{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)).

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\textsuperscript{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-
between carrier transit time 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 LiNbO₃ optical modulator by applying the RF signal at 20 GHz with 2¹⁵-1 non-return-to-zero (NRZ) pseudo random binary sequence (PRBS). V<sub>dc</sub> 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 is expected to be promising for high-bit-rate data transmission.

Finally, smaller footprint of Ge-PD with surface plasmon 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 Al electrode structure in case of (a) TM and (b) TE polarization light input. 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 0.44 V, and very low dark current density of around 0.4 nA/μm² was achieved with high responsivity of 0.8 A/W. In addition, small electrode spacing of 1 μm 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.

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References