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Enhanced Light Sensitivity of Thin SOI Photodiode by Metal Line-and-Space Grating of Various Materials

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1. Introduction

Silicon-on-insulator (SOI) photodetector has advantages of high-speed operation and large voltage gain per electric charge because of the low parasitic capacitances. However, due to the small thickness for light absorption, the sensitivity of SOI photodetector is usually not high. In order to solve this problem, we have proposed a gold (Au) line-and-space (L/S) grating that can be applied to SOI metal-oxide-semiconductor (MOS) p-n photodiode [1], and the enhanced light sensitivity by the grating is experimentally demonstrated for the first time [2]. In this paper, dependence on grating materials, such as Au, silver (Ag) and aluminum (Al) is numerically investigated by finite difference time domain (FDTD) method. It is found that the light sensitivity can be enhanced by any grating material, and the peak wavelengths are almost unchanged as long as the grating periods are the same. These features are very unique, because the grating material can be selected from these materials considering productivity, compatibility with applications, and so on. For example, Al is widely used in the process of large-scale integrated circuits (LSIs). Thus, the study on material dependence will be of great use.

2. Device Structure

Figure 1 shows the proposed SOI-MOS p-n photodiode with binary metal L/S grating and the definition of incident light polarization for the grating direction. As grating materials, Au, Ag and Al are chosen. In the case of Au and Ag, 5-nm-thick Ti is inserted as an adhesion layer between grating and SiO_2. The incident light enters normally to the photodiode surface. The thickness of the top SiO_2, which is called as gate oxide, is optimized for 700-nm-wavelength and TM-polarized light. In SOI layer, the lateral resonance of waveguide modes can be excited by the diffracted light from the grating. Figure 2 shows the top view of one of the fabricated devices with p^- active area of $L = W = 50$ μm.

3. Results and Discussions

Figure 3 shows the simulated and measured spectroscopic external quantum efficiency (QE) for TM polarization in SOI-MOS photodiode with and without Au/Ti grating. The SOI thickness t_{SOI} is 95 nm. Comparing with simulated results, maximum value is decreased, and full width at half maximum (FWHM) is expanded, for the grating period in the measured results. These values are affected at least by the resolution of the spectrometer (8 nm) in our light illumination system. Nevertheless, especially for grating period p = 300 nm, the external QE can be enhanced to 25%, and its enhancement factor is 8.3. Figure 5 shows the material dependence of L/S grating. The SOI thickness t_{SOI} is 100 nm. The peak heights of external QE depend on the grating material especially for the shorter wavelength due to the difference in optical constants. For monochromatic light detection, Au grating is the best choice, because the number of the main peak is only one. On the other hand, the peak wavelengths at the same grating period are almost unchanged independent of the grating material. In order to clarify this reason, Fig. 5 compares the relationships of peak wavelengths of external QE vs. grating period p in Fig. 4, and the propagation wavelengths λ_g of lateral waveguide modes in SOI layer vs. free-space wavelength. Propagation wavelengths are obtained by calculating eigenvalues of symmetrical slab waveguide composed of 100-nm-thick Si core and infinite-thick SiO_2 clads [3]. These two relationships coincide well indicating that the incident light is efficiently coupled to the waveguide mode and absorbed in SOI when p is equal to λ_g.

4. Conclusions

SOI-MOS p-n photodiodes with L/S grating of Au, Ag, and Al have been numerically and experimentally investigated. It has been shown that any grating of these materials could enhance the light sensitivity of SOI-MOS p-n photodiode for TM-polarized light. Also, the reason why the peak wavelength is determined only by the grating period regardless of the material has been clarified. Thus, considering the compatibilities with the application, grating material can be selected from Au, Ag, or Al. Especially, Al grating for enhanced light sensitivity is of great use considering the popularity of the material in LSI processing.

References

[1] H. Satoh and H. Inokawa, *Int. Conf. Solid State Devices and Materials*, E-3-2 (2008) pp.286-287.

[2] H. Satoh, H. Inokawa, and A. Ono, *2011 IEEE Silicon Nanoelectronics Workshop*, 4-3 (2011).

[3] J.M. Liu, Photonic Devices, Cambridge Univ. Press (2005) pp. 95-99.

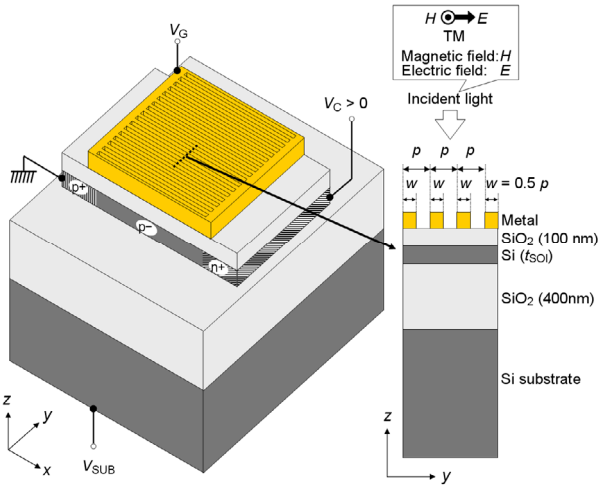

Fig. 1 Devise structure of proposed SOI-MOS p-n photodiode with metal L/S grating and definition of incident light polarization with respect to grating direction.

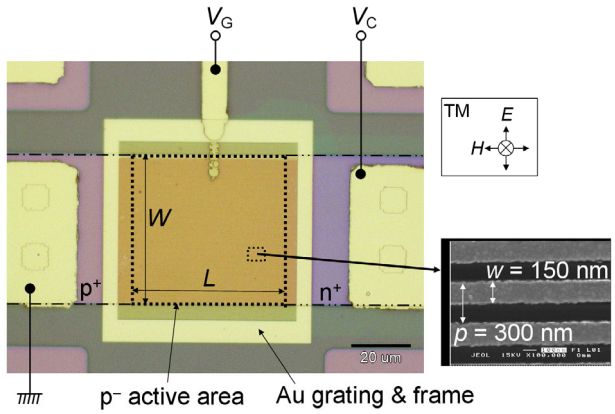

Fig. 2 Top view of the fabricated SOI-MOS p-n photodiode with Au L/S grating. The polarizations with respect to the direction of Au L/S grating are also shown. Dimensions of the p^- active area are $L = 50$ µm and $W = 50$ µm.

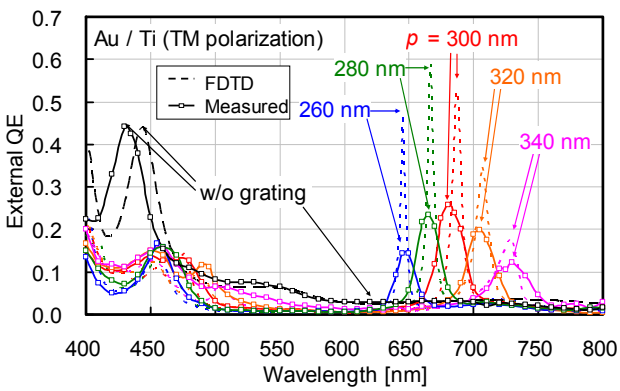

Fig. 3 Simulated and measured spectroscopic external quantum efficiencies (QEs) of SOI-MOS p-n photodiode with and without metal grating. Metal grating is composed of 80-nm-thick Au and 5-nm-thick Ti. SOI thickness t_{SOI} is 95 nm. Measured results are obtained in bias voltage condition of $V_C = 0.2$ V, $V_G = -15$ V, $V_{SUB} = 10$ V.

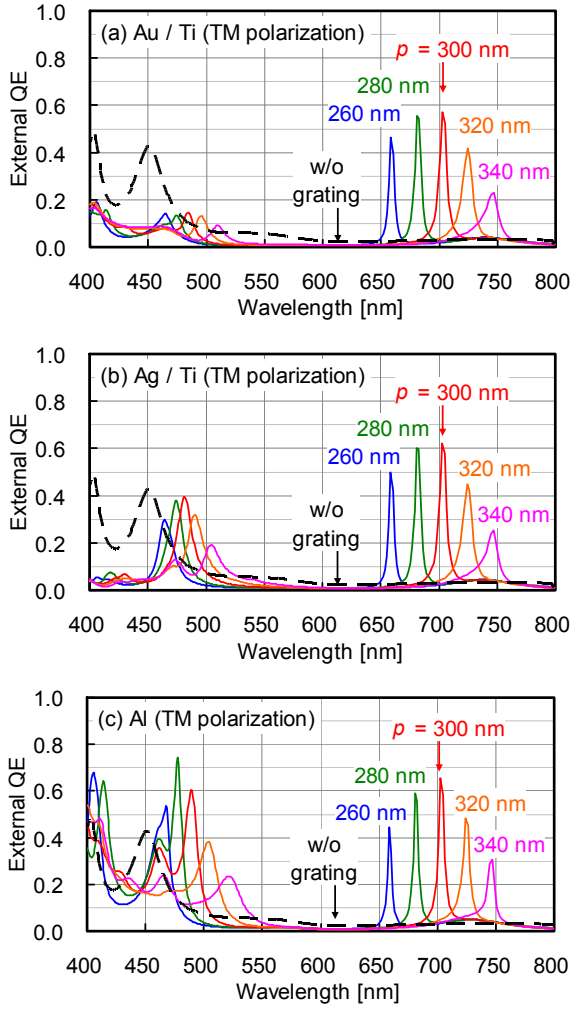

Fig. 4 Simulated spectroscopic external quantum efficiency (QE) of SOI-MOS p-n photodiode with and without metal grating of (a) 100-nm-thick Au / 5-nm-thick Ti, (b) 100-nm-thick Ag / 5-nm-thick Ti, and (c) 100-nm-thick Al. SOI thicknesses t_{SOI} is 100 nm.

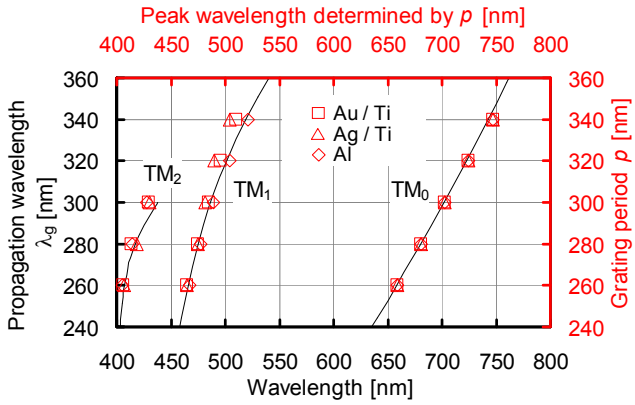

Fig. 5 Comparison between relationships of peak wavelengths of external QE vs. grating period p in Fig. 4, and the propagation wavelengths λ_g of lateral waveguide modes in SOI layer vs. free-space wavelength. Propagation wavelengths are obtained by calculating eigenvalues of symmetrical slab waveguide composed of 100-nm-thick Si core and infinite-thick SiO_2 clads [3].