Material Dependence of Metal Grating on SOI Photodiode for Enhanced Quantum Efficiency

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Hiroaki Satoh, *Member, IEEE*, Ken Kawakubo, Atsushi Ono, and Hiroshi Inokawa, *Member, IEEE*

***Abstract*— Material dependence of line-and-space metal grating among gold, silver, and aluminum, is experimentally investigated for a 100-nm-thick silicon-on-insulator p-n junction photodiode in terms of enhanced light sensitivity. It is found that light sensitivity in visible long-wavelength region is enhanced with any grating material, and the peak wavelengths, which are determined by the grating period, are not much affected by the material. The relationship between the peak wavelength and the grating period is explained theoretically. The results indicate that the grating material can be selected from these materials by taking into account the short-wavelength sensitivity and compatibility with applications.**

***Index Terms*— metal grating, silicon on insulator technology, photodiode, p-n junction**

I. Introduction

SILICON-ON-INSULATOR (SOI) photodetectors have advantages in terms of high-speed operation and large voltage gain per electric charge due to low parasitic capacitances. Thus, SOI technology has been successfully applied to high-performance complementary metal-oxide-semiconductor (CMOS) large-scale integrated (LSI) circuits for servers and gaming machines. Considering applications to light detection, light sensitivity of a photodetector fabricated in SOI is usually quite low due to it being not thick enough as a light absorber. One candidate for solving this problem is the surface plasmon (SP) antenna, which enhances the infrared light sensitivity of a Schottky-junction photodiode (PD) with a small silicon (Si) mesa structure [1, 2]. This SP antenna with a continuous grating structure was used to excite the SP along the antenna surface. The SP was then introduced to the Si mesa PD to attain higher light sensitivity. We also proposed a different type of SP antenna with a gold (Au) line-and-space (L/S) grating that could be applied to an SOI metal-oxide-semiconductor (MOS) p-n junction PD [3-5], and experimentally demonstrated enhanced light sensitivity in the visible wavelength range for the first time [5]. Our PD with a separate binary Au L/S grating utilizes efficient coupling between the diffracted light from the grating and the waveguiding mode in the SOI layer to enhance light sensitivity. In addition, the p-n junction is isolated from the metal grating by gate silicon dioxide (SiO_2), and features a small dark current. This approach is similar to the use of a metal grating directly on an SOI layer proposed by Crouse et al. [6]. They described a diffraction mode produced by the grating coupled into a waveguide mode in the top silicon layer of the SOI with detailed consideration to various resonance mechanisms for enhanced quantum efficiency (QE). Our approach is different in that an insulator is inserted between the grating and the SOI to realize a MOS-type lateral p-n junction PD, which leads to higher QE than that of Crouse et al. [6].

We experimentally investigated the dependence on grating materials among SP media, such as Au, silver (Ag) and aluminum (Al). It is worthwhile to understand how the characteristics of each material, such as the difference in optical constants, affects the characteristics of the PD. This will also lead to the selection of suitable materials for various applications.

II. Device Structure and Bias Condition

Fig. 1 shows the proposed SOI-MOS p-n junction PD with a separate metal L/S grating and the definition of incident light polarization with respect to the grating direction. A commercial SOI wafer with a 200-nm-thick buried oxide (BOX) layer is used. The SOI thickness t_{SOI} is fixed at 100 nm. The materials chosen for the grating materials are Au, Ag, and Al. For Au and Ag, 5-nm-thick Ti is inserted as an adhesion layer between the grating and the upper SiO_2. The incident light normally enters the PD surface. The L/S grating is fabricated using electron beam (EB) lithography, metal evaporations, and liftoff. Since this grating is surrounded by a frame, all the metal lines of the grating are connected electrically. Thus, the grating can work as a gate electrode to control the potential of the light sensitive area, i.e., p^- area. By applying bias voltages to the gate and the substrate, the position and volume of the depletion region can be controlled to maximize light sensitivity. The thickness of the top SiO_2, which is also called gate oxide, is optimized to 100 nm for a 703-nm-wavelength and TM-polarized light by using finite difference time domain (FDTD) calculations [5].

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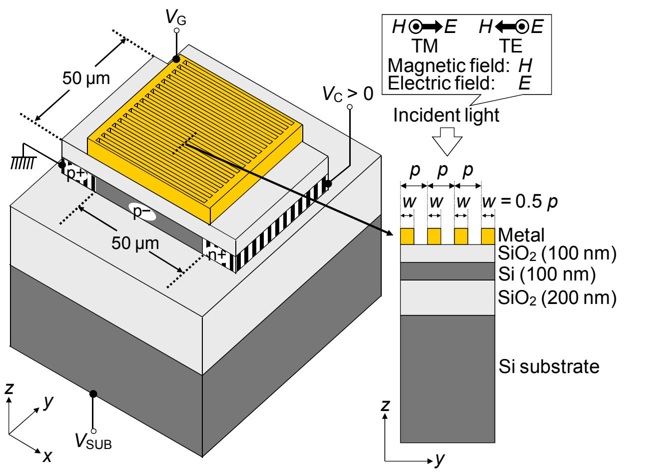

Fig. 1. Device structure of proposed SOI-MOS p-n PD with metal L/S grating gate electrode and definition of incident light polarization with respect to grating direction. Dimensions of light sensitive p^- area are 50 μm ×50 μm.

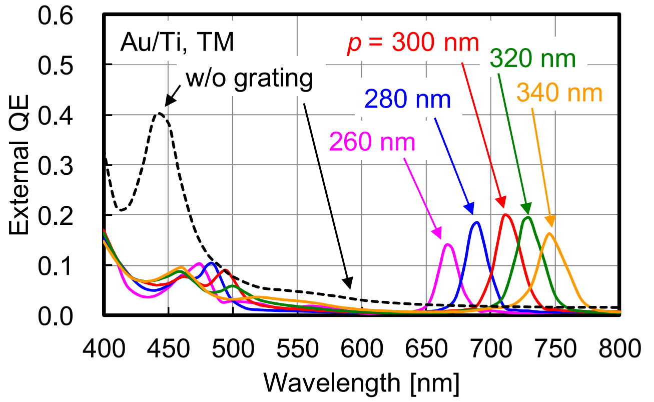

Fig. 2. Measured spectroscopic external quantum efficiencies (QEs) of SOI-MOS p-n PDs with and without Au/Ti grating. Au/Ti grating is composed of 93-nm-thick Au and 5-nm-thick Ti. Bias conditions are fixed at $V_C = 1$ V, $V_G = -7$ V, and $V_{SUB} = 0$ V with grating, and $V_C = 1$ V, $V_{SUB} = -8$ V without grating.

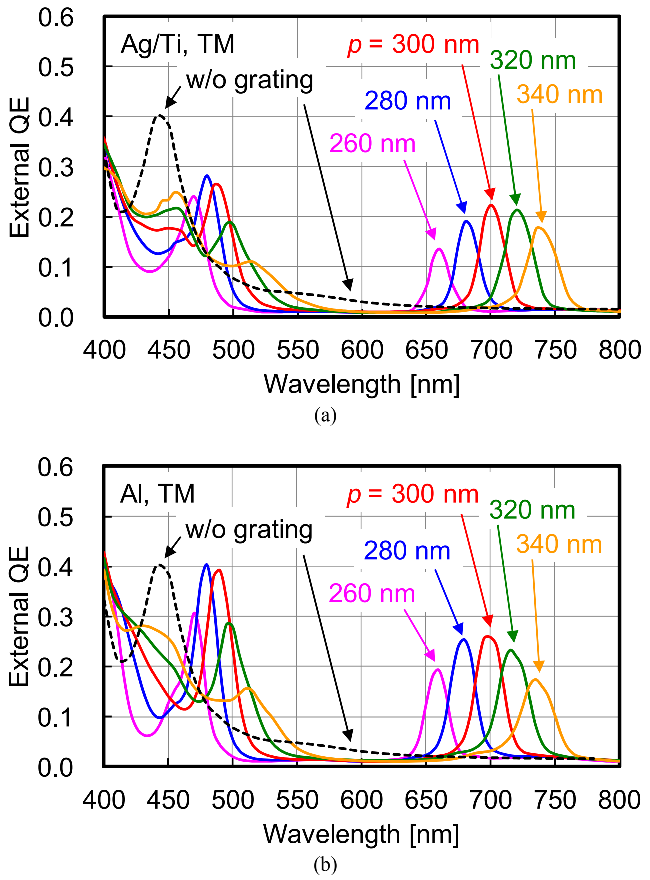

Fig. 3. Measured spectroscopic external quantum efficiencies (QEs) of SOI-MOS p-n PDs with (a) Ag/Ti (103-nm-thick/5-nm-thick) and (b) Al (112-nm-thick) gratings. For comparison, same results without grating in Fig. 2 are also shown. Bias conditions are fixed at $V_C = 1$ V, $V_G = -7$ V, and $V_{SUB} = 0$ V with grating, and $V_C = 1$ V, $V_{SUB} = -8$ V without grating.

III. Measured External Quantum Efficiencies and Discussion

Fig. 2 shows the measured spectroscopic external QEs for TM polarization in SOI-MOS PDs with and without Au/Ti grating composed of 93-nm-thick Au and 5-nm-thick Ti. For the PD without the Au/Ti grating, there is a peak with relatively high external QE at the wavelength of 445 nm due to the higher absorption coefficient of Si in the shorter wavelength region and interferences in the multilayered structure. However, the external QE decreases at wavelengths longer than 500 nm. For the PD with Au/Ti grating, the enhancement effects are observed at wavelengths ranging from 650 nm to 750 nm. For grating period $p = 300$ nm, the external QE reaches 20 % at the wavelength of 710 nm, and its enhancement factor, the ratio of QEs with and without the metal grating, is 11. These peak wavelengths can be controlled by the grating period p. Such a property is caused by the coupling between the diffracted light from the Au/Ti grating and the TM waveguide mode in the SOI layer, as discussed later in this section. This result indicates that multi-wavelength photodetectors can be integrated in a chip just by preparing L/S gratings with different periods. If the incident light is TE-polarized, the external QE can also be enhanced at different wavelengths corresponding to the TE waveguide mode in SOI, but the heights of peak external QEs are smaller than 5 % (data not shown).

Fig. 3 shows the measured external QEs for (a) Ag/Ti (103-nm-thick/5-nm-thick) and (b) Al (112-nm-thick) gratings. For longer wavelengths ranging from 650 nm to 750 nm, both the peak heights and the peak wavelengths of external QE are almost independent of the grating material as long as the grating periods are the same. In addition, the external QEs in shorter wavelengths ranging from 450 nm to 550 nm are also enhanced for both Ag/Ti and Al gratings. For the Ag/Ti grating with $p = 300$ nm, enhanced QEs of 26 % and 22 % are obtained at wavelengths of 490 nm and 700 nm, respectively. The enhancement factors at wavelengths of 490 nm and 700 nm reach 2.6 and 12, respectively. For Al grating with $p = 300$ nm, QEs are 39 % and 26 % at wavelengths of 490 nm and 700 nm, respectively. The enhancement factors at these wavelengths reach as high as 4.0 and 14, respectively. Thus, the Al grating is the best for higher external QE. On the contrary, Au/Ti grating

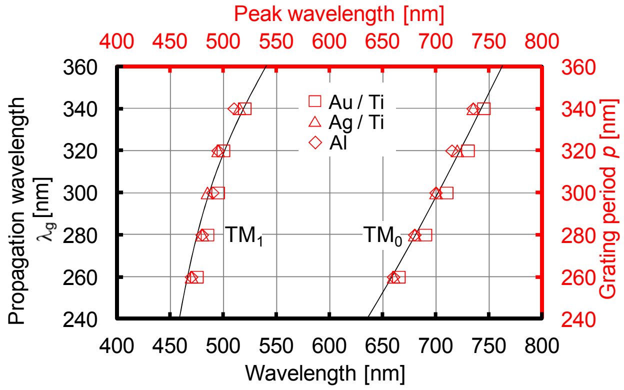

Fig. 4. Comparison between relationships of propagation wavelength λ_g of lateral waveguide modes in SOI layer vs. free-space wavelength (lower and left axes), and peak wavelength of external QE vs. grating period p in Figs. 2 and 3 (right and upper axes). Propagation wavelengths are obtained by calculating eigenvalues of symmetrical slab waveguide composed of 100-nm-thick Si core and infinite-thick SiO_2 claddings [7].

is suitable for monochromatic light detection because there is only one main peak. Even in a shorter wavelength range, the peak wavelengths of external QE are still independent of the grating material as long as the grating periods are the same. To clarify why the peak wavelength is controlled by the grating period, Fig. 4 compares the relationships of the propagation wavelengths λ_g of lateral waveguide modes in the SOI layer vs. the free-space wavelength (lower and left axes) and peak wavelengths of external QE vs. grating period p in Figs. 2 and 3 (upper and right axes). Propagation wavelengths are obtained by calculating the eigenvalues of symmetrical slab waveguide composed of 100-nm-thick Si core and infinite-thick SiO_2 claddings [7, 8]. These two relationships coincide well, indicating that the incident light is efficiently coupled to the waveguide mode and absorbed in SOI when $p = \lambda_g$. These results indicate that higher QEs with sharp peaks are caused mainly by the coupling between the diffracted light from the metal grating and the lateral propagation mode in the SOI waveguide (not mainly by the SP excitations around the metal grating). This also suggests that the peaks in the longer wavelength ranging from 650 nm to 750 nm correspond to the fundamental TM (TM_0) mode in the SOI layer, and the ones in the shorter wavelength ranging from 450 nm to 550 nm correspond to the first-order TM (TM_1) mode, as shown in Figs. 2 and 3.

To explain the material dependence of the peak heights of external QEs, especially around the shorter wavelength of 485 nm in Figs. 2 and 3, the spectroscopic power components of reflectance, transmittance, metal loss, and external QE are evaluated using FDTD calculations, as shown in Fig. 5. The reflection minima at the shorter peak wavelength for Ag/Ti and Al gratings are clearly observed, and the metal losses are much smaller than that of the Au/Ti grating. These results lead to much higher external QEs for the Ag/Ti and Al gratings. To supplement the results of material dependence in Fig. 5, we also calculate the absolute reflectance at the interface between the vacuum and bulk metal of Au, Ag, and Al, by $|R| = |\{(n\text{-}jk)\text{-}1\} / \{(n\text{-}jk)+1\}|$, where n and k are the refractive index and the extinction coefficient of the metal, respectively. Fig. 6 shows that the absolute reflectance of Au is much smaller than those of Ag and Al at wavelengths shorter than 500 nm. In this case, the absorption in Au (complement of reflectance) is as much as 60 %. This results in a much larger metal loss of the Au/Ti grating in the same wavelength range than those of the Ag/Ti and Al gratings, as shown in Fig. 5. In addition, we may correlate the absolute reflectance of grating material to the diffraction efficiency of the grating. The absolute reflectance values of Ag and Al are close to unity; thus the incident light can be efficiently diffracted by the Ag/Ti and Al gratings but not by the Au/Ti grating. As a result, the higher peak heights of external QE can be obtained for the Ag/Ti and Al gratings.

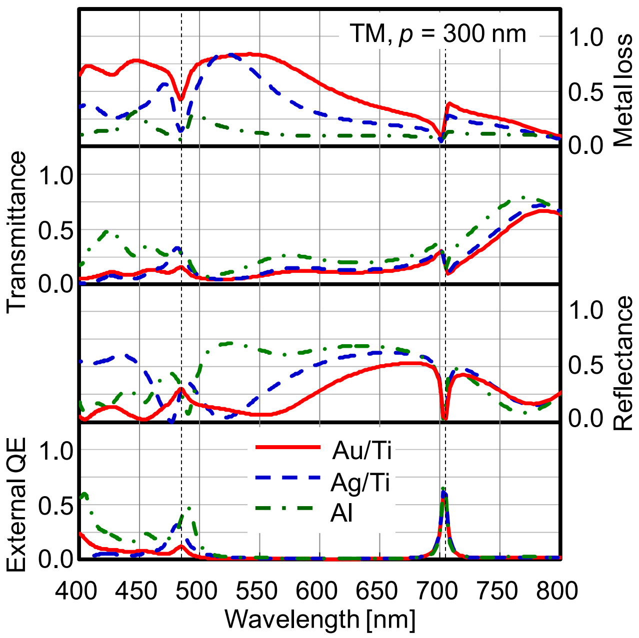

Fig. 5. Calculated spectroscopic responses of SOI-MOS p-n PDs with Au/Ti, Ag/Ti, and Al gratings (TM polarization and grating period p = 300 nm). Au, Ag, and Al thicknesses are 100 nm. Ti thickness for adhesion layer is 5 nm. Transmittance is defined for normalized power entering infinite-thick Si substrate for incident power.

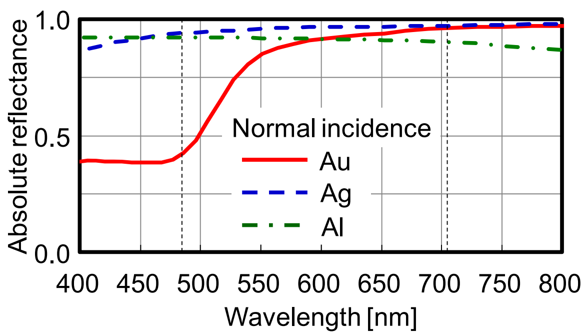

Fig. 6. Calculated spectroscopic absolute reflectance for different metals at interface between vacuum (incident side) and metal for normal incidence. Refractive indices n and extinction coefficients k of Au, Ag, and Al are from [9]. Optical constants of vacuum are fixed at n = 1 and k = 0.

IV. CONCLUSION

We experimentally investigated the material dependence of L/S gratings among Au, Ag, and Al for an SOI-MOS p-n junction PD in terms of spectroscopic QE. It has been shown that any grating of these materials could enhance the light sensitivity of the PD. In addition, the reason the peak wavelength is determined only by the grating period irrespective of the material has been clarified based on the coupling between the diffracted light from the grating and the modes in the SOI waveguide. Since QE spectrum in the short-wavelength region depends largely on materials, and chemical, mechanical and electrical properties also differ, grating material can be selected from Au, Ag, or Al considering them. In particular, Al grating is of great use due to the material compatibility with most Si-based devices.

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REFERENCES

[1] T. Ishi, J. Fujikata, K. Makita, T. Baba, and K. Ohashi, "Si nano-photodiode with a surface plasmon antenna," Jpn. J. Appl. Phys., vol. 44, no. 12 pp. L364-L366, March 2005.
[2] D. Okamoto, J. Fujikata, K. Nishi, and K. Ohashi, "Numerical study of near-infrared photodetectors with surface-plasmon antenna for optical communication," Jpn. J. Appl. Phys., vol. 47, no. 4, pp. 2921-2923, April 2008.
[3] H. Satoh, and H. Inokawa, "Surface plasmon antenna with gold line and space grating for enhanced visible light detection by a silicon-on-insulator metal–oxide–semiconductor photodiode, " IEEE Trans. Nanotechnology, vol. 11, no. 2, pp. 346-351, Mar., 2012.
[4] H. Satoh, and H. Inokawa, "Spectroscopic response of SOI photodiode with gold line-and-space surface plasmon antenna," in Proc. Silicon Nanoelectronics Workshop, 2009, pp. 117-118.
[5] H. Satoh, H. Inokawa, and A. Ono, "Enhancement of light sensitivity of thin SOI photodiode by gold line-and-space grating for selected wavelength and polarization, " in Proc. Silicon Nanoelectronics Workshop, 2011, pp. 33-34.
[6] D. Crouse, and P. Keshavareddy, "A method for designing electromagnetic resonance enhanced silicon-on-insulator metal-semiconductor-metal photodetectors," J. Opt. A: Pure Appl. Opt., vol. 8, no. 2, pp. 175-181, Jan. 2006.
[7] J. M. Liu, Photonic Devices, Cambridge University Press, pp. 95-99, 2005.
[8] (1998). [Online] Available: http://www.sspectra.com/sopra.html
[9] A. D. Rakic, A. B. Djurisic, J. M. Elazar, and M. L. Majewski, "Optical properties of metallic films for vertical-cavity optoelectronic devices," *Appl. Opt.*, vol. 37, no. 22, pp. 5271–5283, Aug. 1998.