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Periodic Arrangement of Au Nanoparticles on SOI Photodiode for Absorption Enhancement

Atsushi Ono[1], Hiroaki Satoh[2], Ryo Kawai[2] and Hiroshi Inokawa[2]

[1] Division of Global Research Leaders, Shizuoka Univ.
3-5-1 Johoku, Naka-ku, Hamamatsu, 432-8561, Japan
Phone: +81-53-478-1370 E-mail: daono@ipc.shizuoka.ac.jp
[2] Research Institute of Electronics, Shizuoka Univ.
3-5-1 Johoku, Naka-ku, Hamamatsu, 432-8011, Japan

1. Introduction

We have investigated the absorption efficiency of silicon-on-insulator (SOI) photodiode with Au nanoparticles by FDTD simulation. SOI photodiodes have a feature of high charge sensitivity and high operation speed due to the low parasitic capacitance [1, 2]. However, its light absorption efficiency is usually low because of the small volume for the absorption. In order to improve the absorption efficiency, we propose an SOI photodiode with Au nanparticles. Incident light is efficiently coupled to the waveguide modes in SOI by metallic nanoparticles to enhance the light absorption in SOI.

Recently, Si photodiodes with varieties of metallic nanostructures, such as bull's eye [3, 4], nanoparticles [5-7] and grating [8-10], have been proposed to improve the absorption efficiency in association with surface plasmon resonance (SPR). It has been proposed that gold line-and-space grating attached to SOI photodiode enhances absorption in SOI at a certain visible wavelength [8, 9].

We have performed 3-*D* FDTD simulations for the characteristics of absorption efficiencies in SOI photodiode with Au nanoparticles varying the structural parameters such as the SiO_2 film thickness *g*, the diameter of Au nanoparticles *d*, and the period of Au nanoparticles array *p*.

2. Simulation results

Figure 1(a) shows the simulated model of the cross-sectional view of the SOI photodiode with Au nanoparticles. In the simulations, we fixed the thickness of the SOI absorbing layer to 100 nm and the buried oxide (BOX) layer to 400 nm. Periodic boundary conditions are set to the both sides of SOI structure and the normal incident light of impulse is irradiated from the top. The power monitored at the both interfaces of SOI is transformed by Fast-Fourier. One of the results of the spectra showing the absorption efficiencies of SOI with (solid line) and without (dashed line) Au nanoparticles is shown in Fig. 1(b). The absorption efficiency of 0.15 at the wavelength of 654 nm was obtained with the period *p* of 260 nm, the SiO_2 thickness *g* of 20 nm and the particle diameter *d* of 100 nm. The absorption efficiency of SOI with Au nanoparticles is about 8.4 times higher than that of the SOI without the nanoparticles.

Figures 2(a), (b) and (c) show the resonant wavelength and the enhancement factor depending on the SiO_2 thickness *g*, particle diameter *d* and array pitch *p*, respectively. These dependences were investigated based on the parameters described in Fig. 1. The resonant wavelength is constant at 654 nm regardless of SiO_2 thickness and particle diameter. On the other hand, the resonant wavelength is linearly shifted to longer wavelength as the array pitch is increased. The enhancement factor becomes higher as the SiO_2 thickness decreases, and the particle diameter increases, and becomes maximum at around the pitch of 230 nm.

Figures 3(a), (b) and (c) show the steady state field distributions of absolute intensities of *Ex*, *Ez* and *Hy* for SOI with Au nanoparticles at the most efficient pitch $p = 230$ nm ($g = 20$ nm, $d = 100$ nm). The light is normally irradiated with *p*-polarization at the wavelength of 632 nm. Enhanced field distributions were observed in the near-field of Au nanoparticle. In SOI region of $|Hy|^2$, enhanced standing wave is generated. From these, it is considered that the absorption efficiency of SOI photodiode is improved by periodically arranged Au nanoparticles due to the coupling between waveguide mode of SOI and the incident light via nanoparticles.

3. Study on Au nanoparticles arrangement

Au nanoparticles with the diameter of 20 nm is immobilized on Si substrate by silane coupling treatment. Figure 4 shows the SEM image of Au nanoparticles attached on Si substrate. The density of the nanoparticles is 3.6×10^{10} cm^{-2}. Although this method has some advantages of process simplicity, high particle density, large processed area, and no aggregation, the periodicity is out of control. Periodic arrangement of Au nanoparticles in a large area might be realized by the lift-off process of metal with a block co-polymer template [10].

4. Conclusions

Enhanced sensitivity of SOI photodiode with Au nanoparticles was verified by FDTD simulations. The photosensitivity is improved by the factor of about 20 due to the coupling with the waveguide mode in SOI. Realization of the periodic arrangement of Au nanoparticles by a simple process remains as the further research.

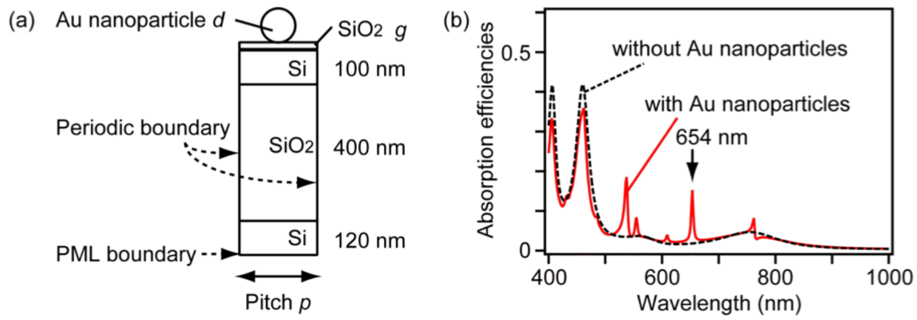

Fig. 1 (a) Simulation model and (b) the spectra of the absorption efficiencies of SOI photodiode with and without Au nanoparticels.

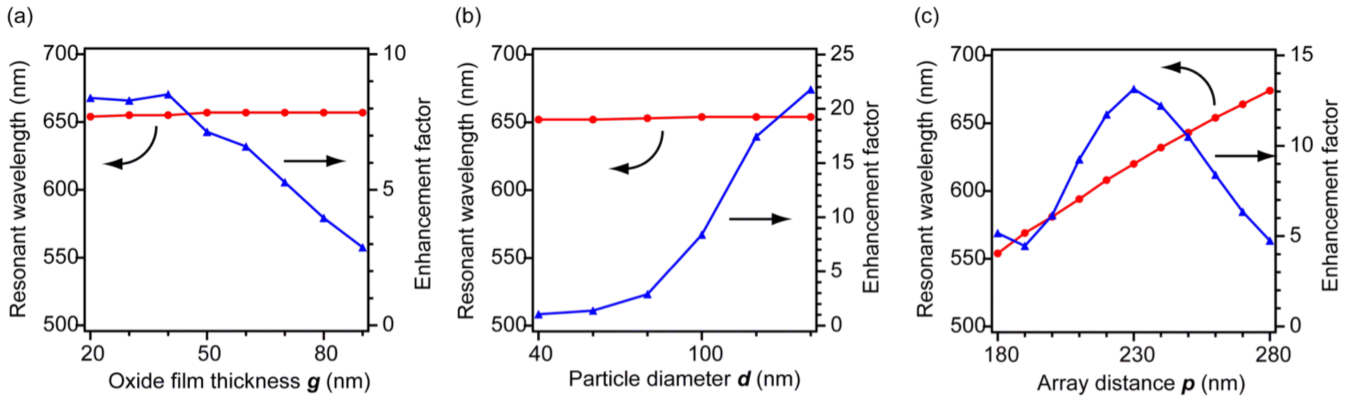

Fig. 2 Resonant wavelength and enhancement factor of the light absorption for SOI photodiodes by Au nanoparticles with respect to (a) SiO2 thickness, (b) particle diameter, and (c) array pitch.

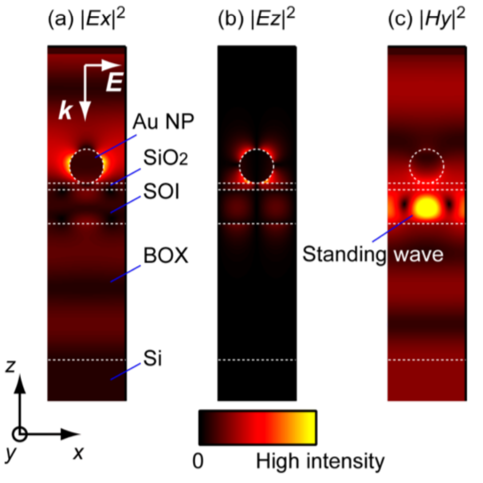

Fig. 3 Field distributions for electro-magnetic components of (a) *Ex*, (b) *Ez* and (c) *Hy*. The standing wave is induced in SOI.

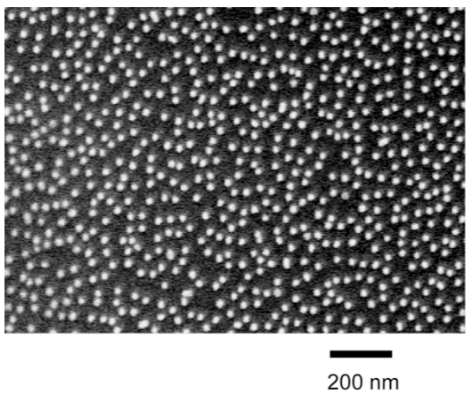

Fig. 4 SEM image of 20 nm gold nanoparticles

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