Sensitivity Enhancement of SOI Photodiode with Randomly Arranged Au Nanoparticles

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Abstract

We demonstrated the quantum efficiency (QE) of silicon-on-insulator (SOI) photodiode was enhanced in visible frequency region by using Au nanoparticles. Two-fold enhancement in the QE was achieved in visible by the optimized particle size and density.

1. Introduction

Silicon-on-insulator (SOI) photodiodes feature 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 photodiodes with Au nanoparticles. Incident light is efficiently coupled to the waveguide modes in SOI induced by metallic nanoparticles to enhance the light absorption in SOI.

Previously, we have developed SOI lateral pn-junction photodiodes for improved quantum efficiency (QE) by Au line-and-space grating [3]. The diffracted light from the grating efficiently couples with the waveguide mode in SOI, leading to the resonant peak which shows an external QE one order of magnitude higher than that without the grating. The resonant peak wavelength is controlled by the grating period, which can be explained by the coupling between the diffracted light from the Au line-and-space grating and the waveguide mode in SOI.

Here, we would like to demonstrate the enhanced QE of SOI photodiode by using randomly arranged Au nanoparticles.

2. Structure optimization of SOI photodiode with periodically arranged Au nanoparticles

We have performed 3-D FDTD simulations for the characteristics of absorption efficiencies in SOI photodiode with Au nanoparticles varying with the structural parameters such as the diameter of Au nanoparticles d, and the period of Au nanoparticles array p. Fig. 1 shows the cross-sectional view of the simulated 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 width and depth sides of SOI structure, and the normal incident light of impulse is irradiated from the top. The power spectra at the both interfaces of SOI are obtained using the fast Fourier transform.

Figs. 2(a), 2(b), and 2(c) show the typical simulation results of enhancement spectra varying with the Au nanoparticle diameter d (50-200 nm) and the period p (200, 240, and 280 nm). The resonant peak wavelength respectively appears in 585, 636, and 682 nm depending on the period that is corresponding to the waveguide mode of TM0 in SOI as shown in Fig. 2(d). Fig. 3 shows the peak map of enhancement factor in the Au particles period and diameter. It is found that the enhancement factor of 29 is achieved in the optimized structural parameters of d =140 nm and p =240 nm. The resonant wavelength in these optimized conditions is 682 nm. Figs. 4(a), 4(b) show the corresponding steady state field distributions of absolute intensities of Ex and Hcy. Enhanced Ex distributions were observed in the near-field of Au nanoparticle due to the excitation of local surface plasmon resonance. In SOI region of Hcy, enhanced standing wave is observed, which can be attributed to the coupling to SOI waveguide mode.

3. QE of SOI photodiode with randomly arranged Au nanoparticles

Figs. 5(a) and 5(b) show the optical images of the fabricated SOI photodiode without and with Au nanoparticles, respectively. Figure 6 shows SEM image of the attached Au nanoparticles on the photodiode. The particle size is 150 nm, and the particle density is 6.0×10^6 particles/cm^2. This high density is achieved by an Au/polyimide nanocomposite film used as an anchor layer for large Au particles.

Figs. 7(a) and (b) show the measured spectra of external quantum efficiencies and the enhancement factor of SOI photodiodes with and without Au nanoparticles. We achieved two-fold enhancement in visible around 620 nm wavelengths. We estimated the absorption efficiencies and in SOI with randomly arranged Au nanoparticles by averaging the spectra for periodically arranged nanoparticles with p=180 -350 nm. The estimated results in Fig. 7(c) show good agreement with the experimental one.

4. Conclusions

The structural parameters of Au nanoparticles attached to the SOI photodiode have been optimized by 3-D FDTD simulations. The particle diameter of 140 nm arranged with the period of 240 nm exhibited 29-fold enhancement at the wavelength of 682 nm.

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arranged Au nanoparticles with diameter of 150 nm and density of $6.0 \times 10^8$ particles/cm$^2$. Two-fold enhancement was achieved in visible frequency region, which showed good agreement with the estimation.

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**References**


Fig. 1 Simulation model for SOI photodiode with Au nanoparticles

Fig. 2 Enhancement spectra varying with Au nanoparticle diameter and the period (a) 200, (b) 240, (c) 280 nm. (d) Waveguide mode spectra in SOI.

Fig. 3 Peak map of the enhancement factor varied with the particle diameter and period.

Fig. 4 Field distributions for electro-magnetic components of (a) $E_x$ and (b) $H_y$.

Fig. 5 (a) Bright- and (b) dark-field optical images of fabricated SOI photodiodes before and after the attachment of Au nanoparticles.

Fig. 6 SEM image of attached Au nanoparticles.

Fig. 7 Measured spectra of (a) external quantum efficiencies and (b) the enhancement factor of SOI photodiodes with and without Au nanoparticles. (c) Simulated efficiencies.