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# Enhanced Sensitivity of SOI Photodiode by Au Nanoparticles

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## 1. Introduction

We have demonstrated that the quantum efficiency of silicon-on-insulator (SOI) photodiode is enhanced by attaching Au nanoparticles on the photodiode. SOI photodiodes have a feature of high charge sensitivity and high operation speed due to the low parasitic capacitance. However, the absorption efficiency of SOI photodiodes is low because of the small volume for the light absorption. In order to improve the absorption efficiency, we propose an SOI photodiodes with Au nanparticles. Multiple scattering by the metallic nanoparticles enhances the light absorption in SOI. The mechanism and the effects of Au nanoparticles on SOI has been investigated by measuring the spectra of quantum efficiency.

## 2. Device structure of SOI photodiode

Figure 1 shows the schematic of the SOI photodiode with Au nanoparticles. This is a lateral $p^+p^-n^+$ junction photodiode on a buried oxide (BOX) layer. The SOI with the thickness of 95 nm is oxidized to 5 nm, and then SiNx is sputtered to 5 nm for passivation. Au nanoparticles with the diameter of 20 nm is immobilized on SiNx by silane coupling treatment.

Figure 2 shows the optical dark field image of fabricated SOI photodiode with Au nanoparticles. The density of the nanoparticles is $3 \times 10^6$ cm$^{-2}$ without causing unfavorable surface leakage current.

## 3. Results of photocurrent measurements

We measured I-V characteristics of the fabricated device and investigated the changes of the quantum efficiency by Au nanoparticles dispersed on the SOI photodiode. Figure 3 shows the absolute value of cathode current as a function of bias voltage for the substrate biases of 10, 0, and −10 V, with (solid lines) and without (dashed lines) Au nanoparticles. We confirmed typical I-V characteristics of photodiode with relatively small dark current for the active area of 50 μm × 50 μm. When light of 60 μW/cm$^2$ at the wavelength of 450 nm is shed on the photodiode, the cathode current are increased by roughly 100 pA for $V_{sub}$ = 0 and 10 V, and 1 nA for $V_{sub}$ = −10 V. For the substrate biases of 10 (Fig. 3(a)) and 0 V (Fig. 3(b)), the cathode current is enhanced thanks to the Au nanoparticles. However, the current is the same either with Au nanoparticles or without them at the substrate bias of −10 V as shown in Fig. 3(c). We assume that the enhancement mechanism by the Au nanoparticles depends on the depletion area in SOI as will be discussed.

We evaluated the spectra of external quantum efficiencies and the ratio of enhancement by the Au nanoparticles as shown in Figs. 4. The external quantum efficiencies (QEs) with Au nanoparticles are generally larger than that without them in the visible wavelength at the substrate biases of 10 (Fig. 4(a)) and 0 V (Fig. 4(b)). The enhancement factors are about 2. On the other hand, the external QEs are almost the same at the substrate bias of −10 V. We also confirmed the absorption spectra by FDTD simulations. Figure 5(a) shows the simulated model of SOI structure with the same size parameters as in the fabricated device. Periodic boundary conditions are set to the both sides of SOI structure and the normal incident light of impulse is irradiated. The power monitored at the both interfaces of SOI is transformed by Fast-Fourier. The results of the spectra of absorption efficiency and the enhancement factor are shown in Fig. 5(b), which is in agreement with the experimental data. From these results, we considered that the enhancement is based on the contributions of Rayleigh scattering and the light trapping in SOI thin-film by multiple and high-angle scattering [1].

Figures 6 shows a model to explain the substrate bias dependence of quantum efficiency and enhancement factor. For negative substrate bias, bottom interface of SOI is accumulated (Acc) with hole, the top interface is inverted (Inv), and depletion layer (Dep), i.e. light-sensitive region, is formed in a large area, resulting in large quantum efficiency. Note that the surface of lightly-doped p-type silicon tends to be inverted [2]. On the contrary, when the substrate is biased to zero or positive voltage, $p^-$ SOI area is mostly inverted (Inv) and the depletion region (Dep) is localized near the $p^+$ region, leading to the smaller quantum efficiency. When Au nanoparticles are dispersed, they scatter light to adjacent areas, and works as an antenna with extended light collecting area. Since the reach of light collection is fixed, effect of the "antenna" is larger for the small light-sensitive area in the case of zero or positive substrate bias (Fig. 6(b)).

## 4. Conclusions

We demonstrated the enhancement of the quantum efficiency of SOI photodiode with Au nanparticles. The enhancement mechanism is explained by the increment of the effective path in SOI due to the scattering and the multiple reflections.

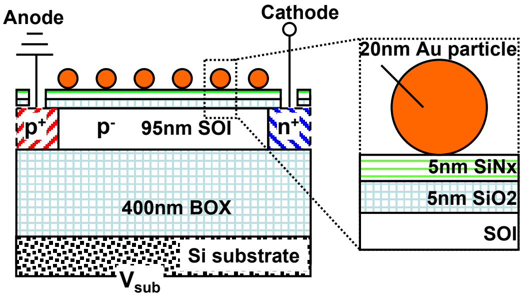



Fig. 1 Device structure.

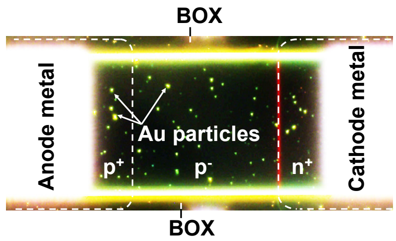



Fig. 2 Optical dark field image of the photodiode with Au particles. $p^-$ area is 50µm×50µm.

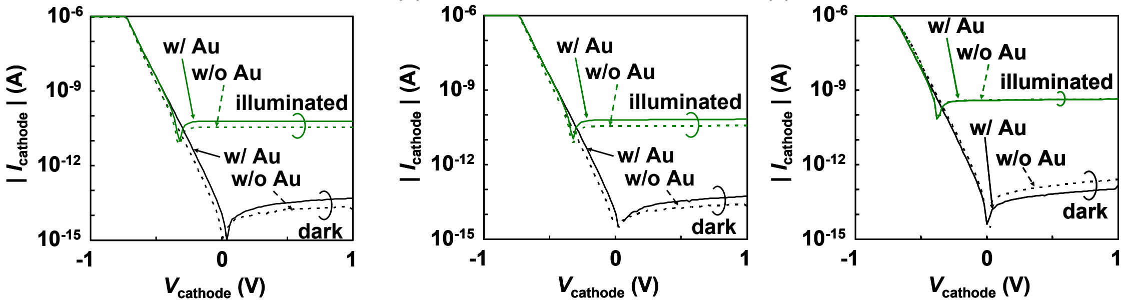



Fig. 3 Characteristics of absolute cathode current against $V_{cathode}$ for different substrate biases, with and without Au nanoparticles. Incident light is fixed at λ=450nm.

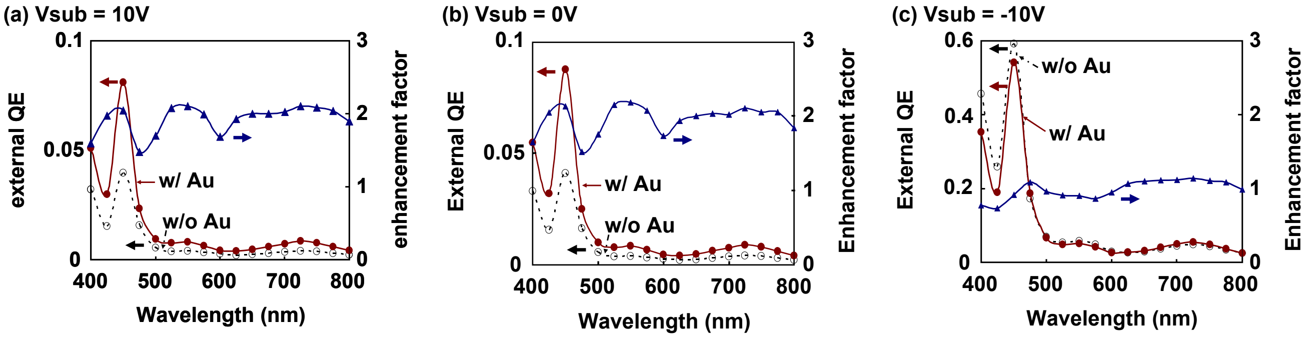
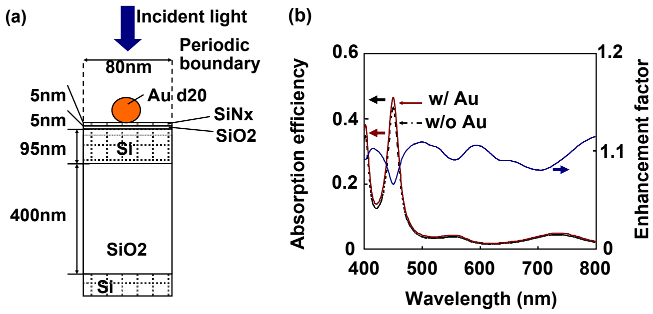



Fig. 4 Spectra of external quantum efficiency and the enhancement factor.



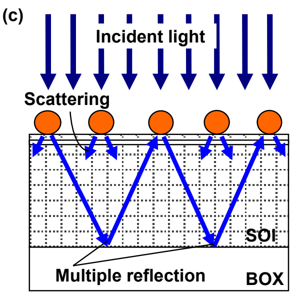




Fig. 5
Simulation results with FDTD method. (a) The model of device structure. (b)Absorption efficiency and enhancement factor with respect to wavelength. (c) Mechanism of enhancement by Au nanoparticles, which includes light scattering and confinement by multiple reflection.

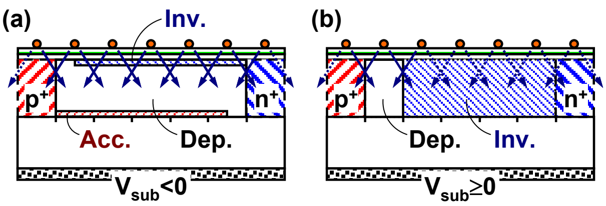



Fig. 6
A Model to explain the substrate bias dependence of quantum efficiency and enhancement factor. Solid arrows indicate the scattered light into the depletion region, which contributes to the photocurrent.

## References

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