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# Broadband absorption enhancement of thin SOI photodiode with high-density gold nanoparticles

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**Abstract:** We demonstrated the quantum efficiency (QE) of silicon-on-insulator (SOI) photodiode was enhanced in visible wavelength region by using gold (Au) nanoparticles. The photons plasmonically scattered by Au nanoparticles couples with the waveguide mode in SOI, and are absorbed efficiently. Optimum size and density of Au nanoparticles have been investigated by 3-D FDTD simulations for sensitivity improvement. The highest enhancement factor of the absorption efficiency in 100-nm-thick SOI is obtained by periodically attaching Au nanoparticles of about 140 nm in diameter and $1.7 \times 10^9$ particles/cm$^2$ in density. Two-fold enhancement in QE was experimentally achieved in visible by the SOI photodiode with randomly arranged Au nanoparticles of the size and density close to the optimized values.

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**OCIS codes:** (040.6040) Silicon; (230.5170) Photodiodes; (230.7370) Waveguides; (290.5850) Scattering, particles; (310.5696) Refinement and synthesis methods.

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## 1. Introduction

Silicon-on-insulator (SOI) complementally metal oxide semiconductor (CMOS) technology is one of the promising techniques for large-scale integration to realize high-speed low-power operation and to mitigate the short-channel effect in scaled-down transistors [1, 2]. Furthermore, the monolithic implementation of photodiode with SOI circuit would be useful in adding new functionality to the SOI-based high-performance integrated circuits. However, the light absorption efficiency of SOI photodiode is usually low because of the small thickness of SOI used in such circuits.

In order to improve the absorption efficiency, we attach metallic nanoparticles on SOI photodiode. Recent experiments have shown that the use of metallic nanoparticles improves the device efficiency and performance for photodiodes and solar cells thanks to the surface plasmons [3–10]. In 1996, H. R. Stuart and D. G. Hall proposed the absorption enhancement of very thin photodiode in the 0.16-μm-thick silicon layer by using metal island films [11]. They have demonstrated the photocurrent enhancement by the factor of 12 and 18 at 800 nm wavelength by copper and silver (Ag) islands film deposition on the photodiode, respectively [12]. They also clarified the absorption enhancement mechanism through these demonstrations, that is the dipole-waveguide coupling process [11–13]. The photon energy scattered by the metal island films transfers into waveguide mode of SOI, which increases the optical path length in SOI. In recent years, this technique has been applied for the absorption enhancement of thin Si solar cells [14, 15].

Previously, we have developed SOI lateral *pin*-junction photodiodes for improved quantum efficiency (QE) by gold (Au), Ag and aluminum line-and-space gratings [16, 17]. 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 metal grating and the waveguide mode in SOI. We also demonstrated the sensitivity improvement of SOI photodiode attached with Au nanoparticles by controlling the substrate bias so that the depletion region, i.e. the photo-sensitive area, in SOI was localized [18]. Twofold sensitivity enhancement was achieved in the whole range of visible wavelength by the attachment of small (20 nm in diameter) and low-density ($3 \times 10^6$ $cm^{-2}$) Au nanoparticles. This sensitivity improvement could be attained only when the initial QE was small, and more practical results were anticipated.

Here, we show the substantial sensitivity enhancement of the fully depleted SOI photodiode with randomly arranged Au nanoparticles of larger size and higher density close to the values optimized by the numerical simulations. We have demonstrated the enhancement using SOI photodiodes provided by Hamamatsu Photonics K.K. for reliable results.

## 2. Optimum size and density of Au nanoparticles for SOI photodiode

In this section, we estimate the optimum size and density of Au nanoparticles by 3-D FDTD simulations for the sensitivity improvement in the fully depleted SOI photodiode (Fig. 1(a)), and verified the effect experimentally with larger and denser nanoparticles. Specifically, we have performed simulations of light absorption in SOI photodiode with Au nanoparticles with various structural parameters such as nanoparticle diameter $d$, and period of nanoparticle arrangement $p$. Figure 1(b) shows the cross-sectional view of the simulated SOI photodiode with Au nanoparticles. In the simulations, we fixed the thickness of SOI absorbing layer to 100 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 and the absorption efficiency is evaluated by subtracting the power spectra at the bottom and the top interfaces of SOI. We have calculated the enhancement factor as the ratio of absorption efficiencies in SOI with and without Au nanoparticles. The simulation takes into account the absorption inside SOI layer, but the possible contribution of outbound energy flow by the surface wave on the periodic Au nanoparticles is not considered, because illumination b a uniform plane wave is assumed. Experimentally, the photodiode is also illuminated by a uniform light with a spot size much larger than that of the photodiode. Contribution of such a surface wave may become conspicuous if the photodiode is illuminated locally.

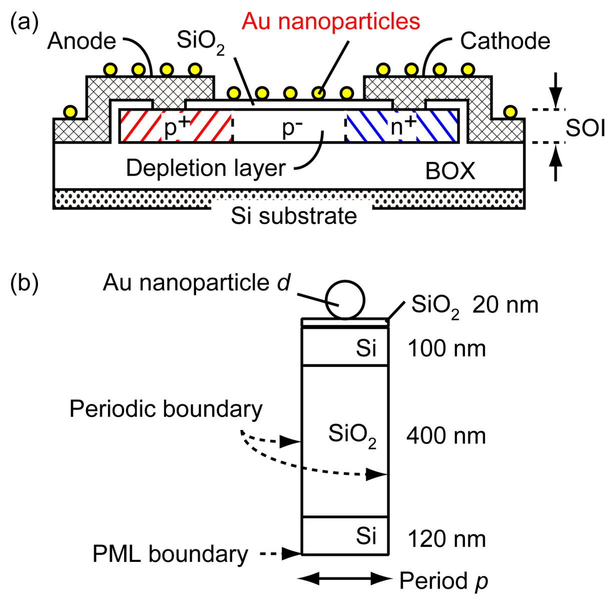


Fig. 1. (a) Schematic cross-sectional image of lateral *pin* SOI photodiode with Au nanoparticles. Au nanoparticles are attached on the surface of photodiode. (b) The model for the simulation of absorption efficiency in SOI by FDTD method. The absorption efficiency dependence on the period and the diameter of Au nanoparticles has been investigated.

Figures 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 peaks appear at the wavelength of 585, 636, and 682 nm, respectively. The resonant wavelength is determined by the period of Au nanoparticles, and the value of enhancement factor depends on the both of the parameters of period and diameter of Au

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nanoparticles. Figure 2(d) shows the dispersion relationship of waveguide modes in SOI of 100-nm-thick Si sandwiched by $SiO_2$. The resonant peak wavelengths and the period of Au nanoparticles correspond to the propagation wavelength spectra of $TM_0$ waveguide mode in SOI. This correspondence indicates the incident photons scattered by Au nanoparticles efficiently couple with the waveguide mode in SOI, resulting in the absorption enhancement due to the prolonged optical path length.

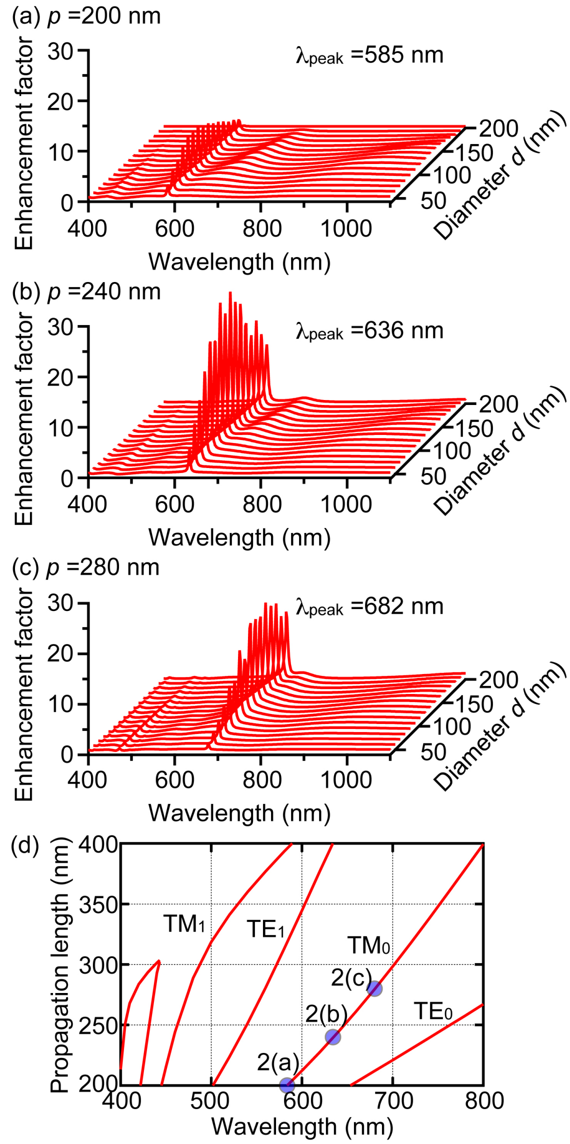


Fig. 2. Enhancement spectra varying with Au nanoparticle diameter and the period (a) 200, (b) 240, (c) 280 nm. (d) Dispersion relationship of the waveguide modes in 100-nm-thick Si sandwiched by $SiO_2$. The resonant peak wavelength and the period of Au nanoparticles correspond to the $TM_0$ waveguide mode.

Figure 3 shows the map of the enhancement factor peaks in the period-diameter plane of Au nanoparticles. There is an area for large absorption enhancement with a certain combination of period and diameter of Au nanoparticles. 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 this optimized condition is 636 nm. The period of 240 nm is

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equivalent to the density of 1.7 × $10^9$ particles/$cm^2$. The high-density arrangement of large nanoparticles such as 140 nm in diameter is required for the best performance of the sensitivity improvement. These optimal parameters of size and separation of Au nanoparticles depend not only on the coupling efficiency to SOI but also on scattering efficiency of and extinction inside the Au nanoparticles [19].

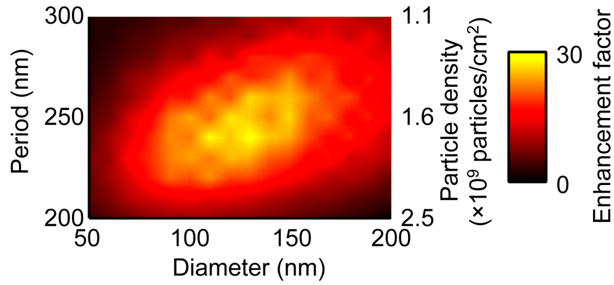


Fig. 3. Peak map of the enhancement factor varied with the Au nanoparticles diameter and period.

Figures 4(a) and 4(b) show the corresponding steady state field distributions of absolute intensities of *Ex* and *Hy*. Enhanced *Ex* distributions are observed in the near-field of Au nanoparticle due to the excitation of local surface plasmon resonance. In SOI region of $|Hy|^2$, enhanced standing wave is observed, which can be attributed to the coupling to the SOI waveguide mode. Therefore, we conclude the absorption enhancement mechanism in the SOI

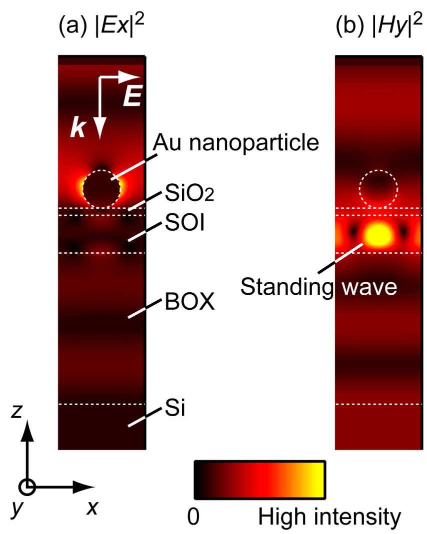


Fig. 4. Intensity field distributions for electro-magnetic components of (a) *Ex* and (b) *Hy*. Enhanced electric field is observed on the side surface of Au nanoparticle by local surface plasmon excitation. Standing wave of magnetic field is observed in SOI layer due to the coupling with $TM_0$ waveguide mode.

photodiode with Au nanoparticles is the increase of the absorption optical path length due to the coupling between incident photons scattered by the periodically arranged Au nanoparticles and the waveguide mode in SOI. Au nanoparticles arranged with high periodicity enhances the absorption efficiency at a single resonant wavelength corresponding to the propagation wavelength in SOI. The broadband enhancement in visible wavelength region would be realized by the random arrangement of Au nanoparticles.

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## 3. Development of SOI photodiode with Au nanoparticles

We have designed and fabricated SOI lateral *pin*-junction photodiodes with randomly attached Au nanoparticles for the demonstration of broadband absorption enhancement in visible wavelength region. Figures 5(a) and 5(b) show the optical images of the fabricated SOI photodiode without and with Au nanoparticles, respectively. The bare SOI photodiode, before the deposition of Au nanoparticles, has been produced by Hamamatsu Photonics K. K. The photosensitive area is 50 × 50 μm$^2$. The SOI thickness of depletion layer is about 100 nm. The anode is connected to the ground and the cathode is supplied with 1 V. In this device, the SOI layer is completely depleted by applying the substrate bias of 20 V. Au nanoparticles are dispersed on the surface of the photodiode and the photosensitivity has been measured with and without Au nanoparticles under the completely depleted conditions. In our simulation, high density distribution nanoparticles such as 1.7 × 10$^9$ particles/cm$^2$ are required for the

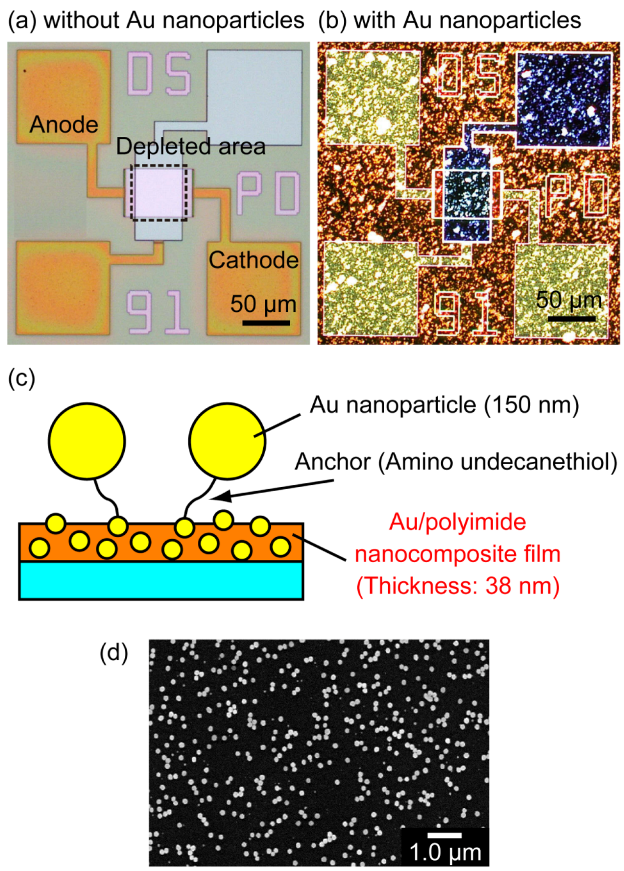


Fig. 5. Optical images of fabricated SOI photodiodes (a) before and (b) after the immobilized Au nanoparticles. (c) Immobilization technique for the large Au nanoparticles by anchoring with Au/polyimide nanocomposite film. (d) SEM image of attached Au nanoparticles. The particle diameter is 150 nm. The density is about 6.0 × 10$^8$ particles/cm$^2$.

optimum absorption enhancement by attaching Au nanoparticles. There are several techniques to immobilize metallic nanoparticles on the substrate without aggregation, e.g., metal deposition through nanohole array template, and surface modification by a surfactant containing thiol or silane [20–24]. Especially, thiol bonding technique is one of the most useful method for the immobilization of Au nanoparticles. However, it has some difficulty for the immobilization of large nanoparticles with high density on a substrate due to the increase of van der Waals force. A. Wei's group developed strategies that enable large Au

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nanoparticles more than 15 nm to self-organize into well-ordered two dimensional arrays at the air-water interface [25]. They have synthesized resorcinarene tetrathiol 1 as a surfactant for large colloidal Au nanoparticles. Hexagonally close-packed arrays of large Au nanoparticles on the micron length scale have been demonstrated by this surfactant.

For the application of attached Au nanoparticles to sensitivity improvement of photodiode, it is necessary to arrange with high density and with appropriate space between nanoparticles as simulated in Fig. 3. Here, we have developed bonding techniques to immobilize large Au nanoparticles with high density. At first, 45-nm-thick Au/polyimide nanocomposite film containing Au nanoparticles of about 4 nm in diameter has been synthesized by the thermal reduction at 160 degrees Celsius for 30 minutes of Au complex solution consisting of polyamic acid (1.79 g), Hydrogen Tetrachloroaurate (III) Tetrahydrate (0.78 g) and N, N-dimethylacetamid (87.71 g). Then, the film was exposed to the oxygen plasma to reduce the thickness to 38 nm, and to make the Au nanoparticles emerge at the film surface as bonding seeds. After this processing, amino-undecanethiol was attached to these seeds of Au nanoparticles as anchors. Finally, Au nanoparticles 150 nm in diameter, which were commercially available as a colloidal solution from TANAKA HOLDINGS Co., Ltd., were immobilized by bonding with this anchor without aggregation (Fig. 5(c)). Figure 5(d) shows SEM image of the attached Au nanoparticles on the photodiode. The attached Au nanoparticle density is about $6.0 \times 10^8$ particles/cm$^2$. This high density is achieved by the above technique.

The thinner interlayer of nanocomposite film would provide higher absorption efficiency due to the closer coupling between thiol-tethered Au nanoparticles and SOI. In our demonstration, we have applied the nanocomposite film of 38 nm in thickness, which is the smallest among the samples we prepared and, at the same time, can realize the large density of immobilized nanoparticles above. Optical density of the nanocomposite film is negligibly small due to an order of magnitude smaller diameter of the Au particles in the film. However, the contribution of the ensemble effects of larger and smaller Au nanoparticles to the absorption efficiency may exist, and should be considered as an additional cause of the enhancement in the future research.

## 4. Demonstration of broadband absorption enhancement

Figures 6(a) and 6(b) show the measured spectra of external QEs and the enhancement factor of SOI photodiodes with and without Au nanoparticles.

The external QE is given as Eq. (1):

$$\eta = \frac{I_c \cdot hv}{e \cdot P}, \tag{1}$$

where $I_c$ is cathode photocurrent, $hv$ is irradiated photon energy, and $e$ is elementary electric charge. Incident light is uniformly illuminated to cover the larger area than the device size, and $P$ is obtained by multiplying optical power per unit area and the $p^-$ area of the photodiode.

We achieved two-fold enhancement in visible around 620 nm wavelength. We estimated the absorption efficiencies 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. 6(c) show good agreement with the experimental one. This broadband enhancement is achieved by the randomness of Au nanoparticles distributions. Clustering of Au nanoparticles is recognized in Fig. 5(d), and it might additionally contribute to the enhancement [26].

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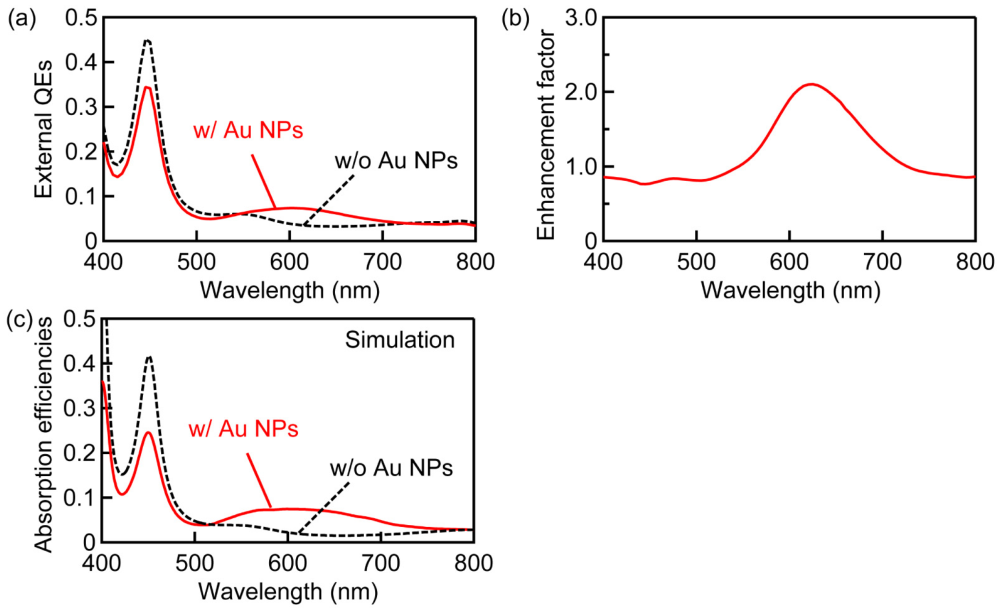


Fig. 6. Measured spectra of (a) external quantum efficiencies with (solid line) and without (dashed line) Au nanoparticles and (b) the enhancement factor of SOI photodiode. (c) Simulated absorption efficiency spectra with randomly arranged Au nanoparticles (solid line) and without Au nanoparticles (dashed line).

## 5. Conclusion

In conclusion, the structural parameters of Au nanoparticles attached to the 100-nm-thick SOI photodiode have been optimized by 3-D FDTD simulations. Particles 140 nm in diameter arranged with the period of 240 nm exhibited 29-fold enhancement of light absorption at the wavelength of 682 nm. We have developed SOI photodiode with randomly arranged Au nanoparticles with diameter of 150 nm and density of $6.0 \times 10^8$ particles/cm$^2$. The maximum enhancement factor of 2.1 was achieved at the wavelength of 625 nm. The sensitivity was improved in the visible wavelength range from 550 to 725 nm. The sensitivity spectra showed good agreement with the estimation.

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