Investigation of optical properties by localized surface plasmon excitation of nanoparticle arrays in photodetectors

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ARTICLE INFO

Keywords:
Photodetectors
Nanoparticles
Surface plasmons
Optical properties

ABSTRACT

We investigate absorption in the active medium by localized surface plasmon excitation of metal nanoparticle arrays. Calculations show for each specific application of the photodetector, which size of the metal nanoparticles should be deposited on photodetector. We show that the power absorption in the active medium in the presence of silver nanoparticle arrays in a certain wavelength range is more than gold nanoparticle arrays. Presence of nanoparticle arrays on surface of active medium can lead to dependence of absorption on wavelength and distance from nanoparticle arrays. Absorption cross-section in active medium strongly depends on distance from nanoparticle array that should be considered in design of embedded semiconductor quantum dots in the active medium.

1. Introduction

Surface plasmon polaritons (SPPs) are coherent electron oscillation at the interface of metal–dielectric that generates electromagnetic waves in both outside and inside of these materials [1,2]. The total excitation, including both the charge motion and associated electromagnetic field, is called either a surface plasmon polariton at a planar interface, or a localized surface plasmon for the closed surface of a small particle. Localized surface plasmons (LSP) is the result of the confinement of a surface plasmon in a nanoparticle, that its size comparable to or smaller than the wavelength of light that excite the plasmon. The optical absorption has a maximum at the plasmon resonant frequency, for noble metal nanoparticles, the resonance occurs at visible wavelengths [3], and for semiconductor nanoparticles at near-infrared and mid-infrared region [4,5].

Plasmon polariton propagation along the interface of metals is very lossy and tightly confined to the interface of metal. This surface confinement wave has been extensively used in enhancing the performance of various optoelectronic devices, including sensors [6–8], solar cells [9,10] and photodetectors [11–14]. Periodic metal nanoparticle arrays can be used to enhance the efficiency [15,16] in photodetectors. The surface plasmon wave for detection applications typically arises from the large electromagnetic field enhancement near the metal surface, the dependence of the resonance wavelength on the nanoparticle’s size, shape, and local dielectric environment.

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https://doi.org/10.1016/j.optcom.2018.06.085
Received 22 April 2018; Received in revised form 24 June 2018; Accepted 29 June 2018
Available online 9 July 2018
0030-4018/© 2018 Published by Elsevier B.V.
A. Bahari, M.G. Salianeh Optics Communications 427 (2018) 567–572

in the previous studies, we have investigated the effect of size, wavelength and location of semiconductor quantum dots on the propagation profile and the maximum absorption cross-section. The effect of the location of semiconductor quantum dots on propagation profile and absorption cross section are calculated in the active medium at different wavelengths. In this study the dependence of the absorption spectrum on the size of nanoparticles and wavelength has been investigated. The effects of gold and silver nanoparticle arrays on absorption in plasmonic detectors are calculated and compared together.

In this paper, the plasmonic effects will be studied for Au and Ag nanoparticle arrays deposited on Si photodetector. In Section 2 the theoretical model to calculate transmission, reflection coefficient and absorption coefficient will be developed. In Section 3 the numerical results for transmission and reflection spectra of electric field, absorption coefficients and enhancement factor of the Au and Ag nanoparticles, generation of surface plasmon polariton in the interface between nanoparticles and semiconductor will be calculated. In the last section a brief summary of the result will be presented.

2. Theoretical model

The interaction of electromagnetic fields with particles can be completely described within the frame of classical Maxwell equations. The FDTD method can be used to solve Maxwell equations to calculate the optical properties in photodetectors. The periodic boundary conditions in the \(x\)- and \(y\)-directions and perfectly matched layer (PML) boundary conditions in the \(z\)-direction are used in our calculations. The incident wave is a plane wave with \(x\)-polarized that propagate in the negative \(z\) direction above the top metal layer.

To describe the properties of surface plasmon polaritons, one can choose various models. Here, instead of the simple Drude model, the general Drude model (modified Debye model) is used to calculate the complex permittivity with the form of \([24]\):

\[
\varepsilon(\omega) = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + i \omega \tau} + \frac{\sigma}{i \omega \varepsilon_0} \tag{1}
\]

Here \(\varepsilon_{\infty}\) is the high frequency dielectric constant, \(\varepsilon_s\) is the static dielectric constant, \(\tau\) is the carrier lifetime, and \(\sigma\) is nanoparticles conductivity. It should be pointed out that the value of dielectric constants for a nanostructure may show great difference from that of bulk material if the size of the nanostructure is smaller than the mean free path of the conduction electrons \([25,26]\). Schematic diagram of Si pn junction diode structure with metallic nanoparticles is shown in Fig. 1. The structure consist of metallic nanoparticle arrays with the length of the period 2000 nm, the distance between the adjoining nanoparticles 500 nm and nanoparticles with radii of 25, 50, 75, 100 and 125 nm at the top (medium 1), followed by Si P+ type active medium (medium 2) and Si n− type substrate (medium 3). In order to calculate optical properties, transmission, reflection and absorption coefficients should be calculated. The transmission \(T\) can be calculated as a function of frequency by using

\[
T(\omega) = \frac{\int S_T \text{Re} [P^2(\omega)] ds}{\int S_R \text{Re} [P^{\text{in}}(\omega)] ds} \tag{2}
\]

where \(P^2\) and \(P^{\text{in}}\) are Poynting vectors at the medium 2 and input radiation, \(S_T\) is the surface of the transmission reference medium. The reflection of the system \((R)\) can be calculated by the same equation (Eq. (1)) by changing the reference medium \(S\) to the appropriate reference plane \(S_R\). After calculation \(T\) and \(R\) the absorption coefficient \(A\) can be calculated. The absorbed power of each nanoparticle can be calculated by integration of the photon flux in the volume of nanoparticle.

\[
P_{\text{abs},NP} = \int_{V_{NP}} \frac{1}{2} |E(\omega, \mathbf{r})|^2 \varepsilon_{\mathbf{1},NP}(\omega) dV \tag{3}
\]
Fig. 3. (a) Power absorption and (b) absorption enhancement in the active medium of the Ag plasmonic photodetectors as a function of wavelength at different nanoparticles radii 25, 50, 75, 100 and 125 nm.

![Graph of power absorption and absorption enhancement for Ag plasmonic photodetectors](image)

where $\varepsilon_{I,NP}$ is imaginary part of dielectric constant of nanoparticle. Total absorbed power by nanoparticle arrays can be calculated by summation on nanoparticle arrays. Absorbed power by Si can be calculated by integration from photon flux in the Si volume.

$$P_{abs,Si} = \int_{S_{Si}} \frac{1}{2} |E(\omega, r)|^2 \varepsilon_{I,Si}(\omega) dV$$

(4)

3. Results of numerical calculations

We consider a plasmonic structure is formed by depositing the Ag (or Au) nanoparticle arrays with radius of 50 nm and the period of 2000 nm on the surface of the $n$ p crystalline silicon. The periodic plasmonic effect of the Ag nanoparticle together with the cavity effect of the finite-thickness dielectric layer enables the incident light field to concentrate at the location of $n$ p crystalline silicon. To investigate the effects of metal nanoparticles in the process of absorption in the photodetector active medium, the interaction of incident radiation with nanoparticles at different wavelengths is calculated. The spectra of the electric and magnetic fields in wavelength range of 300 to 1300 nm according to Maxwell's equations by considering the plasmonic effects have been investigated. Fig. 2a shows the reflection and transmission spectra of the electric field as a function of time for the structure. At the first, nanoparticles reflect some radiation and absorb some. The absorbed field leads to localized excitation of surface plasmon. This Surface plasmon interacts with radiation, and generates localized excited polariton plasmon. Also, when localized polariton plasmon produce, its reflection tends to zero and the transmission spectrum increases. Fig. 2b shows the reflection and transmission spectra of the electric field as a function of wavelength for the structure. This figure shows that the maximum reflection and transmission fields from the surface structure occur in the visible and near-infrared region.

Fig. 3a shows the power absorption as a function of wavelength in the Si volume for different radii of Ag nanoparticles. This figure shows that maximum power absorption can be obtained for radius 25, 50, 75, 100 and 125 nm. Numerical calculations show that the absorbed power strongly depends on particle size. By changing the radius of nanoparticles the absorption spectra are changed but dependence of absorption to nanoparticles radius can be ignored for radius smaller than 25 nm and for radius bigger than 125 nm absorption coefficient in the visible region strongly decreases.

Fig. 3b shows the absorption enhancement in the active medium of silver plasmonic photodetectors as a function of wavelength at different Ag nanoparticle radii. The numerical results show maximum absorption enhancement shift to longer wavelength by increasing the size of the nanoparticles. For Ag nanoparticles with radius 100 nm the maximum enhancement is in the wavelength range 650 to 900 nm. According to the FDTD results, Ag nanoparticles can enhance incident light absorption by approximately 50%.

Fig. 4. (a) Power absorption and (b) absorption enhancement in the active medium of the Au plasmonic photodetectors as a function of wavelength at different nanoparticles radii 25, 50, 75, 100 and 125 nm.

![Graph of power absorption and absorption enhancement for Au plasmonic photodetectors](image)
**Fig. 4a** shows the power absorption for the Au nanoparticles plasmonic photodetectors in the active medium at different radii. This figure shows unlike Ag nanoparticles, power absorption is decreased for gold nanoparticles in wavelength smaller than 570 nm. It is clear from this figure, by increasing the nanoparticle radius in the given wavelength range, absorbed power decreases. In order to investigate more precisely increasing absorption coefficient in different spectra, absorption enhancement factor can be calculated that is defined as ratio of normalized power absorption by the nanoparticles structure to absorbed power in the structure without nanoparticles.

**Fig. 4b** shows the absorption enhancement in the active medium of gold plasmonic photodetectors as a function of wavelength at different gold nanoparticle radii. It is clear from this figure, for wavelengths less than about 570 nm the use of gold nanoparticles lead to decrease absorption enhancement factor. The absorption enhancement decreases by increasing the radius of nanoparticles in this wavelength range.

**Fig. 5** shows that use of Ag nanoparticle arrays on the surface of the active region can lead to transmit the wave scattered by the nanoparticles to the active medium and increase absorption in the active medium. This figure shows generation of the localized surface plasmons at the interface of Ag nanoparticles and semiconductor and its propagation in different wavelengths for active medium. Calculations show that localized surface plasmons at the interface of Ag nanoparticle arrays and active medium are strongly dependent on the wavelength. The maximum absorption occurs for the visible spectrum. The propagation profile is different at different wavelengths and as can be seen from this Fig. at short wavelengths, the propagation has the domical shape and this dome raises by increasing the wavelength but for wavelengths more than 470 nm this dome decreases. Au and Ag nanoparticle arrays deposited on the active medium causes the absorption intensity distribution in the active medium strongly depends on the wavelength. It can be concluded that deposited nanoparticles act as a lens that focus...
or disperse light beam in the active medium. Ag nanoparticles focus light beam for wavelengths smaller than 550 nm and disperse the light beam for larger wavelengths. Therefore, for the incident electromagnetic field with wavelength less than 550 nm, the location of the semiconductor quantum dots should be in the center of symmetry of each array of metal nanoparticles and for the incident electromagnetic field with wavelength more than 550 nm in the boundaries of the nanoparticles period arrays.

In the design and construction of semiconductor quantum wells and quantum dots devices (such as photodetectors, lasers, switches, etc.) the place of nanostructure has high effect on the output of the devices. For example, in quantum dots plasmonic detectors, by putting semiconductor nanostructure at the place that has low absorption coefficient makes designed plasmonic be ineffective. For this reason investigation of profile propagation of the plasmon near-field penetration in active media is very important.

Fig. 6 shows the interaction of incident radiation and the propagation profile of generated localized surface plasmons waves in active medium. This Fig. obviously shows the formation of localized surface plasmons at the metal semiconductor interface at $z = 0$. The place of semiconductor quantum dots in design and construction of semiconductor quantum dots quantum wells is very important for the output of the devices. Fig. 6

![Fig. 6. Propagation profile of localized surface plasmons at the interface Ag nanoparticles and semiconductor at different heights (z) with $\lambda = 487$ nm.](image-url)
shows the propagation of localized surface plasmons at different position of semiconductor quantum dots in active media. Depending on the wavelength, the absorption or field enhancement in the nanoparticles may occur. Our calculations show that the propagation profile of localized surface plasmons in different heights semiconductor is different. Therefore, to optimize the absorption in the semiconductor quantum well-quantum dots structures height, shape and maximum absorption range must be selected with high accuracy.

The absorption cross section can be investigated at different heights in the active media for a maximum absorption for $R = 100$ nm at wavelength 487 nm. Nanoparticle arrays are deposited on the active medium surface ($z = 0$). It can be seen that the absorption cross-section strongly depends on the distance of the nanostructure from the surface of the active medium (distance from nanoparticle arrays) and shape of absorption cross-section depends on the height ($z$), in order to achieve maximum absorption, shape of nanostructure should be the same as cross-section absorption.

The maximum absorption is different at different place in the active medium, up to 300 nm distance it is circular and occurs at center. In the 400 nm range, the maximum absorption coefficient is roughly rectangular in the center of the region. At a depth above 700 nm, the maximum absorption coefficient occurs at the edges and in the form of an ellipsoid. Excitations of dipole and quadrupole modes are the origin of such these changes. The multipolar generated by the interaction depends on the incident wavelength. For wavelengths in the range of 400 nm, both excitation dipole and quadrupole are involved and for larger wavelengths, bipolar excitation prevails. Calculations show that shape of nanostructure in active medium depends on wavelength and distance from nanoparticle arrays. The spectrum range and the nanostructure location in choosing the optimum nanostructure in photodetectors are extremely important. We show that the power absorption in the active medium in the presence of Ag nanoparticle arrays for a wavelength spectrum is more than that of Au nanoparticle arrays. Presence of nanoparticle arrays on the active medium leads to dependence absorption on wavelength and distance from nanoparticle arrays.

4. Conclusions

Localized surface plasmons in metallic nanoparticles have many applications due to the large electromagnetic field enhancement and the dependence of the propagation on the nanoparticle size, shape, and local dielectric environment. The place of semiconductor quantum dots in the design and construction of semiconductor quantum dots quantum wells has very effect on output of the devices. In this study, the absorption coefficients and the enhancement factor of Au and Ag nanoparticles are calculated. Numerical results show that the absorbed power strongly depends on the kind and radius of the nanoparticles. We show that for every application of the photodetectors in a particular spectrum which radius of nanoparticle should be used. Numerical results also show that to optimize the absorbed power in order to detect in the visible range, the radius of the Ag nanoparticles should be selected 75 nm and for infrared applications, nanoparticles with radii larger than 100 nm should be used. Numerical results show that localized surface plasmons on the surface of metal nanoparticles and active medium heavily depend on the wavelength, and the maximum absorption is observed for the visible spectrum. We show that due to the plasmonic coupling in semiconductor quantum dot, power absorption depends on the position of the semiconductor nanostructure in the active medium from the surface of detector. The maximum absorption is different at different place in the active medium, for example up to 300 nm distance it is circular and occurs at center. In the 400 nm range, the maximum absorption coefficient is roughly rectangular in the center of the region. At a depth above 700 nm, we have the maximum absorption coefficient that occurs at the edges and in the form of an ellipsoid. These results can be used to select the shape, length and height of semiconductor quantum dot embedded in the active medium to optimize absorption in quantum dots.

References