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Photodetector Engineering with Plasmonic Properties

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***Abstract*—**In the article, the main goal is to study the effect of the plasmonic properties on the photocurrent generated by a photodetector. Fundamentally, a typical photodetector is designed and simulated using the finite element methods. To utilize the plasmonic effect, gold nanoparticles with different shape, size and morphology are buried into the intrinsic region. Plasmonic effect is arisen through the interaction of the incoming light with nanoparticles by which electrical properties of the photodetector are manipulated. In fact, using plasmonic nanoparticles not only increases the absorption bandwidth of the incoming light, but also generates a high intensity near-field close to the plasmonic nanoparticles. Those properties strongly affect the generated photocurrent. The simulation results show that using plasmonic nanoparticles significantly enhances the electrical properties of the photodetectors. More importantly, one can easily manipulate the plasmonic properties of the gold nanoparticles through engineering the nanoparticles' size, shape and morphology. Another important phenomenon is plasmon-plasmon interaction inside the photodetector. It is shown that plasmon-plasmon interaction improves the electron-hole generation rate by which the rate of the current generation is severely enhanced. This is the key factor that we want to focus on, to improve the photodetector electrical properties.

***Keywords*—**Nanoparticles, plasmonic, plasmon-plasmon interaction, plasmonic photodetector.

I. INTRODUCTION

PHOTODETECTORS are a semiconductor circuit element that converts the light coming on it into electrical energy based on a photoelectric event. They are devices that are widely used in today's technology that converts incoming light energy into electrical signals [2]-[4], [7], [10]. In particular, they provide a basis for areas such as imaging systems (digital cameras, photo cameras, etc.) [3], [13], environmental surveillance [13], space and optical communications [3], [13], medical imaging systems (x-rays) [3] and security [3], [13]. Photodetectors have taken an important place in the areas described above and can be fabricated in a nanometer scale with a suitable bandwidths and a high performance [2], [3], [7], [10]. Electronic and optoelectronic properties of semiconductor circuit elements are used to convert light energy to electrical energy [5]. That is this transformation takes place with the help of a photoelectric effect [5]. Materials such as Si, Ge, InGaAs can be used as a semiconductor circuit element [3], [14]. Furthermore, researchers use different material combinations [10]. For example, because of low dielectric constant and capacitance values of silicon, photodetectors are made by using different 2-D semiconductors [13]. With the help of various methods, the researchers aim to show higher performance results of photodetectors [6]. Thus, photodetectors are produced with different designs and special geometric shapes [7]. In addition that, studies in this field are very important and novel because carriers are usually recombination inside of standard photodetector, carriers have a short life span and fundamental photodetectors have low quantum efficiency [7]. If light absorption capability of photodetectors increases and carriers have fast transportation speed, more sensitive and fast devices can be produced [3]. Some changes on photodetectors can be done in this way; significant results of studies are given below. For example, photodetectors may be having high and spectral sensitivity, signal to noise ratio value, high speed value and being better stable [2]. Especially, some improvements have been made on carriers [10], [14]. New devices are produced with the help of new methods throughout the production, separation and transportation process [13]. In the other study, to increase the quantum efficiency, the amount of hot electrons in the semiconductor material and fermi energy level has been changed [7], [14]. As a different method, 2-D materials such as graphene were used instead of classical materials such as Si and InGaAs used in photodetector [3], [6]. As a result, problems likewise lack of transparency, inelasticity and incompatibility have been solved [7]. If there is no material change, different and special geometric shapes can be preferred during the production phase [14]. That is, in recent studies, silicon can be turned into micro pyramids and gold film coated on it [14]. Hence, internal quantum efficiency (IQE) rises thanks to more photocurrent produced and more light beams absorbed [14].

The main purpose of this study is to design a photodetector based on the plasmonic phenomenon with strong improvements on the electrical properties [10]-[14]. We generally use the classical structure to simulate the photodetector parameters [1], [3] in which some properties are modified due to the plasmonic effect. In this device, gold nanoparticles as a plasmonic particle are employed in which the plasmon resonance is created through the interaction of the incoming light with the metal surface carriers [8], [11], [12]. If the frequency of the incoming light and the natural frequency of the nanoparticle are in the same range, the plasmon resonance will occur [9]. It has been shown that higher photocurrent can be achieved using plasmonic properties [10]. In contrast with the classic photodetector [1]-[15], in this design, the number of free electrons is increased much more due to the plasmonic properties [2]-[8]. Also, the plasmonic properties can strongly enhance the photocurrent and moreover it can be utilized to improve the incoming light bandwidth. In the following, the theoretical and background of the device will be shortly studied.

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II. THEORETICAL BACKGROUND

In this section, the structure definition is shortly explained. Our structure is schematically illustrated in Fig. 1 (a). In this structure, a P-type silicon wafer is used as a substrate and P^+ material is buried in the two areas in the middle of the structure with a manageable space between them. Also, N^+ material is added to the middle bottom of the structure. A silicon dioxide (SiO_2) layer is placed in the left and right bottom corner of the structure and these layers operate as the reflective. It can be shown that when the same layers of SiO_2 are placed in the upper left and right corners, the lifetime of the light into the structure will be increased. Finally a plasmonic effect is achieved by adding the gold nanoparticle into the intrinsic region. In fact, it is the case that we want to study in this article. It is shown that by considering the plasmonic effect, the generation rate of the electron-hole is strongly increased. That is contributed to the plasmonic field effect and this phenomenon is studied in detail in this work.

In the following, the designed device is studied from the mathematical point of view. One of the important factors that the plasmonic field strongly affects is the optical generation rate [2]-[8]. The optical generation rate ($G_{optical}$) is a vital parameter for photodetector devices. It is defined as a term indicating how many electron-hole pairs formed during photon absorption and given by:

$$G_{optical} = \eta_{opt} \times \frac{\left(-\nabla \times S_{ave}\right)}{(\hbar \nu)} \tag{1}$$

where η_{opt}, $S_{ave}, \hbar, \nu$ are optical quantum yield, time averaged poynting vector, Planck's constant and incidence frequency, respectively. The time averaged poynting vector is recognized like the radiant flux around any NPs and calculated by $E \times H^*$. The related components are expressed as S_x, S_y, and S_z:

$$\begin{aligned} S_x &= (E_y \times H_z - H_y \times E_z) \\ S_y &= (-E_x \times H_z + H_x \times E_z) \\ S_z &= (E_x \times H_y - H_x \times E_y) \end{aligned} \tag{2}$$

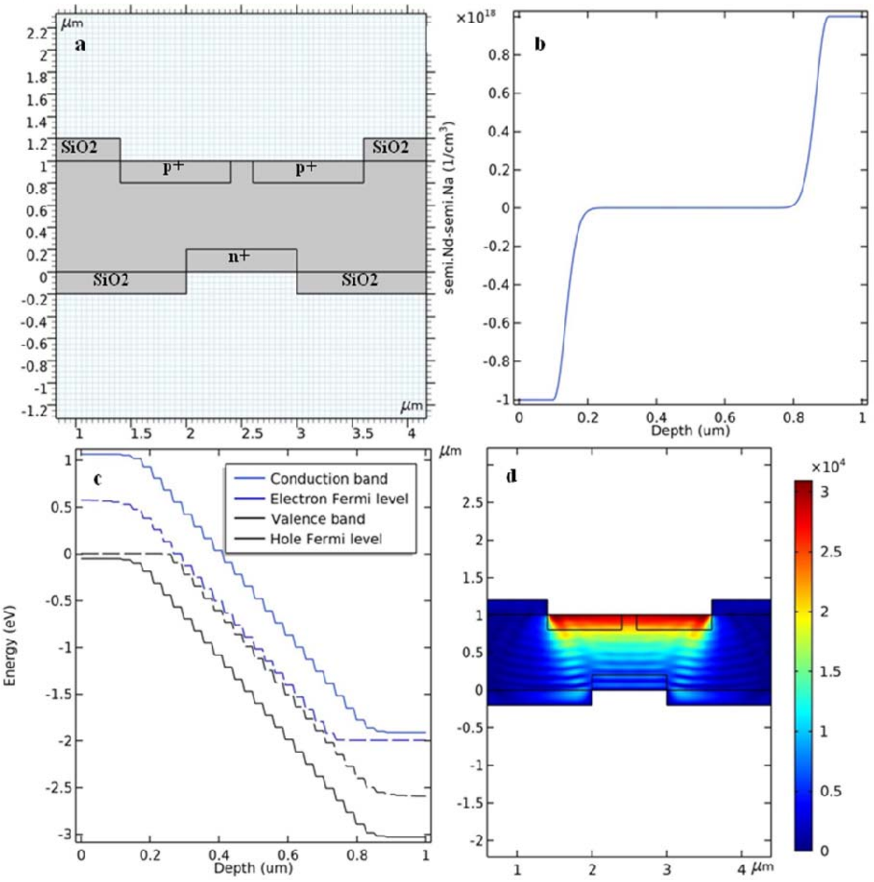

Fig. 1 (a) Device Structure Without NP; (b) Doping Profile Graph 1/cm^3; (c) Energy Level Diagram; (d) 2-D Electric Field Graph (V/m) at λ = 870 nm

Another important factor is the gradient vector which takes the partial derivative of each poynting vector component with respect to x, y and z directions, respectively. Substituting (2) into (1), the related components G_x, G_y, G_z are derived. Normally, G is expressed as the composition of G_{in} and $G_{optical}$. We just focus only on $G_{optical}$ by which the plasmonic effect can be easily explained. G_{pl} is created thanks to the plasmonic effect by the NPs. Also, the current equation in a traditional photodetector can be expressed as:

$$I_{ph} = [I_{phs} + ki \times (T_c - T_r)] \times [\frac{G_{optical}}{G_{ref}}] \tag{3}$$

where I_{phs}, ki, T_c and T_r are the photocurrent standard condition, temperature coefficient of short circuit current, operating temperature and reference temperature, respectively. In addition, G_{ref} is the intensity irradiance of the reference intensity.

III. RESULTS AND DISCUSSIONS

In this section, the simulation results are illustrated. The structure without inserting NPs is schematically shown in Fig. 1 (a). In this structure, multiple SiO_2 layers are used to keep more light in the structure. Thanks to the SiO_2 layers, the light is trapped and its scattering becomes limited. As a result, more electron-hole pairs are generated.

The charge distributions at different layers are illustrated in Fig. 1 (b). Also, for the traditional structure (without Au NPs) the different parameters such as conduction band energy, valance band energy, electron fermi level and hole fermi level energy are shown in Fig. 1 (c). Also, Fig. 1 (d) shows the electric field distribution without Au NPs. It is clear that the distribution of the electric field leads to generate the photocurrent by which the photodetector responsivity is calculated. In the following, the focus concentrated on the improvement of the electric field distribution. It is the reason that we utilized the plasmonic NPs to enhance the field distribution. For this purpose, we utilize a different form of the NPs to manipulate the photodetector characterization. In Fig. 2, we tried to show the effect of the embedded NPs in structure. It is shown that by changing the NPs shape the field distribution is changed. It is contributed to the plasmonic field created by the NPs in structure. Also, the figure shows the effect of plasmon-plasmon interaction [9]-[12]. It is because when two or more NPs are closed to each other, the plasmon resonance of each NP can couple to the other. That is the reason for which the field is strongly enhanced at the gap between NPs shown in figures. This can be used in photodetector to improve the performance of the device. To better illustrate, the exaggerated figures are added as the inset figures. With regard to this point, the change of the NPs number may alter the electric field distribution. One can compare the plasmon-plasmon interaction between two coupled NPs in Figs. 2 (b)-(d). Of course, it should be noted that the plasmon-plasmon interaction is strongly dependent on the frequency.

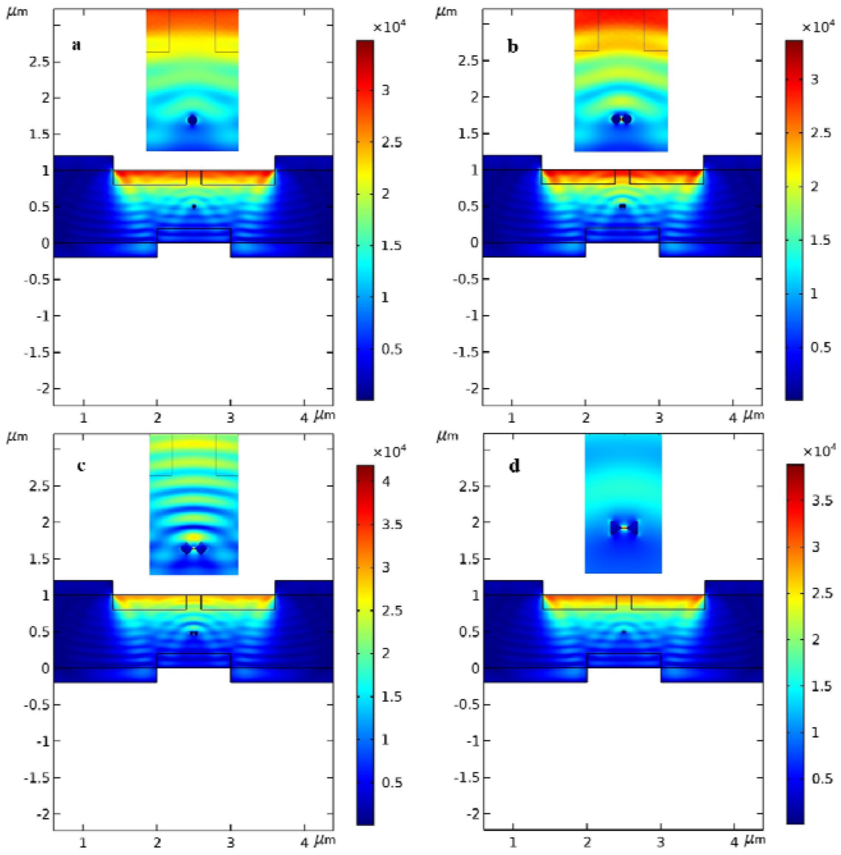

Fig. 2 (a) 2-D Electric Field Graph of Single Circular Au NP at λ = 870 nm; (b) 2-D Electric Field Graph of Double Circular Au NPs at λ = 870 nm; (c) 2-D Electric Field Graph of Double Square Au NPs at λ = 870 nm; (d) 2-D Electric Field Graph of Double Triangular Au NPs at λ = 870 nm

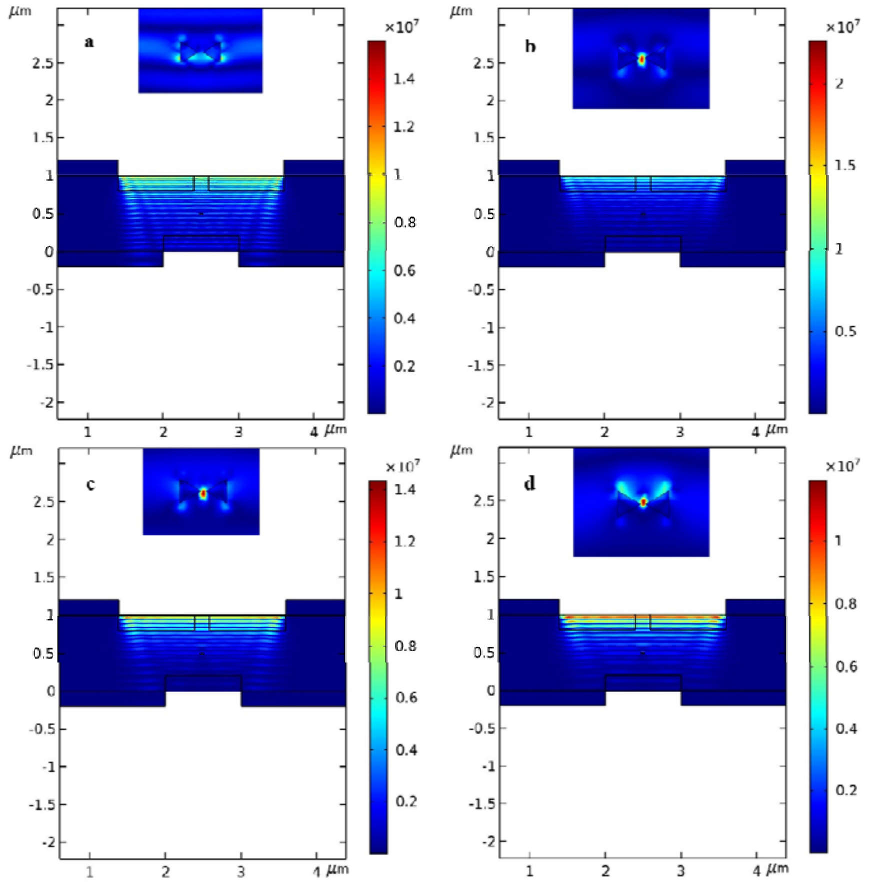

Fig. 3 (a) Gph Graph of Double Triangular Au NPs at λ = 530 nm; (b) Gph Graph of Double Triangular Au NPs at λ = 650 nm; (c) Gph Graph of Double Triangular Au NPs at λ = 770 nm; (d) Gph Graph of Double Triangular Au NPs at λ = 870 nm

In this work, as an important task, we consider the analysis of the generation rate $G_{optical}$ in the device. In essence, we want to investigate the effect of the plasmonic field on the generation rate. From Fig. 2 (d), it is found that the triangular coupled NPs can strongly improve the field distribution by the plasmonic effect. So, to study more, the effect of the incident frequency is considered and the results are shown in Fig. 3. It is shown that at the incident wavelength around 650 nm, the maximum interaction field is generated.

Finally, we study the behavior of the total generation rate at 1100 nm. The results were depicted in Fig. 4. It is shown that at this frequency, the coupling of triangular NPs shows a strong effect. This result reveals that the designed photodetector can operate as effectively as possible in the wide range of the frequency. So, using plasmonic properties gives a good degree of freedom to any engineers to design an efficient optoelectronic device.

IV. CONCLUSION

In this study, the plasmonic effect on the photodetector characterization was investigated. We significantly focused on the optical generation rate affected by the plasmonic effects. For this reason, the simulation of the photodetector was started with the traditional case and some important parameters such as doping profile, energy level diagram, and the distribution of the electric field were considered and simulated. To study the plasmonic effect, some related parameters affecting the plasmon resonance such as the NPs shape and plasmon-plasmon interaction between NPs were examined. It was shown that the plasmon-plasmon interaction has a great effect on the optical generation rate by which the optical current was dramatically enhanced. Also, it was illustrated that the shape of the coupled plasmonic particles strongly manipulated the optical generation rate.

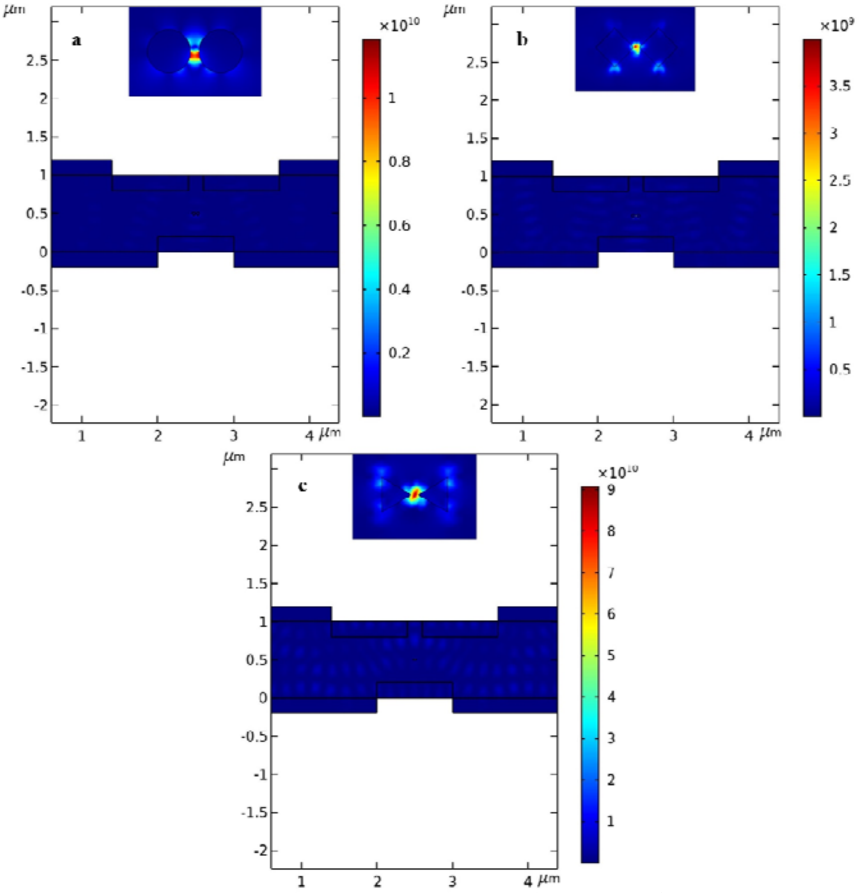

Fig. 4 (a) G_{ph} Graph of Double Circular Au NPs at λ = 1100 nm; (b) Gph Graph of Double Square Au NPs at λ = 1100 nm; (c) Gph Graph of Double Triangular Au NPs at λ = 1100 nm

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