Effect of Plasmonic Nanoparticles on the Electric Field Strength to Improve Performance of Single Crystalline Solar Cell

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Abstract

The effect of metal nanoparticles (MNPs) on the electric field strength and distribution for improvement solar cell performance is investigated and simulated. By manipulating the properties of nanoparticles, distribution of the electric field was altered. In this paper, classical solar cell (p-n junction) and improved structure (add an extra layer of SiO2 and gold nanoparticles on the top of p-n junction) is simulated. Different sizes of NPs, thickness of SiO2 sublayer, and spacing distance between NPs is done to improving the electric field and showing plamonic effect. Gold NPs deposition on single crystalline silicon solar cell is modelled by COMSOL 5.2 2D, Electromagnetic wave propagation in the frequency domain with periodic boundary conditions. The best wavelength found in our work is 550 nm. The electric field enhances when the size of NPs increases but it must be limited. When gold NPs are deposited on the SiO2 sublayer, the plasmonic effect appears due to decreasing the refractive index. Moreover, separation distance between NPs affect the electric field enhancement by manipulating the number of NPs, the distance decreases and the plasmonic interaction appears.

Keywords: Plasmonic, Nanoparticle, Electric Field, Solar Cell.

تأثير الجسيمات النانوية على قوة المجال الكهربائي لتحسين أداء الخلية الشمسية البلورية المفردة

سماح محمد الكرعاوي ، محمد فوزي محمد التميمي

الخلاصة:

تم دراسة تأثير الجسيمات النانوية المعدنية على قوة المجال الكهربائي وتوزيعه لتحسين أداء الخلايا الشمسية ومحاكاته. عن طريق معالجة خصائص الجسيمات النانوية ، تم تغيير توزيع المجال الكهربائي. في هذه الورقة البحثية ،يتم محاكاة الخلية الشمسية الاعتيادية (الوصلة الثنائية) والبنية المحسنة (إضافة طبقة إضافية من SiO2 وكريات الذهب النانوية في الجزء العلوي من الوصلة الثنائية). يتم إجراء أحجام مختلفة من الجسيمات النانوية وسمك الطبقة الفرعية SiO2 ومسافة التباعد بين الجسيمات النانوية لتحسين المجال الكهربائي وإظهار تأثير البلازمونك. ترسيب كريات الذهب النانوية على الخلية الشمسية السيليكونية أحادية البلورة شكلت بواسطة COMSOL 5.2 2D ، انتشار الموجات الكهرومغناطيسية في مجال التردد مع شروط حدود دورية. أفضل طول موجي وجد في عملنا هو 550 نانومتر. يتعزز الحقل الكهربائي عندما يزداد حجم الكريات النانوية ولكن يجب أن يكون محدودا. عندما يتم ترسيب كريات الذهب النانوية على الطبقة الفرعية SiO2 ، يظهر تأثير البلازمونك بسبب انخفاض معامل الانكسار. علاوة على ذلك ، تؤثر المسافة الفاصلة بين الكريات النانوية على تعزيز المجال الكهربائي عن طريق التلاعب بعددهم، تقل المسافة ويظهر التفاعل البلازمي.

1. Introduction

A solar cell is a device that coverts sunlight directly into electricity based on the photovoltaic effect [1]. Silicon is the material of choice for photovoltaic applications due to its low cost, abundance in nature, nontoxicity, long-term stability, and well-established technology [2]. The main requirements for ideal solar cell material are (a) direct band structure, (b) band gap more than1.1 eV, (c) consisting of readily available and non-toxic materials, (d) good photovoltaic conversion efficiency, (e) long-term stability [3]. The c-Si solar cell is the substrate which will be used for the nanotechnology applications due to its many advantages. First of all, the c-Si solar cell exhibits better predictable and uniform behavior than other silicon-based solar cells during experimentation, which allows it to match most of the theoretical and technique developments required in the photovoltaic field. Secondly, it has the highest efficiency rate in all silicon-based solar cells given the standard condition that they are made out of the highest purity silicon. Thirdly, the c-Si solar cell has the longest lifetime than other silicon-based solar cells due to its high purity level [4]. The single-crystalline silicon solar cells are most popular compared to polycrystalline and amorphous silicon solar cell due to better efficiency [5].

High-efficiency silicon solar cells strongly rely on an effective reduction of charge carrier recombination at their surfaces, i.e. surface passivation. Today's industrial silicon solar cells often utilize dielectric surface passivation layers such as SiN_x and Al_2O_3. However, a passivation layer well-known from the microelectronic industry, SiO_2, had and has a strong impact on silicon photovoltaics [6]. The refractive index of the surrounding medium was important for the light scattering ability of MNPs. By using a low refractive index medium as a sublayer between the MNPs and the solar cell, the light scattering ability of MNPs was increased. More light scattered into solar cell caused increased electric field intensity under the MNPs [4].

Noble metals such as silver (Ag), gold (Au), aluminum (Al) and copper (Cu), support surface plasmon due to their free electron like behavior. Surface plasmon is the collective oscillations of excited free electrons of metallic particles. This unique property of (MNPs) can be used to enhance the optical absorption of solar cells through scattering of light and near-field concentration of light [7,8].

Hence, we are improving a new study for comparing between a classical solar cell and our improving structure in different important parameter in solar cells. Sections (2) describes brief about plasmonic MNPs. Section (3) presents the equation of electromagnetic wave that used by COMSOL program for the simulation and presents the three structures of solar cell. Section (4) introduces the result and discussion for the three structures and effect of (size, thickness of SiO2, and spacing distance between NPs) on the electric field enhancement with concluding remarks in Section (5).

2. Plasmonic Metal Nanoparticles

Plasmonics is the science studying the optical phenomenon existing at the interface of metal and dielectric material at the nano-scale [9,10]. It has attracted significant interest due to its capabilities in localizing and guiding light at the nano-scale [11]. In the recent years, plasmonics has attracted significant attention from the photovoltaic (PV) community due to its advanced light trapping mechanisms for enhancing the light absorption in solar cells [12,13]. MNPs are one of many solar cell applications of nanotechnology; they play a significant role in enhancing solar cell optical properties. One of the advantages of applying nanoparticles to solar cells mentioned herein is the ability to scatter incident light to different angles when light illuminates a metal surface. As incident light scatters through the nanoparticles at different angles, light path length through the solar cell substrate is increased. Another advantage of integrating nanoparticles into solar cells is the ability to enhance the localized electric field around the nanoparticles. If the nanoparticles deposit on the solar cell, the electric field inside the cell will be affected by the enhanced localized electric field from the nanoparticles, which results in an increase in photon absorption in the cell [4]. Surface plasmons resonance (SPR) is the collective oscillation of electrons in metal stimulated by illumined light. The SPR condition is established when the frequency of illumined light photons matches the resonance frequency of metal. Therefore, SPR is found in materials that have negative real and small, positive, imaginary dielectric constants, such as noble metals (for examples, silver (Ag) and gold (Au)), SPR is sensitive to incident light and the surrounding dielectric environment and can be used on different optical devices, like solar cells [14].

Localized surface plasmons resonance (LSPR) is a variation of SPR. LSPR is surface plasmons resonance confined to a metal nanostructure much smaller than the wavelength of illuminated light [15]. The plasmons resonance localizes around the nanostructure with a special frequency called the LSPR frequency. LSPR is sensitive to the surrounding dielectric environment and metal nanoparticle geometry. Due to the successful development of nanoparticle fabrication techniques in recent years, nanoparticles enhancing solar cell electrical properties via LSPR has become a popular topic in solar cell applications. When light is illuminated on metal nanoparticles, the conduction electrons are excited by incident photons. Then, movement of charges in the nanoparticle leads to a build-up of charge on the particle surface. The build-up charge on the surface acts as a restoring force, creating a resonance condition for electrons. Hence, the resonance conduction on metal nanoparticle is

LSPR [15]. Electromagnetic distribution in different parts of the cell changes by changing the NPs' materials, shape, geometry and inter-distance between them. The plasmonic NPs are used to manipulate the light interaction with matter in the solar cells regions. Because of plasmonic effect, a high electric field builds around metal nanoparticles so that high conversion efficiency is available [16].

In this paper, plasmonic MNPs deposition on p-n junction solar cell with manipulation of size, thickness of spacer layer, and spacing distance investigated to improve solar cells performance.

3. Formulation and Simulations

Nanoparticles deposition on single crystalline silicon solar cell is modelled as electromagnetic wave propagation in the frequency domain with periodic boundary conditions using COMSOL wave optic module. The equation of electromagnetic wave, frequency domain is [17]:

$$\nabla \times \mu_r^{-1}(\nabla \times E) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)E = 0 \quad \dots (1)$$

Where μ_r: relative permeability, k_0 : magnitude of the free-space wave , ε_r : relative permitivity , σ : electrical conductivity, ω : frequency of the incident e-m wave of photons, ε_0 : permittivity of free space.

A 2-D model with periodic boundary conditions is considered. The model is set to sweep across the incident wave frequency range in the visible spectrum from 400 nm to 800 nm. Three structures of solar cell is considered as shown in Fig.1. The first structure is the Classical structure which includes of p-n junction (silicon single crystalline) without coating or deposition as shown in Fig.1a. The thicknesses of p and n layers are 1 μm and 0.2 μm, respectively, and the width for each other is 0.4 μm. The second structure is illustrated in Fig.1b, which show the deposition of gold nanoparticles with radius 40 nm on the top of solar cell (n-type, n=3.45). The third structure is displayed in Figure 1c, which show coating the n-type by a sublayer (SiO_2, n=1.458) with thickness 10 nm. The task of this study is to alter the distribution of the electric field by manipulating the radius of NP, thickness of coating layer and number of NPs.

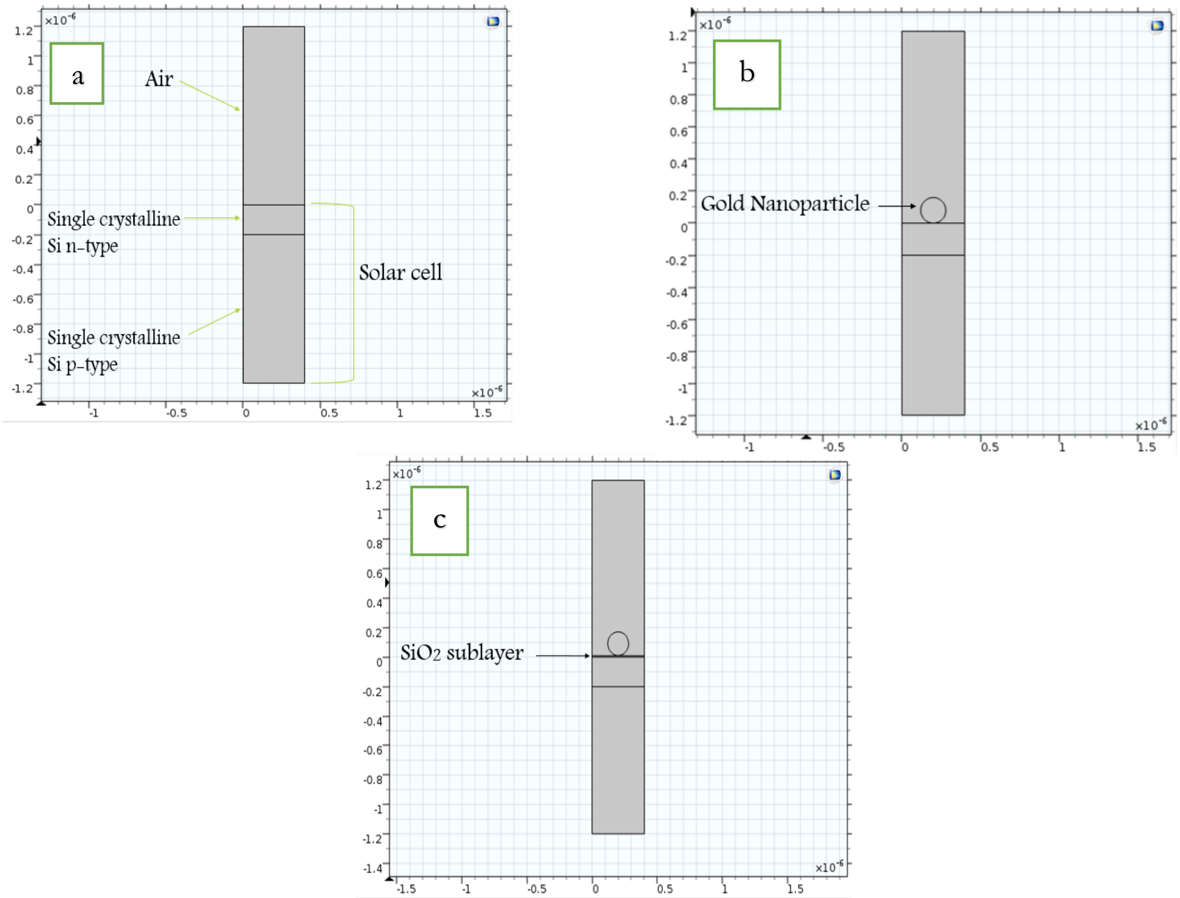

Figure (1): Solar cell structures (a) Classical structure (without NPs), (b) Improved structure (with NPs on n-type), and (c) With NPs on SiO_2 sublayer.

4. Simulation Results and Discussion

In this section, the result and discussion for the three structures and effect of (size, thickness of SiO2, and spacing distance between NPs) on the electric field enhancement are demonstrated. Based on the obtained result, we decided the best result which have a high electric field around the NPs.

Fig.2 show the electric field intensity at 550 nm in these three different structures. Light is

diffused in different parts of the classical solar cell as shown in Fig.2a.

In classical structure, light spreads through the air and then moves in a thick area of silicon. When NP deposits on n-type directly, off resonance was occurred as shown in Fig. 2b, while Fig.2c shows that the plasmonic affects light and make it spread inside the cell when NP deposits on dielectric layer.

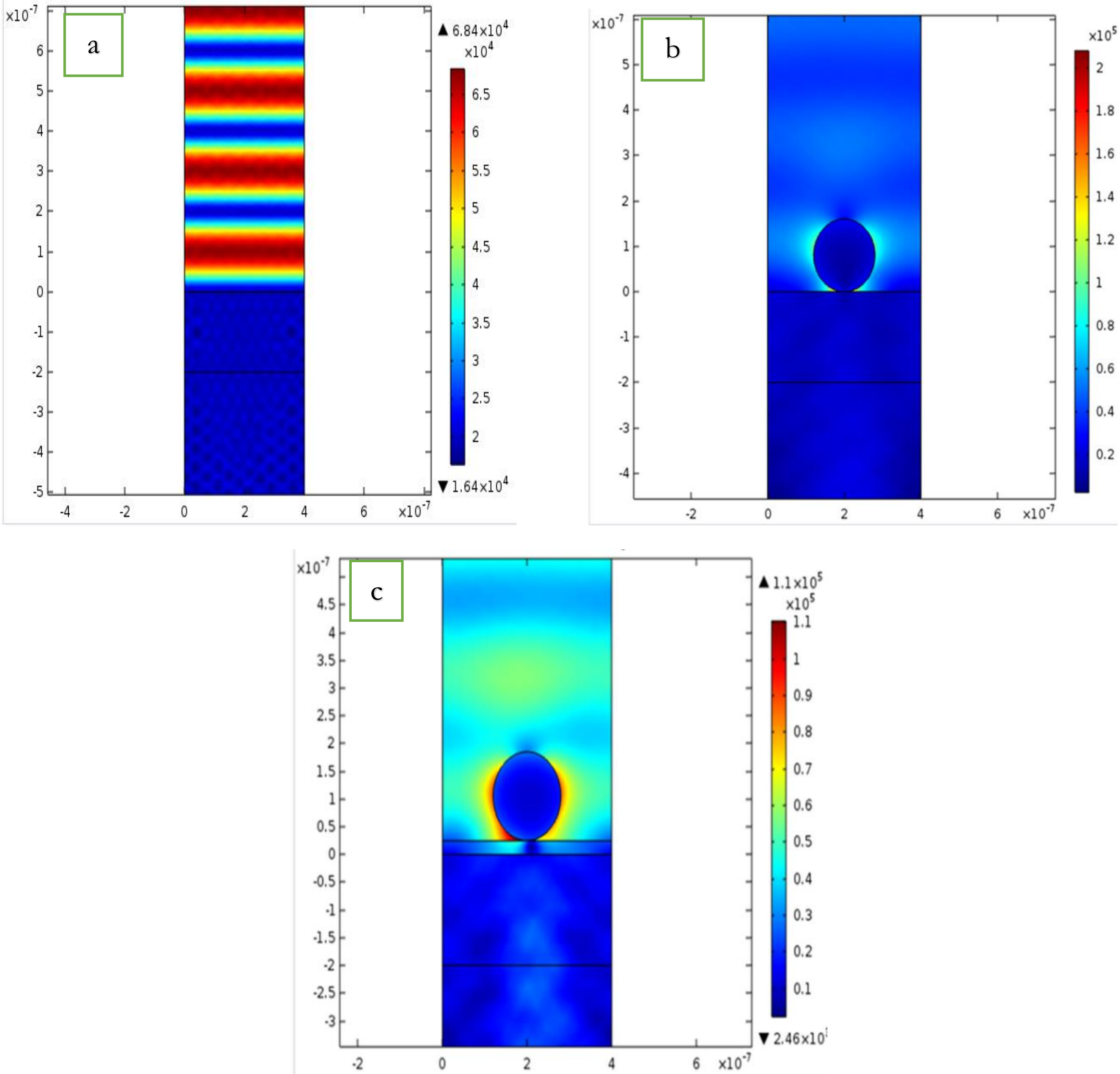

Figure (2): Electric field Intensity at 550 nm in the (a) Classical structure, (b) improved structure with NPs on n-type, and (c) with NPs on SiO_2 sublayer.

4.1 Influence of NPs Size Variation

The first important parameter for manipulating the electric field is the size of NPs. Different nanoshere's radius (r) are used from 10 nm to 80 nm and the results are illustrated in Fig.3. From Fig.3, we are observed a small sizes give little effect and decrease in the electric field enhancement as shown in Fig.3a. But when the size is increasing, the field intensity increasing as shown in Fig.3b and Fig.3c, then the field decreased at radius 80 nm as displayed in Fig.3d.

Finally, the electric field alters according to size of NP sketched in Fig.4. From Figure 4, the field decreased when the radius of NP is decreased at 10 nm ($E=7*10^4$ V/m) and then dramatically increase to (E=10.8*104 V/m and 10.9*104 V/m) at (40 and 50) nm, respectively. Then slightly drop to (E=10.4*104 V/m and 10.3*104 V/m) at (60 and 80) nm, respectively. We obtained the greatest result when r= 40 nm and r= 50 nm, at 550 nm.

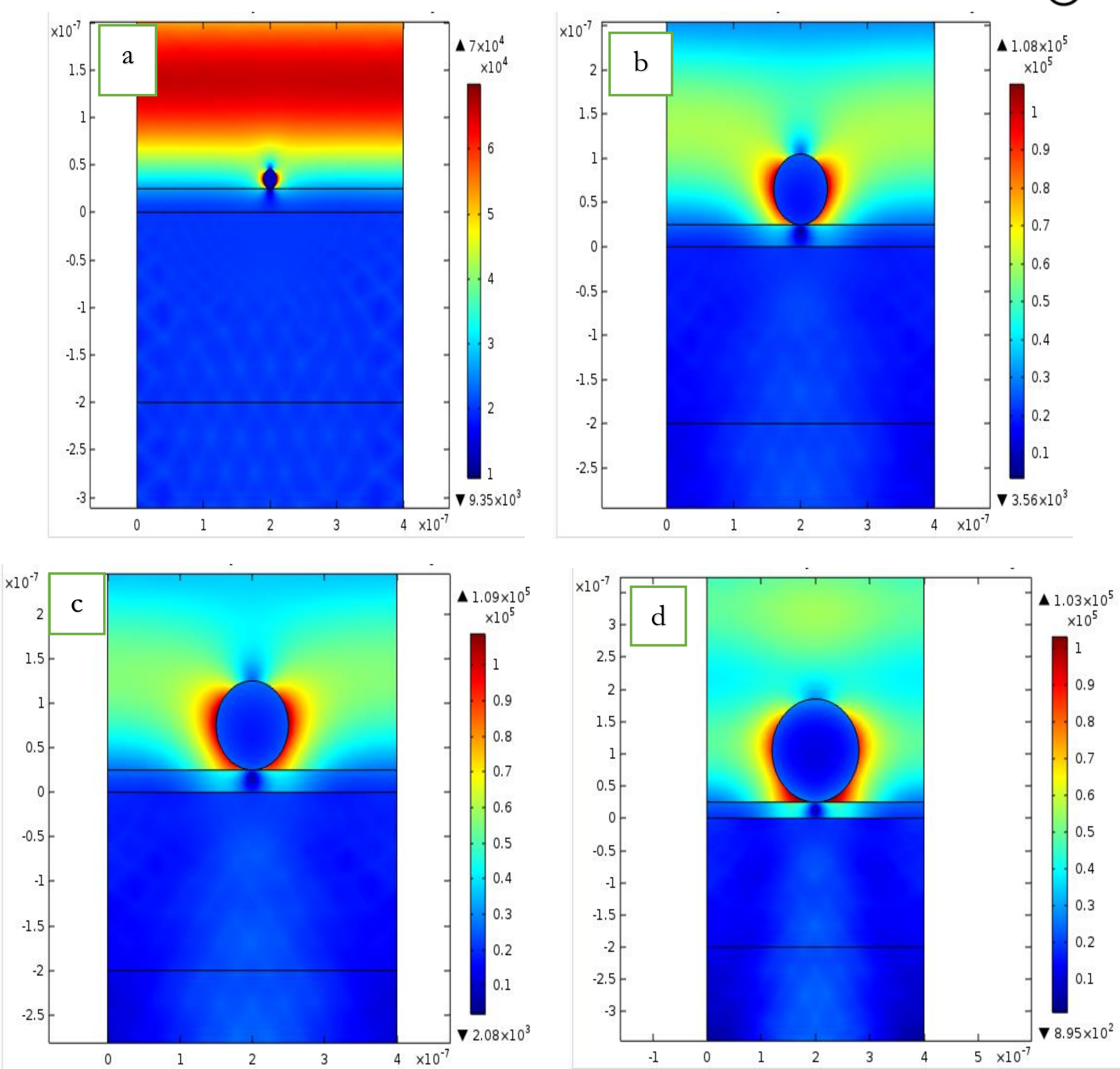

Figure (3): Effect of size of NP on the electric field enhancement, NP radius (a) 10 nm, (b) 40 nm, (c) 50 nm, (d) 80 nm, at 550 nm.

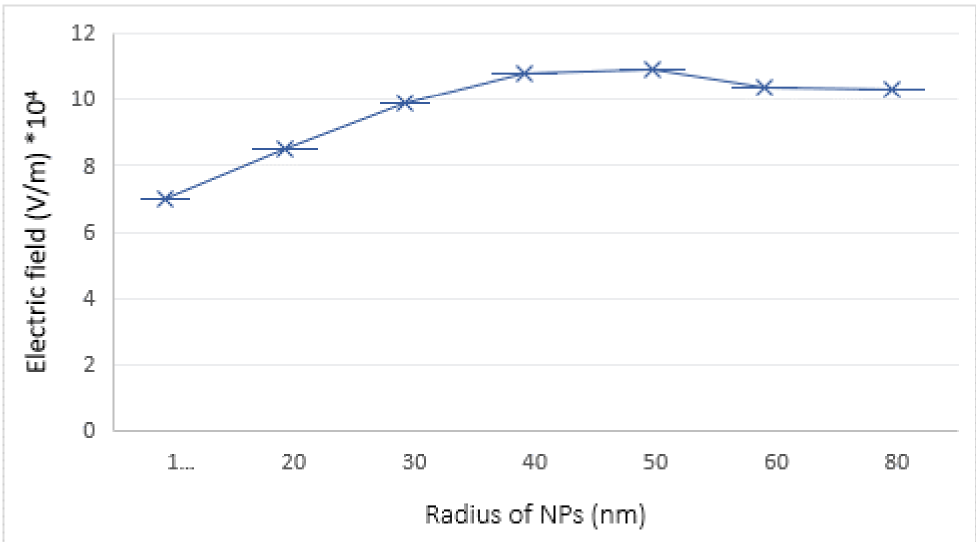

Figure (4): Influence of NP size variation on electric field at 550 nm.

4.2 Influence of spacer layer thickness

The second important parameter is the thickness of spacer layer that effect on the field enhancement. We are used several of thickness from 10 nm to 50 nm and we are selected nanosphere with radius 40 nm. Results are show in Fig.5. From Fig.5a, the electric field intensity at thickness 10 nm is decreased compared with the electric field intensity at 50 nm and the greatest effect shown in Fig.5b.

Also an important sketch between the electric field altering and the thickness of SiO_2 is presented in Fig.6. When the thickness increased the field is increased. At 10 nm ($E=9.44*10^4$ V/m) and steady raise with increasing the thickness of SiO_2 to reach ($E=12*10^4$ V/m) at 50 nm.

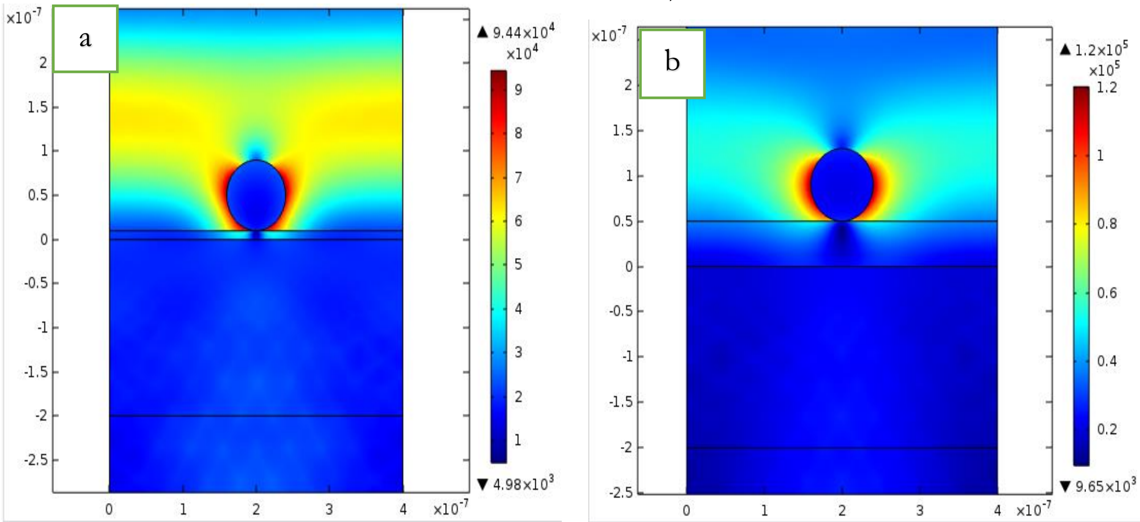

Figure (5): Effect of spacer layer thickness (SiO_2 sublayer) on the electric field enhancement (a) 10 nm, and (b) 50 nm, at 550 nm .

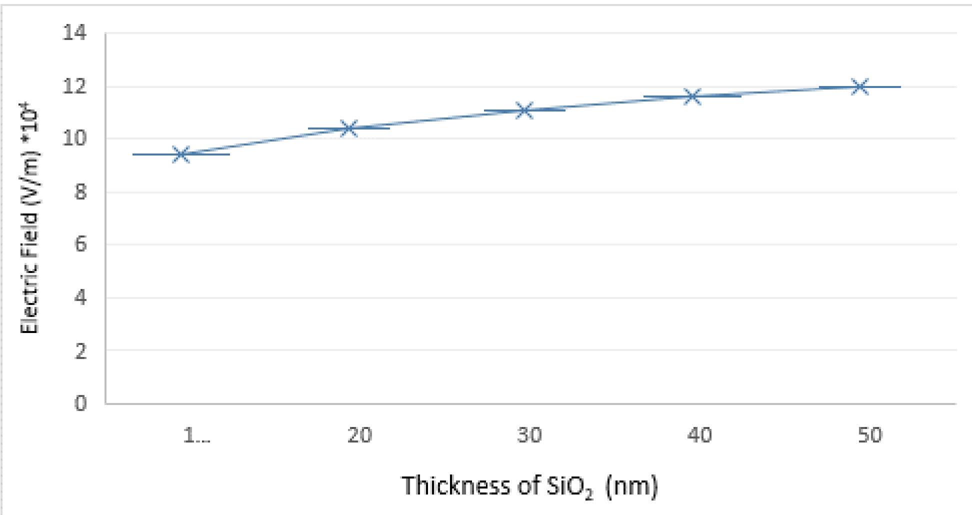

Figure (6): Influence the thickness of SiO_2 sublayer on electric field enhancement.

4.3 Influence of spacing distance

The third affective parameter on the electric field and plasmonic resonance is the spacing distance (d) between NPs.

By using the COMSOL 5.2 model, the effect of spacing between nanospheres of radius 40 nm and thickness of SiO_2 50 nm on the field enhancement is introduced in Fig.7. It should be noted that with decreased number of nanospheres, the spacing is increased. We manipulate with number of particles and not with size of NPs as presented in reference [7].

We see the plasmonic effect between the two neighboring NPs, when the spacing between nanoparticles is decreased, that shown in Figu.7a and 7b (d=0.2 and d=0.25) µm, respectively. But in Fig.7c where d=0.3 µm the effect starts reducing because increasing the spacing between NPs, the NPs appearance as each separately and no coupling between them, as shown in Fig.7d where d=0.4 µm.

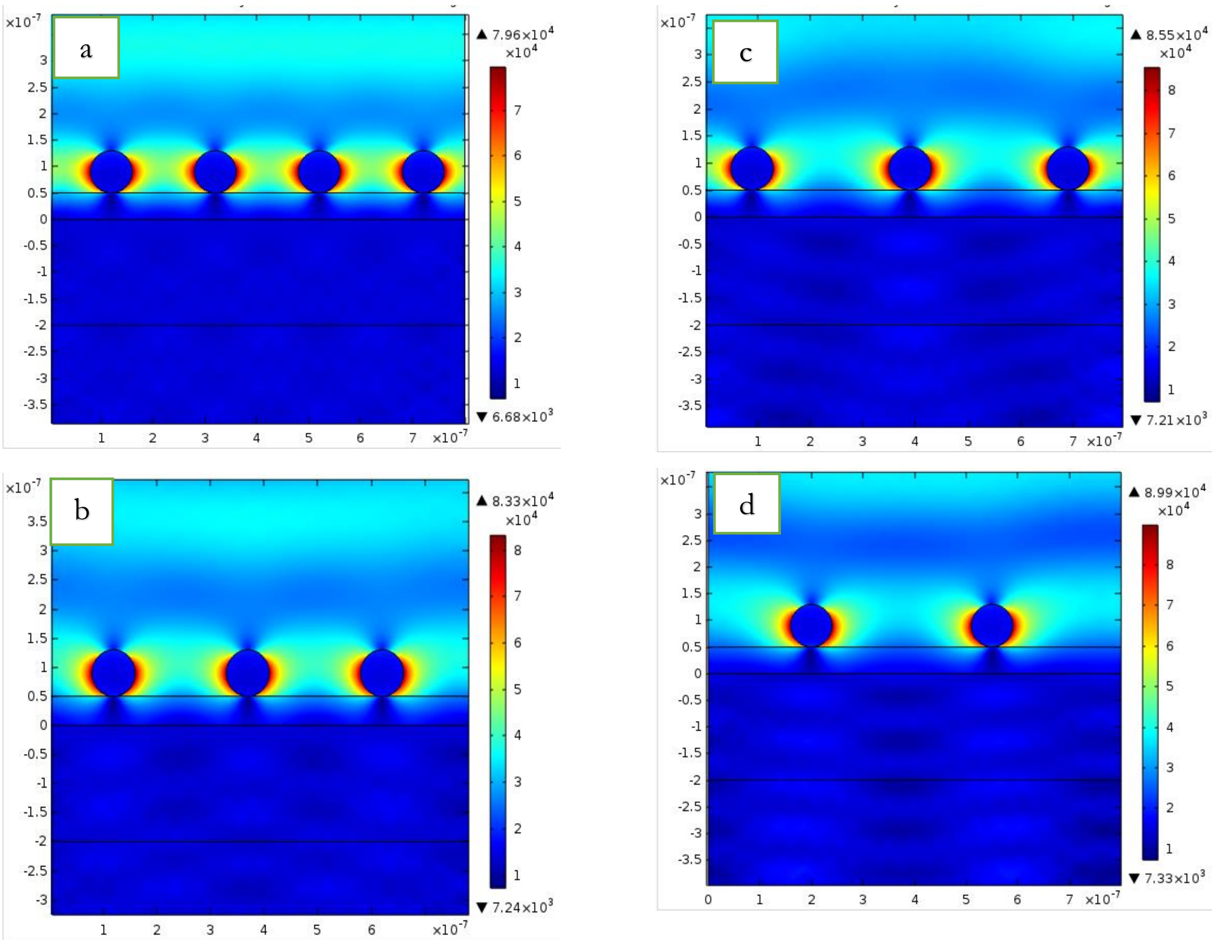

Figure (7): Influence of spacing distance (d) between NPs on the electric field enhancement (a) d= 0.2 μm, (b) d=0.25 μm, (c) d=0.3 μm, and (d) d=0.4 μm.

5. Conclusion

According to simulation results it was shown that to improve the electric field, the NPs' size, spacing, presence SiO_2 sublayer, and thickness of it must be manipulated. The electric field enhances when the size of NPs increases but it must be limited (80 nm and 100 nm) diameter. When gold NPs are deposited on the SiO_2 sublayer, the electric field increased due to decreasing the refractive index (n_{sio2}=1.458). The electric field increases when the sublayer thickness increases to 50 nm, and we obtain on the greatest effect. Moreover, separation between NPs affect the electric field enhancement by manipulating the number of NPs the distance decreases and the plasmonic interaction appears.

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