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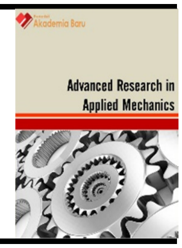

Tapered Metal Nanoantenna Structures for Absorption Enhancement in GaAs Thin-Film Solar Cells

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M. Aboul-Dahab[1,*], Mina Dawoud[1,2], S. H. Zainud-Deen[3], H. A. Malhat[3]

[1] Arab Academy for Science, Technology and Maritime Transport, Cairo, Egypt
[2] Higher Technological Institute, Tenth of Ramadan, Egypt
[3] Faculty of Electronic Engineering, Menoufia University, Egypt

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ABSTRACT

This paper focuses on absorption by metal nanoantennas as a means to enhance light trapping into thin-film solar cells. It determines the optimum metal nanoantennas distribution for solar cell applications, taking into account interactions between the particles as well as including the interaction with the absorbing substrate. Tapered structure is proposed for absorption enhancement using different metal nanoantennas like gold, silver, copper and aluminium. The sizes of nanoantennas are tapered in one direction. The tapered structures are composed of an array of metal nanoantennas and the sizes are tapered using two different ways according to a tapering direction. The degree of tapering can be set by controlling a scaling element. All simulation data are obtained using finite element method. Larger than 20% increase in the absorption can be achieved.

1. Introduction

The utilization of thin film solar cells in solar energy conversion to electricity is a promising technology that may permit the generation of very large scale electric power [1]. Thin film solar cells, with thin absorber layer, have the advantages of relatively low fabrication cost and mechanically flexible devices. Still, thin absorber layer leads to poor absorption of the infrared portion of the solar spectrum. One of the proposed solutions for this problem is light trapping [2]. In thin film solar cells, light trapping is achieved by using metal nanostructures that support surface plasmons. By proper engineering of these structures, light can be concentrated and folded into a thin semiconductor layer leading to high energy absorption [3]. The metallic nanostructures are used as scattering elements or as nanoantennas in which the surrounding near-field is coupled to the semiconductor layer which increase the absorption [4]. In [5], a solution-based Au nanoparticles to improve performance of amorphous silicon solar cells is used. A novel approach that uses noble metallic nanostructure to obtain effective light trapping for thin-film solar cells has been

[*] *Corresponding author.*
E-mail address: mdahab@aast.edu (M. Aboul-Dahab)

investigated in [4]. Metal nanoantennas are strongly scattered of light at wavelengths near the plasmons resonance, which is due to a collective oscillation of the conduction electrons in the metal [6].

In this paper, a tapered structure of nanoantennas for the absorption enhancement in the GaAs substrate solar cell is proposed. It consists of a periodic array of tapered size nanoantennas in one direction. Different tapering methods are studied for the absorption enhancement. A parametric study on the effect of nanoparticle material, dimensions and tapering arrangement on the absorption magnitude and bandwidth has been presented [7,8]. Numerical investigation of light absorption enhancement of solar cells using the finite element method has been introduced. Finally, the results are concluded.

2. Numerical Results

A schematic diagram of 7×7 uniformly distributed nanoantennas with dimensions of 560×560×50 nm3 is shown in Fig.1a. Each nanoparticle consists of cylindrical metal nanoparticle with elliptical cross section with semi-major axis radius, RL, equal twice the semi-minor axis radius, Rs (aspect ratio of 2) and of height, h, as presented in Fig.1b. The 49 nanoantennas are deposited on GaAs substrate and covered with conductive indium tin oxide (ITO) layer. The dimensions of GaAs substrate and ITO on x-y plane are 560×560 nm2. The thickness of each layer is 25 nm. The permittivity of GaAs and ITO are assumed equal 12.86 and 4.67, respectively.

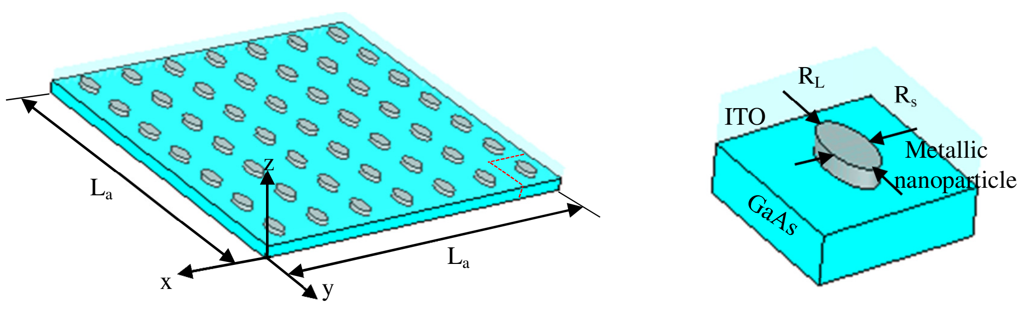


Fig. 1. Schematic diagram of a unit-cell consisting of 7×7 uniform nanoantennas array deposited on GaAs substrate, L_a= 560 nm

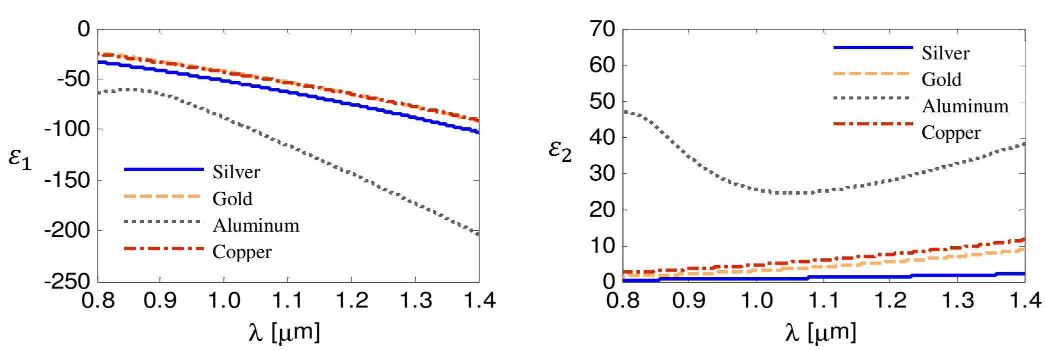
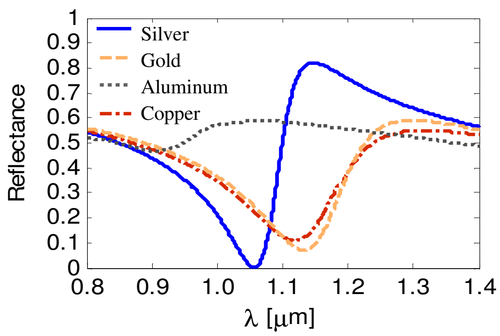


Fig. 2. The dispersive properties response of different metals at THz range

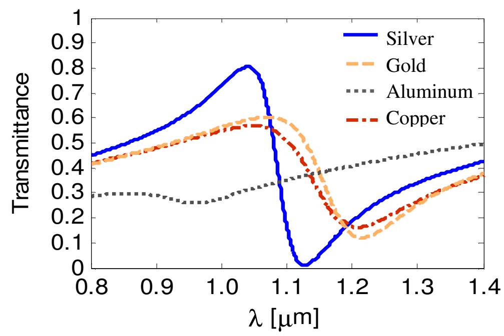
The metal nanoparticle dispersive properties are described by the Drude-Lorentz model [9]. The frequency dependent relative complex permittivity of metal nanoantennas as a function of frequency can be calculated from

$$\varepsilon_1 = \left[1 - \frac{\omega_p^2}{\omega^2+\vartheta_p^2}\right], \varepsilon_2 = \left[\frac{\omega_p^2\vartheta_p}{\omega^3+\omega\vartheta_p^2}\right] \tag{1}$$

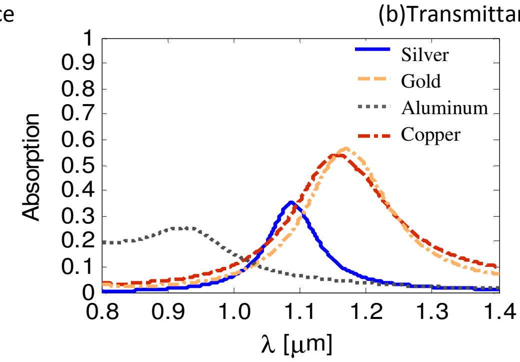
where ε_1 is the real part of the relative permittivity, ε_2 is the imaginary part. ϑ_p is the angular collision frequency within the material of the nanoparticle, and ω_p is the electron plasma angular frequency. Figure 2 shows the variation of electric permittivity versus the wavelength λ for gold, copper, silver and aluminum. Throughout the analysis a y-polarized plane wave is used as an incident wave. All the simulation data are obtained using FEM method. The reflectance, the transmittance from the structure and the absorption for different metal nanoantennas are depicted in Fig. 3. The nanoparticle dimensions are: R_s=10 nm, L_a=560 nm, h=10 nm, and d=0 (the nanoantennas deep in GaAs layer). The absorption A can be calculated from A=1–R–T, where R= $|S_{11}|^2$, is the reflectance and T= $|S_{21}|^2$, is the transmittance [10]. The maximum absorption is achieved by gold nanoparticle material; the frequency corresponding to the maximum absorption is changed according to the nanoparticle material. The absorption of the gold and copper nanoantennas has a maximum around 1.2 µm. The transmittance and the reflectance exhibit significant reduction around 1.2 µm. In this case the nanoantenna is used to capture the incident wave into a localized near field spot around it.



(a) Reflectance



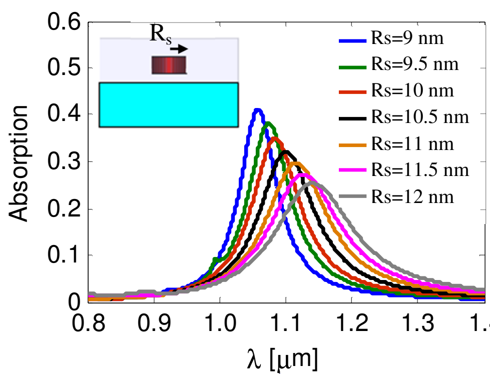
(b)Transmittance



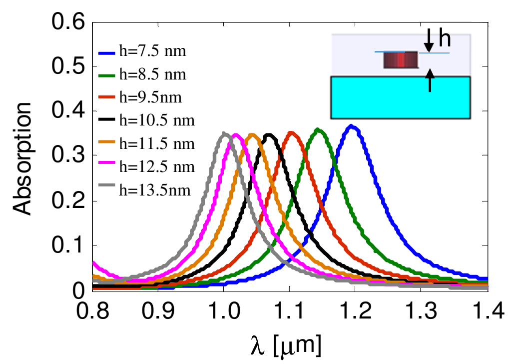
(c) Absorption

Fig. 3. Light reflectance, transmittance, and absorption spectra for elliptical cylindrical nanoparticle over GaAs unit-cell with different metals illuminated by incident light polarized along the y- axis.

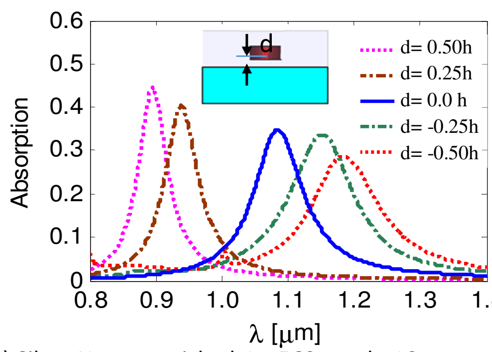
A parametric study on the effect of metal nanoparticle dimensions on the energy absorption in the GaAs unit-cell is simulated and analyzed. The nanoparticle unit-cell is illuminated by incident light polarized along the semi-major axis R_L. Figure 4a shows the effect of changing the semi-minor axis, R_s, from 9 nm to 12 nm, for nanoparticle fixed dimensions of: h = 10 nm, L_a= 560 nm, and d=0. The absorption peaks for R_s= 9, 9.5, 10, 10.5, 11, 11.5, and 12 nm were found at λ = 1.06, 1.075, 1.085, 1.1, 1.12, 1.13, and 1.14 μm with maximum absorptivity of 0.41, 0.38, 0.35, 0.32, 0.30, 0.27 and 0.25, respectively. The frequency of the maximum absorption moves toward lower frequencies as R_s increased due to the increase of the physical dimensions of the nanoparticle. FWHM is increased by increasing R_s, which indicated broadband absorption of the solar spectrum. The FWHM is 66 nm for R_s=9 nm compared to 147 nm for R_s=12 nm. Figure 4b illustrate the absorption spectra for silver nanoparticle with different height, h, at dimensions: R_s=10 nm, L_a=560 nm, and d=0. The maximum absorption value is approximately the same of 0.35 for different values of nanoparticle height with slightly decrease in FWHM from 96 nm to 80 nm for h= 7.5, 13.5, respectively. By increasing the nanoparticle height, the frequency corresponding to maximum absorption moves toward the higher frequencies. This is due to the increase of the physical size of the nanoantena and the change of current distribution on its surface The absorption response of the silver nanoantennas as the distance d increases from – 0.5h to +0.5h is presented in Fig. 4c. Other nanoparticle parameters are L_a=560 nm, h=10 nm, R_s=10 nm. The absorption increases as the distance d increases. The frequency corresponding to maximum absorption moves toward higher frequencies as the distance d increases.



(a) Silver Nano-particle R_s, h=10 nm, L_a=560 nm, and d=0 nm.



(b) Silver Nano-particle h, Rs=10 nm, L_a=560 nm, and d=0 nm.



(c) Silver Nano-particle d, L_a=560 nm, h=10 nm, and

Fig. 4. Light absorption spectra for elliptical cylinder unit cell illuminated by incident light polarized along the long axis R_L.

3. Tapered Structure of the Nanoantennas

A proposed tapered structure of the 49 silver nanoantennas is shown in Figure 5. The tapered structure consists of a periodic array of silver nanoantennas arranged in 7×7 matrix deposited on GaAs substrate. The GaAs substrate and ITO layer dimensions assumed on x-y plane have 560×560 nm^2. The size of the nanoantennas in each raw is fixed, while the size of the nanoantennas in each column is tapered in one direction. Two different types of tapered arrangements are shown in Fig. 6. The first type, the nanoparticle semi-minor axis radius, R_s, is tapered from one side to the other in y- direction as shown in Fig. 6a. The semi-minor axis radius, R_s, in the n^{th} row is calculated from

$$R_{sn} = R_{so} - (n - \zeta) \,.\, \alpha \tag{2}$$

where n is integer 1, 2…,7, ζ is the offset factor, R_{so} is an initial semi-minor axis radius of the reference nanoparticle, and α is a scaling coefficient. The direction and degree of the tapering in the tapered structure can be adjusted by the offset factor ζ and the scaling coefficient α, respectively. If the scaling coefficient α is positive number and n is greater than ζ, then the nanoparticle R_s is reduced. In the second type, the nanoparticle semi-minor axis radius, R_s, is tapered from or toward the center of the structure as depicted in Fig. 6b and Fig. 6c respectively. Figure 7a presents the absorption response versus the wavelength λ for different tapered structures. The maximum absorption coefficient occurs for distribution "b" is about 0.57. In Figure 7b. The absorption for different scaling coefficient α are compared with that of the original uniform structure (α=0). The scaling factor α is varying from -0.5 to -0.1. Other parameters are R_{so}=10.5 nm, L_a=560 nm, h=10 nm and d=0. For all values of α local maximum of the absorption gather around λ = 1.1 μm, at which the absorption of the original uniform distribution structure. The maximum absorption is achieved when the scaling coefficient α= -0.5 with FWHM of 112 nm. This value is about 0.2 higher than that of the same size structure composed of uniform distribution structure. Figure 7c shows the absorption response for different values of R_{so}. The frequency corresponding to maximum absorption increases as R_{so} decrease and the maximum absorption is also increased.

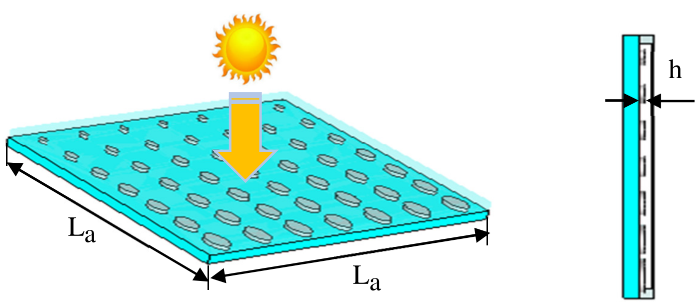


Fig. 5. Schematic diagram of 7×7 graded unit cell array deposited on GaAs substrate

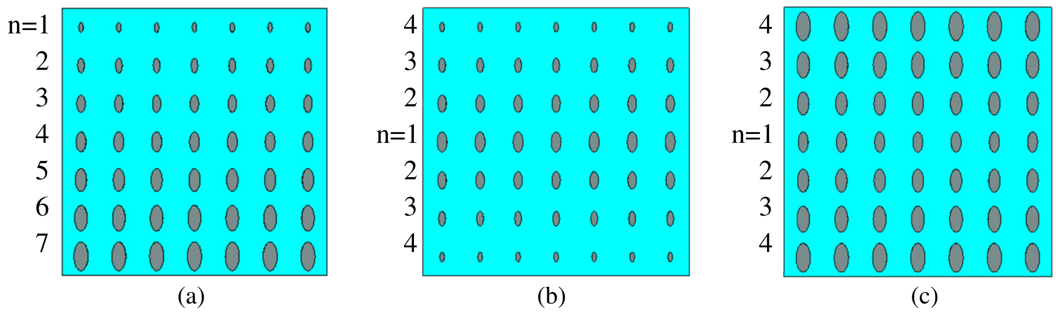
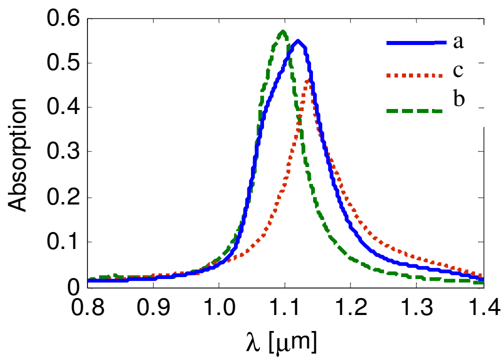
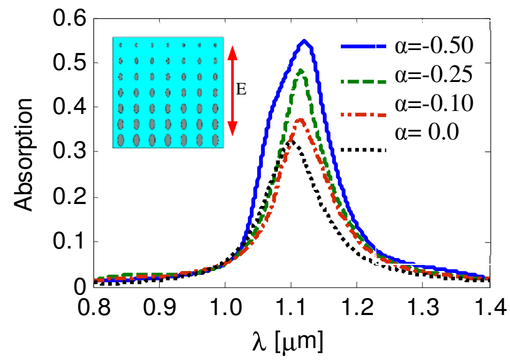


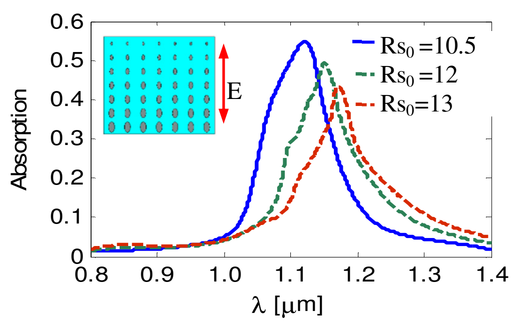
Fig. 6. Different configurations of 7×7 graded array deposited on GaAs for different tapering techniques



(a) Silver Nano-particle R_{so}=10.5, α=-0.5 (for a, c), α=0.5 (for b), L_a=560 nm, h=10 nm, and d=0 nm.



(b) Silver Nano-particle α, R_{so}=10.5nm, L_a=560nm, h=10nm, and d=0nm.



(c) Silver Nano-particle R_{so}, α=-0.5nm, L_a=560nm, h=10nm, and d=0nm.

Fig. 7. Light absorption spectra for elliptical cylinder graded unit cell array illuminated by incident light polarized along the y-axis R_L.

4. Conclusion

In this paper, different tapered metal nanoantenna structures for absorption enhancement are proposed. Different metal nanoantennas like gold, silver, copper and aluminum are considered. Approximate 20% increases in the absorption is obtained. The frequency corresponding to the maximum absorption is changed according to the nanoparticle material. The maximum absorption is achieved by gold nanoparticle material. The frequency of the maximum absorption moves toward lower frequencies as R_s increased due to the increase of the physical dimensions of the nanoparticle and broadband absorption of the solar spectrum is achieved. The tapered structure consists of a periodic array of tapered metal nanoantennas with different sizes. The effect of the tapered geometry on the absorption enhancement is investigated. The maximum absorption occurs for distribution “b” is about 0.57 and distribution “a” achieve wider FWHM compared to other configurations. The effect of nanoparticle semi-minor axis of the reference element in the tapered structure has been investigated. The frequency corresponding to maximum absorption increases as R_{so} decrease and the maximum absorption is also increased.

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