Plasmonic Yolk-Shell Nano Structures for Solar Cells Absorbance Enhancement
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Abstract
In this research we study the enhancement in power absorbance of thin film silicon solar cells by plasmonic yolk-shell (YS) nano particles. Plasmonic YS nano particles are simulated on top/bottom position of thin film Si layers. We suggest different structures of YS and simulate the behaviour of such structures using a FDTD simulations. We calculate the limiting photocurrent taking into consideration the enhanced absorbance of the cell. The simulation results show multi-peaked and broad band power absorbance enhancement all over the solar spectrum. The power absorbance enhanced into solar cell by 64% over planar ultra-thin 300 nm Si cell.

1. Introduction
To achieve high absorbance, the first prototype of solar cells was based on thick films. About half of the cost of solar cell comes from material cost [1]. The designs of the second-generation solar cell suggest reducing the amount of materials and facilitating fabrication methods. Thin film solar cells (TFSC) offer cost reduction and large scalability fabrication. However (TFSC) faces the problem of low absorption of light especially for incident photons with low energy [2]. Trapping light techniques are used to boost up the efficiency of (TFSC) [3], [4], [5]. Many researchers studied the effects of plasmonic nano particles on TFSC for Si material [6], [7], [8]. In a phenomenon called localized surface plasmon resonance (LSPR), plasmonic nano structures can squeeze, confine and localize electromagnetic waves (EMW) inside nano range. Free electrons couple with photons of EMW to make collective oscillations "plasmons". This phenomenon integrated with solar cells and the cells are called plasmonic solar cell (PSC). Plasmonics are very sensitive to geometry, size, material and location of nano particles. Top/bottom solar cell’s surface located plasmonic nano particles are proposed as an efficient way to increase absorbance of (TFSC) by scattering and creating additional paths inside solar cell [9]. Gold and silver are the dominant used materials in the field of plasmonic in the visible region [10]. Plasmonic yolk-shell (YS) is a special form of core-shell nano particle with a void shell layer. The name inspired from the "rattle toy" as indication of movable core [11]. Nano YS has 2 forms (i) metal core -void -dielectric shell and (ii) metal core -void -metal shell. This second type can be mono or bi-metallic as Au-void-Ag or Au-void-Ag. The void layer could be liquid or air. Plasmonic nano YS attracts many researches because of its unique properties that arisen from its asymmetry, the existence of a void layer, and the ability of core movement. The LSPR of plasmonic asymmetric nano particles has many peaks over simple spherical or symmetric shells structures. As a hybrid structure (composed of 2 shells and a core), plasmonic nano YS properties can be interpreted by (PHT) theory. In [12] the plasmonic Au/Pd nano YS resonance is a hybrid or a mixture of the plasmon resonance of spherical Au core and the Pd nano shell. The narrow LSPR of Au sphere, and the broaden spectrum of Pd nano shell hybridize with each other to form the plasmon resonance of plasmonic nano YS. The experimental calculations agree with theoretical discrete dipole approximations (DDA). In [13] they report the fabrication of Au-void-Silica nano YS by etching of Au core for the use of photo catalytic reaction. In [14] the availability to fabricate Ag -void -silica nano YS was introduced. Plasmonic (YS) are mainly used in solar energy conversion applications and photo catalysis [15],[16],[17] and can easily be fabricated by galvanic replacement which is a chemical reaction to produce the YS from nano shell [18]. The main properties that affects the (YS) structure is the core and shell material, the sizes of core and shell and the void space. By The proper engineering of nano YS, it can boost the
efficiency of thin film solar cell. In our study, seeking for improving solar cell absorbance we will study the effects of noble metal plasmonic nano YS on the enhancement of solar cells.

2. Structure and Methods

Nano YS shape has many configurations with many material parameters. In this study we are interested in nano YS shape with core and shell plasmonic materials like gold and silver. The YS shape studied here, as shown in Fig. (1) is a metal core with radius r and two shells, the first shell is void or hollow shell and the second shell is another metal. All the YS are with core radius of r=60 nm, shell 1 of radius R1=70 nm and shell 2 of radius R2=100 nm. We changed the plasmonic materials to see the changing effects in solar cell power absorbance enhancement.

![Fig. (1): Schematic diagram of plasmonic YS (a) 2D (b) 3D](image)

Fig. (2) shows the structure of a thin Si solar cell layer of 300 nm with nano yolk-shells on its surface. An array of plasmonic YS nano particles with periodicity of 400 nm is considered. We performed a 3D FDTD study. In our simulation we assume a perfect matched layer (PML) along the z-direction and periodic boundary conditions (PBCs) along x and y-directions. A parametric study is performed for the PSC with changing the materials of core and shells of the nano yolk shell structure. In this simulation, the AM1.5 solar spectrum [19] is represented by a plane wave source injected along the z-direction. To calculate the amount of absorbed power, two power monitors are placed inside cell. The first monitor positioned at the cell surface to measure reflected power; another monitor positioned at the bottom of the cell. Therefore, the absorbed power is the subtraction of both. The quantity power absorption is defined as neither reflected nor transmitted power [20].

\[
A(\lambda) = 1 - R(\lambda) - T(\lambda) \quad (1)
\]

where, \(A(\lambda)\) is the absorbance, \(R(\lambda)\) is the reflectance and \(T(\lambda)\) is the transmittance. To quantify the solar cell absorbance enhancement, we define a Figure of Merit (FoM) as the ratio between the power absorbed of PSC to that of a reference planar cell. FoM is calculated considering that a single electron-hole pair is produced for every photon absorbed with energy bigger than the band gap of Si [21].

\[
FoM = \frac{\int \lambda P_{PSC}(\lambda) I_{AM1.5}(\lambda)d\lambda}{\int \lambda P_{Planar}(\lambda) I_{AM1.5}(\lambda)d\lambda} \quad (2)
\]

where, \(P_{PSC}\) is the power absorption in solar cell with plasmonic YS and \(P_{planar}\) is the power absorption in planar cells. Also, FoM can be calculated at every wavelength of the solar spectrum.
3. Results and Discussion

3.1 Plasmonic YS on a Si Substrate

The plasmonic YS Ag-void-Ag and Ag-void-Au are used either on the top surface of Si or at the bottom surface. The absorbance, $A(\lambda)$, of thin film planar 300 nm Si solar cell with different top/bottom Ag-void-Au YS is shown in Fig. (3). The absorbance spectra of thin film Si solar cell enhanced by using bottom located Ag-void-Au YS as it reaches 47% absorbance of the spectra at $\lambda=514$ nm. Fig. 4 shows the distribution of the relative power absorption per unit volume (log scale) in W/m$^2$µ at different three peaks of the absorbance curve of Fig. (3). Fig. 4 (a), (b) show the distribution of the relative power absorption per unit volume for top YS Ag-void-Au at $\lambda=514$ nm and 950 nm, respectively. Fig. 4 (c) shows the distribution of the relative power absorption per unit volume of the bottom YS at $\lambda=514$ nm. These figures show that at $\lambda=514$ nm the absorbance enhancement results from the bottom Ag-void-Au YS is higher than that of top located YS. For $\lambda=950$ nm, top located Ag-void -Au YS causes higher absorbance inside Si layer. In comparison to the reference cell, Fig. 4.6 (d, e) show that the absorption is enhanced effectively at $\lambda = 514$ nm and 950 nm, respectively due to plasmonic YS. The reference cell suffers from high reflectance and transmittance in compare to plasmonic solar cell.
Fig. (3) Absorbance of Si 300 nm with top and bottom Ag-void-Au YS particles (R2=100 nm, R1=70 nm and r=60 nm)

Fig. (4): The distribution of the relative power absorption per unit volume (W/µm³) (log scale) of PSC with Ag−void−Au (R2= 100 nm, R1= 70 nm and r= 60 nm) located at (a) top at λ = 514 nm, (b) top at λ = 950 nm, (c) bottom at λ = 514 nm, and reference 300 nm Si cell at (d) λ = 514 nm, (e) λ = 950 nm

Plasmonic effects of Ag-void-Ag YS in enhancing solar cell absorbance is shown in Fig. (5). The usage of plasmonic top/ bottom located Ag-void-Ag YS enhances the absorbance of ultra-thin 300 nm Si layer solar cell. Bottom located plasmonic Ag-void-Ag YS exceeds 64% absorbance of the solar spectrum at λ=514 nm. The top located Ag-void-Ag YS enhances the absorbance compared to the reference cell, but the enhancement of the bottom located YS is much better. For each corresponding absorbance peak, the distribution of the relative power
absorption per unit volume (log scale) in W/m$^3$ is calculated for top Ag-void-Ag plasmonic solar cell at $\lambda=560$ nm and 816 nm in Fig. 6 (a, b). For plasmonic solar cell with bottom Ag-void-Ag, the distribution of the relative power absorption per unit volume (log scale) is calculated at $\lambda=514$ nm and 721 nm in Fig. 6 (c, d). These figures show that the Ag-void-Ag YS enhanced the absorption of light incident on Si solar cell all over the spectrum in comparison to the relative power absorption distribution profile of the planar cell Fig. 6 (e-h) at $\lambda=560, 816, 514$ and 721 nm, respectively.

![Absorbance of Si 300 nm with top and bottom located Ag-void-Ag (R2=100 nm, R1=70 nm and r=60 nm).](image)

**Fig. 5** Absorbance of Si 300 nm with top and bottom located Ag-void-Ag (R2=100 nm, R1=70 nm and r=60 nm).
Fig. (6): The distribution of the relative power absorption per unit volume (W/µm\(^3\)) (log scale) of PSC with Ag-void-Ag Ag (R2=100 nm, R1=70 nm and r=60 nm) top located at wavelength (a) 560 nm and (b) 816 nm and bottom at wavelength (c) 514 nm and (d) 721 nm.

Fig. (7) shows the FoM of different PSC with different YS at each wavelength of the solar spectrum. FoM is always greater than one, except at some wavelengths of top Ag-void-Au. the inclusion of plasmonic top/bottom YS nano particles have an enhancement effect on the absorption of Si. Integrating of the bottom Ag-void-Ag YS shows advantage to other YS as the absorbance enhancement has many peaks at \(\lambda\) = 514 nm, 586 nm, 765 nm, 936 nm, and 1100 nm, respectively.
The calculation of FoM using equation (2) is introduced in Table 1 for a reference cell, PSC with top/bottom Ag-void-Ag and Ag-void-Au with \((r=60 \, \text{nm}, \, R1=70\, \text{nm}, \, R2=100 \, \text{nm})\). FoM indicates the overall absorbance enhancement all over the spectrum compared to the reference cell. Generally using plasmonic YS nano particles enhances the absorption of ultra-thin 300 nm Si layer. The bottom Ag-void-Ag YS has the highest figure of merit of 1.64. The enhancement in the absorption affects the values of ideal short circuit current of solar cell. The plasmonic YS nano particles could trap light efficiently inside Si especially when placed on bottom surface of Si layers.

Table 1: FoM and limiting short circuit current of different solar cells. Nano particles, if used, are yolk shell nano rattles of radius \(r=60 \, \text{nm}, \, R1=70\, \text{nm}, \, R2=100 \, \text{nm}\) and the embedded shell is void

| Type of Solar Cell | Nano Particles | Location | FoM  |
|--------------------|----------------|----------|------|
| Planar Si 300 nm   | —              | —        | 1    |
| PSC                | Ag-void-Ag     | Top      | 1.51 |
| PSC                | Ag-void-Ag     | Bottom   | 1.64 |
| PSC                | Ag-void-Au     | Top      | 1.40 |
| PSC                | Ag-void-Au     | Bottom   | 1.47 |
Conclusion

Our aim is to produce highly absorptive thin film Si solar cells. The plasmonic YS nano particles are placed on top or bottom surface of ultra-thin 300 nm Si layer to explore the plasmonic enhancement effect on the absorption of Si solar cell. Plasmonic Ag-void-Ag YS nano particles increased the absorbance of thin film Si solar cell especially when placed on the bottom surface. Compared to a reference planar cell, the PSC with YS nano particles enhanced the absorption with a figure of merit of 1.64 and with as high-quality absorption in the near infra-red region for $\lambda > 600$ nm where the reference cell absorbance in this region is very small.

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