Absorption enhancement in thin film solar cells with bilayer silver nanoparticle arrays

Shuyuan Zhang1,2, Min Liu1,2, Wen Liu1, Yusheng Liu1 3, Zhaofeng Li1, Xiaodong Wang1,2 and Fuhua Yang1,2
1 Engineering Research Center for Semiconductor Integrated Technology, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, People’s Republic of China
2 School of microelectronics, University of Chinese Academy of Sciences, Beijing 101408, People’s Republic of China
3 University of Chinese Academy of Sciences, Beijing 101408, People’s Republic of China
4 State Key Laboratory for Superlattices and Microstructures, Beijing 100083, People’s Republic of China

E-mail: xdwang@semi.ac.cn

Keywords: photovoltaic, plasmonics, surface plasmons, solar energy

Abstract

In this paper, a systematic design and analysis of thin film crystalline silicon solar cells decorated with bilayer silver nanoparticles with different particle dimensions is presented. The particles are located on the rear of the solar cell. Using numerical simulations, we showed that the light absorption is enhanced when the particle radii of the upper layer Ag NPs is less than that of the lower. Moreover, our proposed structure showed a 9.97% increase in short-circuit current density and a 9.94% increase in intergraded quantum efficiency across the solar spectrum compared with the optimized counterpart decorated with uniform Ag NPs.

1. Introduction

Thin film crystalline silicon (c-Si) solar cells have become a promising alternative due to its less material consumption and lower manufacturing cost. However, compared with conventional c-Si solar cells, thin film solar cell suffers from poor light absorption efficiency due to the finite thickness. Therefore, structuring the thin film solar cell so that light is trapped inside to increase the absorbance is very important. Strategies for conventional thick solar cells such as pyramidal surface texture and anti-reflecting coating, have been widely applied to improve the light trapping and absorption. However, these measures cannot be directly applied for thin film solar cell due to its small length scale. People turn to the wavelength-scale textures to enhance light trapping and increase photocurrent of the thin film solar cells. However, the surface recombination rate increases with a rough surface and such solar cells have low material quality, resulting in degradation. A method for achieving light trapping in thin film solar cells is the use of metallic nanoparticles (NPs) [1–13]. Metallic NPs exhibit the phenomenon of surface plasmon resonance when illuminated with light of suitable frequency [14]. And the metallic NP shows a promising potential for enhancing light absorption and photocurrent in photovoltaic devices, whether placed at the interface of two media with different dielectric constants or embedded in only one medium [15, 16].

Much work has been done to improve the performance of solar cells using plasmon excitation. It is concluded that locating the particles on the rear of the absorber layer is more effective in enhancing photocurrent than that located on the front [17, 18]. However, most of the researches have concentrated on single layer metallic structure, just a few reports about multilayer plasmonic structures [4, 6, 18–21]. Shi et al [19] reported on a numerical simulation study of the multilayer silver (Ag) NPs for light trapping in thin film solar cells, shown that the bilayer Ag NPs provide better light trapping performance than single layer Ag NPs when the Ag NPs are located on the rear of the solar cell. Ho et al [20] integrated a double layer of Au NPs embedded in the transparent conducting oxide to a-Si solar cell and obtained an improved efficiency of 18.4%. Most existing multilayer plasmonic structures involve a uniform size, but the added benefits of varying the structural dimensions offered by the double or more layers plasmonic structures have not been thoroughly investigated.
In this work, a systematic design and analysis of thin film c-Si solar cells decorated with a new style of bilayer Ag NPs array with different particle sizes is presented. And the main parameters of our structure is inherit from our previous work [19]. Using numerical simulations, the studies indicate that the light absorption is enhanced when the particle radii of the upper Ag NPs is less than that of the lower. Our proposed structure showed a 9.97% increase in short-circuit current density and a 9.94% increase in intergraded quantum efficiency across the solar spectrum compared with the optimized counterpart decorated with uniform Ag NPs.

2. Numerical method

The electromagnetic field features are numerically analyzed by the finite-difference time-domain (FDTD) method [22]. The dielectric functions are modeled using a Drude model for Ag and a Drude–Lorentz model for Si. The cells are exposed to light wavelengths from 400 to 1100 nm. The absorption is calculated by the difference of power flux through the monitors (M1, M2) surface. And the monitors are put just on the front and the rear surface of the active layer to exclude the parasitic absorption of Ag NPs [6, 19, 23]. The short-circuit current density, $J_{sc}$, is calculated under an AM1.5 solar spectrum [24] to obtain a quantitative evaluation of the photon-capturing capability of the c-Si light-trapping structures.

Figure 1(a) shows the schematic diagram of the proposed structure which is decorated with rear bilayer hemispherical Ag NPs with varying radii, and the cross-section view of the device is illustrated in figure 1(b) where the characteristic sizes are defined. One reason for the use of Ag is that Ag is usually the preferred one for plasmonic applications among various metallic materials, and it offers a lower absorption loss and a higher optical cross section [25]. The main parameters of the structure is inherit from our previous work [19]. The Si film thickness is 0.8 $\mu$m and a 0.02 $\mu$m interlayer of SiO$_2$ acts as a passivation layer, which hinders the formation of Ag NP recombination centers [21]. The period is 0.4 $\mu$m. Only three parameters (i.e. $R_1$, $R_2$ and $d$) are left to control and optimize the light trapping performance of the thin film solar cells. The parameters $R_1$, $R_2$ and $d$ represent the radius of upper layer Ag NPs, the radius of lower layer Ag NPs and the interlayer thickness between the two NPs layers, respectively. In this study, the system will be compared to its planar counterpart and a counterpart with bilayer uniform Ag NPs for discussion convenience.

3. Simulation results

3.1. The configuration with uniform Ag NPs dimensions

We firstly optimize the system with uniform Ag NPs, namely the $R_1 = R_2$ system. It is theoretically possible to find the configuration that maximizes the $J_{sc}$ by scanning simultaneously the radius $R$ (between 0.01–0.20 $\mu$m) and the interlayer thickness $d$ (between 0.02–0.14 $\mu$m). $R$ is the unified representation of the radii $R_1$ and $R_2$, as $R_1$ and $R_2$ are equal. The result of this scan is depicted on figure 2, where the $J_{sc}$ is given as a function of $R$ under various values of $d$. It is shown that almost all curves have the same varying tendency under different $d$ configurations. And the maximum $J_{sc}$ of the $R_1 = R_2$ system is attained when $R_1 = R_2 = 0.12$ $\mu$m and $d = 0.08$ $\mu$m.

The $J_{sc}$ versus $d$ under different $R$ configurations is shown in figure 3. The interlayer thickness $d$ varies from 0.02–0.14 $\mu$m with a step of 0.01 $\mu$m. As is shown in figure 3(a), the $J_{sc}$ curves mainly have three kinds of tendencies. Some curves present first decrease and then increase as $d$ increases. Some are almost maintained as $d$ increases. And the others firstly increase with $d$ and then decrease. Obviously, the short-circuit currents of each $R$ configuration are influenced by the interlayer thickness $d$. And the maximal $J_{sc}$ of each curve is obtained at
4. Discussion

As is shown in figures 5(a) and (b), we compare the absorption performance and the corresponding \( J_{sc} \) of our proposed structure to the solar cell with uniform NPs radii and the planar silicon film with the same equivalent thickness of 0.8 \( \mu m \). The planar silicon film is displayed in order to better assess the photon-capturing performances of our proposed configuration, labeled as ‘Ref’. The solar cell with uniform NPs radii is labeled as ‘\( R_1 = R_2 \)’. Our proposed structure is labeled as ‘\( R_1 < R_2 \)’. As is shown in figure 5(a), one can see that the

\[ \text{Figure 2. } J_{sc} \text{ versus } R \text{ under different } d \text{ configurations. Here the radii } R_1 \text{ and } R_2 \text{ are equal, } R \text{ is the unified representation of them. The inset shows a magnification of some curves when } R = 0.12 \mu m. \]

...
absorptions of the $R_1 = R_2$ and $R_1 < R_2$ are nearly the same when $\lambda < 0.55 \mu m$. This is attributed to the high absorption coefficient of silicon material in the short wavelengths. And the minor difference between the two absorption spectra at the short wavelengths is owing to the different dimensions of the upper layer Ag NPs in the two kinds of systems. However, the absorption of $R_1 < R_2$ has an obvious enhancement at the long wavelengths, which is ascribed to two reasons. First is that the Ag NPs with uniform size are more likely to localize the light interact between the upper and lower Ag NPs layers. While the $R_1 < R_2$ configuration makes it easier to couple the light into the active layer. Second is that the lower layer NPs in the $R_1 < R_2$ system are the

![Graph](image-url)
larger particles. And the larger ones contribute to providing the plasmonic enhancement at longer wavelengths, which is beneficial to increase the light absorption. Figure 5(b) illustrates the short-circuit currents for the planar system- Ref, the solar cell with uniform NPs radii ($R_1 = R_2$) and the solar cell with varying NPs radii ($R_1 < R_2$). The $J_{sc}$ of the solar cell $R_1 < R_2$ presented in our paper is 84.7% and 9.97% higher than that of the planar system and the $R_1 = R_2$ counterpart, respectively.

To investigate effects of light trapping in the structures, the Intergraded Quantum Efficiency (IQE) is calculated according to the following equations:

$$IQE = \frac{\int \frac{\lambda}{hc} QE(\lambda) I_{AML5}(\lambda) d\lambda}{\int \frac{\lambda}{hc} I_{AML5}(\lambda) d\lambda}.$$
Where $I_{AM1.5}$ is reference solar spectral irradiance, $P_{abs}$ is the power absorbed by silicon, $P_{in}$ is the incident power, $h$ is Planck’s constant, and $c$ is the velocity of light. Figure 5(c) shows the calculated IQE of the reference, $R_1 = R_2$ and $R_1 < R_2$ solar cells. Compared with the reference cell, the IQEs of solar cells $R_1 = R_2$ and $R_1 < R_2$ increase by 68.0%, and 84.7%, respectively. The solar cell $R_1 < R_2$ exhibits a remarkable 9.94% improvement in IQE compared with the solar cell $R_1 = R_2$.

Figure 6 illustrates the normalized scattering ($Q_{scat}$) and the absorption ($Q_{abs}$) cross section for plasmonic solar cells with bilayer Ag NPs, calculated by monitor array and total field scattered field plane wave source supplied by FDTD [19, 26]. $Q_{scat}$ and $Q_{abs}$ reflect the scattering and absorption ability of Ag NPs, respectively. Although $Q_{abs}$ in the solar cells $R_1 = R_2$ and $R_1 < R_2$ are slightly different, both of them are relatively low, indicating low light absorption of Ag NPs. As for the scattering cross section, $Q_{scat}$s are enlarged when the sizes of metal NPs are much smaller than the exciting wavelengths. $Q_{scat}$ of Ag NPs in the solar cell $R_1 < R_2$ is significantly larger than that of the solar cell $R_1 = R_2$ in the wavelength ranges 0.4–0.62 $\mu$m and 0.78–1.1 $\mu$m.

As is well known, there are many traditional working principles of Ag NPs [15]. First, the energy from surface plasmons is emitted as light and scattered back into the absorber layer [27], increasing the optical path length in silicon and leading to enhanced absorption. Second, surface plasmons excitation enhances the localized electric field, leading to enhanced absorption due to the high density of photon states [16]. However, the working principles of double layer Ag NPs with different particle sizes are not explicit. To intuitively understand the physics behind the ultimate device for optical absorption enhancement, the electric-field intensity profiles are analyzed in detail. As demonstrated in figure 7(a), the domains with high electric field intensity are distributed in the SiO$_2$ layer. Owning to the Ag NPs with uniform size. The uniform NPs are more likely to localize the light interact between the upper and lower Ag NPs layers. While the $R_1 < R_2$ configuration makes it easier to couple the light into the active layer, thus the electric field intensity in SiO$_2$ layer of the $R_1 < R_2$ system is weak. This also is one of the reasons why the light transmission loss in $R_1 < R_2$ system is reduced (see figure 7(b)). The second reason to explain the reduction in light transmission loss in $R_1 < R_2$ system lies in the backscattering of the lower layer Ag NPs with larger particle size, which plays an important role in enhancing the scattered light and decreases light transmission of the solar cell. In addition, as is shown in figure 7, the electric field domains inside
the active layer in both systems are regular but discrete. But it is obvious that the light absorption is greatly improved in almost the entire photoactive region in the $R_1 < R_2$ system compared to the $R_1 = R_2$ counterpart. This is attributed to three reasons. First is the synergy between the upper and lower layer Ag NPs with different particle sizes. The smaller particles are placed in the upper layer to enhance the light absorption at shorter wavelengths, while the larger particles are employed in the lower layer for providing the plasmonic enhancement at longer wavelengths, since an increase in particle size causes a red shift in the resonance frequency. Second is that the $R_1 < R_2$ configuration breaks the geometric symmetry of the structure to some extent, contributing to the generation of resonant modes [28]. The third one lies in the reduction in light transmission loss in the $R_1 < R_2$ system.

5. Conclusion

In summary, we presented a new style of bilayer Ag NPs with different particle sizes for the light trapping in thin film crystalline silicon solar cells. The smaller particles are placed in the upper layer to enhance the light absorption at shorter wavelengths, and the larger particles are employed in the lower layer for providing the plasmonic enhancement at longer wavelengths. The interaction between the upper and lower NPs layers contributes to the absorption enhancement. In addition, the backscattering of the double layer Ag NPs with different particle sizes enhances the diffused scattered light and decreases the light transmission, which plays a dominant role in improving the light trapping inside the solar cell. Therefore, the design put forward in this paper shows a 9.97% increase in short-circuit current density and a 9.94% increase in integrated quantum efficiency across the solar spectrum compared with the optimized counterpart decorated with uniform Ag NPs. In addition, the $I_{sc}$ also shows a 1.87% increase by adding a 0.1 $\mu$m thick Ag back-reflector placed below the lower Ag NPs layer of the structure with different particle sizes. As is well known, the surface plasmon resonance depends on the particle shape as well as the refractive indices of surrounding media. Hence, our future work will focus on varying the shape of NPs and investigating the dielectric environment of Ag NP multilayer structures.

Acknowledgments

The authors greatly acknowledge the support from the National Natural Science Foundation of China (NSFC) (Grant Nos. 61474115, 61504138 and 61274066).

ORCID iDs

Shuyuan Zhang © https://orcid.org/0000-0002-8439-3264

References

[1] Catchpole K R and Polman A 2008 Design principles for particle plasmon enhanced solar cells Appl. Phys. Lett. 93 191113
[2] Catchpole K R and Polman A 2008 Plasmonic solar cells Opt. Express 16 21793–800
[3] Beck F J, Polman A and Catchpole K R 2009 Tunable light trapping for solar cells using localized surface plasmons J. Appl. Phys. 105 114310
[4] Krishnan A, Das S, Krishna S R and Khan M Z A 2014 Multilayer nanoparticle arrays for broad spectrum absorption enhancement in thin film solar cells Opt. Express 22 1800–11
[5] Mendes M J, Morawiec S, Simone F, Priolo F and Crupi I 2014 Colloidal plasmonic back reflectors for light trapping in solar cells Nanoscale 6 4796–805
[6] Shokeen P, Singh Y P, Jain A and Kapoor A 2015 Enhanced performance of thin-film solar cell by metallic nanostructural vertical dual model J. of Nanophotonics 9 093066
[7] Manali L, Rezgui B D, Zaghouni R B, Barakel D, Torchio P, Palais O and Bessais B 2016 Tuning of light trapping and surface plasmon resonance in silver nanoparticles/c-Si structures for solar cells Plasmonics 11 1273–7
[8] Dabirian A, Byranvand M M, Naqavi A, Kharat A N and Taghavinia N 2016 Self-assembled monolayer of wavelength-scale core–shell particles for low-loss plasmonic and broadband light trapping in solar cells ACS Appl. Mater. Interfaces 8 247–55
[9] Yuan M, Zhou N, Li D and Yang D 2018 The desirable reflection-enhanced lumpy silver particle and its application in thin film amorphous silicon solar cell J. Mater. Sci., Mater. Electron. 29 3153–9
[10] Wang Z X, Sun C and Wang X Q 2017 Modification of front surface antireflection of silicon solar cells with composite metallic nanoparticle arrays Plasmonics 12 589–96
[11] Mopuriysetty M S, Bajaj M and Ganguly S 2016 Beyond optical enhancement due to embedded metal nanoparticles in thin-film solar cells Appl. Phys. Express 9 032301
[12] Sun C, Wang Z X, Wang X Q and Liu J 2016 A surface design for enhancement of light trapping efficiencies in thin film silicon solar cells Plasmonics 11 1003–10
[13] Sun C and Wang X Q 2015 Efficient light trapping structures of thin film silicon solar cells based on silver nanoparticle arrays Plasmonics 10 1307–14
[14] Pillai S, Catchpole K R, Trupke T and Green M A 2007 Surface plasmon enhanced silicon solar cells J. Appl. Phys. 101 093105
[15] Atwater H A and Polman A 2010 Plasmonics for improved photovoltaic devices Nature Mater. 9 205–13
[16] Pillai S and Green M A 2010 Plasmonics for photovoltaic applications Sol. Energy Mater. Sol. Cells 94 1481–6
[17] Beck F J, Mokkapati S and Catchpole K R 2011 Light trapping with plasmonic particles beyond the dipole model Opt. Express 19 25230–41
[18] Saleh Z M, Nasser H, Özkol E, Günöven M, Altuntas B, Bek A and Turan R 2014 Enhanced optical absorption and spectral photocurrent in a-Si:H by single- and double-layer silver plasmonic interfaces Plasmonics 9 357–65
[19] Shi Y P, Wang X D, Liu W, Yang T S, Xu R and Yang F H 2013 Multilayer silver nanoparticles for light trapping in thin film solar cells J. Appl. Phys. 113 176101
[20] Ho C-I, Yeh D-J, Su V-C, Yang C-H, Yang P-C, Pu M-Y, Kuan C-H, Cheng I-C and Lee S-C 2012 Plasmonic multilayer nanoparticles enhanced photocurrent in thin film hydrogenated amorphous silicon solar cells J. Appl. Phys. 112 023113
[21] Choi H, Lee I P, Ko S J, Jung J W, Park H, Yoo S, Park O, Jeong J R, Park S and Kim J Y 2013 Multipositional silica-coated silver nanoparticles for high-performance polymer solar cells Nano Lett. 13 2204–8
[22] Lumerical Solutions, Inc. (http://lumerical.com/tcad-products/fdtd/)
[23] Starowicz Z, Kulesza-Matlak G and Lipiski M 2015 Optimization studies on enhanced absorption in thin silicon solar cell by plasmonic silver nanoparticles for the front side configuration Plasmonics 10 1639–47
[24] ASTM (http://rredc.nrel.gov/solar/spectra/am1.5/)
[25] Shi Y P, Wang X D, Liu W, Yang T S, Ma J and Yang F H 2014 Nanopyramids and rear-located Ag nanoparticles for broad-spectrum absorption enhancement in thin-film solar cells Opt. Express 22 20473–80
[26] Xu R, Wang X D, Song L, Liu W, Ji A, Yang F H and Li J 2012 Influence of the light trapping induced by surface plasmons and antireflection film in crystalline silicon solar cells Opt. Express 20 5061–8
[27] Stuart H R and Hall D G 1998 Island size effects in nanoparticle-enhanced photodetectors Appl. Phys. Lett. 73 3815
[28] Zhang S Y, Liu M, Liu W, Li Z F, Liu Y S, Wang X D and Yang F H 2017 High-efficiency photon capturing in ultrathin silicon solar cells with double-sided skewed nanopyramid arrays J. Opt. 19 105901