Enhanced absorption of Ag diamond-type nanoantenna arrays[*]

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The optical metal nanoantenna on thin film solar cell is effective to enhance light absorption. In this paper, the diamond-type Ag nanoantenna arrays are proposed for increasing the efficiency of solar cells by localized surface plasmons resonance (LSPR). The effect of metal nanoantenna on the absorption enhancement is theoretically investigated by the finite difference time domain (FDTD) method. Broadband absorption enhancements in both visible and near-infrared regions are demonstrated in case of solar cell with diamond-type Ag nanoantennas. The spectral response is manipulated by geometrical parameters of the nanoantennas. The maximum enhancement factor of 1.51 for solar cell is obtained. For comparison, the other three nanoantennas are also analyzed. The results show that the solar cell with optimized diamond-type nanoantenna arrays is more efficient in optical absorption.

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In order to improve the efficiency of the thin film solar cell, several approaches have been used to successfully improve light absorption in optically-thin semiconducting films. For example, one method attempts to reduce the reflection of light at the top surface of the solar cells through the use of an SiNx antireflection coating (ARC)[1,2]. However, it cannot prevent the transmission of light through a very thin photovoltaic layer. Another example is to use a distributed Bragg reflector at the rear of the cell for extending the optical path length. But the solar cell with back reflector may suffer from the back surface recombination loss[3].

Using plasmonic noble-metal nanoantennas is a more effective method to enhance fluorescence[4] and luminescence[5] and to increase the optical absorption due to their strong light scattering properties[6]. Metallic nanoantennas, which support localized surface plasmon resonance (LSPR), have demonstrated the ability of improving the light absorption in the solar cell significantly[7]. The properties of metallic optical nanoantennas are dependent on the highly local field feature of metallic nanoparticles and the radiation characteristics of antenna structures[8]. When incident light interacts with metallic nanostructures, it results in LSPR. Electromagnetic fields localize on the metal surface to form a field enhancement and increase the optical path length within the solar cell. Metal nanoantennas have been extensively studied, and the most popular antenna is the dipole antenna. Many

nanostructures, such as dipole antenna[9], bow-tie antenna[10], V-shaped antenna[11], and cross resonant antenna[12], have been designed to achieve preferable effects of field enhancement and localization. These structures show the enormous potential application in high efficiency solar cell in theory. However, few of them are applied in the solar cell in practice due to the difficulty of fabrication. The common used shapes of nanoparticles are sphere[13], cylinder[14] and bow-tie[10]. Though these nanostructures applied in solar cells display better performance compared with the conventional solar cell, it is a useful work to study more effective and feasible optical nanoantenna application in solar cell and develop new nanostructure for higher efficient thin film solar cell.

In this paper, a novel type of light-trapping nanostructure based on diamond-type nanoantenna arrays is proposed. The effect of the nanoantennas on optical absorption enhancement in silicon layer of solar cell is discussed in detail. A careful study is taken for the optimization process of the parameters of diamond-type Ag nanaoparticles and their distribution period. The physical mechanism behind the absorption enhancement is also discussed. Moreover, a comparison for the solar cells with rhomboid-type Ag nanoantennas, cylindrical Ag nanoparticles, Si$_3$N$_4$ ARC, both Si$_3$N$_4$ and rhomboid-type nanoantennas is presented.

Fig.1 shows the schematic diagram of the investigated structures. Fig.1(a) illustrates the overall view of the

structure, and Ag nanoantennas are uniformly distributed on the silicon layer with the thickness of 500 nm. L and h represent the side length and the height of diamond-type Ag nanoantenna, respectively. P_x and P_y are the periods of the nanoantenna array in x and y directions, respectively, and t is the thickness of the silicon layer. The top view of the diamond dipole nanoantennas is depicted in Fig.1(b), where θ represents an apex angle of the diamond. Ag is used as the metal material because it has the obvious LSPR effects as well as low light absorption. The optical properties of silicon and Ag are all from Ref.[15].
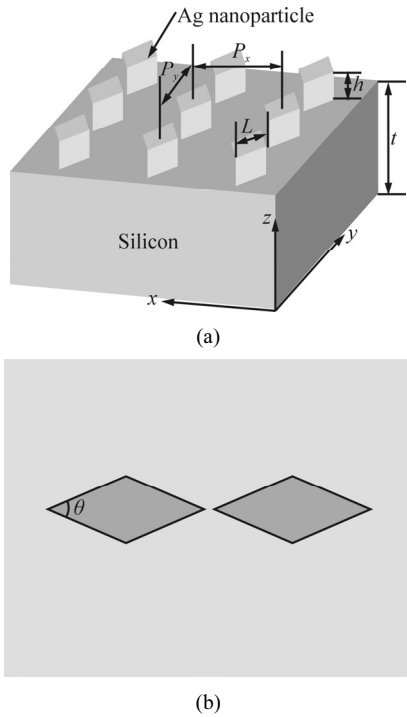

(a)

(b)

Fig.1 (a) The structure of thin-film solar cell with Ag nanoantenna arrays; (b) Top view of the diamond nanoantenna

A commercial software of Lumerical FDTD Solutions is adopted for the numerical simulations. The incident source produces a uniform plane wave with a wavelength range from 400 nm to 1 100 nm, and the electric field is polarized along the x-axis. Perfectly matched layer (PML) absorbing boundary conditions are used in the incident direction to prevent the interference effect. Periodic boundary conditions are used at the lateral (x-y) boundaries of the simulation volume. Two power monitors are used for calculating the power absorbed in the silicon. One is located at the surface of the silicon, and the other is located at the bottom. In following paragraphs, the absorption of solar cell refers to the absorption in silicon layer particularly, and the bare solar cell is the one without any light trapping structure.

The integrated quantum efficiency (*IQE*) is used to estimate the efficiency of the solar cell, which is defined as

$$IQE(\lambda) = \frac{\int \frac{\lambda}{hc} \frac{P_{abs}(\lambda)}{P_{in}(\lambda)} I_{AM1.5}(\lambda)\mathrm{d}\lambda}{\int \frac{\lambda}{hc} I_{AM1.5}(\lambda)\mathrm{d}\lambda}, \qquad (1)$$

where h is Plank's constant, c is the speed of light in the free space, $I_{AM1.5}$ is AM 1.5 solar spectrum, and $P_{in}(\lambda)$ and $P_{abs}(\lambda)$ are the incident light and absorbed light within solar cell at the wavelength of λ, respectively. In Eq.(1), the numerator is equal to the number of photons absorbed by the solar cell, while the denominator means the number of photons falling onto the solar cell. The AM 1.5 solar spectrum $I_{AM1.5}$ is taken from Ref.[16]. For comparing the light absorption efficiency of the solar cell with metal nanoantennas with that of the bare solar cell, the absorption enhancement factor G is calculated. The absorption enhancement factor G is defined under the assumption that each absorbed photon with energy greater than the band gap produces one and only one electron-hole pair, which is given by

$$G = \frac{IQE_{particle}}{IQE_{bare}} = \frac{\int \lambda P_t(\lambda) I_{AM1.5}(\lambda)\mathrm{d}\lambda}{\int \lambda P_{bare}(\lambda) I_{AM1.5}(\lambda)\mathrm{d}\lambda}, \qquad (2)$$

where $P_t(\lambda)$ and $P_{bare}(\lambda)$ represent the light absorption power spectra of silicon layer with and without metal nanoantennas, respectively. $IQE_{particle}$ and IQE_{bare} are the whole powers absorbed by the silicon with and without Ag nanantennas, rspectively.

Fig.2 shows the enhancement factor G versus the period of the diamond-type nanoantennas in x and y directions when the apex angle of the diamond is θ=60°. Because two diagonals of the diamond may be not equal, two different types of the period distributions are discussed. As can be seen from Fig.2(a), when P_y=100 nm, with the increase of period along the x-axis deriection, G value increases until reaches a maximum, then it begins to decrease gradually. The maximum G is 1.34 at P_x=80 nm. Fig.2(b) shows the same trend as that shown in Fig.2(a), and the difference is that the variables on the horizontal axis are P_y and the fixed period in x-deriection P_x=100 nm. The maximun G is 1.37 at P_y=110 nm. This is bacause the change of the period leads to the filling ratio changes for the fixed diamond dimension, and then the near-field electromagnetic fields arising from nanoantennas can be influenced as well as LSPR effects.
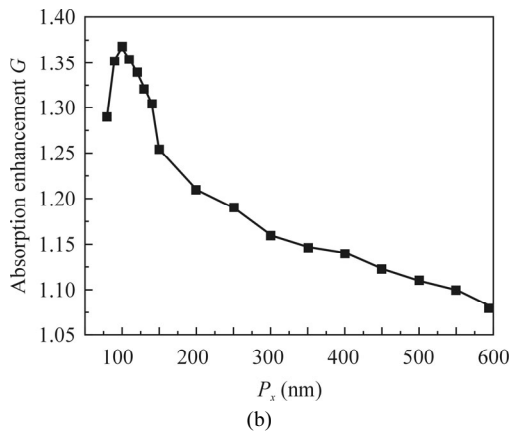

(a)

(b)
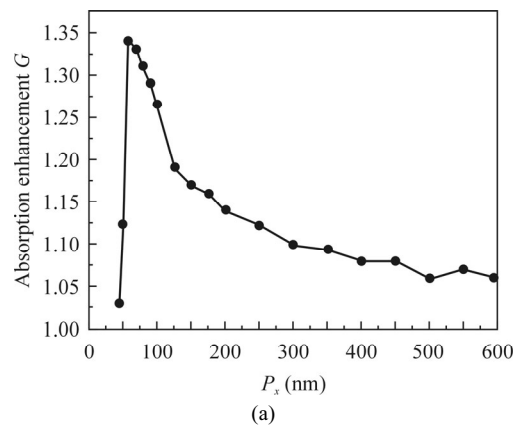
Fig.2 (a) Enhancement factor *G* versus the period in *x*-direction of arrays with P_y=100 nm, *L*=45 nm and *h*=60 nm; (b) Enhancement factor *G* versus the period in *y*-direction of arrays with P_x=100 nm, *L*=45 nm and *h*=60 nm

Fig.3 shows the factor enhancement *G* versus height *h* at fixed P_x=P_y=100 nm and *L*=45 nm and versus side length *L* at fixed P_x=P_y=100 nm and *h*=60 nm, respectively. The apex angle is 45° in this case. As shown in Fig.3(a), the *G* value increases with the increase of height until it reaches the maximum, and then it begins to decrease dramatically. The maximum *G* is obtained when the strongest LSP resonance is achieved. The optimal enhancement factor *G* is 1.36, corresponding to *h*=60 nm. Fig.3(b) shows the relation between absorption enhancement factor *G* and the side length. The results show the similar trend to that shown in Fig.3(a). The dimension of antenna changes along with varied side length, and then leads to the fill factor changes, which is responsible for the trend in Fig.3(b). The maximum *G* is 1.36 at *L*=45 nm.

Fig.4 illustrates the results of absorption spectra with different apex angles, and the inset of Fig.4 shows the absorption enhancement *G* versus the apex angle. It can be seen from Fig.4 that the maximum absorption goes up along with the increase of apex angle, but the corresponding wavelength position is not changed. As the apex angle increases, the absorption peak appears in the near-infrared region due to LSPR effect which is excited by Ag nanoantennas. The light absorption is enhanced greatly as well. The results indicate that the apex angle of the diamond plays an important role in enhancing light absorption, and there is an optimal apex angle at which *G* gets the maximum value.

Furthermore, the bare solar cells with Si_3N_4 layer, periodic cylindrical nanoparticles, both Si_3N_4 and diamond-type nanoantennas are considered respectively for comparison. Si_3N_4 layer is placed on the top of the silicon layer and serves as the ARC to enhance the light absorption. The thickness of the ARC is set to be 75 nm, and the maximum light transmission in the silicon layer is around λ=600 nm, which is the approximate peak of the AM-1.5 solar spectrum[17]. With the same optimization process,

the maximum *G* is 1.33 for the solar cell with periodic cylindrical nanoparticles when *h*=80 nm, *r*=40 nm and *p*=160 nm. Moreover, the combination of the optimized diamond nanoantennas and Si_3N_4 ARC which are discussed above is another light trapping structure. Fig.5 shows the reflection and transmittance spectra of solar cells with different light trapping structures and bare solar cell.
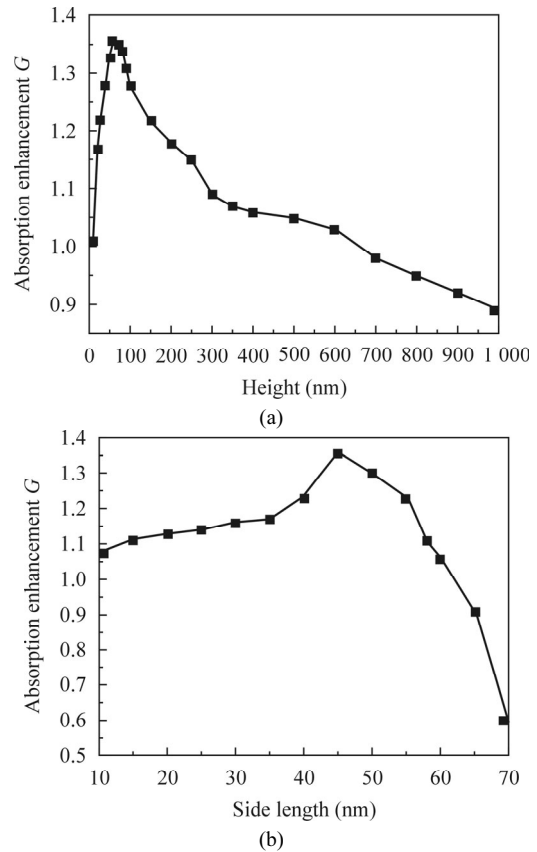

(a)

(b)

Fig.3 Variations of the enhancement factor *G* with (a) height and (b) side length of diamond
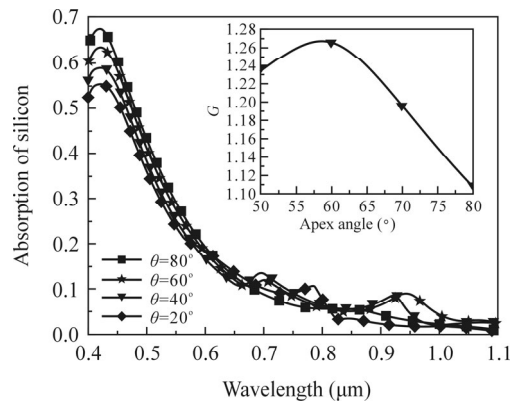

Fig.4 Absorption spectra with different apex angles when P_x=P_y=100 nm, *L*=45 nm and *h*=60 nm (The inset is the absorption enhancement *G* versus apex angle.)

Fig.5(a) shows that the reflectivity of solar cell with Si_3N_4 layer is much lower than that of bare solar cell. And

the reflectivities of solar cells with cylindrical and diamond Ag nanoparticles are much lower than that of the bare solar cell in the visible region, while are much higher in the near-infrared region. It is attributed to the high reflectivity of Ag nanoparticles and the LSPR effects arising from metal nanoparticles. In particular, the solar cell with both Si_3N_4 and diamond nanoantennas shows the lowest reflectivity. This feature can be explained by two main effects: one is the predominant scattering of light into the high refractive index substrate, and the other is the change in phase of the scattered light near the LSPR wavelength. Fig.5(b) shows the transmittance spectra of five types of solar cells corresponding to Fig.5(a). In Fig.5(b), the transmittances of solar cells with cylindrical and diamond Ag nanoparticles are much lower than that of bare solar cell in the near-infrared region. Meanwhile, the transmittance of the solar cell with both Si_3N_4 and diamond nanoantennas is higher in the near-infrared region compared with that of bare solar cell. Fig.6 shows the absorption spectra of the solar cells with different light trapping structures corresponding to Fig.5.
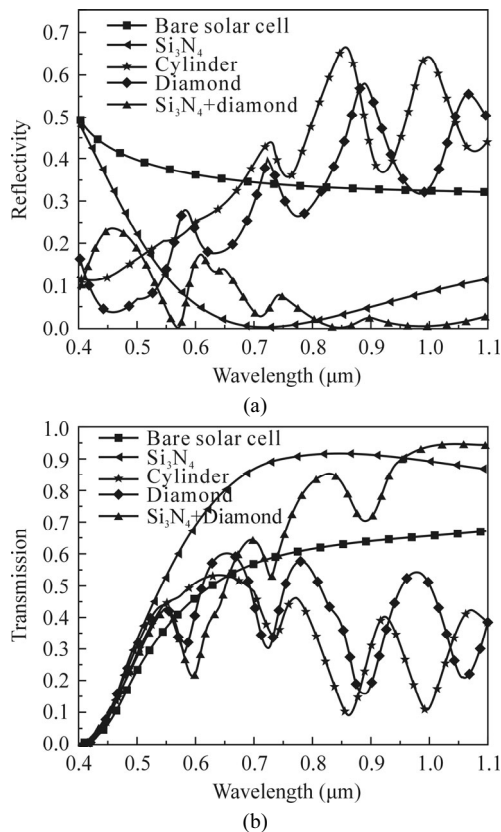

(a)

(b)

Fig.5 (a) Reflection and (b) transmission spectra of solar cells with different light trapping structures

It can be observed from Fig.6 that the solar cells with light trapping structures have more optical absorption compared with the bare solar cell. The solar cell with diamond-type nanoantennas attains the largest absorption over the entire region, especially in near-infrared region. The maximum absorption is up to 0.66 at λ=785 nm, and

G value is 1.51. Cylindrical Ag nanoparticles can also enhance the light absorption greatly, and its maximum G value is 1.33. A universal behavior is observed, which is the metal nanoantenna can enhance the optical absorption in near-infrared region significantly, due to the LSPR effects and the large scattering cross-sections of metal particles. Si_3N_4 just enhances the absorption in visible region, but has little contribution in near-infrared region, and the enhancement factor is G=1.26. The absorption enhancement of the solar cell with both diamond nano-antennas and Si_3N_4 is not obvious as expected. The G value is 1.12. As demonstrated here, simply putting plasmonic nanoparticles on the top of the conventional ARC may reduce the performance compared with they work alone. The ARC and metal nanoantennas should be optimized simultaneously as a combined system. The results demonstrate that diamond-type Ag nanoantenna arrays outperform other light trapping structures in enhancing light absorption in thin film solar cell.
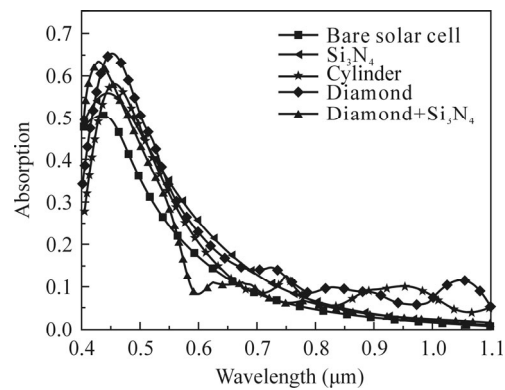

Fig.6 Absorption spectra of solar cells with different light trapping structures with optimal parameters

In this paper, an approach for enhancing the light absorption in thin film solar cell by placing diamond-type Ag nanoantenna arrays on the top of the solar cell is proposed. The absorption enhancement of the silicon layer with the diamond-type nanoantenna arrays is numerically investigated. The presence of the Ag nanoantennas is demonstrated to greatly enhance light absorption over a broad range of wavelengths, especially in near-infrared region due to LSPR effects. The optimization process of the parameters of diamond-type nanoantennas is presented. The maximum enhancement factor G=1.51 is obtained when h=60 nm, L=45 nm, P_x=30 nm, P_y=110 nm and θ=30°. For comparison, the solar cells with other three types of light trapping structures of Si_3N_4 ARC layer, cylindrical Ag nanoparticles, both Si_3N_4 and diamond-type nanoantennas are proposed. The reflectance, transmittance and absorption spectra for solar cells with different types of light trapping structures are discussed in detail. The better performance of solar cell with diamond-type nanoantenna arrays for light absorption is determined from the comparison. This approach can be applied to a variety of

solar cells operating in the visible and infrared frequency range for designing thin film solar cells with higher efficiency.

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