Absorption Enhancement of Thin-film Solar Cell with Rectangular Ag Nanoparticles

1,2Zongheng Yuan, 1Xiaolan Li and 3Huang Jing
1School of Electronic Engineering and Automation, Guilin University of Electronic Technology, Guilin, 541004, China
3School of Information Engineering, Guizhou Minzu University, Guiyang, 550025, China

Abstract: Solar power has gained a great deal of attention as a clean energy source with the potential to replace fossil fuel. Researchers have focused on increasing the efficiency of thin film solar cells. In this study, rectangular Ag nanoparticles were placed on the silicon layer of a silicon solar cell. The absorption enhancement of the silicon was systematically investigated via the Finite Difference Time Domain Method (FDTD). The improvement in silicon absorption of the solar cell because of the addition of Ag nanoparticles was studied by calculating the enhancement factor by using the Numerical FDTD solutions simulation package. The results demonstrated that the light absorption was significantly improved because of the localized surface plasmon resonance of the Ag nanoparticles. The structure with rectangular Ag nanoparticles obtained the most efficient absorption enhancement compared with the sphere and cylinder Ag nanoparticles. The effects of nanoparticle parameters on the absorption enhancement were also thoroughly analyzed. The optimal absorption enhancement was achieved by adjusting the parameters of nanoparticles. The structure may be used to develop highly efficient thin film solar cells.

Key words: Thin-film solar cell, nanoparticles, FDTD, absorption enhancement

INTRODUCTION

Solar energy is one of renewable and clean energy sources that can be changed to the electrical energy with photovoltaic which has the potential to successfully replace the fossil fuel for electrical power generation (Bahrami et al., 2013; Gavin, 2007). However, currently most of the cost of a solar module made from crystalline is the cost of the silicon wafers (Catchpole and Polman, 2008). In order to save material and reduce costs, high efficiency thin film solar cell has been become the focus of research of the solar cell. Compared with the conventional solar cell, thin film solar cell has the thinner semiconductor absorbing layer. Meanwhile, due to the typically weak absorption of the silicon, these may result in inefficient absorption and low device efficiency (Chopra et al., 2004). Therefore, a better design of the device structure is crucial for light trapping and enhancing photocurrent.

In recent years, a great number of studies on enhancing optical absorption and device efficiency have been carried out. Various methods for enhancing the absorption of the thin film solar cell have been proposed (Xu et al., 2012; Cortes-Juan et al., 2013; McPheeters and Yu, 2012; Kuo et al., 2012; Li et al., 2012). Silicon nanowire arrays are set as an antireflection film to reduce the surface reflection and then increase the light absorption (Lin and Povinelli, 2009). Another important way is to use the textured back reflector for enhancing light trapping (Wiesendanger et al., 2013; Song et al., 2011). The textured back reflectors have been proposed for extending the optical path length and scatter light from the bottom boundary (Zeng et al., 2006). But the solar cell with back reflector may suffer from the back surface recombination loss. A nanostructure which is placed on the top surface of a solar cell, is an effective method (Tsai et al., 2010). The use of metallic nanostructures could cause the excitation of Localized Surface Plasmon (LSP). When the surface plasmon resonance occurs, the light absorption in the solar cell significantly improved (Kim et al., 2012). It has been demonstrated that the use of metal nanostructures in solar cells could produce stronger field and greater absorption enhancement (Zheng et al., 2012; Scholl et al., 2012). However, the light absorption in the solar cell sometimes overestimated (Bai et al., 2009). This phenomenon occurs because in addition to the absorption layer, some other materials can absorb light as well but do not contribute to the photocurrent.

Corresponding Author: Zongheng Yuan, School of Electronic Engineering and Automation, Guilin University of Electronic Technology, Guilin, 541004, China
(Chao et al., 2010). Only light absorbed by the absorption layer can contribute to the external electricity, so it is not suitable to estimate the efficiency of the solar cell just by the whole absorption of the cell. Thus, it is important to analyse the absorption in the absorption layer of the thin film solar cells in detail.

In this study, the absorption enhancement of silicon layer in solar cell with rectangular Ag nanoparticles has been discussed in detail by using Numerical FDTD Solutions. A detailed analysis and interpretation have also been made for the absorption enhancement phenomenon.

**MATERIALS AND METHODS**

Figure 1 is the structures used for the simulation study. The Ag cuboids are deposited on the surface of the silicon substrate. In Fig. 1, \( h \) represents the height of the rectangular particles, \( L \) represents the side length of the base of the rectangular particles, \( p \) is the period of the nanoparticle array and \( t \) is the thickness of the silicon substrate. Ag is used as the metal material because it has the obvious LSP effects as well as low light absorption. Since the wide application of monocrystalline silicon solar cells, silicon is selected as the absorbing layer. The optical parameters of silicon and Ag are from (Palík, 1991).

Numerical FDTD Solutions is adopted for the numerical simulations. The incident source is a uniform plane wave with a wavelength range from 400 to 1100 nm which the electric field is polarized along the \( x \)-axis. Perfectly Matched Layer (PML) absorbing boundary conditions are used on the upper and bottom boundaries of the computational domain that absorb the reflected and transmitted fields. Two power monitors are used for calculating the power absorbed in the silicon and one is located at the surface of the silicon, another is located at the bottom. Thus, the absorbed power can be easily calculated by subtraction between them.

In order to estimate the solar cell efficiency. The quantum efficiency of a solar cell, \( \text{QE}(\lambda) \), is defined as:

\[
\text{QE}(\lambda) = \frac{P_{\text{abs}}(\lambda)}{P_{\text{inc}}(\lambda)}
\]

(1)

where, \( P_{\text{inc}}(\lambda) \) and \( P_{\text{abs}}(\lambda) \) is the incident light power and absorbed light power within the silicon solar cell respectively at a wavelength \( \lambda \). Meanwhile, using the integrated quantum efficiency, \( \text{IQE} \) is defined as:

\[
\text{IQE}(\lambda) = \frac{\int \text{QE}(\lambda) I_{\text{ext}}(\lambda) d\lambda}{\int I_{\text{inc}}(\lambda) d\lambda}
\]

(2)

where, \( I_{\text{inc}}(\lambda) \) is the spectrum of the intensity of the incident light, \( I_{\text{ext}}(\lambda) \) is the spectrum of the external quantum efficiency, \( \lambda_{	ext{ext}} \) is the wavelength of the external quantum efficiency.

![Fig. 1: Structure of solar cell with cuboid Ag nanoparticle arrays](image)

where, \( h \) is Plank’s constant, \( c \) is the speed of light in the free space and \( I_{\text{AM1.5}} \) is AM 1.5 solar spectrum. In Eq. 2, 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 sun spectrum \( I_{\text{AM1.5}} \) is taken from (ASTM G173-03, 2003). The absorption enhancement spectrum \( g(\lambda) \) and absorption enhancement factor \( G \) are used to see how the light absorption efficiency of the solar cell with metal particles is improved compared with a bare solar cell. Here, the absorption enhancement spectrum \( g(\lambda) \) and absorption enhancement factor \( G \) are defined as:

\[
g(\lambda) = \frac{\text{QE}_{\text{metal}}(\lambda)}{\text{QE}_{\text{ext}}(\lambda)} = \frac{P_{\text{abs}}(\lambda)}{P_{\text{inc}}(\lambda)}
\]

(3)

And:

\[
G = \frac{\text{IQE}_{\text{metal}}}{\text{IQE}_{\text{ext}}} = \frac{\int \lambda P_{\text{abs}}(\lambda) I_{\text{AM1.5}}(\lambda) d\lambda}{\int \lambda P_{\text{inc}}(\lambda) I_{\text{AM1.5}}(\lambda) d\lambda}
\]

(4)

where, \( \text{IQE}_{\text{metal}} \) is the integrated quantum efficiency of the silicon with Ag nanoparticles and \( \text{IQE}_{\text{ext}} \) is the integrated quantum efficiency of the silicon without Ag nanoparticles, \( P_{\text{inc}}(\lambda) \) and \( P_{\text{abs}}(\lambda) \) represent the light absorption of silicon layer with and without periodic metal particles at the wavelength \( \lambda \), respectively.

**RESULTS AND DISCUSSION**

In this section, the optimization process of the structures is performed by systematically varying the
Fig. 2(a-b): At \( p = 100 \text{ nm}, \ L = 44 \text{ nm}, \ t = 500 \text{ nm} \), (a) Absorption of silicon with height of the rectangular Ag nanoparticles and (b) Relationship of the absorption enhancement factor \( G \) with the height of the rectangular Ag nanoparticles.

**Effect of height and period on the absorption:** Figure 2 are the curves of the absorption of silicon and absorption enhancement when \( p = 100 \text{ nm}, \ L = 44 \text{ nm}, \ t = 500 \text{ nm} \). Figure 2a shows that from \( h = 60 \) to \( 700 \text{ nm} \), the wavelength position of absorption peak red shifts and the peak value decreases with the increase of the height. When the height is over \( 700 \text{ nm} \), the absorption becomes much lower than that of the bare solar cell. The cause is that as the height increases, the phase shift between the scattering field and the incident field changes periodically.

Fig. 3(a-b): (a) Absorption spectrum of silicon with period of the Ag nanoparticles, at \( L = 50 \text{ nm}, \ h = 60 \text{ nm}, \ t = 500 \text{ nm} \) and (b) Relation of the absorption enhancement factor \( G \) with period of Ag nanoparticles at \( h = 60 \text{ nm}, \ t = 500 \text{ nm} \).

(Bohren and Huffman, 2008) and weakens the electromagnetic field. Besides, Ag nanoparticles absorb more light as the height increases which result in poor absorption of silicon. From Fig. 2a, it can also been seen that in the near-infrared wavelength range, the absorption peaks are enhanced greatly which are influenced by scattering effects due to LSP resonance of Ag particles. Figure 2b shows that the absorption enhancement factor \( G \) becomes greater firstly with the increase of the height, then decreases. At \( h = 60 \text{ nm} \), \( G \) gets a maximum value of 1.35.

Figure 3 is the diagrams of the absorption with the period of the Ag nanoparticles. Figure 3a shows that the position of the peak blue shifts and the peak value increases when the period increases from 75 to 125 nm,
Fig. 4: Relation of the absorption enhancement factor $G$ with base side lengths of the nano cuboid, when $p = 700 \text{ nm}$, $h = 60 \text{ nm}$, $t = 500 \text{ nm}$

Table 1: Optimal parameters of Ag nanoparticles and the corresponding to the maximum enhancement factor $G_{\text{max}}$ at $t = 500 \text{ nm}$

<table>
<thead>
<tr>
<th>Shape</th>
<th>Length (nm)</th>
<th>Height (nm)</th>
<th>Period (nm)</th>
<th>$G_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>75</td>
<td>150</td>
<td>400</td>
<td>1.28</td>
</tr>
<tr>
<td>Cylinder</td>
<td>40</td>
<td>80</td>
<td>160</td>
<td>1.33</td>
</tr>
<tr>
<td>Cuboid</td>
<td>45</td>
<td>60</td>
<td>100</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Meanwhile, more obvious absorption peaks appear in the near-infrared range which leads more light absorbed in the silicon. When $p = 50 \text{ nm}$, rectangular Ag nanoparticles array become a layer of Ag film and absorption of silicon is approximate to zero which means that less light can arrive the silicon layer. Figure 3b shows that the $G$ values change with period for fixed base side length and height of Ag particles. For each L value, the $G$ value always rises dramatically firstly, when it reaches a maximum then begins to decrease with the increase of the period. G has a maximum value of 1.32 at $p = 100 \text{ nm}$, $L = 50 \text{ nm}$ in Fig. 3b.

**Effect of base side length on the absorption of enhancement:** Figure 4 is the relation of the absorption enhancement factor $G$ with base side lengths of the nano cuboid. Figure 4 shows that the $G$ value increases with the increase of the base side length of the cuboids, until $G$ reaches a maximum then begins to decrease gradually. The maximum $G$ value is 1.06 at $L = 100 \text{ nm}$, $p = 700 \text{ nm}$, $h = 60 \text{ nm}$, $t = 500 \text{ nm}$.

**Comparisons:** In order to see the enhanced effect of the rectangular Ag particle, the absorption enhancement factors $G$ of the spherical and cylindrical Ag nanoparticles are also calculated by Eq. 4. Their maximal absorption enhancement factors ($G_{\text{max}}$) are obtained under the condition of their optimal parameters. The optimal parameters of Ag nanoparticles, $G_{\text{max}}$ are demonstrated in Table 1.

Table 1 shows that for silicon with spherical, cylindrical and rectangular Ag particles, in the case of the optimal parameters of Ag nanoparticles, when $t = 500 \text{ nm}$, their maximum $G_{\text{max}}$ are 1.276, 1.32 and 1.35, respectively. Obviously, the rectangular Ag nanoparticles have the greatest absorption enhancement of these three shapes Ag nanoparticles.

For comparison with previous work, the absorption enhancement factor is calculated when $t = 80 \text{ nm}$, $h = 65 \text{ nm}$ which is the same case with Rockstuhl's study (Rockstuhl and Lederer, 2009) and the enhancement of 1.86 is obtained. However, In his study, the Ag nanodics are used and the enhancement is approximately to 1.5 correspond to the same h and t. The comparison results show that a higher enhancement was achieved in our study when rectangular Ag nanoparticles were used at the condition of Rockstuhl's study (Rockstuhl and Lederer, 2009). The efficiency of thin film solar cells could be increased greatly by placing rectangular Ag nanoparticles on the silicon layer of a silicon solar cell.

**CONCLUSION**

The absorption enhancement of silicon layer in silicon solar cell with rectangular Ag nanoparticles is investigated by calculating the absorption enhancement spectrum and the absorption enhancement factor. The effects of parameters of rectangular Ag nanoparticles on the absorption enhancement have been demonstrated. The trend of absorption enhancement with different periods, heights and side lengths is convenient for finding the optimal parameters of nanostructure and optimizing the design of plasmonic solar cell. As a result, G has the maximum value of 1.35 at $p = 100 \text{ nm}$, $L = 44 \text{ nm}$, $h = 60 \text{ nm}$ in this study. Comparing with spherical, cylindrical Ag nanoparticles, the rectangular Ag nanoparticles can get the greatest absorption and absorption enhancement. This work is useful for the further study and optimization for the plasmonic thin-film solar cell.

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REFERENCES


