

Enhancement of light trapping in thin-film solar cells through Ag

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Forward-scattering efficiency (FSE) is first proposed when an Ag nanoparticle serves as the light-trapping structure for thin-film (TF) solar cells because the Ag nanoparticle's light-trapping efficiency lies on the light-scattering direction of metal nanoparticles. Based on FSE analysis of Ag nanoparticles with radii of 53 and 88 nm, the forward-scattering spectra and light-trapping efficiencies are calculated. The contributions of dipole and quadrupole modes to light-trapping effect are also analyzed quantitatively. When the surface coverage of Ag nanoparticles is 5%, light-trapping efficiencies are 15.5% and 32.3%, respectively, for 53- and 88-nm Ag nanoparticles. Results indicate that the plasmon quadrupole mode resonance of Ag nanoparticles could further enhance the light-trapping effect for TF solar cells.

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Light-trapping structures are very important for high-performance silicon solar cells because of their weak absorption at long wavelengths. For wafer-based cells, surface texture and anti-reflection coating light-trapping structures have been widely developed. However, for thin-film (TF) solar cells, which show promise for lowering the cost of power generation compared with bulk materials, conventional light surface textures which are 10 μm in size are not suitable for TF solar cells. Recently, the use of plasmonic metal nanoparticles has attracted much attention because of their surprising optical properties, leading to the expectation that they will become a new type of light-trapping structure^[1].

The interaction of incident light with metallic nanoparticles induces collective electron oscillations known as surface plasmon resonance (SPR), which results in greatly enhanced local fields and a strong scattering of incident light into the active region of solar cells. A remarkable increase in optical absorption has already been observed, which is highly desirable in the application of TF solar cells^[2,3]. Thus far, there have been several experimental investigations on the use of metal nanoparticles as a new type of light-trapping structure for TF solar cells^[4-7]. Pillai *et al.* investigated Ag nanoparticles enhanced silicon-on-insulator solar cells, which led to a 16-fold enhancement in photocurrent at $\lambda=1050$ nm^[2]. Schaadt *et al.* studied the Au nanoparticles SPR for enhancing the performance of amorphous silicon solar cells, which showed an 8.1% increase in short-circuit current density and an 8.3% increase in energy conversion efficiency^[3]. Nakayama *et al.* conducted research on Ag nanoparticles for improving light absorption in GaAs solar cells, which demonstrated a relatively enhanced ef-

iciency of 5.9%^[4]. By applying the Au nanoparticle cluster in triple-junction cell, Yang *et al.* obtained a 15.3% increase in energy conversion efficiency^[6]. Catchpole *et al.* developed a method to measure light-trapping efficiency in the view of path length enhancement^[8].

Metal nanoparticles are known to enhance the optical absorption of solar cells by the strong scattering light of SPR. However, only the fraction of forward scattering light into the cell is effective, while the fraction of backward scattering light into air contributes nothing to the enhancement of optical absorption. To date, there has been no systematic study on the influence of scattering direction on the light-trapping efficiency for solar cells to our knowledge. This is unfortunate considering that scattering direction would be very helpful in designing and optimizing the light-trapping structures of metal nanoparticles, and in further improving the efficiency of TF solar cells.

In this letter, we propose the forward-scattering efficiency (FSE), which quantitatively describes the light-trapping enhancement, because the light-trapping efficiency lies on the light-scattering direction of the metal nanoparticles. In addition, Ag nanoparticles with long-term stability and suitable resonance frequency appropriately serve as the light-trapping structures of TF solar cells^[9]. The characteristic of scattering angles for different plasmon resonance peaks, the forward-scattering spectra and light-trapping efficiencies of Ag nanoparticles are calculated and analyzed in detail based on the Mie theory.

The Mie theory provides exact expressions of spatial distributions for an electromagnetic field scattered by spherical particles, and its correctness has been testi-

fied by many experimental results^[10–12]. According to the Mie theory, the amplitude-scattering matrix elements of parallel and perpendicular polarizations for spherical nanoparticles may be written as^[13]

$$S_1(\cos \theta) = \sum_n \frac{2n+1}{n(n+1)} (a_n \sigma_n + b_n \tau_n), \quad (1)$$

$$S_2(\cos \theta) = \sum_n \frac{2n+1}{n(n+1)} (a_n \tau_n + b_n \sigma_n), \quad (2)$$

where a_n and b_n are the scattering coefficients of the n th scattering electromagnetic mode, and σ_n and τ_n are the angle-dependent functions of the n th mode. The scattering angle θ is in the range of $0 \leq \theta \leq \pi$. The extinction of nanoparticles consists of scattering and absorption. Hence, the value of $Q_{\text{sca}}/(Q_{\text{sca}} + Q_{\text{abs}})$ indicates the ratio of scattering light to total light extinction^[6], where Q_{sca} and Q_{abs} are scattering and absorption cross-sections, respectively. Scattering and absorption cross-sections are given by^[13]

$$Q_{\text{sca}} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) (|a_n|^2 + |b_n|^2), \quad (3)$$

$$Q_{\text{abs}} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) \text{Re}(a_n + b_n) - Q_{\text{sca}}, \quad (4)$$

where $k = 2\pi N/\lambda$, N is the refractive index of the medium, and λ is the light wavelength. Given that light scattering into the forward hemisphere is useful, while scattering into the backward hemisphere contributes nothing to enhancing light trapping for solar cells, we can thus define FSE $\eta_{\text{sca}}^{\text{fw}}$ as

$$\eta_{\text{sca}}^{\text{fw}} = \frac{Q_{\text{sca}}}{Q_{\text{sca}} + Q_{\text{abs}}} \int_0^{\pi/2} |S_j(\theta)|^2 d\theta / \int_0^{\pi} |S_j(\theta)|^2 d\theta, \quad (5)$$

where $j = 1, 2$ correspond to parallel and perpendicular polarizations, respectively.

Set $I_0(\lambda)$ as the AM1.5 solar spectrum. The forward-scattering spectrum for light-trapping structures of nanoparticles can be introduced as

$$I_{\text{fw}}(\lambda) = \eta_{\text{sca}}^{\text{fw}}(\lambda) I_0(\lambda). \quad (6)$$

The light-trapping effect can then be characterized more appropriately by the FSE for light-trapping structures. Therefore, the light-trapping efficiency η_{trap} for the total absorption spectrum range Ω of solar cells is defined as

$$\eta_{\text{trap}} = \int_{\Omega} I_{\text{fw}}(\lambda) d\lambda / \int_{\Omega} I_0(\lambda) d\lambda. \quad (7)$$

To analyze the distribution of scattering angles and the forward-scattering characteristics of Ag nanoparticles, we mainly focus on two sizes of Ag nanoparticles: one has a radius of 53 nm and the other has a radius of 88 nm. The reason for these choices consists of two aspects. 1) For Ag nanoparticles with a radius of 53 nm, only dipole resonances occur, while for Ag nanoparticles with a radius of 88 nm, both dipole and quadrupole resonance would be

observed. Thus, we could conduct a comparison analysis on the characteristics of their scattering angles between the dipole resonance and the quadrupole mode resonance. 2) The role of scattering in the extinction can be almost neglected for Ag nanoparticles with a radius less than 50 nm, while it is difficult to fabricate for Ag nanoparticles with sizes larger than 100 nm. In calculations, the dielectric functions of metal Ag are taken from the experimental data in Ref. [14]. In this study, we assume that the absorption spectrum region of the solar cells is located in the range of 300–1120 nm.

Figure 1 shows the scattering efficiencies and light intensity distributions with scattering angle at plasmon resonance peaks corresponding to the nanoparticle radii of 53 and 88 nm, respectively. The dipole peak for the 53-nm nanoparticle appears at the 415-nm wavelength, while the dipole and quadrupole peaks for the 88-nm nanoparticle exhibit at the 530- and 388-nm wavelengths, respectively. For the dipole resonance peaks of both nanoparticles, the characteristics of light intensity distributions are almost alike, i.e., the scattering light intensities for perpendicular polarization are uniformly distributed throughout the range of scattered angle from 0° to 180° , while for the parallel polarization, the scattering intensities gradually decrease to zero as the scattering angle increases from 0° to 90° , and then gradually increase when the scattering angle varies from 90° to 180° . That is, one half of the light is scattered into solar cells and the other half is scattered back into the air, which has the same ratio between the forward- and backward-scattering light. For the quadrupole resonance peak that occurs only in the 88-nm nanoparticle,

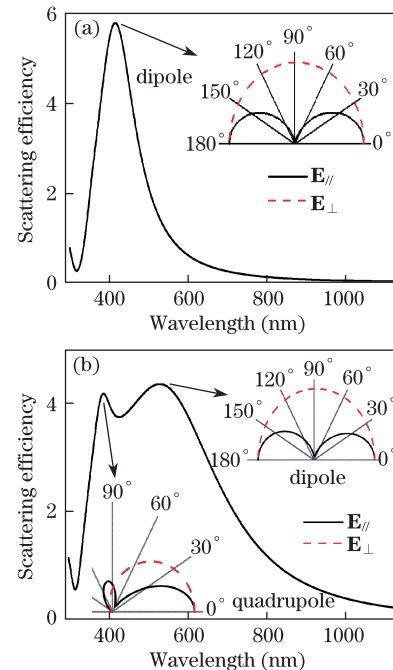


Fig. 1. Scattering efficiency as a function of wavelength, and the light intensity distribution with scattering angle (a) at the plasmon dipole resonance peak of the nanoparticle with a radius of 53 nm, and (b) at the dipole and quadrupole resonance peaks of the nanoparticle with a radius of 88 nm. Insets show the normalized angular scattering distributions at the plasmon resonance peaks in polar coordinates.

the scattering light intensity for perpendicular polarization decreases in the entire range from 0° to 180° . Meanwhile, the scattering light intensity for parallel polarization declines to zero in the range of 0° to 60° , and initially increases then decreases to zero when the angle varies from 60° to 180° . Based on Fig. 1(b), both polarizations at the quadrupole resonance peak have more fraction of the forward scattering light than that of the backward scattering light, which has a stronger trapping efficiency compared with the dipole mode resonance. Thus, compared with the dipole resonance, the quadrupole resonance has a stronger light-trapping capability.

Figure 2 shows the relationships between the FSE and wavelength for the two nanoparticle sizes, respectively, and also illustrates the scattering spectrum together for comparison. For both polarizations, we find that both particles have a higher FSE in the short wavelength range from approximately 300 to 400 nm, which gradually decreases as the wavelength increases. For the FSEs of both particles, the one for of the 88-nm Ag nanoparticle is higher than that of the 53-nm Ag nanoparticle at the short wavelength range. From the overlapping proportion between the curves of FSE and the scattering spectrum, the overlapping proportion of the 88-nm nanoparticle is obviously higher than that of the 53-nm particle. Therefore, the appearance of the quadrupole resonance peak significantly improved the light-trapping effect of Ag nanoparticles.

For quantitative analysis of the light-trapping effect for light-trapping structures formed by both nanoparticles, we calculate the forward-scattering spectrum and light-trapping efficiency according to Eqs. (6) and (7) under the condition of AM1.5 solar spectrum. In the calculation, both perpendicular and parallel polarizations are assumed to have the same proportion of 50%. The nanoparticles are also assumed to cover the cell uniformly

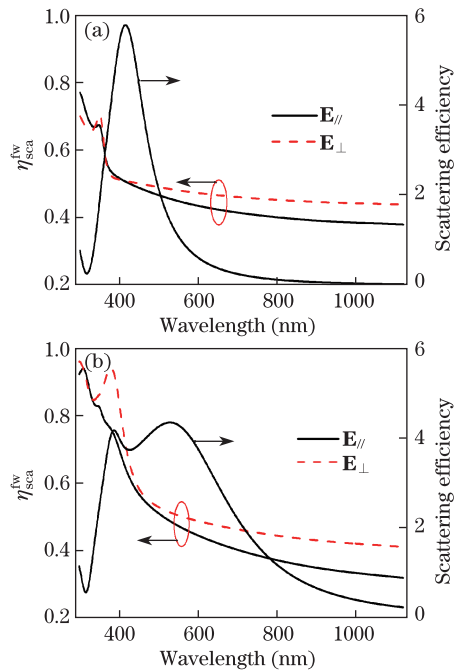


Fig. 2. FSE η_{sca}^{fw} as a function of wavelength corresponding to the nanoparticles (a) with a radius of 53 nm and (b) with a radius of 88 nm. Their scattering spectra are also shown.

with a surface coverage of 5%. The absorption spectrum region of the solar cell is located in the range of 300–1120 nm.

The forward-scattering spectra are presented in Fig. 3 for the nanoparticle sizes of 53 and 88 nm. For comparison, the standard AM1.5 solar spectrum is also shown. By comparing the intensity of the forward-scattering spectra for both light-trapping structures in Fig. 3, the intensity of the 88-nm Ag nanoparticle is shown to be higher than that of the 53-nm Ag nanoparticle at the short wavelength range of 300–600 nm. The light-trapping efficiencies are 15.5% and 32.3% for the nanoparticle sizes of 53 and 88 nm, respectively. That is, the light-trapping efficiency of the latter is more than two times that of the former.

Since the plasmon for the 53-nm nanoparticle only exhibits dipole resonance, while both dipole and quadrupole resonances exist for the 88-nm nanoparticle, calculation results directly indicate that the quadrupole mode resonance of plasmons could further enhance the light-trapping effect for solar cells.

For the nanoparticle light-trapping structures of solar cells, we analyze their light-scattering characteristics from the view of normal modes based on the Mie theory, but we cannot take the underlying layers and substrate into account. Finite-difference time-domain method can overcome this disadvantage, but it cannot reveal the characteristics of the normal modes of nanoparticles. However, because the nanoparticle surface coverage is only 5% here, the effect of the underlying layers and substrate on the scattering light could be neglected^[15]. Therefore, studying the light-scattering characteristics using the Mie theory is more appropriate here.

In conclusion, a quantitative calculation of light-trapping efficiency for Ag nanoparticles with radii of 53 and 88 nm is carried out by introducing the FSE. Light-trapping efficiencies are 15.5% and 32.3% for the 53- and 88-nm nanoparticles, respectively, when the nanoparticle surface coverage is 5%. By comparing the light-trapping efficiency of Ag nanoparticles with radii of 53 and 88 nm, we find that the light-scattering direction is vital to light-trapping efficiency. In addition, the quadrupole mode resonance exhibits a stronger light-trapping ability compared with that of the dipole resonance. Results indicate that a stronger light-trapping efficiency could be achieved by adjusting Ag nanoparticle size until the

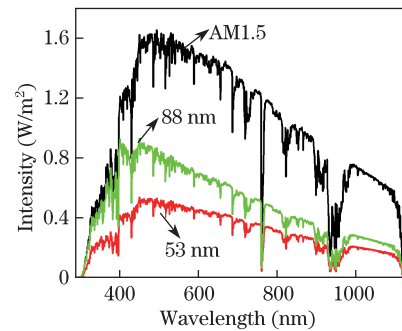


Fig. 3. Forward-scattering spectra of light-trapping structures formed by the nanoparticles with radii of 53 and 88 nm; both surface coverages of light-trapping structures are 5%. For comparison, the standard AM1.5 solar spectrum is also shown.

appearance of the quadrupole mode plasmon resonance. The conclusion of this study will be very helpful in optimizing metal nanoparticle light-trapping structures and in further increasing the conversion efficiency of TF solar cells.

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References

1. A. Polman, *Science* **322**, 868 (2008).
2. S. Pillai, K. R. Catchpole, T. Trupke, and M. A. Green, *J. Appl. Phys.* **101**, 093105 (2007).
3. D. M. Schaadt, B. Feng, and E. T. Yu, *Appl. Phys. Lett.* **86**, 063106 (2005).
4. K. Nakayama, K. Tanabe, and H. A. Atwater, *Appl. Phys. Lett.* **93**, 121904 (2008).
5. D. Derkacs, S. H. Lim, P. Matheu, W. Mar, and E. T. Yu, *Appl. Phys. Lett.* **89**, 093103 (2006).
6. M. D. Yang, Y. K. Liu, J. L. Shen, C. H. Wu, C. A. Lin, W. H. Chang, H. H. Wang, H. I. Yeh, W. H. Chan, and W. J. Parak, *Opt. Express* **16**, 15754 (2008).
7. T. V. Teperik, F. J. García de Abajo, A. G. Borisov, M. Abdelsalam, P. N. Bartlett, Y. Sugawara, and J. J. Baumberg, *Nature Photon.* **2**, 299 (2008).
8. K. R. Catchpole and A. Polman, *Appl. Phys. Lett.* **93**, 191113 (2008).
9. D. Wu, X. Xu, and X. Liu, *J. Chem. Phys.* **129**, 074711 (2008).
10. S. J. Oldenburg, J. B. Jackson, S. L. Westcott, and N. J. Halas, *Appl. Phys. Lett.* **75**, 2897 (1999).
11. W. Ma, H. Yang, J. Liu, Z. Ni, D. Tang, and J. Yao, *Acta Opt. Sin.* (in Chinese) **30**, 2629 (2010).
12. J. Liu, H. Yang, X. Luo, W. Ma, and Y. Liu, *Acta Opt. Sin.* (in Chinese) **30**, 1092 (2010).
13. C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles* (Wiley, New York, 1983).
14. E. D. Palik, *Handbook of Optical Constants of Solids* (Academic, Washington, 1985).
15. Yu. A. Akimov, K. Ostrikov, and E. P. Li, *Plasmonics* **4**, 107 (2009).