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Light trapping characteristics of metal nanoshells deposited on photovoltaic silicon films

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ABSTRACT

Light trapping characteristics of Ag nanoshells deposited on photovoltaic silicon films were studied theoretically using finite difference time domain (FDTD) method. The light absorption changes in Si films are found dependent on the localized surface plasmon resonance (LSP) including scattering, absorption and their respective portions, which can be tuned by varying the size of the metal nanoshells. Predominant scattering over absorption is demonstrated to be a prerequisite for the absorption enhancement. Metal absorption loss at LSP cavity mode resonance is responsible for the light absorption suppression. It is also found that the thickness of the active layer, which has effect on the LSP interference-induced field, influences light trapping characteristics of the Ag nanoshells.

1. Introduction

Recently, localized surface plasmon (LSP) resonance, which is coherent oscillation of the free electrons in metal nanoparticles upon excitation by incident light, has attracted much attention [1–3]. Excitation of LSP at specific wavelengths at which resonance occurs can result in strong light-scattering with the appearance of intense surface plasmon resonance bands. It is deemed that a metal nanoparticle in air has a light scattering cross-section that is about 10 times the geometrical cross-sectional area of the particle. Meanwhile, LSPs can trap and confine light in dimensions much smaller than the wavelength, which may greatly enhance the interaction of light with thin active layer. Therefore, there have been many reports on the application of metal nanoparticles to increase the light absorption of the active layer in solar cells, especially for thin film solar cells [4–10].

Metal nanoparticles with different shapes and sizes have been utilized to achieve absorption enhancements over a large range of wavelengths in solar cells [11–15]. However, contradictory experimental results were obtained in different structure designs [14,15]. Besides photo-current gain at wavelengths in the visible to NIR region, a substantial loss is also observed at wavelengths below a certain wavelength point, resulting in a poor relationship between gains and losses. The cross-over point is closely related to the position of the LSP resonance which includes contributions from both scattering and absorption in metal nanoparticles. Thus it is highly interesting to shift the LSP resonance, tune the scattering and absorption efficiency and thereby improve the balance between reduction and enhancement effects from the nanoparticles.

Nanoshells of noble metal have attracted much attention because of their controllable local LSP resonance properties by adjusting their structural parameters, such as radius ratio and shell thickness [16]. The LSP resonance band of metal nanoshells can be tuned from visible to infrared spectra range, at where the absorption of photovoltaic film, such as amorphous and polycrystalline silicon films, is inefficient. We have done exploratory research on the application of Ag nanoshells to increase the light absorption in amorphous silicon film, and enhancement was found at LSP resonance and infrared range where plasmon coupling happened [17]. However, absorption reduction was also observed at blue spectral region. To make clear the spectral dependent light trapping characteristics of metal nanoshells in solar cells, in this article, the scattering, absorption band and their respective portions in LSP resonance was tuned by changing the size of the metal nanoshells, and the light absorption in silicon films was simulated numerically. The effect of silicon film thickness on the light absorption was also studied to elucidate the LSP light trapping characteristics in thin film solar cells.

2. Methods

The structure schematics are illustrated in Fig. 1. A stack consisting of Ag nanoshells deposited on silicon film with the

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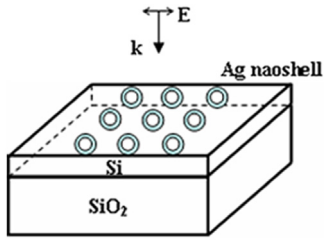

Fig. 1. Schematics of the sample structure.

substrate of quartz slides was simulated using FDTD. The size of the Ag nanoshell with a silica sphere core is denoted by $[r_1, r_2]$, in which r_1 and r_2 are inner and outer radius of the core–shell structure respectively. In our calculations, three kinds of Ag nanoshells with different size (i.e., [200, 210] nm, [200, 250 nm] and [200, 280 nm]) were used. The nanoshells are arrayed in square. When the radius of the Ag nanoshells is varied, the coverage ratio is kept unchanged. To study the influence from the active layer thickness, the Si film was reduced from 280 nm to 140 nm. Numerical simulation of the extinction spectra including scattering and absorption of Ag nanoshells, the absorption spectra and the E field distributions in the structures were carried out using a FDTD solver (Lumerical solution, Inc). Periodical boundary condition was used in the directions (x and y shown in Fig. 1) perpendicular to the light incident direction (z shown in Fig. 1), and PML conditions was used in z direction. The refractive indexes n and absorption coefficients k of materials were taken from the FDTD solver database. To preclude the influence from metal absorption losses on the evaluation of the light absorption in Si film, both light absorptions of Ag nanoshells coated Si film and that of the separate Ag nanoshell arrays were simulated theoretically. The light absorption in active Si layer was obtained by subtracting losses in Ag nanoshell arrays.

3. Results and discussions

Fig. 2(a)–(c) demonstrate the LSP extinction spectra of [200, 210] nm, [200, 250] nm and [200, 280] nm Ag nanoshells. Scattering and absorption spectra are also included. An isolated metal nanoshell in vacuum with the dielectric coefficient equal to 1 was adopted in the calculation. It is observed that the LSP resonance is significantly broadened and red-shifted due to dynamic depolarization of conduction electrons in big size metal particles [18]. For [200, 210] nm Ag nanoshell in Fig. 2(a), we can find that the plasmonic scattering efficiency is higher than absorption efficient at short wavelength, whereas absorption dominates at long wavelength. The overall portions of scattering and absorption are nearly identical. For [200, 250] nm and [200, 280] nm Ag nanoshell in Fig. 2(b) and (c), plasmonic scattering is predominant over absorption in the whole spectral range. Absorption is negligible except at short wavelength. It means that radiative plasmonic scattering is the principal relaxation channel of LSP resonance for metal nanoshells with a large shell thickness. Comparing Fig. 2(b) and (c), it is found that Ag nanoshells with a thicker shell have a larger scattering cross section.

Fig. 3 compares the influence of Ag nanoshells of distinct size on the absorption spectra of Si films. The thickness of the Si film is 280 nm. Note that the absorption loss from Ag nanoshells has been deducted to obtain the absolute light absorption in Si film. From Fig. 3, it can be found that for Ag nanoshells with a size of [200, 210] nm, metal depositing induces a decrease of light absorption in the whole spectrum range. The absorption peaks caused by F–P interference are almost coincident with that of bare silicon films. For [200, 250] nm Ag nanoshells, however, the absorption changes in the Si film are tremendous. First, light absorption enhancement is observed in two spectral regions including 600–800 nm and long

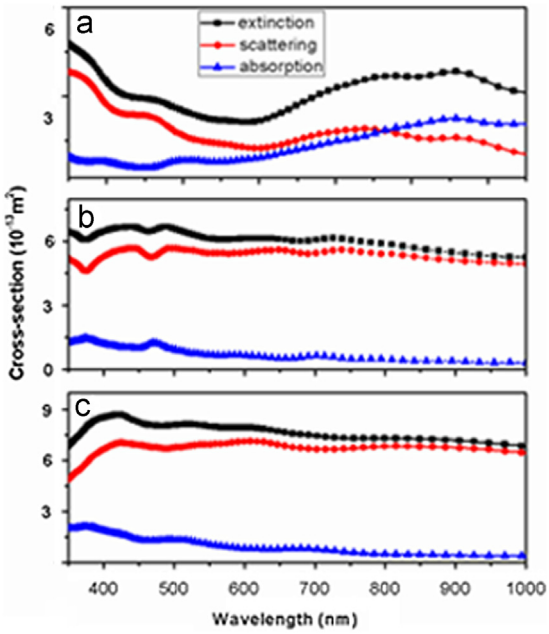

Fig. 2. Extinction, scattering and absorption spectra of the LSP resonance of Ag nanoshells. (a) [200, 210] nm, (b) [200, 250] nm and (c) [200, 280] nm.

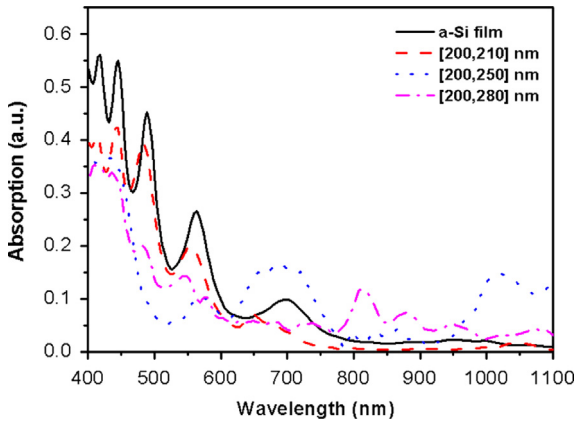

Fig. 3. Absorption spectra of Si film before and after deposited with Ag nanoshells of different sizes.

wavelength range beyond 900 nm. Secondly, light absorption decrease is presented at spectral range lower than 600 nm, and moreover, the absorption decrease is more prominent than that of [200, 210] nm Ag nanoshells deposited Si film. For [200, 280] nm Ag nanoshells, the absorption decrease is also observed at short spectral range. Absorption enhancement is presented in 750–1100 nm range, but the enhancement is less than those in [200, 250] nm Ag nanoshells. The maximum enhancement occurs near 810 nm.

Further insight into the absorption changes for Ag nanoshells with different size may be realized by simulating the electric field distribution of Ag nanoshells deposited silicon film. The electric field E plotted over a plane perpendicular to the interface, bisecting the particle with the incident polarization along z directions is shown in Fig. 4. Fig. 4(a)–(c) shows the field distribution of [200, 210] nm Ag nanoshells coated Si film at 460 nm, 710 nm and 950 nm respectively. Fig. 4(d)–(f) and (g)–(i) shows those for [200, 250] nm and [200, 280] nm Ag nanoshells. Apparently, strong field concentration that related to the cavity mode is found in the core of the Ag nanoshells at 460 nm in Fig. 4(a). Apart from waveguide mode in Si film, plasmonic light scattering by the Ag nanoshell induced