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A Simple Optical Model Well Explains Plasmonic-Nanoparticle-Enhanced Spectral Photocurrent in Optically Thin Solar Cells

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Abstract

A simple optical model for photocurrent enhancement by plasmonic metal nanoparticles placed on top of solar cells has been developed. Our model deals with the absorption, reflection and scattering of the incident sunlight as well as the radiation efficiencies on metallic nanoparticles. Our calculation results well reproduce a series of experimental spectral data for optically thin GaAs solar cells with various-dimensioned Ag and Al nanoparticles, demonstrating the validity of our modelling. Our model can be a handy but powerful tool for investigations of surface-plasmon-enhanced thin-film solar cells.

1. Introduction

Metal nanoparticles placed on solar-cell surfaces can enhance sunlight collection, owing to their large extinction cross section which is dominated by scattering rather than absorption for appropriately chosen particle sizes [1-3]. This effect has potential for cell-cost and weight reduction resulting from use of thinner absorber layers and also for efficiency enhancement associated with increased carrier excitation level. In this work, we have developed a relatively simple electromagnetic model to reproduce and thus explain the experimental photocurrent-enhancement spectra of plasmonic solar cells [3] for a purpose to provide future device-improvement directions.

2. Theory and Calculations

We assume that the angular distribution of the light intensity scattered by sub-wavelength sized particles in the quasistatic limit is

$I_{sca} \propto (1+\cos^2\theta) I_0$, [4] (Eq. 1)

where the angle θ is measured from the forward to the scattered directions. The absorption fraction for the scattered light is;

$$A_\theta(\lambda) = \int_0^{\pi/2} \frac{1+\cos^2\theta}{\int_0^{\pi}(1+\cos^2\theta)d\theta} \left\{1-\exp\left(-\alpha(\lambda)\frac{L}{\cos\theta}\right)\right\} d\theta, \quad \text{(Eq. 2)}$$

accounting that the optical path in the GaAs layer is increased from L into $L/cos\theta$. The total absorption fraction for the GaAs layer with nanoparticles on top with a surface coverage ξ is;

$A_{tot}(\lambda) = \xi Q_{ext}(\lambda)\eta_{rad}(\lambda)A_\theta(\lambda) + (1-\xi Q_{ext}(\lambda))(1-R(\lambda))A_0(\lambda)$

($\xi Q_{ext} < 1$), (Eq. 3) where Q_{ext} and η_{rad} are the extinction efficiency factor and the radiation efficiency for the nanoparticles as defined in Ref. 4 and 2, respectively. ξ was 0.4 and 0.3 for the cases of the diameter d of 60 nm and 150 nm, respectively, as determined from SEM images in Ref. 3. Values for Q_{ext} and η_{rad} were calculated for oblate spheroidal metal particles with a minor axis parallel to the incident light corresponding to the height h of the experimental nanoparticles in the quasistatic limit using an effective medium approximation for the complex dielectric function of the surrounding medium [5]. Particularly for Al nanoparticles, Q_{ext} and η_{rad} were calculated for concentric Al-Al_2O_3 core-shell spheroidal particles with an Al_2O_3 shell thickness t of 4 nm accounting for surface oxidation of Al particles in the atmosphere. The spectral Fresnel reflectivity at the air/GaAs interface is also incorporated.

3. Results and Discussion

The computed photocurrent enhancement factors, defined as the ratio of the photocurrent between the cells with and without metal nanoparticles, are superposed to the experimental plasmonic-GaAs-cell data of Ref. 3 in Fig. 1 and 2. This model calculation well reproduces the experimental results qualitatively, including the peaks around at 300 nm and 900 nm and the dips around at 600 nm for 60-nm-diameter Ag and 350 nm for 60-nm-diameter Al. The dip around at 600 nm in the normalized photocurrent for the cell with 60-nm-diameter Ag particles, presumably due to the surface plasmon resonance in the Ag particles, is not seen for 150-nm-diameter. This result is attributed to the significantly higher η_{rad} (~ 0.9) for the 150-nm-diameter case than that (~ 0.6) for the 60-nm-diameter case suppressing the absorption loss in the Ag nanoparticles, as shown in Fig. 3. For both of Ag and Al, higher photocurrent enhancement at 900 nm for 150-nm-diameter cases than for 60-nm-diameter cases is reproduced in the modeling, caused mainly by the higher Q_{ext} for the larger metal nanoparticles. It is important to note that both Ag and Al particle cells suffer from the loss back scattering from metal nanoparticles into the air as seen in Eq. 1.

Fig. 4 summarizes the calculated photocurrent enhancement factors for various kinds of metals. These calculations were conducted for a particle diameter of 150 nm, height of 75 nm and surface-coverage fraction of 0.3. Note that this particle-size condition is chosen as a saturated, sufficiently large size optimized for the photocurrent enhancement, accounting for our series of calculation results to be presented elsewhere. Au and Cu suffer from the absorption loss due to the surface-plasmon resonance in the

region of 300 - 600 nm. Above 800 nm, all the metals exhibit similar spectral photocurrent enhancement factors except for Al with a little inferiority. In view of these aspects, Ag may be the most suitable metal element for nanoparticle-enhanced photovoltaic devices.

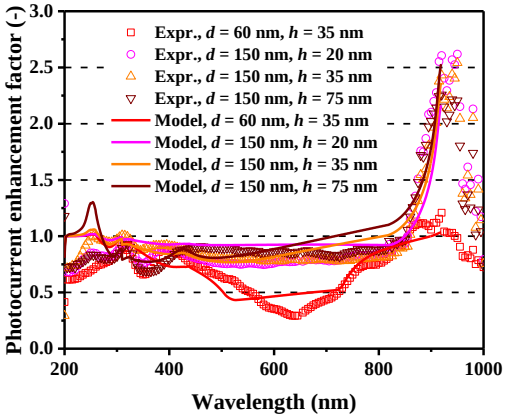

Fig. 1 Spectral photocurrent enhancement factors of optically thin GaAs solar cells with Ag nanoparticles.

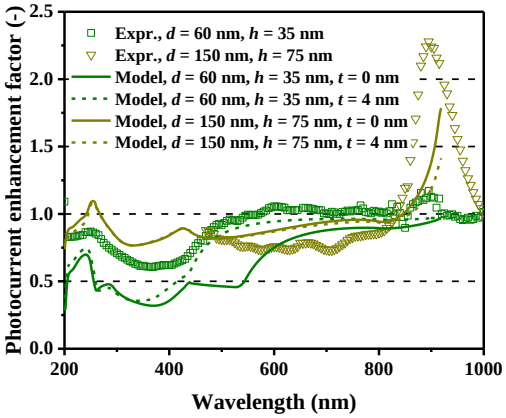

Fig. 2 Spectral photocurrent enhancement factors of optically thin GaAs solar cells with Al nanoparticles.

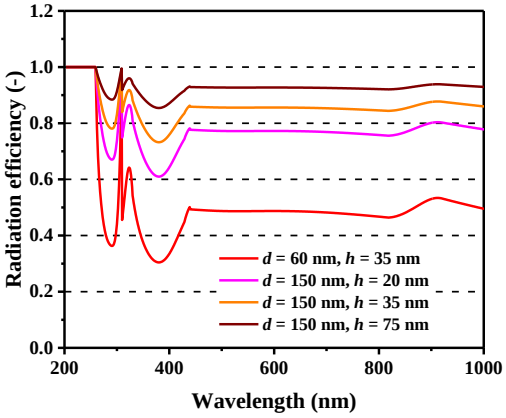

Fig. 3 Optical radiation efficiencies of Ag nanoparticles with varied dimensions.

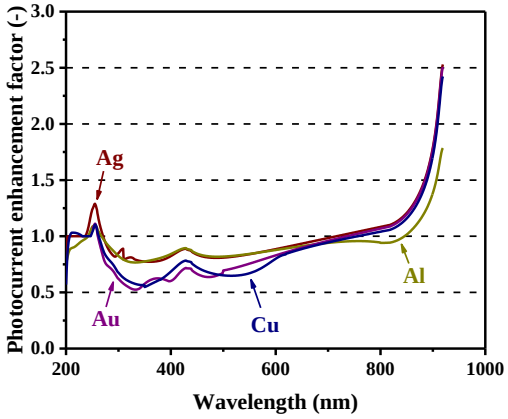

Fig. 4 Calculated spectral photocurrent enhancement factors of optically thin GaAs solar cells with varied metal-element nanoparticles.

4. Conclusions

In this work, we developed a relatively simple optical model for photocurrent enhancement by plasmonic metal nanoparticles placed on top of solar cells. Our model deals with the absorption, reflection and scattering of the incident sunlight as well as the radiation efficiencies on metallic nanoparticles. Our calculation results well reproduce a series of experimental spectral data for optically thin GaAs solar cells with various-dimensioned Ag and Al nanoparticles presented in Ref. 3, demonstrating the validity of our modelling scheme. Our model can be used as a handy but powerful tool for investigations of surface-plasmon-enhanced thin-film solar cells to provide design principles for the improvement of device performance.

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