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ENHANCEMENT IN LIGHT COUPLING INTO SILICON SOLAR CELLS USING LOW COST AND EARTH ABUNDANT ALUMINIUM NANOPARTICLES

Y. Prem kumar Singh[1, 2], Amit Jain[3], A. Kapoor[1*]

[1] Department of Electronic Sciences, University of Delhi, India
[2] Motilal Nehru College, University of Delhi, India
[3] Rajdhani College, University of Delhi, India
avinashi_kapoor@yahoo.com

ABSTRACT:

In this paper, we study the light coupling into a Si substrate by depositing Al nanoparticles on the surface using FDTD calculations and compared with the most commonly used Ag nanoparticles. It has been found that Al nanoparticle has the potential to improved light in coupling integrated over AM1.5G solar spectral range and can have much better enhancement than Ag nanoparticles. Lesser Fano reduction is observed in Si with Al nanoparticles on the surface, thereby minimizing the losses in the short wavelengths usually reported with Ag nanoparticles.

Keywords: *surface plasmons, transmission of light, Fano effect, FDTD.*

1. INTRODUCTION

The use of surface Plasmon's in photovoltaic is a promising and fast emerging field that exploit the special scattering abilities of metallic Nano-structures. Metallic nanoparticles supporting localized surface plasmon, the collective oscillations of the conduction electrons, can be used to improve the optical absorption in solar cells, hence the conversion efficiency [1-3]. On excitation with incident light, polarization charges are developed on the particle surface due to the movement of conduction electrons. This acts as a restoring force, allowing a resonance to occur at a particular frequency, called the surface plasmon resonance frequency [2,3]. At resonance wavelength, the scattering cross-sections of metal nanoparticles are much larger than their geometrical cross-sections [1-3]. The surface plasmon resonance is dependent on the particle material, shape, size, surface density and refractive index of the surrounding dielectric [1-3]. Wavelength response of the metallic nanoparticles can be tuned by changing these parameters and optimized the cell performance.

Several groups have demonstrated that arrays of metallic nanoparticles deposited on the surface of a substrate can enhance the transmission of light into the substrate [4-9]. Silver (Ag) whose surface plasmon resonance lie in the visible range, is the most commonly used noble material. However, metallic nanoparticles placed on the surface of solar cells always introduce a reduction of the in-coupled power below the resonance wavelength where the solar spectrum is still very intense. This reduction occurs due to a Fano effect, i.e. a destructive interference between scattered and incident light occurring at wavelength below resonance [10]. This loss can be minimized with Al nanoparticles on the surface since their Plasmon resonance lies in the ultraviolet range, thereby improving the solar cell performance [11-13]. Moreover, the advantages of Al over Ag are the cost, earth abundant and its resistance to photo-degradation through the formation of thin oxide layer on the particles [11]. In the present work, we demonstrate the enhancement in light

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transmission into a silicon substrate by Al nanoparticles placed on the front surface by using the finite difference time domain (FDTD) method. For nanoparticle radii ranges from 20-70 nm, the surface coverage is optimized for maximum enhancement on the performance of solar cell.

2. SIMULATION MODEL

Numerical simulations were performed with 3-D finite-difference time-domain (FDTD) method [14] using open-source software package, MEEP [15]. FDTD is a widely used technique for computational electromagnetism in which space and time are divided into a regular discrete grid and simulates the time evolved fields. It can be used to investigate a large variety of electromagnetic wave interaction problems accurately. Since it is a time domain method, FDTD solutions can cover a wide frequency range with a single simulation run.

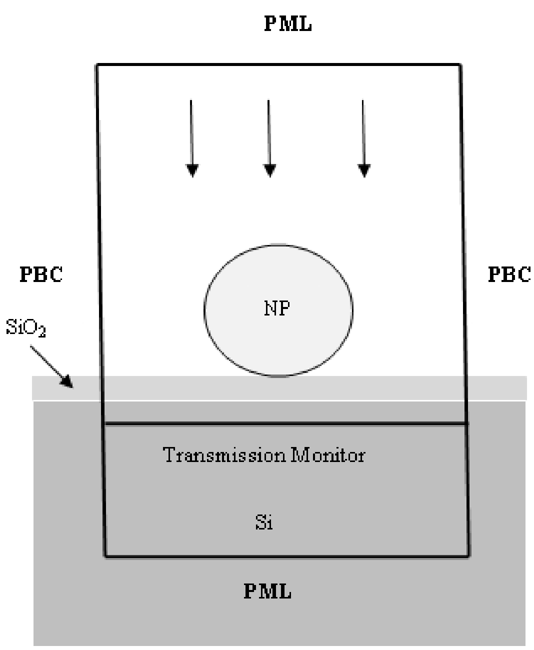

Figure 1. Schematic of the computational domain used for FDTD simulations.

In our simulation model, a spherical metallic nanoparticle of radius R is placed on the top of a semi-infinite Si substrate with a SiO_2 dielectric spacer layer of 10 nm thick (*Figure1*). A broadband (wavelength 300-1100 nm) plane wave is normally incident onto the front surface with nanoparticles. Perfectly matched layer (PML) absorbing boundary conditions are used at the upper and lower boundaries to prevent reflections, and periodical boundary conditions (PBC) are used at the lateral boundaries of the simulation volume to model a periodic array of nanoparticles. All the wavelength-dependent dielectric constants were taken from Palik [16]. The surface coverage parameter S [= $\pi R^2 / (\text{period})^2$] describes the percentage of the overall surface area of SiO_2 covered by the nanoparticles. A transmission monitor is placed 10 nm below the Si surface to measure the total power that is coupled into the substrate. Transmission enhancement ratio, t_n within the spectral range of 300-1100 nm was calculated as

$$t_n = \frac{\int_{300}^{1100} T_n(\lambda) S(\lambda) d\lambda}{\int_{300}^{1100} T_0(\lambda) S(\lambda) d\lambda}$$

where $S(\lambda)$ is the irradiance spectrum of AM1.5G, $T_n(\lambda)$ and $T_0(\lambda)$ are the transmittance of light in the Si substrate with and without nanoparticles respectively.

3. RESULTS AND DISCUSSION

Figure 2 shows the transmission spectra of Al and Ag nanoparticles of R=30 nm at S=35% and R=60 nm at S=25%. Transmission spectrum without nanoparticles as reference and AM1.5G solar spectrum are also included.

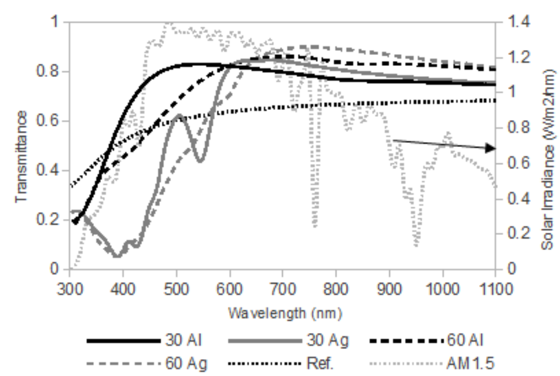

Figure 2. Transmission spectra in the Si substrate with Al and Ag nanoparticles of R=30 nm at S=35% and R=60 nm at S=25%.

Both materials show enhancement in light coupling into substrate in spectral ranges above resonance due

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to the constructive interference between the surface plasmon enhanced forward scattered and incident waves. In contrast, the scattered wave is out of phase with respect to incident wave for wavelength smaller than resonance, resulting in a destructive interference effect [8,10]. It can be clearly observed that Al nanoparticles have a much smaller Fano reduction in the short wavelengths and a broadband light coupling enhancement over the solar spectrum as compare to Ag nanoparticles since the surface plasmon resonance of Al nanoparticles lies in the ultraviolet region. *Figure 3* shows the spatial distribution of electric field energy density with Al nanoparticles of R=60 nm at S=30% under resonance wavelength 455 nm illumination. The field distribution is clearly dominated by the excitation of a dipolelike resonance in the nanoparticle.

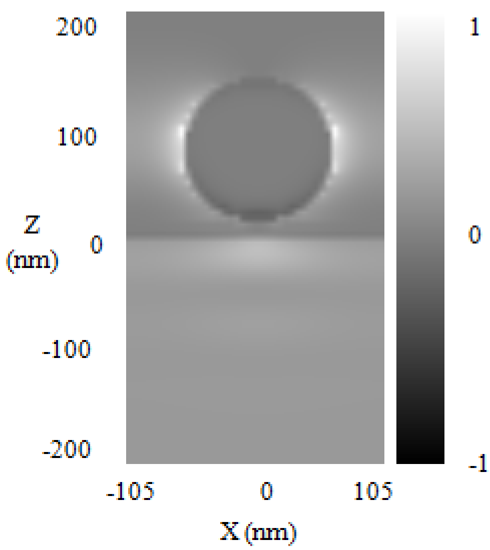

Figure 3. Spatial distribution of electric field energy density for Al nanoparticles of R=60 nm at S=30% under resonance wavelength 455 nm illumination.

The strength of coupling between surface plasmons of metallic nanoparticles depends on the inter-particle separation. For closely spaced particles, a strong coupling causes a broadening of plasmon resonance and a large nonradiative loss, resulting in a weak transmission of light [9]. Moreover, for widely spaced particles, the effect of nanoparticles can be almost disregarded and the structure converges to the case with no nanoparticles. A high transmission region appears at optimized spacing indicating the existence of an optimal surface coverage for maximum transmission of light into Si. This phenomenon is depicted in *Figure 4*.

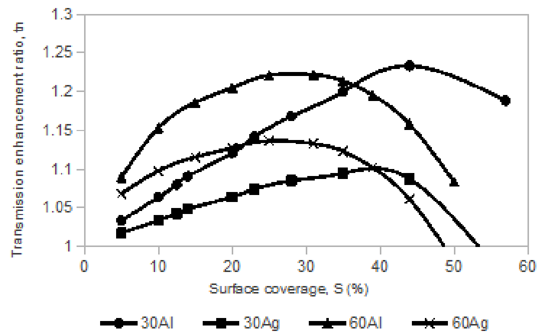

Figure 4. Transmission enhancement ratio curves for Al and Ag nanosparticles of R=30 nm and 60 nm as a function of S.

Figure 5 shows the maximum enhancement of light transmission *(a)* and the corresponding optimum surface coverage S *(b)* for nanoparticles of various radii. In *Figure 5(a)*, both the enhancement curves experience increase-peak-decrease transitions as particle size increases. The size of the nanoparticles should be sufficiently large for efficient transmission enhancement. For smaller particles, absorption within nanoparticles is greater than scattering of light, hence more surface coverage is needed for efficient plasmon coupling. As the particle size increases, scattering starts dominating over absorption within nanoparticles, so the optimum surface coverage decreases.

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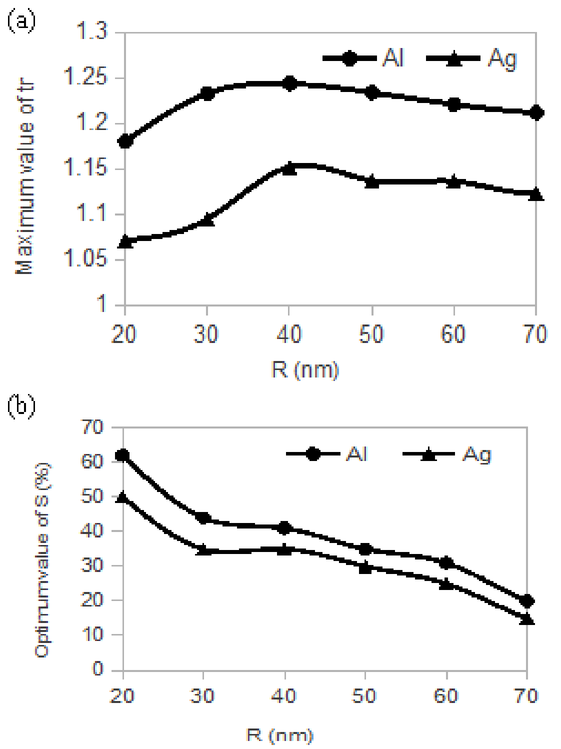

Figure 5. Maximum transmission enhancement (a) and corresponding optimum surface coverage (b), of Al and Ag nanoparticles as a function of nanoparticle radius, R.

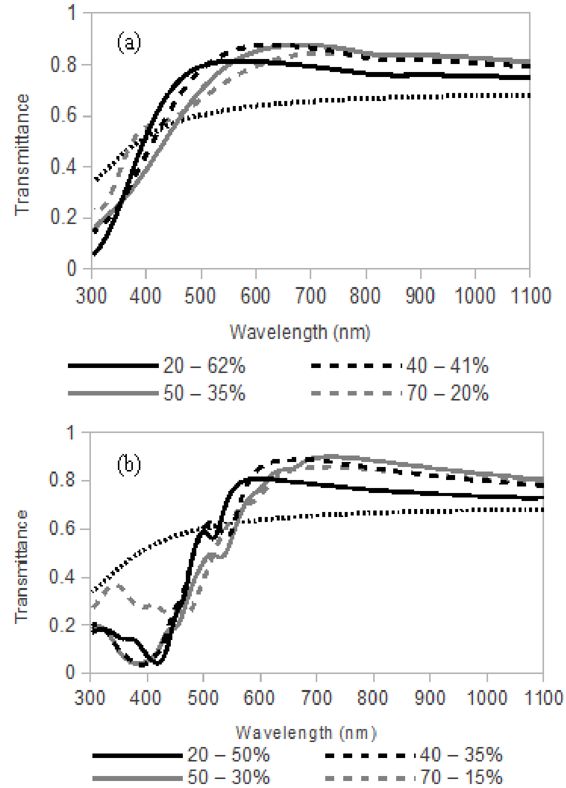

Figure 6. Transmission spectra for Al (a) and Ag (b) nanoparticles of various radii at their optimal surface coverage. In the legend, the first number indicates the radius of particles (in nm) and second indicates the surface coverage (in %).

Figure 6 shows the transmission spectra for Al *(a)* and Ag *(b)* nanoparticles of various radii at their optimal surface coverage. Among the various radii under investigation, Al nanoparticles provide a better transmission enhancement over the entire spectral range of interest.

4. CONCLUSION

We have demonstrated that low cost and earth abundant Al nanoparticle has the potential to enhanced coupling of AM1.5G solar radiation into a Si substrate, keeping in mind the practical large-scale implementation of metal nanostructures for solar cell performance enhancement. It has been found that the Fano reduction in Si with Al nanoparticles on the surface has reduced significantly compared to Ag nanoparticles, which reduced losses in the short wavelengths, thereby improving the solar cell performance.

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