

LIGHT TRAPPING FOR SOLAR CELLS USING LOCALISED SURFACE PLASMONS IN SELF-ASSEMBLED AG NANOPARTICLES

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ABSTRACT: Ag nanoparticle arrays, located on the front or rear surface of a Si solar cell, can provide effective light-trapping via the excitation of localised surface plasmons. We identify key parameters in engineering random Ag nanoparticle arrays for optimum plasmonic light-trapping. We demonstrate that there is an asymmetry in scattering behaviour between particles located on the front and rear of a Si substrate, which we attribute to differences in the driving field at the position of the nanoparticles. Applying the design considerations presented, we report a relative photocurrent increase of 27% over the light trapping spectral region for thin c-Si solar cells incorporating a rear-located self-assembled Ag nanoparticle array, constituting the largest reported enhancement due to plasmonic light trapping for such cells. Inclusion of a detached rear reflector behind these particles increases the photocurrent enhancement to 33%.

Keywords: Light trapping, nanoparticles, localised surface plasmons

1 INTRODUCTION

Recent innovations in solar cell design favour thin active regions which offer the advantages of increased carrier collection efficiency and reduced material costs. However, the trade off for these devices is that light-trapping is necessary to avoid transmission losses becoming significant. Traditional light-trapping techniques, such as texturing, rely on geometrical optics to randomise light and employ feature sizes of up to tens of microns textured in the cell surface. This large scale texturing can reduce the quality of the solar cell, degrading performance, and is not easily achieved for thin cells or cells based on materials other than crystalline Si (c-Si).

Scattering from sub-wavelength metal particles, which can support localised surface plasmons, has been shown to provide light-trapping for different types of solar cell, without compromising surface quality [1-6]. Arrays of metal nanoparticles can be fabricated on finished solar cells, separated from the semiconductor surface by dielectric spacer layers which can include passivation layers. Incident light excites localised surface plasmons resonances in the confined geometry of the metal particles, which strongly scatter light. Due to the high optical density of the semiconducting layer, a large fraction of the light is coupled into the active region of the cell over a broad angular range, effectively trapping the light in the solar cell.

Nanoparticles located on the front, illuminated surface of the solar cell have been shown to suppress absorption in Si photodiodes at certain wavelengths [7]. This has been attributed to destructive interference between incident and scattered light in the substrate, and can lead to an overall decrease in photocurrent for solar cells with good blue response [2, 7]. Locating the nanoparticles on the rear of the cell ensures that short wavelength light is absorbed before reaching the particles and avoids suppression at these wavelengths, while long wavelength light transmitted at the rear surface is scattered back into the cell at high angles and trapped. External quantum efficiency enhancements have been reported for c-Si solar cells with rear located Ag nanoparticles arrays, at wavelengths where light is

weakly absorbed in Si [4].

The scattering cross-section and the coupling efficiency (defined as the fraction of light scattered by the particles that is scattered into the cell) of the nanoparticles is sensitively dependent on the local dielectric environment and the geometry and material of the nanoparticles [8]. For effective light-trapping these parameters must be chosen to achieve maximum nanoparticle scattering cross-section and coupling efficiency [9]. In particular, strong dipolar scattering resonances are required in the wavelength region where transmission losses become prevalent for the solar cell under consideration.

In this paper we discuss key parameters in engineering self-assembled Ag nanoparticle arrays for optimum plasmonic light-trapping and demonstrate that tunable light trapping can be achieved using localised surface plasmons in Ag nanoparticles on the front and the rear of thin Si solar cells. We identify, experimentally and by numerical calculation, that asymmetry in the scattering behaviour exists between nanoparticles located on the front and rear of a Si substrate. Using a simple analytical model we establish a clear relationship between the scattering cross-section and the driving field at the nanoparticle. We present results for optimal self-assembled Ag nanoparticles on thin c-Si solar cells. A relative photocurrent increase of 27% is reported over the light trapping spectral region, constituting the largest reported enhancement due to plasmonic light trapping for such cells. Inclusion of a detached rear reflector behind these particles increases the photocurrent enhancement to 33%.

2 DESIGN CONSIDERATIONS

In our approach Ag nanoparticles are fabricated by simple a self-assembly method that is relatively cheap and compatible with the fabrication of large area solar cells. Thin Ag layers are deposited by thermal evaporation followed by a 50 minute anneal in N₂ atmosphere at 230°C. The Ag films coalesce under surface tension to produce isolated metal “islands”.

These nanoparticles have a “flattened” hemispherical shape which has been shown to couple well with the substrate [9]. Increasing the thickness of the initial Ag film deposited results in larger average particle diameters and broader size distributions. Nanoparticle size is a factor in determining the strength and wavelength range of the nanoparticle scattering resonance. As the particle size increases, parasitic absorption decreases and the contribution of scattering increases. However, as the particle size is increased further multipole resonance can be excited, which do not couple well with the substrate, compared to dipolar resonances. Thus the particle diameter should be chosen to ensure a strong dipolar scattering resonance.

To achieve effective light-trapping for thin Si solar cells the nanoparticle scattering resonance should occur at wavelengths where light is weakly absorbed in the Si. The wavelength at which resonance occurs (λ_{spr}) can be tuned to longer wavelengths by increasing the effective dielectric constant of the surrounding environment of the particle due to the depolarising effect of the dielectric medium. This can be achieved by changing the refractive index of the underlying dielectric spacer layer[4] or by bringing the particle closer to the optically dense semiconductor material, using thinner spacer layers between the solar cell surface and the nanoparticles.

3 ASSYMETRY IN SCATTERING BEHAVIOUR

Figure 1 shows external quantum efficiency (EQE) enhancements derived from photocurrent measurements on 100 μm thick bifacial crystalline silicon solar cells with self-assembled Ag nanoparticles, of average diameter ~ 130 nm, on one surface of the cell. The cells have different dielectric spacer layer geometries, with SiO_2 (RI = 1.5) and TiO_2 (RI = 2.5) as the uppermost layer.

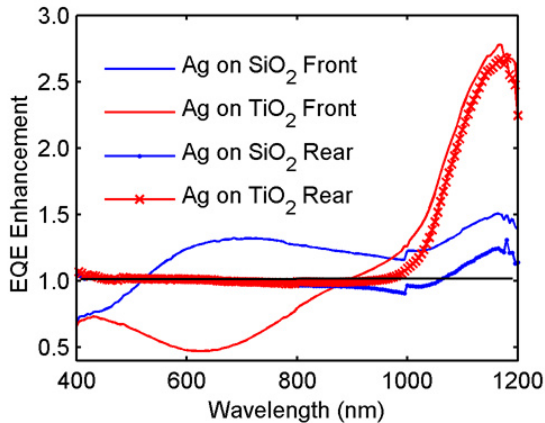


Figure 1: External quantum efficiency enhancements due to the presence of silver nanoparticles on TiO_2 and SiO_2 spacer layers. Results are shown for illumination from the front (solid lines) and the rear (broken lines).

Measurements were made with nanoparticles on the front and the rear of each cell and enhancement is calculated as the EQE with nanoparticles normalised to the EQE without nanoparticles. The high refractive index dielectrics red-shift the scattering resonances of the

nanoparticles to wavelengths at which transmission losses become prevalent. For particles fabricated on TiO_2 spacer layers, EQE is more than doubled at a wavelength of 1100 nm, whether particles are illuminated from the front or the rear, demonstrating the benefits of tuning λ_{spr} to wavelengths where light-trapping is needed [4].

It is also clear from Fig. 1 that there are differences in the efficiency of the light trapping provided by nanoparticles located on the front and the rear. Suppression at shorter wavelengths below resonance can be observed in all cases for front located nanoparticles, which is not seen for rear located nanoparticles as expected. However, we observe additional asymmetry in the light-trapping provided as front located nanoparticles perform better above wavelengths of 920 nm, where transmission losses exceed 10% for these Si cells, for all dielectric spacer layer geometries shown. Figure 1 shows that this effect is dependent on the dielectric geometry and is more pronounced in the SiO_2 case.

To investigate the difference in scattering behaviour between front and rear located nanoparticles, we use FDTD simulations to calculate the scattering cross-section (Q_{scat}), and the coupling efficiency (F_{subs}), defined as the fraction of scattered light scattered into the Si substrate, of a 100 nm diameter, 50 nm tall Ag disk, separated from a semi-infinite Si substrate by SiO_2 spacer layers of 5, 10 and 40 nm [10]. These two quantities give a good measure of the effectiveness of the light trapping provided by the nanoparticle [9]. Although experimentally nanoparticles of roughly hemispherical shape are observed, we chose a symmetrical disk shape for our investigation to exclude possible effects of shape asymmetry.

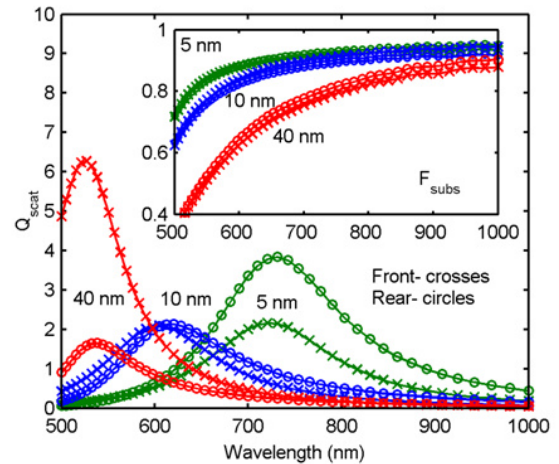


Figure 2: Calculated scattering cross section (Q_{scat}) and coupling efficiency (F_{subs} , inset) of a disk shaped nanoparticle on the front (crosses) and rear (circles) of a Si substrate for different spacer layer thicknesses of 5, 10 and 40 nm.

Figure 2 shows the calculated Q_{scat} and, inset, F_{subs} . The normalised scattering cross-section at resonance, $Q_{scat}(\lambda_{spr})$, is observed to shift to longer wavelengths as the SiO_2 layers become thinner. This is due to the increasing overlap of the particle near-field with the high-index Si substrate; the effective dielectric constant of the local dielectric environment increases as the spacer layer thickness reduces red-shifting λ_{spr} . The increased overlap

of the near-field with the substrate also causes the coupling efficiency to increase as the layers become thinner. The inset shows that F_{subs} converges to values as high as 90% for the thinnest layers at longer wavelengths, in agreement with previous work on disk-shaped nanoparticles placed close to the substrate [9].

Figure 2 shows that the magnitude of $Q_{\text{scat}}(\lambda_{\text{spr}})$ depends on the particle location. For particles on the front $Q_{\text{scat}}(\lambda_{\text{spr}}) = 6.3$ for the 40 nm spacer layer, reducing to $Q_{\text{scat}}(\lambda_{\text{spr}}) = 2.2$ for the thinner spacer layers of 5 and 10 nm. Conversely, for particles on the rear $Q_{\text{scat}}(\lambda_{\text{spr}}) = 3.8$ for the thinnest spacer layer of 5 nm and reduces to a value of 1.7 for the thicker 40 nm case. No significant difference in F_{subs} is observed between simulations of front and rear located nanoparticles. From these results it is clear that for a given spacer layer thickness the strength of the scattering cross-section, and hence the light-trapping provided by the nanoparticles, is dependent on the location of the nanoparticles.

We attribute these differences in scattering cross section magnitude to differences in the intensity of the electric field driving the localised surface plasmon resonance[10].

4 OPTIMISING SELF-ASSEMBLED AG NANOPARTICLE ARRAYS FOR LIGHT-TRAPPING

Applying the design principles discussed previously we present results for optimal self-assembled Ag nanoparticles, providing light-trapping for thin c-Si solar cells [11].

External quantum efficiency measurements were performed on 22 μm thick, bifacial c-Si solar cells, with a double dielectric structure of 10 nm of thermally grown SiO_2 and 8 nm of low pressure chemical vapour deposited Si_3N_4 , on both front and rear surfaces of the cells.

Nanoparticles were fabricated on the rear of the cells to avoid suppression at short wavelengths. This allowed us to optimise the particles for light-trapping and to incorporate a single layer anti-reflection coating (ARC) to ensure low reflectance losses at the front surface. For the ARC we used 82 nm of atmospheric pressure chemical vapour deposited (APCVD) TiO_2 , deposited at 200°C, with a refractive index of 2.1 at a wavelength of 630 nm. The scattering resonance of the nanoparticles was tuned to long wavelengths, near the band edge of Si (1180 nm), by over-coating the particles with 89 nm of APCVD TiO_2 ($\text{RI} = 2.1$). This ensured that the dielectric spacer layers isolating the particles from the Si were kept thin, keeping the particles close to the Si interface to ensure good coupling while maintaining electrical passivation of the Si surface. A detached Ag mirror was incorporated behind the nanoparticles at the rear of the cells to provide multiple scattering opportunities for light that is not initially scattered by the nanoparticles into the substrate.

The short circuit current density at each wavelength ($J_{\text{sc}}(\lambda)$) for a cell illuminated with the AM1.5g spectrum is calculated from the experimentally measured EQE multiplied by the number of photons at each wavelength and the charge of an electron. Since the nanoparticles are located on the rear of the cells they only affect short circuit current in the wavelength region where the light is weakly absorbed. In order to quantify the effect of the

nanoparticles on $J_{\text{sc}}(\lambda)$ we define the light-trapping spectral region, from the wavelength at which transmission losses exceed 5% for 22 μm of Si, to the absorption edge for single photon absorption in Si (750-1180 nm).

Figure 4 shows $J_{\text{sc}}(\lambda)$ for optimised, rear located nanoparticle arrays on the rear of thin c-Si solar cells with (crosses) and without (circles) a detached rear reflector present, behind the nanoparticles, at the rear of the cell. For reference, we show the same cell with only an ARC coating (dashed line) and with an ARC and the detached mirror behind the cell (solid line).

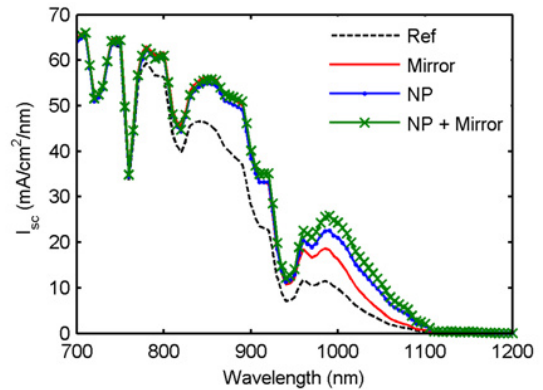


Figure 4: Short circuit current density ($J_{\text{sc}}(\lambda)$), calculated from experimentally measured external quantum efficiency data for 22 μm , Si solar cells without (Ref, dashed line) and with Ag nanoparticles on the rear (NP, dots). Data for the same cell with a detached rear reflector is also shown, with (crosses) and without NP (solid line).

The cell with only a mirror present performs as well as the cells with nanoparticles on the rear up to a wavelength of 870 nm. This is due to the fact that specular reflection from the mirror increases the path length of light in Si to $\sim 44 \mu\text{m}$ which absorbs 90% of the incident light up to a wavelength of 870 nm. Beyond this wavelength the nanoparticle arrays (crosses and dots) perform better than the cells with only a mirror present (bare line). By scattering light at high angles the nanoparticles can trap a significant portion of the light inside the Si by total internal reflection, leading to an increase in the path length of light in the cell, compared to cells with a mirror present. When a mirror is included behind the nanoparticles (crosses), light that is not initially scattered by the particles into the Si substrate is reflected back to provide multiple scattering opportunities, increasing the photocurrent further. Integrating $J_{\text{sc}}(\lambda)$ over the wavelength range 750-1180 nm gives the total J_{sc} in the light-trapping region, $J_{\text{sc}}^{\text{LT}}$. The enhancement in photocurrent is calculated by dividing the $J_{\text{sc}}^{\text{LT}}$ for the nanoparticle sensitised cells by the $J_{\text{sc}}^{\text{LT}}$ of cell with only an ARC. For a cell with an ARC and an optimised random Ag nanoparticle array on the rear (dots) $J_{\text{sc}}^{\text{LT}}$ is enhanced by 27%; when a detached Ag mirror is present behind the particles (crosses) the $J_{\text{sc}}^{\text{LT}}$ enhancement is increase to 33%.

Previous reported measurements from nanoparticle

enhanced, wafer based, c-Si solar cells have utilised front-located nanoparticle arrays [1]. These particles provide anti-reflection as well as light-trapping, and the quoted enhancements of 19% are calculated in comparison to planar Si cells with no ARC, over the whole wavelength spectrum from 300-1200 nm. In our experiment with rear-located nanoparticle arrays we are able to optimise the nanoparticle scattering for light-trapping and incorporate a dielectric ARC, which can be optimised independently. If we compare the anti-reflection and light-trapping provided by our experimental cell structures (incorporating the detached mirror behind the cells) to a planar cell with no ARC, over the measured spectrum from 350-1200 nm, the photocurrent enhancement is increased to 39%.

5 SUMMARY

We demonstrate tunable light trapping for solar cells provided by self-assembled Ag nanoparticles on the front and on the rear of Si solar cells. We show that there is an asymmetry in the efficiency of the light-trapping provided by front and rear located nanoparticles, which is dependent on spacer layer geometry, and which we attribute to differences in the scattering cross section magnitude. We present the largest reported photocurrent enhancements due to plasmonic light trapping on thin c-Si solar cells. By optimising rear-located, self-assembled nanoparticle arrays for light trapping, and incorporating a dielectric ARC and a detached rear reflector, we achieve a 33% relative increase in photocurrent over the light trapping spectral region.

6 REFERENCES

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