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Optical characterisation of a spectrally tunable plasmonic reflector for application in thin-film silicon solar cells

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ABSTRACT

We have investigated the interaction between a random two-dimensional array of Ag islands near a Ag reflector, with the aim of producing a plasmonic back reflector structure with high diffuse reflectivity in the near-infrared, 600–1100 nm wavelength, region. We have demonstrated the ability to tune the power scattered and absorbed by varying the distance between the plasmonic layer and the reflector. Finite-difference-time-domain (FDTD) simulations demonstrate the tunability of the scattered and absorbed power with separation distance for a single Ag nanosphere near a planar Ag reflector. The tunability of the optical properties can be attributed to the modulation in the electric field driving the plasmonic resonance with separation distance. The simulation results indicate an intermediate distance where the scattered power peaks with minimal absorption losses. Random arrays of metal-islands were fabricated on varying thicknesses of a ZnO separation layer on a Ag reflector. Compared to a conventional textured Ag reflector, which has ~2% diffuse reflectance in the near-infrared spectral region, the fabricated plasmonic reflector with ~200 nm sized Ag metal islands at 100 nm separation distance from the Ag reflector shows a relatively higher, ~24%, integrated diffuse reflectance in the near bandgap, 600–1100 nm wavelength, region for thin film silicon solar cells.

1. Introduction

Decreasing the thickness of the absorption layer of a solar cell reduces material costs and improves carrier extraction, but also reduces the absorption of photons. Light-trapping methods can be used to improve absorption by increasing the effective optical path length within the silicon. The standard method to achieve this is to exploit textured interfaces with feature sizes in the order of the wavelength of the light to be scattered [1]. The requirement for light-trapping is strongest for thin film silicon, where the absorption coefficient decreases significantly with increasing wavelength, and so light-trapping is primarily required in the near-infrared (NIR), 600–1100 nm wavelength range. However, there is a limit to the surface roughness that can be introduced before the electronic performance of the silicon device deteriorates as a result of growth defects [2,3]. So in a traditional device a compromise has to be found between the maximum light-trapping that can be attained and the electrical performance of the device.

Metal nanoparticles can strongly scatter light despite having dimensions substantially smaller than the wavelength [4,5]. A two-dimensional array of metal nanoparticles can be placed at the front or rear of a solar cell to scatter a broad range of wavelengths without the need to texture the semiconductor. The optical properties of metal nanoparticles are strongly sensitive to the nanoparticle geometry and the surrounding medium, and these parameters must be optimised to maximise scattering of light into the semiconductor layer and minimise parasitic absorption within the nanoparticle. The scattering peak can be tuned to the NIR by increasing the nanoparticle size or aspect-ratio, or by embedding the particle within a layer that has a high refractive index [6–8]. Parasitic absorption can be minimised by restricting designs to Ag nanoparticles larger than approximately 100 nm, with geometries that do not have sharp features [9,10]. The position of the nanoparticles within the solar cell must also be optimised. Situating nanoparticles on the front surface allows for both anti-reflection and light-trapping [11] but can result in losses due to absorption at short wavelengths and back-scattering [9,12,13]. Nanoparticles situated at the rear of the device only interact with photons that are weakly absorbed by the semiconductor, and out-coupling losses can be eliminated by the inclusion of a rear reflector.

Thin-film silicon solar cell designs typically include a transparent conductive oxide (TCO) layer between the silicon layer and the back contact. Metal nanoparticles embedded on or within the rear TCO layer have been shown to increase the efficiency of amorphous, microcrystalline and crystalline silicon solar cells [14–16]. Further gains in efficiency may be possible if the position

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of the metal nanoparticle array within the TCO is adjusted to optimise the distance-dependent optical interaction with both the silicon layer and the mirror. The interaction with the silicon layer for rear-mounted nanoparticles has been studied in bifacial solar cells, and optimum results were found for nanoparticles in direct contact with the silicon layer [11,16]. In this study we will investigate the interaction between metal nanoparticles and the back contact, with the aim of producing a back reflector structure with a high diffuse reflectivity in the NIR.

2. Localised surface plasmons and driving field

Localised surface plasmons (LSP) are collective oscillations of electrons on the surface of an illuminated metal nanoparticle. An excited plasmon, i.e., a quantum of the oscillating electron cloud, may decay non-radiatively, resulting in absorption losses and by photon emission, resulting in ‘scattering’ of the incident electromagnetic field. The LSP resonance frequency can be tuned by varying the refractive index of the surrounding medium as well as the shape, size and metal type of the nanoparticle [6].

For thin film photovoltaic devices, the LSP resonance frequency can be tuned to comply with the optical absorption properties of the absorber layer. For example, in μc-Si thin film solar cells, the optical absorption efficiency needs to be increased in the near bandgap range, i.e., in the NIR wavelength range of 600–1100 nm. In this case, a plasmonic scattering system can be integrated at the rear of the device to scatter and consequentially increase the optical path length of inefficiently absorbed photons with energies close to the bandgap of the absorber layer. Given a conventional thin film solar cell configuration, the scattering properties of a plasmonic system at the rear of the device can be reinforced by exploiting the optical properties of the planar metal contact at the rear. In this paper, we will explore this possibility by simulation and fabrication of a plasmonic back reflector comprising of Ag nanoparticles near a planar Ag reflector. The key challenge is to modulate the electric field driving the LSPs and spectrally optimise the scattering properties while minimising the inherent absorption losses of the plasmonic reflector.

Fig. 1 is a simple 2D illustration of the electric fields which dictate the optical properties of a metal nanosphere near a planar reflector. For the case of an isolated sphere in a homogeneous medium, we will consider Fig. 1 without the planar reflector, i.e., without the contribution of the reflected-scattered field, $\mathbf{E_{rs}}(\theta_{rs})$ and the unscattered-reflected field, $\mathbf{E_r}$. There are then three fields to consider: the parallel polarised incident field, $\mathbf{E_i}$, the LSP driving field, $\mathbf{E_d}$, and the scattered field, $\mathbf{E_s}(\theta_s)$. For ease of explanation, we will consider the case of normal incidence and the excitation of the dipolar LSP mode. Although the optical properties of a metal nanosphere are independent of the polarisation of $\mathbf{E_i}$ for normal incidence, the polarisation of $\mathbf{E_i}$ has been included to emphasise its effect on $\mathbf{E_d}$.

$\mathbf{E_i}$ induces a dipole moment $\mathbf{P}$ which oscillates in a direction parallel to the polarisation of $\mathbf{E_i}$. The dipole moment for the case of an isolated metal nanoparticle in a homogenous medium is given by

$$\boldsymbol{P} = \alpha\varepsilon_0 \boldsymbol{E}_\mathbf{d} \tag{1}$$

where α is the polarisability of the particle and ε_o is the free-space permittivity. The radiative decay of the excited LSPs results in the scattered field $\mathbf{E_s}(\theta_s)$.

However, when the plasmonic particle is near a planar reflector, as in Fig. 1, two important changes occur. Firstly, $\mathbf{E_d}$ is influenced by the interference among $\mathbf{E_i}$, $\mathbf{E_r}$ and $\mathbf{E_{rs}}(\boldsymbol{\theta}_\mathbf{rs})$. Secondly, the polarisability, α in Eq. (1), is modified into an ‘effective polarisability’, α_{eff} to account for the effect of the reflected-scattered field [17]. As a result of these two changes, the induced dipole moment in Eq. (1) is also modified and this in turn has an effect on the resultant total scattered power P_{scat} and optical scattering cross section σ_{scat} which are given by [17,18]:

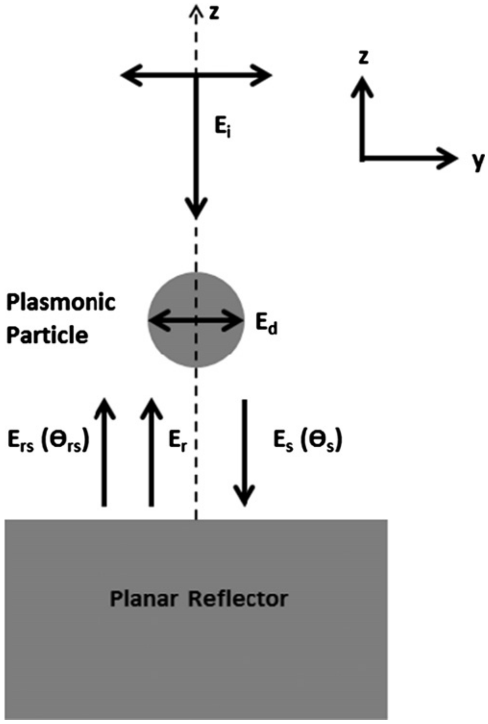

Fig. 1. 2D illustration of the electric fields which dictate the optical properties of a metal nanosphere near a planar reflector. $\mathbf{E_i}$ is the parallel polarised incident field at normal incidence, $\mathbf{E_r}$ is the unscattered-reflected field, $\mathbf{E_d}$ is the LSP driving field, $\mathbf{E_s}(\theta_s)$ is the scattered field radiated from the plasmonic particle and $\mathbf{E_{rs}}(\theta_{rs})$ is the reflected-scattered field.

$$P_{scat} = \frac{\pi}{\lambda}\mathrm{Im}\left[\mathbf{P}^{*}\cdot\mathbf{E}_\mathrm{d}\right] \tag{2}$$

$$\sigma_{scat} = \frac{P_{scat}}{I_{in}} = \frac{2\pi}{\lambda}\mathrm{Im}\left[\alpha_{eff}\right]I_d \tag{3}$$

where I_d is the intensity of the $\mathbf{E_d}$ and I_{in} is the intensity of $\mathbf{E_i}$. The power absorbed and the absorption cross section are derived in a similar method to Eqs. (2) and (3). Hence, for the design of an efficient plasmonic reflector, based on Eqs. (2) and (3), it is clear that the interdependence of $\mathbf{E_d}$, $\mathbf{E_{rs}}(\theta_{rs})$ and $\mathbf{E_s}(\theta_s)$ can be exploited to spectrally optimise the power scattered and minimise the power absorbed by the plasmonic scattering system.

3. Simulated optical properties of a single Ag nanosphere near a planar reflector

Varying the separation distance between the metal nanosphere and the reflector is one way to modulate the effective driving field. We have simulated the percentage power absorbed and scattered for the case of a single 100 nm diameter Ag sphere in vacuum for a range of distances from a semi-infinite Ag reflector. The simulations have been conducted using the three-dimensional finite-difference-time-domain (FDTD) method (Lumerical FDTD Solutions software). In accordance with the Mie theory, the radiative efficiency, i.e., the scattering to extinction ratio (where extinction is the sum of scattering and absorption) of a 100 nm Ag sphere is more than 0.9 in the visible to near-infrared wavelength range. The simulated