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Colloidal self-assembled nanosphere arrays for plasmon-enhanced light trapping in thin film silicon solar cells

Manuel J. Mendes[a,*], Seweryn Morawiec[a], Isodiana Crupi[a], Francesca Simone[a] and Francesco Priolo[a,b]

[a]*MATIS CNR-IMM and Dipartimento di Fisica e Astronomia, Università di Catania, via S. Sofia 64, 95123 Catania, Italy*
[b]*Scuola Superiore di Catania, Via Valdisavoia 9, 95123 Catania, Italy*

Abstract

To realize high-efficiency thin-film silicon solar cells it is crucial to develop light-trapping methods that can increase absorption of the near-bandgap light in the silicon material. That can be achieved using the far-field scattering properties of metal nanoparticles (MNP) sustaining surface plasmons. The MNPs should be inserted in the back of the cell, embedded in the transparent conductive oxide (TCO) layer which separates the rear mirror from the silicon layers. In this way, a plasmonic back reflector (PBR) is constructed that can redirect light at angles away from the incidence direction and thereby increase its path length in the cell material.
In this work, a novel technique is presented to fabricate PBRs (composed of Ag mirror/TCO/MNPs/TCO) containing colloidal gold MNPs patterned with a self-assembly wet-coating method. The method allows the construction of long-range ordered arrays of MNPs with monodisperse size and shape using fast, scalable, low-cost and low-temperature (<120^{o}C) procedures.
Colloidal MNPs are synthesized with spherical shapes, so their scattering properties are analytically modeled with Mie theory. Such formalism allowed the computation of the preferential MNP sizes that provide the best scattering performance for light-trapping in amorphous and microcrystalline thin-film silicon solar cells.

Keywords: Thin film solar cells; Plasmonics; Light trapping; Colloidal Metal Nanoparticles; Mie theory

1. Introduction

Thin-film (TF) solar cells have stimulated enormous research interest as a low-cost alternative to bulk crystalline cells [1,2]. However, a limitation common to all thin-film photovoltaic (PV) technologies is that the absorption of the near-bandgap light is small, due to their reduced material thickness. The application of light trapping methods is a promising strategy to increase the optical density (and consequently the quantum efficiency) of TF cells at the wavelengths that are poorly absorbed by its PV material [3-6]. In addition, light trapping enables further reduction in the thickness of the PV material, which improves the conditions for charge carrier collection and lowers even more the material costs of the devices.

* Corresponding author. Tel.: +39-095-378-5239; fax: +39-095-378-5243.
E-mail address: manuel.mendes@ct.infn.it

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Nowadays, most commercial TF solar panels are composed of thin-film silicon (Si) layers grown on textured substrates. The texturing redirects the incident light to angles away from the incidence direction, thereby enhancing the path length of the photons inside the cell and, consequently, their absorption probability. However, the roughness induced in the Si layers causes dislocations and defects in the cell material, which have been shown to be detrimental to the open-circuit voltage and fill-factor of the devices [7].

The light trapping method developed in this work allows the enhancement of the light absorbed in the cell without producing roughness in the Si layers. The method makes use of the light scattering properties of metallic nanoparticles (MNPs) sustaining surface plasmons (SPs) [3,8,9]. Sub-wavelength MNPs can act as antennas at optical frequencies, gathering the light from their surroundings and scattering it to their far-field over a broad angular range. This makes the light follow more horizontal paths, in a similar way as occurred with texturing, increasing its absorption in the PV material. The SP resonance can be particularly pronounced in MNPs made of noble metals such as silver (Ag) or gold (Au), due to their low imaginary permittivity. Nevertheless, MNPs can also exhibit significant light absorption, so they should be preferentially located in the rear side of the cell, acting as a plasmonic back reflector (PBR), in order for them to interact only with light that is not absorbed in the first pass through the cell material [4,10,11]. The proposed PBR configuration is depicted in Fig. 1.

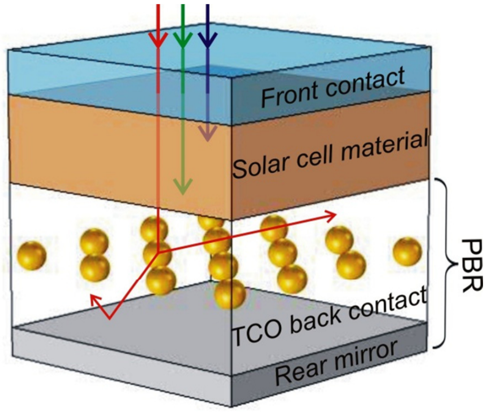

Fig. 1: A typical back reflector (also back contact) of a TF cell is composed of a metallic mirror (made of silver or aluminum) separated from the p-n junction(s) (referred in the image as solar cell material) by a TCO layer. The MNP structure should be preferentially located inside such TCO layer, since the TCO acts as a barrier for the diffusion of metallic impurities to the cell material [12] and prevents current degradation through carrier trapping and recombination at the MNPs surface.

Most studies performed so far, aimed at developing PBRs, construct the MNP structures by annealing a thin layer of a precursor metal [10,13]; a technique known as thin-film annealing (TFA). It has already been demonstrated that Ag MNPs, fabricated by TFA and embedded in a back reflector configuration, can provide light trapping performance comparable to state-of-the-art random textures in hydrogenated amorphous silicon (a-Si:H) solar cells [4,11]. However, there is a high non-uniformity in the geometry of MNPs fabricated with TFA and their material is usually not purely crystalline [10], which results in an attenuation of the resonant optical response of the overall nanostructures. Besides, TFA requires high-temperature (>300^{o}C) annealing to produce nanoparticles with appropriate sizes, so the MNP structure has to be fabricated prior to the deposition of the Si cell layers, otherwise the high temperature would damage the hydrogen bonds of the hydrogenated TF Si material.

The approach presented here is promising to overcome the aforementioned issues. A self-assembly colloidal deposition technique was developed to construct long-range ordered arrays of crystalline Au nanoparticles with monodisperse size and shape [14,15]. Using such wet-coating method, MNP arrays have been patterned throughout indefinitely large surfaces employing low-cost and low-temperature (<120^{o}C) procedures, which are compatible with large-scale production and allow the fabrication of the MNP structures as a post-process after the deposition of the Si cell layers.

Colloidal MNPs are synthesized in solution with approximately spherical shapes, so their scattering properties can be analytically modeled using Mie theory. This is an electromagnetic separation-of-variables method that can compute scattering by spherical particles of any size immersed in a homogeneous medium. In this work, a modified Mie theory formalism is used to account for absorption in the medium surrounding the particles [16]. Such formalism allowed the determination of the preferential particle diameters that can provide the best scattering performance, for distinct types of TF Si solar cells.

2. Mie theory studies

An important advantage of colloidal Au nanoparticle structures is that their optical response can closely match Mie theory computations, since they can be synthesized with highly mono-dispersed spherical shapes and with pure crystalline materials. In