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Plasmonic nanoparticle films for solar cell applications fabricated by size-selective aerosol deposition

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Abstract

A soft deposition method for incorporating surface plasmon resonant metal nanoparticles within photovoltaic devices was studied. This self-assembly method provides excellent control over both nanoparticle size and surface coverage. Films of spherical Ag nanoparticles with diameter of ~100 nm were fabricated by depositing size-selected aerosols on various substrates using electrophoresis. This novel deposition method opens the route to embed plasmonic nanoparticles in the intermediate reflector of a micromorph silicon tandem PV cell. We have for the first time fabricated working tandem cells of this type. Compared to a flat reference device the Ag particles enhanced the short-circuit current density due to improved light trapping. The enhancement is, however, limited by the sulfidation on the surface of Ag nanoparticles and a further optimization of the cell fabrication method is required to prevent a reduction of open-circuit voltage and fill factor.

Keywords: light trapping; plasmonics; silver nanoparticles; aerosol; thin-film solar cells.

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1. Introduction

A film of plasmonic nanoparticles can improve solar cell performance by trapping incident light into the photo-absorbing layer. However, the optical properties of the film depend strongly on the size, shape and surface coverage of the nanoparticles. Ag nanoparticles of ~100 nm diameter are especially attractive due to their large scattering cross sections and relatively low parasitic absorption [1]. Self-assembly methods present advantages over nanofabrication methods for the scalable production of large area nanoparticle films at low cost, as is required for solar cell applications. Metal-island films, formed by annealing a thin metal layer deposited on a substrate, present the most common self-assembly approach. This technique is simple and uses conventional technology. However, to obtain sufficiently large particles and a sufficiently low surface coverage, high annealing temperatures of ~400 °C are required [3]. Particles formed by a lower annealing temperature have a different morphology and suffer from too high parasitic absorption losses [4]. Promising results have been obtained using a plasmonic back reflector in amorphous silicon and micro-crystalline silicon solar cells [5,6]. This back reflector can be fabricated firstly at 400 °C and the thin-film solar cell can be deposited on top afterwards. Embedding the particles inside the intermediate reflector of a micromorph tandem cell would be very interesting as well, as both the forward and backward scattered light can be utilized by top and bottom cell, respectively. However, this would require the formation of the nanoparticles onto an already deposited cell, which limits the processing temperature to ~200 °C.

Exposing the solar cell to high temperatures can be avoided when the silver particles are formed at high temperature separately (i.e. not directly on the substrate) and then deposited onto the solar cell substrate at low temperature. Colloidal routes provide an excellent control of particle size, allowing the formation of ordered nanoparticle layers [7,8]. However, the colloidal suspensions contain large amounts of impurities which are difficult to remove from solar cells, specifically surfactants, and which can seriously deteriorate the performance of thin-film silicon solar cells. Moreover, the surface coverage of nanoparticles is difficult to control. Our objective is to develop a low temperature, low cost, and scalable process to manufacture films of silver nanoparticles with precise control of the size and surface coverage of Ag nanoparticles. Low temperature processing makes it possible to deposit the film directly onto an existing semiconductor layer. To achieve this, we use an aerosol approach that involves the generation of an aerosol of spheroid nanoparticles, isolating particles of a given mobility to obtain a monodisperse particle size, and softly depositing the particles under an electric field [2,9]. In this study, we demonstrate that Ag nanoparticle films of higher purity can be obtained using a spark generator rather than a furnace as the primary aerosol source. We report on the performance of two solar cell configurations: a single junction cell with Ag nanoparticles deposited on micro-crystalline silicon (μc-Si), and a tandem cell with Ag nanoparticles placed between the amorphous silicon (a-Si:H) top cell and μc-Si:H bottom cell.

Nomenclature

d_p	diameter of particle
EQE	external quantum efficiency
FF	fill factor
J_{sc}	short-circuit current density
$Q_{\mathrm{scat.}}$	scattering cross-section
$Q_{\mathrm{abs.}}$	absorption cross-section
R_{s}	series resistance
R_{sh}	shunt resistance
V_{oc}	open circuit voltage
η	efficiency
θ	surface coverage
Φ	flow rate at 20°C and 1 atm, in L min^{-1}