

ENHANCED PHOTOCURRENT IN EVAPORATED SOLID-PHASE-CRYSTALLISED POLY-SI THIN-FILM SOLAR CELLS USING REAR SURFACE PLASMONS

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ABSTRACT: We demonstrate enhancements in photocurrent and conversion efficiency for thin-film Si cells on glass due to plasmonic light-trapping. In this work, silver nanoparticles were formed on the rear surface of evaporated solid-phase-crystallised poly-Si thin-film solar cells coated with an intermediate dielectric layer. We find that localised surface plasmon excited in nanoparticles can increase the light absorption of the Si films and thereby enhance the spectral response and efficiency of the cells. Short-circuit current and efficiency under standard illumination condition increased by 13% and 10% respectively compared to the same cell without surface plasmons. This is a very important finding as evaporated Si thin-film solar cells have few options for effective light trapping which are simple and do not harm the cell structure, like surface plasmons. Effects of different dielectric layers on enhancement are also investigated.

Keywords: Thin Film Solar Cell, Light Trapping, Surface Plasmon

1 INTRODUCTION

Polycrystalline Si (poly-Si) thin-film solar cell on glass is one of the promising and fast developing thin-film PV technologies. A conversion efficiency of 10.4% has been demonstrated on a lab scale mini-module [1]. A possible way to further advance this technology by reducing its manufacturing cost is replacing the low rate and expensive PECVD with the much faster and cheaper e-beam evaporation [2]. Evaporated Solid-Phase-Crystallised (SPC) Poly-Si Thin-film Solar Cells (EVA) on planar glass fabricated at UNSW have so far reached a conversion efficiency of 5.2% [3]. This is comparable with about 6% for PECVD based planar cells and primarily limited by the relatively low light absorption in planar 2-3 μm thick poly-Si films. Significantly higher efficiencies can only be achieved with efficient light trapping, conventionally done by glass texturing. However, the evaporation method appears much less compatible with textured glass compared to PECVD due to a defective microstructure commonly formed in evaporated films on textured substrates leading to poorly performing devices [4]. An alternative light-trapping technique, which does not involve textured glass, is therefore preferred. The excitation of surface plasmons on metal nanoparticles is one of such novel techniques. Surface plasmons have previously been applied to enhance the light trapping in Si wafer-based solar cells, amorphous, micromorph, organic, dye sensitised and GaAs thin-film solar cells [5, 6]

Localised Surface Plasmons (LSP) on Silver (Ag) nanoparticles can scatter a large fraction of incident light into a nearby Si film at large angles. This makes surface plasmons very attractive for light trapping in Si thin-film solar cells. With the adjustment of nanoparticle material and size, and the local dielectric environment, the LSP resonance can be excited by incident light at a controllable range of frequencies. When the nanoparticles are in the vicinity of a high refractive index substrate, the angular emission spectrum is modified such that a large fraction of the light scattered by the particles is directed into the optically dense layer over a large angular range. See the schematic diagram in Fig. 1. It has been shown that nanoparticles on the rear of the cell can provide light

trapping at wavelengths where light is weakly absorbed in Si [7] while avoiding suppression at short wavelengths due to interference effects for the front located nanoparticles [8]. Catchpole et al. have developed fundamental design principles for the application of LSP for light trapping [6, 9]. For effective light trapping the LSP scattering resonance should be shifted to wavelengths at which transmission losses become significant. This can be achieved by increasing the refractive index of the underlying dielectric layer [7].

In this work we demonstrate light-trapping in functional poly-Si thin-film solar cells on glass, with a superstrate configuration, by the application of Ag nanoparticles to the rear surface. With Ag nanoparticles on an optimal intermediate dielectric layer, we have so far achieved 13% short-circuit current (J_{sc}) enhancement and 10% efficiency enhancement under AM1.5G illumination.

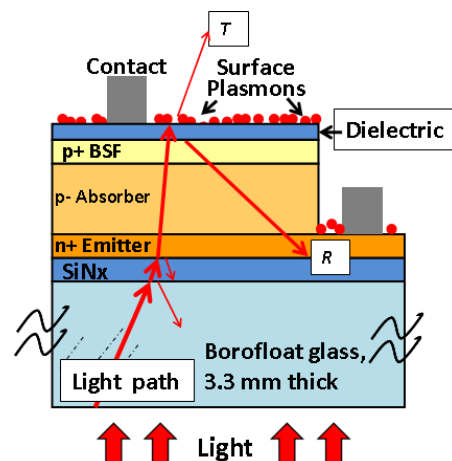


Figure 1: Schematic diagram of an EVA solar cell in superstrate configuration. Surface plasmons applied to the rear surface (not to scale). T is the transmittance of light coupled out to the air. R is the reflectance back to solar cell. Note the high R/T ratio and large R angle (to normal) due to the surface plasmons.

2 EXPERIMENTAL METHODS

The solar cells used in this work were deposited by e-beam evaporation onto planar nitride coated borosilicate glass (deposition pressure about $1E-7$ Torr, absorber deposition rate about 300 nm/min). The 70 nm thick SiN_x coating functions as antireflection and barrier layer. The total cell thickness is of the order of $2\ \mu m$ and the diode structure is n+/p-/p+. After SPC at $600^\circ C$ for 48 hrs, the films received a rapid thermal anneal (RTA, 4 min at $900^\circ C$) and a hydrogen plasma passivation (~ 20 min at $\sim 650^\circ C$). Then the poly-Si films were metallised to bifacial solar cells with interdigitated line contacts on the emitter and the back surface field layers as described elsewhere [10]. The structure of a standard EVA solar cell is shown in Fig. 1. Note that typically our cells work in superstrate configuration, i.e. the cells are illuminated through the supporting glass.

Ag nanoparticles were formed on the rear surface of metallised EVA cells. Prior to the plasmon deposition two kinds of dielectric layers of SiO_x (RI=1.7, 24.8 nm thick) and SiN_x (RI=2.2, 21.3 nm thick) were separately sputtered on two cells for each case for comparison. Ag nanoparticles were formed by thermal evaporation of a thin film of Ag (on top of the dielectric layer) followed by a 50 min anneal in N_2 atmosphere at a temperature of $250^\circ C$. Note that such a low temperature should not affect the electrical properties of the poly-Si solar cells. The structure of a finished cell is also demonstrated in Fig. 1.

Cell characterisation methods used in this work are spectral response measurements (300 nm to 1200 nm wavelength range), light I-V measurements, spectrophotometer measurements (300 nm to 1200 nm wavelength range) and scanning electron microscope (SEM) imaging. Except for SEM, all other characterisations were performed before and after surface plasmon formation.

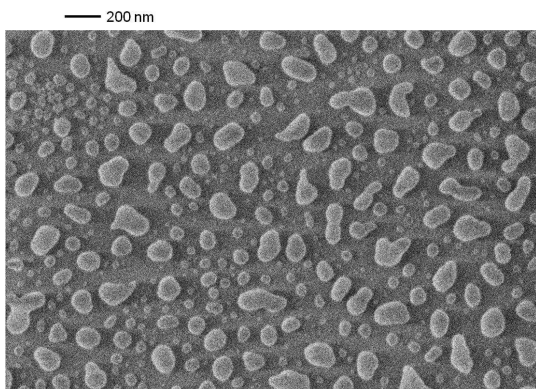


Figure 2: SEM image of the rear surface of an EVA cell where Ag nanoparticles are formed. The surface coverage of the nanoparticles is about 1/3. The average diameter of these particles is about 120 nm.

3 RESULTS AND DISCUSSION

3.1 Ag particle formation

The SEM image of the surface of a finished cell is presented in Fig. 2, showing the Ag nanoparticle formation. Ag particles have a large size distribution with

an average diameter of 120 nm. The approximately hemispherical shape of the nanoparticles has been shown to provide efficient coupling of scattered light into the Si [6]. The surface coverage of the nanoparticles (ratio of particle area to total area) is $\sim 33\%$. The normalized scattering cross-section of Ag nanoparticles of this size on a Si substrate has been calculated by numerical simulation to be around 3 at resonance, which is sufficient to scatter most of the incident light into the cell.

3.2 Spectral response

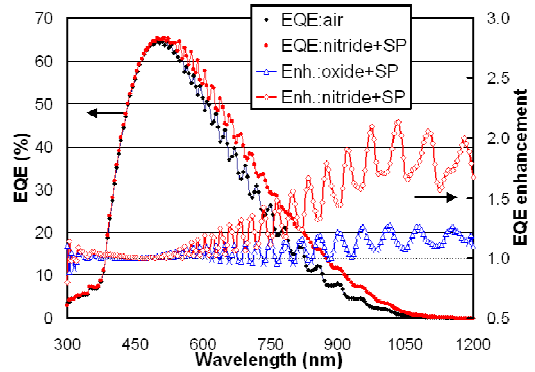


Figure 3: EQE (left axis) and EQE enhancement (right axis) of surface plasmon treated EVA cells. Surface plasmons (SP) on nitride (red) provide better EQE enhancement than those on oxide (blue). EQE of surface plasmon treated cells also have reduced interference fringes than initial (black).

The External Quantum Efficiency (EQE) was measured on all cells. The EQE enhancement ($EQE_{plasmon} / EQE_{initial}$) due to the surface plasmon effects are shown in Fig. 3 (right axis). Since surface plasmons are applied to the rear surface of the solar cells, the spectral response is unaffected for wavelengths shorter than about 500 nm, where almost all photons are absorbed during the first pass through the $2\ \mu m$ thick films, and do not reach the rear surface at all. Although both nitride and oxide as intermediate dielectric layers show EQE enhancements, nitride performs significantly better than oxide. The peak EQE enhancement for nitride is 213% (relative) at 1035 nm; while the peak EQE enhancement for oxide is only 27% (relative) at 1015 nm. The refractive index difference between nitride (RI=2.2) and oxide (RI=1.7) is responsible for this difference in spectral response - the higher RI nitride red-shifts the LSP scattering resonance peak to longer wavelengths where transmission losses become significant so more light at these wavelengths is scattered at large angles and trapped in Si films.

The EQE for the case with nitride as intermediate dielectric layer is also shown in Fig. 3 (left axis). It is noticeable that the surface plasmons lead to a decrease of the EQE interference fringe amplitude. This indicates that light is coupled back into Si film at a wide range of scattering angles, which results in the desired significant pathlength enhancement. Further modeling is necessary in order to fully understand the angular distribution of the reflected light and the resulting pathlength enhancement factors.

The EQE analysis does not reflect the photon density in AM1.5G at a certain wavelength. However, in reality response for wavelengths with high photon density in

sunlight contributes more to photocurrent. To bridge EQE with current flow in the diode circuit, an integral J_{sc} is obtained from:

$$J_{sc} = \frac{q}{hc} \int \lambda \times EQE(\lambda) S(\lambda) d\lambda \quad (1)$$

Where $\eta_{EQE}(\lambda)$ is EQE at wavelength λ , $S(\lambda)$ is AM1.5G spectrum, q is the charge of electron, h is Plank's constant and c is the speed of light in vacuum. For the case of nitride, J_{sc} increased from avaragly 12.3 mA/cm² to 13.9 mA/cm² with an enhancement of 13%; while for the case of oxide, J_{sc} increased from avaragly 12.1 mA/cm² to 12.5 mA/cm² with an enhancement of 3.3%.

3.3 Light I-V characteristics

The resulting light I-V measurements are The surface coverage of the nanoparticles shown in Table 1. It can be noted that the surface plasmons significantly enhance the short-circuit current density J_{sc} , as previously demonstrated by EQE measurements. Surprisingly, the open-circuit voltage V_{oc} for Cell-A (nitride) and Cell-B (oxide) increased slightly. However, a more comprehensive study has shown that V_{oc} remains statistically almost unchanged after surface plasmon formation. The solar cell fill factor FF decreased by about 1% to 2% (absolute) after processing. This is a result of the increased current and the related series resistance losses. The total efficiency enhancements are 10% and 1.5% (relative) for the case of nitride and oxide, respectively. The enhancement of efficiency is slightly lower than the J_{sc} gain due to the lower FF.

Ligh I-V characteristics of EVA cells with and without Ag nanoparticles (NP) as light trapping. A nitride intermediate dielectric layer was used for Cell-A and oxide was used for Cell-B.

Sample	J_{sc} (mA/cm ²)	V_{oc} (mV)	FF (%)	Eff. (%)
A: air	12.5	420	60.7	3.21
A: nitride + NP	14.1 (13%)*	421	59.2	3.53 (10%)
B: air	12.6	431	62.3	3.37
B: oxide + NP	13.1 (4%)	437	59.8	3.42 (1.5%)

* Numbers in the brackets are the percentage increase.

One favorable feature of rear surface plasmon light trapping is that it can be applied to EVA cells by simply adding a few processing steps to the existing EVA fabrication sequence. Note that both dielectric layer deposition and Ag nanoparticle formation can be performed at temperatures low enough to not electronically degrade the poly-Si film performance.

4 CONCLUSION

We demonstrate a significant photocurrent enhancement in evaporated solid-phase-crystallised thin-film poly-Si solar cells on glass resulting from the application of Ag nanoparticles to the rear surface. The Ag nanoparticles were successfully fabricated on two kinds of intermediate dielectric layers (nitride and oxide) on rear side of EVA cells. Localised surface plasmons on Ag nanoparticles provide light trapping by scattering a large fraction of light into Si films (absorber) and at

comparatively large angles. Surface plasmons on the nitride intermediate layer enhance J_{sc} by 13% and the efficiency by 10%, respectively. This enhancement is greater than the enhancement provided by surface plasmons on the oxide intermediate layer of the same thickness.

Further development seems necessary through: (i) optimising dielectric layer thickness and refractive index, (ii) optimising the Ag nanoparticle size, and (iii) combining plasmonic light trapping with other light trapping schemes, for example rear texturing or back side reflectors. Our group is currently performing experiments in order to further advance this light trapping method.

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