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Optimisation of the Back Surface Reflector for Textured Polycrystalline Si Thin Film Solar Cells

Hongtao Cui*, Patrick R. Campbell, Martin A. Green

School of Photovoltaic and Renewable Energy Engineering, The University of New South Wales, Sydney NSW 2052, Australia

Abstract

The back surface reflector of a solar cell not only enhances back reflection, but also may contribute to further randomising light. In this paper, three different types of back surface reflectors (dielectric/metal bi-layer, pigmented diffuse reflector and Ag nanoparticles) are investigated and compared with one another to determine the optimal for polycrystalline Si (poly-Si) thin film solar cells grown on textured glass superstrates. The optimal dielectric layer material and thickness of an interposed dielectric layer between Si and metal contact is optimised via WVASE simulation for ~2 μm random textured poly-Si thin film solar cells on glass. Experimentally, the Si thin films are deposited on Aluminium Induced Textured (AIT) glass and those with optical absorption close to Lambertian limited absorption are selected for investigation. The experiment confirms the simulation results and finds the best back reflector configuration—500 nm MgF₂+Ag. Theoretically Ag nanoparticles on the rear surface of a cell should induce surface plasmon effects, scattering light obliquely into the Si film. However, this work indicates that Ag nanoparticles degrade J_{sc} of textured poly-Si thin film solar cells. The reason why Ag nanoparticles do not work on textured poly-Si thin film solar cells needs further investigation.

* Corresponding author. Tel.: +61-430006325
E-mail address: h.cui@unsw.edu.au

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1. Introduction

Poly-Si thin-film solar cell on glass technology, inheriting the advantages of both wafer Si solar cell technology which dominates the market and the low cost potential of thin-films is promising for future solar applications [1]. A schematic of the poly-Si thin-film solar cell on glass in the superstrate structure is shown in Fig. 1.

Light management of this type of solar cells involves three interfaces functioning to either couple more light into a Si film, or enhance light trapping inside the Si film. The air/glass interface structured to reduce the primary and secondary light reflection, therefore couple more light into the Si film. The glass/Si interface is structured via glass texturing to enhance light trapping inside the Si film. The Si/ back reflector interface designed to maximise back reflection and to potentially enhance light trapping as well. The first two effects have been investigated intensively over past years [2-5].

In this paper, three types of back reflectors are investigated and compared with one another to determine the optimal: (1) interposing a dielectric layer between Si and metal contact; (2) pigmented diffuse reflector (i.e. white paint) and (3) Ag nanoparticles. The three reflectors are introduced briefly in the following paragraph.

A sensible reflector design requires an intermediate dielectric layer (or rear encapsulant) so that total internal reflection can be relied on for light travelling at oblique angle [6]. For a wafer based solar cell, interposing a SiOx layer between Si and Al contact enhances back reflection [7] and also improves back surface passivation [8], and is therefore adopted in high efficiency cell design [9]. This scheme was also applied on poly-Si thin film solar cell on glass and led to a significant short circuit current density enhancement [10]. To determine the optimal back reflector configuration, a WVASE simulation is used to identify the optimal dielectric layer material and thickness. Additionally, white paint is also used for comparison with the optimal configuration above, since it is widely available, cost effective and reflects light diffusely [11, 12]. However, even assuming a Lambertian distribution of light in the paint, refraction at the Si/paint interface results in a focused Lambertian distribution [11]. Paint is proved not as effective
as Ag nanoparticles for poly-Si films on planar glass, though it is not necessarily true for poly-Si films on AIT glass. Ag nanoparticles on the rear surface of a cell induces surface plasmon effects, scatters light obliquely into the Si film, [13] and is therefore also investigated in this work.

2. Experiments

2.1. Experimental details

AIT glass superstrate is prepared according to procedures reported elsewhere [3]. Silicon nitride and amorphous silicon are deposited on the AIT glass prepared above in a KAI800 chamber at Suntech R&D Australia. Subsequently, solid phase crystallisation (SPC), rapid thermal anneal (RTA), and hydrogenation are then performed as in the baseline process [5]. The hydrogenated samples are then metallised using a bifacial metallisation scheme [14].

The back reflector application procedure has largely been reported in ref [13]. Ag nanoparticles are produced by thermally evaporating a thin Ag layer onto the Si diode, followed by annealing at ~200°C for 1 hour in a nitrogen purged oven. The Ag nanoparticle size, shape and coverage are tuned by varying the as-deposited Ag thickness. The dielectric spacing layer and related metal reflector is deposited by thermal evaporation. The white paint is brushed onto the Si diode.

A Perkin Elmer Lambda 1050 spectrophotometer with an integrating sphere (IS) is used to measure hemispherical reflectance (R) and transmittance (T) of the poly-Si film on glass. The absorbance (A) is calculated as A=1-R-T. External quantum efficiency (EQE) is measured for metallised samples. The short circuit current (Jsc) is deduced by multiplying EQE with AM1.5G spectrum datum at each wavelength and then integrating the obtained values in the wavelength range 300-1200 nm. Secondary electronic microscope (SEM) is used for the morphology scan of Ag nanoparticles grown on textured Si film surface.

2.2. Light absorption evaluation

Internal quantum efficiency (IQE) is the ratio of collected photon generated electron hole pairs to the photons absorbed in the semiconductor regions of the cell and is given by: [15, 16]

\[
IQE = \frac{EQE}{1 - R - T} = \eta_{CO} \cdot \frac{\alpha_{eff}}{\alpha_{eff} + \alpha_p} = \eta_{CO} \cdot \frac{\alpha_{Si}}{\alpha_{Si} + \alpha_p}
\]

(1)

where \( \eta_{co} \) is the current collection efficiency, \( \alpha_{eff} \) is the effective absorption coefficient for generating electron hole pairs, usually assumed to be the c-Si absorption coefficient, and \( \alpha_p \) is the total parasitic absorption coefficient. Reorganising the equation gives:

\[
IQE^{-1} = \eta_{CO}^{-1} + \eta_{CO}^{-1} \cdot \alpha_p \cdot \alpha_{Si}^{-1}
\]

(2)

EQE reflects both the device electrical property (current collection efficiency) and optical property (light trapping scheme). The issue with EQE measurement is its dependency on metallisation scheme, the carrier collection efficiency profile and the light trapping scheme. Therefore, an effective criterion other than EQE is needed to evaluate effective light absorption of various solar cell designs. Effective EQE is
proposed as the criterion. Effective EQE at each wavelength equals EQE at each wavelength divided by \( \eta_{c0} \) with \( \eta_{c0} \) calculated by Eq. (2) by linear fitting of IQE\(^{-1}\) versus \( 1/\alpha_{Si} \). To minimise errors, effective EQE is integrated over the wavelength range 700-950 nm to get effective current collection in this wavelength range. This method targets the light trapping wavelength range ~700-1000 nm reported in the literature [2] and does not require identical solar cell design for effective light absorption comparison, which makes it attractive.

2.3. Simulation of interposed dielectric layer

The ideal back reflector (BR) requires highest possible reflection. WVASE simulation is used to determine the optimal dielectric spacing, layer material and thickness between the random textured c-Si film and a metal reflector. In the simulation, the specular reflectance at each incident angle and each wavelength has been simulated for a planar back surface case. Then the weighted reflectance at each wavelength for a randomising back surface reflector can be obtained as [17]:

\[
\bar{R}_b = \frac{\int_0^{\pi/2} R_b(\theta) \exp(-\alpha W / \cos \theta) \cos \theta \sin \theta d\theta}{\int_0^{\pi/2} \exp(-\alpha W / \cos \theta) \cos \theta \sin \theta d\theta}
\]

(3)

where \( \theta \) is the incident angle varying from 0 to 90° and \( W \) is the Si film thickness. For easy comparison, solar spectrum weighted average back reflection \( R_{sw} \) is calculated via the equation below assuming light hits the rear Si film surface with full intensity:

\[
R_{sw} = \frac{\int_{700nm}^{950nm} f(\lambda) \bar{R}_b(\lambda) d\lambda}{\int_{700nm}^{950nm} f(\lambda) d\lambda}
\]

(4)

where \( f(\lambda) \) is the photon flux rate in the AM1.5G spectrum in the wavelength range 700-950 nm.

The back reflector configurations studied in this simulation are: MgF\(_2\)+Ag, SiO\(_2\)+Ag, Si\(_3\)N\(_4\)+Ag, MgF\(_2\)+Al, SiO\(_2\)+Al, Si\(_3\)N\(_4\)+Al, Ag and Al with the dielectric layer thickness varied.

3. Results and discussions

3.1. Simulation of interposed dielectric layer

The \( R_{sw} \) results for each back reflector (BR) configurations are shown in Fig. 2. These indicate that direct Al contact is the worst BR configuration; also, for dielectric thickness above 1000 nm, both MgF\(_2\) and SiO\(_2\) are the ideal interposed dielectric layers; for dielectric layer thickness below 1000 nm, MgF\(_2\) is the best option for the interposed dielectric layer. Additionally, one generally observes that the back reflection increases with increasing dielectric layer thickness and decreasing refractive index of the dielectric layer, with a small fluctuation of \( R_{sw} \) in the dielectric layer thickness range 100-250 nm. Unbalanced interference may account for this fluctuation.
3.2. Paint versus interposed dielectric layer

In order to validate the simulation, various thickness MgF₂+Ag combinations are applied on to textured samples which have optical absorption close to the Lambertian limited absorption. Besides this, paint, 2 μm sol-gel (Methyltriethoxysilane)+paint, 5 μm sol-gel+paint are also applied on the metallised cells for comparison. The sol-gel, Methyltriethoxysilane (MTES), has a refractive index of 1.383 [18], very close to MgF₂ [19]. Effective current in the 700-950 nm wavelength range is used as a criterion to estimate the effectiveness of different back reflector configurations. Note that the back reflector configuration details are listed in Table 1. Figure 3 shows relative current enhancement by applying different back reflectors on 2.2 μm poly-Si solar cells compared to the corresponding cells with air as the back reflector. Combining the Table 1 and Fig. 3, one observes that the current enhancement increases with increasing thickness of MgF₂, which agrees with the simulation. Also, 500 nm MgF₂+Ag are slightly better than white paint as a back reflector with less than 1% absolute difference. Additionally, sol-gel+ white paint is found inferior to white paint as a back reflector. Effective current enhancement in the 700-950 nm wavelength range follows the same trend as effective current enhancement in the 950-1050 nm wavelength range and as overall J_{sc} enhancement.
Table 1. Details of back reflectors in Fig. 3.

<table>
<thead>
<tr>
<th>BR number</th>
<th>BR detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR1</td>
<td>100 nm MgF₂+Ag</td>
</tr>
<tr>
<td>BR2</td>
<td>200 nm MgF₂+Ag</td>
</tr>
<tr>
<td>BR3</td>
<td>300 nm MgF₂+Ag</td>
</tr>
<tr>
<td>BR4</td>
<td>400 nm MgF₂+Ag</td>
</tr>
<tr>
<td>BR5</td>
<td>500 nm MgF₂+Ag</td>
</tr>
<tr>
<td>BR6</td>
<td>paint</td>
</tr>
<tr>
<td>BR7</td>
<td>2 μm sol-gel+paint</td>
</tr>
<tr>
<td>BR8</td>
<td>5 μm sol-gel+paint</td>
</tr>
</tbody>
</table>

Fig. 3. Relative current enhancement by applying varying back reflectors on 2.2 μm poly-Si solar cells compared to the same cells with air as the back reflector. The back reflectors are listed in Table 1. BR6 represents averaged value of paint applied on 3 cells on the same 5*5 cm² AIT sample.

Also for the reflector BR6, Fig. 3 shows that effective current enhancement has no observable deviation, however \( J_{sc} \) enhancement does, indicating the effective current value is a reliable method for light trapping comparison. Figure 4 presents EQE comparison of cells with different back reflector configuration. Figure 4 reveals that BR6-paint is applied on three cells cell1, cell2, cell3 fabricated on the same 5*5 cm² substrate. \( J_{sc} \) enhancement deviation shown in Fig. 3 is due to non-uniformity introduced by the metallisation process as displayed in Fig. 4. Figures 3 & 4 indicate that effective current in the wavelength range 700-950 nm is suitable for light trapping comparison for different EQE performance solar cells.
3.3. Ag nanoparticles as a back reflector

Aside from back reflectors above, surface plasmon effects due to Ag nanoparticles deposited onto rear cell surfaces attract much research attention because these scatter light obliquely and have a high potential to enhance light trapping [13]. In this investigation, the optimal configuration for planar cell, 16 nm as-deposited Ag to produce the nanoparticles plus 350 nm MgF₂ + paint, is investigated initially [13]. Figure 5 compares EQE results of an AIT cell with and without applying the ‘optimal’ back Plasmon as back reflector.
It demonstrates that the back Plasmon configuration degrades EQE dramatically for light of wavelength below 950 nm, causing $J_{sc}$ dropping from 24.3 mA/cm$^2$ to 23.3 mA/cm$^2$. Shunting was considered as a possible reason of this EQE degradation; however, Suns-V$_{oc}$ measurement (Suns-V$_{oc}$ measures $V_{oc}$ by varying the flash intensity—solar concentration [20]) does not indicate any shunt. Another suspect is plasmon absorption [21], which may account for this EQE degradation. The SEM image of the Ag nanoparticles on textured Si film is shown in Fig. 6, which indicates that large particles tend to grow on relative smooth regions like the plateau and the trough and small particles tend to grow on slops.

![SEM image of Ag nanoparticles produced with the as-deposited Ag thickness of 16nm on textured Si film surface.](image)

Further plasmon optimisation finds the new optimal processing parameters for a planar cell: 14 nm as-deposited Ag, anneal at 230°C for 50 minutes [22]. Attempts based on this new optimal condition also do not produce good results, as indicated in Fig. 7. The typical SEM image of relevant Ag nanoparticles on textured Si film is shown in Fig. 8, which presents a quite different morphology compared with Fig. 6. Figure 8 shows a combination of distributed large conjoint islands and small nanoparticles. This island feature may be one major reason of the EQE degradation observed in Fig. 7.
Fig. 7. EQE of 2.2 μm AIT poly-Si cells with air as a back reflector and the same cells with varying Ag nanoparticles as a back reflector. Ag nanoparticles are prepared under different conditions according to the reported optimal conditions. The legend refers to the Ag nanoparticle preparation conditions. Cells 4 and 5 have air as the back reflector; cell5+Ag14nm-230°C refers to cell 5 with Ag nanoparticles as the back reflector, which is prepared at an as-deposited Ag thickness of 14 nm and an anneal temperature of 230°C; likewise cell 5+Ag13nm-230°C and so on.

Fig. 8. Typical SEM image of Ag nanoparticles on textured Si film surface produced with parameters listed in Fig. 7.
4. Conclusions

For poly-Si thin film solar cells on AIT glass superstrates, the optimal back reflector is found to be ≥500nm MgF2+Ag combination as determined by both WVASE simulation and experiment. This enhances effective current in the 700-950 nm wavelength range by ~14%, compared to white paint enhancement by ~13%. WVASE simulation indicates that both SiO2 and MgF2 can be the ideal interposed dielectric layer for the dielectric layer thickness above 1000 nm; and MgF2 is the optimal interposed dielectric layer for the dielectric layer thickness below 1000 nm; also back reflection generally increases with the dielectric layer thickness. Ag nanoparticles on the rear cell surface surprisingly drag down Jsc, which may be due to parasitic absorption and geometrical morphology of the nanoparticles.

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