Optical Enhancement of Amorphous Silicon Solar Cells

Furong Zhu, P.J. Jennings, J.C.L. Cornish, G.T. Hefter and C.P. Lund

School of Mathematical and Physical Sciences
Murdoch University
Murdoch WA 6150
Australia
Telephone: 61 8 9360 2433
Facsimile: 61 6 9310 1711
Email: jennings@fizzy.murdoch.edu.au

Abstract

In this paper we describe the optical admittance method [1, 2] and discuss its use as a design tool to improve the conversion efficiency and the stability of typical single and double junction a-Si:H solar cells of the type: glass/TCO/*pin*/TCO/metal, and glass/TCO/*pin*/*pin*/metal. The use of silver, aluminium and combined TCO/metal rear contacts is also analysed.

1 INTRODUCTION

Amorphous hydrogenated silicon (a-Si:H) is a promising material for use in large area, thin film solar cells. However, its application is still limited by low photovoltaic efficiency and light-induced degradation of the devices. Considerable efforts are being made to overcome these problems and some success has been achieved in recent years. This paper reports on efforts to optimize the optical performance of thin film a-Si:H solar cells using the technique of optical admittance analysis. This procedure takes into account the interference effects in multilayer thin film systems and enables calculation of the optical properties of thin film solar cells with a multilayer configuration. It also allows us to optimise the structure of such cells and utilise interference effects to maximise usage of incident solar radiation.

2 OPTICAL ADMITTANCE METHOD

Any solar cell with a thin film configuration can be considered generally as a multilayer system composed of materials with different optoelectronic properties. For example, if a thin film photovoltaic device has *m* layers, the effective optical admittance, y_{eff}, of this multi-layer structure can be defined as $y_{eff} = C / B$, where B and C can be determined by solving the following characteristic matrix equation [3,4]:

$$\begin{pmatrix} B \\ C \end{pmatrix} = \left[\prod_{j=1}^{m} \begin{pmatrix} \cos\delta_j & (i \sin\delta_j)/y_j \\ i y_j \sin\delta_j & \cos\delta_j \end{pmatrix} \right] \begin{pmatrix} I \\ y_{m+1} \end{pmatrix}. \tag{1}$$

where y_j and y_{m+1} are the admittance of the *j*th layer and substrate respectively. I is the unit matrix, δ_j is the angular phase given by:

$$\delta_j = \frac{2\pi N_j d_j \cos\theta}{\lambda}, \tag{2}$$

where d_j is the actual thickness of the jth layer in this m layered structure, and N_j is the corresponding complex refractive index given by $N_j = n_j(\lambda) - ik_j(\lambda)$. Where $n_j(\lambda)$ and $k_j(\lambda)$ are real and imaginary parts of N_j, respectively. The characteristic matrix Eq.(1) takes into account the effect of the multiple reflections in a multi-layer structure. Using the value y_{eff} calculated from an m layered thin film system, the total reflectance as a function of wavelength, $R(\lambda)$, can be expressed as [4,5]:

$$R(\lambda) = \left| \frac{N_0 - y_{eff}}{N_0 + y_{eff}} \right|^2, \tag{3}$$

Where N_0 is the refractive index of air. The reflectance thus obtained depends on the wavelength of the incident radiation. Assuming normal incidence, the total transmittance as a function of wavelength, $T(\lambda)$, can be expressed as [4,5]:

$$T(\lambda) = [1 - R(\lambda)] \prod_{j=1}^{m} \psi_j \tag{4}$$

where ψ_j is the ratio of the time averaged numerical magnitude of the Poynting's vector at the jth and (j-1)th boundaries, and is given by [4,5]:

$$\psi_j = \frac{\mathrm{Re}(Y_{j+1})}{\mathrm{Re}(Y_j) \left| \cos\delta_j + \frac{Y_{j+1} \sin\delta_j}{N_j} \right|^2}, \tag{5}$$

where Re(Y_{j+1}) and Re(Y_j) represent the real parts of the effective admittance Y for the (j+1)th, and jth, layers respectively. The total absorbance as a function of wavelength, $A(\lambda)$, in this m layer system can be calculated from the following expression [5,6]:

$$A(\lambda) = 1 - T(\lambda) - R(\lambda). \tag{6}$$

Similarly, the net absorbance of the ith layer, $A_i(\lambda)$, in an m layer structure can be determined by [5,6

$$A_i(\lambda) = [1 - R(\lambda)]\,[1 - \psi_i(\lambda)] \prod_{j=1}^{i-1} \psi_j(\lambda), \tag{7}$$

Using the flux of the incident solar radiation $F(\lambda)$, measured in Wm^{-2} μm^{-1}, the integrated absorbance of any individual layer, $\bar{A}_i$, and the total absorbance of an m-layered system, $\bar{A}$ can be calculated as [15,16]:

$$\bar{A}_i = \frac{\int A_i(\lambda) F(\lambda)\, d\lambda}{\int F(\lambda)\, d\lambda}. \tag{8}$$

$$\bar{A} = \frac{\int A(\lambda) F(\lambda)\, d\lambda}{\int F(\lambda)\, d\lambda}. \tag{9}$$

The aim of the overall device design for a-Si:H solar cells is to maximise the efficiency and minimise the photo-degradation. It has been found that an effective way to improve the stability of a-Si:H solar cells is to use the stacked multijunction structure which consists of two or three *pin* single junctions in series. This allows each *pin* junction to respond actively to different parts of the incident solar radiation. Thus the thickness of the *i*-layer in each *pin* junction can be reduced so that a high electric field can be maintained across the *i*-layer. The thickness of the *i*-layer in the multijunction a-Si:H solar cell can be optimised through maximising the integrated absorbance of the *i*-layer and the total absorbance of a cell. By calculating $\bar{A}_i$ and $\bar{A}$ from Eqs. (8) and (9) we can optimise the thickness of the cell through maximising the integrated absorbance of the cells. An optimal structure of a thin film solar cell thus designed will be useful in the fabrication of such cells with multijunction configuration.

3 OPTICAL PROPERTIES OF SINGLE JUNCTION a-Si:H SOLAR CELLS

We have applied this approach to study the optical properties of typical single junction and double junction a-Si:H solar cells of the type: glass/TCO/*pin*/TCO/metal, and glass/TCO/*pin*/*pin*/metal, respectively. Silver, aluminium and TCO/metal, are used as rear contacts. The optical constants $n(\lambda)$ and $k(\lambda)$ used for these metals, TCO, *p*-, *i*- and *n*- type layers of a-Si:H materials in the single junction and multijunction solar cells are taken from published experimental results [6,7].

In this study we first calculated the spectral absorbance, A(λ), of the two typical single junction a-Si:H solar cells with the structures of glass/TCO/*pin*/Al and glass/TCO/*pin*/TCO/Al as a function of wavelength, λ. The results are shown in Figure 1, where $A(\lambda)$ is plotted as a function of λ for both cells containing a 0.5 μm thick *i*-layer. The dashed curve in Figure 1 is calculated for a cell with an Al rear contact, and the solid curve in Figure 1 is obtained for a cell with TCO/Al back contact.

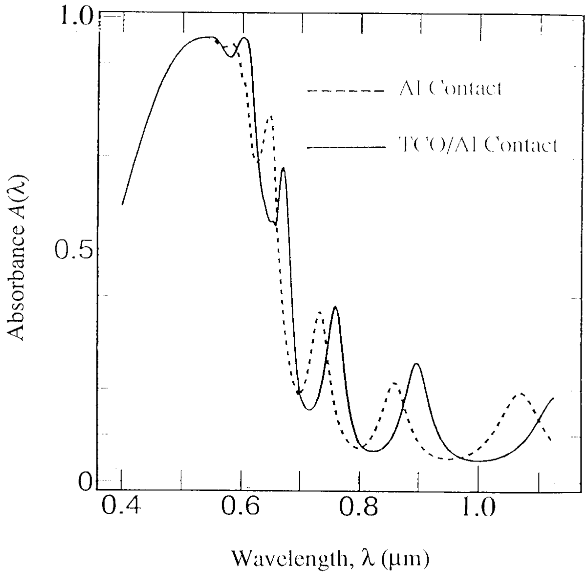

Figure 1: Calculated absorbance, A(λ), as a function of wavelength, λ.

It appears that in the short wavelength region, for instance $\lambda \leq 0.55$ μm, the calculated A(λ) of the two cells are almost the same. This is because most incident photons with high energies are absorbed before reaching the back contact. In the longer wavelength region, $\lambda \geq 0.6$ μm, it is found that absorbance peaks in A(λ) of a cell with a TCO/Al back contact show red shifts in positions compared with those of a cell with only an Al metal contact.

From this analysis, it is obvious that the combined TCO/metal back contact will mainly affect the A(λ) of the cell in the long wavelength region. It is well known that the spectral absorbance in the long wavelength region is important for the improvement of photocurrent. From an optical point of view, we can optimise the interference peaks to achieve the maximum absorption by choosing an appropriate *i*-layer thickness and back contact to boost the internal reflection and hence enhance the spectral absorbance of the cell in the long wavelength region.

In order to understand the effect and to choose the best thickness of the bottom TCO layer in a combined rear TCO/metal contact, we have also calculated the integrated absorbance of a cell as a function of the thickness of the bottom TCO layer for three different cells with *i*-layer thickness equal to 0.4, 0.5 and 0.6 μm. The calculated results are given in Figure 2. They show that the integrated absorbances of these three different cells have a similar pattern of dependence on the bottom TCO layer thickness. The maxima of the integrated absorbance are located over the TCO thickness regions 0.05 μm to 0.09 μm and 0.25 μm to 0.28 μm. For a cell with an *i*-layer of thickness 0.5 μm the results show that the bottom TCO layer thickness can be chosen as 0.05 μm to enhance the absorbance in the long wavelength region.

The integrated absorbances $\bar{A}$ as a function of *i*-layer thickness for three different cells with Al, TCO(0.05 μm)/Al and TCO(0.25 μm)/Al back contacts were also calculated and the results are plotted in Figure 3. The TCO layer is also an absorbing layer and therefore a 0.25 μm thick rear TCO layer may not increase the absorption in the *i*-layer effectively since a thick TCO layer will also absorb the light. From Figure 3, it appears that in a single *pin* junction a-Si:H solar cell with TCO(0.05 μm)/Al back contact there is generally a higher integrated absorbance in comparison with Al alone or TCO(0.25 μm)/Al as the rear contact electrode. For example, with an *i*-layer thickness of 0.45 μm as shown in Figure 3, the integrated absorbance of a cell with an optimal bottom TCO layer thickness of 0.05 μm is about 4% higher than that of a similar cell with glass/TCO/*pin*/Al structure. This is due to the effect of the highly reflecting rear contact of TCO/Al which boosts the internal reflection and hence enhances the effective absorbance in the active layer.

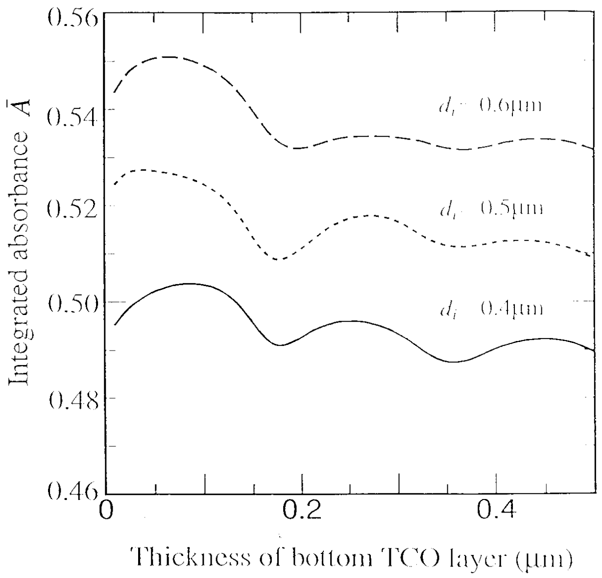

Figure 2: Integrated absorbance as a function of the thickness of rear TCO layer.

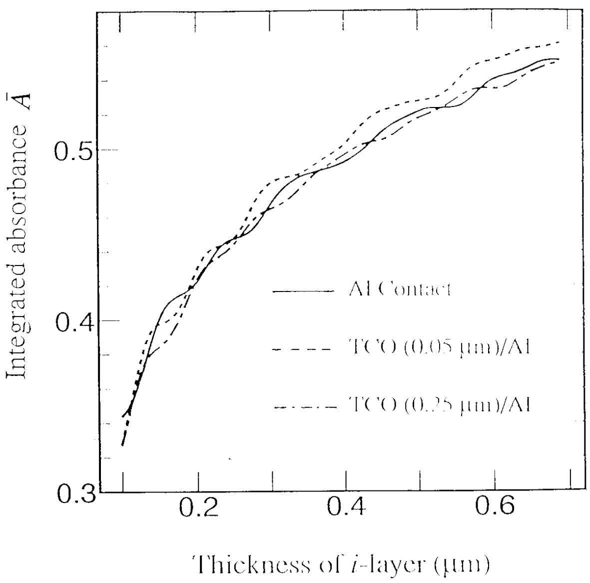

Figure 3: Integrated absorbance as a function of the i-layer thickness.

Using this approach, with the help of the calculated results in Figures 2 and 3, we can propose an optimised single junction solar cell based on choosing appropriate thicknesses of a-Si:H films and TCO layers to achieve the maximum absorption of the incident solar radiation. From previous studies [2,5] it appears that an optimal *pin* type single junction solar cell can be obtained with the structure of Glass/TCO(0.06μm)/*p*(0.01μm)/*i* type a-Si:H (0.3 μm)/*n*(0.01 μm)/TCO(0.05 μm)/Al.

4 OPTICAL PROPERTIES OF MULTI JUNCTION a-Si:H SOLAR CELLS

We have also applied the present method to a tandem cell with the configuration of glass/TCO/*pin*(a-Si:H)/*pin*(a-SiGe:H)/Ag. The spectral absorbances of the top and bottom cells in this structure are shown in Figure 4. It is found that the spectral absorbance of the top cell is mainly dependent on the thickness of its active layer whilst that of the bottom one depends on both the thickness of the a-SiGe:H layer, the active layer of the bottom cell, and the type of back contact. This is because the highly reflecting rear contact enhances the interference effect, and thus increases the spectral absorption in the long wavelength region. Our calculations imply that the use of a highly reflecting rear contact will improve the spectral absorbance of the dual junction cell mainly in the long wavelength region.

In the design of multijunction solar cells, the requirement of photocurrent matching may be achieved by appropriate combinations of optical energy gaps for the material in the *i*-layers and by optimising the thicknesses of the cells to give the maximum spectral absorbance. The optical admittance technique provides a way to optimize the design of thin film optoelectronic devices with multilayer configuration.

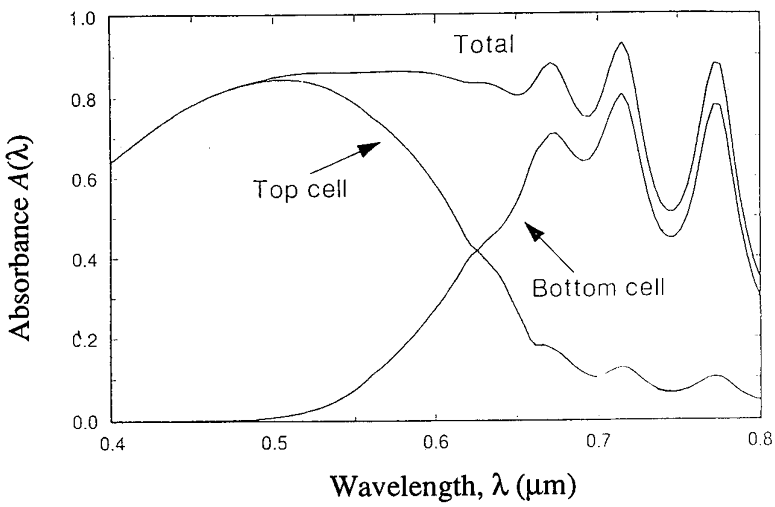

Figure 4: Calculated absorbance as a function of λ for a double junction cell with the configuration of glass/TCO/*p-i-n* (a-Si:H)/*p-i-n* (a-SiGe:H)/Ag.

In the above calculations, we used ITO for the TCO layer. In practical thin film a-Si:H solar cells however ZnO, SnO_2 and other transparent conductive oxide films are also often used. The optimal thickness of SnO_2 film used for AR coating and ZnO films used for the highly reflective TCO/metal back contact for the glass/TCO/a-Si:H *pin* junctions/TCO/metal cells can also be determined using the approach discussed above. As the actual TCO layers are absorbing materials, when light strikes a cell of the type glass/TCO/a-Si:H *pin* junctions/TCO/metal, an appreciable quantity of light may be lost by absorption in the thick TCO layers of the device. Therefore from the optical point of view the thickness of TCO layers in the cells also needs to be optimised. The selection of the thickness of TCO layers in this simulation is realistic and compares with those obtained from experimental studies [8,9].

5 SINGLE JUNCTION a-Si:H SOLAR CELLS ON TEXTURED SUBSTRATES

Recent progress in a-Si:H solar cells has been achieved by using textured TCO substrates such as the Asahi U-type textured TCO coated glass substrates which we also used in our depositions [10]. In comparison with the flat TCO coated glass substrate, Asahi U-type textured TCO/glass substrates have a haze value of 12%. The corresponding *rms* surface roughness of this type of textured TCO substrate is estimated to be about 33 nm.

For a cell with a textured substrate, the reflected light at a rough interface will have two components, one comes from the specular reflection and the other arises from the diffuse reflection and is known as light scattering. Scattered reflected light has an angular distribution. The scattered light in the glass substrate which strikes the surface at angles greater than the critical angle, $\theta = arc\sin(n_{air}/n_{glass})$, where n_{air} and n_{glass} are the refractive indices of air and glass, will not escape from the substrate. This part of the reflected light is totally internally reflected at the air/glass interface and is confined within the thin film structure.

In order to study the improvement of cell performance using Asahi U-type textured TCO substrates, we have used optimised deposition parameters previously determined for making *pin* devices on flat TCO coated glass substrates [10]. For this type of textured substrate, light will undergo many passes through the a-Si:H layers and will be trapped by total internal reflection until it is eventually absorbed by the thin film. This is also known as the optical confinement or light trapping effect.

Figure 5 shows typical I-V curves measured from our sample cells deposited on two different types of substrates prepared with the same deposition conditions. These results show that the efficiency of cells deposited on textured substrates were generally improved by about 30 % compared with cells made with flat TCO substrates under identical conditions.

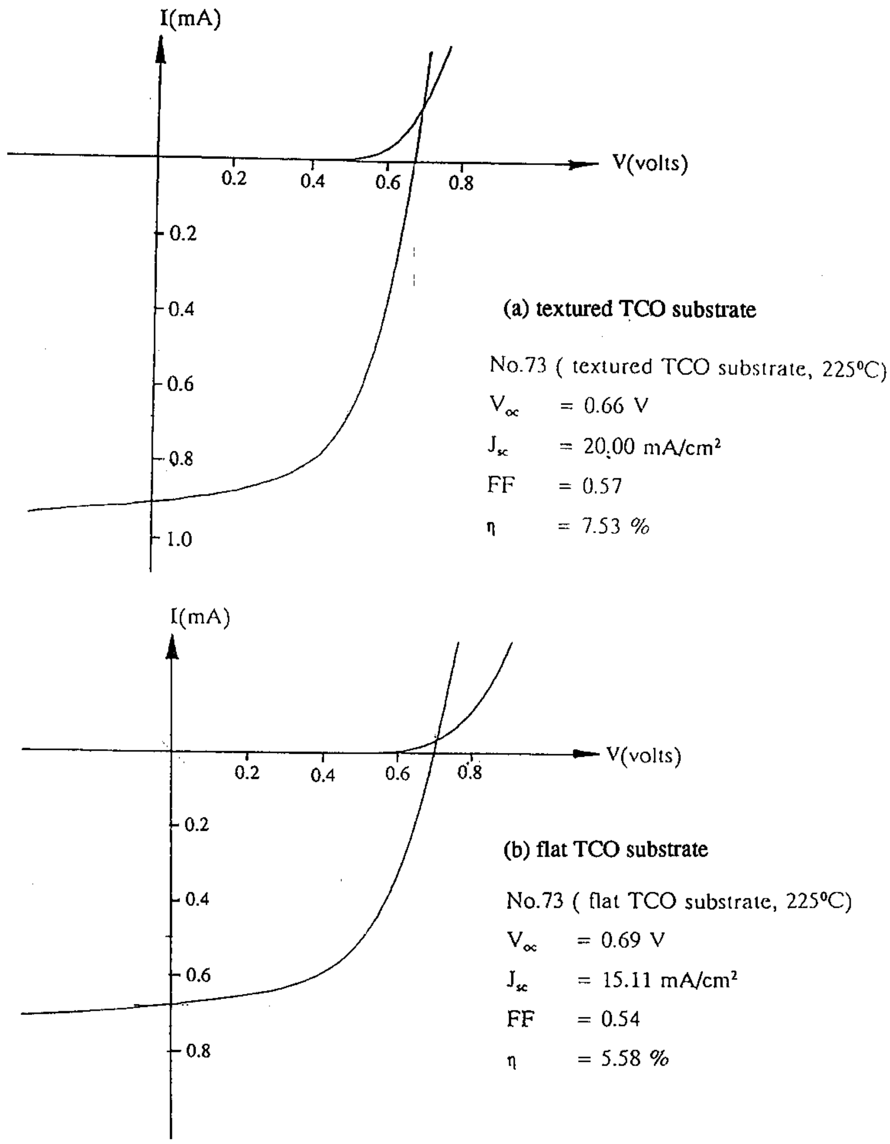

Figure 5: Typical I-V characteristics of a) textured and b) flat a-Si:H solar cells of the type glass/TCO/*p-i-n*/Al prepared in our single chamber deposition system.

In some cases, sample cells made with textured TCO substrates produced a small gain in V_{oc}, however no major improvement in open circuit voltage was observed in cells produced using textured substrates. This is probably because the deposition conditions, which are optimised for cells on flat substrates may not be optimised for textured substrates. It is also known that shunting paths caused by rough substrates in a textured *pin* device may increase the junction areas leading to a reduced V_{oc}. However we expected that the main effect of light trapping would be to increase light absorption in the device and thus increase the photocurrent and the initial results show that a significant increase in photocurrent density was obtained due to the light trapping effect.

6 DIRECTIONS FOR FUTURE WORK

The results of this work have yielded high-quality a-Si:H single junction solar cells with reproducible mean cell efficiencies of 5.5% on flat substrates and 7.5% on textured substrates. Cells on textured substrates generally show an efficiency improvement of 30 % over those on flat plate substrates. Preliminary studies on optimisation have yielded promising results but further gains will require detailed optical admittance analyses based on appropriate optical data for our materials.

Tandem structures could produce higher efficiencies and some modelling has been carried out on such strictures. However these must be deposited in a multichamber system which we do not currently have access to.. Future work in this project will be directed towards the preparation and characterisation of thin film materials for use in multilayer a-Si:H devices. The optical admittance technique will be refined by collecting further data and using the model to simulate the performance of single junction devices based on these materials.

7 REFERENCES

[1] H.A. MacLeod, “Thin-film Optical Filters”, 2nd Ed. (Adam Hilger, Bristol, 1986) P.15.

[2] F. Zhu, T. Fuyuki, H. Matsunami and J. Singh, Sol. Energy Mater. Sol. Cells 39 (1995) 1.

[3] F. Zhu and J. Singh, Sol. Energy Mater. & Solar cells 31 (1993)119.

[4] J.A. Berning and P.H. Berning, J. Opt. Soc. Am. 50 (1960) 813.

[5] F. Zhu and J. Singh, J. Non-Cryst. Solids 163 (1993) 65.

[6] K.L. Eskenas and S.C. Miller, in: Proc. 20th IEEE PV Spec. Conf., Las Vegas, NV, Sept.1988, p.176.

[7] American Institute of Physics Handbook, 3rd Ed. (Mc-Graw Hill, New York,1977) p.136.

[8] K. Okuda, H. Okamoto and Y. Hamakawa, Jpn. J.Appl. Phys. 22 (1983) L605.

[9] B. Schroder, Materials Science and Engineering A139 (1991) 319.

[10] J.C.L Cornish, Subaer, P. Jennings and G.T. Hefter, Proc.1st WCPEC, 5-9 Dec., Hawaii (1994) 686.