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Study of the optical properties of amorphous silicon solar cells using admittance analysis

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A comprehensive optical admittance method is described to study the optical properties of amorphous silicon thin film solar cells. The method is applied to Schottky barrier solar cells of the type TCO/Au/a-Si:H/rear contact, and p–i–n type solar cells of the type TCO/p/i/n/rear contact, considering them as multilayer systems composed of absorbing and non-absorbing layers. The numerical technique uses experimental results of refractive index, $n(\lambda)$, and extinction coefficient, $k(\lambda)$, to calculate the optical absorbance and reflectance of such cells. The interference absorbing peaks thus obtained in the absorbance of a multi-layered cell are found to agree well with experimental results. The results reveal that a high reflecting rear metal contact increases the spectral absorbance in the wavelength region 0.60–0.70 μm, and peak positions in the absorption spectrum depend on the cell thickness. The optimised TCO parameters are found to be almost independent of the thickness of a-Si:H layer. The optimisation of the thickness of p layer in a p–i–n type solar cell is also discussed. This method can be applied for calculating the optical properties of any thin film solar cell. It is expected that, using the present method, one can design a solar cell of optimal efficiency. It is found that by maximising the integrated absorbance in an optimal cell structure, one can increase the short circuit current density by 5.3%.

1. Introduction

Since solar cells operate on the electro-optical behaviour of a semiconducting material, much interest has developed in studying the optical properties of semiconductors used for solar cells [1–3]. For most domestic purposes, amorphous silicon solar cells are manufactured by thin film technology. In order to optimise the design of such cells, it becomes a prerequisite to understand the optical characteristics of thin films used. There are at least two methods known in the literature to study the optical properties of amorphous silicon single junction solar cells. Den Boer and van Strijp [4] have calculated the absorbance in a-Si:H Schottky diode solar cell considering it as a multilayer structure and using any one of the electric or magnetic field components of the incident electromagnetic wave. Demichelis et al. [5] have introduced another method for calculating the absorbance, reflectance and transmittance in an a-Si:H solar cell by treating it as a multilayer interference filter. Both methods involve quite complicated recursion formulae for calculating reflectance and transmittance of electromagnetic wave at each interface.

In this paper, we propose another method based on a theory due to Macleod [6] for analysing optical admittance of thin films. Following this method, one can express both reflectance and transmittance as a function of admittance. Therefore, from only the calculation of the admittance of a cell, one can obtain all optical properties, such as reflectance, transmittance and absorbance as a function of the wavelengths of the incident solar radiation.

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We consider here both Schottky barrier and p–i–n types of a-Si:H solar cells. The Schottky barrier cells are assumed to be composed of thin films of a non-absorbing rear contact, absorbing a-Si:H, barrier metal layers and non-absorbing transparent conducting oxide (TCO). Also, p–i–n type cells are assumed to have thin films of a non-absorbing rear contact, absorbing layers of p-, i- and n-types of a Si:H and non-absorbing TCO. Here we direct our attention only to the optical behaviour of solar cells. The results obtained from the present method are in agreement with the experimental results [7] as well as theoretical results of den Boer and van Stijl [4] and Demichelis et al. [5].

This paper is organised as follows: section 2 contains theoretical method, and section 3 describes the calculated results for Schottky barrier and p–i–n junction a-Si:H solar cells.

2. Theoretical method

A thin film a-Si:H solar cell typically consists of layers of transparent conducting oxide (TCO), absorbing amorphous silicon and rear contact materials. From the optical point of view, one can consider such a semiconductor device as a multilayer thin film system composed of absorbing and non-absorbing materials. In such a layered structure device, the optical admittance, y, of the incident electromagnetic wave can be defined as

$$y(\boldsymbol{k}\cdot\boldsymbol{E}) = \boldsymbol{H}, \tag{1}$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are electric and magnetic field vectors. $\boldsymbol{k}$ is a unit vector in the direction of propagation. The admittance is a dimensionless parameter given by

$$y = \frac{|\boldsymbol{H}|}{|\boldsymbol{k}\cdot\boldsymbol{E}|}, \tag{2}$$

and for a medium it is usually expressed as $y = Ny_0$, where N is the complex reflective index of the medium and y_0 is the admittance in vacuum ($y_0 = 1/377$ Siemens). For a cell with m layers, the total reflectance can be determined by solving the following matrix equation given by [6]

$$\begin{pmatrix} B \\ C \end{pmatrix} = \left[\prod_{j=1}^{m} \begin{pmatrix} \cos\delta_j & i\sin\delta_j/\eta_j \\ i\eta_j \sin\delta_j & \cos\delta_j \end{pmatrix} \right] \begin{pmatrix} I \\ \eta_{m+1} \end{pmatrix}, \tag{3}$$

where B and C are functions of $\boldsymbol{E}$ and $\boldsymbol{H}$ such that the effective admittance of the layered structure cell can be written as

$$y_{\text{eff}} = C/B, \tag{4}$$

and η_j and η_{m+1} are the admittance of the jth layer and the admittance of substrate respectively. I is the unit matrix, and δ_j is the angular phase given by

$$\delta_j = \frac{2N_j d_j \cos\theta}{\lambda}, \tag{5}$$

where d_j is the actual thickness of the jth layer, and N_j is the corresponding refractive index given by $N_j = n_j - ik_j$, where n_j and k_j are the real and imaginary parts of the N_j, respectively. Both n_j and k_j are functions of the wavelength, λ, of the incident electromagnetic wave. The matrix equation (3) is derived from Maxwell's equations and it takes into account the effect of multiple reflections in a single as well as multilayer structures.

The total reflectance, $R(\lambda)$, is then obtained as

$$R(\lambda) = \frac{|(n_0 - y_{\text{eff}})|^2}{|(n_0 + y_{\text{eff}})|^2}, \tag{6}$$

where n_0 is the refractive index of air. We assume the normal incidence, and then the total transmittance can be expressed as [8]

$$T(\lambda) = [1 - R(\lambda)] \prod_{j=1}^{m} \Psi_j, \tag{7}$$

where

$$\Psi_j = \frac{\text{Re}(Y_{j+1})}{\text{Re}(Y_j)|\cos\delta_j + Y_{j+1}\sin\delta_j/N_j|^2}. \tag{8}$$

$\text{Re}(Y_{j+1})$ and $\text{Re}(Y_j)$ represent the real parts of effective admittance for $(j+1)$th and jth layers, respectively. The total absorbance for the multilayer system can thus be written as

$$A(\lambda) = 1 - T(\lambda) - R(\lambda). \tag{9}$$

Defining $F(\lambda)$ as the flux of the incident solar irradiation, measured in W m^{-2} μm^{-1} and using eqs. (6), (7) and (9), the normalised integrated reflectance, $\bar{R}$, transmittance, $\bar{T}$, and absorbance, $\bar{A}$, can also be calculated as

$$\bar{R} = \frac{\int R(\lambda)F(\lambda)\,d\lambda}{\int F(\lambda)\,d\lambda}, \tag{10}$$

$$\bar{T} = \frac{\int T(\lambda)F(\lambda)\,d\lambda}{\int F(\lambda)\,d\lambda}, \tag{11}$$

$$\bar{A} = \frac{\int A(\lambda)F(\lambda)\,d\lambda}{\int F(\lambda)\,d\lambda}. \tag{12}$$

The advantage of calculating $\bar{R}$, $\bar{T}$ and $\bar{A}$ is these quantities are only a function of the real thickness of an amorphous silicon cell. It therefore becomes possible to optimise the thickness of the cell in order to maximise the integrated absorbance.

3. Discussion

In the previous section, we have presented a method for determining the optical properties of layered structure solar cells. In this section we will apply our method first to study these properties in a Schottky diode solar cell of the type: TCO/Au/a-Si:H/rear contact, and then in a p–i–n type of a-Si:H solar cell with structure TCO/p/i/n/rear contact.

Using eqs. (10)–(12), we have calculated the reflectance, $R(\lambda)$, transmittance, $T(\lambda)$, and absorbance, $A(\lambda)$, for both types of solar cells. The optical constants, $n(\lambda)$ and $k(\lambda)$, for various rear contact materials used are taken from the American Institute of Physics Handbook [9], and those used for a-Si:H in Schottky diode type solar cells are taken from experimental results by Cody et al. [10]. The optical constants $n(\lambda)$ and $k(\lambda)$ for p-, i- and n-types of a-Si:H are taken from Eskenas and Miller [12]. Since the contribution of photons of wavelength longer than 1250 nm to the photocurrent is regarded to be negligible, the integration is carried over the wavelength range from 320 to 1250 nm. For integrations in eqs. (10)–(12), the values of optical constants are obtained from linear interpolation of the experimental data.

3.1. Schottky diode a-Si:H solar cells

For Schottky diode a-Si:H solar cells, we have used rear contacts of Ag, Au, Al, Mo and Pt. The top transparent gold film is taken to be 7.5 nm thick [7]. In order to check the accuracy of our method, we have applied it to calculate $A(\lambda)$ using the data used by den Boer and van Strijp [4] in their work and found that our calculated results of spectral absorbance, $A(\lambda)$, agree very well. For the results obtained in this paper, however, we have used the data of $n(\lambda)$ and $k(\lambda)$ for a-Si:H measured by Cody et al. [10]. This is because den Boer and van Strijp [4] have measured only $k(\lambda)$ for a-Si:H thin films, and used $n(\lambda)$ from Zanzucchi et al. [13]. It is therefore possible that the results of $n(\lambda)$ and $k(\lambda)$ used by den Boer and van Strijp [4] may not have come from the same a-Si:H thin films. Since Cody et al. [10] have measured both $n(\lambda)$ and $k(\lambda)$, we have used their results in our calculation.

We have shown $A(\lambda)$ as a function of λ, calculated from our method, for rear contact of Ag, Au, Al, Mo and Pt in fig. 1. We find that in the short wavelength region, $A(\lambda)$ is same for all rear contacts studied here; this is because the light is completely absorbed before reaching the back contact. In the long wavelength region, however, $A(\lambda)$ is found to behave differently for different rear contact metals. The relative maximum absorbance for all metals occurs in about the same wavelength region from 0.62 to 0.64 μm at 7.5 nm thick barrier metal and 0.25 μm thick a-Si:H layer, but the maximum heights of the peak vary significantly. Our calculated results, shown in fig. 1, reveal that cells with silver, gold or aluminium as a rear contact metal will achieve a higher spectral absorbance in comparison with those with molybdenum or platinum as a rear

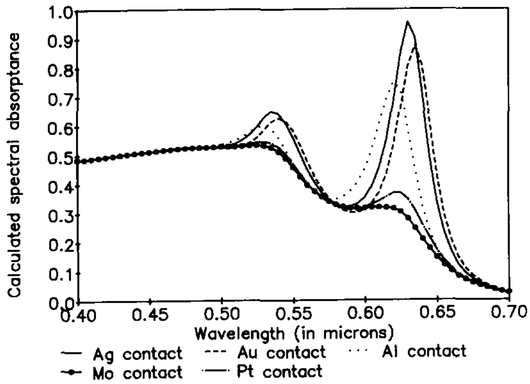

Fig. 1. Calculated spectral absorbance as a function of wavelength of the incident radiation for different rear contact metals.

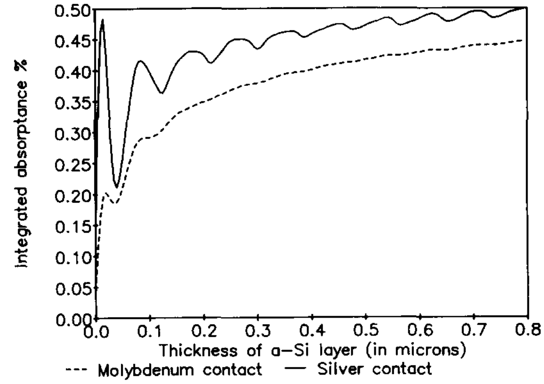

Fig. 3. AM1 integrated absorbance as a function of a-Si:H film thickness.

contact metal. Figure 2 shows the calculated reflectance at the interface of a-S:H and rear metal contact for all five metals. Results of fig. 2 reveal that silver, gold or aluminium give higher reflection than molybdenum or platinum as rear contact metals. For a device with the lower reflectivity at the rear contact such as Mo and Pt, the interface effect is much smaller than in a device with high reflectivity metals such as Ag and Al. The intensity differences in the absorbance peaks for various contacts shown in fig. 1 are directly related to the reflectivity of the rear contact metals. Thus, by choosing a high reflecting metal such as Ag for the rear contact, one can obtain a high spectral absorbance, which is a well known experimental result. High reflecting rear contacts

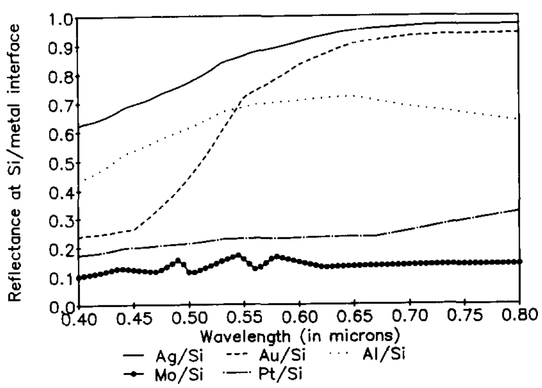

Fig. 2. Reflectance at a-Si:H/metal interface as a function of wavelength of the incident radiation.

can lead to a substantial increase in the conversion efficiency of a-Si:H based solar cells [14,15].

In fig. 3, we show the integrated absorbance, $\bar{A}$, calculated from eq. (12) at AM1 as a function of the thickness of a-Si:H in a Schottky type solar cell with Ag and Mo as rear contact metals. For molybdenum contact, we find that initially the integrated absorption, $\bar{A}$, increases rapidly with the film thickness, then it oscillates a little at about 0.08–0.15 μm and eventually becomes constant at larger thicknesses. By contrast with this, for Schottky solar cells with Ag rear contact, $\bar{A}$ shows prominent oscillations at all thicknesses although the amplitude of oscillations decreases at large thickness. The position of relative maximum absorption occurs at film thicknesses d = 0.09, 0.18, 0.27, 0.37, 0.46, 0.54, and 0.71 μm, and absorption minimum at d = 0.04, 0.13, 0.22, 0.30, 0.39, 0.48, 0.57 and 0.66 μm. In order to understand the oscillating behaviour of the integrated absorption in a-Si:H film, we have calculated absorbance in a-Si:H films of different thicknesses. The results are shown in fig. 4, where AM1 spectral absorbance is plotted as a function of incident wavelength for film thicknesses of 250 nm, 270 nm and 300 nm chosen on the basis of the results shown in fig. 3. The film thickness d = 270 nm corresponds to a maximum integrated absorption peak and d = 300 nm to a minimum. From fig. 4 it is obvious that the peaks show a red shift in their position as the thickness of a-Si:H increases. In order to illustrate our point, we

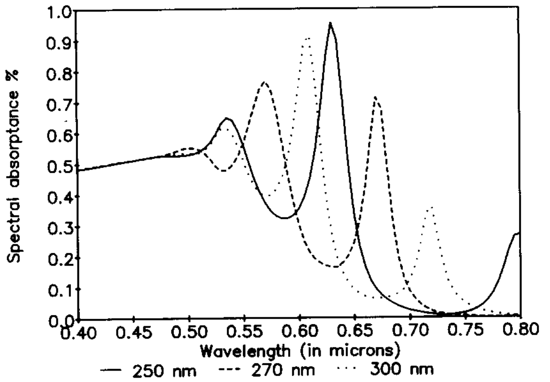

Fig. 4. Spectral absorbance as a function of wavelength of the incident radiation for a-Si:H film of three different thicknesses.

choose a wavelength of 0.67 μm at which a minimum occurs for thin film thickness of 300 nm, and a maximum occurs for film thickness of 270 nm. The change in the position maximum and minimum in absorption with change in film thickness is a result of interference from rear contact which is silver in this case. It is therefore apparent that the appearance of maxima and minima in the integrated absorbance, $\bar{A}$, as shown in fig. 3, is due to interference from the rear contact. In the case of silver as the rear contact metal, interference is more prominent than in the case of molybdenum. Thus, from an optical point of view, with the help of fig. 3, one can optimise the interference peak to achieve the desired integrated absorption by choosing an appropriate film thickness of a-Si:H and rear contact. This analysis is expected to help design an optimal solar cell.

The calculation presented here is based on the optical constants of a-Si:H films measured by Cody et al. [10]. However, a more recent set of data on a-Si:H in a narrower wavelength region is given in a comprehensive review by Cody [11]. Using the recent data, we have evaluated $R(\lambda)$, $T(\lambda)$ and $A(\lambda)$ in the common wavelength region of 0.34–0.825 μm for a Schottky diode solar cell with a structure of Au/a-Si:H/Ag. For a particular set of values of 7.5 nm for the thickness of Au film and 0.25 μm for the thickness of a-Si:H film, we have calculated the relative maximum absorbance using both sets of data for optical constants. The recent data showed the maximum absorbance occurring at a wavelength of 0.64 μm in comparison with 0.63 μm obtained from the previous data used above in the paper. Also using the recent data, we have found that the maxima of integrated absorption occur at film thicknesses $d = 0.09$, 0.15, 0.23, 0.33, 0.41, 0.49 and 0.56 μm, which are comparable with the corresponding thicknesses $d = 0.09$, 0.18, 0.27, 0.37, 0.46, 0.54 and 0.71 μm obtained from the previous data. Although one may conclude that the results obtained from the recent data should be more accurate, these data, as stated above, are available only in a narrower wavelength region of 0.34–0.825 μm in comparison with that of 0.32–1.25 μm which covers a wider range and hence are more suitable for the integrations used in this paper. We have therefore preferred to use the previous data for the results obtained in this paper. The method of calculation of absorbance as presented here is of course applicable with the recent set of data as well.

Capacitance–voltage measurements of thin a-Si:H film indicate that most cells with a thickness < 0.4 μm are depleted at zero bias. That means an a-Si:H solar cell with a thickness of about 0.4 μm can act fully as a depletion region and therefore the recombination loss will be minimum. The absorption in a 0.37 μm silver back contact cell is almost equal to the AM1 absorption in a 0.46 μm cell. However, from an electronic point of view, a 0.37 μm thick cell is preferable to a 0.46 μm thick cell because the ratio of the drift length to the cell thickness is higher, and therefore the recombination loss is reduced. Although from fig. 3 one finds that a thickness of 0.02 μm has the maximum integrated absorption, such a thickness will not be practical due to interdiffusion processes taking place at the interface.

For a given structure of a solar cell we have calculated the optimal refractive index, n, and thickness, t, of TCO using the AM1 integrated absorption in the a-Si:H film for a range of values of n and t. The results are shown in fig. 5 where the contour map of absorption is plotted by normalising it to the optimum value. For a cell

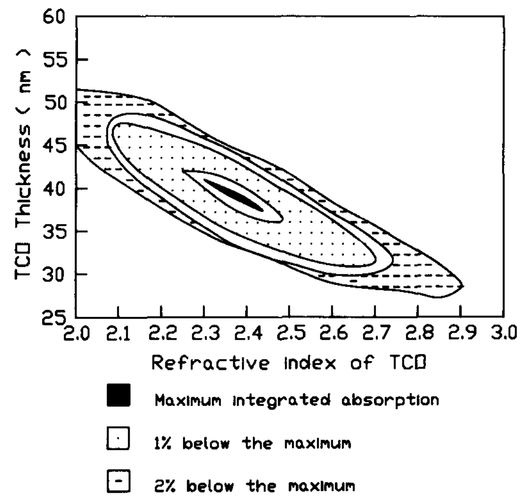

Fig. 5. Contour map of normalising AM1 integrated absorbance as a function of the refractive index and the thickness of an TCO.

with 0.37 μm thick a-Si:H film, the optimal value of the refractive index of TCO is $n = 2.4$ and that of its thickness is $t = 38$ nm. It can be seen from fig. 5 that for the maximum absorption in a solar cell one should choose a TCO with n in the range of 2.3–2.45 and t in the range of 37–41 nm. In fig. 5 we have also shown the contours of absorption for combinations of the refractive index, n, and thicknesses of TCO, t, which represent 1% and 2% below the maximum absorption.

In fig. 6 we plot the integrated reflectance as a function of the thickness of TCO for two different thicknesses of the a-Si:H film. It shows that the TCO thickness that gives the minimum reflectance does not depend on the thickness of the a-Si:H film. Therefore the optimal thicknesses of both TCO and a-Si:H can be chosen independently to reduce the reflection and maximise the absorption in an a-Si:H Schottky barrier solar cell. In fig. 7 we have shown the effect of TCO on the absorbance, $A(\lambda)$, of a Schottky a-Si:H solar cell, where it is obvious that the absorbance increases significantly for a cell with optimal TCO layer.

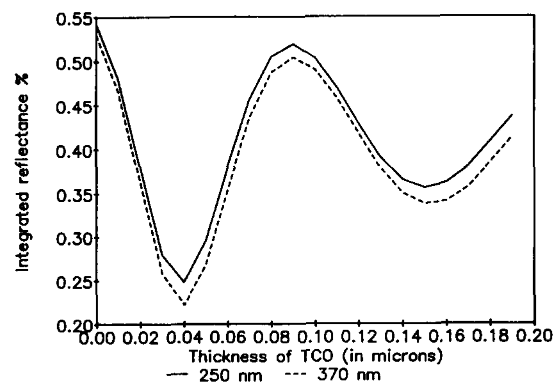

Fig. 6. Integrated reflectance as a function of wavelength for two different thicknesses of a-Si:H.

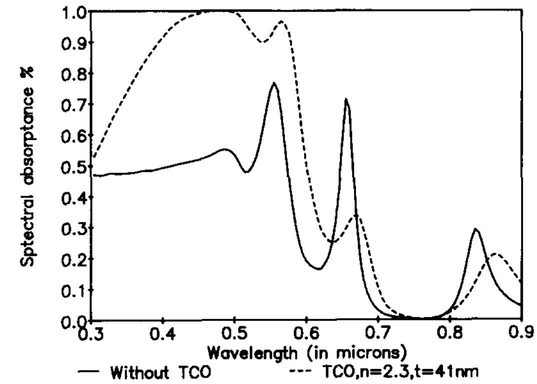

Fig. 7. Calculated spectral absorbance as a function of wavelength of the incident radiation for a cell with and without TCO coating.

3.2. p–i–n a-Si:H solar cells

The calculation of absorbance, $A(\lambda)$, for p–i–n type solar cells is done using the same method as that for Schottky barrier a-Si:H solar cell. Here we consider a p–i–n cell with three layers of p-, i- and n-types of a-Si:H which have different optical properties. For a given layer configuration of a solar cell, the integrated absorption are shown in fig. 8. The solid curve is obtained for different thicknesses of p layer by keeping the thicknesses of i and n layers constant at 0.25 μm and 0.01 μm, respectively. Likewise, the dashed curve is calculated by taking a constant thickness of 0.01 μm of both p and n layers, and the dotted curve is calculated by keeping the thicknesses of p and i layers as 0.01 μm and 0.25 μm, respectively. These values are chosen in accordance with our results discussed for the case of Schottky barrier cells. We find from fig. 8 that the maximum integrated absorbance of the cell occurs at a thickness of 13 nm for the p-doped layer, which is in good agreement with the experimental results [16] suggesting that the p layer should have a thickness of 8–13 nm for high efficiency p–i–n-type amorphous silicon solar cells. Our results also indicate that a further increase in the thickness of p layer will reduce the integrated absorbance of the cell. This analysis, therefore, indicates that the optimal thickness of p layer in a p–i–n a-Si : H solar cell can be chosen as 13 nm. By contrast with the solid curve, in dashed and dotted curves shown in fig. 8, $\bar{A}$ increases slowly with the thickness of n layer, but it fluctuates with the thickness of i layer. This fluctuation differs from the case of a Schottky barrier solar cell shown in fig. 3.

The spectral absorbance as a function of the wavelength is plotted in fig. 9 for three different i layers of thicknesses $d_i = 0.25$, 0.30 and 0.35 μm. Figure 9 reveals that $A(\lambda)$ has different peak structures for three different thicknesses in the long wavelength region, which is related to the interference. Thus the fluctuations in the dashed curve in fig. 8 are mainly due to interference effect which changes the $A(\lambda)$ in long wavelength region, as shown in fig. 9.

Yablonovitch and co-workers [1,2] have shown that the absorption of incident radiation is enhanced in textured optical sheets for solar cells.

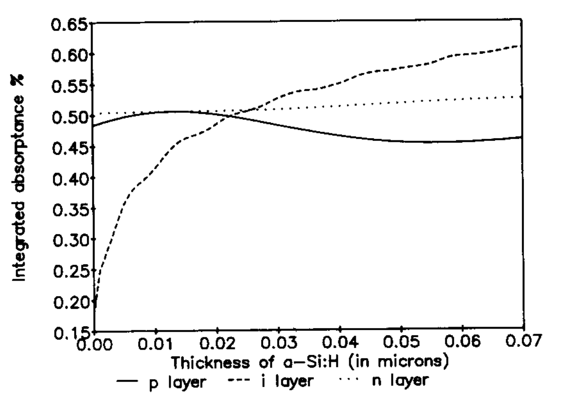

Fig. 8. AM1 integrated absorbance of a cell as a function of the thickness of p-, i- and n-layers.

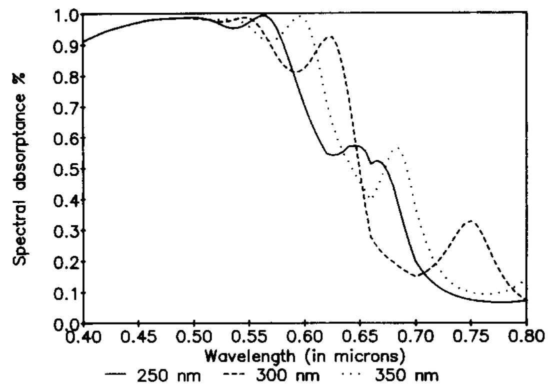

Fig. 9. Calculated spectral absorbance of the cell as a function of wavelength of the incident radiation for three different intrinsic layers.

This enhancement occurs due to scattering and fractional trapping of the incident light through total internal reflections. Such enhancement of absorption may be expected for a-Si : H solar cells as well, because most thin films are expected to have textured optical structures as consequence of their deposition processes. However, this enhancement is not explicitly dependent on the thickness of thin films. Therefore, an optimisation of the thickness of various layers in a-Si : H solar cells can only be made using the present method. This method implies that an a-Si : H thin film solar cell designed with optimal thickness according to our method will also have the advantage of optical absorption enhancement suggested by Yablonovitch and Cody [1].

The relevance of above analysis can be seen by calculating the short circuit current density in a cell. Using eq. (9) we can calculate the number of normally incident photons of wavelength, λ, on a cell given by

$$N(\lambda) = A(\lambda)F(\lambda)(\lambda/hc), \tag{13}$$

where $F(\lambda)$ is the flux of incident solar radiation measured in W m^{-2} μm^{-1}. From eq. (13), J_{sc} can be calculated as

$$J_{sc} = e\int N(\lambda)f(\lambda)\,d\lambda, \tag{14}$$

where e is the electronic charge and $f(\lambda)$ is defined as a non-recombination factor by Demichelis et al. [5]. As we discussed before in the case of Schottky barrier solar cells for optimal absorbance, a thinner cell is preferable because the ratio of the drift length to the cell thickness, $\mu\tau E/d$, is higher. The higher values of $\mu\tau E/d$ reduce the electron–hole recombination process, and hence the non-recombination factor increases. As mentioned above, for a cell of thickness less than 0.4 μm, one can neglect electron hole recombination, as an approximation, and then the non-recombination factor, f, can be taken as unity. According to this approximation, we have calculated J_{sc} for Schottky barrier solar cells with a-Si:H layer of thicknesses 0.27 μm that gives maximum, $\bar{A}$, and 0.30 μm that gives minimum $\bar{A}$.

We then find

$J_{sc}(0.27\ \mu m) = 7.94\ mA/cm^2$, and

$J_{sc}(0.30\ \mu m) = 7.54\ mA/cm^2$.

Therefore at the optimal cell thickness of 0.27 μm, the short circuit current density increases by 5.3%. For a p–i–n cell with optimal absorbance, we obtain $J_{sc} = 14.88\ mA/cm^2$.

4. Conclusions

We have presented a method of optimising the thin film structure of both Schottky and p–i–n types a-Si:H solar cells by maximising their integrated absorbance. This method is expected to be easier to use for the calculation of admittance in comparison with other methods already known in the literature. Using this method, one can select the most suitable TCO coating by minimising the spectral reflectance, and determine the optimal thickness of a-Si:H layers and rear contact metal by maximising the absorbance. For a Schottky barrier solar cell, one can increase J_{sc} by 5.3% at an optimal thickness of the a-Si:H film. The method introduced in this paper can easily be used for calculations on other multi-layered solar cells such as tandem cells, multijunction cells as well as $CuInSe_2$ thin film solar cells.

References

[1] E. Yablonovitch and G.D. Cody, IEEE Trans. Electron Device ED-29,2 (1982) 300.

[2] T. Tiedje, E. Yablonovitch, G.D. Cody and B.G. Brooks, IEEE Trans. Electron Device ED-31 (1984) 711.

[3] J.C. Van den Heuvel, M.J. Geerts and J.W. Metselaar, Solar Energy Mater. 22 (1991) 185.

[4] W. Den Boer and R.M. van Strijp, Solar Cells 8 (1983) 169.

[5] F. Demichelis, A. Tagliaferro and E. Tresso, Solar Cells 11 (1984) 375; F. Demichelis, Solar Cells 14 (1985) 149.

[6] H.A. Macleod, Thin-film Optical filters, 2nd Ed. (Adam Hilger, Bristol, 1986) p. 15.

[7] W. Den Boer and M. Ondris, Solar Cells 3 (1981) 209.

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

[9] American Institute of Physics Handbook, 3rd Ed. (McGraw Hill, New York, 1977) p. 136.

[10] G.D. Cody, C.R. Wronski, B. Abeles, R.B. Stephens and B. Brooks, Solar Cells 2 (1980) 227.

[11] G.D. Cody, in: Semiconductors and Semimetals, Vol. 21B, ed. J. Pankove (Academic Press, New York, 1984) p. 11.

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

[13] P.J. Zanzucchi, C.R. Wronski and D.E. Carlson, J. Appl. Phys. 48 (1977) 5227.

[14] R.R. Arya, M.S. Bennett, A. Catalano and K. Rajan, in Proc. 3rd Int. Photovoltaic Science and Engineering Conf., Tokyo, 1987, p. 725.

[15] A. Catalano, R.R. Arya, C. Fortmann, J. Morris, J. Newton and J.G. O'Dowd, in: Proc. 19th IEEE Photovoltaic Specialists Conf., New Orleans, LA, 1987, p. 1506.

[16] S. Tsuge, Y. Hishikawa, S. Tsuda, S. Nakano, Y. Kishi, Y. Kuwano and N. Nakamura, in: Proc. 5th Int. Photovoltaic Science and Engineering Conf., Kyoto, Japan, 1990, p. 207.