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Optical optimization of high resistance transparent layers in thin film cadmium telluride solar cells

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ABSTRACT

Thin film photovoltaic devices are multilayer opto-electrical structures in which light interference occurs. Light reflection at the interfaces and absorption within the window layers reduces transmission and, ultimately, the conversion efficiency of photovoltaic devices. Optical reflection losses can be reduced by adjusting the layer thicknesses to achieve destructive interference within the structure of the cell. The light transmission to the CdTe absorber of a CdS/CdTe cell on a fluorine doped tin oxide transparent conductor has been modeled using the transfer matrix method. The interference effect in the CdS layer and high resistance transparent buffer layers (SnO_2 and ZnO) has been investigated. The modeling shows that due to relatively high absorption within the SnO_2 layer, there are modest benefits to engineering anti-reflection interference in the stack. However, a ZnO buffer layer has limited absorption and interference can be exploited to provide useful anti-reflection effects. Optical modeling and optimization shows that for a 50 nm CdS layer, a maximum transmission of 78.5% is possible using ZnO as a buffer layer at 58 nm thickness, and 78.0% for a SnO_2 buffer layer at a thickness of 48 nm.

1. Introduction

Thin film CdTe solar cells have achieved commercial success through low manufacturing costs and increasingly high efficiencies. Energy conversion efficiencies of 22.1% have been reported for thin film CdTe solar cells [1]. However, the theoretical efficiency limit for this type of device is ~30% [2]. Both optical and electrical losses occur in CdTe solar cells. Electrical losses are normally of greater magnitude than optical losses, but if light fails to reach the active layer of the stack, a photocurrent is not generated. As such, optical losses precede electrical losses, imposing limitations on photocurrent if not addressed. The losses occur due to reflection and light absorption in layers which do not contribute to the photocurrent, such as the CdS window layer [3].

Light interference effects occur in the multilayer structure of the cell. The reflection losses can be controlled and reduced by tuning the thickness of individual layers to achieve an interference minimum. The absorption losses in the window layer can be reduced by thinning the window layer thickness, which usually requires use of a high resistance transparent layer to prevent voltage and shunt losses [4]. Optical modelling has been used to assess the optical losses within the CdTe solar stack in a simpler model [5], and to evaluate internal reflection losses in a-Si solar cells [6]. In this work, optical modeling was used to investigate how optimizing the various layer thicknesses can increase light transmission to the CdTe absorber layer to increase the photocurrent generated.

1.1. The thin film CdTe solar cell

The CdTe solar cell is a thin film stack with a total thickness typically ~3 µm. For commercial modules, the layers are deposited on to a low cost soda lime glass substrate coated with a transparent conducting oxide (TCO). NSG Pilkington TEC glass is an industrial standard substrate. The TEC glass consists of SnO_2, SiO_2 and SnO_2:F layers deposited on 3.2 mm thick float glass. Depending on the properties required, there are different types of TEC glass characterized by different light transmission, sheet resistance, and surface roughness. TEC 10 glass is an option for CdTe solar cells. The glass is characterized by 70% light transmission in the AM1.5 solar spectrum and a 9 Ω/□ sheet resistance [7].

The CdTe solar cell is deposited onto a TCO coated glass. A simple

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cell structure consists of CdS-CdTe hetero-junction and a back contact. The CdS layer is usually ~100 nm thick. The CdS acts as an n-type semiconductor and enables the photovoltaic effect in the solar cell. The band-gap of CdS is 2.4eV which corresponds to an absorption edge at ~500 nm. The photons absorbed in the window layer do not contribute to the photocurrent of the solar cell, as recombination is very likely to occur, resulting in scattering of light. Therefore, absorption in the CdS layer is a source of significant loss. In a typical cell utilizing CdS, the photocurrent is limited to 22–23 mA/cm^2, although 31 mA/cm^2 is available in the spectrum utilized by CdTe absorber [8], [9].

CdTe is a semiconductor material with a band-gap of 1.45eV which corresponds to an 850 nm absorption edge. Soda lime glass absorbs light at wavelengths of 350 nm and below [10]. Optically, therefore, the CdTe device absorbs wavelengths between 350 nm and 850 nm.

The ideal refractive index of a typical single layer anti-reflection coating is the product of the refractive indices of the materials at the media interface, square rooted [11](equation (1)).

$$n_c = \sqrt{n_0 n_1} \quad (1)$$

In equation (1), n_c is the refractive index of the coating, n_0 is the refractive index of the incident material, and n_1 is the refractive index of the substrate material.

1.2. High resistance transparent (HRT) buffer layers

High resistance transparent buffer layers have been shown to improve solar cell efficiencies by reducing the necessary thickness of the CdS layer and reducing shorting through the CdS layer [12], [13].

The buffer layer is located between the CdS layer and the fluorine doped tin oxide TCO layer. The refractive indices are 1.9 and 2.5 respectively, at the maximum in the AM1.5 spectrum ~550 nm wavelength. Using equation (2), the ideal refractive index to maximize transmission at a wavelength of 550 nm is ~2.2. The refractive indices of ZnO and SnO_2 are 2.0 and 1.9 respectively. As the refractive index of ZnO is closer to that of an ideal anti-reflection layer in the 350 nm–850 nm region, the destructive interference of reflections from different interfaces within the system is more complete. This results in lower reflection minima when ZnO is implemented as the buffer layer.

Bulk SnO_2 is a transparent n-type semiconductor with a band-gap of 3.6 eV and a refractive index of ~1.9 at 550 nm [14], [15]. Thin film SnO_2 has been used as a HRT buffer layer in CdTe solar cells at a variety of thicknesses between 12.5 nm and 100 nm [16]. Fig. 1 shows the structure of a thin film CdTe solar cell incorporating an HRT buffer layer. It has been shown that the inclusion of a SnO_2 HRT buffer layer in a standard CdTe/CdS solar cell, with Fluorine doped tin oxide transparent conducting oxide, leads to a 90 mV improvement to open-circuit voltage (Voc) and a 6% improvement in Fill Factor [16]. The inclusion of a SnO_2 HRT buffer layer has a negligible effect on spectral response and Jsc, whilst raising the shunt resistance of the device [16].

An alternative HRT buffer layer material to SnO_2 is Zinc Oxide (ZnO). The refractive index of ZnO at 550 nm is ~2.0 and the band-gap of ZnO is ~3.3eV [17]. ZnO has been modeled previously as a HRT buffer layer in CdTe solar cells using a thickness of 115 nm [18]. The addition of a ZnO HRT buffer layer has been shown to be beneficial to CdS/CdTe solar cell efficiency [19]. ZnO has also been used as a HRT buffer layer in Cu(InGa)Se_2 (CIGS) solar cell devices [20].

The dispersion relationships and absorption coefficients of SnO_2 and ZnO are shown in Figs. 2 and 3 respectively.

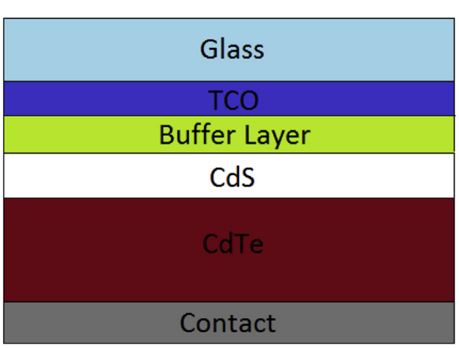

Fig. 1. A schematic diagram of the CdTe solar cell structure showing the position of (from bottom to the top), the back contact, the CdTe absorber, the CdS window layer, the buffer layer, the TCO layer, and the glass substrate.

2. Optical modeling

The thin film CdTe solar cell was modeled and optimized for maximum light transmission to the CdTe layer, using software based on the transfer matrix method [21]. The performance of the solar cells was assessed by calculating the weighted average transmission (WAT) of light into the CdTe absorber in the 350 nm–850 nm spectral range, by incorporating the photon flux in the AM1.5 g solar spectrum (Φ) [22].

$$WAT(\lambda_{max}, \lambda_{min}) = \frac{\int_{\lambda_{min}}^{\lambda_{max}} \Phi \bullet T d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} T d\lambda} \quad (2)$$

Initially, a simple solar cell consisting of TEC10 substrate with a CdS (thickness 50 nm–300 nm) and CdTe junction was modeled for comparison. Complete light absorption in the CdTe layer was assumed. Such devices can usually achieve ~12% conversion efficiency with a photocurrent of 22 mA/cm^2 [2], [4]. The effect of the addition of a HRT buffer layer on the optical performance was then modeled. Because thicknesses below 50 nm are not electrically viable, the buffer layer materials initially were investigated at thicknesses in the range 50 nm–500 nm. However, low thickness HRT buffer layer interference effects were investigated at select

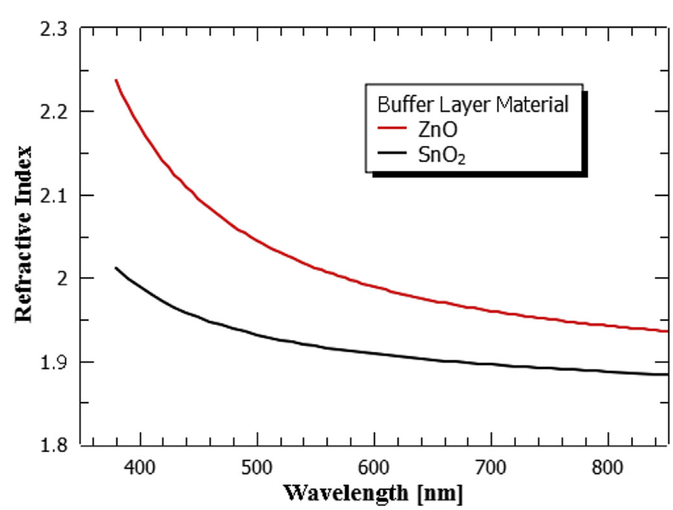

Fig. 2. The refractive index dispersion for SnO_2 and ZnO, the candidate high resistance buffer layer materials.

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