Optical optimization of perovskite solar cell structure for maximum current collection

This item was submitted to Loughborough University's Institutional Repository by the/an author.

Citation: KAMINSKI, P.M. ...et al., 2016. Optical optimization of perovskite solar cell structure for maximum current collection. Energy Procedia, 102, pp. 11-18.

Additional Information:

- This paper was presented at the E-MRS Spring Meeting 2016 Symposium T - Advanced materials and characterization techniques for solar cells III, 2-6 May 2016, Lille, France. This is an Open Access Article. It is published by Elsevier under the Creative Commons Attribution Non Commercial-No Derivatives 4.0 Unported Licence (CC BY-NC-ND). Full details of this licence are available at: http://creativecommons.org/licenses/by-nc-nd/4.0/

Metadata Record: https://dspace.lboro.ac.uk/2134/23969

Version: Published

Publisher: © The Authors. Published by Elsevier Ltd

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: https://creativecommons.org/licenses/by-nc-nd/4.0/

Please cite the published version.
Optical Optimization of Perovskite Solar Cell Structure for Maximum Current Collection

P.M. Kaminski*a, P.J.M. Isherwooda, G. Womacka,b, J.M. Wallsa

*CREST (Centre for Renewable Energy Systems and Technology), Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, LE11 3TU, United Kingdom

bNational Structural Integrity Research Centre (NSIRC Ltd.), Granta Park, Great Abington, Cambridge, CB21 6AL, United Kingdom

Abstract

High conversion efficiency has been recently demonstrated for Perovskite thin film photovoltaic devices. Perovskite thin film solar cells are multilayer opto-electrical structures in which light interference occurs. This phenomenon can be used to maximise the light transmission into the absorber material and increase the device efficiency. Fine tuning of the layer thicknesses within the stack can be used to control interference at the interfaces. Optical reflection losses can be reduced by achieving destructive interference within the structure of the cell. The light transmission to the Perovskite absorber of a thin film solar cell on a fluorine doped tin oxide transparent conductor has been modelled using the transfer matrix method. Alternative transparent conductor materials have been also investigated including AZO and ITO. The modelling showed that replacing FTO with ITO could increase the photocurrent by as much as 4.5%. The gain can be further increased to 6.5% by using AZO as the TCO material. Fine tuning of the TiO2 layer thickness can increase the current density by 0.3%. Furthermore, the current density of a Perovskite solar cell can be increased by application of a multilayer anti-reflective coating by another 3.5%. Optical optimisation of the stack design offers a significant increase in conversion efficiency.

© 2016 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of The European Materials Research Society (E-MRS).

Keywords: Thin film; Perovskite; Solar cell; Anti-reflection Coating; Photo Current.

1. Introduction

Photovoltaic devices (PV) are becoming an attractive energy source even without subsidy. Grid parity has been reached in a number of locations around the globe and it is only a matter of time before PV will be an economically competitive source of energy [1]. The market is currently dominated by crystalline silicon based technologies which are driving reductions in cost. At the same time innovation is creating new technologies which can offer cost and performance advantages. The most important recent innovation is the discovery of solar cells based on Perovskite materials [2]. The astonishing rate of increase of device efficiency has not been observed previously for any other type of PV device. Currently, long term stability remains an issue for the technology [3]. However, it is an immature
technology with scope for significant impact in the future. For example, the Perovskite solar cells are also being investigated for application in tandem solar cells with crystalline silicon [4].

Perovskite solar cells, in common with other PV materials, suffer losses which are either optical or electrical in origin. As the optical losses occur before the Photovoltaic effect takes place, they must be addressed since they cannot be compensated for later. Optical losses in PV are associated with light reflection and absorption in the solar cell structure [5], [6]. The reflection losses can be eliminated through interference – controlled by the layer thickness and the refractive index of material used. The absorption can only be addressed by thinning the responsible layer or by replacement with a more transparent material.

2. Experimental

The perovskite solar cell was modelled as a thin film stack. The refractive index of perovskite and solar cell structure reported by Ball has been used as the model for this work [5]. The cell structure is shown in Figure 1; complete absorption in the perovskite layer was assumed. The reference cell is built on a NSG-Pilkington TEC 15 glass substrate. The cell is deposited on top of a FTO layer and comprises of a TiO\textsubscript{2} and a perovskite layer. First, the model was used to investigate interference effects within the model solar cell structure. We then focus on the performance of the TCO. Investigating the effect of replacing the FTO layer by indium doped tin oxide (ITO) or aluminium doped zinc oxide (AZO) [7]. The modelling was completed by adding an Anti-reflection (AR) layer on the surface of the cover glass. The calculations were carried out using software based on the transfer matrix method [8]. In all calculations, the transmission into the perovskite layer was considered. Based on the maximum transmitted light, estimates of the corresponding attainable current have been calculated.

3. Results

Figure 2 shows the reflection losses at the glass surface and the transmission into the absorber layer modelled for the perovskite cell structure shown in Figure 1. The average transmission weighted by photon flux in the AM1.5 spectrum to the absorber layer for wavelength between 350nm and 800nm was calculated to be 86.55%.

Figure 1 Structure of Perovskite solar cell used for the optical modelling.

Figure 2 Performance of standard solar cell. Light reflections at the glass surface and the transmission into absorber layer have been modelled.
3.1. TiO2

The TiO2 layer is located between the front contact and the absorber layer. To investigate the effect on transmission to the absorbing layer the thickness of the TiO2 layer within the model was varied between 30nm and 70nm; the FTO layer was held at a thickness of 340nm. Figure 3 shows a plot of the transmission as a function of wavelength and the thickness of the TiO2 layer. The transmission data was then used to calculate the resulting photocurrent density at each thickness of TiO2. A plot of current density against TiO2 is shown in Figure 4.

![Figure 3 A 3D plot of transmittance against TiO2 layer thickness and wavelength.](image)

Figure 3 A 3D plot of transmittance against TiO2 layer thickness and wavelength.

![Figure 4 A graph showing the photocurrent density [mA/cm2] dependence on the thickness of the TiO2 layer [nm].](image)

Figure 4 A graph showing the photocurrent density [mA/cm²] dependence on the thickness of the TiO2 layer [nm].

Figure 4 shows that a 41nm thick TiO2 layer, as reported by Ball [5], has near optimal thickness. It achieves current densities up to 24.27mA/cm². The results show scope for a modest increase of the attainable current density. A 0.3% gain, increasing the limit to 24.27mA/cm², can be obtained if the thickness of the layer is reduced to 30nm. Layer thicknesses below 30nm were not modelled for practical reasons.

3.2. Transparent conductor selection

Transparent conductors play a vital role in all thin film solar cells [9], [10]. The choice is usually dictated by a compromise between the conductivity of the front contact and transparency. Increasing the thickness of the TCO layer improves electrical performance but may reduce the light transmission into the absorber. The refractive index, extinction coefficient and the thickness of the TCO layer can be very important for the photocurrent of the solar cell. Therefore, alternative TCO materials have been investigated for potential gains in current density using popular TCO materials such as ITO and AZO.
The conductivity of TCO materials is achieved by the introduction of free electrons through doping [11]. This leads to more efficient extraction of current from the device. Unfortunately, the adverse effects of doping include additional absorption and increased reflectivity in some parts of the spectrum. The spectral properties are specific for each TCO material. The refractive index of the TCO depends on the host material and is altered by the dopant [12], [13]. Selecting the material with optimal optical properties can significantly improve light transmission into the absorber layer [14]. Increasing the thickness of the TCO layer improves electrical performance but may reduce the light transmission into the absorber.

The conductivity of a TCO is material specific, defined by the dopant and the doping concentration. Therefore the starting point in TCO modelling is to choose the material thickness that delivers the same $R$ as the reference FTO layer. The required thickness was calculated to be: 100nm for ITO ($\rho=1.5 \times 10^{-4} \Omega\text{-cm}$) and 233nm for AZO ($\rho=3.5 \times 10^{-4} \Omega\text{-cm}$). Both materials required a much thinner layer to achieve same conductivity as FTO. The refractive index matching structures, which are used in TEC15 glass, were not included in the AZO and ITO models.

### 3.3. ITO

ITO is a commonly used transparent conductor in PV devices and consumer electronics applications [15]. It is a highly conductive material and hence at $15 \Omega/\square$ (100nm), it is thinner than AZO and FTO. To investigate the effect of varying the ITO layer thickness, the thickness of the TiO$_2$ layer was held constant at 41nm. The thickness of the ITO layer was then varied between 50nm ($3 \Omega/\square$) and 450nm ($3 \Omega/\square$), the photocurrent density was calculated from the transmission data. A plot of the resulting current density against the thickness of the ITO layer is shown in Figure 5.

![Figure 5](image_url) A graph showing the photocurrent density [mA/cm$^2$] dependence on the thickness of the ITO layer [nm].

Figure 5 shows that the transmission into the absorber layer decreases with the thickness of ITO. The loss is caused by absorption losses. The maximum transmission was found at a thickness of 62nm; which corresponds to a photocurrent density of 26.93mA/cm$^2$. At a thickness of 100nm (corresponding to the reference $15 \Omega/\square$), the use of ITO results in greater current density of 1.17mA/cm$^2$ than that obtained with FTO. This is an increase of 4.5%.

Though the effect of increasing the ITO layer thickness generally results in a lower photocurrent density the rate at which the current decreases is not constant due to interference effects.

Figure 6 shows the modelled current density loss based on the reflection from the ITO back to the cover glass. Using interference enables the thickness of ITO to be increased without optical losses. In a solar cell this reduces electrical losses without affecting the optical properties of the stack.

The optical performance of ITO in perovskite solar cells is driven by absorption. However, interference can be used to reduce the losses. Thickness variation between 175nm and 200nm has little effect on the light transmission into the cell. In this thickness range the interference effects compensate for the absorption losses. This enables a reduction in the sheet resistance of the TCO from $10 \Omega/\square$ to $7.5 \Omega/\square$ without increasing the optical losses. For ITO thickness in the range 140nm to 175nm, increased reflection and absorption losses result in a reduction of the current density.
3.4. AZO

AZO is an alternative transparent conducting oxide [7]. The model was modified to incorporate a layer of AZO as the TCO to compare the transmissivity and electrical properties. Figure 7 shows a 3D plot of the transmission as a function of light wavelength in range from 200nm to 1000nm and the thickness of the AZO layer between 50nm and 500nm. The data presented in Figure 7 was used to calculate the resulting photocurrent in the perovskite solar cell. A plot of photocurrent against AZO thickness is shown in Figure 8.

Figure 8 shows the photocurrent as function of AZO layer thickness. For AZO a sheet resistance of 15 Ω/□ is achieved at 232nm. At this thickness the current density is 1.58mA/cm² higher than that achieved in a FTO based cell. The maximum current density is achieved for a 244nm thick AZO layer, which corresponds to a small increase in photocurrent and a small reduction in sheet resistance to 14.3 Ω/□. AZO has the lowest optical losses of the TCO materials considered here. Current losses due to reflection for different AZO thicknesses are plotted in Figure 9. The analysis shows that AZO has more intense interference effects within the perovskite stack than ITO. Compared to using FTO, the use of AZO results in a 6.5% increase in current density.
Figure 8 A graph showing the photocurrent [mA/cm²] dependence on the thickness of the AZO layer [nm].

Figure 9 Reflection losses modelled for Perovskite solar cell as function of AZO thickness

Figure 10 shows comparisons between the FTO and AZO T% and R% characteristics. The use of AZO results in higher transmission despite higher reflection losses in some region of the spectrum.

Figure 10 Optical properties of perovskite solar cell using AZO (dotted lines) and FTO (solid lines) as TCO.
4. Multi-Layer AR (MAR)

Figure 11 shows a comparison of the reflection modelled for uncoated glass and MAR coated glass surfaces. The design details of the MAR have been described elsewhere [16]. Applying an MAR coating to a perovskite solar cell could achieve an additional 3.5% gain in power from the cell.

![Reflection spectra of MAR designed for Perovskite solar cells, deposited on soda lime glass.](image)

5. Summary

The optical performance of the Perovskite solar cell structure has been modelled. Modelling the perovskite solar cell shows that modest gains can be achieved by reducing the thickness of the TiO$_2$ layer to 30nm. This would increase the photocurrent by 0.3%.

The influence of the TCO has been investigated. The performance of using TEC15 FTO coated glass has been used as reference. We have investigated the effect on transmission by replacing FTO with ITO and AZO at a range of different thicknesses. Modelling showed that using these alternative TCO materials can lead to significant improvement in photocurrent. The calculated increases were 4.5% using ITO and 6.5% for AZO.

Moreover, for AZO it was possible to increase the thickness of TCO and thereby reduce resistance losses without reducing transmission into the absorber. During the thin film PV manufacturing process, the PV material is divided into cells which are then interconnected in series to increase module voltage and avoid resistance losses [17]. The pitch used during the formation of the solar cell interconnect defines the number of cells required per m$^2$ of module. The interconnects are required to avoid resistance losses but they introduce dead areas into the module. The choice of pitch used for the interconnect formation is a compromise between resistance and optical losses. With high quality PV devices the resistive losses are mainly determined by the properties of the TCO. Thus the use of a TCO with higher conductivity leads to a reduction in losses at the interconnect level.

The benefits of tuning the optical structure of the cell can be further improved by the application of a broadband anti-reflective coating. The application of an MAR coating can provide an additional 3.5% relative improvement in photocurrent. This is in addition to the 6.8% relative improvement made possible by replacing the FTO layer with AZO and by using a thinner TiO$_2$ layer. Modelling shows that by combining the use of AZO as the TCO, a broadband MAR and thinner TiO$_2$ could increase the photocurrent of the perovskite cell by a useful relative 10.3%.
6. References


