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High efficiency 4-terminal perovskite/c-Si tandem cells

Dong Zhang[a,*], Mehrdad Najafi[a], Valerio Zardetto[b], Maarten Dörenkämper[a], Xuedong Zhou[a], Sjoerd Veenstra[a], L.J. Geerligs[c], Tom Aernouts[d], Ronn Andriessen[e]

[a] ECN part of TNO-Solliance, High Tech Campus 21, 5656 AE Eindhoven, the Netherlands
[b] TNO-Solliance, High Tech Campus 21, 5656 AE Eindhoven, the Netherlands
[c] ECN part of TNO, Westerduinweg 3, 1755 LE Petten, the Netherlands
[d] IIMEC - partner in Solliance and Energyville - Thin-film Photovoltaic, Thor Park 8320, 3600 Genk, Belgium
[e] Holst Centre-Solliance, High Tech Campus 21, 5656 AE Eindhoven, the Netherlands

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ABSTRACT

The perovskite/c-Si tandem technology is considered as a cost-effective approach to realize a cell efficiency beyond the limit of single-junction (SJ) c-Si cells. Compared to its counterpart of 2-terminal (2T) configuration, 4-terminal (4T) tandem has the advantages such as no constraint of current matching and potentially simple mechanical stacking. But one of the largest challenges is the limited near-infrared (NIR) transmission of the semi-transparent perovskite solar cell (ST-PSC), which has been a bottleneck to the c-Si bottom cell performance and eventually the whole tandem cell performance. The highest NIR transmittance that has been reported is about 84%. In this contribution, we demonstrate a p-i-n planar ST-PSC with an efficiency as high as 15.7% and with a record NIR transmittance of about 92%. It is realized by optimization of the tin-doped indium oxide (ITO) material properties and light management. This NIR-transparent and high-efficiency ST-PSC leads to a 4T tandem cell efficiency of 25.7%, using an interdigitated-back-contact (IBC) c-Si bottom cell.

1. Introduction

As the fraction of the balance of system (BOS) costs are overtaking the solar module in the whole photovoltaic (PV) system cost, the efficiency of the PV module becomes increasingly important to reduce the levelized cost of energy (LCOE) for PV. Tandem technology combining bottom crystalline silicon (c-Si) cells with low-cost thin-film top cells, by enabling a major increase in efficiency, can possibly significantly contribute to LCOE reduction. Amongst all the thin-film PV technologies, the perovskite solar cell is considered a promising candidate for the top cell. Modelling has shown that an optimized perovskite/c-Si tandem can result in a large efficiency increase to single-junction (SJ) c-Si cells [1]. In fact, several authors have calculated that the efficiency of a perovskite/c-Si tandem cell is able to exceed 30% which is beyond the Auger recombination limit of the SJ c-Si cells [2–4]. Over the last three years large progress has been made in the field of perovskite/c-Si tandem cells [5]. A cell efficiency as high as 23.6% has been demonstrated for a monolithic 2-terminal (2T) perovskite/c-Si tandem cell [6] and 26.4% for a 4-terminal (4T) tandem cell [7]. The sketches for 4T and 2T tandems are illustrated in Fig. S1. The difference between those two tandem configurations is that the top and bottom cells in 4T tandems have their own electrical leads separately but are connected in series for 2T tandems. Therefore, in comparison to the 2T tandem concept, the 4T tandem has no constraint of current matching. In addition, the top cell and bottom cell can be processed separately and then mechanically laminated together. However, the complexity on the module and system level caused by two excess electrical leads has to be solved. One of the biggest challenges for reaching high 4T tandem cell efficiency is to obtain high transmission of semi-transparent perovskite solar cells (ST-PSCs) at wavelengths longer than the perovskite absorption cut-off wavelength, which will otherwise cause large optical losses to c-Si bottom cells. For typical perovskite with bandgap of about 1.55 eV, the absorption cut-off wavelength is about 800 nm and thereby the NIR transmission of ST-PSCs is critical. Lal et al. [8] gave an overview about transmittance of ST-PSCs published by different authors, showing that the NIR transmittance was limited to about 80% at that time. Last year Duong et al. [7] demonstrated higher NIR transmittance of about 84%. However, considering the state-of-the-art c-Si cells with external quantum efficiency (*EQE*) that can approach 100% [9], limited NIR transmittance of ST-PSCs inevitably induces large optical losses to c-Si bottom cells. This limitation is especially severe for 4-terminal tandem since ST-PSCs have to utilize two layers of transparent electrodes which are the main causes for NIR parasitic absorption losses. Depending on the thickness and doping concentration, the hole

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[*] Corresponding author.
E-mail address: dong.zhang@solliance.eu (D. Zhang).

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and electron transport layers can also induces NIR parasitic absorption losses. Thus, in results published at the time of writing the *EQE* of c-Si bottom cells in 4T tandem configuration could only peak at about 80% due to the optical losses caused by the ST-PSCs. In this contribution, the detailed optical analysis and optimization of NIR transmission of the ST-PSC is carried out. It is shown that by optimizing transparent electrodes and light management, it is possible to reach ultrahigh NIR transmittance of the ST-PSC which is very important for realizing high-efficiency 4T perovskite/c-Si tandem cells.

2. Experimental data

Regarding the fabrication of the ST-PSC, Corning XG glass with a size of 9 cm^2 is used as substrate and it is cleaned sequentially with soap water, deionized water and isopropanol in an ultrasonic bath. Both bottom and top tin-doped indium oxide (ITO) are deposited at room temperature with RF magnetron sputtering, using a AJA sputtering system. The 4 in. target has 10 wt% SnO_2, the deposition power is 56 W and the pressure is 2 mTorr. The sputter gas is pure Ar before optimization and Ar with a small amount of O_2 (O_2 partial pressure of 0.6 mPa) after optimization. A ~ 20 nm thick hole transport layer (HTL) made of NiO nanoparticles (NPs) capped by poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA), a ~ 500 nm thick perovskite ($Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{0.9}Br_{0.1})_3$) absorber layer, and two electron transport layers (ETLs) consisting of ~ 40 nm thick phenyl-C61-butyric acid methyl ester (PCBM) and ~ 30 nm thick ZnO NPs, are all processed with spin coating. ~ 30 nm thick compact ZnO is deposited with spatial atomic layer deposition on the ZnO-NPs, which is very critical to protect the cell from the sputtering damage of the top ITO layer deposition. MgF_2 layers are thermally evaporated on glass and top ITO to enhance the NIR transmission. Details about the synthesis of NiO-NPs and ZnO-NPs, and preparation of perovskite and PCBM have been published in our previous article [10]. Concerning the c-Si cells used in this study, 5 in. interdigitated-back-contact (IBC) c-Si cells from SunPower are used.

The reflectance (*R*) and transmittance (*T*) are measured with Agilent Cary UV–VIS–NIR spectrophotometer. The sheet resistance of ITO is obtained by four-point probe measurements and the layer thickness by Dektak profilometer. The free carrier density and Hall mobility of ITO are calculated with the hall measurement using the Van-der-Pauw method. The perovskite solar cells were measured under a white light halogen lamp in a glove box, using a stainless steel mask (0.09 cm^2) to define the active area. The light intensity was calibrated by a silicon reference cell. The *J-V* curves are measured using a Keithley 2400 at a scanning rate of 200 mV/s. The stabilized PCE is obtained by tracking the output power for 5 min. The *J-V* characteristics of c-Si cells are measured by Neonsee solar simulator. The external quantum efficiency (*EQE*) is measured by a setup from Rera Solutions. Since the ST-PSC and c-Si bottom cell have very different area, they cannot be measured simultaneously in a tandem configuration. The 4T tandem cell efficiency is obtained with the characterization procedure that has been published in detail by Werner et al. [11,12] and used by many other authors in this field of 4T tandem research. There is an air gap between the ST-PSC and c-Si bottom cell.

Optical modelling is carried out with the GenPro4 program [13]. To ensure the reliability of any conclusions drawn from optical modelling, each component material of the ST-PSCs is prepared individually on glass and characterized with a J.A. Woollam ellipsometer to acquire optical constants. Furthermore, measured *R* and *T* of each material are compared to those simulated with its optical constants for validation.

3. Results and discussion

3.1. Loss analysis of ST-PSC NIR transmission

The NIR transmission of the ST-PSC has dominant impacts on the short-circuit current density of the c-Si bottom cells ($J_{sc\text{-}b}$). In the case that there is an air gap between the ST-PSC and c-Si bottom cell, the $J_{sc\text{-}b}$ can be calculated with the following equation:

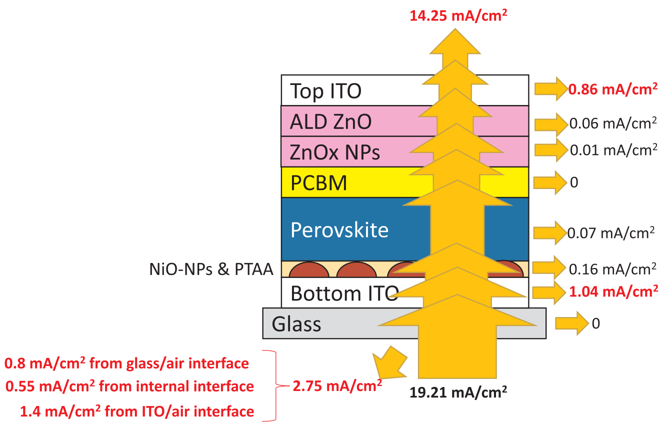

Fig. 1. Detailed optical loss analysis of ST-PSCs in NIR (800–1200 nm). ITO layer thickness is set at 140 nm.

$$J_{sc-b} = e\bullet \int_{300}^{1200} T_{PSC}(\lambda)\bullet EQE_{SJ}(\lambda)\bullet \phi(\lambda)d\lambda, \tag{1}$$

where *e* is the elementary charge, T_{PSC} is the transmittance of the ST-PSC. EQE_{SJ} is the *EQE* of SJ c-Si cells, ϕ is the photon flux of AM1.5 spectrum and λ is the wavelength. Fig. S2 shows T_{PSC} multiplied by EQE_{SJ} is in line with *EQE* of a c-Si bottom cell (EQE_B) directly measured when it is filtered by the ST-PSC, validating the accuracy of this equation. Several authors have pointed out that free carrier absorption (FCA) of the transparent conductive oxide (TCO) and highly doped carrier transport layers can induce significant optical losses, reducing the NIR transmission of the ST-PSC [2,14]. Detailed optical analysis (Fig. 1) is carried out in the wavelength range of 800 nm, corresponding to the bandgap energy (E_g) of perovskite, to 1200 nm, at which the *EQE* response of c-Si cells ends. The current density in Fig. 1 is calculated by the following equations:

$$J_A = e\bullet \int_{800}^{1200} A(\lambda)\bullet \phi(\lambda)d\lambda, \tag{2}$$

$$J_T = e\bullet \int_{800}^{1200} T(\lambda)\bullet \phi(\lambda)d\lambda, \tag{3}$$

$$J_R = e\bullet \int_{800}^{1200} R(\lambda)\bullet \phi(\lambda)d\lambda, \tag{4}$$

where the *A* is the absorptance. When all the photons in the wavelength range of 800–1200 nm can be converted to carriers and then be collected, the maximum current density is 19.21 mA/cm^2. The parasitic absorption loss of the TCO, i.e. ITO in this case, is as high as 1.9 mA/cm^2. However, the carrier transport layers only induce negligible parasitic absorption losses since they are quite thin and not highly doped. In addition, the reflection loss is 2.75 mA/cm^2 among which 0.8 mA/cm^2 stems from the glass/air interface, 1.4 mA/cm^2 from the ITO/air interface and 0.55 mA/cm^2 from multiple internal interfaces inside the cell. The reflection loss from internal interfaces is not high since the refractive indices of component materials in this ST-PSC are close to each other, and is hard to mitigate without degrading the cell performance. However, the reflection losses from the glass/air and ITO/air interfaces can be minimized by applying an optimized anti-reflective (AR) coating.

3.2. Optimization of ST-PSC NIR transmission

To reduce the ITO parasitic absorption in NIR, the free carrier density needs to be limited. That is why we tune ITO properties to decrease the free carrier density from 3.5×10^{20} to about 2×10^{20}