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Design of 4-terminal solar modules combining thin-film wide-bandgap top cells and c-Si bottom cells

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Abstract

Optical simulations of 4-terminal hybrid tandem modules combining high-efficiency crystalline silicon (c-Si) cells with three different thin-film top cells respectively are presented. We considered three types of thin film PV cells: 1. Enlarged-bandgap oxygenated amorphous silicon (a-SiO:H) cells, 2. Wide-bandgap chalcopyrite ($CuGaSe_2$) cells, and 3. Perovskite ($CH_3NH_3PbI_3$) cells. A methodology for evaluating the efficiency gain of the 4-terminal hybrid tandem module is proposed and used to show how the efficiency of an interdigitated back contact (IBC) c-Si module with an efficiency of about 19.5% can significantly be increased through this 4-terminal tandem concept. In our model we also included the change in electrical output parameters by the color-filtering effect of the top cells.

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1. Introduction

For single-junction crystalline silicon (c-Si) solar cells, the previous efficiency record of 25% has been established in 1998 [1]. This record stood for 15 years until last year, when Panasonic announced their back-contacted HIT® cell that reached efficiency of 25.6% [2]. The difficulty in improving the c-Si cell efficiency inevitably limits the module efficiency (current maximum about 22%). The practical limit for single junction c-Si

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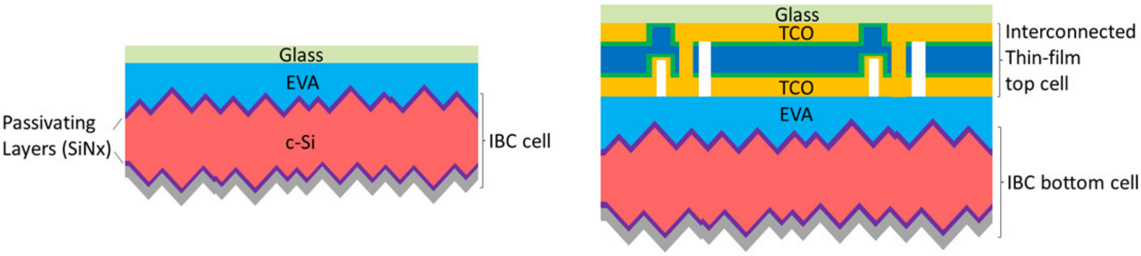
modules is generally thought to be 24-25%. To surpass the practical efficiency limits of single-junction c-Si modules, 4-terminal hybrid tandem modules consisting of wide-bandgap thin-film cells and high-efficiency c-Si bottom cells have been suggested [3]. Compared to the common 2-terminal structure, the 4-terminal hybrid tandem structure has several advantages: no need of current or lattice matching, simple mechanical stacking, more freedom for choosing the top and bottom cells, and most of all the possibility to use monolithic series connection for the thin-film top cell.

In this contribution, a 4-terminal hybrid tandem module structure combing thin-film top cells and c-Si bottom cells is proposed. On the basis of a single-junction IBC module structure (Fig. 1(a)), a thin-film solar cell can be deposited and interconnected on the inner side of the module cover glass as shown in Fig. 1(b), implying a minor change of the single-junction IBC module structure. In the simulation and optical design, an IBC solar cell processed at ECN is adopted as the bottom cell. The design of three types of thin-film solar cells as the top cell has been studied, 1. enlarged-bandgap oxygenated amorphous silicon (a-SiO:H) cells, 2. Wide-bandgap chalcopyrite ($CuGaSe_2$) cells, and 3. perovskite ($CH_3NH_3PbI_3$) cells, and the potential efficiency gain is evaluated.



(a) (b)

Fig. 1. Schematic layer stacks of (a) a single-junction IBC module and (b) a 4-terminal hybrid tandem module combining an interconnected thin-film top cell and a bottom IBC cell.

2. Optical simulation

The optical simulations are carried out with Advanced Semiconductor Analysis (ASA) software developed at Delft University of Technology [4, 5]. Both wave and geometrical optics are included. Layer geometry of solar modules and optical properties of each material are used as input. To evaluate the optical effectiveness of a certain module structure, the weighted fractional absorbance ($\bar{A}$) of a layer in the solar module is defined by the equation:

$$\bar{A}(\%) = \frac{\int_{1200}^{300} A(\lambda)\phi(\lambda)d\lambda}{\int_{1200}^{300} \phi(\lambda)d\lambda}, \tag{1}$$

where $A(\lambda)$ is the net absorbance of a layer in the solar module taking into account the transmission and reflection of all other layers in the stack, $\phi(\lambda)$ is the photon flux of the AM1.5 solar spectrum and thereby $\bar{A}$ indicates the fraction of the absorbed photons in the AM1.5 solar spectrum. Note that only the wavelength range of 300 nm to 1200 nm is considered since the photon flux at wavelengths shorter than 300 nm is negligible and c-Si has no absorption at wavelengths longer than 1200 nm. The photocurrent density corresponding to absorption (either photocurrent gain or loss) in a specific layer (J_a) can be estimated from the equation:

$$J_a(\text{mA/cm}^2) = q\int_{1200}^{300} A(\lambda)\phi(\lambda)d\lambda = \bar{A} \times 46.46\,\text{mA/cm}^2 . \tag{2}$$