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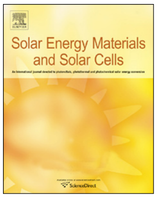

Voltage-matched thin film solar cells in 3-terminal configuration

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ABSTRACT

Multijunction solar cells, proven technological route for achievements of highest PV conversion efficiencies, require accurate tuning of the sub-cell absorption to ensure that every cell in the stack delivers the same current density. Even though currents of the sub-cells can be precisely matched for a fixed illumination spectrum, current mismatch cannot be avoided in real terrestrial applications due to variations of the irradiance spectrum. The issue becomes critical when a solar cell has to cover wider range of applications such as a mixture of direct sun / shadow / artificial light – the case for various distributed PV-powered electronics. Furthermore the current matching constrains choice of materials and designs of sub-cells for a tandem device. A straightforward basic configuration with decoupling the sub-cell's currents is a 3-terminal configuration with one additional contact sheared by the top and bottom cell. This concept requires voltage-matching between the top and bottom cell when these cells are integrated in modules. A realistic concept for the voltage-matched 3-terminal cell reported recently includes a wide gap top cell combined with a tandem bottom cell made of 2 sub-cells with lower bandgaps. The concept is a hybrid between 2 and 3-terminal configurations with voltage matching and relaxed current matching constrains. Established thin film silicon solar cell technology provides interesting option to realize the hybrid 3-terminal cell with amorphous Si top cell ($V_{OC} \approx 0.9$ V) and two microcrystalline Si cells ($V_{OC} \approx 0.5$ V). In this work we present proof of concept of the voltage matched 3-terminal tandem cell prepared with highly transparent and conductive IOH intermediate contact. The efficiency of 10.4% has been achieved made up of independently operating 7.9% efficient top cell and 2.5% efficient bottom tandem cell. The paper summarizes the development and discusses optical losses identified in the 3-T devices.

1. Introduction

Thermalization of photo-excited charge carriers to the band edges of absorber semiconductor is one of the major factors limiting power conversion efficiency of a single junction solar cell [1]. The traditional way to overcome the limitation is to stack cells with different bandgaps of absorber layers so that each sub-cell absorbs and converts a narrow part of the solar spectrum minimizing the thermalization loss. Absolute power conversion efficiency record is held by multijunction devices [2], however these cells require accurate tuning of the sub-cell absorption to ensure that every cell in the stack delivers the same current density. Otherwise the current of the multijunction device will be limited by the lowest sub-cell current. This current mismatch will reduce power output of a multijunction solar cell (in some cases it can be partially compensated by fill factor increase [3]). Even though currents of the sub-cells can be precisely matched for a fixed spectral irradiance, the mismatch cannot be avoided in real terrestrial applications due to variations of the spectral irradiance. The current mismatch becomes a critical issue when a solar cell has to cover wider range of applications, including operation in low-light, shaded conditions, or indoors. [4]. For example, development of solar cells for a PV battery power unit for variety of illumination conditions requires versatile and compact PV device tolerant to the spectrum changes [5,6]. Another aspect is that the current matching constrains the choice of materials and design of sub-cells. A straightforward solution for the problem is to contact the sub-cells individually and design a multiterminal multijunction cell. Realization of this conceptually simple design encounters problem of increased optical losses introduced by the additional contact layers. Compromise between current decoupling and minimalization of optical losses leads to a 3-terminal (3-T) design with only one additional contact introduced between top and bottom cell. This concept requires voltage matching between the top and the bottom cell because the cells are connected in parallel once they are integrated in a solar module [7]. Since the sub-cells in a tandem stack have different bandgaps of absorber layers they have different open circuit and maximum power point voltages too, which is an obvious problem for module integration. One solution to the problem proposed by Guo et al. [8] is a hybrid design where a wide bandgap top cell is combined with a tandem

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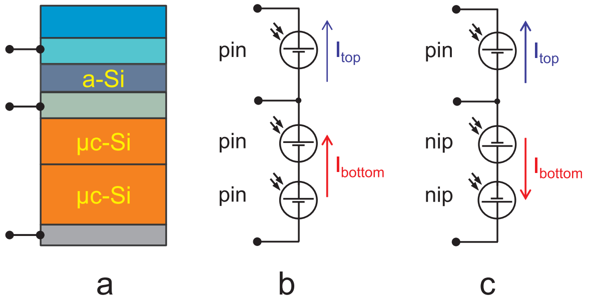

Fig. 1. (a) Sketch of the voltage-matched 3-terminal solar cell stack. Note that each sub-cell consists of p-type, intrinsic, and n-type Si layers not shown in a simple schematic presentation. (b) Equivalent circuit of the voltage-matched stack with all cells prepared in p-i-n configuration. (c) Equivalent circuit of the voltage-matched stack with the top cell prepared in p-i-n configuration and the bottom tandem in n-i-p/n-i-p configuration.

bottom cell made of 2 sub-cells with low bandgaps as sketched in Fig. 1a. The cells are selected to fulfill $V_{OC\ top} = V_{OC\ bottom1} + V_{OC\ bottom2}$, the condition which for the maximum power point (mpp) is defined as $V_{mpp\ top} = V_{mpp\ bottom\ 1} + V_{mpp\ bottom\ 2}$. Established thin film silicon solar cell technology provides suitable option to realize the hybrid 3-terminal cell, because of two types of single cells available: cells with amorphous Si absorber (a-Si) with V_{OC} of 0.85 – 0.95 V, and cells with microcrystalline Si absorber (μc-Si) with V_{OC} of 0.45 – 0.55 V. Combination of the cells can provide voltage-matched hybrid 3-T device where the top a-Si cell is voltage-matched to a μc-Si / μc-Si bottom tandem as shown in Fig. 1(a). The device can have two configurations: one where all cells are prepared in same p-i-n sequence (Fig. 1(b)), or one where top cell and the bottom tandem are prepared in opposite layer sequences e.g. p-i-n a-Si and n-i-p/n-i-p μc-Si (Fig. 1(c)). In both configurations the cells can be measured independently but only the configuration in Fig. 1(b) has 2-terminal operation option and therefore can be directly compared to the same reference 2-T cell without intermediate contact (traditional triple junction configuration). The latter point was the reason to focus on the p-i-n a-Si and p-i-n / p-i-n μc-Si configuration Fig. 1(b) in our study.

Properties of an intermediate contact are crucial for the performance of 3-T cell. The contact has to be highly transparent and conductive as well as the front contact, but there are additional technological requirements for its preparation. For the thin film Si technology such requirements are low temperature and soft deposition to prevent damage of the top cell. Hydrogen doped indium oxide In_2O_3:H (IOH) [9–12] has been applied in our work as an intermediate contact for the voltage-matched 3-terminal Si solar cells. The device development has been divided in 5 main steps:

1. Development and characterization of IOH layers for the intermediate contact.
2. Test of IOH as a back contact of a-Si solar cell with a reference a-Si cell with traditional ZnO:Al/Ag back contact [13] (sketched in Fig. 2a).
3. Test of IOH as a front contact of μc-Si cell with a reference cell prepared on ZnO:Al [14] with ZnO:Al/Ag back contact (sketched in Fig. 2b).
4. Development of a simple tandem in 3-T configuration with a-Si top cell, μc-Si bottom cell and IOH intermediate contact finalized with ZnO:Al/Ag back contact. Reference cell is usual 2-T a-Si / μc-Si tandem with ZnO:Al/Ag back contact (sketched in Fig. 2c).
5. Development of the target device - the voltage-matched 3-T hybrid tandem cell with a-Si top cell, IOH intermediate contact, and μc-Si / μc-Si tandem as bottom cell finalized with ZnO:Al/Ag back contact. The reference cell is 2-terminal a-Si / μc-Si / μc-Si triple junction device with ZnO:Al/Ag back contact (sketched in Fig. 2d).

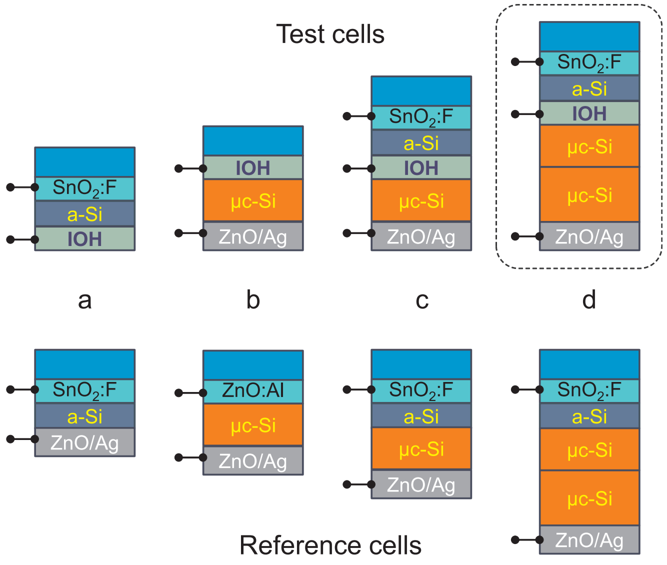

Fig. 2. Summary of the solar cells prepared for the study. The cells in a top row are test cells where various aspects related to the study were tested. The cells on bottom are the reference counterparts for the test cells. Note that each sub-cell consists of p-type, intrinsic, and n-type Si layers not shown in a simple schematic presentation. (a) single junction a-Si top cell with IOH back contact and the reference cell with ZnO:Al/Ag back contact to test function of IOH as a back contact for the top cell; (b) single junction μc-Si bottom cell with IOH front contact and the reference cell with ZnO:Al front contact [14] to test function of IOH as a front contact for the bottom cell and effect of μc-Si deposition on IOH; (c) simple 3-terminal tandem with IOH intermediate contact and the reference cell in 2-terminal configuration to test feasibility of the 3-T cell operation; (d) highlighted with dashed frame is the target device - the hybrid voltage-matched 3-terminal cell, the reference is prepared without intermediate contact in 2-terminal configuration.

2. Experiment

2.1. Thin film Si solar cells

Single junction amorphous silicon cells and 3-T cells were deposited on Asahi-VU substrates or IOH- and ZnO-coated Corning Eagle XG glass substrates (Fig. 2). Thin film Si layers were deposited using a plasma-enhanced chemical vapor deposition (PECVD) in a Large Area experimental PECVD system with deposition area of 30 × 30 cm^2. The single junction and multijunction cells had typical p-i-n structure [4,15]. The back contact for all solar cells except for a test cell with IOH back contact [Fig. 2a] was made of 80 nm room temperature ZnO:Al and 200 nm Ag prepared with magnetron sputtering.

2.2. IOH intermediate contact

Hydrogen-doped indium oxide films In_2O_3:H (IOH) were deposited using a commercial sputter tool from the company Kurt. J Lesker via RF magnetron sputtering of a 6-in. ceramic In_2O_3 target in static mode at room temperature, sputtering power of P = 80 W, total pressure of 2 mTorr, with the following gas flows: Ar = 9.6 sccm; O_2 (10% in Ar) = 0.45 sccm; H_2 (10% in Ar) = 0.9 sccm. Note the utilization of hydrogen gas instead of water vapor as hydrogen precursor [12]. Deposition times were varied from 21 to 90 min, providing thin films with thickness between 140 and 450 nm. IOH layers on glass and as a part of a solar cell have been annealed at 200 °C, in vacuum, for 20 min

2.3. Preparation of 3-terminal cells with laser scribing

Realization of the thin film solar cell in 3-terminal configuration requires advanced patterning procedure to provide access to the