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Thin-film silicon tandem (MICROMORPH™) module design and key reliability topics

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ABSTRACT

Thin-film silicon tandem (MICROMORPH™) module design optimization process for performance maximization is described together with an analysis of some key reliability topics.

In the first part, the procedure for module layout optimization to achieve the maximum module power output is described. In monolithic thin-film modules the layout is realized through a laser scribing interconnection process: a well-controlled laser scribing process is therefore essential to ensure optimal module performance and to minimize unwanted losses.

The second part of the paper focuses on some of the materials used in the fabrication of a solar cell and module of such technology and the processes used to achieve such module assembly, as well as a description of some of the possible failure modes. Special attention is paid to the zinc oxide transparent conductive oxide (ZnO TCO) layers used for the front and back contacts.

The bottom cell (BoCe) and its stability is also analyzed in detail: the influence of process parameters on the BoCe degradation behavior including the differences observed using different thin-film silicon (TF-Si) deposition reactor types, different lamination foils and the impact using different front contact haze is discussed.

In the final part of the paper the effect of particle contamination on the module performance is reviewed: specifically contamination by particles generated during deposition and handling processes. Finally relevant countermeasures to prevent additional module performance loss are discussed.

1. Introduction

In photovoltaic modules a proper module design ensures the maximum module performance, its durability and reliability.

The module design is given essentially by the module layout, the material used and how the different materials are assembled together.

In a TF-Si module the module layout is defined by the laser scribes, which also enable the monolithic serial interconnection of the cells [1]. The set of scribes include 3 patterns: pattern 1 (P1), which isolates the front contact (FC) between the adjacent cells, pattern 2 (P2), which removes part of the silicon layer lying on the top of the front contact and enables the electrical connection between two adjacent cells, and pattern 3 (P3), which selectively removes both the absorber and the ZnO back contact (BC) layers from the top of the FC.

By an optimization of the module layout it is possible to minimize losses resulting from the serial interconnection [2]. In this study a simple equivalent electrical model [3,4] was used to determine the optimal cell width in the module layout and results are presented in Section 3.1.

If from one side the laser scribes offer a great versatility for the module layout, on the other side a not well controlled laser process can be really harmful for the module performance. In fact the laser scribing process can easily generate shunts, which create losses for the module output. The influence of the laser scribing processes on module performance is described in Section 3.2. An explanation of how to find, in practice, a laser scribing process window for patterning of MICROMORPH™ layers is also given.

The module design includes also the choice of materials and processes used in the module construction to ensure not only the module performance but also the module reliability

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Particular attention is given to the ZnO (TCO). Due to its properties of high transparency, high electrical conductivity and ability to scatter incident light, this material is ideal to be used as transparent electrode layers in TF-Si solar cells [5]. It is well known that some common chemical elements such as water vapor can deteriorate the electrical properties of this material. A comprehensive explanation of the electrical degradation mechanism under high temperature combined with high humidity conditions (commonly termed damp heat, abbreviated as DH) was previously reported by [6]. In order to better understand the behavior of ZnO in PV modules the electrical degradation of ZnO under different conditions was investigated and results are presented in Section 3.3.

Another material susceptible to degradation is the μc-Si:H of the BoCe. It has been observed that MICROMORPH™ modules stored in dark conditions at ambient temperatures can degrade over time. Such modules suffer from a reduction in open circuit voltage (V_{oc}) and fill factor (*FF*), whilst the short circuit current (I_{SC}) remains constant. This behavior is referred to as dark degradation (DD) in this study. It has been already shown from different groups that the compactness and the quality of the BoCe influence the cell stability [7–10]. In particular the oxygen and water diffusion thorough the BoCe is reduced by a high compactness of high quality μc-Si:H material.

In this work, the impact on DD by using different reactor configurations, different encapsulation materials and TCO FC with different haze, was investigated and results are presented in Section 3.4.

Another important topic in order to ensure reliability and durability of the product is the environmental cleanliness of some specific module processing phases. During the fabrication of semiconductor microelectronic devices the importance of clean substrate surfaces has been recognized for more than 60 years. Impurities on the semiconductor surface are detrimental for both the correct functionality and the reliability of the devices [11]. The impact of particle contamination on TF-Si photovoltaic modules was investigated in detail.

2. Materials and methods

All samples described in this paper were produced and measured within the pilot line at TEL Solar AG, Trübbach according to processes described in [1]. The pilot line disposes from equipment that are similar to equipment and processes used in a production facility. The setup allows for a variety of hardware and process adaptions that can improve the technology to be successfully and rapidly implemented.

Secondary Electron Microscopy (SEM) imaging was performed using a JEOL JSM6510 system and energy-dispersive x-ray spectroscopy (EDX) was performed using a Bruker Quantax system. Focused Ion Beam (FIB) milling was carried out at EMPA Dübendorf Switzerland using a dual beam FEI Strata DB235 FIB/SEM.

Laser scribing was performed using the 'through-the-glass' process together with TEL Solar's LSS1200 production tools that have been described in [12].

ZnO:B samples deposited by Low-Pressure Chemical Vapor Deposition (LPCVD) were degraded in a controlled environment of 85 °C and 85% relative humidity corresponding to the standard DH test. The sheet resistance (R_{sq}) was evaluated using a 4-probe-method. Hall measurements were measured using an Ecopia HMS 3000 system. The mobility and charge carrier density were measured using the Van der Pauw method at room temperature. Selected ZnO:B samples were subjected to a hydrogen plasma treatment that was performed on a Gen. 5 size KAI™ reactor at 200 °C substrate temperature, 0.8 mbar pressure, 1500 W RF-power and 4000 sccm H_2 flow, for 500 s treatment time. Light soaking (LS) treatment was performed at 1 sun (AM1.5 spectrum, 1000 W/m^2) and at 50 °C.

Fourier-Transform Infrared (FTIR) spectra were recorded with a Thermo Scientific Nicolet 8700 FTIR spectrometer. A KBr beam splitter and a deuterated triglycine sulfate (DTGS) detector were used. The measurements were performed in reflection mode using a VeeMax reflection unit from Thermo Fisher at 30° angle of incidence. The measurements were averaged over 32 scans and the resolution of the spectra was 4 cm^{-1}.

Lock-in Thermography (LIT) was used to qualitatively identify shunts [13].

3. Results and discussion

3.1. Layout selection and impact

In the up-scaling of TF-Si cells to modules various losses arise from the serial interconnection (Fig. 1). The two dominating mechanisms are dead zone (DZ) losses and resistive losses from the TCO [14,15].

The DZ loss is due to the part of the module between P1 and P3, which does not contribute to the conversion of incident solar energy to electric power. To reduce the DZ area the number of cells in a given module can be reduced by increasing their width. At the same time, however, the cell width determines the resistivity losses due to the FC and BC layers, the wider the cell, the higher the losses.

Eq. (1) can be used to estimate the loss factor *f*, which is the sum of area losses and resistive losses in TCO (adapted from [14]).

$$f = \frac{w_d}{w_a + w_d} + \frac{R_{sq}}{3}\frac{J_{MPP}}{V_{MPP}}\frac{w_a^3}{w_a + w_d} \quad (1)$$

where current density J_{MPP} and voltage V_{MPP} are at the maximum power point (MPP) of the device, the TCO sheet resistance is represented by R_{sq}, the active cell width by w_a and the dead zone width by w_d.

Fig. 2 shows the relative power loss calculated from Eq. (1) for Gen. 5 module size (1.3 m × 1.1 m, 1.43 m^2 total area) as a function of the number of segments and for a range of R_{sq} values of both the ZnO:B front and back contact layers. The DZ width was set at 0.20 mm (a typical value for mass-production laser scribing processes) and the edge deletion (ED) [16] width at 11.0 mm. The reference module has 142 segments connected in series and R_{sq} magnitudeseach of 16 $\Omega_\square$ for both the FC and BC TCO layers.

An asymptotical saturation of relative power losses starts at about 190 segments. Afterwards the losses start to increase again due to an increase of number of segments and therefore the overall dead zone width for the entire module.

In a module, another source of power loss is the ED width. By application of the previously calculated power losses and the additional power loss due to the ED width, a prediction of the stabilized module power as a function of the number of segments (in series) can

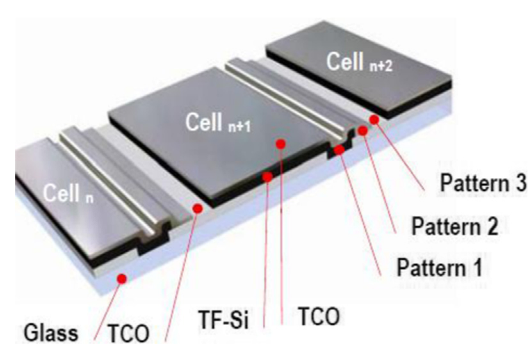

Fig. 1. Schematic serial interconnection in TF-Si modules.