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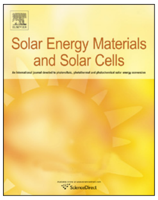

Modeling and testing the mechanical strength of solar cells

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ABSTRACT

The strength and fracture behavior of solar cells govern the failure of cells in a photovoltaic module under thermal and mechanical loads. In this study, the testing and modeling of strength of silicon solar cells with aluminium metallization are presented. Therefore, the contribution of microstructure in solar cells was analyzed regarding stiffness and fracture behavior. With this knowledge, a simulation model was created to evaluate the influence of each layer to the stress field inside the silicon part of the solar cell. The model was used to evaluate 4-point bending experiments, which were performed to determine the strength of solar cells on front and backside and in two different directions, parallel and perpendicular to the busbars. It is shown that the strength and breakage depend strongly on the side and direction of loading. The lowest strength was detected for the backside being loaded with tensile stress parallel to the busbars.

1. Introduction

The mechanical integrity of solar cells is an essential part of their reliability during handling and processing solar cells and photovoltaic modules. Cracks in modules are currently strongly investigated [1–3], since cracks due to mechanical or thermal load can significantly reduce the electrical efficiency and reliability of modules. Though the mechanical and thermal loads in application are only one parameter for cell breakage, the critical limit or strength values for the solar cell breakage has to be considered regarding the loads. Furthermore, this strength is defined by the given defect structure results from the cell manufacturing process starting with the wafering of silicon. Although defects and strength of silicon wafers are investigated in detail, e.g. [4–9], the strength of solar cells has been rarely analyzed. Current silicon solar cells consist of different layers with different materials (e.g. Si, Al and Ag), the influence of each layer should be analyzed in contribution to the strength of the silicon solar cell.

Kohn et al. [10,11] has shown with representative metallization structure for ring-on-ring tests that the firing process for different paste materials (AgAl and Al) can reduce the cell strength, especially due to the AgAl/Al overlap. It was observed that during the fracture tests cracks in the AgAl/Al overlap region occur and lead to local stress concentrations, which lead to fracture at lower stress. Popovich et al. [12] performed strength tests with 4-point bending on standard solar cells with an analytical stress evaluation. It could be shown that higher drying and lower firing temperatures lower the strength of the solar cell for the backside in tensile stress. Furthermore, the microstructure and mechanical properties of the aluminium back contact have been investigated [13]. Amstel et al. [14] presented a thermo-mechanical solar cell model after firing for predicting internal stresses and the maximum amount of deflection. A Mori–Tanaka homogenization method was used to predict mechanical response of the Al layer. However, a comprehensive mechanical model of a solar cell, which can be used for interpreting stresses in mechanical tests like 4-point-bending, is missing.

In this work, a mechanical model is developed and used to determine strength of solar cells with the current standard concept (Al-BSF, H-pattern). Therefore, the layer system of solar cells, especially the backside metallization of AlSi and Al, is analyzed using different models of mechanical homogenization. Using the elastic data from this investigation, Finite Element Analysis (FEA) is used to model and characterize the bending behavior and the stress fields in solar cells, considering the different material layers. By the use of the FE model and Weibull analysis, the strength of typical solar cells (Al-BSF, H-pattern) is determined in 4-point-bending experiments regarding different orientations of load. Furthermore, fractography is performed by the use of electro-luminescence to analyze the crack pattern.

2. Material and methods

2.1. Samples

For the strength measurements 200 full-square monocrystalline solar cells with standard concept (Al-BSF, H-pattern, 3 busbars) with the size of 156 mm × 156 mm × 200 μm (TTV: 30 μm) were used. All

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cells are from one batch, so the materials (i.e. pastes) are consistent. The backside contact consisted of continuous Ag-busbars (width: 3 mm, length: 126 mm) and an Al-paste with aeutectic layer (AlSi). On the sunny side (front side) there were also three Ag-busbars (width: 1.5 mm, length: 153 mm) and an alkaline textured Si-surface with anti-reflection layer. Further data on the thicknesses and mechanical material parameter used for each layer in simulation model are summarized in Table 2.

2.2. *Strength testing*

Methods for testing the strength of silicon wafers [15] are also applicable to silicon solar cells. The 4-point bending setup is most commonly used in the literature for testing wafer strength. It loads a large area homogeneously by uniaxial bending moments including the surface and edges of the sample. The load occurs as homogeneous tensile stress on the bottom surface of the sample in the test. The 4-point bending configurations in this work (cf. Fig. 1b) had an outer span (outer rollers) of 110 mm and inner load span (inner rollers) of 55 mm. The rollers are made of steel with a diameter of 10 mm. For better contact behavior and reduced friction, PTFE foils were put between the rollers and the cells. The rollers have small grooves at the region of the busbars when testing the busbars across to the rollers. In the area of the grooves there are no foils between the cell and the roller during testing. Four different testing configurations were performed, as shown in Fig. 1a and Table 1. Thus, the backside and sunny side of the solar cells are analyzed in tensile stress with the busbars perpendicular (across) and parallel to the rollers. For each configuration, 50 solar cells were tested. All tests were performed on a universal testing machine ZWICK 005, using a load cell of 1 kN. The deflection of the sample was measured by the machine position. The load speed was defined to be 0.1 mm/s. During testing the force and deflection were recorded for every sample beginning after reaching an initial force of 0.5 N and ending at fracture for the solar cell. In order to avoid shattering of the cell in 4-point bending tests, adhesive tape was attached on the compressive stress side of the cells in stripes perpendicular to the rollers.

The mechanical model (see Section 3) was used to calculate the fracture stresses in the 4-point bending experiment. The fracture stresses σ_i were statistically evaluated using a two parameter Weibull distribution [16,17]:

$$P(\sigma_i) = 1 - \left[\exp\left(-\frac{\sigma_i}{\sigma_\theta} \right)^m \right] \quad (1)$$

where σ_θ is the characteristic fracture stress at which 63.2% of all samples fail and m is the Weibull modulus which represents the scattering of the fracture stresses. A high Weibull modulus means a small variation and a low Weibull modulus represents large variation in fracture stress values. The Weibull parameters were calculated using the Maximum-Likelihood estimation (MLE) according to [18,19].

2.3. *Microstructure and fractography*

For investigations regarding the fracture origin after 4-point bending tests optical inspection without a microscope for macroscopic fracture behavior, as well as high resolution scanning electron microscopy (SEM) and electroluminescence (EL) was used for microscopic fractographic analysis. For each tested configuration two to three samples were analyzed with EL. The EL pictures were done with a voltage of 0.8 V. The cells were contacted all over on the backside and pointwise with a grid of small metal pins at the front side busbars. For SEM fractured pieces of the cell were prepared so that the cross section of the cell could be analyzed in terms of layer structure and fracture origin.

3. Modeling

3.1. *Properties of layers*

The solar cell consists of different layers which are shown in Fig. 2. The contact metallizations for solar cell concept analyzed in this work consist of screen printed silver pastes (busbars at front and backside and fingers) and aluminum paste (back contact). During the firing process, the eutectic (AlSi) and back surface field (BSF) were formed from the diffusion of aluminum into silicon. Details can be found in the literature [20]. The bulk porous Al layer after firing consists of loosely connected AlSi particles covered by alumina [21] (see Fig. 3a). The silicon part of the cell (p-type Si and BSF) has a cubic crystal structure whereas in the BSF represents a zone of Al dopped region. Though the mechanical parameters in the dopped region are assumed to be equal to pure silicon, the Ag paste used for the busbars and fingers has a more regular microstructure than the Al layer on the backside (see Fig. 3b).

Theoretical mechanical investigations of eutectic and the Al paste were conducted using the Mori–Tanaka method [22] to homogenize the elastic modulus. By the use of this method it was theoretically determined that the Young modulus of the eutectic layer AlSi is approximately 72 GPa, which is in good

Table 1
Sample batches and configurations used for strength tests of solar cells in 4-point bending.

Name	Side in tensile stress	Position rollers to busbars	Number of cells	Direction tensile stress to busbars
SP	**S**unny side	**P**arallel	50	Across
SC	**S**unny side	**A**cross	50	Parallel
BP	**B**ackside	**P**arallel	50	Across
BC	**B**ackside	**A**cross	50	Parallel

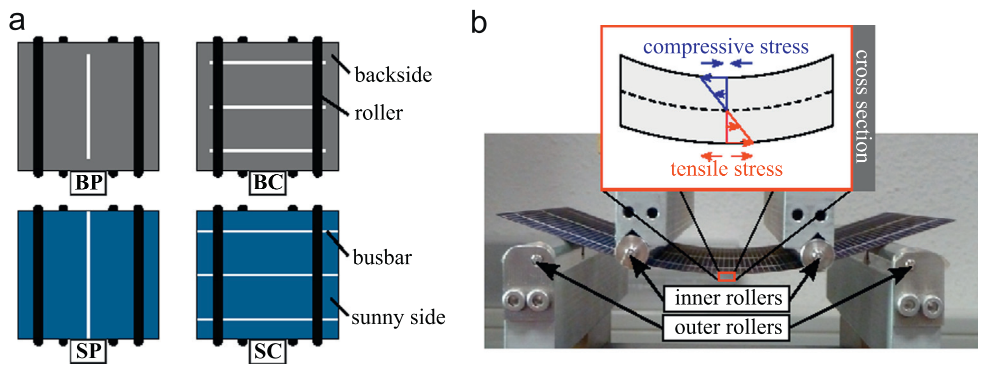

Fig. 1. Strength testing with 4-point-bending: (a) schematic view of all configurations used for strength testing, (b) picture of configuration BC without PTFE foils during test (tension side: B – backside, S – sunnyside; busbars to rollers: C – cross, P – parallel).