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Potential induced degradation of N-type bifacial silicon solar cells: An investigation based on electrical and optical measurements

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ABSTRACT

This paper reports an extensive analysis of the potential-induced degradation (PID) of N-type bifacial solar cells. The analysis is based on combined electrical characterization, electroluminescence and external quantum efficiency measurements, carried out on solar cells submitted to high PID stresses. We investigate the impact of two different encapsulation materials: (i) polyolefin elastomer (POE) and (ii) ethylene-vinyl-acetate (EVA). We describe the degradation and recovery kinetics as a function of the temperature and the stress voltage. Moreover we demonstrate that the POE can be adopted to reduce the decrease of conversion efficiency during PID stresses. Finally we investigate the effects of PID with an optical analysis in order to find the main cause of the performance degradation.

1. Introduction

In the last years, monocrystalline N-type bifacial silicon solar cells have received attention due to their higher efficiency with respect to p-type solar cells [1]. The primary motivation for the better performance is related to the higher tolerance to transition metal impurities [2]. The higher performance compared to p-type solar cells have been thoroughly studied and demonstrated [3–5]. In 2015 the market of monocrystalline n-type solar cells was limited to less than 7% but it is expected to grow up to 30% before 2025 [6].

Despite the excellent technological advances, several factors may favor the degradation of solar cells during long-term operation, including: (i) the decrease in shunt resistance of the single solar cells due to the generation of hot spots [7,8], (ii) the degradation of the encapsulants [9], (iii) light induced degradation (LID) [10,11], (iv) ambient related issues like humidity and temperature [12] and (v) potential induced degradation [13].

Potential induced degradation (PID) occurs when a large potential difference is applied between the solar cells (that can reach hundreds of volts in series-connected modules) and the grounded frame that surrounds the module, and may lead to a significant degradation of the electrical characteristics of the cells, and to a not negligible leakage current through the encapsulant material. PID was extensively studied on p-type silicon solar cells [14–16]. Only recently, some research groups tried to address the PID issue in n-type silicon solar cells [17,18]. The main cause of the PID degradation is not yet understood, and several explanations have been given so far in the literature: Naumann [19] associated the degradation of p-type solar cells subjected to PID to the presence of sodium (Na) in the active layers; Hara [17] and Swanson [20] explained the effects on n-type solar cells as due to an enhanced front surface recombination between electrons and holes; Halm [18] attributed the PID effects to a degradation of the front surface passivation; finally, Naumann [21] divided the PID effects into two categories: shunting potential induced degradation (PID-s) and degradation of the front surface passivation (PID-p).

The aim of this paper is to contribute to the understanding of the PID effects on the performance of monocrystalline n-type silicon solar cells. More specifically, we analyze: (i) the impact of the encapsulant material on PID robustness; (ii) the effect of four different temperatures (35 °C, 50 °C, 65 °C and 80 °C) and three different applied voltages (−300 V, −450 V and −600 V), by subjecting various solar panels to different PID stresses and recovery phases with a positive applied voltage; we extrapolated the Arrhenius plot of the temperature-dependent degradation, and we describe the dependence of the degradation kinetics on the applied voltage. (iii) In order to achieve a detailed description of the PID effects, we performed an optical analysis through electroluminescence (EL) and external quantum efficiency (EQE) measurements. The EL analysis allowed to identify two different

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degradation processes, a permanent one and a recoverable one. The results of the EQE measurements were related to the electrical measurements in order to investigate the recombination effects with varying incident wavelength. (iv) Finally, we performed and compared two PID stresses carried out with the aluminum sheet in the front side and in the rear side of a solar module in order to better explain the physical cause of the degradation induced by the PID on the performance of the solar cells.

2. Technology details

The study was carried out on $15.6 \times 15.6\ cm^2$ n-type bifacial solar cells, based on mono-crystalline silicon. The solar cells and mini-modules were manufactured by MegaCell s.r.l. using four busbars. MegaCell produces high efficiency solar cells up to 21% efficiency, with a bifacial factor > 88% (ratio between rear and front efficiency). The solar cell process has been developed and patented by the German ISC Konstanz Institute (ISC) and consists of a front alkaline texturing process with ozone cleaning, a front and back SiNx antireflection layer creation by PECVD, a double diffusion process (front BBr3 and rear POCl3), a laser edge isolation phase, a screen printing phase and a fast firing metallization process.

The cell architecture is schematically represented in Fig. 1a. In order to study the effect of the encapsulation on PID, two different materials were used: i) conventional good quality ethylene-vinyl-acetate (EVA) encapsulant with 450 µm thickness typically used for p-type cells lamination; ii) high quality pre-reticulated polyolefin elastomer (POE) film with 450 µm thickness and improved volume resistant properties. An extra clear 2 mm glass on the front side and a transparent back sheet on the back side have been used.

The 2 × 2 solar panels (Fig. 1b) have been soldered manually using standard ribbon SnPb 60/40 with dimensions 1.2 mm × 0.2 mm. For the lamination a one-step laminator has been used.

For the mini module assembly, the lamination recipe has been adjusted in order to obtain a minimum Gel content of 80%.

3. Experimental details

During the PID stress tests, the main cell parameters were monitored by means of (i) I-V measurements, both in dark condition and under illumination, (ii) electroluminescence characterization and (iii) external quantum efficiency measurements. The dark characterization was carried out by using a Keithley 2651 A source meter, programmed via LabView®. The characterization was carried out dynamically changing the current range in order to reach high accuracy in the current measurement from the microampere to ampere range. The light characterization was carried out by using the Keithley 2651 A and a microcontroller-based white LED solar simulator, properly calibrated and synchronized with the source meter. The solar simulator can produce different illumination levels from 0.2 suns up to 4 suns, by varying the current through the LEDs.

The electroluminescence images were carried out by using an InGaAs camera (Xenics), while biasing the solar cells or mini-modules with a forward current of 7 A. Finally the external quantum efficiency measurements were performed by using the commercial system LOANA (PV tools) with a light spot of 2 mm × 1 mm and a biasing light of 0.3 suns. The system is able to extrapolate the calibrated external quantum efficiency in the wavelength range between 300 nm to 1200 nm, and the map of the external quantum efficiency at fixed wavelength on a region of the solar cell. This system allowed to compare the EQE map signal with the EL signal extrapolated during the PID stress (see paragraph 4.3 for the results).

The stress experiments were carried out on 1-cell and 4-cells mini-modules, encapsulated by using POE and EVA. An aluminum sheet was applied on the front or back of the cells, to emulate the grounded frame of a real solar panel. The stress bias was applied between the (short circuited) solar cell and the aluminum foil, consistently with previous reports on the topic [22]. Degradation was induced as described in the following: after the preliminary characterization at 25 °C, the solar cell or module was subjected to a 1 h PID test @ − 600V and 65 °C. Then the system was cooled down at 25 °C and the characterizations were carried out (dark and light IV, EL characterization and EQE characterization). This scheme was repeated for different steps with this cumulative timing: 1 h, 3 h, 7 h, 15 h, 39 h and 55 h. After the stress, a recovery phase @ + 600 V and 65 °C for 48 h was applied with measurements at 24 h and 48 h in order to investigate the recovery of the PID stress.

This stress strategy allows to follow the evolution of the cell parameters (short circuit current I_{SC}, open circuit voltage V_{OC}, maximum power P_{MAX}, fill factor FF, series resistance R_S, shunt resistance R_{SH}, etc.) during the stress test and to investigate the failure point where the cells stop working properly. In particular, the EL can be monitored during the stress test, thus identifying the actual causes of failure.

4. Results and discussion

This paragraph is divided in 4 sections: Section 4.1 describes the electrical results of the PID stress @ − 600 V for 55 h (T = 65 °C) and the related recovery phase @ + 600 V for 48 h (T = 65 °C) performed on two bifacial solar cells encapsulated with two different encapsulants: (i) ethylene-vinyl-acetate (EVA-BSC) and (ii) polyolefin elastomer encapsulant (POE-BSC). Moreover the two diode model was used on the EVA-BSC cells in order to explain the nature of the degradation. Section 4.2 shows the results of the PID stresses carried out on a four solar cells module. In particular the stresses were performed at different voltages and at different temperatures in order to extrapolate the kinetics of the degradation. Section 4.3 shows the results of the optical analysis (electroluminescence (EL) and external quantum efficiency (EQE)). The correlation between the IV characterizations and the EL analysis was investigated. A physical motivation of the PID phenomena is given.

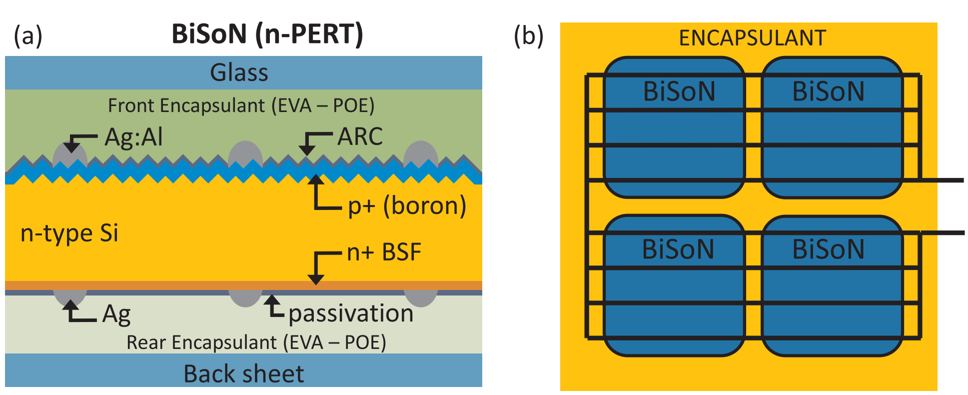

Fig. 1. (a) Cell architecture and (b) scheme of a 2 × 2 solar panel.