Solar Energy Materials & Solar Cells 140 (2015) 361–365

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Potential-induced degradation in photovoltaic modules based on n-type single crystalline Si solar cells

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ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form
20 April 2015
Accepted 24 April 2015

Keywords:
Potential-induced degradation (PID)
Crystalline Si
Solar cell
Photovoltaic module
Surface recombination
Ionomer

ABSTRACT

Potential-induced degradation (PID) in photovoltaic (PV) modules based on n-type single crystalline Si solar cell (front junction cell) was experimentally generated by applying negative voltage from an Al plate, which was attached on the front cover glass of the module, to the Si cell. The solar energy-to-electricity conversion efficiency of the standard n-type Si PV module decreased from 17.8% to 15.1% by applying −1000 V at 85 °C for 2 h. The external quantum efficiency in the range from 400 to 600 nm significantly decreased after the PID test, although no change was observed from 800 to 1100 nm. PID in n-type Si PV modules can be basically explained by enhanced front surface recombination between electron and hole on the Si cell, whereas the polarity of voltage leading to PID depends on structure of Si cell. An ionomer encapsulant instead of EVA has significantly suppressed PID in n-type Si PV modules.

1. Introduction

Potential-induced degradation (PID) in crystalline Si photovoltaic (PV) modules causes significant power losses in the PV systems. High voltage stress toward partial PV modules seems to result in PID, because huge numbers of PV modules are serially interconnected in large PV systems. PID has been typically studied in p-type-based Si PV modules [1–8]. Metal ions, such as Na^+, which are involved in the soda lime front cover glass, and migrate toward the Si cell by high-voltage stress, are considered to cause PID [9–13]. Decrease in the shunt resistance of modules owing to influence of Na^+ on p–n junction seems to be main reason leading to PID in p-type Si PV modules (Shunting type mechanism [12]).

Taking into consideration the mechanism of PID in p-type Si PV modules, PID can be basically avoided by using Na-free front cover substrates [14,15] or encapsulant whose volume resistivity is high [16–19], to diminish migration of Na^+ toward the surface of Si cells. For instance, when a chemically strengthened glass whose Na^+ in the surface of glass is exchanged by K^+ is used as the cover front glass instead of a conventional soda lime glass, no degradation of crystalline Si PV module by PID was observed [14].

In contrast, detail studies on PID in PV modules based on n-type-based Si solar cells have been much less than p-type Si PV modules, since SunPower firstly reported in n-type back contact (BC) Si PV modules. Swanson et al. reported that surface polarization effect decreased the PV performance of a high efficiency n-type BC Si solar cell by applying high positive voltage to the Si cell [20]. By the polarization effect, negative charges are left on the front surface of the n-type Si cell, enhancing front surface recombination between electron and hole at the surface [20]. Recently, Naumann et al. also have reported PID in n-type interdigitated BC solar cells [21]. Thus, degradation mechanism of PV modules by high voltage stress significantly depends on the structure and type of Si cell. Because n-type Si PV modules have attracted attention owing to their high efficiency, detail mechanism of PID in several n-type Si PV modules should be investigated furthermore.

In order to prevent PID and consequently improve the long-term stabilities of PV modules furthermore, we are currently studying PID in terms of understanding mechanism and consequently producing low-cost PID-resistant modules. For instance, we have reported that PID can be significantly suppressed by using a acrylic-film as a front cover substrate [15], control of anti-reflection coating on the surface of crystalline Si solar cell [22], using TiO_2-thin film coated on the inner side of the cover glass [23], and introducing a thin polyethylene (PE) film into a conventional p-type Si PV module [24]. These results imply possibilities of promising PID-resistant techniques. In this paper, we focus on PID in PV modules with an n-type-based single crystalline Si solar cell, which is front junction (FJ) cell, to understand PID furthermore. PID was experimentally observed in n-type FJ Si PV

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http://dx.doi.org/10.1016/j.solmat.2015.04.037
0927-0248/

modules in our laboratory. The different degradation behavior was demonstrated, compared to p-type based Si PV modules, and degradation mechanism is discussed.

2. Experimental

2.1. Module fabrication

A commercial n-type-based single crystalline Si solar cell (FJ cell, size is 156 mm × 156 mm, ca. 200 μm thickness) was used in this study. The standard Si PV module consisted of a front cover glass (Asahi Glass Co., Ltd., soda lime glass, 3.2 mm thickness, 180 mm × 180 mm), two films of commercial EVA (fast-cure-type, 0.45 mm thickness) as the encapsulant, the n-type Si cell, and a commercial back sheet whose structure is polyvinyl fluoride (PVF)/polyethylene terephthalate (PET)/PVF. The PV module components (glass/EVA/c-Si cell/EVA/back sheet) were laminated by using a laminator (LM-50 × 50, NPC Inc.) under vacuum condition at 150 °C for 15 min. A commercial chemically strengthened glass (CSG, 0.8 mm thickness) was also employed as the front cover glass instead of soda lime glass to investigate the influence of glass composition on PID. Also, a layer of ionomer (IO, copolymer of ethylene and methacrylic acid) whose thickness is ca. 0.45 mm (Tamapoly Co., Ltd., HM-52, thickness of one film is ca. 30 μm) was utilized as an alternative encapsulant instead of EVA.

2.2. PID test and characterization

In order to apply homogeneously voltage to the Si cell, an Al plate (thickness is ca. 0.5 mm) was strictly attached on the entire front cover glass of the module as the electrode for PID test. The negative high voltage (−1000 V) was applied to the Si cell with respect to the Al plate by using a power supply (Kikusui Electronics Corp., TOS7200) at 85 °C for 2 h in a chamber. The humidity in the chamber was not controlled during the PID test (ca. 2% at 85 °C).

The solar energy-to-electricity conversion efficiency (η) and the electroluminescence (EL) images of the modules before and after PID tests were measured, as have been reported in the previous paper [23]. Spectra of external quantum efficiency (EQE) for the modules were estimated with a spectral photocurrent response measurement system (Bunkoukeiki Co., Ltd., BQE-100L). The EQE was measured using PV modules through glass and encapsulant, because we do not use adhesive to fix the Al electrode on the glass of module in the PID test. Therefore, we can avoid influence of residues, which affects the glass transmittance. Dynamic secondary ion mass spectrometry (D-SIMS) measurement was conducted to estimate the Na concentration in the surface of Si cells by Toray Research Center, Inc. In order to measure SIMS data of the Si cell, the PV module was cut off after the PID test, and then the Si cell was detached from EVA encapsulant.

3. Results and discussion

3.1. Effects of voltage and temperature on PID

Fig. 1 shows the *I–V* curves for a standard n-type FJ Si PV module before and after PID tests for 2 h by applying −50 V at 85 °C, −1000 V at 25 °C, and −1000 V at 85 °C. Similar degradation was observed after the PID test for 2 h under three conditions. For example, η of the module decreased from 17.8% to 15.1% after the PID test of −1000 V at 85 °C for 2 h (the power output decreased about 15%). Both the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) decreased from 9.07 A to 8.04 A and from 0.64 V to 0.61 V, respectively, although fill factor was not changed as 0.73. The change in the *I–V* curve is different from that observed in p-type multicrystalline Si PV module by PID, which is due to decrease in the shunt resistance of the module (Shunting type mechanism), as shown in other papers [1,4,12]. Naumann et al. have reported that decrease in the shunt resistance of an n-type BC Si solar cell did not occur by PID [21]. In our experiment, no PID occurred in p-type Si PV modules by applying −1000 V at 25 °C for 2 h and applying below −400 V at 85 °C for 2 h. These results suggest that PID easily occurred in n-type single crystalline Si PV modules, compared to p-type multicrystalline Si PV modules with different degradation mechanism. Leakage current during the PID test by applying −1000 V at 85 °C was ca. 7 nA/cm^{-2} in our experiment. Swanson et al. reported the leakage current probed to be 0.6 nA/cm^{-2} at 1000 V in an n-type BC Si PV module [20].

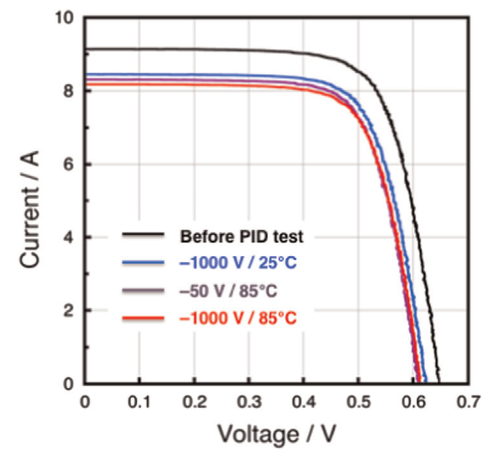

Fig. 1. The *I–V* curves for standard n-type FJ Si PV modules before and after PID test for 2 h: (black) before, (blue) −1000 V at 25 °C, (purple) −50 V at 85 °C, and (red) −1000 V at 85 °C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

On the other hand, no degradation was observed in n-type FJ Si PV module after the PID test by applying −50 V at 25 °C for 2 h and by applying positive voltage, +1000 V at 85 °C for 1 week. These results obviously indicate that high negative voltage to the Si cell with respect to the Al plate and high temperature are important factors causing PID in n-type FJ Si PV modules used in our experiment, while the polarity of voltage, which results in PID, is different from that for a BC Si PV module reported in other paper [20]. When we applied positive voltage (+1000 V) to a PID-degraded module at 85 °C for 1 h, η was completely recovered. This indicates that PID in n-type FJ Si PV modules used in this work is reversible by our PID test.

Fig. 2 shows the EL images for the module before and after the PID test (−1000 V at 85 °C for 2 h). After PID occurred, the entire Si cell was homogeneously darkened, whereas the EL inactive darkened areas were partially observed in p-type Si PV modules [1,6,8,23]. This change in the EL images after the PID test also suggests different degradation mechanism between n-type and p-type Si PV modules.

3.2. Spectrum of EQE for a PID-degraded module

Because I_{sc} of the module decreased after the PID test (Fig. 1), the spectra of EQE for the module before and after the PID test were measured (Fig. 3). Interestingly, only EQE in the range from 400 to 600 nm significantly decreased after the PID test, although no change was observed in the range from 800 to 1100 nm, as shown in Fig. 3. Sharma et al. reported that when the value of front surface recombination velocity increases, spectral response of crystalline Si PV cell decreases in the short-wavelength region (e.g. $\lambda < 500$ nm) [25]. Because of the high absorption coefficient of Si