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Letter

Reduction in the short-circuit current density of silicon heterojunction photovoltaic modules subjected to potential-induced degradation tests

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ABSTRACT

This letter deals with the potential-induced degradation (PID) of silicon heterojunction (SHJ) photovoltaic (PV) modules. After rapid indoor PID tests applying a voltage of −1000 V at 85 °C, the modules exhibited a significant reduction in short-circuit current density (J_{sc}). On the other hand, the dark current density–voltage characteristics of the modules were intact after the PID tests, indicating that the reduction in J_{sc} is attributed not to carrier recombination but to optical loss. A degraded module slightly recovered its performance loss upon applying a positive bias but complete recovery was not observed, showing that the PID of SHJ PV modules is not reversible. A module with an ionomer encapsulant showed high PID resistance, revealing that the degradation of SHJ PV modules can be prevented by the use of ionomer encapsulants.

1. Introduction

Silicon heterojunction (SHJ) photovoltaic (PV) cells have recently attracted attention owing to their high power-conversion efficiency [1–6]. Typical SHJ cells have an n-type crystalline silicon (c-Si) base and hydrogenated amorphous silicon (a-Si:H)-based passivation films on both sides, which leads to a high open-circuit voltage (V_{oc}) and high efficiency [1–5]. A high V_{oc} of over 730 mV and efficiency of over 24% have been reported for both-side-contact structures [4,5]. Masuko et al. have achieved an efficiency of 25.6% for an interdigitated back-contact (IBC) SHJ structure [6]. Furthermore, Kaneka Corporation has very recently achieved the highest efficiency of 26.3% for the IBC SHJ structure [7]. According to the International Technology Roadmap for Photovoltaic (seventh edition) [8], the market share of SHJ solar cells is expected to increase. With the growing market share, the reliability and long-term stability of SHJ PV modules will become increasingly important.

Potential-induced degradation (PID), which is associated with high electric potential differences between grounded frames and cells, has been identified as one of the most important reliability issues, particularly in large-scale PV systems [9–11]. To utilize SHJ PV cells, it is therefore important to understand the PID behavior of modules fabricated using the cells. There have been several studies on the PID of commercial SHJ PV modules [12–14], all of which reported that commercial SHJ PV modules exhibit high PID resistance under both negative and positive biases. These studies did not, however, demonstrate the higher PID resistance of the SHJ PV cells themselves because the encapsulation materials used in the studies were not disclosed, and their high PID resistance may have been due to cover glass and/or an encapsulant. In one of the studies [13], it was argued that SHJ solar cells do not undergo PID because they have no insulating layers and charge accumulation does not occur. This argument is probably based on several earlier studies on the mechanism of the PID of conventional p-type c-Si PV modules (for example Refs. [15,16]). In these studies [15,16], it was argued that the PID of p-type c-Si PV modules is associated with charge accumulation in the insulating passivation layer. However, researchers now consider the root cause of the PID of p-type c-Si PV modules to be the short-circuiting of the p–n junctions due to two-dimensional conductive sodium (Na) layers segregated in stacking faults (so-called Na-decorated stacking faults) near the front c-Si-surface [17,18]. To understand the actual effect of PID on SHJ PV cells, one should investigate SHJ PV modules with a standard encapsulation configuration involving conventional tempered cover glass and an ethylene-vinyl acetate copolymer (EVA) encapsulant.

In this work we demonstrate, through a rapid indoor PID test, that SHJ PV modules undergo PID characterized by a reduction in short-circuit current density (J_{sc}), which is probably due to the optical loss occurring in the front transparent conductive oxide (TCO) layer and/or in the encapsulant. Moreover, we investigate whether the PID of SHJ PV modules can be prevented by the use of a high-electric-resistance encapsulant.

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2. Experimental procedure

Single-cell SHJ PV modules with an area of $180 \times 180\ mm^2$ were fabricated using commercial bifacial SHJ solar cells with a rear-side emitter and indium-oxide-based TCO layers with an area of $156 \times 156\ mm^2$. The module had a 3.2-mm-thick tempered white cover glass/450-µm-thick EVA sheet (fast cure type)/SHJ solar cell (with the emitter side down)/450-µm-thick EVA sheet (fast cure type)/typical white backsheet [38-µm-thick poly(vinyl fluoride) sheet/250-µm-thick poly(ethylene terephthalate) sheet/38-µm-thick poly(vinyl fluoride) sheet] structure. The EVA sheets used in this study were also typical ones with a volume resistivity of $1.5 \times 10^{14} \Omega \cdot$ cm, and they were not capable of preventing PID [19–27]. Our module-lamination process consisted of two steps: a degassing step for 5 min and an adhesion step for 15 min, and both steps took place at 135 °C.

The PID tests were performed by applying a negative bias to connected module-interconnector ribbons with respect to an aluminum plate placed on the module cover glass in a heating chamber maintained at 85 °C. Herein, we use the terms “negative bias” and “positive bias” for biases that produce cells with negative and positive potentials with respect to the aluminum plate, respectively. We disregarded the effect of moisture ingress into the modules on the PID phenomena because the humidity in the heating chamber was very low (approximately 2% RH). To evaluate the degradation, we performed dark and one-sun-illuminated current density–voltage (J–V), external quantum efficiency (EQE), and electroluminescence (EL) measurements on the modules before and after the PID tests.

3. Results and discussion

It has been reported that applying a high negative bias to cells leads to the degradation of many types of PV modules, such as conventional p-type c-Si [9–11], n-type front-emitter c-Si [24,25], n-type rear-emitter c-Si [26], n-type IBC c-Si [28], amorphous Si (a-Si) [12,27], Cu(In, Ga)Se_2 (CIGS) [27,29], and CdTe [12,29] PV modules. Herein, we first clarify how the J–V characteristics change upon applying negative bias. Fig. 1 shows representative one-sun-illuminated J–V characteristics of the SHJ PV modules before and after the PID tests in which a voltage of −1000 V was applied. J_{sc} gradually decreases with increasing PID-stress duration. The fill factor (FF) and V_{oc} are, on the other hand, almost unchanged after the PID tests. These results indicate that SHJ PV modules undergo PID under negative bias and that the degradation is mainly characterized by a reduction in J_{sc}. The reduction in J_{sc} originates not from enhanced carrier recombination but from optical loss because their dark J–V characteristics are unchanged after the PID tests (not shown here). This can also be verified from

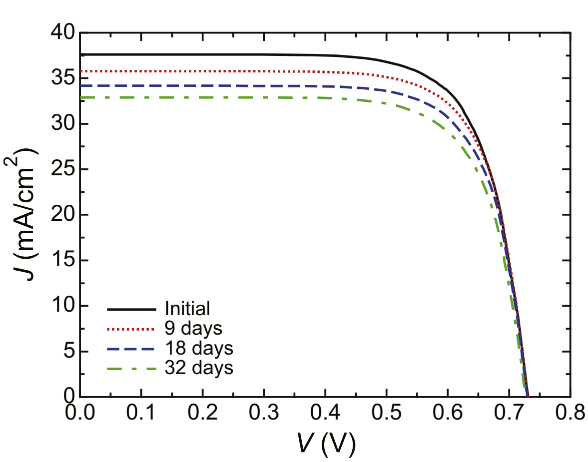

Fig. 1. Representative one-sun-illuminated J–V characteristics of the SHJ PV modules before and after the PID tests applying a voltage of −1000 V.

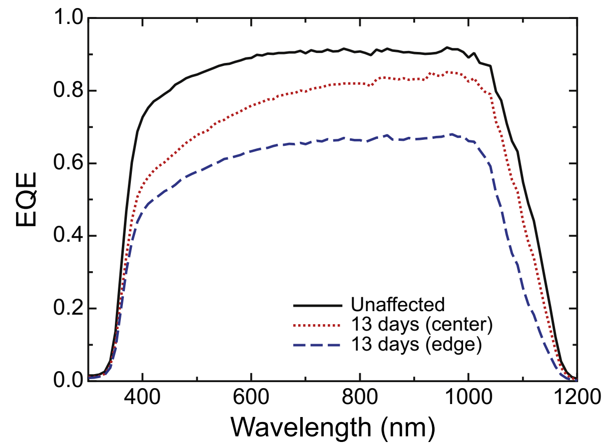

Fig. 2. EQE characteristics of the unaffected SHJ PV module and those after the PID tests applying a voltage of −1000 V for 13 days. For the degraded module, EQEs were extracted from two positions near the center and the edge of the cell. The area of illumination in this EQE measurement was $10 \times 10\ mm^2$.

Fig. 2, which shows the EQE characteristics of the unaffected and degraded SHJ PV modules. After the PID test for 13 days, the EQE is reduced in the entire wavelength range (see the dotted red line in Fig. 2). This suggests that the reduction in J_{sc} originates from optical loss, because the EQE must be reduced only in a specific wavelength range if there is recombination loss in the cell. Also shown in Fig. 2 is a comparison of EQEs extracted from positions near the center and the edge of the cell. The reduction in EQE near the cell edge is greater than that near the center, indicating that the extent of optical loss depends on the position in the cell. The optical loss is probably due to the darkening of the TCO layer, which will be explained below. The position dependence of the reduction in EQE may be due to the nonuniformity of the properties of the TCO film, such as its composition.

Fig. 3 shows the dependence of $J_{sc}/J_{sc,0}$ on the applied voltage during PID tests, where $J_{sc,0}$ is the initial J_{sc}. The reduction rate of J_{sc} seems to be affected by the voltage. The degradation is characterized only by a reduction in J_{sc} even when the applied voltage is increased from −1000 V to −2000 V, which may suggest that the PID behavior is unchanged regardless of the magnitude of applied voltages. At present, it is unclear whether the PID of SHJ PV modules saturates for longer duration than that employed in this study.

The optical loss is probably caused by the darkening of the front TCO layer. As shown in Figs. 4a and 4b, the EL image of a module becomes darkened after the PID test with a voltage of −1000 V applied for 32 days. The loss in luminescence is not attributed to the

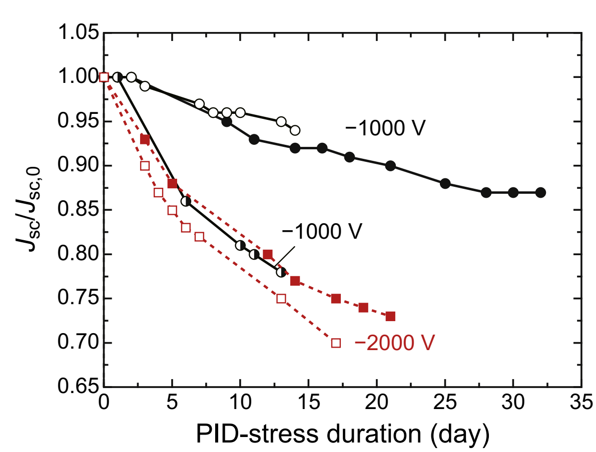

Fig. 3. Dependence of the $J_{sc}/J_{sc,0}$ reduction behavior of SHJ PV modules on applied voltage during PID tests.