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Description	

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.

Keywords: Potential-induced degradation, Silicon heterojunction solar cell, Photovoltaic module, Optical loss, Ionomer encapsulant

1. Introduction

Silicon heterojunction (SHJ) photovoltaic (PV) cells have recently attracted attention owing to their high power-conversion efficiency [1–6]. Typical SHJ cells

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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 layers segregated in stacking faults (so-called sodium-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

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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.

2. Experimental procedure

Single-cell SHJ PV modules with an area of 180×180 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 156×156 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 1.5×10^{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
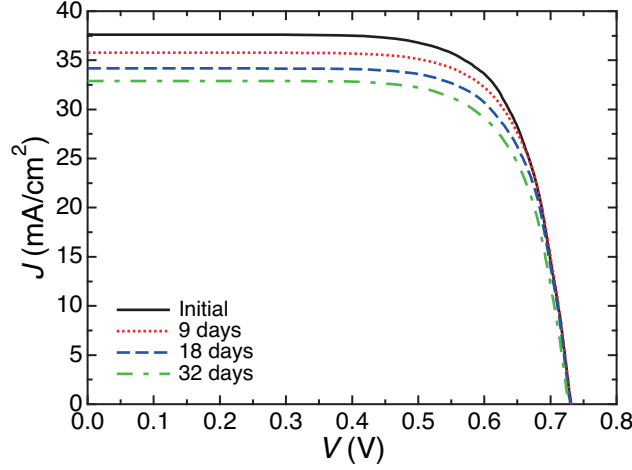
Figure 1: Representative one-sun-illuminated *J–V* characteristics of the SHJ PV modules before and after the PID tests applying a voltage of −1000 V.

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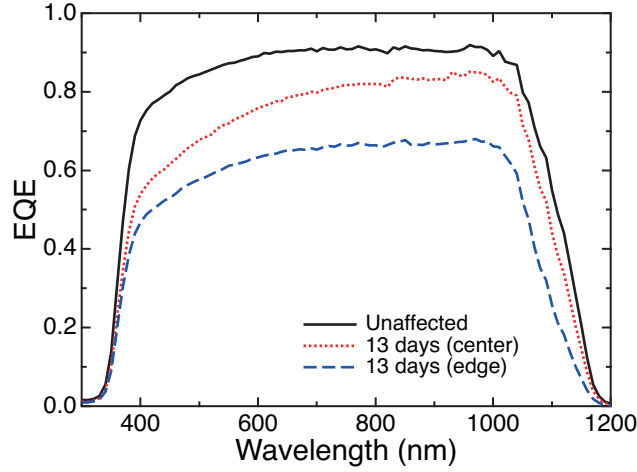
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Figure 2: EQE characteristics of the unaffected SHJ PV module and those after the PID tests applying a voltage of −1000 V for 13 days. For the degraded module, EQEs were extracted from two positions near the center and the edge of the cell. The area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

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 enhancement of a non-radiative recombination process but indicates enhanced optical loss because the diode characteristic is unchanged after the PID test, as mentioned above. Figs. 5a and 5b show EL images of a module before and after the PID test, respectively, with a voltage of −2000 V applied for 21 days. Note that only the degradation is accelerated by the increase in the applied voltage and that the degradation behavior is the same as that under a bias of −1000 V. In Fig. 5b, a characteristic circle-shaped bright pattern can be seen in the middle of the cell. This indicates that the optical loss near the edge is greater than that near the center, which is consistent with the results of the EQE measurement. This pattern can also be seen by eye under light from a fluorescent lamp. The darkened TCO layer interrupts the incident light, lead-
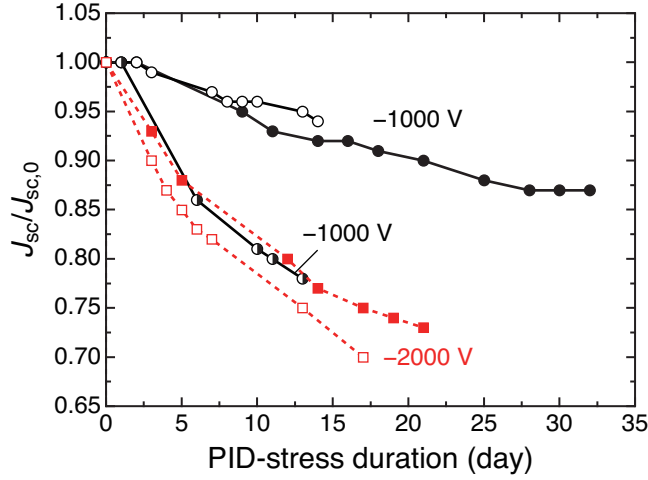
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Figure 3: Dependence of the $J_{sc}/J_{sc,0}$ reduction behavior of SHJ PV modules on applied voltage during PID tests.

ing to a significant reduction in J_{sc}. The darkening might be due to precipitates formed by the chemical reduction of the TCO. It is well known that indium-oxide-based TCO films are relatively easily reduced by exposure to a strongly reducing environment, and metal precipitates can be formed by the chemical reduction of oxidized species in such an environment [30–36]. In our PID tests, the PV cells correspond to the cathode in the oxidation-reduction reaction. Some reactions involving chemical reduction should occur on the cell surface. One candidate is the chemical reduction of sodium (Na) ions, which may originate from the cover glass [11] and/or contaminants on the cell surface [37]: $Na^+ + e^- \rightarrow Na$. The Na atoms and/or other reductants that are produced in oxidation of the Na atoms might induce the formation of metal precipitates. In superstrate a-Si thin-film PV modules, the delamination of fluorine-doped tin oxide layers has been reported to be induced by a high negative bias and moisture ingress [38]. According to a model proposed by Jansen *et al.* [39], this delamination involves the reduction of the TCO induced by elemental hydrogen produced in chemical reaction between reduced Na and moisture. In our experiment, the effect of moisture ingress was able to be neglected because the relative humidity was very low. Moisture originally contained in the EVA encapsulant may affect the chemical reduction of the TCO layer, or chemical reduction unrelated to moisture may occur. Regarding the PID of CIGS PV modules, darkening of the front zinc-oxide (ZnO)-based TCO
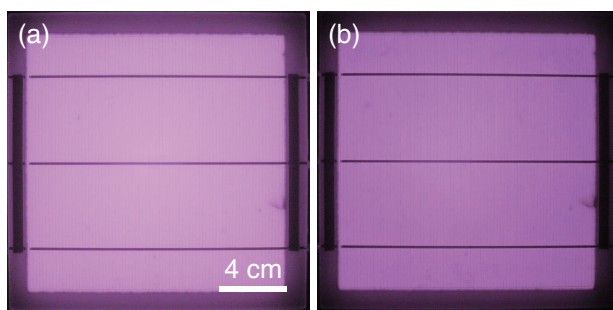
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Figure 4: EL images of SHJ PV modules (a) before and (b) after the PID tests with −1000 V applied for 32 days.
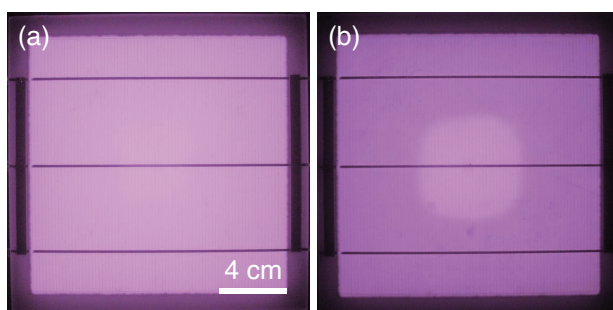

Figure 5: EL images of SHJ PV modules (a) before and (b) after the PID tests with −2000 V applied for 21 days.

layers does not occur during PID tests despite an increased Na content in the ZnO layers [27]. This is likely due to the fact that ZnO-based TCO films are resistant to chemical reduction compared with indium oxide-based TCO [36]. Much additional work is, however, required to understand the darkening of the TCO.

At present, we cannot deny the possibility of the darkening of the encapsulant material. We have not yet analyzed the optical properties of the EVA encapsulant of PID-affected PV modules. However, it should be noted that in our previous studies, EVA encapsulants have not been confirmed to be darkened by high voltages.

It has been reported that the PID of many types of PV modules, such as conventional p-type c-Si [9], n-type front-emitter c-Si [24], and CIGS [27] modules, can be recovered by applying a positive bias. To investigate whether the PID of SHJ PV modules is reversible, we applied a positive bias of +2000 V to mod-
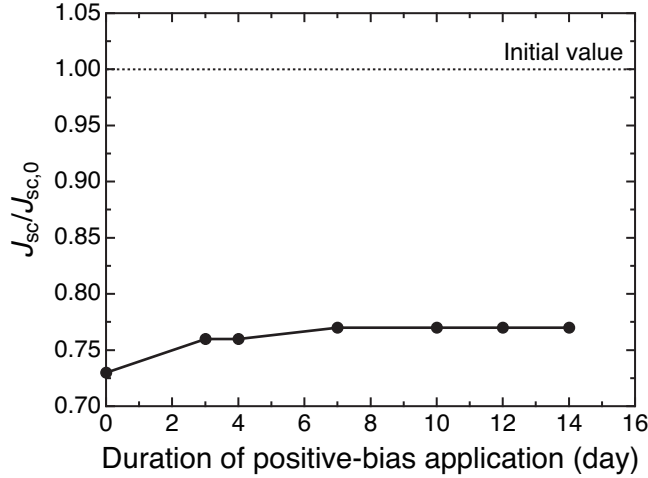
Figure 6: Dependence of $J_{sc}/J_{sc,0}$ of a degraded SHJ PV module on the duration of the recovery test with a positive bias of +2000 V. The module was degraded in a PID test applying a voltage of −2000 V for 21 days prior to the recovery test.

ules after the PID test in which a voltage of −2000 V was applied for 21 days at 85 °C. Shown in Fig. 6 is the dependence of $J_{sc}/J_{sc,0}$ of the SHJ PV module on the duration of bias application. Note that V_{oc} and FF are almost unchanged after the PID and recovery tests. In the initial stage, J_{sc} can be seen to slightly recover. However, J_{sc} then reaches a constant value. These observations indicate that the PID of SHJ PV modules is almost irreversible, unlike the PID of many types of modules. This irreversibility might be due to that of the darkening of the TCO, which is limited by an irreversible chemical reaction. The mechanism of the slight recovery of J_{sc} shown in Fig. 6 is not clear but might be related to the back-diffusion of Na$^+$ or the oxidation of metal precipitates.

From the viwepoint of installation in large-scale PV systems, it is important to compare the PID resistance of the SHJ PV modules with that of other types of modules. We previously reported the PID test results of p-type c-Si [27], a-Si thin-film [27], CIGS thin-film [27], n-type front-emitter c-Si [24], and n-type rear-emitter c-Si [26] PV modules. Note that all the PV modules except for the a-Si thin-film module have the same encapsulant and cover glass. (The a-Si thin-film module has a superstrate configuration; thus, there is no encapsulant between the front glass and the cells.) After the tests for 1 day under the same temperature and voltage conditions as those in this study, $P_{max}/P_{max,0}$ for the a-Si [27], CIGS [27],
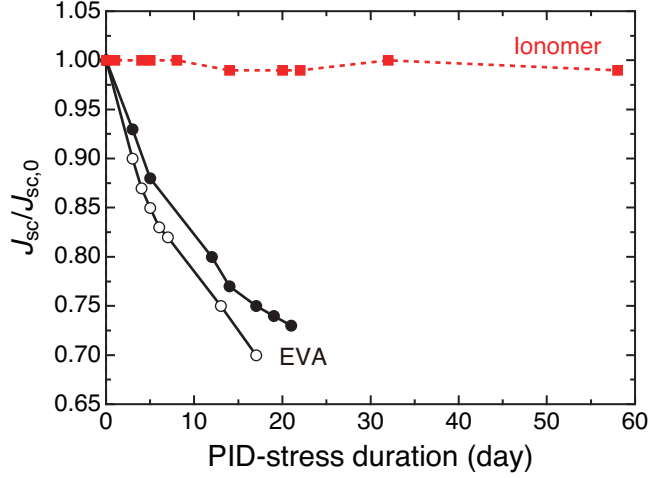
Figure 7: Dependence of $J_{sc}/J_{sc,0}$ of the SHJ PV modules with the EVA encapsulant or the ionomer encapsulant on PID-stress duration. The applied voltage was set to -2000 V in this experiment.

and n-type rear-emitter c-Si [26] PV modules decreases to 0.23, 0.95, and 0.93, respectively, where P_{max} is the maximum output power and $P_{max,0}$ is the initial P_{max}. After the same tests for 2 h, $P_{max}/P_{max,0}$ for the p-type c-Si [27] and n-type front-emitter c-Si [24] PV modules decreases to 0.04–0.4 and 0.85. In contrast, $P_{max}/P_{max,0}$ for the SHJ PV modules is almost unchanged after the PID test for 2 days. These results indicate that the SHJ PV modules have a high PID resistance. This may be an advantage of the SHJ PV modules. Moreover, we can further improve the reliability and long-term stability of SHJ PV modules, as mentioned below. Note that the PID of p-type c-Si [9], n-type front-emitter c-Si [24], and CIGS thin-film [27] PV modules can be recovered by applying a positive bias whereas the PID of SHJ PV modules cannot be recovered by such a simple way.

To determine a possible measure to prevent PID, we performed PID tests on an SHJ PV module with an ionomer encapsulant with a volume resistivity of 10^{16} $\Omega \cdot$cm. Ionomer encapsulants have been reported to effectively prevent the PID of several types of modules, such as conventional p-type c-Si [40], n-type front-emitter c-Si [24], and CIGS thin-film [27] PV modules. Note that the PID conditions of -2000 V and 85 °C used in this experiment are severe. Fig. 7 shows the dependence of $J_{sc}/J_{sc,0}$ for the SHJ PV modules with the EVA and with the ionomer on the PID-stress duration. Note that V_{oc} and FF for both modules are almost the same before and after the PID tests. $J_{sc}/J_{sc,0}$ for the EVA module de-

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creases to 0.73 after the PID test for 21 days. In contrast, the ionomer module maintains the initial value of $J_{sc}/J_{sc,0}$ even after the PID tests for 58 days. These results indicate that the use of ionomer encapsulants can effectively prevent the PID of SHJ PV modules. This is likely due to a strongly reduced leakage current caused by the noteworthy high electric resistance of the ionomer encapsulant.

4. Conclusions

In this study, we have investigated the PID of SHJ PV modules by performing a rapid indoor PID test. We have demonstrated that SHJ PV modules undergo PID characterized by a reduction in J_{sc} due to optical loss that probably occurs in the front TCO layer. This optical loss may be due to metal precipitates formed by the chemical reduction of oxidized species. We have also shown that SHJ PV modules have high PID resistance compared with conventional p-type c-Si, n-type front-emitter c-Si, n-type rear-emitter c-Si, a-Si thin-film, and CIGS thin-film PV modules. This high reliability can be further improved by the use of ionomer encapsulants.

Acknowledgements

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