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Multistage performance deterioration in n-type crystalline silicon photovoltaic modules undergoing potential-induced degradation

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ABSTRACT

This study addresses the behavior of n-type front-emitter (FE) crystalline-silicon (c-Si) photovoltaic (PV) modules in potential-induced degradation (PID) tests with a long duration of up to 20 days. By PID tests where a negative bias of −1000 V was applied at 85 °C to 20 × 20-mm^2-sized n-type FE c-Si PV cells in modules, the short-circuit current density (J_{sc}) and the open-circuit voltage (V_{oc}) started to be decreased within 10 s, and strongly saturates within approximately 120 s, resulting in a reduction in the maximum output power (P_{max}) and its saturation. After the saturation, all the parameters were almost unchanged until after 1 h. However, the fill factor (FF) then started to decrease and saturated again. After approximately 48 h, FF further decreased again, accompanied by a reduction in V_{oc}. The first degradation is known to be due to an increase in the surface recombination of minority carriers by the accumulation of additional positive charges in the front Si nitride (SiN_x) films. The second and third degradations may be due to significant increases in recombination in the space charge region. The enhancement in recombination in the space charge region may be due to additional defect levels of sodium (Na) introduced into the space charge region in the p–n junction. We also performed recovery tests by applying a positive bias of +1000 V. The module with the first degradation completely recovered its performance losses, and the module with the second degradation was almost completely recovered. On the contrary, the modules with the third degradation could not be recovered. These findings may improve the understanding of the reliability of n-type FE c-Si PV modules in large-scale PV systems.

1. Introduction

Large-scale photovoltaic (PV) systems have been installed worldwide over the last decades. These large-scale PV systems can efficiently generate a large amount of electricity. However, there can be unfavorable potential differences between grounded frames and cells, which may lead to significant performance losses in deployed PV modules, so-called potential-induced degradation (PID) [1–4]. PID has been considered one of the most important reliability issues because PID can, in many cases, lead to large power losses in a relatively short time.

PID in conventional p-type crystalline-silicon (c-Si) PV modules has been studied in detail thus far [1–9]. The PID of p-type c-Si PV modules occurs only when they have negative electrical potential with respect to aluminum (Al) frames, and is characterized mainly by a reduction in the fill factor (FF) due to a decrease in the parallel resistance (R_p). In the case of conventional p-type c-Si PV modules, sodium (Na) can drift from the cover glass and/or contaminants at the interfaces between cells and encapsulants into the n-type emitters of cells, with assistance from an electric field, through their front Si nitride (SiN_x) antireflection/passivation films, which are known as excellent diffusion barriers against Na [10,11]. From the mechanistic aspect, Naumann et al. have studied PID in p-type c-Si PV modules, and have revealed that the shunting is caused by the formation of Na-decorated stacking faults penetrating the front n-type emitters [8,9].

n-type c-Si PV cells generally have higher efficiencies than p-type ones, since the capture cross-sections of many types of impurities for minority carriers in n-type c-Si, holes, are smaller than those for electrons, and longer minority-carrier lifetimes can be obtained [12]. From this reason, the market share of these n-type c-Si PV cells is expected to increase in the near future. To ensure the long-term stability and the reliability of the n-type c-Si modules, it is important to understand their possible degradation behaviors. However, there are relatively fewer previous studies on PID occurring in n-type c-Si PV modules [13–23]. Hara et al. have reported that n-type front-emitter (FE) c-Si PV modules suffer PID characterized by reductions in the short-circuit current density (J_{sc}) and the open-circuit voltage (V_{oc}) under a negative bias [16]. Bae et al. have experimentally demonstrated that the degradation

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is caused by an increase in fixed positive charges in the front passivation layer [19]. We have reported that the degradation saturates within quite a short time, for instance, several minutes [17]. However, detailed progression behavior after the saturation of the degradation has not been clarified. Although Barbato et al. have reported the degradation behavior of n-type c-Si PV modules in PID tests with a long duration of up to 55 h [20], their PID tests were performed at a bias of up to −600 V, and different degradation phenomena may be found by performing severer PID tests.

In this study, we investigated the degradation behavior of n-type FE c-Si PV modules in PID tests with a long duration of up to 20 days, and found that the modules undergo three-stage degradations. We also investigated whether the degradation on each stage can be recovered by applying a positive bias, and found that the degree of performance recovery depends on that of degradation. We attempted to explain possible degradation mechanisms of the multistage PID, on the basis of the obtained results.

2. Experimental procedure

20×20-mm^2-sized n-type FE c-Si PV cells with SiN_x/Si dioxide (SiO_2) passivation stacks were prepared into mini modules by using a laminator. The lamination process used in this study was the same as that used in a previous study [18]. The modules were composed of conventional tempered cover glass/ethylene-vinyl acetate copolymer (EVA) encapsulant/cell/EVA encapsulant/typical backsheet. The size of the cover glass was 45×45 mm^2 and contained alkali metals such as Na. The EVA encapsulants had a relatively low volume resistance of 1.5×10^{15} Ω·cm. The backsheets were composed of polyvinyl fluoride (PVF)/polyethylene terephthalate (PET)/PVF.

PID tests were performed by applying a negative bias of −1000 V to shorted interconnector ribbons of the modules with respect to an Al plate placed on the cover glass surface at a temperature of 85 °C and a relative humidity of < 2%, for up to 20 days in total. The PID tests were performed for three identical modules on each condition. After confirming the degradation by the PID tests, recovery tests were performed by applying a positive bias of +1000 V to the cells with respect to the Al plate placed on the cover glass surface at a temperature of 85 °C and a relative humidity of < 2%. The recovery tests were conducted on the modules degraded by the PID tests for 120 s, 12 h, and 480 h. The durations of the recovery tests were the same as those of the degradation tests. A recovery test under each condition was performed on one module. The same PID test was also performed using a module containing a commercial size cell with an area of 156×156 mm^2 for comparison. To ensure contact between the Al plate and the cover glass, an electrically conductive rubber sheet was inserted between them.

To evaluate the performance degradation, dark and one-sun-illuminated current density–voltage (*J–V*), and external quantum efficiency (EQE) measurements were performed before and after the PID tests and recovery tests. From these results, the J_{sc}, V_{oc}, FF, and maximum power (P_{max}) values were obtained. We obtained the results by ex-situ measurements. After taking out PV modules from the test chamber, we performed dark and one-sun-illuminated *J–V* measurements, EQE measurements on the modules. The measured dark *J–V* data before and after the PID tests were fitted to the two-diode equation [24], to obtain the saturation current densities J_{01} and J_{02} of the first and second diodes, respectively, the ideality factors n_1 and n_2 of the first and second diodes, respectively, the R_p, and the series resistances R_s. In the two-diode fitting, n_1 was restricted to one, and n_2 was limited to greater than one, J_{01}, J_{02}, R_p and R_s were positive. Additionally, we assumed that the R_s of the modules after degradation was not lower than that of the initial modules. Dark *J–V* characteristics are expressed by the following equation:

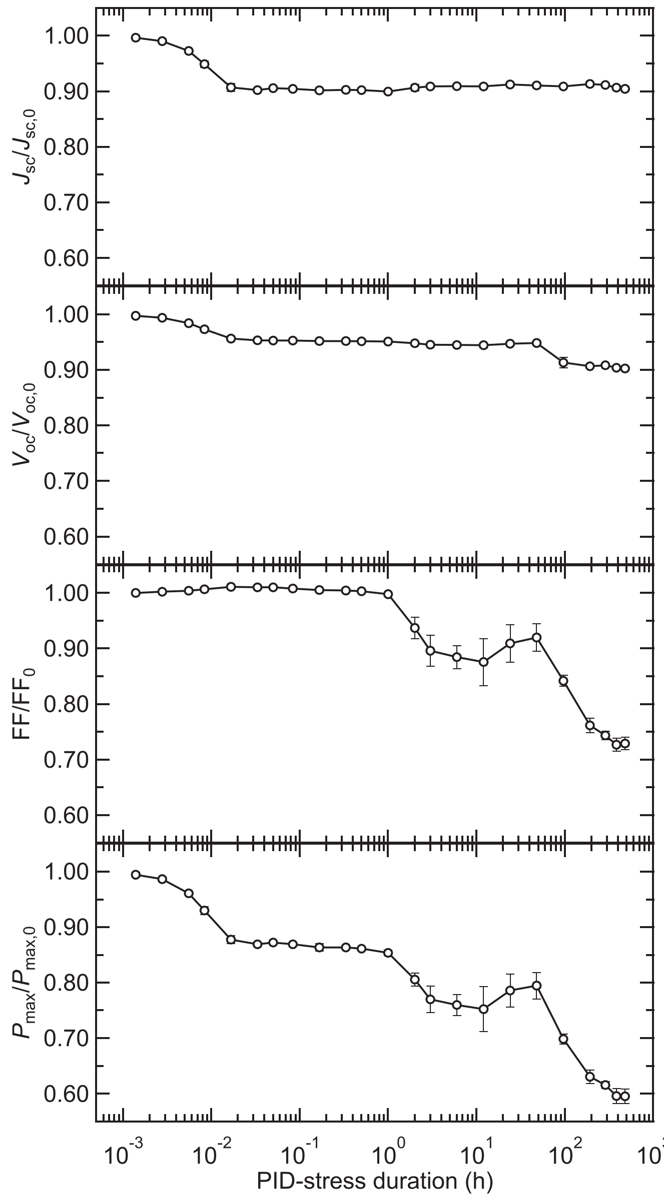

Fig. 1. PID-stress duration dependence of the performance of the n-type FE c-Si PV modules undergoing the PID tests applying −1000 V. Each data point shows the mean value for the three modules, and each error bar corresponds to the standard deviation of the mean. The solid lines are included as guides for the eye.

$$J(V) = J_{01}\left[\exp\left(\frac{q(V - JR_s)}{n_1 kT}\right) - 1\right] + J_{02}\left[\exp\left(\frac{q(V - JR_s)}{n_2 kT}\right) - 1\right] + \frac{V - JR_s}{R_p}, \tag{1}$$

where q is the elementary charge, k the Boltzmann constant, and T the absolute temperature.

3. Results

3.1. Degradation behavior in long-term PID tests

The PID of n-type FE PV modules is known to rapidly occur and to saturate within a quite a short time, for instance several minutes. So far, most researchers have mainly dealt with the initial-stage degradation, and behavior after the initial-stage degradation has not yet been