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Effect of a SiO₂ film on the potential-induced degradation of n-type front-emitter crystalline Si photovoltaic modules

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We investigated the effect of silicon dioxide (SiO₂) film in n-type front-emitter (n-FE) crystalline Si (c-Si) solar cells on the potential-induced degradation (PID) of n-FE photovoltaic (PV) modules. After PID tests by applying a bias of -1000 V at 85 °C for a few min, the modules with the cells without SiO₂ did not degrade in the short-circuit current density (J_{sc}) and the open-circuit voltage (V_{oc}). Since the degradation is known to be due to positive charge accumulation in SiN_x films, the result suggests that such SiO₂ acts as barriers to retain accumulated positive charges. After further PID tests, modules without SiO₂ show faster and more significant degradation by a decreases in the fill factor (FF) and the V_{oc} . It has been proposed that the degradation in the FF and V_{oc} is caused by sodium (Na) introduction into cells. The results therefore suggest that SiO₂ delays Na migration.

1. Introduction

Large-scale photovoltaic (PV) systems, capable of generating a large amount of electricity, have been installed over the last decade, most of which consist of crystalline silicon (c-Si) PV modules. In such systems, PV modules can be exposed to high electric potentials from grounded frames. These electric potential differences may trigger potential-induced degradation (PID)¹⁻⁴⁾ of PV modules which can cause significant performance losses of the modules. PID is considered to be one of the most important reliability issues because it can often be accompanied by large power losses in a relatively short time, such as several months.

n-type c-Si PV modules have higher conversion efficiencies than conventional p-type ones.^{5, 6)} In addition, n-type c-Si PV cells show no light-induced degradation due to boron–oxygen complexes.⁷⁾ Therefore n-type c-Si PV modules are suitable for use in large-scale PV systems, and the findings of their PID are of great importance. So far, a large number of studies have been conducted on PID in conventional p-type crystalline silicon (c-Si) PV modules which have been already widely used.^{1-4, 8-13)} On the other hand, there have been fewer number of studies on PID of n-type Si-wafer-based PV cell modules.¹⁴⁻²⁹⁾ As for n-type front-emitter (n-FE) c-Si PV modules which are the most basic n-type ones, we have previously reported degradation behaviors and mechanisms.²⁵⁻²⁷⁾ The n-FE c-Si PV modules have been reported to exhibit three stage degradations.²⁶⁾ The first degradation is characterized by decreases in the short-circuit current density (J_{sc}) and the open-circuit voltage (V_{oc}).²⁵⁻²⁷⁾ Hara et al. have proposed that the first degradation is due to surface recombination enhanced by positive charge accumulation in the front-side silicon nitride (SiN_x) antireflection films. We have proposed that the accumulated positive charges can be formed by the extraction of electrons from K centers present in

the SiN_x films, which are dangling bonds backbonded to three nitrogen atoms.²⁷⁾ The second degradation is characterized by a decrease in the fill factor (FF). This degradation may be caused by the introduction of sodium (Na) atoms into the depletion layers through the surface SiN_x and/or the cell edges.²⁶⁾ The third degradation is characterized by additional reductions in the V_{oc} and the FF. This has been reported to be related to further introduction of Na and the formation of dome-like protrusions composed mainly of Na on the top of pyramids on the cell surface.²⁸⁾

On the other hand, the degradation behaviors can be affected by the cell structure, which are important to understand degradation mechanisms in more detail and to develop preventive measures. The effects of the cell structure, however, have not yet been clarified. We have proposed that SiO_2 passivation films underneath the SiN_x films play a quite important role in the first degradation. Further, the SiO_2 films may affect the second and third degradations because SiO_2 films are considered to affect Na drift process.

In this study, we investigate how the SiO_2 passivation films underneath the front SiN_x films in n-FE c-Si cells affect their PID behaviors to elucidate more detailed PID degradation mechanisms.

2. Experiment methods

We fabricated n-FE c-Si solar cells with and without SiO_2 passivation films underneath the SiN_x antireflection films. The cells were cleaved into $20 \times 20\text{-mm}^2$ -sized squares. We then fabricated PV modules composed of cover glass/ethylene vinyl acetate copolymer (EVA)/cell/EVA/backsheet. The backsheets were composed of polyvinyl fluoride (PVF)/polyethylene terephthalate (PET)/PVF. The modules then received a PID test based on the Al-plate method.³⁰⁾ PID tests were performed on the modules by applying a

negative bias of -1000 V to shorted interconnector ribbons of the modules with respect to a grounded Al plate placed on the cover glass surface at a temperature of 85 °C and a relative humidity of $<2\%$.

To evaluate degradation, we performed dark and one-sun-illuminated current density–voltage (J – V), and external quantum efficiency (EQE) measurements on the PV modules before after the PID tests. To obtain more detailed findings on the effect of SiO_2 , the surfaces of solar cells degraded were analyzed by using a scanning electron microscope (SEM) FE-SEM Merlin (ZEISS) with coupled to an energy dispersive X-ray spectroscopy (EDX) detector X Flash 6130 (Bruker AXS).

3. Results and Discussion

Figure 1 shows the normalized J_{sc} , V_{oc} , FF, and maximum output power (P_{max}) values of n-FE c-Si PV modules with n-FE cells with and without SiO_2 as a function of PID-stress duration. The modules with n-FE cells with SiO_2 showed the three-stage degradation processes²⁶⁾. On the other hand, the modules with cells without SiO_2 showed no first degradation, characterized by reductions in the J_{sc} and the V_{oc} . Furthermore, the modules with cells without SiO_2 exhibit faster and more significant second and third degradations. Based on these results, we can discuss the effects of SiO_2 films on their PID as follows.

As for the first degradation, SiO_2 films seem to induce this degradation. In our previous studies^{25–27)}, we have proposed that SiO_2 films retain accumulated positive charges in SiN_x films by preventing carrier transport between the SiN_x films and c-Si emitters. The observed result is consistent with and supports the hypothesis. Figure 2 shows a schematic diagram of a model on the basis of the hypothesis. The first degradation is caused by accumulated positive charges in the SiN_x .²⁷⁾ The accumulated positive charges attract

electrons, minority carriers in the p^+ emitter, in the vicinity of the interface between the SiO_2 and the emitter, and, thereby, surface recombination via interface defects is enhanced. On the other hand, if there is no SiO_2 film underneath the SiN_x , accumulated positive charges can readily dissipate through carrier transport between the SiN_x and the emitter. It should be noted that SiO_2 films act as passivation films, and it is possible that the absence of the first degradation might be hidden by a low performance due to a very low passivation quality. To confirm this, we compared EQE characteristics of PV modules with cells with and without SiO_2 before and after the PID tests for 120 s, as shown in Fig. 3. The module with the cell with SiO_2 shows lower EQE than that without SiO_2 before and after the PID test for 120 s. Therefore, the absence of the first degradation in the cells without SiO_2 is not due to the very low passivation quality.

Regarding the second degradation, the SiO_2 films seem to delay this degradation. This effect may be because the SiO_2 films reduce Na introduction into the depletion layer. Figure 4 shows a schematic representation of the mechanism of the second degradation. The second degradation may be caused by the formation of defect levels due to Na introduction into the depletion layer.²⁶⁾ These defect levels may enhance recombination currents and reduce the FF. On the basis of the above results, we suggest that the SiO_2 films delay the penetration of Na into the depletion layer. However, there are still many open questions. A detailed process of how Na migrates in n-FE c-Si cells is unknown at present. It is also important to consider voltages applied to the individual films (SiO_2 and SiN_x). These findings are important to understand Na^+ drift processes. A voltage applied to SiN_x in the cell without SiN_x becomes greater than that in cells with SiO_2 , which might decelerate the drift of Na^+ through SiN_x and resultingly delay the second PID in the cells with SiO_2 . The results give us another important finding for the route of Na introduction

into cells. Na can be, in principle, introduced to the depletion layer not only through SiN_x but directly from the cell edges. The introduction of Na from the cell edges is likely particularly in our PV modules since the cells in the modules are prepared just by cleaving larger-sized cells and thus have bare edges. If Na is introduced into the depletion layer mainly through the cell edges, the second degradation must start simultaneously independent of the presence or absence of SiO_2 . The retardation of the second degradation due to the existence of SiO_2 clearly indicates that Na is introduced to the depletion region mainly through SiN_x .

The third degradation is discussed on the basis of SEM/EDX images of the cells after the PID tests for 20 days. Figure 5 shows a cross-sectional SEM image and EDX images of Si nitrogen (N), oxygen (O), and Na for the cell without SiO_2 . O and Na seem to be detected on the same spots. This may be due to the oxidation of Na during air exposure after the formation of a cross-section and before the introduction of the samples in the SEM system. Therefore the actual chemical state of the Na precipitation is unknown at present. In the SEM/EDX images, a dome-shaped protrusion composed mainly of Na can be observed on the top of a texture pyramid. As shown in the EDX image, N signal becomes discontinuous near the protrusion. This indicates the partial disappearance of SiN_x on c-Si surface, and induces the deterioration of the passivation quality and resulting reduction in V_{oc} . These features are similar to the results for the n-FE cell with SiO_2 after the third degradation.²⁸⁾ As a feature observed only for the cell without SiO_2 , we can point out the Na film formation on the cell. A Na film was formed on the cell, as shown in the cross-sectional SEM-EDX image. The film is considered to activate surface recombination and enhance optical losses. On the other hand, such a Na film has been reported not to be formed on the cell with SiO_2 receiving a PID test for the same

duration.²⁸⁾ Figure 6 shows the EQE spectra of the cells without SiO₂ before and after the PID tests for 20 days in total. According to this, the J_{sc} decrease after the third degradation is accompanied by EQE decreases in the entire wavelength range. On the basis of the SEM/EDX and EQE results, the decrease in the J_{sc} after the third degradation may be due to optical losses by light absorption in the Na film and/or degraded antireflection property. It is not clear why the Na film was formed only on the cell without SiO₂. However, the amount of Na on the c-Si surfaces in cells without SiO₂ films is considered to be larger than that in cells with SiO₂ films. This may explain the Na film formation.

4. Conclusion

In this study we have investigated the effect of SiO₂ films underneath SiN_x antireflection coatings in n-FE c-Si cells on their PID. It was clearly indicated that the presence of the SiO₂ films is one of the reasons for the first degradation and that the SiO₂ films reduce the second and third degradations. For the first degradation, the SiO₂ films are considered to retain positive charges accumulated in the SiN_x films by preventing carrier transport between the SiN_x films and the emitters. For the second degradation, the SiO₂ films may play an important role in delaying the introduction of Na. For the third degradation, it was observed that a Na film was formed only on the cell without the SiO₂ film. This can lead to further reduction in its PV performance. From the EQE result, it was suggested that the Na film formation reduces the J_{sc} by an increase in an optical loss.

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Figure Captions

Fig. 1. (Color online) PID-stress duration dependence of the performance of the n-type FE c-Si PV modules with cells with and without SiO₂. Each data point shows the mean value for three modules, and each error bar corresponds to the standard deviation of the mean.

Fig. 2. (Color online) Schematic representation of the effect of the SiO₂ film on the first degradation. The arrows for E only indicate the existence and the direction of electric field.

Fig. 3. (Color online) EQE spectra of n-FE c-Si PV modules with cells with and without SiO₂ in initial and after the PID tests for 120 seconds.

Fig. 4. (Color online) Schematic representation of the effect of the SiO₂ film on the second degradation. The arrows for E only indicate the existence and the direction of electric field.

Fig. 5. (Color online) Cross-sectional SEM/EDX images of the n-FE cell without SiO₂ subjected to the PID tests for 20 days in total.

Fig. 6. (Color online) EQE spectra of the cells without SiO₂ before and after the PID tests for 20 days.

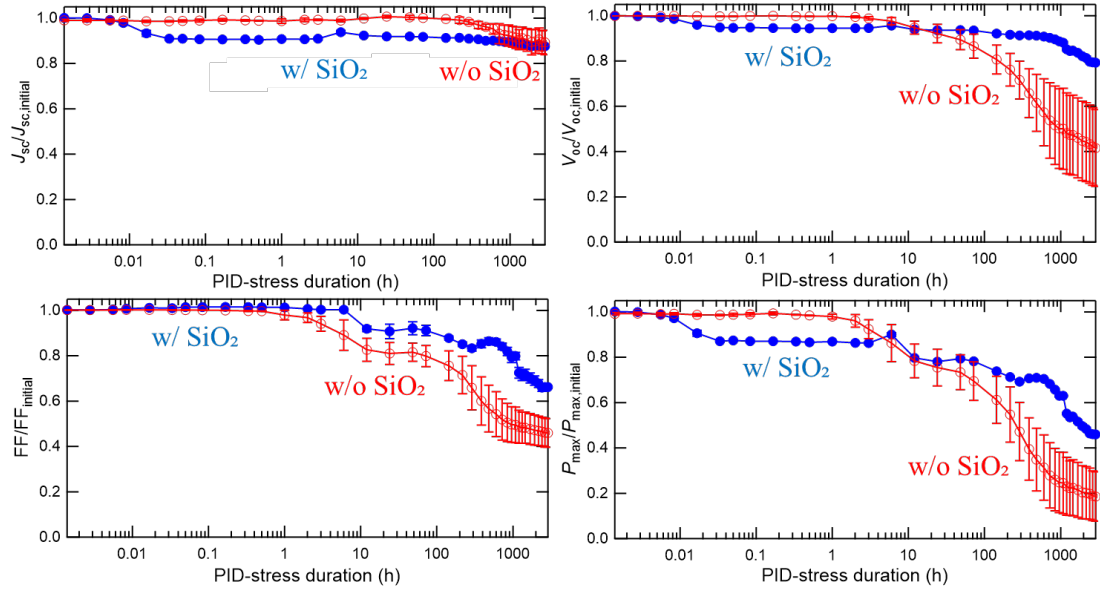


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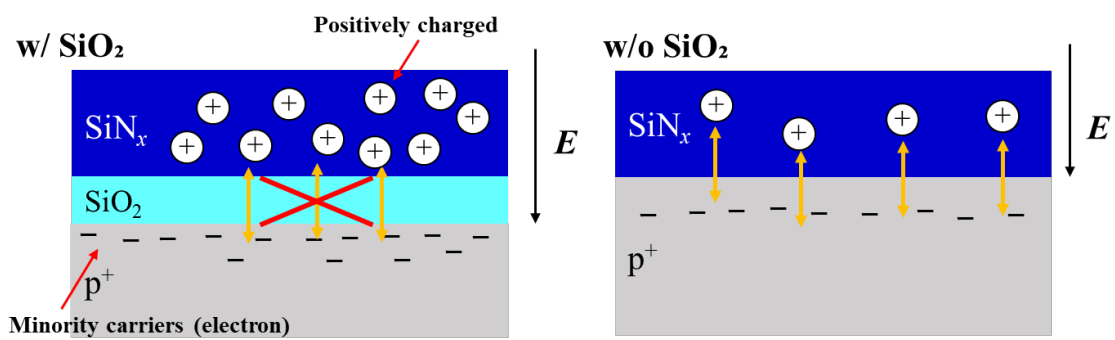


Fig. 2. (Color Online) T. Suzuki *et al.*

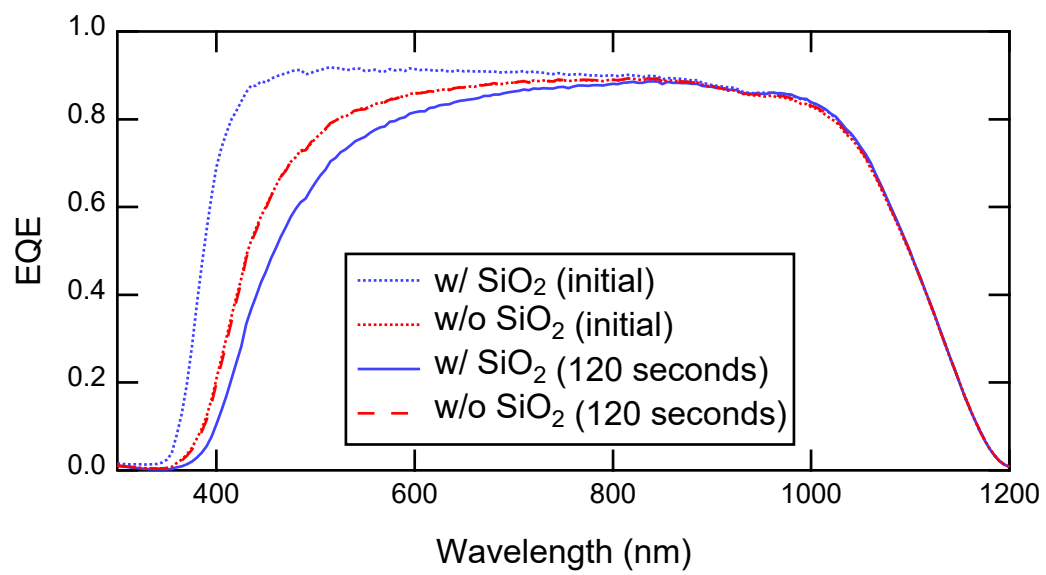


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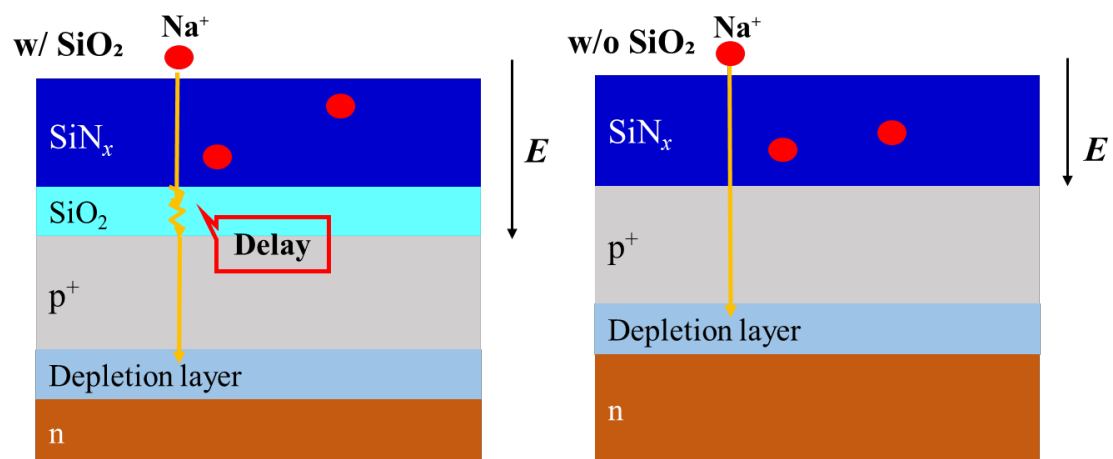


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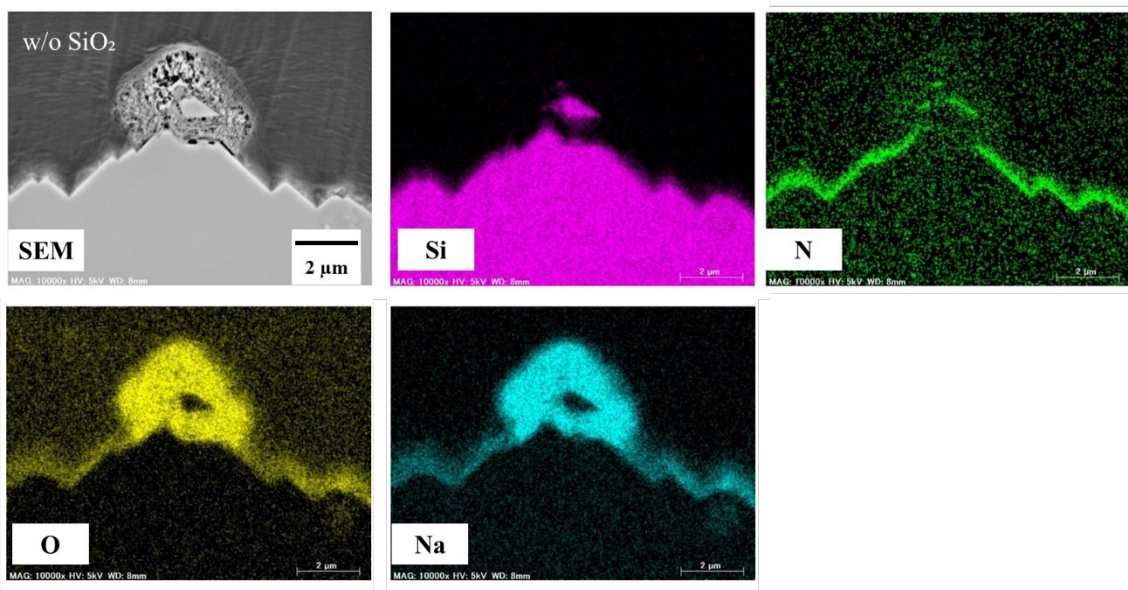


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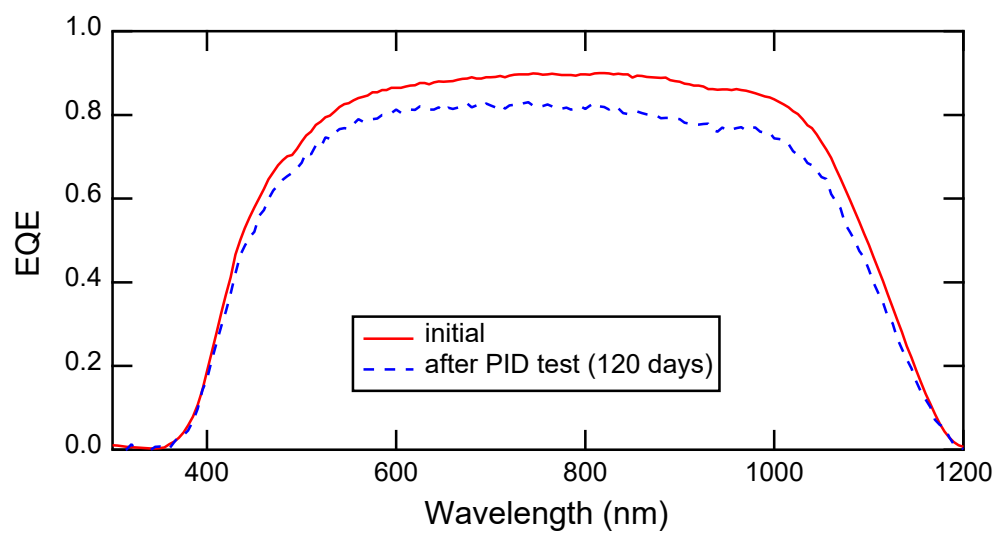


Fig. 6. (Color Online) T. Suzuki *et al.*