

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

Kohjiro Hara*, Sachiko Jonai, Atsushi Masuda

Research Center for Photovoltaics, National Institute of Advanced Industrial Science and Technology (AIST), 807-1 Shuku-machi, Tosu, Saga 841-0052, Japan

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 $85\text{ }^{\circ}\text{C}$ 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.

© 2015 Elsevier B.V. All rights reserved.

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

* Corresponding author. Tel.: +81 942 81 3675.

E-mail address: k-hara@aist.go.jp (K. Hara).

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

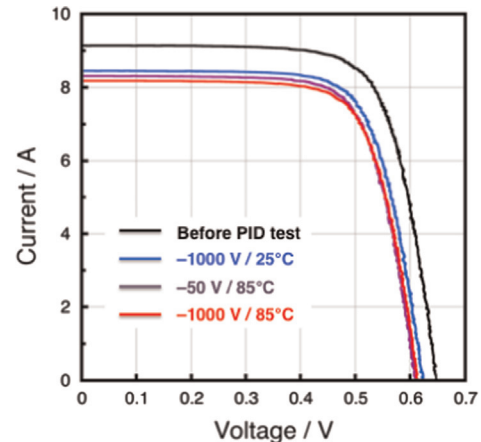


Fig. 1. The I – V curves for standard n-type FJ Si PV modules before and after PID test for 2 h: (black) before, (blue) −1000 V at 25 °C, (purple) −50 V at 85 °C, and (red) −1000 V at 85 °C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version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

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/cm² in our experiment. Swanson et al. reported the leakage current probed to be 0.6 nA/cm² at 1000 V in an n-type BC Si PV module [20].

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

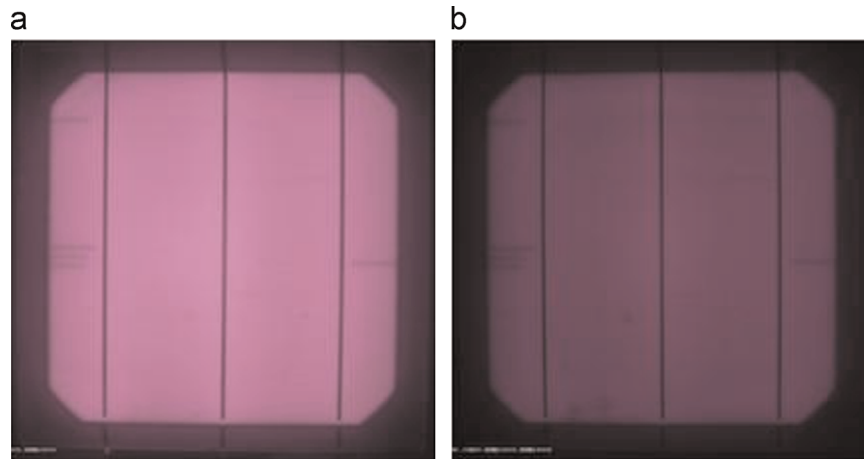


Fig. 2. The EL images for a standard n-type FJ Si PV module (a) before and (b) after PID test (-1000 V at 85 °C for 2 h).

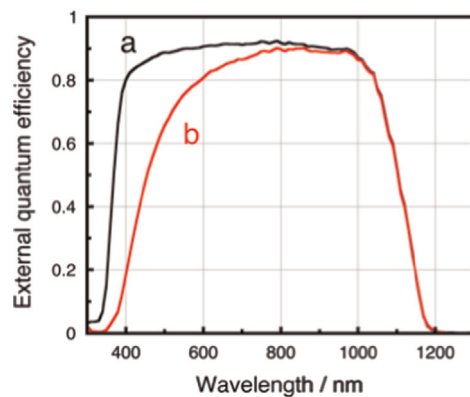


Fig. 3. The spectra of external quantum efficiency for a standard n-type FJ Si PV module (a) before and (b) after PID test (-1000 V at 85 °C for 2 h).

for photons of short wavelength region, such as $\lambda < 500$ nm, the most of the incident photons are absorbed in the heavily doped front emitter region of the cell [25]. Therefore, the change in the spectrum of EQE shown in Fig. 3 is considered to be caused by the enhanced front surface recombination, as has been reported by Sharma et al.

3.3. SIMS measurement

In order to investigate the degradation mechanism, we have analyzed the Si surface of the PID-tested module by SIMS measurement. The D-SIMS data of Na concentration in the surface of Si cells for a non-degraded module and PID-degraded modules are shown in Fig. 4. The concentration of Na in the PID-degraded module after applying -1000 V at 85 °C is much higher than that for the non-degraded module (Fig. 4). Increased Na concentration was also observed in a PID-degraded module applied -1000 V at 25 °C, compared to that for the non-degraded module, as shown in Fig. 4. Interestingly, no change in the Na concentration was observed in the PID-degraded module applied -50 V at 85 °C for 2 h, whereas degradation occurred after the PID test, as shown in Fig. 1. This result strongly suggests that PID in n-type FJ Si PV modules was not caused by Na^+ diffused from the front cover glass, as has been reported in p-type Si PV modules. No change in the concentration of other metal species, such as K and Ca, was observed in the Si cell before and after the PID test.

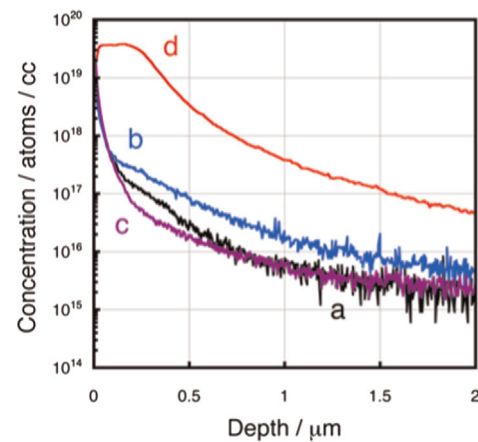


Fig. 4. The D-SIMS data of Na concentration in the surface of Si cells before and after PID test for 2 h: (a) before, (b) -1000 V at 25 °C, (c) -50 V at 85 °C, and (d) -1000 V at 85 °C.

3.4. Influence of glass material on PID

When a CSG whose Na^+ in the surface is exchanged by K^+ is used as the cover front glass instead of a conventional soda lime glass, no degradation was observed in p-type Si PV module by a PID test by applying -1000 V at 85 °C for 2 h [14]. We have investigated the influence of CSG on PID in n-type Si PV modules. The I - V curves for the n-type FJ Si PV modules with CSG before and after the PID test by applying -1000 V at 85 °C for 2 h are shown in Fig. 5. In contrast to p-type Si PV modules, η of the n-type Si PV module based on CSG decreased from 17.2% to 13.9% by the PID test (Fig. 5), which is similar to the module with soda lime glass (Fig. 1). This result suggests that Na^+ is not essential factor resulting in PID, as have been reported as the main factor causing PID in p-type Si PV modules [2,9–13].

3.5. Mechanism of PID in n-type Si PV modules

In the case of p-type Si PV modules, it has been reported that diffusion of Na^+ from the soda lime front cover glass to the Si cell occurs by applying high negative voltage, and consequently the cations influence the Si cell, resulting in PID [2,9–13]. At least, however, we can conclude that Na^+ is not essential factor causing PID in n-type FJ Si PV modules in this work, because the SIMS data indicated that the Na concentration on the PID-degraded Si cell did not increase by applying -50 V at 85 °C for 2 h (Fig. 4). Additionally, PID was observed in the modules with CSG whose

Na^+ at the surface is exchanged by K^+ , as shown in Fig. 5. As mentioned in Section 1, it has been reported that the surface polarization effect decreased the PV performance of high efficiency n-type BC Si PV module by applying high positive voltage to the Si cell [20]. The polarization effect enhances charge recombination between electrons and holes at Si surface [20]. Similar surface charge recombination would occur on the n-type FJ Si cell in our experiment, as has been suggested by the spectral change in EQE after PID occurred (Fig. 3).

Fig. 6 shows the schematic diagrams demonstrating PID in n-type Si PV modules: (a) an n-type BC Si cell [20] and (b) an n-type FJ Si cell used in this work. Swanson et al. reported that PID in an n-type BC Si PV module was observed by applying high positive voltage to the Si cell with respect to the ground, although negative voltage did not occur PID [20]. Therefore, positive voltage stress results in PID. They proposed a mechanism that negative charge due to leakage current trapped in the silicon nitride layer, leading to increasing the concentration of the minority carrier (hole) at the front of n-layer, and consequently increasing surface charge recombination rate [20], as shown in Fig. 6a. Saint-Cast et al. have discussed about effect of

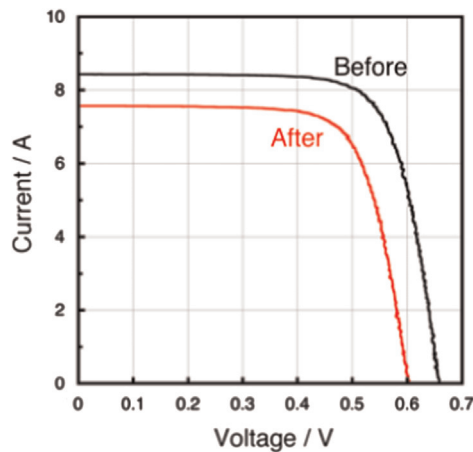


Fig. 5. The I - V curves for a standard n-type FJ Si PV module based on CSG before and after PID test by applying -1000 V at 85°C for 2 h.

negative charge on PID in p-type Si solar cells by inversion layer [26]. The solar cell with an inverted emitter on the front surface behaves like a solar cell with infinite recombination velocity on the front surface [26].

On the other hand, PID in n-type FJ Si PV modules was observed by applying negative voltage to the Si cell with respect to the Al plate in our experiment. In this case, positive charge due to leakage current would be trapped in the silicon nitride layer, leading to increasing the concentration of the minority carrier in p-layer (electron), and consequently increasing charge recombination rate at the surface (Fig. 6b). Naumann et al. reported that PID occurred in n-type BC Si solar cells by applying negative high voltage to the Si cell with respect to the grounded metal plate [21]. They also proposed the degradation is related to an increased surface charge recombination. It has been reported that the output of a PV module based on a FJ Si cell decreased 10% upon application of a positive 1000 V to the cells [20]. This output reduction is less than that for BC cells (ca. 30%), because FJ cells are less sensitive to front surface recombination velocity [20]. In this work, the decrease of 15% in the output of the module was observed by applying negative 1000 V to the Si cell, as shown in Fig. 1. Thus, the polarity of voltage stress causing PID and the output reduction in n-type Si PV modules would depend on the surface component, structure, and condition of Si cell, although further detailed investigation is necessary.

3.6. PID-resistant module based on IO encapsulant

As mentioned in Section 1, it has been reported that IO whose volume resistivity is higher than that of EVA significantly suppresses PID in p-type Si PV modules [16–19]. Therefore, we also have investigated the PID-resistant property of IO encapsulant for n-type FJ Si PV modules. Fig. 7 shows the I - V curves for a module employing an IO encapsulant before and after the PID test by applying -1000 V at 85°C for 2 weeks. Even after the PID test for 2 weeks, no degradation was observed in the module involving the IO encapsulant (Fig. 7). This result indicates that IO encapsulant is significantly effective to suppress PID in not only p-type Si PV modules, but also n-type Si PV modules.

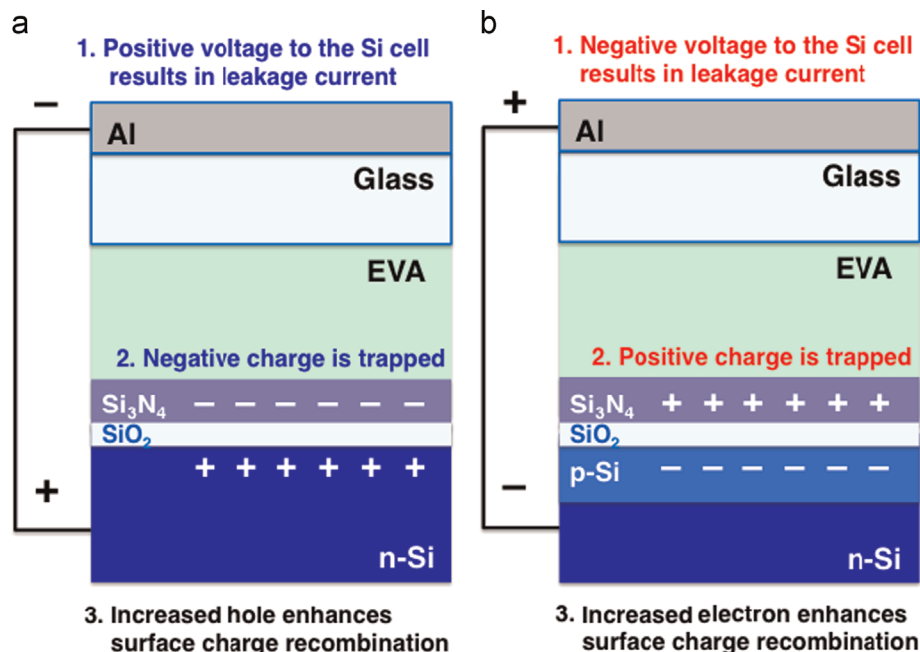


Fig. 6. The schematic diagram demonstrating the proposed mechanism of PID in n-type Si PV modules: (a) a BC Si cell reported in Ref. [20] and (b) a FJ Si cell used in this work.

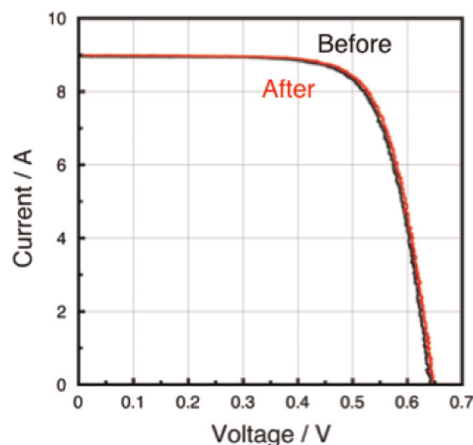


Fig. 7. The I - V curves for a standard n-type FJ Si PV module based on an IO encapsulant before and after PID test by applying -1000 V at 85°C for 2 weeks.

We have reported that a thin PE film (thickness is $30\ \mu\text{m}$) whose volume resistivity is higher than that of EVA remarkably suppresses PID when it was introduced into a standard Si PV module using a conventional EVA encapsulant [24]. This suppression effect would be owing to higher volume resistivity of PE film. In n-type FJ Si PV modules, however, PID cannot prevent perfectly by using the combined encapsulant of EVA and PE film. This implies that higher volume resistivity of the encapsulant is necessary in order to perfectly prevent PID in n-type Si PV modules than p-type Si PV modules.

4. Conclusions

PID was observed in PV modules based on an n-type single crystalline Si solar cell (FJ cell) by applying -1000 V from an Al plate attached on the front cover glass of the module to the Si cell for 2 h at 25°C and 85°C , and by applying -50 V at 85°C for 2 h. The EQE in the range from 400 to 600 nm significantly decreased after PID occurred, although no change was observed from 800 to 1100 nm. PID in n-type FJ Si PV modules can be basically explained by the enhanced front surface recombination between electron and hole on the Si cell, whereas the polarity of voltage leading to PID depends on the structure of Si cell. No PID occurred in an n-type FJ Si PV module based on an IO encapsulant instead of EVA even after a long-term PID test.

Acknowledgments

We acknowledge Dr. K. Shirasawa in AIST, Dr. K. Sakamoto in Chemitox, Inc., and Dr. T. Tanahashi in Espec Corp. for their helpful discussion.

References

- [1] S. Pingel, O. Frank, M. Winkler, S. Daryan, T. Geipel, H. Hoehne, J. Berghold, Potential induced degradation of solar cells and panels, in: Proceedings of the 35th IEEE Photovoltaic Specialists Conference (IEEE PVSC), Honolulu, HI, USA, 2010, pp. 2817–2822.
- [2] P. Hacke, K. Terwillinger, R. Smith, S. Glick, J. Pankow, M. Kempe, S. Kurtz, System voltage potential-induced degradation mechanisms in PV modules and methods for test, in: Proceedings of the 37th IEEE PVSC, Seattle, WA, USA, 2011, pp. 814–820.
- [3] S. Koch, C. Seidel, P. Grunow, S. Krauter, M. Schoppa, Polarization effects and tests for crystalline silicon cells, in: Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), Hamburg, Germany, 2011, pp. 1726–1731.
- [4] M. Schütze, M. Junghänel, O. Friedrichs, R. Wichtendahl, M. Scherff, J. Müller, P. Wawer, Investigations of potential induced degradation of silicon photovoltaic modules, in: Proceedings of the 26th EU PVSEC, Hamburg, Germany, 2011, pp. 3097–3102.
- [5] H. Nagel, A. Metz, K. Wangemann, Crystalline Si solar cells and modules featuring excellent stability against potential-induced degradation, in: Proceedings of the 26th EU PVSEC, Hamburg, Germany, 2011, pp. 3107–3112.
- [6] M. Martin, R. Krause, H. Eckert, M. Pfeifer, D. Kohake, Investigation of potential induced degradation for various module manufactures and technologies, in: Proceedings of the 27th EU PVSEC, Frankfurt, Germany, 2012, pp. 3394–3398.
- [7] S. Hoffmann, M. Koehl, Effect of humidity and temperature on the potential-induced degradation, Prog. Photovolt.: Res. Appl. 22 (2014) 173–179.
- [8] H.C. Liu, C.T. Huang, W.K. Lee, M.H. Lin, High voltage stress impact on p-type crystalline silicon PV module, Energy Power Eng. 5 (2013) 455–458.
- [9] J. Bauer, V. Naumann, S. Großer, C. Hagendorf, M. Schütze, O. Breitenstein, On the mechanism of potential-induced degradation in crystalline silicon solar cells, Phys. Status Solidi RRL 6 (2012) 331–333.
- [10] V. Naumann, C. Hagendorf, S. Grosser, M. Werner, J. Bagdahn, Micro structural root cause analysis of potential induced degradation in c-si solar cells, Energy Procedia 27 (2012) 1–6.
- [11] V. Naumann, D. Lausch, S. Großer, M. Werner, S. Swatek, C. Hagendorf, J. Bagdahn, Microstructural analysis of crystal defects leading to potential-induced degradation (PID) of Si solar cells, Energy Procedia 33 (2013) 76–83.
- [12] V. Naumann, D. Lausch, A. Hähnel, J. Bauer, O. Breitenstein, A. Graff, M. Werner, S. Swatek, S. Großer, J. Bagdahn, C. Hagendorf, Explanation of potential-induced degradation of the shunting type by Na decoration of stacking faults in Si solar cells, Sol. Energy Mater. Sol. Cells 120 (2014) 383–389.
- [13] D. Lausch, V. Naumann, A. Graff, A. Hähnel, O. Breitenstein, C. Hagendorf, J. Bagdahn, Sodium outdiffusion from stacking faults as root cause for the recovery process of potential-induced degradation (PID), Energy Procedia 55 (2014) 486–493.
- [14] M. Kambe, K. Hara, K. Mitarai, S. Takeda, M. Fukawa, N. Ishimaru, M. Kondo, PID-free c-Si PV module using aluminosilicate chemically strengthened glass, in: Proceedings of the 28th EU PVSEC, Paris, France, 2013, pp. 2861–2864.
- [15] T. Kajisa, H. Miyauchi, K. Mizuhara, K. Hayashi, T. Tokimitsu, M. Inoue, K. Hara, A. Masuda, Novel lighter weight crystalline silicon photovoltaic module using acrylic-film as a cover sheet, Jpn. J. Appl. Phys. 53 (2014) 092302-1–092302-7.
- [16] S. Koch, J. Berghold, O. Okoroafor, S. Krauter, P. Grunow, Encapsulation influence on the potential induced degradation of crystalline silicon cells with selective emitter structures, in: Proceedings of the 27th EU PVSEC, Frankfurt, Germany, 2012, pp. 1991–1995.
- [17] J. Kapur, A. Bennett, J. Norwood, B. Hamzavytehrany, I. Kueppenbender, Tailoring ionomer encapsulants as low cost solution to potential induced degradation, in: Proceedings of the 28th EU PVSEC, Paris, France, 2013, pp. 476–479.
- [18] S.-H. Schulze, A. Apel, R. Meitzner, M. Schak, C. Ehrich J. Schneider, Influence of polymer properties on potential induced degradation of PV-modules, in: Proceedings of the 28th EU PVSEC, Paris, France, 2013, pp. 503–507.
- [19] C.G. Reid, S.A. Ferrigan, J.L.F. Martinez J.T. Woods, Contribution of PV encapsulant composition to reduction of potential induced degradation (PID) of crystalline silicon PV cells, in: Proceedings of the 28th EU PVSEC, Paris, France, 2013, pp. 3340–3346.
- [20] R. Swanson, M. Cudzinovic, D. DeCeuster, V. Desai, J. Jürgens, N. Kaminar, W. Mulligan, L.R. Barbosa, D. Rose, D. Smith, A. Terao, K. Wilson, The surface polarization effect in high-efficiency silicon solar cells, in: Proceedings of 15th International Photovoltaic Science and Engineering Conference (PVSEC-15), Shanghai, China, 2005.
- [21] V. Naumann, T. Geppert, S. Großer, D. Wichmann, H.-J. Krokoszinski, M. Werner, C. Hagendorf, Potential-induced degradation at interdigitated back contact solar cells, Energy Procedia 55 (2014) 498–503.
- [22] K. Mishina, A. Ogishi, K. Ueno, T. Doi, K. Hara, N. Ikono, D. Imai, T. Saruwatari, M. Shinohara, T. Yamazaki, A. Ogura, Y. Ohshita, A. Masuda, Investigation on antireflection coating for high resistance to potential-induced degradation, Jpn. J. Appl. Phys. 53 (2014) 03CE01-1–03CE01-4.
- [23] K. Hara, H. Ichinose, T.N. Murakami, A. Masuda, Crystalline Si photovoltaic modules based on TiO_2 -coated cover glass against potential-induced degradation, RSC Adv. 4 (2014) 44291–44295.
- [24] K. Hara, S. Jonai, A. Masuda, Crystalline Si photovoltaic modules functionalized by a thin polyethylene against potential and damp-heat-induced degradations, RSC Adv. 5 (2015) 15017–15023.
- [25] A.K. Sharma, S.K. Agarwal, S.N. Singh, Determination of front surface recombination velocity of silicon solar cells using the short-wavelength spectral response, Sol. Energy Mater. Sol. Cells 91 (2007) 1515–1520.
- [26] P. Saint-Cast, H. Nagel, D. Wagenmann, J. Schön, P. Schmitt, C. Reichel, S.W. Glunz, M. Hofmann, J. Rentsch, R. Preu, Potential-induced degradation on cell level: the inversion model, in: Proceedings of the 28th EU PVSEC, Paris, France, 2013, pp. 789–792.