

Polarization effects and tests for crystalline silicon solar cells

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Abstract: We try to find a fast and simple potential induced degradation effect (PID) test procedure for crystalline silicon solar cells. With sodium chloride (NaCl) solution as Na⁺ source, PVB as lamination material, we can carry out the test in 1 h. Solar cells with newly developed PID resistance process were also tested. The increase of reverse current of solar cell can be considered a key standard to determine if the solar cell was prone to PID. Moreover, it showed that the increase of reverse current for the PID resistance solar cell was less than 2. In addition, the test results of the solar cells fitted very well with that of the modules by standard procedure.

Key words: crystalline silicon solar cells; potential induced degradation; rapid test

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1. Introduction

Potential-induced degradation (PID) effect of crystalline silicon solar cells was first reported by Sunpower in 2005 for n-type cells when they were operated in modules at high positive voltage^[1]. In 2010, NREL and Solon demonstrated that PID is a fundamental risk whenever state-of-the-art p-type crystalline silicon solar cells were used in standard modules at high negative bias^[2–5].

Intensive study was carried out to understand the mechanism of the PID^[6–8]. The impact of the refractive index and thickness of the silicon nitride antireflection coating, the cell's base resistivity and emitter sheet resistance, the modules' encapsulation material, cover glass and the humidity and temperature on PID were investigated. The mechanism is that the high voltages between cells and the encapsulation material leads to migration of sodium (Na) ions which stem from the soda lime glass used as a cover of the modules. Subsequently, Na might migrate to the surface of SiN antireflection coating and interact with the emitter, finally causing shunting. Several models explained the shunt as an inversion region at the surface of the emitter^[9–12]. According to the above physical process, it is assumed that sodium plays an important role in the formation of PID. The encapsulation material ethylene vinyl acetate (EVA) combined with the silicon nitride antireflection coating of the solar cells is also required for PID formation.

To check the PID stability of solar modules, an accelerated procedure was proposed^[3]. During the test, a negative 1000 V was applied between the aluminum frame and junction box in a temperature of 85 °C and a relative humidity of 85 for 96 h.

Such a procedure is time-consuming when applied for solar cell PID stability test. An alternative fast method is proposed. Corona-discharge assembly is used in Reference [13]. Polarizing a mini module consisting of a single solar cell will take about 24 h. In the test setup, the module contacts were short circuited and grounded and a high positive voltage (~11 kV) was applied to a thin wire positioned about 10 cm above the front surface of the sample.

In this work, we try to find a quick test procedure on cell level with little preparation work and simple equipment. We also investigated the PID behavior of the newly developed solar cells featuring high PID stability—solar cells with oxidation layer deposited by PEVCD using N₂O as additional work gas and oxidation layer grown by ozone. The test results of solar cells were also compared with the results of the modules by stand test sequence. Finally, a quick polarization test sequence has been developed to help module and cell manufactures to check their different products.

2. Experiment

Solar cells from the same batch were laminated to material-cell-material samples. Before the test, sodium chloride (NaCl) solution with concentration of 5%–20% (weight) was painted on the surface of silicon nitride coating used as Na ion source. Figure 1 shows the sandwich test setup which was used for the following test sequences. The front surfaces of the samples were covered with a copper foil with a dimension of 40 × 40 mm². Then they were connected to the positive pole of a laboratory DC power supply of 600 V. Meanwhile the cell contacts were soldered by ribbon and connected to the negative pole. The test was performed in a climate chamber with a temperature of 85 °C and a relative humidity of 85%, which corresponds to the damp heat conditions according to the standard IEC 61215. *I*–*V* curves of the cells were measured before and after the test. Electroluminescence technique was used to detect the defect induced by PID after the test.

3. Results and discussion

3.1. Samples with different encapsulation materials

The goal of the first experiment is to find an encapsulation material which is able to polarize cells as fast as possible. During the test, the encapsulation material carries the water vapor to the test area on the surface of the solar cells. Meanwhile it provides good adhesion with the surface of the silicon ni-

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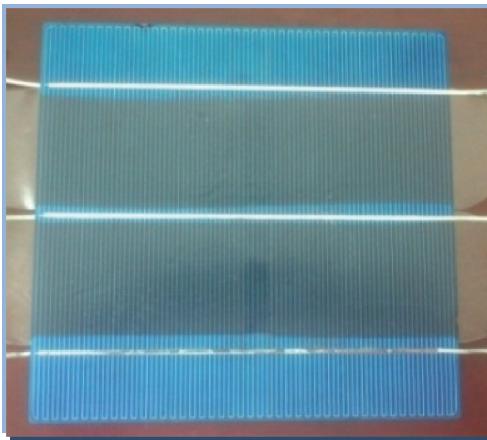


Figure 1. Schematic test setup with two-EVA laminates and a crystalline silicon cell in between. The outside surface of the front EVA has been equipped with copper foil. The foil and the cell's contacts have been connected to a laboratory DC power supply and have been stressed with a voltage of -600 V at 85°C at 85% RH.

tride coating so that high voltages can be applied. So the resistivity of the encapsulation material should be carefully controlled. Materials with high resistivity will reduce the electric field strength. While materials with low resistivity can accelerate movement of Na ion, they will cause a short circuit since they may become a good conductor under high temperature and high humidity environment.

Three different encapsulation materials were evaluated in terms of their behavior during PID-provoking test. The NaCl solution with concentration of 5% (weight) was used. After 1 h, the cell laminated by PVB showed characteristic patterns of inhomogeneous polarization in electroluminescence images (Figure 2). Conversely, there was no obvious change for the cells laminated by EVA. Finally, the cells laminated by the third material were short-circuited due to lower resistivity. No electroluminescence image was showed here. To confirm the PID effect, a positive 1000 V was applied to the solar cells laminated by PVB at the same area for 1 h at the same temperature and humidity. After that, the dark area reduced which indicated that it was not caused by finger corrosion. According to the above results, PVB laminated samples showed the highest susceptibility regarding PID effect. All following tests will be performed with PVB as encapsulation material.

3.2. Samples painted by NaCl solution with varied concentration

The second experiment is to find the effect of the concentration of NaCl solution on the PID-provoking rate. NaCl solutions with concentration of 5% and 20% (weight) were used.

Figure 3 shows the EL images of the solar cells tested with NaCl concentration of 5% (weight) and 20% (weight). Both the solar cells showed characteristic patterns of inhomogeneous polarization. In particular, the inactive area in the EL image for the solar cell painted with 20% concentration is much darker than that painted with 5%. It indicated that with increasing the concentration of NaCl solution, the solar cell's susceptibility regarding PID effect of solar cells increased. Therefore, PVB and 20% NaCl concentration solution were chosen for all fol-

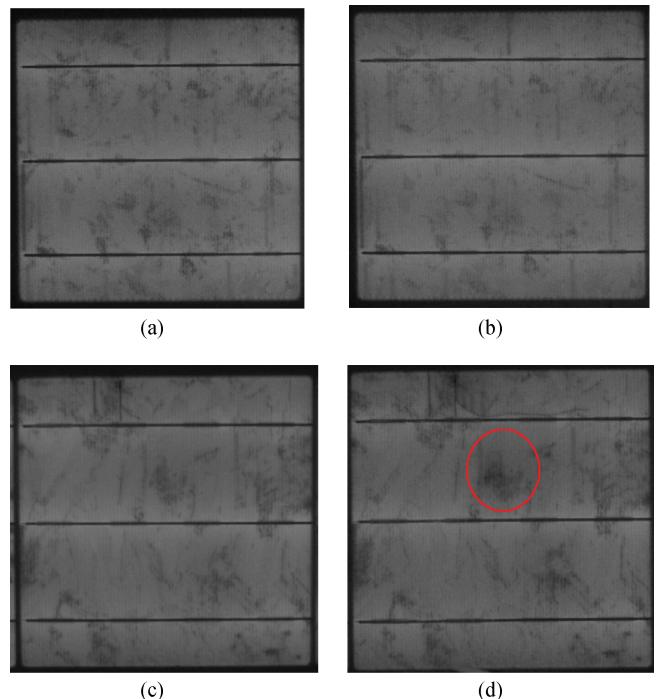


Figure 2. Electroluminescence images of the solar cell laminated by EVA (a) before and (b) after the test. Electroluminescence images of the solar cell laminated by PVB (c) before and (d) after the test.

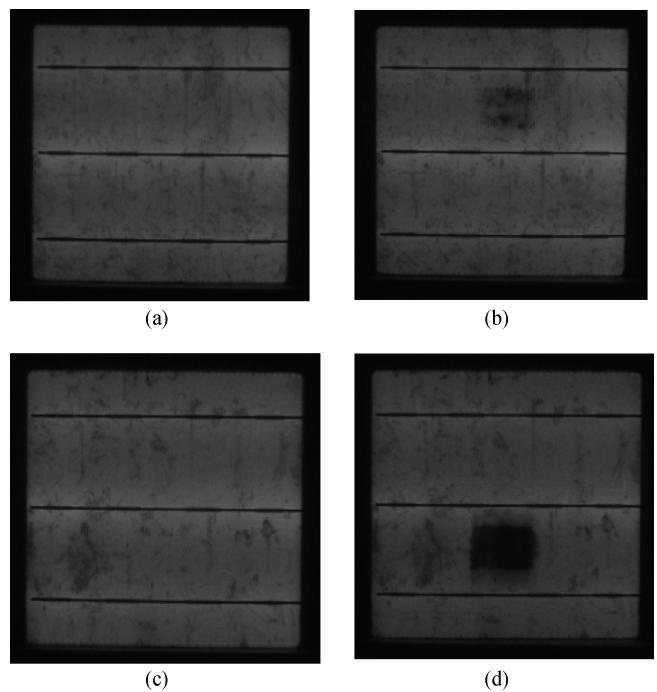


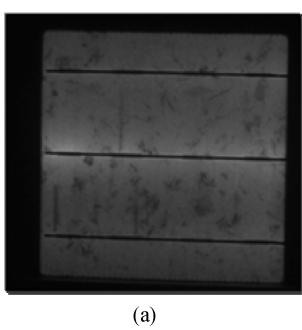
Figure 3. Electroluminescence images of the solar cell painted by 5% NaCl solution (a) before and (b) after the test. Electroluminescence images of the solar cell painted by 20% NaCl solution (c) before and (d) after the test.

Table 1. The electrical parameters of the solar cell with silicon nitride layer featuring a refraction index of 2.08 before and after the test.

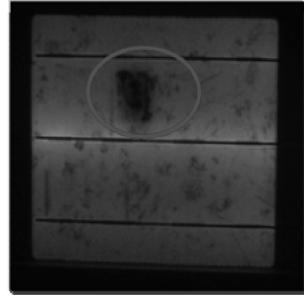
Parameter	U_{oc}	I_{sc}	R_s	R_{sh}	FF	NCell	I_{rev2}
Before	0.62712	8.5794	0.00290	223.663	78.1615	0.17280	0.0688
After	0.62315	8.5295	0.00262	1.06728	72.0967	0.15746	7.3769
Loss				-99.5%			122

Table 2. The electrical parameters of the solar cell with silicon nitride layer featuring a refraction index of 2.12 before and after the test.

Parameter	U_{oc}	I_{sc}	R_s	R_{sh}	FF	NCell	I_{rev2}
Before	0.62453	8.4531	0.00464	83.5164	75.801	0.1644	0.3098
After	0.62316	8.5146	0.00513	2.9233	72.3773	0.1578	3.2297
Loss				-96.5%			10.45

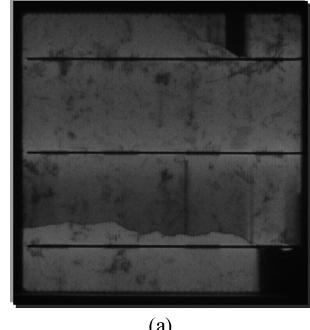


(a)

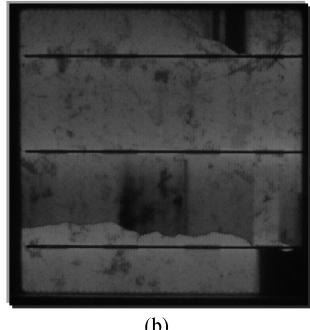


(b)

Figure 4. Electroluminescence images of the solar cell with silicon nitride layer featuring a refraction index of 2.08 (a) before and (b) after the test.



(a)



(b)

Figure 5. Electroluminescence images of the solar cell with silicon nitride layer featuring a refraction index of 2.12 (a) before and (b) after the test.

lowing tests.

3.3. Cells with varied refractive index (RI) of silicon nitride layer

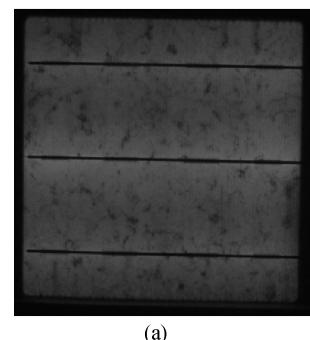
One of the solutions for PID on solar cell level is to modify the refractive index (RI) of silicon nitride film through modifying the deposition parameter, which can even prevent the PID. Study showed that RI exceeding 2.14 is required. So we first test the PID behavior of solar cells with increasing RI of the silicon nitride layer.

Figure 4 shows the EL images of solar cell with a silicon nitride layer featuring a refraction index of 2.08 before and after the test. It obviously showed PID phenomenon, a dark area due to the inactive part.

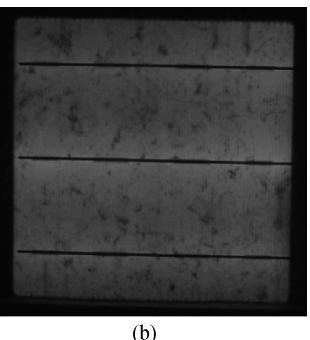
Table 1 shows the electrical parameters of the solar cell before and after the test. A pronounced change took place for the shunt resistivity and reverse current. The shunt resistance decreased from 223 to near 1.0 and the reverse current increased by a factor of 122, which is a typical change of the electrical performance parameters caused by PID.

The solar cell with silicon nitride layer featuring a refraction index of 2.12 still showed a dark area in the EL after the test, as shown in Figure 5. However, the area is less dark than the cells featuring a refraction index of 2.08. The electrical parameters showed the shunt resistivity still had a high decrease of 96.5%, as shown in Table 2. But the reverse current increased only by a factor of 10, which indicate that the PID stability of the solar cells were considerably improved.

Figure 6 shows the EL images of the solar cell with sil-



(a)



(b)

Figure 6. Electroluminescence images of the solar cell with silicon nitride layer featuring a refraction index of 2.14 (a) before and (b) after the test.

icon nitride layer featuring a refraction index of 2.14 before and after the test. No obvious change was observed in the EL images. The electrical parameters of the solar cell after the test showed the reverse current increased only by a factor of 1 and the shunt resistance decreased by 4.4%, which indicated no PID occurred, as shown in Table 3. It is determined that increasing the refraction index of SiN coating to 2.14 finally prevented the PID.

According to the above results, the EL images and the electrical parameter of the solar cells showed a dramatic change with respect to the refraction index of SiN coating as we expected. It indicated we can distinguish the different PID behavior of solar cells with different susceptibility regarding to PID effect by our method.

Table 3. Electrical parameters of the solar cell with silicon nitride layer featuring a refraction index of 2.14 before and after the test.

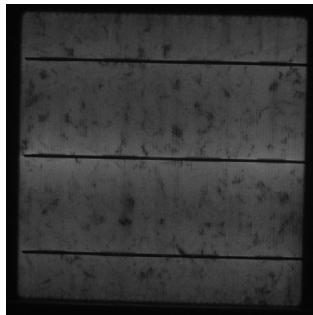
Parameter	U_{oc}	I_{sc}	R_s	R_{sh}	FF	NCell	I_{rev2}
Before	0.6234	8.6363	0.00344	268.032	76.689	0.1696	0.0752
After	0.6242	8.6126	0.00408	256.160	75.793	0.1674	0.0814
Loss				-4.43%			1.08

Table 4. Electrical parameter of the solar cell with SiO_2 film deposited by PECVD before and after the test.

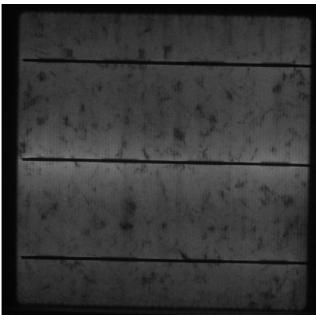
Parameter	U_{oc}	I_{sc}	R_s	R_{sh}	FF	NCell	I_{rev2}
Before	0.62672	8.4921	0.00289	92.442	78.253	0.17113	0.1887
After	0.62830	8.4966	0.00325	84.154	77.869	0.17081	0.2015
Loss				-9.1%			1.06

Table 5. Electrical parameter of the solar cell grown by ozone before and after the test.

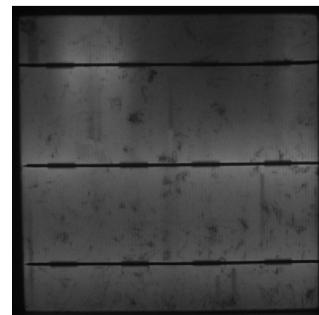
Parameter	U_{oc}	I_{sc}	R_s	R_{sh}	FF	NCell	I_{rev2}
Before	0.6287	8.732	0.00426	300.16	76.6	0.1728	0.052
After	0.6279	8.735	0.00456	241.4	76.18	0.1717	0.0579
Loss				-19.6%			1.11



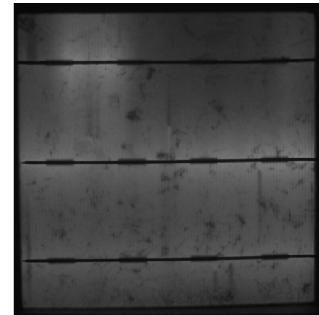
(a)



(b)

Figure 7. Electroluminescence images of the solar cell with SiO_2 film deposited by PECVD (a) before and (b) after the test.

(a)



(b)

Figure 8. Electroluminescence images of the solar cell with SiO_2 grown by ozone (a) before and (b) after the test.

3.4. Oxidation layer grown by PECVD and ozone

New solutions on cells lever include growing SiO_2 film with a thickness of 10–15 nm by plasma enhanced chemical vapor deposition (PECVD) which act as an effective obstacle to Na^+ . Commonly, growing the film uses N_2O and SiH_4 as work gas, while the thin SiO_2 film grown by ozone on the H-terminated silicon surface has a thickness about 1–2 nm and works in another mechanism. The two kinds of solar cells were also tested to check the universality of the test method.

Figure 7 shows the EL image of the solar cell with SiO_2 film deposited by PECVD before and after the test. No obvious change was observed. The electrical parameter change showed that the shunt resistivity reduced 9.1% and the reverse current increased by a factor of 1.06, which indicated that the solar cell showed a good PID stability, as shown in Table 4.

The SiO_2 films grown by ozone, though only having a thickness of 1–2 nm, still showed a good stability PID, as shown in Figure 8. The EL showed no dark area and the reverse current increased only by a factor of 1.1, as shown in Table 5.

Table 6 shows the power loss of the modules fabricated by a solar cell with various processes after the PID test by standard test procedure. For modules, the pass standard is power

Table 6. Power losses of the modules fabricated by solar cells with various processes after PID test.

Solar cell process	Module power loss after test (%)
Reflective index 2.08	51.1
Reflective index 2.12	10.89
Reflective index 2.14	1.2
SiO_2 grown by PECVD	1.3
SiO_2 grown by ozone	1.5

loss less than 5% after the test. It showed that the power loss with varied RI of silicon nitride decreased from 51.1% to 1.2% with RI increase from 2.08 to 2.14. Correspondingly the reverse current change decreased from 122 times to 1.2 times in our test. In addition, the power loss of the SiO_2 grown by different processes were 1.3% and 1.5% respective, both showed good stability for PID. Finally, the above results suggested a correlation between the result of the modules test by standard procedure and the result of solar cells test by our method.

4. Discussion

It is shown that the high voltage leads to migration of sodium (Na) ions to the surface of the solar cells, which stem

from the soda lime glass. When sodium ions reach the SiN_x various options occur. On the one hand the charged ions concentrate on the surface of the layer building up an electric field leading to an anti-passivating effect resulting in an increasing surface recombination rate. On the other hand the sodium may diffuse into the bulk and act as a donator atom. This leads to a rising concentration of sodium ions in the emitter, so the negative doping will be neutralized, the p–n-junction will be diminished. Hence, the sodium and ethylene vinyl acetate foil, combined with the SiN anti-reflection coating of the solar cells plays an important role in the formation of PID. Moreover, the PID affected solar cells showed a dark appearance in EL images, while the reversed current also increased remarkably. The same mechanism makes it work very well in our test setup using NaCl as Na^+ source and PVB as laminated material. The high voltage applied between the surface of the SiN_x and the PVB pushes the Na^+ into the SiN film, even into the emitter. So the same dark area identified in the PID affected modules can be observed in the solar cell tested by our method. Bauer and Breitenstein^[9] suggested that the PID is caused by the micro-sized shunt at which increased Na^+ concentration was found. In our test, increasing Na concentration in the solution precisely increased the sum of the micro-sized shunt. So the reverse current increased as a consequence of increased shunting when more Na^+ diffused into the SiN_x or emitter.

The light intensity of the EL image depends on the partial voltage of the solar cell. Due to losing the P–N junction, the voltage of inactive area could not be established. So the area shows a dark appearance. It has been showed that the dark area and degree of darkness of the modules was a good indicator for PID. In particular, the size of the affected area even correlated with the actual degree of degradation. In our case, due to the copper coil size being constant, the shunt is limited to the area under the copper coil. Therefore, only the degree of darkness is correlated with the actual degree of degradation.

Berghold^[4] studied the key parameter change of single cell module by PID test with increasing test time. Solar cells which undergo PID are characterized by a significant decrease of their shunt resistance. More precisely, the shunt resistivity decreased from 80.4 to 0.2 after 100 h, the reverse current increased by a factor of 50. The study showed a similar result with our single cell test. Though the shunt resistivity is always used as an indicator of PID for solar modules, we believed that the change of the reverse current can also be used to determine if the solar cell is prone to PID. By way of comparison, our 1 h test was equal to the test of a module of 100 h. Unlike the result of the module, the loss of shunt resistivity is very near and the reverse current shows a much better sensitivity in our test.

In the test, SiN film featuring a high RI can prevent PID. That can be explained by the high conductivity of the film due to high ratio of silicon to nitrogen can release the positive charge^[14]. The SiO_2 film formed by PECVD can hinder the migration of Na^+ into the surface of the emitter. SiO_2 films grown by ozone can provide a tunnel channel for the electron to neutralize the Na^+ at high negative voltage. Though a different mechanism of preventing the PID, the reverse current of these PID-resistance solar cells after test was less than 2 times, which we believed is the criteria for PID resistance solar cells.

The test results of the solar cells by our method fitted very well with the result of modules tested by standard method.

However, this method is only suitable to check the vulnerability of the solar cells to the PID effect and predict the PID behavior of modules with common EVA and soda lime glass. For the modules using strong anti-PID encapsulation material (such as POE) or glass in absence of Na ions, the method will be ineffective. It also must keep in mind that the PID resistance of the solar cell also depended on the quality and homogeneity of silicon nitride or oxidation film. If the silicon nitride or SiO_2 film did not grow perfectly for some solar cell, it will fail to predict the degradation of the module. We found in a failure module after PID test for 96 h that only one solar cell appeared dark in the EL image, which is due to lower index silicon nitride film or thin oxidation film. Different results were also found by different EVA materials. So it is hard to make sure that the result of the solar cell can predict the degradation of the module accurately.

5. Conclusion

A fast method was proposed for solar cell PID stability test. In our method, 20% concentration NaCl solution was used as Na^+ source and PVB was used for enhancing the movement of the Na^+ ions. A voltage of 600 V was applied to the solar cell at 85 °C and relative humidity of 85. Our results showed that testing PID stability of the solar cell can be finished in 1 h with an accelerated rate about 100 with respect to the standard test procedure. The newly developed solar cells were also successfully tested showing that our method was qualified to test upcoming solar cells besides solar cells fabricated by conventional process. Finally, comparing with the results of the modules showed the results of the solar cells is a good prediction for PID behavior of modules.

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