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Effect of Photoconductive Properties of SiN_x Passivation Film on Anti-potential Induced Degradation Performance of Photovoltaic Cells and Modules

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We investigated the impact of the photoconductive properties of crystalline silicon solar cells, having a SiN_x passivation film, on potential induced degradation (PID) using voltage-corona (V-Q) and self-adjusting stead state (SASS) tests. The experimental results show that the conductivity of SiN_x on the cell surface was gradually enhanced by the increase in refractive index, which effectively decreased the accumulated charge on the cell surface. Thus, changes in the conductivity of SiN_x were found to be the cause of the different PID performance of the modules. The present work provides a theoretical basis for solving the PID problem of solar modules and power stations, and the exploration of the V-Q and SASS techniques provides a new, convenient method and corresponding basis for testing the PID performance of solar cells during industrial production.

Keywords: potential-induced degradation, sinx film, solar cell, refractive index.

1. INTRODUCTION

In recent years, solar energy has become a hot area of competitive development among many countries. In solar power stations, to meet load requirements, modules must be connected in series and parallel to build arrays. However, the connection of single modules in series may produce a high voltage relative to the plane of zero potential (ground). The efficiency of the modules degrades prematurely under the long-term effect of this high voltage. This phenomenon is known as potential induced degradation, PID [1]. The phenomenon was discovered and first investigated by R. Swanson in 2005 [2]. The occurrence of this phenomenon has gradually increased as PV power stations have become more and more widely used, and has had a huge impact on PV power station stability. In recent years, some large scale domestic and overseas PV power stations have suffered PID to different degrees after several years' operation. The probability of this phenomenon occurring and the degree of degradation may greatly differ between locations because of the differences in temperature and humidity in different areas and environments. The Camania power station in Italy exhibited the PID phenomenon after installation in September 2010, which caused the power of the modules to decrease by about 20 %. The situation may have been worsened by continued use; the highest power degradation reached 70 %. In October 2010, the PV power station of Sheyang, Jiangsu Province, China began to exhibit PID, and the power of some modules degraded by 49 % – 91 %, which brought huge losses to the station.

At present, the available research indicates that the PID phenomenon may be related to parameters such as the design of the power station, the encapsulation and material of the modules, and the cell production procedure [3 – 6].

In terms of power station design, the probability of PID occurring is increased by the high voltage, which modules bear near the negative pole of the power station. In terms of module encapsulation, although the performance of the cells in a module may be the same, the cells at the edge may be more easily influenced by the temperature and humidity of the surrounding environment, and thus will more obviously suffer from PID (as shown in Fig. 1). Cells are the core component of PV modules, and are the primary cause of PID. General research has shown that the passivation dielectric layer, especially the SiN_x layer, greatly influences the PID phenomenon. Pingel et al. verified the presence of a relationship between PID and the Si/N ratio of the SiN_x antireflection coating (ARC) layer1, but did not analyze the relationship deeply. Some reports [7, 8] have claimed that the destruction of the passivation layer by Na+ is the origin of PID, but evidence for this may be lacking. In this paper, we verified the relationship between PID and the conductivity of SiN_x passivation film by adjusting the production procedure of SiN_x ARC film. At the same time, the voltage-corona (V-Q) and self-adjusting steady state (SASS) tests were used to verify the primary cause of PID. The current method used to test for PID in industrial manufacture involves first encapsulating the cells into modules, then testing them for 96 h under identical conditions of temperature, humidity, and bias voltage. This complicated test procedure is insufficient for the timely and effective monitoring of anti-PID performance during industrial manufacture. Therefore, as well as revealing the primary reason why the refractive index [9, 10] of SiN_x influences PID, which provides a theoretical basis to solve

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the PID problem of PV power stations, the shorter duration of the proposed test method based on V-Q and SASS and the coherence of the results are expected to have great significance for the monitoring of anti-PID performance during the industrial manufacture of cells.

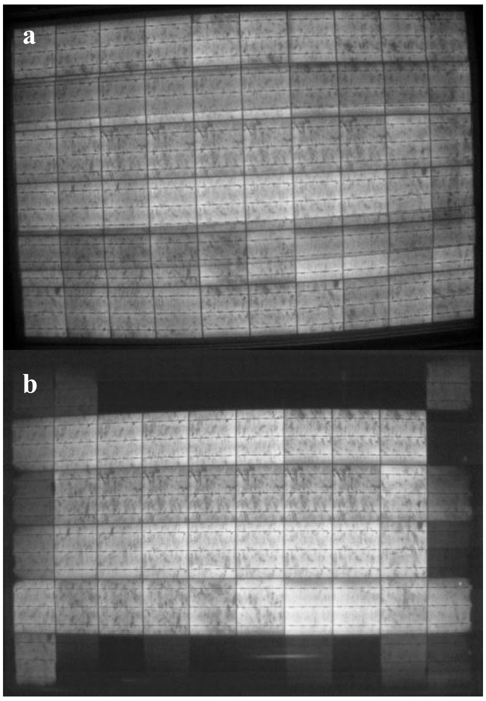


Fig. 1. Electroluminescent (EL) images of PV module before and after typical PID phenomenon [1]

2. EXPERIMENTAL

P-type polycrystalline silicon wafers from the same batch were used in this experiment. The wafers had a resistivity of 1 – 3 Ω·cm and thickness of about 190 µm. Industrial texturing, diffusion, and edge isolation were used to prepare the samples. By adjusting the ratio of the silane and ammonia precursor gases, SiN_x films of different refractive index were produced on the silicon samples by plasma-enhanced chemical vapor deposition (PECVD). The depositing process includes two steps. In the first step, the pressure and power are set at 1500 mTorr and 6100 W, the flow of NH_3 and SiH_4 is 6.2 slm and 1450 sccm respectively, the depositing time is 165 s. In the second step, the pressure and power are same with step 1, the flow of NH_3 and SiH_4 is 6.8 slm and 780 sccm respectively, the depositing time is 550 s. A spectroscopic ellipsometer was used to measure the refractive index and film thickness of the SiN_x films. All samples were divided into two groups. One group was characterized via V-Q and SASS remnant voltage tests using a WT-2000 (Semilab, Hungary). During V-Q measurement, the surface of solar cell is charged by a scanning linear charger, the surface potential measurements are performed with a Kelvin probe after each charging step. SASS measurement also includes two steps. The first step is corona charging, in this step, positive corona charges are deposited on the wafer. The second step is surface potential degradation, in this step, there is no corona charge, surface potential decreased with time, the retained voltage is measured with time.

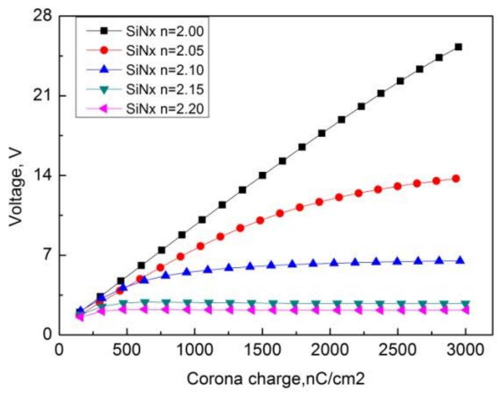
The second group was encapsulated into modules after electrode printing and sintering, which were then PID tested under identical temperature and humidity conditions. The PID tests were carried out for 96 h at 85 °C, 85 % humidity, and −1000 V backward voltage. Finally, the electrical performance of the small modules before and after PID tests was compared using I-V and electroluminescence (EL) measurements.

The present experiments were designed to mainly study the relationship between the saturation voltage and voltage drop ratio and the refractive index of the SiN_x passivation layer on the cell wafer, as well as reveal the primary reason why the refractive index affects PID.

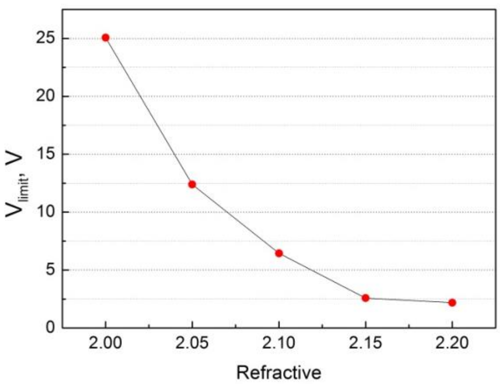
3. RESULTS AND DISCUSSION

3.1. Relationship between photoconductivity and refractive index of the silicon nitride

To verify the relationship between charge conductivity and SiN_x refractive index, a V-Q charging test was carried out on the surface of SiN_x films with different refractive index. While the silicon wafer was charged continuously, a Kelvin probe [11] was used to measure the change in the silicon surface voltage with increasing electric charge. As the electric charge was increased from 0, the SiN_x surface voltage first increased quickly and then gradually saturated, until it stabilized at VB, the extra charges were lost after it reached VB, which is called the saturation voltage (Vlimit).



a



b

Fig. 2. a – surface voltage vs corona charge density at different refractive index; b – V_{limit} of samples vs refractive index

Fig. 2 a shows the trends of the change in silicon surface voltage with corona electric charge for SiN_x passivation films of different refractive index, which were prepared by adjusting the flow rate of silane and ammonia gases during its deposition process. The plot shows that increasing the refractive index of the SiNx caused the surface voltage of the silicon to reach saturation more easily when a positive corona charge was applied to the thin film. Additionally, once the saturation voltage had been reached, the surface voltage did not change with further increases in corona charge. This means that after saturation, the excess positive charge would have left the film as the electric leakage, and did not contribute to the silicon surface voltage. Fig. 2 b shows the relationship between saturation voltage (Vlimit) and the refractive index of the SiNx. The saturation voltage at the wafer decreased as the refractive index of the SiNx was increased. When the refractive index was increased from 2.00 to 2.10, the saturation voltage decreased quickly from 25.00 V to 6.45 V (as shown in Fig. 2 b). Then by the increasing of refractive index, the curve reached to a stable status gradually. When the refractive index was increased to 2.20, the saturation voltage was just 2.19 V, which meant that the influence of the external corona charge on the silicon energy band was weak.

Table 1. SASS remnant voltage test

Refractive index	Vat					Vat30s/Vat3s
	1 s	3 s	5 s	30 s	60 s	
2	28.4	28.2	28.0	27.1	26.5	96 %
2.05	16.3	15.7	15.4	13.9	13.2	89 %
2.1	7.0	6.5	6.2	5.2	4.8	80 %
2.15	4.6	4.2	4.0	3.2	2.9	76 %
2.2	2.6	2.3	2.2	1.7	1.5	71 %

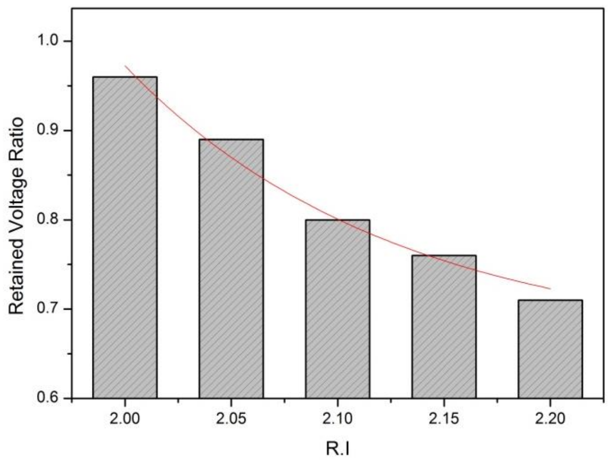


Fig. 3. Relationship between SASS test results and SiN_x refractive index

A SASS voltage test was carried out to verify the reliability of the V-Q test results. For the test, charging was stopped when the wafer voltage reached saturation, and the subsequent change in the silicon surface voltage was then measured under illumination. The obtained voltage drop data is given in Table 1, in which Vat30s/Vat3s refers to the voltage drop ratio. Fig. 3 shows a plot of the relationship between the voltage drop and the refractive index, and reveals that the degradation of the silicon surface voltage increased with the refractive index of the SiN_x under illumination. This result can be explained by the higher silicon concentration of the SiN_x thin films with greater refractive index [12]. As the photoconductive effect of thin film was improved, the photo-generated carriers were neutralized by the external charge on the surface of thin film, which increased the rate of degradation of the silicon surface voltage and further weakened the influence of the external charge on the silicon energy band.

3.2. Impact of SiN_x refractive index on the PID of the modules

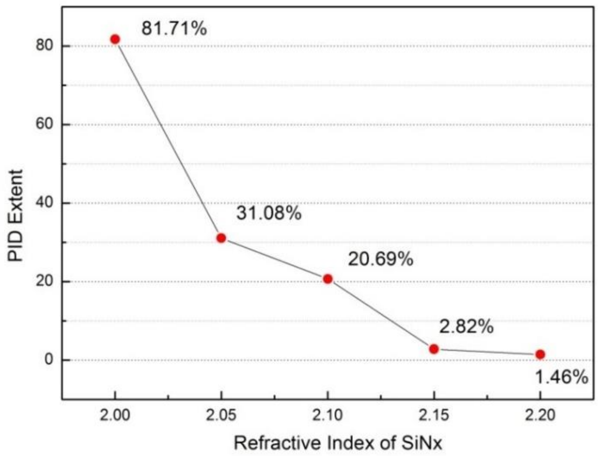


Fig. 4. Relationship between extent of PID and refractive index of single layer SiN_x

Fig. 4 shows the influence of the refractive index of the SiN_x layer (deposited film thickness 85 nm) on the trend in PID extent, PID extent is the degradation of solar efficiency after testing. SiN_x films with different refractive index were prepared by adjusting the flow rate of silane and ammonia gases during the deposition process. The results indicated that the extent of PID can be decreased by increasing the refractive index of the SiN_x single layer. There was an obvious linear downward trend in PID as the refractive index was increased from 2.05 to 2.15, after which the extent of PID gradually stabilized. Overall, changing the refractive index from 2.05 to 2.20 decreased the extent of PID from 86.35 % to 3.02 %. The images obtained during EL tests confirmed this trend in degradation. The EL light intensity of the modules observed after PID increased with the refractive index of the SiN_x. When the refractive index was increased to 2.20, there appeared to be no significant change in EL intensity before or after the PID test, which indicated good anti-PID performance for this sample.

3.3. Results discussion

In most pre-existing reports on the effect of SiNx refractive index on the anti-PID performance of cells and modules, the authors mostly just verified the relationship using experimental results, instead of with deeper analysis based upon fundamental principles. With respect to cells, the main cause of PID is high voltage, at which large numbers of carriers concentrate on the surface of the cells and change the surface charge distribution [13]. This charge redistribution destroys the original passivation of the cell surface.

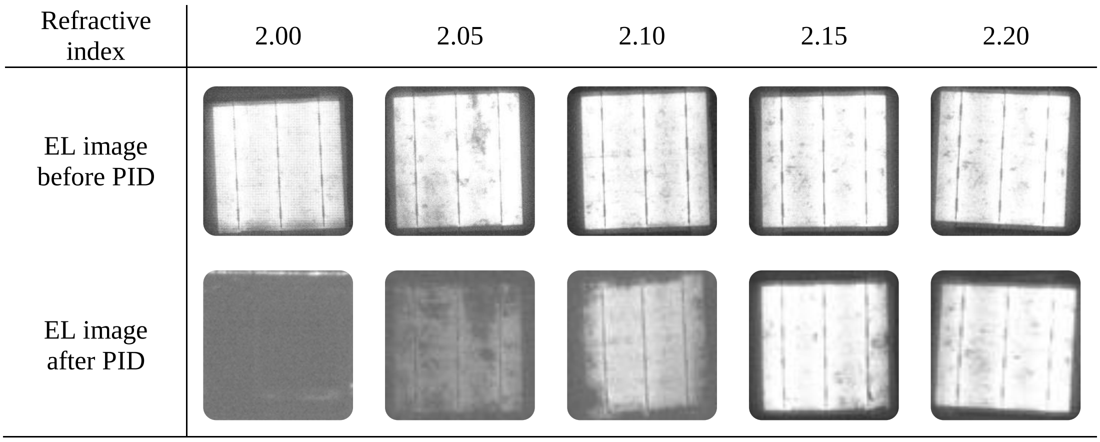


Fig. 5. EL pictures of cells with SiN_x layers of different refractive index before and after PID test

Taking the above experimental results into account, when the SiN_x refractive index is increased, not only may the electric current leakage increase, which decreases the charge accumulation ability of the SiN_x surface, but the photoconductive properties of thin film also may increase, which can generate carriers and additional charge under illumination, decreasing the voltage of the surface.

Together, these effects can decrease the amount of charge accumulated on the surface of the cell, which weakens the impact on the active layer of the cell and its passivation by the external electric field. Thus, it can fundamentally remit the extent of PID, and effectively suppress it.

Moreover, the traditional test of cell anti-PID performance requires the encapsulation of modules and testing for 96 h under identical temperature, humidity, and bias voltage conditions [14]. The whole process (from cell selection to the test result acquisition) involves a complicated preparation and long time, which is not good for the effective monitoring of anti-PID performance and adjusting of production processes. However, the whole V-Q and SASS test used here takes less than 20 s, and is thus suitable for real-time and on-line monitoring during cell manufacture. The present results therefore have great significance to the monitoring of cell quality.

4. CONCLUSION

This study has investigated the impact of SiNx film refractive index on PID through V-Q and SASS tests. The results confirm that the change in SiNx conductivity with refractive index affected the amount of electric charge accumulated on the surface of the cells. Accordingly, changing the applied voltage to change the passivation of the cells affected the observed PID of the prepared cells and modules. When the refractive index of the SiNx layer was increased to 2.2, the saturation voltage of the cell surface decreased to 2.5 V, indicating good photoconductive properties. As a result, the extent of PID observed for this sample decreased to about 2 %. Moreover, we also investigated the monitoring of anti-PID performance during cell production based on the V-Q and SASS tests, which is expected to simplify the testing process for the industrial production of solar cells.

REFERENCES

1. **Pingel, S., Frank, O., Winkler, M., Daryan, S.** Potential Induced Degradation of Solar Cells and Panels *IEEE Photovoltaic Specialists Conference* 12 2010: pp. 002817 – 002822. https://doi.org/10.1109/PVSC.2010.5616823
2. **Bot, G., Braak, N.V.D., Challa, H., Hemming, S., Rieswijk, T., Straten, G.V.** The Solar Greenhouse: State of The Art in Energy Saving and Sustainable Energy Supply *Acta Horticulturae* 691 2005: pp. 501 – 508. https://doi.org/10.17660/ActaHortic.2005.691.59
3. **Naumann, V., Lausch, D., Hähnel, A., Bauer, J., Breitenstein, O., Graff, A., Werner, M., Swatek, S., Großer, S., Bagdahn, J., Hagendorf, C.** Explanation of Potential-Induced Degradation of the Shunting Type by Na Decoration of Stacking Faults in Si Solar Cells *Solar Energy Materials and Solar Cells* 120 2013: pp. 383 – 389. https://doi.org/10.1016/j.solmat.2013.06.015
4. **Naumann, V., Lausch, D., Großer, S., Werner, M., Swatek, S., Hagendorf, C., Bagdahn, J.** Microstructural Analysis of Crystal Defects Leading to Potential-Induced Degradation (PID) of Si Solar Cells *Energy Procedia* 33 2013: pp. 76 – 83. https://doi.org/10.1016/j.egypro.2013.05.042
5. **Schutze, M., Junghanel, M., Koentopp, M.B., Cwikla, S., Friedrich, S., Muller, J.W., Wawer, P.** Laboratory Study of Potential Induced Degradation of Silicon Photovoltaic Modules *Photovoltaic Specialists Conference (PVSC), 37th IEEE* 2011: pp. 000821 – 000826. https://doi.org/10.1109/PVSC.2011.6186080
6. **Hacke, P., Terwilliger, K., Smith, R., Glick, S., Pankow, J., Kempe, M., Bennett, S.K.I., Kloos, M.** System Voltage Potential-Induced Degradation Mechanisms in PV Modules and Methods for Test *Photovoltaic Specialists Conference (PVSC), 37th IEEE* 2011: pp. 000814 – 000820. https://doi.org/10.1109/PVSC.2011.6186079
7. **Naumann, V., Hagendorf, C., Grosser, S., Werner, M., Bagdahn, J.** Micro Structural Root Cause Analysis of Potential Induced Degradation in c-Si Solar Cells *Energy Procedia* 27 2012: pp. 1 – 6. https://doi.org/10.1016/j.egypro.2012.07.020
8. **Bauer, J., Naumann, V., Grosser, S., Hagendorf, C., Schuetze, M., Breitenstein, O.** Micro Structural Root Cause Analysis of Potential Induced Degradation in c-Si Solar Cells *Physica Status Solidi-Rapid Research Letters* 6 2012: pp. 331 – 333. https://doi.org/10.1002/pssr.201206276

9. **Aldosari, M., Sohrabpoor, H., Gorji, N.E.** Optical modeling of Graphene Contacted CdTe Solar Cells *Superlattices & Microstructures* 92 2016: pp. 242 – 248. https://doi.org/10.1016/j.spmi.2016.02.023
10. **Houshmand, M., Zandi, M.H., Gorji, N.E.** Modeling of Optical Losses in Perovskite Solar Cells *Superlattices & Microstructures* 97 2016: pp. 424 – 428. https://doi.org/10.1016/j.spmi.2016.06.031
11. **Wilson, M., Savthouck, A., Amico, J.D., Lagowski, J., Schmitt, S., Schneider, A., Olibet, S.** Investigation on Antireflection Coating for High Resistance to Potential-Induced Photovoltaic Specialists Conference (PVSC) *39th IEEE* 75 2013: pp. 257 – 258.
12. **Wei, L., Yong, S.K., Hacke, P., Naumann, V., Lausch, D., Harvey, S.P.** Potential-induced Degradation in Photovoltic Modules: A Critical Review *Energy & Environmental Science* 10 2017: pp. 43 – 68. https://doi.org/10.1039/C6EE02271E
13. **Goranti, S., Tamizhmani, G.S.** Potential Induced Degradation (PID) Study on Accelerated Stress Tested PV Modules *Photovoltaic Specialists Conference IEEE* 2012: pp. 002438 – 002441. https://doi.org/10.1109/PVSC.2012.6318088
14. **Herrmann, W., Schweiger, M., Mathiak, G.** Potential-Induced Degradation – Comparison of Different Test Methods and Low Irradiance Performance Measurements *27th European Photovoltaic Solar Energy Conference and Exhibition* 2012: pp. 3157 – 3162. https://doi.org/10.4229/27thEUPVSEC2012-4DO.6.3