Micro Structural Root Cause Analysis of Potential Induced Degradation in c-Si Solar Cells

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Abstract

The Potential Induced Degradation (PID) of crystalline Si solar modules has attracted a strong interest in recent years as one of the most prominent failure modes observed in solar park installations. In recent publications the influence of elevated voltages applied to the modules has been studied in detail. Depending on the electrical interconnection scheme, material properties of the modules as well as environmental conditions, in particular cases the total breakdown of module power has been observed. However, until now a clear understanding of the underlying degradation mechanism and the physical failure mode is still missing.

Based on PID experiments on mini modules we have reproduced the degradation mechanism under laboratory conditions (elevated voltage, increased temperature and humidity). The local electrical shunting of the degraded mini modules has been investigated by high resolution Lock-in Thermography (LIT). Samples from regions with different degrees of degradation have been prepared. The material properties have been investigated using Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) and Scanning Electron Microscopy (SEM) with Electron Beam Induced Current (EBIC) measurements at cross sections. The shunted regions of the solar cells show an accumulation of alkali metals at the interface of the front side coatings of the solar cell. In the same regions dramatic changes of the p-n junction contrast can be detected by SEM/EBIC. Based on these data, we propose a simple model that may explain the PID effect in solar cells through induced negative charges at SiN\textsubscript{x}/Si interface.

Keywords: solar cells; Silicon; potential induced degradation; LIT; REM; EBIC; TOFSIMS

1. Introduction

Crystalline Si solar modules may suffer strong power losses when the panels are exposed to elevated voltages at increased humidity. In recent years the effect known as Potential Induced Degradation (PID) has lead to the total breakdown of module power in solar parks where a large number of solar panels are...
serially interconnected. The PID effect has been investigated with respect to the underlying electrical and environmental conditions on a phenomenological level in a several publications.[1-4]. Furthermore, a number of test procedures have been developed in order to estimate the sensitivity of modules regarding the PID. It was recently published that the PID effect strongly depends on the SiN antireflection layer. It was shown that the PID effect decreases with higher refraction index of the SiN layer.[5] However, the physical degradation processes and their interconnection with the electrical breakdown have not been investigated on a material scientific level, yet. The focus of this work is to understand the change of SiN layer material and Si interface of PID affected cells.

In this study we performed degradation experiments on laboratory scale mini modules. The local shunting is analyzed by Lock-in Thermography (LIT). After subsequent sample separation, microstructural investigations of the elemental composition (ToF-SIMS depth profiling) and the p-n junction properties (SEM/EBIC) in the degraded solar cell regions are performed. The data will be summarized within a simple model of induced negative charges at the SiNx/Si interface.

2. Experimental

Mini modules have been produced from multicrystalline Si solar cells with a specific sensitivity to PID. The cells have been laminated with the sunny side onto sheets from clear glass through standard EVA foils. The back side of the solar cells is left blank without any cover. These test samples have been exposed to a voltage of +600 V between the front side of the glass and the grounded cells for up to 72 hours at elevated temperature and humidity (50 °C/50 % RH). The state of degradation has been monitored by parallel resistance measurements. Lock-in Thermography (LIT) and Electroluminescence (EL) imaging have been used for the localization of areas with different shunting intensities. After that, small pieces from selected regions have been cut out. Two types of samples have been prepared subsequently: cell fragments after mechanical or chemical delamination and cross sections of complete stacks (without delamination) after breaking. ToF-SIMS depth profile measurements have been carried out at planar cell fragments. SEM/EBIC investigations have been performed at cross sections with attached electrical contacts. For both, samples from unaffected regions have been used as reference.

3. Results

3.1. Potential induced degradation experiments

In our PID experiments the typical behavior reported for large area modules [4] could be reproduced on mini modules. After a retardation of several hours a rapid drop of the parallel resistance (R_p) is observed. It is decreased by about two orders of magnitude within the first 30-40 hours. For our test samples final R_p values below 1 Ω have been measured after the degradation.

The PID test has been verified on different mono- and multicrystalline Si solar cells from industrial production and on model solar cells without surface texture. Test on PID immune solar cells did not show any degradation under identical testing conditions. Furthermore, various mini module lamination methods have been tested, with backside encapsulants and uncovered back sides. PID was observed in both cases.

In order to perform LIT measurements after PID testing, samples without backside foils have been chosen for subsequent investigations at solar cell level. Solar cells without polymer coverage yield an improved resolution in LIT due to a reduced lateral extension of temperature gradients because of heat conduction. Furthermore, a simple front side lamination allows an improved access to individual parts of the solar cells after disassembling of the mini modules.
3.2. Electro-optical mini module inspection

EL measurements at multi crystalline Si mini modules after PID reveal reduced local intensity as shown in Fig. 1a. Mono crystalline Si solar cells exhibit a similar shape and extension of degraded regions (not shown here). Totally black spots with almost no light emission in EL are often found in the middle of the cells. They have dimensions in the range of centimeters. At the same regions LIT yields high levels of heat production (Fig. 1b). Investigations under variation of the bias reveal (from -2.5 to +0.5 V) ohmic characteristics of these extended shunted regions.

High resolution LIT has been performed on fragments of the solar cells after delamination of shunted regions (inset in Fig. 1b). No correlation between structural properties like grain boundaries and degradation is observed. Thus, we assume that degradation is not related to structural imperfections of the Si material. Lateral variations of degradation have to be explained by inhomogeneities in the SiNx coating, properties of the encapsulant or variations of the local electric fields during PID testing.

3.3. Micro structure investigations

The vertical distribution of impurities is measured by means of ToF-SIMS depth profiling at delaminated cell fragments (plain view). For these experiments specific solar cells with planar surface topography have been prepared, since the depth resolution of ToF-SIMS is known to be limited by surface and interface roughness.

Areas that are apparently affected i.e. shunted, by PID show strongly increased concentrations of Na and some other alkali metals at the surface and within the SiNx layer (Fig. 2a). Besides, the depth distribution of Na shows a pronounced peak at the interface between SiNx and Si. For reference samples without PID impact Na intensities are much lower and no interfacial peak is observed (Fig. 2b).

Regarding the presence of Na at the SiNx/Si interface, it is known from previous investigations that contaminations from wafer cleaning and handling may lead to interface contaminations. The measure-
ments in Fig. 2a and b have been performed on similarly prepared solar cells at degraded and non-degraded regions. The results have been verified by different solar cells and PID tests. Accordingly, we exclude the presence of Na contaminations at the SiN/Si interface due to previous processing steps. Within the Si material of the solar cell the Na signal is declining exponentially. This indicates a sputter induced Na intermixing during ToF-SIMS depth profiling.

Based on the ToF-SIMS results we conclude that a significant amount of Na is present at the surface, within the SiN layer and at the SiN/Si interface of the degraded regions of the solar cells. Additionally, K has been found to show a similar behavior (not shown here). These findings are in agreement with previous studies where Na has been suspected to play a major role in the PID effect.[3] Furthermore, the results coincide with electro-optical investigations (Fig. 1) and studies on monocrystalline Si solar cells. Laterally extended degradation affecting the surfaces and the interfaces of the SiN layer is more likely than local changes at imperfections within the Si solar cell.

A detailed investigation of the p-n junction is performed by combined SEM/EBIC imaging at fractured cross sections of cell fragments (Fig. 3). The measurements have been performed on a planar model solar also used for ToF-SIMS to achieve a direct comparison of the data. The acquisition of local I-V curves of the sample fragments allows a correlation to the integral electrical solar cell properties observed during PID testing as well as LIT and EL measurements.

The non-degraded regions exhibit a strong and undisturbed EBIC signal (red within the SEM/EBIC overlay images) at the p-n junction and diode-like I-V-characteristics (Fig. 3b). In contrast the SEM/EBIC investigation of fractured PID cells displayed in Fig. 3a result in a poor EBIC signal, lowered by 3 orders of magnitude. Additionally, the sharp field gradients at the p-n junction have completely disappeared over the field of view (several 100 μm). The investigated fragment exhibits almost perfect ohmic behavior. Some EBIC contrast changes are observed in regions with grain boundaries. However, these EBIC variations are close to the signal-to-noise ratio.

The data obtained on a microscopic scale confirm and explain the macroscopic electrical properties of PID cells. Obviously, the PID shunts result from an extended modification of the space charge region underneath the affected areas of the solar cells. The presence of defects at the p-n junction leading to local shunts like grain boundaries, inclusions or precipitates may be excluded.

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Fig. 2. ToF-SIMS depth profile of a PID cell (a) and a reference sample (b) showing Na accumulation within the SiN layer and at the SiN/Si interface region
Fig. 3. combined SEM/EBIC image of a PID cell (a) and a reference (b) showing the disappearance of the EBIC signal (red) at p-n junction of the degraded solar cell. In the insets the respective I-V curves are displayed. The characteristic ohmic behaviour is found at the PID fragment (a)

4. Discussion

A qualitative comparison of LIT, EL, ToF-SIMS and SEM/EBIC data in PID affected regions and non-degraded reference areas show a strong correlation between Na diffusion into the SiNx layer and the electrical properties of the solar cell. In particular, the space charge region at the p-n junction seems to be strongly disturbed by changes of the chemical composition of the SiNx layer. These findings are in agreement with previous studies on MOSFET threshold voltage instabilities caused by Na contaminations of the gate oxide.[8] It is known, that Na⁺ ions are formed an aqueous solution in contact with float glass. Under the influence of electric fields the positive ions drift towards the surface of the solar cells. Depending on the properties of the SiNx layer (density, refraction index) Na⁺ ion may diffuse in the SiNx layer but are stopped at the crystalline Si interface. ToF-SIMS data presented above reveals the enrichment of Na⁺ ions within degraded SiNx layers. Thus, a distribution of positive charges within the SiNx layer (thickness ca. 70 nm) may be assumed. In a similar way PID effects could be activated by deposition of positive corona discharges above the front surface of solar cells.[6,7] With reference to the electrostatic neutrality condition we assume that negative charges are induced at the SiNx/Si interface (Fig. 4). These negative charges may lead to the repulsion of majority charges from the surface in the n-doped emitter. Depending on the surface charge density and the charge carrier density in the emitter an inversion layer is formed. Consequently, band bending occurs in the emitter region and the built-in field gradient at the pn junction disappears. Thus, regions with elevated Na⁺ concentrations in the SiNx layer are affected by extended ohmically shunted regions.

The location of the charges within the atomic structure of the SiNx layer and at the SiNx/Si interface is currently under discussion. A quantitative estimation of the electronic properties at the interface will be subject of a forthcoming publication.
5. Summary

The PID of solar cells in mini modules has been investigated on laboratory scale. The appearance of local shunts has been visualized by EL and LIT on differently prepared solar cells at progressive levels of PID. ToF-SIMS investigations of solar cell fragments from disassembled mini modules on microstructural level show an accumulation of alkali metals within the SiNx layer as well as at the interface to the Si. At the same locations changes of the p-n junction properties are observed by SEM/EBIC. In comparison to not degraded regions the EBIC signal of the p-n junction has disappeared at PID affected regions, confirming their ohmic behavior. In conclusion, a simple band structure model of the solar cell that explains the solar cell shunting induced by the PID effect has been proposed.

Acknowledgement

The authors thank Jan Bauer and Otwin Breitenstein (Max Planck Institute of Microstructure Physics, Halle) for the discussion regarding the proposed degradation model.

Financial support within the BMBF project “FutureFab” (13N11446) is gratefully acknowledged.

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