KINETIC DESCRIPTION AND MODELING OF POTENTIAL INDUCED DEGRADATION

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ABSTRACT: Potential induced degradation (PID) is one of the failure modes in today's photovoltaic (PV)-systems with strong impact on PV-module performance. Potential-induced shunting (PIS) is one of the most severe types of PID leading to shunting of p-type silicon solar cells. Previously, the kinetics of PIS was investigated in detail. It was shown that the temperature dependence of PIS as well as regeneration from PIS is Arrhenius-like, opening the opportunity to develop a kinetic model based on Arrhenius-like expressions. In addition a so called transition-phase was found leading to continued shunting even after the voltage stress has been removed.

In this work the transition-phase is investigated in detail. It is shown that this phase is only present in the PIS-kinetics if previous PIS stress has decreased the shunt resistance $R_{sh,PIS}$ to values below 14 kΩcm^2. It is found that the duration of the transition-phase $t_{transition}$ is temperature dependent and can be described with an Arrhenius-like expression.

Based on these findings a preliminary model for the kinetics of PIS was developed. This model considers temperature, as well as other environmental conditions to describe the progression of PIS for a specific location. By using meteorological data measured at Thalheim (Germany) during the year 2012 we present results modeling PIS behavior over time.

Keywords: Degradation, Module, Reliability, PID

1 INTRODUCTION

In modern photovoltaic (PV)-systems solar cells incorporated in PV modules can be exposed to voltage bias of several hundred volts with respect to the module frames/mounting. This voltage bias can cause various kinds of different module damage, which are commonly called potential-induced degradation (PID) [1]. One of the most severe types of PID is potential-induced shunting (PIS) leading to shunting of p-type silicon solar cells [2]-[3]. The kinetics of PIS was the subject of various previous studies (e.g. [2]-[9]). Recently also regeneration from PIS was investigated in more detail [3], since fielded modules are exposed to alternating conditions for both, shunting and regeneration [4][6][10]. It was found that the temperature dependences of PIS as well as the regeneration from PIS are Arrhenius-like, which opens the opportunity to develop a kinetic model based on Arrhenius-like expressions [3]. It could also be shown that switching off the voltage stress does not lead to an immediate stop of the progression of PIS. A so-called transition phase between PIS progression and regeneration from PIS was found to be present.

In this work the kinetics of the transition phase is investigated in detail, which is essential in order to develop an appropriate kinetic model. Combining the descriptions of the kinetics for shunting, regeneration and transition phase, a simulation of the PIS behavior under field conditions is proposed. First simulation results are presented.

2 EXPERIMENTAL

In this work mini modules consisting of single p-type solar cells were produced to investigate the PIS kinetics. The cells were specially engineered to be prone to PIS.

The modules were shunted by applying a voltage bias of -1 kV to the cell with respect to a grounded aluminum-foil covering the mini module front glass. The experiments were performed in a climate chamber at different temperatures.

The shunting was monitored by measuring the dark current I_d in the linear part of the current-voltage (I-V) curve of the cell. To perform the measurement, the solar cell was biased with a constant voltage $V < 0.3$V. From these measurements the R_{sh}-value was calculated. Separation of the initial cell-shunt from this measured shunt resulted in the shunt value related to the voltage stress, which was used as a measure for the degree of PIS. In the following this value will be referred to as $R_{sh,\ PIS}$. The experimental setup and the calculations used to monitor the PIS kinetics are described in detail in [3].

The transition phase investigated in this work starts when the voltage stress is switched off after a degradation phase and is characterized by ongoing shunting although the stress is switched off. The duration of the transition phase $t_{transition}$ is defined by the time the $R_{sh,\ PIS}$ needs to regain the value measured at the voltage-bias stop ($R_{sh,\ vbs}$). The second value used to describe the transition phase is the minimum of the $R_{sh,\ PIS}$ -value ($R_{sh,\ min}$), which is considered relative to $R_{sh,\ vbs}$ ($R_{sh,\ min} / R_{sh,\ vbs}$). In Fig. 1 $t_{transition}$ and $R_{sh,\ min}$ are shown.

3 RESULTS AND DISCUSSION

3.1 Analysis of the transition phase

In Fig. 1 $R_{sh,PIS}$ measurements of two mini-modules at 90 °C are presented. The shunting phase (A), the transition phase (B) and the regeneration phase (C) are colored yellow, blue and green, respectively. The two measurements shown in Fig. 1 differ in the value of $R_{sh,vbs}$. The shunting of the modules was stopped at $R_{sh,vbs}$ = 16.5 kΩcm^2 and at $R_{sh,vbs}$ = 9.5 kΩcm^2, respectively. A transition phase only occurred for the second module with $R_{sh,vbs}$ = 9.5 kΩcm^2. Two different regeneration processes can be distinguished from this.

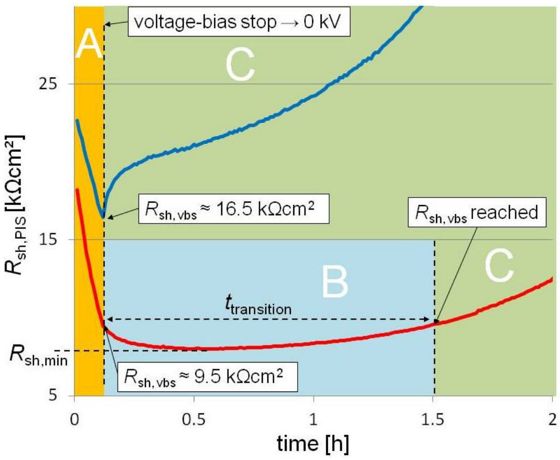

Fig. 1: $R_{sh,PIS}$ measurements of two mini-modules, with (red) and without (dark blue) transition phase. The shunting phase (A), transition phase (B) and regeneration phase (C) are shown using different colors.

In the following the $R_{sh,vbs}$-value dependence of the transition phase was investigated in more detail. In Fig. 2 the duration of the transition phase $t_{transition}$ and the relative minimum $R_{sh,min}$ / $R_{sh,vbs}$ measured for various mini modules at 90 °C are plotted versus $R_{sh,vbs}$. It was found that only mini modules for which the previous shunting period had decreased the R_{sh}-value below a specific value show a transition phase. For $R_{sh,vbs}$ > 14 kΩcm^2 no transition phase was observed. Furthermore the measurements for $R_{sh,vbs}$ < 14 kΩcm^2 indicate that both values $t_{transition}$ and $R_{sh,min}$ / $R_{sh,vbs}$ are not correlated with the actual $R_{sh,vbs}$ value.

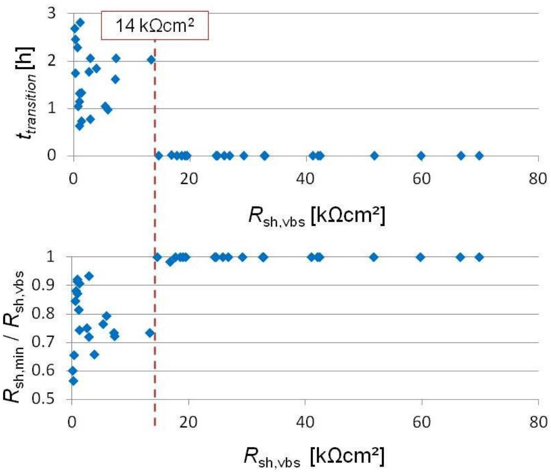

Fig. 2: Measurement of $t_{transition}$ and $R_{sh,min}$ / $R_{sh,vbs}$ of various mini modules plotted versus $R_{sh,vbs}$.

In order to investigate the temperature dependence of the transition-phase duration, $t_{transition}$ was measured at 90°C, 80°C, 70°C and 49°C. For every temperature four mini modules were measured, respectively. Figure 3 shows an Arrhenius plot of the measured data. The linear alignment of the data reveals a temperature dependence of $t_{transition}$ which can be described by an Arrhenius-like expression. The straight line represents the best fit to the data and corresponds to an activation energy E_a of approximately 0.7 eV.

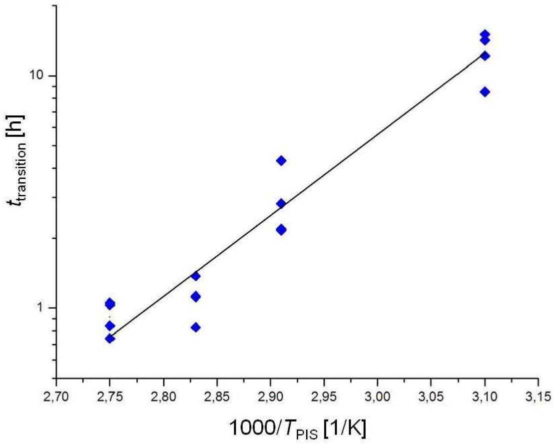

Fig. 3: Arrhenius plot of $t_{transition}$.

In addition to $t_{transition}$ also the temperature dependence of $R_{sh,min}$ / $R_{sh,vbs}$ was investigated. In Fig. 4 $R_{sh,min}$ / $R_{sh,vbs}$ of mini modules measured at 90°C, 80°C, 70°C and 49°C are shown. The collected data indicate no pronounced temperature dependence for $R_{sh,min}$ / $R_{sh,vbs}$. The measured ratios cluster around 0.85 for all temperatures.

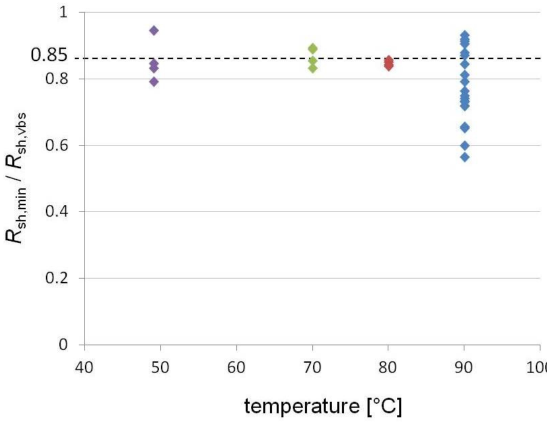

Fig. 4: $R_{sh,min}$ / $R_{sh,vbs}$ measured at different temperatures.

3.2 Kinetic model for PIS

Based on the temperature dependence and $R_{sh,PIS}$ progression found for the shunting- and regeneration phase [3] combined with the findings concerning the transition phase described in this work, a preliminary model simulating the PIS kinetics in outdoor installations was developed.

Meteorological data was used to define the temporal development of the parameters relevant for PIS. The deviation of module temperature from air temperature was calculated using measured solar irradiation. Additionally, the voltage stress was assumed to scale logarithmically with irradiation level. Relative humidities in the vicinity of the module were calculated from measured relative humidities of the air and the calculated module temperatures.

The result was used to decide whether a conducting moisture film is present on the module's surface using a threshold relative-humidity as a parameter. As long as the relative humidity of the module was above this threshold at daytime, the module was considered to be in shunting phase A. Rain events at daytime also triggered the phase A. If none of these two conditions was detected, the module was considered to be in transition phase B or regeneration phase C depending on the time after the last shunting event and the final $R_{sh,PIS}$ value calculated for the end of this shunting event.

Depending on the assigned PIS phase the appropriate kinetic data were used to calculate the temporal evolution of $R_{sh,PIS}$.

In order to test the model, cells with different PIS-resistance levels were investigated. The measurements presented in section 3.1 are related to cells with a medium PIS-resistance level (cell-type B). In addition also cells with a low resistance level were investigated (cell-type A). Two parameter sets were found representing the PIS-kinetics of the three phases A-C for the two cell-types. In Fig. 5 simulation results for these two parameter-sets are presented. Both simulations use meteorological data measured during the year 2012 in Thalheim, Germany, and assume a voltage stress of -1 kV with respect to the module frame at an irradiation level of 1 kW/m². The simulation for cell-type A shows a fast decrease of the shunt resistance indicating a major performance-loss occurring already after a short time (several days). Although regeneration is able to recover the $R_{sh,PIS}$-value temporarily in warm and dry summer days, an overall degradation is observed leading to very low $R_{sh,PIS}$-values. The simulation employing the parameter-set determined for cell-type B also predicts a decrease of the shunt resistance but $R_{sh,PIS}$ is found to remain > 250 kΩcm^2 throughout the whole year. Since the shunt resistance starts to affect the cell performance significantly only for $R_{sh,PIS}$ < 2 kΩcm^2 [3], the values reached for cell type B would not lead to a performance-loss of the module .

A detailed description of the PIS-kinetic model and simulation results will be published soon.

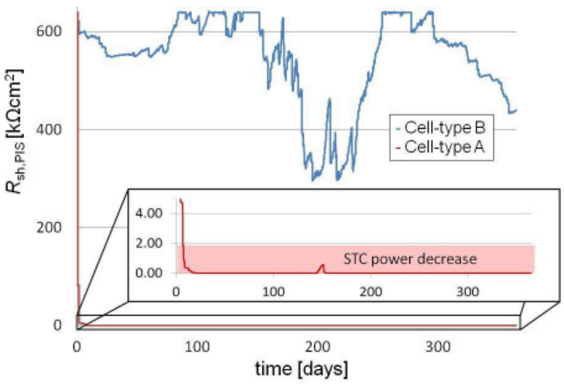

Fig. 5: Simulated PIS-kinetics based on meteorological data of 2012 for Thalheim (Germany) for two different cell-types.

4 SUMMARY

In this work the kinetics of the PIS transition phase, which can occur after stopping the voltage stress and before regeneration starts, was investigated in detail. It was found that the transition phase is only present in the PIS-kinetics if the cell has degraded to $R_{sh,PIS}$-value below 14 kΩcm^2 at the voltage-bias stop of the previous shunting ($R_{sh,vbs}$). In addition it was shown that the duration of the transition phase $t_{transition}$ is temperature dependent and can be described with an Arrhenius-like expression. In contrast to this the relative minimum of the transition phase $R_{sh,min}$ / $R_{sh,vbs}$ was neither dependent on $R_{sh,vbs}$ nor on temperature.

Based on the findings concerning the PIS-kinetics a preliminary model was developed. This model considers temperature, as well as shunting- and regeneration-conditions for PIS. By using meteorological data measured at Thalheim, Germany, in 2012, the temporal evolution of PIS during this time period was simulated. The simulation-results for two mini-module types consisting of cells with different PIS-resistance levels showed strong differences in the progression of PIS.

5 ACKNOWLEDGEMENT

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