VOLTAGE AND TIME DEPENDENCE OF THE POTENTIAL INDUCED DEGRADATION EFFECT FOR DIFFERENT TYPES OF SOLAR MODULES

By

Wael Fareed Fouad Mohamed

A Thesis Submitted to the Faculty of Engineering at Cairo University and Kassel University In Partial Fulfillment of the Requirements for the Degree of Master of Science In RENEWABLE ENERGY AND ENERGY EFFICIENCY

Kassel University, Kassel, Germany

Faculty of Engineering, Cairo University, Giza, Egypt

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Under the Supervision of

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Approved by the
Examining Committee

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Prof. Dr. Sayed Kaseb (Internal Examiner)
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Declaration

I, Wael Fareed do hereby declare, that the work presented here is, to the best of my knowledge and belief, original and the result of my own investigations, except as acknowledged, and has not been submitted, either in part or whole, for a degree at this or any other university. Formulations and ideas taken from other sources are cited as such. This work has not been published yet.

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Title of Thesis:

Voltage and time dependence of the potential induced degradation effect for different types of solar modules

Key Words:

PV Modules, Potential Induced Degradation, High Voltage, Leakage Current

Summary:

Since the generation of solar energy is increasing and getting important worldwide, PV systems is becoming bigger with increasing the amount of serially interconnected panels. These panels are exposed to high potential relative to the ground which causing high voltage stresses (HVS). This HVS causing instability of the solar panels depending on some factors which cause an unwanted property called potential induced degradation (PID). The factors which effect on the PID are (Voltage, humidity and high temp) which generate leakage current between the solar cells and the ground. The key is to understand the PID phenomenon and the leakage current property which still not understandable.
ACKNOWLEDGEMENTS

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DEDICATION

To my Family
To my beloved country Egypt
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ARC</td>
<td>Anti reflection Coating</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium Telluride</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DHT</td>
<td>Damping Heat Test</td>
</tr>
<tr>
<td>EL</td>
<td>Electroluminescence</td>
</tr>
<tr>
<td>EVA</td>
<td>Ethylene Vinyl Acetate</td>
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<tr>
<td>FF</td>
<td>Fill Factor</td>
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<tr>
<td>HVST</td>
<td>High Voltage Stress Test</td>
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<tr>
<td>$I_{sc}$</td>
<td>Short Circuit Current</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>MLT</td>
<td>Mechanical Load Test</td>
</tr>
<tr>
<td>PID</td>
<td>Potential Induced Degradation</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>RI</td>
<td>Refractive Index</td>
</tr>
<tr>
<td>$R_{sh}$</td>
<td>Shunt Resistance</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Series Resistance</td>
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<tr>
<td>Si</td>
<td>Crystalline Silicon</td>
</tr>
<tr>
<td>SiNx</td>
<td>Silicon Nitride</td>
</tr>
<tr>
<td>TCT</td>
<td>Thermal Cycling Test</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>Open Circuit Voltage</td>
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The reliability of solar modules is an important factor to guarantee continuing growth of the photovoltaic (PV) industry. Using the standard qualification tests for PV modules is not sufficient to detect all possible phenomena. One such phenomenon is the so-called Potential induced degradation (PID) of solar modules, which occurs when the module frame is positively biased. This effect has recently been discovered in solar power plants, where the system voltage can be up to 1000 V, building a potential between frame and solar cells. The voltage increases linearly along a string of modules in series and can be positive or negative, depending on the position of the grounding along the module string. Because of the practical importance, the investigation of the PID has attracted huge interest since its first discovery. Although many details have been found out, the physical basis of the effect is not completely clear yet. The current understanding is, that under the influence of the applied voltage alkaline ions (Na⁺ or others) from the cover glass of the module are driven through the module towards the solar cells, where they accumulate at the top surface, the anti-reflection layer. There exist several models, how this additional charge can affect the cell performance, but none is sufficiently established. Although some solar cell manufacturers have found ways to make cells PID resistant, it is not sure, how effective the measures are over many years, since the origin is not clear yet. The PID effect can be intensified if higher voltages are applied. Fraunhofer THM has built a test set-up, where voltages up to 20 kV can be applied to an entire module and the leakage currents can be measured. One can vary the leakage current by changing the ion transport properties of the glass by using a special treated glass, for example.

It is however not clear at present how the leakage current is related to the generation of Na⁺ ions from the glass, which is hypothetical to be the starting point of the degradation effect.
The goal of the work is to understand the origin and transport paths of Na$^+$ ions in the modules. This project involved to investigate the PID effect with time dependent measurements, carried out under various test conditions, such as high voltages, and different glasses and so on. The PID investigation will be carried out by using different types of silicon solar modules, i.e. new standard silicon modules. As well as previously stressed modules. In addition, special mini-modules using varying glass materials have been investigated. Furthermore, the susceptibility of CdTe modules for PID was tested. The performance of the modules before and after the high voltage tests is characterized by current-voltage measurements and electroluminescence.
Chapter 1 Introduction

1.1 Background

Due to the increased demand for renewable energy sources, the manufacturing of solar cells and photovoltaic arrays has advanced considerably in recent years. Photovoltaic (PV) is considered to be one of the most committed source of renewable energy technologies after hydro and wind power. PV is one method to generate electrical power by converting the solar radiation into DC voltage by using semiconductors that exercise the photovoltaic effect by using solar panels which composed of number of solar cells containing photovoltaic materials, for example mono-crystalline, poly-crystalline and amorphous silicon as well as cadmium telluride (CdTe) and copper indium gallium selenite/sulfide (CIGS). Till now, nearly 100 countries use photovoltaic as a main source of renewable energy, done by various ways of installation, e.g. on the roof top or walls of buildings or as a power plant string arrays. [1]

1.1.1 Solar Cells

The main target of solar cells is to convert the solar radiation energy into a flow of electrons and produce DC voltage which can be used directly as a power or charge for batteries. Nowadays most photovoltaic modules are used for grid connected power generation by converting the DC into AC using converters. [1] The six steps process of producing solar cells is shown in details in figure 1.1.

Figure 1.1: The traditional screen-printed silicon solar cell manufacturing process which consists of six steps. Images courtesy of Newport Corp. /Spectra-Physics. [2]
Step 1: Damage and Texture by acid
Step 2: Doping and Diffusion process.
Step 3: Glass layer removal.
Step 4: Deposition of an antireflection thin-film coating of silicon nitride (SiNx)
Step 5: Screen printing of the back and front surface contacts.
Step 6: Metallization and co-firing process. [2]

After solar cells manufacturing, they are assembled together to form solar modules in order to be protected from the harshness of the environment.

1.1.2 Silicon solar modules

Solar modules consist of several solar cells, which are connected in series and parallel strings and sandwiched together as shown in Figure 1.2.

A silicon solar cell produces about 0.6V at standard conditions. For example, a module containing 36 cells may produce enough voltage to charge a 12Volt battery. The cells are placed between a front glass and a back surface within a frame and sealed, as shown in Figure 1.2. [3]

![Figure 1.2: Crystalline photovoltaic module assembly. [3]](image)

1.1.3 Cadmium telluride (CdTe) solar modules

Cadmium telluride is another of several industrially used photovoltaic materials. [4] To build CdTe solar modules, amorphous CdTe is deposited on glass. Cadmium telluride offers some advantages over the crystalline silicon (Si), since it can be produced as very thin layers, as shown in Figure 1.3. CdTe also offers higher efficiency at high temperature and at low levels of sun irradiance. CdTe PV has the potential to consume less energy in production than silicon modules.
Both of Cadmium (Cd) and Tellurium (Te) are products from copper, gold and zinc mining. The negative side of cadmium telluride (CdTe) concerns environmental issues. Some environmental groups expressed their worry about the existence of Cd element on the cells. Elementary Cd it is a heavy toxic metal (similar to lead and mercury). However, because CdTe has high ionization energy of 5.9 eV and will, for example, not evaporate in fire and release elemental Cd.

CdTe technologies could in future be a better choice for producing electricity as an alternative energy if it could be produced at significant lower costs. Also it may be deposited on glass or stainless steel film, and it is considered a cheap material. [5]

1.2 Potential Induced Degradation (PID) effect

About 5 years ago a new phenomenon was observed in solar modules, which are connected in strings in a solar power plant. This effect has recently been discovered in solar power plants, where the system voltage can be up to 1000 V. Depending on the potential a degradation effect of the module power can occur after a certain period of time. This so-called potential induced degradation (PID) only occurs when the frame is positively biased. The exposure of the solar modules to the hard environment conditions such as high temperature and humidity accelerates the power degradation. [6]

1.3 Study Objective

The objective of the study is to investigate the potential induced degradation problem on different types of solar modules and for varying times and voltages.
1.4 Study Scope

Different kinds of solar modules (mini silicon module (one cell), CdTe modules and 60 cells silicon modules) were investigated. The following performance measurements were carried out:

- Leakage current measurements under various conditions and for different module types (mini silicon module, CdTe modules and 60 cells silicon modules).
- Characterization of the tested different module types.
- Taking a closer look at the PID effect on the panel level by using electroluminescence photo.
- Analyses of the experimental data to obtain the PID effect on the different module types.
Chapter 2 Literature review

2.1 Introduction

The dependence on solar energy for electricity generation has increased worldwide. In PV systems and solar parks, solar modules are serially interconnected. The solar panels experience a high potential towards the ground (High Voltage Stress - HVS). This additional stress could lead to a higher rate of degradation on the solar module power in the long term. It has been found that a leakage current between the cell itself and the ground is responsible for the so-called potential induced degradation (PID). HVS could have a great effect on long term stability of the solar module for large leakage currents between the solar cells and the ground as has been found by NREL in 2005[7]. This kind of degradation mechanism is not monitored by using the typical PV qualification tests (IEC61215). [8]

2.2 What is the PID?

Potential Induced Degradation (PID) is a relatively new phenomenon appearing in solar modules that leads to a loss in the module performance. The potential induced degradation (PID) only occurs when the frame is positively biased. This effect has recently been discovered [9-12].

The PV string array in a power plant is exposed to an external potential which depends on the grounding scheme of the PV system. This external potential is between the inside cells and the frame which is grounded (for safety). The electrical voltage drives charges from the PV materials and directly discharges with different paths into the Al frame which causes a small amount of leakage current [13-15].

The external potential can be up to 1000 V high. Since the voltage increases linearly along a string of modules in series and can be positive or negative depending on the position of the grounding along the module string as shown in figure 2.1, only those modules are affected where the frame potential is positive. Although many details have been found out, the physical origin of the effect is not completely clear yet. The factors which influence the occurrence of the PID will be discussed in the next section.
2.3 PID impacts parameters

The affecting parameters can be classified upon previous researches into three categories as shown in table 2.1[15]. There is a possibility not to let PID to occur by controlling the system, module and cell factors. [16]

Table 2-1: Classification of the affecting parameters on PID effect [15].

<table>
<thead>
<tr>
<th>Influencing test parameters</th>
<th>Influencing on cell level</th>
<th>Influencing on module level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>AR-Coating</td>
<td>EVA encapsulation</td>
</tr>
<tr>
<td>Temperature</td>
<td>Emitter depth</td>
<td>Glass Front sheet</td>
</tr>
<tr>
<td>Humidity</td>
<td>Type of base doping</td>
<td>Back sheet</td>
</tr>
<tr>
<td>Ground</td>
<td></td>
<td>Module design</td>
</tr>
</tbody>
</table>
2.3.1 Environmental parameters

It has been found, that both temperature and relative humidity could have negative effects on a PV power plant performance. There are different kinds of tests set (for example, damping heat test (DHT), temperature cycling (TCT)) to detect the influence of temperature and humidity on module reliability furthermore, the degradation due to high potential (PID) is influenced by temperature and humidity. [17, 18]

2.3.2 System parameters

At the system level, the most important parameters are the potential applied on the modules and its sign which depends on the module position on the string array and the system grounding. The U.S. has started its research to understand the influence of higher voltages on PID. It adopted the PV string array to 1000V and more and it found at positive frame potential of 1500V or more new failure mechanisms. [19] PID is mostly affected by negative potential relative to the ground. Also, the issue of the positive to ground has been documented by sun power. [10]

2.3.3 Module materials:

It has been found that the module materials influence the magnitude of the PID effect. The main materials are [11, 16, 20, and 21]:

- EVA (Ethylene Vinyl Acetate)
- Front glass sheet
- Back sheet
- Module design

2.3.4 Cell parameters:

The use of an Anti-Reflection Coating layer (ARC) increases the cell efficiency by collecting most of the incident light on the surface. A lot of researches has been conducted on the ARC and it has been found that the ARC has a great effect on the PID effect as reported before [9, 11]. Recently, it has been found that the sodium ions (Na+) migrate from the front glass sheet and impact on the cell surface. [16, 22]
2.4 Investigation on the leakage current

There is a voltage bias of any string array system of PV module with respect to their frame. Since the insulation between the module frame and the active layer is finite, this bias results in a small but not negligible leakage current (nA-µA). [14]

2.4.1 Leakage current paths

There was a study conducted by NREL about the different leakage current pathways inside the module [14].

Figure 2.2 shows the cross section of one of the thin film modules and it is analyzed as:

I₁- Leakage current conducting through the top glass layer and along the glass surface.
I₂- Leakage current conducting through interfaces (EVA).
I₃- Leakage current through module packaging materials Ethylene Vinyl Acetate (EVA).
I₄- Leakage current through the back sheet.

Figure 2.2: Leakage current paths I₁, I₂, I₃, I₄ through a typical thin film PV module. [14]
NREL studies showed that the most of all leakage currents are influenced by ambient conditions under the high voltage stress. [23]. In figure 2.3 it is shown, that the leakage current is highly influenced by the relative humidity (red color).

The described path I₁ in figure 2.2 is the main current pathway influenced by relative humidity (RH).

![Image of a graph showing leakage currents at different polarities (+), (-) 600VDC for c-Si modules against inverse absolute module temperature, in three bands of relative humidity values, 10%, 50%, and 95%.]

**Figure 2.3:** Leakage currents at different polarities (+), (-) 600VDC for c-Si modules against inverse absolute module temperature, in three bands of relative humidity values, 10%, 50%, and 95%. [23]

### 2.4.2 Recommendation for module level

It has been found that to decrease or avoid PID effect [11], suitable materials, for example alternative EVA layer for encapsulation, should be selected or redesigning the solar panels to ensure low leakage currents. Some factors should be taken into consideration when choosing new materials to avoid PID such as:

- material prices,
- long term stability and
- handling.
2.5 PID Testing

It is very important to conduct a test on large scale PV power plant to detect the PID problem that is useful in calculating the finance. Also, testing determines which mechanism effects on PID occur in order to avoid it, and which conditions are used for testing. There are some organizations that offer testing for PID with different levels (module level test, string level test and system level test).

2.5.1 Why doing PID tests

The aim of doing the tests is to focus on how to produce PV with low economic cost and with the technology improvements in both cell and panel levels, and also to enhance the cell efficiency and overcome the PID effect. So, there is an important approach to reduce the cost and increase the lifetime of the modules by enhancing the reliability of PV modules. The main target is to identify the failure modes and mechanisms to estimate the lifetime of PV modules by using bathtub curve as shown in figure 2.4. This is done in the first few years of field operation, and also represented the decreasing failures components, identified the failures beyond qualification testing and addressed the performance loss due to degradation modes.

Figure 2.4: Photovoltaic reliability illustrated and explained using bathtub curve.[24]
2.6 Degradation under high voltage stress

There are a lot of investigations on the potential induced degradation of different cell technologies (p-type, n-type and thin film). Most of the tests done before were using p-type cells under application of high voltage stress at 1000V. Maximum conductivity of the glass surface was obtained by covering the front glass with aluminum or copper foils or by continuous water films over the front glass. There are a lot of benefits from using high voltage stress test on a single solar module simulating the potential which can occur in the PV string, which are [11]:

- Faster detection of the long term effect on an established PV string arrays.
- Investigate the leakage currents between the PV cells and ground (cell to frame).
- Investigate the electrochemical corrosion effects.

A lot of investigations were conducted and a lot to understand all the possible factors which impacting the PID effect. All tests were done at different levels (cell level, module level and system level).

The cells or modules were evaluated mainly by two standard measurements:

- Characterization of the cells before and after the PID test by measuring the (I-V) curve.
- Capture high quality Electroluminescence (EL) before and after the PID test to detect the infected cells which will take black colors.

2.7 Cell level test

The main purpose of the cell level test is to investigate different cell materials which may contribute to the PID, e.g. the anti-reflection coating layer (ARC). Single cells were tested in mini modules. Typical results are shown in figure 2.5 for a module tested for 100 hours under high negative potential stress of 1000V [11].
Figure 2.5: Showing the I-V curve before and after PID test (left) and its percentage over time (right). [11]

Another investigation on the cell level is to investigate different ARC layers in order to find which layer reduces or prevents PID. The investigation is based on different kinds of mini modules which contain one cell. The voltages of 50-200 V are applied by covering a copper foil sheet over the front glass surface as one pole and the other pole the cells contacts. It has been found, that ARC layer has a great effect on the PID. Mostly ARC layers are consisting of SiNx which is applied on the cell by using different deposition methods such as chemical vapor deposition. SiNx results in a certain thickness and refractive index (RI). By using suitable combinations between RI and thickness PID can be completely prevented on the cell level as shown in figure 2.6 [11]. The figure shows a PID comparison between three different cells with the same material but with different coating on the layer.

Figure 2.6: Comparison between different ARC- RI and thickness against the PID. [11]
2.7.1 Corona charging of mini modules

This test was used to deposit charges on the surface of mini modules which induce a voltage directly between glass surface and cell. The test setup as shown in figure 2.7, is under high applied volt (-11kV) and kept at room temperature (25ºC) for 24 hours [26].

![Corona discharge test setup](image)

Figure 2.7: Corona discharge test setup. [26].

After 24 hours current - voltage (I-V) curves were recorded to calculate both series resistance $R_s$ and shunt resistance $R_{sh}$ which is the inverse slope of the I-V curve. A low shunt resistance indicates a high PID susceptibility. Figure 2.8 shows that there is reduction in $R_{sh}$ depending on the corona charge.

![Shunt resistance over time intervals](image)

Figure 2.8: Shunt resistance over time intervals after corona discharge test. [26].
2.7.2 Corona charging with 1-cell without encapsulation

Corona charging without encapsulation was performed to detect the influence of the encapsulation layer on PID. A special sample without encapsulation and a reduced front metallization was tested (figure 2.9(left)). After a 4 hours test, it has been found that the same degradation occurs as in mini modules see figure 2.9 (right)[27].

Figure 2.9: Special cell without encapsulation (left) Light intensity-V_{oc} curve after a 4 hours test (right). [27].

2.8. Module level test

The aim of the module level test is to prevent or reduce the PID effect. There are a lot of investigations on the module level with different test conditions. A standard PID test uses 1kV and (85° C/ 85% RH) by using a closed chamber to obtain the required RH value. This test was done for a standard silicon module (60 p-type cells). The results of the electroluminescence measurements are shown in figure 2.10 [15]. It was found that the cells after the PID test showed a high degradation (black color).
The time dependence of the power loss is shown in figure 2.11. It begins after 10 hours and reaches up to 20% losses after 38 hours of test.

Figure 2.11: Power losses percentage relative to its initial state after different time intervals. [15].
The effect of applying different voltage at the same conditions of (85º C/ 85% RH) is shown in figure 2.12. This test is done by using standard 60 cell silicon module and applied under different voltages ranging from 100V to -1500V. At lower (100V) applied voltage a lower degradation was found than at higher applied voltage (1500V).

![Figure 2.12: Damping heat test with increasing the applied voltage. [15].](image)

Another test has been conducted to see the influence of different temperatures on PID. Two experiments were set with fixed conditions (85%RH, 48 hours,-1000KV, frame grounding) and only the temperature was changed to be 25ºC in one test and 85ºC in another. After the tests it was clear that at high temperatures a rapid PID effect occurs more than at lower temperatures, as shown in figure 2.13.[17].

![Figure 2.13: Comparison between two modules was tested under different temperatures: (a) at 25ºC, (b) at 85ºC. [17](image)
Investigations conducted with a number of modules under 60ºC, 85%RH over 96 hours were compared with another test, the water film method [21]. In the water film method the PV modules are installed horizontally to expose the upward surface directly to an air conditioned room at temperature 25ºC. The front surface is covered with a water film, which again is covered with a plastic foil to reduce water evaporation. The chamber method and the water film method are compared regarding their PID sensitivity. It has been found that water film method does not always give the same results compared to the chamber method. Sometimes modules showed less degradation in water film method compared to the chamber method as shown in figure 2.14 [25].

![Figure 2.14: Normalized power after the test for some modules names (A-O). [25]](image)

### 2.9 Influence of grounding situation

Different grounding situations and their influence on the PID effect were tested in reference [28]. In the first test frame grounded field modules were investigated. The results in figure 2.15 show that only cells in the lower row were affected by PID. This was compared with frame grounded test modules in the laboratory. They showed that the affected cells were also near to the frames. In the third tests the full module surface was grounded. The EL measurements showed that affected cells were distributed randomly.
2.10 PID on system level

As mentioned before as it has been found in any string array that the effect of PID occurs due to the high voltage of the solar system. It depends on the type of grounding of the frame which determines the potential between cell and frame of a module in a string [15].

Figure 2.16 shows 20 modules connected in string array. 10 modules are exposed to a positive voltage potential (between cell and frame) and 10 modules to negative voltage potential. It has been found that the most affected p-type solar modules in the above string array are the 10 modules which exposed to the negative potential voltage as shown in figure 2.17[15].
It has been found that the best way to prevent from PID effect is to avoid the negative potential relative to ground for the p-type standard cells. This could be done by using special inverters using transformers. Since the last few years mainly inverters without transformers were used, this resulted in free floating grounding and a higher risk of PID.

Furthermore, it is possible to recover the affected modules by applying high positive voltage stress, as shown in figure 2.18, and taking into inconsideration the following parameters:

- Time.
- Voltage.
- Humidity.
Chapter 3 Methodology

3.1 Introduction

A potential induced degradation test was developed using high external voltage between the solar cells and the module aluminum frame with negative or positive sign. This kind of tests called high voltage stress test (HVST) will be used in the experimental method.

This chapter describes the applied methods for potential induced degradation under HVST. A pre and post I-V characterization under illumination was done for all photovoltaic modules. Electroluminescence imaging was used to detect defect cells after the high voltage test. Leakage current measurements were performed during high voltage exposure. All these test setups and measurements will be described sequentially. The work flowchart for investigating the PID problem on different kind of solar modules is shown in figure 3.1. All tests were carried out at the Fraunhofer Technology Center for Semiconductor Materials (THM) in Freiberg, Germany.

3.2 Project definition

The PID effect can be intensified if higher voltages are applied [28]. At Fraunhofer THM a test setup was built, where voltages up to 20 kV can be applied to an entire module and the leakage currents be measured. One can influence the leakage current by changing the resistance of the glass surface. For a given module, higher leakage currents lead to faster degradation. It is however not clear at present how the leakage current is related to the generation and drift of alkaline ions from the glass, which is supposed to be the starting point of the degradation effect. The goal of the work is to contribute to the understanding of the origin and transport paths of alkaline ions in the modules. All tested modules used in this project are certified and passed qualifications tests. This project is divided into three phases as shown in table 3.1. The first phase, called mini module phase comprised the testing of four mini modules: 2 with reference glass/back sheet, 1 with reference glass and back glass sheet and 1 module with special front glass/back sheet. The second phase, called the silicon module phase contained 4 standard solar modules with 60 cells, divided into: 2 new unstressed modules and 2 stressed modules (1 tested before with damping heat test (DHT) and the other one tested with thermal cycling test (TCT)). Furthermore, two unstressed modules were tested. In the third phase, which is called CdTe phase, 2 CdTe modules were tested.
3.3 Test procedures

- I-V characterization pre applying the high voltage under illumination was done for all photovoltaic modules.
- High voltage stress test and leakage current measurements were performed during high voltage exposure
- I-V characterization post the (HVST)
- Electroluminescence imaging was used to detect defect cells after the high voltage test.

Table 3-1: The three phases project test sequence

<table>
<thead>
<tr>
<th>Project Phases</th>
<th>Test sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase #1 Mini modules</td>
<td>Flasher test Pre (I-V) characterization</td>
</tr>
<tr>
<td>Phase #2 60 cells modules</td>
<td>Flasher test Pre (I-V) characterization and EL</td>
</tr>
<tr>
<td>Phase #3 CdTe</td>
<td>Flasher test Pre (I-V) characterization</td>
</tr>
</tbody>
</table>
Figure 3.1: Flowchart showing the project workflow sequence with the different stages.
3.4 Test equipment

To investigate the PID problem, time and voltage dependent measurements were carried out under various test conditions, such as varying voltages, different surface resistances, different glasses etc.

3.4.1 Solar Simulation test

The solar simulation test with flash light is optimized for solar modules in order to analyze the I-V characteristics under illumination. It is the first test to check the module performance at standard test conditions STC. The solar simulator can produce different flash intensities from 100 up to 1000W/m² on the test area. The time between successive measurements is 60 seconds. Figure 3.2 shows the solar simulator device.

![Solar Simulator Device](image)

**Figure 3.2: Devices used for I-V curve measurement** (a) solar simulator device. [29], (b) Load and measurements device.

In figure 3.2 (b) 3 load sets for different module types are shown. Mini modules with a single cell, for instance require a smaller voltage range compared to standard modules. Figure 3.3 shows the screen shot from the flasher PC after measure. The load to the module during the measurement is completely negative, and its standard measurements range is 1/5/10/15/30/60/90/120 V and 6/8/18 A.
Figure 3.3: Solar simulator screenshot showing both I-V and P-V curves (left side) and the module performance data (right side).

3.4.2 High voltage PID tester

As mentioned before, the PID effect can be intensified if higher voltages are applied between the cells itself and the front glass side of the module which is connected to the frame. The applied voltage can be up to 20kV with both negative and positive sign. The high voltage generator also allows measuring the leakage current from the range of (1nA up to 200 µA or more). The modules are placed inside a high voltage chamber which ensures high voltage safety standards as shown in figure 3.4. All the tests were done on modules with completely covered front glass by an aluminum foil to increase the conductivity, the chamber ambient temperature of 23±5°C, and relative humidity of45±5%.
It is very important to analyze the voltage and time dependency of the leakage current in detail for different solar module types. This investigation is helpful to understand more about the charging and discharging behavior of the solar modules under high voltage stress. In figure 3.5, a screen shoot from the controlling software is shown. The test conditions inside the isolated chamber (temperature and humidity) are recorded during the entire high voltage test. The leakage current is recorded by the software as well and it can be imported by word file which contains the time, the current temperature, the humidity, and leakage current.
Figure 3.5: Screenshot from high voltage test software to detect the leakage current at different intervals of time.

After every high voltage test the module performance was checked again with the solar simulator and compared with the data measured before the test.

3.4.3 Electroluminescence (EL) imaging test

The electroluminescence imaging allows detecting defects in solar cells, which reduce the performance in a relatively short time. Defective regions appear as dark (black) areas, referring to a poor contact or shunted cell areas, for example. The principle of the electroluminescence imaging is the following. The applied current enters the cells during the test and causes light emission in the near infrared range. The light emission is caused by radiative band to band recombination of carriers. Nonradiative recombination processes at defects reduce the band to band recombination and can thus be detected as dark areas. The radiation is recorded by a charge coupling device (CCD)-camera.

Electroluminescence images are helpful to discover defects in the cells of the modules such as micro cracks, finger defects, shunting and recombination defects. The method can therefore be used to show degradation due to PID. Electroluminescence imaging was done by connecting the module poles with 45V and a current of 8 A for higher intensity and for lower by reducing the pass current to be 2 A. The module are
put horizontally under two CCD- cameras with high resolution to obtain a merged module image as shown in figure 3.6.

Figure 3.6: Electroluminescence test machine. [30]

3.5 Tested modules description

Three different types of solar modules (mini modules, standard solar modules and CdTe) have been investigated. The characteristics are described in the following:
<table>
<thead>
<tr>
<th>Module name</th>
<th>Module type</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>One cell</td>
<td>One cell encapsulated with a conventional reference front glass and back sheet.</td>
</tr>
<tr>
<td>M2</td>
<td>One cell</td>
<td>One cell encapsulated with a conventional reference front glass and back sheet.</td>
</tr>
<tr>
<td>M3</td>
<td>One cell</td>
<td>One cell encapsulated with a conventional reference front and back glass.</td>
</tr>
<tr>
<td>M4</td>
<td>One cell</td>
<td>One cell encapsulated with a conventional, special front glass (modified to reduce the sodium ions) and normal back sheet.</td>
</tr>
<tr>
<td>M5</td>
<td>60 cells</td>
<td>One new and unstressed 60 cells mono-crystalline module with reference front glass sheet and the ordinary back sheet.</td>
</tr>
<tr>
<td>M6</td>
<td>60 cells</td>
<td>One new and unstressed 60 cells poly-crystalline module with reference front glass sheet and the ordinary back sheet.</td>
</tr>
<tr>
<td>M7</td>
<td>60 cells</td>
<td>One stressed by damping heat test before with 60 cells poly-crystalline solar cells with reference front glass sheet and the ordinary back sheet.</td>
</tr>
<tr>
<td>M8</td>
<td>60 cells</td>
<td>One stressed by thermal cycling test before with 60 cells poly-crystalline solar cells with reference front glass sheet and the ordinary back sheet.</td>
</tr>
<tr>
<td>M9</td>
<td>CdTe</td>
<td>CdTe module fabricated by a German company which have been outdoors for over 1 year.</td>
</tr>
<tr>
<td>M10</td>
<td>CdTe</td>
<td>CdTe module fabricated by a German company which have been outdoors for over 1 year.</td>
</tr>
</tbody>
</table>
3.6 Tested modules photos

3.6.1 Mini modules

Figure 3.7: Photography photo for all the tested mini modules with its symbols.

3.6.2 Standard 60 cells silicon modules

Figure 3.8: Photography for all the 60 cells silicon modules, M5 new mono (a), M6 new poly (b), M7 stressed DHT(c) and M8 stressed TCT (d).
3.6.3 CdTe solar modules

Figure 3.9: Photography of the tested CdTe solar module
Chapter 4 Results

Potential induced degradation (PID) was investigated in laboratory experiments within three phases, using a set of mono and poly crystalline silicon solar modules as well as CdTe solar modules. All modules were covered completely with a thin aluminum foil on the front glass side. The benefits from the covering method are to generate a homogenous electric field to achieve maximum conductivity of the front glass sheet. In all phases a high negative voltage bias was applied between the front glass layer via the covered aluminum foil and the cells. The leakage current was directly measured between the two electrodes. The external applied voltage was varied at a room temperature, while the humidity was set at a fixed value (45% ±5) since the front glass is covered with AL foil, the humidity has no influence on the experiment. The modules characterization was done before and after the high voltage stress test by measuring the I-V curve and electroluminescence (EL) imaging.

4.1 PID test results for mini modules

To study the influence of cell properties on potential induced degradation. Investigations were done in phase #1 were 4 units brought to the Fraunhofer THM institute were used for this study. This part aimed at identifying the relation between the cell and the PID by using 4 different kinds of mini modules (M1, M2, M3 and M4). At this stage the PID relation could not be identified and this will be further explored in phase #2(60 cells silicon modules).

The positive pole of the power supply is connected to an aluminum foil which covers the top glass layer, the negative pole connected to the solar cell surface. High voltage stress was applied between the two poles. The leakage current was measured by the high voltage set-up; the data are saved into a text file after the experiment.

4.1.1 I-V characterization

The characterization was done before and after PID test by using different flash intensities of 100, 200, 500 and 1000 W/m². Using different intensity measurements will be helpful in comparing solar irradiance radiations in different countries. For example, higher intensities correspond more to the Middle East countries, while the lower belong to North Europe countries. The data for the M1 (Reference glass/back sheet) pre and post the high voltage test are shown in table 1(a, b).
Table 4-1(a, b): first mini modules IV parameters (a) before PID (b) after 139 hours of PID.

(a)

<table>
<thead>
<tr>
<th>Flash intensity</th>
<th>$V_{oc}$</th>
<th>$V_{mp}$</th>
<th>FF(%)</th>
<th>eff(%)</th>
<th>$P_m$(W)</th>
<th>$R_{sh}$(Ω)</th>
<th>$R_{d}$(Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100W/m²</td>
<td>0.555</td>
<td>0.452</td>
<td>57.81</td>
<td>11.31</td>
<td>0.275</td>
<td>1.94</td>
<td>0.08</td>
</tr>
<tr>
<td>200W/m²</td>
<td>0.582</td>
<td>0.491</td>
<td>69.71</td>
<td>14.11</td>
<td>0.687</td>
<td>2.65</td>
<td>1.08</td>
</tr>
<tr>
<td>500W/m²</td>
<td>0.555</td>
<td>0.452</td>
<td>57.81</td>
<td>11.31</td>
<td>1.851</td>
<td>2.27</td>
<td>0.02</td>
</tr>
<tr>
<td>1000W/m²</td>
<td>0.633</td>
<td>0.494</td>
<td>71.15</td>
<td>15.45</td>
<td>3.763</td>
<td>1.64</td>
<td>0.01</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Flash intensity</th>
<th>$V_{oc}$</th>
<th>$V_{mp}$</th>
<th>FF(%)</th>
<th>eff(%)</th>
<th>$P_m$(W)</th>
<th>$R_{sh}$(Ω)</th>
<th>$R_{d}$(Ω)</th>
<th>ΔP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100W/m²</td>
<td>0.528</td>
<td>0.387</td>
<td>33.43</td>
<td>6.2</td>
<td>0.15</td>
<td>0.88</td>
<td>0.23</td>
<td>45.45</td>
</tr>
<tr>
<td>200W/m²</td>
<td>0.576</td>
<td>0.387</td>
<td>33.43</td>
<td>6.2</td>
<td>0.543</td>
<td>0.91</td>
<td>0.05</td>
<td>20.96</td>
</tr>
<tr>
<td>500W/m²</td>
<td>0.609</td>
<td>0.478</td>
<td>56.38</td>
<td>11.16</td>
<td>1.671</td>
<td>0.69</td>
<td>0.02</td>
<td>9.72</td>
</tr>
<tr>
<td>1000W/m²</td>
<td>0.633</td>
<td>0.499</td>
<td>68.82</td>
<td>14.8</td>
<td>3.601</td>
<td>0.58</td>
<td>0.01</td>
<td>4.31</td>
</tr>
</tbody>
</table>

After 139 hours of PID test as shown in table (1-b), decreasing open circuit voltage ($V_{oc}$) values reflect that the P-N junction deteriorates. The shunt resistance ($R_{sh}$) and the fill factor (FF) also decreased. $R_{sh}$ calculation was done by getting the inverse of the $V_{oc}$ slope line as shown in figure 4.1. It was also observed that the short circuit current $I_{sc}$ is less affected.
Figure 4.1: First mini module (M1) IV curves at different flash intensities before PID with solid lines and after (-2kv- 139 hours) PID test with dotted lines.

The power losses percentage over time curve were calculated after every PID test and a diagram was plotted for different intensities measurements as shown in figure 4.2.
Figure 4.2: PID corresponding power behavior in time (a) and the PID power losses progress percentage (b).

From figure 4.2 shows for example that the M1 module lost nearly 45% from its original power at 100 W/m² and only 4% at 1000W/m², so the shunting effect of PID is particularly strong at lower light intensities. The difference between measuring at low and high flash intensities is shown in figure 4.3 as a function of the PID test time.
Figure 4.3: IV curves for the M1 mini module after and before the PID test at 100W/m² (top) and 1000W/m² (bottom)

The same steps of investigations were repeated on another mini module M2 fabricated with the same materials (reference glass and ordinary back sheet) but a different solar cell. The PID tested time in this case was only 69 hours. After every test step it was noticed, that this module did not show any kind of power degradation and had a good PID resistance.

The third and fourth investigations on mini modules were done on (M3 and M4) modules with different front and back side covers. In the first case a normal front and back side glass was used. The second is made with the specially treated front glass containing less sodium ions and again a back sheet. The PID test for the last two modules was done at the same conditions as the first two investigation steps (-2000 V, T =25±5°C, RH =45±5%) but with different time interval PID tests. Figure 4.4 shows
the comparison of the power over time for all the investigated mini modules at low and high flash intensity (100W/m$^2$, 1000W/m$^2$).

![Graph a](image1.png)

![Graph b](image2.png)

**Figure 4.4:** Power over time for all mini modules at lower (a) and higher flash intensities (b).

There was a higher degradation rate at lower flash intensity. However, the second type of the (reference glass/back sheet) M2 did not show any degradation. The power
losses percentages were different among the other three modules. For example, one of the two reference glass modules (M1) showed higher degradation rate of nearly 45% from its original state, while the other one (M2) showed only 10% reduction of the original state at 100W/m². The power losses percentage for the M3 (glass /glass) type was nearly 48% from its original state. Finally for the M4 (special glass/back sheet) type was showed 43% power loss from its original state. Table 4.2 shows the power loss percentage for the entire tested mini modules at four different flash measurements.

Table 4-2: Comparison between the tested mini modules in power losses by using different flash tests.

<table>
<thead>
<tr>
<th>Module Type</th>
<th>ΔP (Reference glass/back sheet)</th>
<th>M1 (Reference glass/back sheet) 139hr</th>
<th>M2 (Reference glass/back sheet) 67hr</th>
<th>M3 (Glass/Glass) 140hr</th>
<th>M4 (Special glass/back sheet) 115hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔP (%) at 100W/m²</td>
<td>45.45</td>
<td>9.97</td>
<td>48.33</td>
<td>43.01</td>
<td></td>
</tr>
<tr>
<td>ΔP (%) at 200W/m²</td>
<td>20.96</td>
<td>4.63</td>
<td>22.52</td>
<td>21.70</td>
<td></td>
</tr>
<tr>
<td>ΔP (%) at 500W/m²</td>
<td>9.72</td>
<td>2.03</td>
<td>10.12</td>
<td>10.81</td>
<td></td>
</tr>
<tr>
<td>ΔP (%) at 1000W/m²</td>
<td>4.31</td>
<td>1.01</td>
<td>6.04</td>
<td>5.52</td>
<td></td>
</tr>
</tbody>
</table>

All the power loss percentages are shown in figure 4.5 to highlight the difference.
Figure 4.5: Comparison of the power losses among the tested mini modules at 100W/m$^2$ (a) and 1000W/m$^2$(b).
4.1.2 Mini modules leakage current investigations

The leakage current flows between the frame and the solar cell contacts. It results from a finite resistance of the module materials, mainly the glass, EVA and back sheet foils. Particular charges (e.g. sodium ions) are part of the leakage current and may interact with the active layers of the solar cell [7].

The leakage current data were measured during the PID test by the high voltage setup every 11 seconds and record it as shown in figure 4.6 for the M1 module at the first time dependence experiment. As shown in figure 4.6 the leakage current recorded a lower value at the beginning till reachingenter the saturation level with a fixed value over the PID test period.

Calculating the average leakage current was done by getting the average value of every PID test period.

![Figure 4.6: Leakage current produced during the first PID time dependent test for the M1 module](image)

The transferred charge was calculated from the following formula [31] in order to understand more about the behavior of charging and discharging of the solar modules under high voltage:

\[ I = \frac{dQ}{dt} \]

Where I is the measured current and Q is the electric charge transferred between the frame and the cell surface over atimet.
The first comparison of the leakage current investigation was done for the first two mini modules M1 and M2 (reference glass/back sheet) as shown in Figure 4.7. The M1 showed a higher degradation rate than the M2. The measurements were carried out at 2 kV (T = 25±5° C, RH = 45±5%).

The leakage current for the first reference glass module M1 (red color) was increasing with time. The second mini module M2 (violet color) showed lower values of the leakage current comparing with the other module, so it was noticed that, there is a direct relation between the power losses and the leakage.
Figure 4.7: The first two mini modules (reference glass/back sheet) investigations on the leakage current (a) and the transferred charge (b).

The average leakage current is plotted for both the mini modules in figure 4.7 (a). The leakage current for the M1 module (red color) was increasing with time.
Exemplary, the measurements was at 2 kV (T = 25±5º C, RH = 45±5%) conditions. The M2 module (violet color) showed lower values of the leakage current comparing with the other module, so it was noticed that, there is a directly proportional relation between the power losses and the leakage. It was also observed that the average leakage current was increasing with time that means in stepwise. The average leakage current and the transferred charges for the M3 (reference glass/glass) mini module during the PID test is shown in figure 4.8.

![Figure 4.8: Investigation on the Glass/Glass mini modules (M3) leakage current (a) and the mobile charges (b).](image-url)
The M3 mini module was put under high negative voltage stress for nearly 140 hours and it was observed that the leakage current is decreasing at the beginning but increasing again after some hours. For reasons of comparison, the transferred charge is plotted in fig 4.8(b).

For the M4 mini module (special glass/back sheet) the leakage current yields a lower average value. In this case it increases first and after certain time it decreases again as shown on figure 4.9. The reasons for the unexpected behavior in both cases are not clear but are considered to be measurements uncertainties.

![Figure 4.9: M4 (special glass/back sheet) mini modules leakage current (a) and the transferred charge with time dependence (b)](image-url)
4.2 PID test results on mono-crystalline module

This section describes the second phase of the potential induced degradation test, where standard PV panels with sixty silicon solar cells were investigated. The tested solar panels are divided into two categories: new un-stressed modules (M5 and M6) and pre-stressed modules (M7 and M8). The new modules contain one mono-crystalline and one poly-crystalline. The pre-stressed modules are containing one module stressed with damping heat test (DHT) and one with thermal cycling test (TCT). For all the modules the front glass is covered with aluminum foil. This aluminum cover is connected to the positive pole and the panel contacts are connected to the negative pole of the high voltage setup. Then, a standard test is performed with both time and voltage dependence in order to investigate the potential induced degradation on the panel level.

4.2.1 Time dependence test

4.2.1.1 I-V characteristics

The PID test for the new mono-module (M5) has been conducted with a time dependence test, which means applying a voltage of -1000V over a time period of 203 hours in fixed time intervals. Figure 4.10 shows an electroluminescence image of the mono-module before and after the PID test (-1000V, 203 hour, temperature of 25±℃ and relative humidity 45%±5). The cells which appear black in the image after test are highly affected by PID and show a strong loss in output power. One can also see that the affected cells are randomly distributed over the module.
Figure 4.10: Electroluminescence images of the new mono-crystalline (M5) module before (left) and after the PID test (V=-1000V, T=25ºC±5, RH=45%±5 for t=203 hour) (right).

Table 4.3 shows the characterization results from the current voltage measurements before and after the PID test at a flash intensity of 1000W/m² (STC conditions). Figure 4.11 shows the corresponding IV curves for the mono-crystalline modules.

Table 4-3: M5 module parameters before and after the PID test (V=-1000V, T=25ºC±5, RH=45%±5 for t=203 hour).

<table>
<thead>
<tr>
<th></th>
<th>V_{oc}(V)</th>
<th>I_{sc}(A)</th>
<th>V_{mp}(V)</th>
<th>FF(%)</th>
<th>Eff.(%)</th>
<th>P_{mp}(W)</th>
<th>R_{sh}(Ω)</th>
<th>R_{s}(Ω)</th>
<th>P_{loss}(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before PID</td>
<td>37.75</td>
<td>8.67</td>
<td>29.99</td>
<td>74.32</td>
<td>16.66</td>
<td>243.32</td>
<td>625</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>After-1kv,203hr</td>
<td>32.54</td>
<td>8.33</td>
<td>21.23</td>
<td>39.08</td>
<td>7.26</td>
<td>105.793</td>
<td>7.60</td>
<td>1.30</td>
<td>56.52</td>
</tr>
</tbody>
</table>

The reduction of the shunt resistance and the increase of the series resistance after PID test become obvious. There is clear the difference between the power before and after the PID test. The power loss is nearly 56 % after 203 hours at STC measurements.

Figure 4.11: IV curves for the mono crystalline module before and after the PID test.
Table 4.4 presents the time dependence of the power losses after each PID experiment till 203 hours, and the power loss values are plotted in the diagram in figure 4.12.

Table 4-4: Power loss of the mono crystalline module in the time dependent PID test.

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>22</th>
<th>27</th>
<th>44</th>
<th>49</th>
<th>66</th>
<th>71</th>
<th>88</th>
<th>93</th>
<th>158</th>
<th>163</th>
<th>180</th>
<th>185</th>
<th>203</th>
</tr>
</thead>
<tbody>
<tr>
<td>P$_{\text{loss}}$(%)</td>
<td>0.5</td>
<td>1.6</td>
<td>10.6</td>
<td>13.6</td>
<td>23</td>
<td>26</td>
<td>34</td>
<td>35</td>
<td>51.56</td>
<td>52.03</td>
<td>54.85</td>
<td>55.2</td>
<td>57</td>
</tr>
</tbody>
</table>

Figure 4.12: Mono crystalline power losses due to time dependence PID test.

The time dependent PID test on the mono crystalline module yields lower power degradation at the beginning of the test as it decreased by only 1 Watt from its initial power after 27 hours. Then, the degradation accelerated with time. After 160 hours of PID test the power degradation became slower again as for additional 5 hours it degrades by only 1 Watt. After 203 hours the nominal power decreased to 106 W. The degradation rate was slow at two stages, the beginning and the final period of the PID time dependent test.
4.2.1.2 The leakage current and transferred charges

The measured leakage current and the entire charge are shown in figure 4.13. The leakage current is increasing at the beginning of the PID test till it reaches a constant value. The transferred charges increase linearly with time.

Figure 4.13: Time dependent leakage current (top) and the entire charge (bottom) of the mono crystalline module.
4.2.2 Mono crystalline voltage dependence test

After finishing the time dependence experiment, it was a must to recover the module to its original state before beginning with the voltage dependence test. The recovery has been done by applying high positive voltage potential for a certain time. The mono crystalline module has been placed under +6000V for 69 hour to speed up its recovery. Since it has not recover completely, it has been placed again under +6000V for additional 23 hours. However, it could only be recovered to 214W, while initial power was 243W. An irreversible degradation of 12% was observed so, the voltage dependent test started with an initial power of 214W. Voltage dependence test has been done by setting different values of the applied negative voltage with a fixed experiment time. The benefits from the voltage dependence test [29] are to detect, whether there are additional degradation effects beside the potential induced degradation at these high negative bias voltages. Furthermore it could be favorable to yield more details about the charging and discharging behavior of the solar modules under the high voltage. Also, it could be helpful for the future, when the system applied voltage of the PV strings is possibly increased.

The voltage dependency of the leakage current has been investigated in the range of 1 to 10kV and at fixed experiment time of 6 hours. The module recovery has been done by placing the module under the same external voltage, but with opposite polarity for 12 hours. The mono crystalline module has again been completely covered with aluminum foil. The temperature was 25±5º C and the relative humidity is 45±5%. The resulting voltage dependency of leakage current and the entire charges is shown in figure 4.14.
Figure 4.14: Mono crystalline leakage current (a) and charge (b) in the voltage dependent PID test.
Figure 4.14 (a) shows that there is a directly linear relation between the external voltage and the leakage current. Figure 4.14 (a) also shows the leakage current for the positive external voltage is almost the same as for negative voltage and has the same linear relation with the external voltage. Figure 4.14(b) is showing the relation between the applied voltage and the entire charge for both negative and positive states. At the recovery process the entire charges yields a higher value than in PID test because the recovery was done over 12 hours, while PID test was only 6 hours.

![Graph showing power loss and shunt resistance relation to applied external negative potential for mono crystalline module.](image)

**Figure 4.15: Power loss and shunt resistance relation to the applied external negative potential for the mono crystalline module.**

As shown in figure 4.15, the power loss is directly proportional to the external voltage and, at the same time, the shunt resistance is reversely proportional. The high negative stress leads to the decrease of the shunt resistance and the maximum output power which leads to the increase in the power losses.
4.3 PID test results on new poly-crystalline module

The second investigation on the standard PV new modules has been conducted on an un-stressed poly-crystalline 60 cells module. The PID test started with a time dependence test by placing the module under high negative voltage (-1000V) over a time period of 186 hours. Figure 4.16 shows a higher current electroluminescence image of the poly-crystalline module before and after PID test at (-1000V, 186 hours, temperature of 25±5°C and relative humidity 45±5%). The black color of cells indicates that the cells are affected by the PID test.

4.3.1 Poly crystalline PID time dependent test

![Electroluminescence images of poly crystalline module before (left) and after PID test at (-1000V, T=25±5°C, RH=45±5% and t=186 hour) at 8A (middle) and 2A (right).]

Figure 4.16: Electroluminescence images of poly crystalline module before (left) and after PID test at (-1000V, T=25±5°C, RH=45±5% and t=186 hour) at 8A (middle) and 2A (right).

The IV characteristic of the module has been measured before and after the PID test and is summarized in table 4.5 at STC irradiance of 1000W/m².
Table 4-5: Poly-crystalline fresh module characterization’s before and after the PID test ($V=-1000V$, $T=25°\pm 5C$, $RH=45\% \pm 5$ for $t=186$ hour).

<table>
<thead>
<tr>
<th></th>
<th>$V_{OC}(V)$</th>
<th>$I_{SC}(A)$</th>
<th>$V_{M}(V)$</th>
<th>FF(%)</th>
<th>Eff.(%)</th>
<th>$P_{M}(W)$</th>
<th>$R_{M}(W)$</th>
<th>$R_{S}(W)$</th>
<th>$P_{Loss}$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before PID</td>
<td>37.21</td>
<td>8.81</td>
<td>29.45</td>
<td>72.95</td>
<td>16.37</td>
<td>239.14</td>
<td>125</td>
<td>0.53</td>
<td>7.99</td>
</tr>
<tr>
<td>After-1kv,186hr</td>
<td>37.07</td>
<td>8.81</td>
<td>28.84</td>
<td>67.30</td>
<td>15.05</td>
<td>219.78</td>
<td>83.33</td>
<td>0.58</td>
<td>7.99</td>
</tr>
</tbody>
</table>

From table 4.5, the reduction of the shunt resistance after the PID test and at the same time some increasing of the series resistance can be noticed. The lower value of the shunt resistance causes some reduction in the power value. Compared to the mono-crystalline module there, is only a small reduction of the module power. The power loss is nearly 8% after 186 hours at the STC measurements. Figure 4.17 shows the IV curves for the poly-crystalline module before and after PID test. The EL image has been taken after each time interval as well. The cells with black color are affected by the PID test as shown in figure 4.17.

**Figure 4.17: IV curves for the new poly crystalline module before and after the PID test.**

As shown in figure 4.17, only a small reduction of the maximum power by nearly 8% occurred after 186 hours. Table 4.6 presents the power loss after each PID experiment till 186 hours. The same values are plotted on in figure 4.18.
Table 4-6: Poly crystalline power losses in time dependence PID test.

<table>
<thead>
<tr>
<th>Time(h)</th>
<th>0</th>
<th>5</th>
<th>22</th>
<th>27</th>
<th>45</th>
<th>50</th>
<th>115</th>
<th>120</th>
<th>138</th>
<th>143</th>
<th>161</th>
<th>166</th>
<th>186</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{losses}(%)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
<td>0.8</td>
<td>3.7</td>
<td>4.1</td>
<td>5.0</td>
<td>5.2</td>
<td>6.3</td>
<td>6.5</td>
<td>8.0</td>
</tr>
</tbody>
</table>

The time dependence PID test on the poly crystalline module did not show any power degradation within the first 45 hours of PID test. It started to degrade after 115 hours (9 watt from its original power) and then the degradation became slower with time. After 168 hours, it degraded 20 watt for the maximum power. This means that there is no degradation at the beginning of the PID test, and it also remains at slow rate at the final step of the PID time dependence test. The leakage current and the transferred charges are shown in figure 4.19. The leakage current at the beginning of the PID test was 1.3µA, the value decreased with increasing time. The transferred charge is linearly increasing with time.
Figure 4.19: Time dependent leakage current (top) and the transferred charge (bottom) for the poly crystalline module.
4.3.2 Poly crystalline module PID voltage dependence test

After finishing the time dependence experiments and recovering the module to its original state, the modules are now ready for the voltage dependence test. The recovery was done by applying high positive voltage potential for a certain time. The poly crystalline module is set under +8000V for 16 hour. Nearly 98% of its original state (the original power was 239W and after recovery it was 233W) gained so, the voltage dependent test started at an initial power of (233W).

The voltage dependence test has been done by setting different values of the applied negative voltage with fixed experiment time. The voltage dependency of the leakage current has been investigated in the range of 1 to 10kV and at a fixed experiment time of 6 hours. The module recovery has been done by placing the module under the same external voltage but with opposite polarity for 12 hours. Poly crystalline module has been completely covered with aluminum foil. The ambient temperature was 25±5º C and the relative humidity 45±5%. The resulting voltage dependency of leakage current and the entire charge is shown in figure 4.20.
Figure 4.20: Leakage current (a) and charge (b) in voltage dependent PID test for the poly crystalline module.

Figure 4.20 (a) shows that there is a second order polynomial relation between the external PID voltage and the leakage current. Figure 4.20 (a) shows that there is a small difference between the measured leakage current on both the negative and positive external applied voltages. The charge accumulation shows a big difference between the
positive and negative bias voltages as shown in figure 4.20(b) due to the difference in the experiment time.

\[\text{Figure 4.21: Power loss and shunt resistance relation to the applied external negative potential for the poly crystalline module.}\]

Figure 4.21 shows a relation between the power loss and shunt resistance to the external applied voltage. The power loss is directly proportional to the external voltage and, at the same time, the shunt resistance is reversely proportional. The high negative stress leads to a decrease of the shunt resistance and to an increase of the power loss.

**4.4 PID test results on a stressed DHT module**

In order to find a possible difference in the PID behavior, also pre-stressed modules were investigated. The first pre-stressed modules contained poly crystalline silicon cells and was attributed to a damping heat test (DHT) before. The EL image in figure 4.22 (left side) is showing the initial condition before the PID test. The black color on the cell refers to the cells affected by DHT. At this condition of the module, the PID is being tested by exposing the module to negative 2000V for 91 hours, and then recovering it again by exposing it to positive 8000V for 23 hours.
Figure 4.22: EL image of the DHT module before the PID test (left), after 91 hour -2000V (middle) and after recovery test for 23 hour at +8000V (right).

4.4.1 DHT module Time dependent PID test

Two experiments on the DHT modules have been conducted. The first experiment on the DHT module shows, that the module loses nearly 74% of its initial power at standard test conditions (1000W/m²) and nearly 96% of its power at lower intensity (100W/m²) after 91 hours at -2000 V. The IV curves are shown in figure 4.23. The dotted lines in the graph referred to the module condition after the PID test, and the solid line refer to the module condition before the test.
A big difference between the shunt resistance and the series resistance before and after the PID has been found. All measured characteristic of the module before and after the PID test are shown in table 4.7. After applying the positive bias voltage the module has not been recovered completely and lost nearly 8% of its initial power after the recovery step.

Table 4-7: DHT module IV parameters change for time dependent PID test.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$V_{oc}$</th>
<th>$V_{mp}$</th>
<th>FF (%)</th>
<th>eff (%)</th>
<th>$P_{max}$ (W)</th>
<th>$R_{sh}$</th>
<th>$R_{s}$</th>
<th>$P_{bias}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before(-)2000V</td>
<td>32.19</td>
<td>25.83</td>
<td>53.31</td>
<td>11.86</td>
<td>17.33</td>
<td>278</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>After(-)2000V,9hr</td>
<td>4.318</td>
<td>2.15</td>
<td>16.65</td>
<td>0.49</td>
<td>0.72</td>
<td>6</td>
<td>5</td>
<td>95.85</td>
</tr>
<tr>
<td>After(+)/8000V,23hr</td>
<td>28.30</td>
<td>18.34</td>
<td>40.57</td>
<td>6.38</td>
<td>9.32</td>
<td>61</td>
<td>10</td>
<td>46.00</td>
</tr>
<tr>
<td>Before(-)2000V</td>
<td>36.17</td>
<td>25.55</td>
<td>55.22</td>
<td>10.92</td>
<td>159.51</td>
<td>56</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>After(-)2000V,9hr</td>
<td>21.02</td>
<td>11.23</td>
<td>29.70</td>
<td>2.83</td>
<td>41.33</td>
<td>4</td>
<td>2</td>
<td>74.09</td>
</tr>
<tr>
<td>After(+)/8000V,23hr</td>
<td>35.89</td>
<td>25.08</td>
<td>51.76</td>
<td>10.00</td>
<td>146.20</td>
<td>32</td>
<td>1</td>
<td>8.00</td>
</tr>
</tbody>
</table>

Figure 4.23: IV curves for DHT module before and after the PID at different measurement intensities.
The second experiment has been done after recovering the module to nearly 92% from its original performance, and then the external voltage was decreased to be 1000V. The time dependent behavior was measured for 108 hours. Figure 4.24 shows the IV curves for this experiment, measured at the standard test conditions.

![IV Curves](image)

**Figure 4.24:** DHT module time dependent PID test for 108 hours at -1000V.

After the 108 hours, the DHT module has nearly lost 77% of its initial power and the shunt resistance has decreased from 32Ω to 3Ω. Figure 4.25 shows the power loss over the time for different flash intensities. The lower the intensity, the higher is the power loss. For example, at 100 W/m² we got 93% power loss and at 1000W/m² we got 77% power loss.
Figure 4.25: Power loss of the DHT module at different flash intensities test.

The investigation on the leakage current and the transferred charge during the time dependent test is shown in figure 4.26. It is noticed that the leakage current for DHT module starts to decrease at the beginning of the experiment and then stabilizes at a fixed value. The transferred charge is increasing, but not linearly as in the cases before.
Figure 4.26: Leakage current (a) and the transferred charge (b) in the time dependent test of the DHT module.
4.4.2 DHT PID test voltage dependency

The third experiment for the DHT module was the voltage dependent PID test. It has been done by fixing the time of every experiment and setting different values for the applied negative bias voltage. As mentioned before and it is favorable to learn more about the charging and discharging behavior of the solar modules under the high voltage. The voltage dependence test has been done in the range of 1 to 10kV with a fixed time of 6 hours. The temperature was 25±5º C and the relative humidity 45±5%. Figure 4.27(a) is showing the resulting voltage dependency of the leakage current and the transferred charges is shown in figure 4.27(b).

Figure 4.27(b) shows the relation between the applied voltage and the entire charges for both negative and positive states. At the recovery process the entire charges records a higher values than in PID test because the PID test was done for 6 hours while, the recovery done at 12 hours.

From figure 4.27 (b), there was a big difference between the negative and positive applied voltages. There has been a high value of the entire charges for the positive polarity while for the leakage current there has been nearly the same value. As for both polarities, a straight line between the different values of the leakage current has been increasing by increasing the external applied voltage.
Figure 4.27: Voltage dependency of (a) the leakage current (b) the transferred charges, for the DHT module with both polarities results.
The relationship between the voltage dependent leakage current and the power losses is shown in figure 4.28. There is a polynomial relationship between the leakage current and the power loss due to change in the applied external voltage.

\[ y = -0.0031x^2 + 1.0609x - 10.399 \]
\[ R^2 = 0.9961 \]

Figure 4.28: Power loss as function of leakage current in the voltage dependent test of the DHT module.

Figure 4.29 shows the voltage dependent power loss at different flash tests. Increasing the external applied voltage leads to increase of the power losses, the difference between the power loss at low and high intensity is more pronounced at lower PID damage, i.e. at lower external potential.
Figure 4.29: Voltage dependent power loss for the DHT module at different intensities.

4.5PID test results on stressed TCT module

The second investigation on pre-stressed PV modules was conducted on a thermal cycling tested (TCT) module. The electroluminescence image in figure 4.30 is showing its initial condition before the PID test. In general, the black color on the cell refers to cells not working properly.
The first experiment conducted was the time dependent test with a fixed applied voltage of -1000V at fixed time intervals till 104 hours were reduced. Aluminum foil again covered the whole module front glass surface. The module has been characterized at different flash intensities. Table 4.8 shows the characterization results at lower intensity (100W/m²) and at the standard test condition (1000W/m²).

There is a strong reduction of the shunt resistance values before and after the PID test is observed. In both, the two measurements are marked by dark circles for the lower intensity measurements and by red circles for the higher intensity measurements. The low shunt resistance causes a power loss in the solar cells. The power reduction appears is higher at the lower intensity measurements compared to the STC measurements.

4.5.1 TCT module time dependent PID test

Figure 4.30: TCT module EL image at high forward current (left) and at low forward current (right).
Table 4-8: TCT module characterization before and after PID test for -1000V, 104 hours at lower and higher intensity flash measurement.

<table>
<thead>
<tr>
<th>100W/m²</th>
<th>Experiment</th>
<th>V_sc</th>
<th>V_mp</th>
<th>FF(%)</th>
<th>eff(%)</th>
<th>P_mp(W)</th>
<th>R_s(Ω)</th>
<th>R_m(Ω)</th>
<th>P_surv(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>31.70</td>
<td>25.14</td>
<td>17.66</td>
<td>10.04</td>
<td>14.67</td>
<td>32.58</td>
<td>4.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After(-)1000V, 104hr</td>
<td>1.63</td>
<td>0.82</td>
<td>5.82</td>
<td>0.18</td>
<td>0.25</td>
<td>2.44</td>
<td>98</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1000W/m²</th>
<th>Experiment</th>
<th>V_sc</th>
<th>V_mp</th>
<th>FF(%)</th>
<th>eff(%)</th>
<th>P_mp(W)</th>
<th>R_s(Ω)</th>
<th>R_m(Ω)</th>
<th>P_surv(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>36.34</td>
<td>28.56</td>
<td>69.03</td>
<td>13.36</td>
<td>195.29</td>
<td>88.50</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After(-)1000V, 104hr</td>
<td>12.25</td>
<td>6.71</td>
<td>26.58</td>
<td>1.47</td>
<td>21.49</td>
<td>1.54</td>
<td>89</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The IV curve for the TCT modules before and after PID test is illustrated in Figure 4.31 at different intensities. The EL image has been taken after each PID test experiment. During the experiment, the number of the dark cells increased as shown in figure 4.32. Finally, after 104 hours almost all cells were completely black in EL-image, corresponding to 89% power loss.

![IV curve of TCT module](image)

Figure 4.31: IV curves of the TCT module before (solid lines) and after PID test (-1000V of 104 hours with different measurement intensities.)
Figure 4.32: Power loss curve of the time dependent PID test with the TCT module.

Figure 4.33 shows the power loss for the TCT module with the different intensities values (100, 200, 500 and 1000W/m²). The PID effect appears to be stronger at the beginning of the test at lower intensities, but with growing time, the power loss values are approaching for all the intensities.
Figure 4.33: Power loss of the TCT module in the time dependent test with different measurements intensities.

During the PID tests on the TCT module, the leakage current between the front glass surface and the solar cells has been investigated. As shown in the figure 4.34(a), the leakage current curve increases by time till it reaches a maximum values after 65 hours and then decreases slightly. The transferred charge increases linearly with time, see figure 4.34(b) inside charges increase by time.
Figure 4.34: Leakage current (a) and transferred charge (b) during the time dependent test of the TCT module.
4.5.2 Voltage dependent PID test

The second experiment was the voltage dependent test which has been done by setting different values of the applied negative voltage with a fixed experiment time of 6 hours. The module recovery was done by putting the module under the same external voltage but with opposite polarity over 12 hours. The temperature was 25±5º C and the relative humidity 45±5%. The resulting voltage dependency of the leakage current and the transferred charge is shown in figure 4.35.

Figure 4.35(a), shows the leakage current in the voltage dependent PID test for both positive and negative voltage. It yields nearly the same values for both polarities with a linear relation, respectively. The transferred charge has been calculated and is shown in figure 4.35(b). There was a difference between the positive and negative curves due to the facts that the PID test was done for 6 hours, while the recovery was done at 12 hours.
Figure 4.35: Voltage dependent leakage current (a) and transferred charge (b) at different external voltages for the TCT module.
Figure 4.36(a) shows the power loss for the different applied voltages. It has been noticed, that the power loss at fixed experiment time (6 hours) start to increase till it reaches saturation at an applied voltage over 6000V. The comparison between the different measurements intensities is shown in figure 4.36(b). Higher relative power loss has been achieved at lower intensity and the power loss decreases when increasing the measurement intensity for a given voltage step.
Figure 4.36: Voltage dependent test of the TCT module with different applied external voltages at different measurements intensities.
4.6 PID test results on CdTe modules

Cadmium telluride (CdTe) is one of the so-called second generation PV cells [34], which showed great progress towards higher efficiency over the past twenty years. CdTe cells have advantages over conventional silicon modules, since they are interconnected monolithically during the line production process and soldering individual cells into strings is avoided. This means, that for example cracks on the cells are avoided. Furthermore, there is a different method for the front glass process than the silicon module called lamination process, which is an essential process in cells module production due to utilizing the front glass layer as a substrate on the CdTe production process. The most important issue for manufacturing CdTe modules are the lower production costs per watt, while the efficiency should be the same as for silicon. Up to now, there is no data available on PID of CdTe modules so, CdTe PV modules were set under high negative voltage to check its response upon the potential induced degradation.

To study the influence of CdTe properties on potential induced degradation, investigations were done in phase #3 on two CdTe PV modules (M9 and M10). High voltage stress took place by applying different negative voltage stresses (1.5-2kV). The positive pole of the voltage source is again connected to an aluminum foil covering the top glass layer. The CdTe before and after PID tests was characterized by IV curve measurements. Leakage current was measured during the test as well.

4.6.1 CdTe IV characterization curve

The characterization was done before and after PID test; taking into consideration different flash intensities of 100, 200, 500 and 1000W/m². The initial conditions of the first CdTe module (M9) are shown in Table 4.9 for the different flash intensities.

<table>
<thead>
<tr>
<th>Flash intensity</th>
<th>$V_{oc}$ (V)</th>
<th>$V_{mp}$ (V)</th>
<th>FF (%)</th>
<th>$P_{max}$ (W)</th>
<th>$R_{sh}$ (Ω)</th>
<th>$R_{s}$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100W/m²</td>
<td>54.33</td>
<td>41.49</td>
<td>62.83</td>
<td>6.27</td>
<td>3333</td>
<td>38</td>
</tr>
<tr>
<td>200W/m²</td>
<td>57.07</td>
<td>43.64</td>
<td>64.34</td>
<td>13.64</td>
<td>2500</td>
<td>20</td>
</tr>
<tr>
<td>500W/m²</td>
<td>59.68</td>
<td>44.87</td>
<td>63.82</td>
<td>35.71</td>
<td>1429</td>
<td>10</td>
</tr>
<tr>
<td>1000W/m²</td>
<td>61.38</td>
<td>44.28</td>
<td>60.98</td>
<td>71.41</td>
<td>1250</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 4.9: The first CdTe characterizations at different intensities before the PID test.
The test conditions were external voltage = 1500 V, T = 25º±5 C, RH = 45%±5 and time = 26 hours. After the first time dependence PID test, it has been found that there is no change in the module performance. So, the module was placed again under the same as the previous conditions, but this time the applied voltage polarity was changed to be +1500V for another 26 hours. The result was that the module performance was also not affected. The results are shown in table 4.10 for both experiments.

Table 4-10: Different intensities measurements were set after negative and positive stress at 1500V.

<table>
<thead>
<tr>
<th>Flash intensity</th>
<th>Test conditions</th>
<th>V_{oc}(V)</th>
<th>V_{mp}(V)</th>
<th>FF(%)</th>
<th>P_{m}(W)</th>
<th>R_{sh}(Ω)</th>
<th>R_{s}(Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100W/m²</td>
<td>After(−)1500V,26h</td>
<td>54.29</td>
<td>41.69</td>
<td>63.73</td>
<td>6.37</td>
<td>3333</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>After(+)1500V,26h</td>
<td>54.22</td>
<td>41.66</td>
<td>63.61</td>
<td>6.35</td>
<td>5000</td>
<td>38</td>
</tr>
<tr>
<td>200W/m²</td>
<td>After(−)1500V,26h</td>
<td>56.97</td>
<td>43.72</td>
<td>65.20</td>
<td>13.79</td>
<td>3333</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>After(+)1500V,26h</td>
<td>56.88</td>
<td>43.68</td>
<td>65.14</td>
<td>13.77</td>
<td>5000</td>
<td>19</td>
</tr>
<tr>
<td>500W/m²</td>
<td>After(−)1500V,26h</td>
<td>59.54</td>
<td>44.90</td>
<td>64.56</td>
<td>36.07</td>
<td>2000</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>After(+)1500V,26h</td>
<td>59.45</td>
<td>44.84</td>
<td>64.54</td>
<td>36.01</td>
<td>2000</td>
<td>10</td>
</tr>
<tr>
<td>1000W/m²</td>
<td>After(−)1500V,26h</td>
<td>61.18</td>
<td>44.20</td>
<td>61.57</td>
<td>71.91</td>
<td>1250</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>After(+)1500V,26h</td>
<td>61.04</td>
<td>44.03</td>
<td>61.34</td>
<td>71.84</td>
<td>1000</td>
<td>7</td>
</tr>
</tbody>
</table>

As shown in tables 4.9 and 4.10, there is no change between the initial performances and after placing the module under HVST with both negative and positive voltage of 1500V at a fixed time of 26 hours. That means that the CdTe is stable under high voltage stress within the tested time intervals. So, it is worth to place this module under PID test again but with increasing the external applied voltage.

Table 4-11: The characterizations results after increasing the negative stress test to 2000V for 120 hours.

<table>
<thead>
<tr>
<th>Flash intensity</th>
<th>V_{oc}(V)</th>
<th>V_{mp}(V)</th>
<th>FF(%)</th>
<th>P_{m}(W)</th>
<th>R_{sh}(Ω)</th>
<th>R_{s}(Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100W/m²</td>
<td>54.43</td>
<td>41.84</td>
<td>63.84</td>
<td>6.38</td>
<td>5000</td>
<td>38</td>
</tr>
<tr>
<td>200W/m²</td>
<td>57.07</td>
<td>43.95</td>
<td>65.41</td>
<td>13.85</td>
<td>5000</td>
<td>20</td>
</tr>
<tr>
<td>500W/m²</td>
<td>59.67</td>
<td>45.09</td>
<td>64.83</td>
<td>36.22</td>
<td>1667</td>
<td>10</td>
</tr>
<tr>
<td>1000W/m²</td>
<td>61.26</td>
<td>44.32</td>
<td>61.80</td>
<td>71.30</td>
<td>1250</td>
<td>7</td>
</tr>
</tbody>
</table>
The second experiment was set at the following conditions external voltage= 2000 V, T=25°C ±5, RH=45%±5 and experiment time = 120 hours, the results are shown in table 4.11. The results after increasing the external voltage to -2000V for 120 hours, there was also no change in the module performance compared to the results in tables 4.9 and 4.10.

![Graph](image)

Figure 4.37: I-V curve for M9 module before and after PID test with different external voltages (a) 100W/m² measure (b) 1000W/m².
Figure 4.37(a, b) shows the I-V curves of this module in the previous experiments at low and high intensities.

In Figure 4.37(a) shows the IV curves at 100 W/m² for all the tested time intervals in different colors. As we can notice, all are drawn on the same line due to the fact that there is no change in both the current and voltage before and after the high negative voltage stress. The same behavior is observed when measuring at the standard test conditions as shown in figure 4.37(b).

To assure the above results, the same test sequence was done for another CdTe PV module (M10), but this time with fixed voltage dependence (negative 2000 V) for 89 hours with the same conditions as the previous experiment. The characterization results of the second CdTe PV module before and after the high voltage stress test is summarized in table 4.12. There were no changes in the module performance from the initial condition of the PID test.

**Table 4-12: The second CdTe PV module IV characteristics at different intensities (a) before and (b) after PID test.**

<table>
<thead>
<tr>
<th>Flash intensity</th>
<th>$V_{oc}$(V)</th>
<th>$V_{mp}$(V)</th>
<th>FF(%)</th>
<th>$P_{m}$(W)</th>
<th>$R_{sh}$(Ω)</th>
<th>$R_{s}$(Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 W/m²</td>
<td>49.10</td>
<td>34.23</td>
<td>48.67</td>
<td>4.47</td>
<td>1250</td>
<td>59</td>
</tr>
<tr>
<td>200 W/m²</td>
<td>54.19</td>
<td>39.31</td>
<td>55.40</td>
<td>11.38</td>
<td>1429</td>
<td>25</td>
</tr>
<tr>
<td>500 W/m²</td>
<td>57.98</td>
<td>42.27</td>
<td>58.35</td>
<td>32.29</td>
<td>1000</td>
<td>11</td>
</tr>
<tr>
<td>1000 W/m²</td>
<td>60.37</td>
<td>42.68</td>
<td>57.48</td>
<td>67.33</td>
<td>588</td>
<td>7</td>
</tr>
</tbody>
</table>

(a)

<table>
<thead>
<tr>
<th>Flash intensity</th>
<th>$V_{oc}$(V)</th>
<th>$V_{mp}$(V)</th>
<th>FF(%)</th>
<th>$P_{m}$(W)</th>
<th>$R_{sh}$(Ω)</th>
<th>$R_{s}$(Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 W/m²</td>
<td>49.27</td>
<td>34.61</td>
<td>49.28</td>
<td>4.54</td>
<td>1111</td>
<td>57</td>
</tr>
<tr>
<td>200 W/m²</td>
<td>54.32</td>
<td>39.78</td>
<td>56.37</td>
<td>11.54</td>
<td>1250</td>
<td>24</td>
</tr>
<tr>
<td>500 W/m²</td>
<td>58.00</td>
<td>42.58</td>
<td>59.23</td>
<td>32.67</td>
<td>909</td>
<td>11</td>
</tr>
<tr>
<td>1000 W/m²</td>
<td>60.36</td>
<td>42.83</td>
<td>58.27</td>
<td>68.17</td>
<td>667</td>
<td>7</td>
</tr>
</tbody>
</table>

(b)
Figure 4.38 shows the IV curve for the M10CdTe PV module at both low and high intensity. The time intervals test after every PID test gave the same results for both the higher and lower intensities. That means that the CdTe has the ability to prevent the potential induced degradation.

Figure 4.38: I-V curve for the 2\textsuperscript{nd} CdTe before PID, after 89 hours at 2kV negative bias at both low and high intensities.

4.6.2 CdTe leakage current investigations

As mentioned before, the PID phenomena are accelerated by covering the whole module front glass surface with either water film or aluminum sheet to increase the glass conductivity. The current between the panel surface and the laminated cell is called the leakage current which increases significantly. The value of leakage current was detected and measured on the two CdTe modules. Figure 4.39 shows the leakage current and the entire charge in all the tested time for the M9CdTe module. The leakage current measurements of the M9CdTe PV modules are shown in Figure 4.39. It has been found several kinds of fluctuations on the reading. The voltage and time dependence tests were applied on this module (-1.5kv, +1.5kv,-2kv). At the beginning of the experiments, the leakage current increased and after few moments it went down again. So, the leakage current didn’t show any increment during the time tests. In comparison, of the results of the leakage current with the power performance, it has been found that there is a great relation between the power losses and the leakage current. Figure 4.39 (a) shows that the entire charge of the M9CdTe module was
calculated in every time dependence test and it has been found that the entire charge was always in increasing state. In the M10 CdTe module, the high negative voltage was fixed at different time intervals test.

Figure 4.39: Leakage current of the first CdTe PV modules in time intervals (top) and the calculated entire charge (bottom).
The leakage current and the entire charges that were investigated in the M10CdTe module experiment are shown in figure 4.40. The leakage current was constant at -2kv with different time interval test and the entire charge was linearly increasing. The characterization performance of this module did also not change.

Figure 4.40: Leakage current of the second CdTe PV modules in time intervals (top) and the calculated entire charge (bottom).
Chapter 5 Discussions

5.1 Leakage current comparison for all mini modules

Figure 5.1: All investigated mini modules leakage current over time of experiments with the same conditions.

The average leakage currents for all the investigated modules are plotted in one diagram as shown in figure 5.1. For M4 (special glass), this special glass successfully reduced the leakage current compared to the other modules. However, this reduction of the leakage current did not prevent the PID degradation. For the other modules leakage current it was always increasing by the time. On the other hand, one of the modules M2 (reference glass/back sheet) showed PID resistance, but its average leakage current was relatively higher.
5.2 Comparison of the time dependent tests

PID test has been conducted on standard silicon solar modules with four different types (two new and two pre-stressed). The two new modules contain one mono-crystalline while the other was multi-crystalline. This section contains the comparison between the four modules. As shown in figure 5.2(a), a wide variation in the power loss percentage between all the tested modules was observed. The TCT module (green line) degraded faster than the others, while the new poly-crystalline module (blue line) showed the lowest PID effect. After 105 hours of PID test for all the modules, the TCT module lost nearly 89% from its initial power, while the new poly-crystalline module lost only 4%. Also the degradation rate was higher at the beginning of the PID test for the TCT module while it was slow in the new poly module case.

Figure 5.2 (b) shows the leakage current comparison. It was noticed, that the TCT module has the highest leakage current values, while the new poly-crystalline module had the lowest values, corresponding to the lowest power loss of the four modules. However, the leakage current is not the only criteria for PID as the comparison of the new mono-crystalline and the DHT module shows. Both have almost the same leakage current at -1000V but degrade significantly different.
Figure 5.2: Comparison of all the standard modules in time dependent PID test, power loss (a) and leakage current (b).
5.3 Comparison of the voltage dependent tests

Figure 5.3 shows the comparison of all the tested modules in the voltage dependent PID test. Both the new mono-crystalline module and DHT module showed higher power degradation at the higher applied external voltages, while the poly-crystalline module showed a lower degradation rate among the four modules. Also, it is remarkable that the power loss of the TCT module saturated at higher voltages.

Figure 5.3: Comparison of all the standard modules in the voltage dependent PID test regarding the power loss.
Figure 5.4 shows the measured leakage current for the entire tested modules. Both the new mono-crystalline module and the DHT showed a linear relation for the measured leakage current with the external applied voltage. For the new poly crystalline it was a second order polynomial relation of the measured leakage current and the applied.

Figure 5.4: Comparison of the leakage current of the four modules in the voltage dependent PID test.
5.4 Antireflection coating observation

A difference of the cells colors between the two new fresh modules was observed. Figure 5.5 shows a captured photo of these modules.

![Image of solar panels showing a comparison of two modules with different colors.]

**Figure 5.5:** Photographic comparison of the highly degrading fresh mono-crystalline module (right) and the lower degrading fresh poly-crystalline module (left).

It seems there was a difference on the ARC manufacturing. For the black color it is a new invention on AR coating layer by comprises two layers of SiNx. The first SiNx layer having a high refractive index while the second SiNx one having a lower refractive index[33]. For the blue black color it is be a different on SiNx layer as it probably have a higher conductivity which it maybe can release the positive charges came from the front glass. For cells without AR coating there was no PID effect [21].
Figure 5.6 shows the TCT accelerated module in photographic and EL image after PID test (External Voltage= -1000V, T=25°C±5, RH=45%±5 and t=89 hours). A difference in the ARC color among the cells (some in blue while the others in black) was observed. The blue cells were marked with yellow squares. The cells with blue colors were not PID affected, while the black cells were completely affected that could mean, that there is maybe a lower ARC conductivity in the case of the black cells.

From the previous observation the PID test was performed on two different techniques of AR coating. It concluded that there is a strong relation between PID and the properties of the ARC.
5.5 Outdoor performance test

It is known that if the water adsorbs the solar glass, it cause increasing the conductivity of the encapsulation [25] materials so, there was a motivation to decrease the glass conductivity by using some materials which be able to prevent the water adsorption on the front glass surface and hence, could prevent from PID due to the lower conductivity. In figure 5.7 there was an observation about sprayed and non-sprayed CdTe modules with a sprayer called (Titan Protect) which able to protect the solar glass from both water penetration and the dusts. The benefits from this experiment are to check the module performance after spraying and enable to compare between the non-sprayed modules.

![Figure 5.7: Comparison of Two CdTe modules set outside in rains at 45° tilt angle with sprayed one (right) and non-sprayed (left).](image-url)
The Titan spray protected the modules glass from water. This sprayer was tested on the standard silicon module by spraying half of the glass surface to compare between the sprayed and non-sprayed surfaces after PID test. The results from this experiment were the sprayer cannot prevent the PID phenomenon.

The investigation of the leakage currents at external voltages up to 10000V showed clear differences between the pre-stressed modules and new modules. In the pre-stressed case, the leakage current is higher. The leakage current density for all the tested modules is shown in table 5.1. It was observed, that increasing the module area leads to increase of the leakage current average

**Table 5-1: Comparison between all the tested modules under PID test in the leakage current density.**

<table>
<thead>
<tr>
<th>Module type</th>
<th>Leakage current(A)</th>
<th>External Voltage(V)</th>
<th>Area(m2)</th>
<th>Current Density(μA/m2)</th>
<th>P_leak(%)</th>
<th>Test time(h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. Glass</td>
<td>6.64E-08</td>
<td>2000</td>
<td>0.04</td>
<td>1.84</td>
<td></td>
<td>67</td>
</tr>
<tr>
<td>Ref. Glass</td>
<td>8.95E-08</td>
<td>2000</td>
<td>0.04</td>
<td>2.48</td>
<td>4.4</td>
<td>139</td>
</tr>
<tr>
<td>Glass/Glass</td>
<td>8.30E-08</td>
<td>2000</td>
<td>0.04</td>
<td>2.30</td>
<td>4</td>
<td>140</td>
</tr>
<tr>
<td>Spec.Glass</td>
<td>4.38E-08</td>
<td>2000</td>
<td>0.04</td>
<td>1.21</td>
<td>5.51</td>
<td>115</td>
</tr>
<tr>
<td>CdTe</td>
<td>2.62E-06</td>
<td>2000</td>
<td>0.72</td>
<td>3.63</td>
<td>0</td>
<td>120</td>
</tr>
<tr>
<td>CdTe</td>
<td>2.76E-06</td>
<td>2000</td>
<td>0.72</td>
<td>3.83</td>
<td>0</td>
<td>89</td>
</tr>
<tr>
<td>DHT</td>
<td>6.93E-06</td>
<td>1000</td>
<td>1.6</td>
<td>4.33</td>
<td>80</td>
<td>108</td>
</tr>
<tr>
<td>TCT</td>
<td>8.2E-06</td>
<td>1000</td>
<td>1.6</td>
<td>5.13</td>
<td>89</td>
<td>104</td>
</tr>
<tr>
<td>IBC-Mono</td>
<td>7.3E-06</td>
<td>1000</td>
<td>1.6</td>
<td>4.56</td>
<td>57</td>
<td>203</td>
</tr>
<tr>
<td>ILB-Poly</td>
<td>0.97E-06</td>
<td>1000</td>
<td>1.6</td>
<td>0.61</td>
<td>8</td>
<td>185</td>
</tr>
</tbody>
</table>
Chapter 6 Conclusions and Recommendations

6.1 Conclusions

A potential induced degradation (PID) laboratory test was used at Fraunhofer THM in Freiberg, for the investigation of different solar modules. Different values of positive and negative potential were applied. For mini modules, PID tests were performed on four different modules as mentioned before. Results from these tests were compared to PID tests on the four modules. It was observed, that under a negative bias voltage of 2000V, only three modules show a significant performance loss of 5% from initial power. The fourth module did not show any kind of degradation. It was observed, that the leakage current for all modules was increasing during the time dependent PID test. In the case of the special glass module, there was a lower peak value compared to the others.

For the standard modules PID tests were performed on accelerated stressed modules, including thermal cycled and damp heat stressed modules. Results from these tests were compared to PID tests on new, unstressed modules. It was observed that under negative bias voltage of 1000V, the performance loss of the pre-stressed modules was drastic, showing almost 90% degradation from the initial power. The new modules showed less degradation at the same time periods (for mono nearly 37% losses and for poly nearly 4% loss).

Leakage currents were observed to be constant after beginning the PID test for the accelerated situation, while in new modules it was slightly decreasing over time.

In order to investigate the PID voltage dependency, all the modules were put under higher voltage negative bias from 2000V to 10000V. For all modules no additional destruction was observed at these higher voltages. Also, the PID caused by -10000V was reversible for all.

6.2 Recommendations for future work

For future investigations, the following is recommended:

- To investigate the PID on cells with the same aspects (same manufacturing process) but different AR coating thickness.
- To investigate any kind of materials to be sprayed on the module front glass surface which can be able to protect from undesired phenomenon like PID due to increased glass conductivity by humidity.
- Further investigations on CdTe modules, since it completely resists the PID phenomenon during my investigations.
- The allowed system voltages should be less than 1000V to decrease the PID effect (expensive solution).
- To avoid applying bias voltage to the PV module by grounding the negative pole of the PV string array and using a transformer inverter [35] (expensive solution).
References


[16] Schüetze, et al, Laboratory Study of Potential Induced Degradation of Silicon Photovoltaic Modules, Q-Cells SE, Sonnenallee 17-21, 06766 Bitterfeld-Wolfen


[32] Boyuan Qi and Jizheng Wang, ”Open-circuit voltage in organic solar cells”, Received 10th June 2012, Accepted 4th September 2012 DOI: 10.1039/c2jm33719c


الملخص

تعتبر الثقة في كفاءة أداء وحدات الطاقة الشمسية العامل الأساسي لضمان النمو المستمر في صناعة وحدات الخلايا الشمسية. فلم يعد كاف استخدام الاختبارات التقليدية في حالات الطائرة الكهربي خاصة لكشف كل الظواهر الغريبة المحتملة في ضمن هذه الظواهر ظاهرة تسمى (الاعتماد في التدورة المستحث) لألات الطاقة الشمسية. وتحدث عادة هذه الظاهرة عندما يكون الأطرال الخارجي للأراس الشمسية المصغر من الالمنيوم مشحونا بشحن موجب. وقد تم مؤخرا الكشف عن التأثير السلبي لهذه الظاهرة بين الأطرال الخارجي للأراس والخلايا الشمسية في المحلاة توليد الطاقة الشمسية التي تعمل بهدف يصل الجهد بالآهة 1000 فولت، ويقمع الجهد بشكل حد على طول الواردات المنزلة على التوازي. تكون أدنا مذكرون مشحونة بشحن موجب أو سالبينذك بحسب المدارات الأرضية للالراس. ومع أول اكتشاف لها، استطاعت هذه الظاهرة جذب اهتمام العديد من الباحثين، وربما من اكتشاف العديد من الأسباب التي تؤدى إلى حدوث ظاهرة احتمالية التدورة المستحث. لأن السبب الفيزيائي وراء الظاهرة ليس واضحا.

وأيضا اكتشافات ما تم مؤخرا تأثير ضحى في الألآراس التأدية عالي الجهد في الألآراس الشمسية التي تتحرك أيونات الصوديوم الموجودة في الزجاج الأمامي للأراس بإتجاه الخلايا الشمسية المصغر بسحوب موجييجي تتمتع على السطح العلوي للخلايا، تحديدا على الطبق المصادع للإلكانس. وعند عدد نماذج توضع كمية تأثير هذه الشحنات الإضافية على الأداء الخلايا، لكنها غير قادرة لتفسير هذه الظاهرة. فهناك العديد من الاكتشافات من قبل الشركات المصغرة للأراس الشمسية أثناء مراحل التصميم، والذين تم تفسيرها ورق للإذاعة في النهاية لم يتم تأسيس الظاهرة من قبل الألآراس، وتم تكثيف المحاولات لطرك فرق جهد عال على الأراس.

وأيضا الأسباب أنشأ معهد فراونهوفر لأبيات إشباع السوسيوم وجودة الألآراس الشمسية. وتم تكثيف المحاولات على أية أربع الكهربائي، يمكن أيضا إنشاء التيار المستمر بين الألات الشمسية والخلايا الشمسية. ومن ناحية الشحن من أطرال الكشف عن قيمة التيار المستمر يمكن أن يكون بها عن طريق تغير حساس الشكل أو لجذب الأرات الشمسية في الأرات الأمامي. وعلى سبيل المثال، يمكن استخدام دمج معالج سيارة، عبر أن حالها ميالي في الوقت الحالية للفاعلية بين توليد أرات الكهربائي من الأرات وينتقل ضحى لبداية تكون ظاهرة إحتمالية التدورة المستحث.

وأيضا الأسباب أنفاستفورد إثبات أن أرات الأمامية متكاملة مع إمكانية تطبيق فرق الجهد العالي على الأراس التي قد يصل إلى 20 ك.ف. ومن خلال هذه الحالة يمكن أيضا إنشاء التيار المستمر بين الأرات الأمامي والخلايا الشمسية. ومن ناحية الشحن، يتم تحسين جودة وحرارة التيار المستمر. ومع ذلك، تم استخدام دمج معالج سيارة على سبيل المثال، يمكن استخدام دمج معالج سيارة، عبر أن حالها ميالي في الوقت الحالية للفاعلية بين توليد أرات الكهربائي من الأرات وينتقل ضحى لبداية تكون ظاهرة إحتمالية التدورة المستحث.

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عنوان الرسالة:
الأعتماد علي الوقت والجهد لتحديد تأثير امكانيات التدهور المستحث علي مختلف أنواع ألواح الطاقة الشمسية

الكلمات الدالة:
الوحدات الضوئية، احتمالية التدهور المستحث، جهد عالي، التيار المتسرب.

ملخص الرسالة:
منذ أن أصبح الاعتماد في توليد الطاقة باستخدام الطاقة الشمسية في ازدياد، أذدادت أهميته في جميع اتجاهات العام، إذادت النمط الكهربائي الضوئي مع زيادة عدد ألواح الطاقة الشمسية الموصورة على التوالي. هذه الألواح تتعرض إلى فرق جهد عالي بالنسبة إلى الت-version الأرضية، وهذا الجهد العالي على الألواح قد يؤدي إلى حالة عدم استقرار وذلك اعتبارًا علي بعض العوامل التي قد تسبب في ظاهرة غير مرغوب فيها تدعى "امكانيات التدهور المستحث". إن العوامل (الجهد، الرطوبة، درجة الحرارة العالمية) التي تؤدي إلى حدوث هذه الظاهرة تؤدي إلى توليد تيار كهربائي متسرب بين الخلايا الشمسية والخليدي الأرضي. إذاً المفتاح الرئيسي هو تفسير هذه الظاهرة وتحديد خواص التيار الكهربائي المتسرب.
عنوان الرسالة

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كجزء من متطلبات الحصول على درجة الماجستير
في الطاقة المتجددة وكفاءة الطاقة

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