Correlation of Leakage Current Pathways and Potential Induced Degradation of CIGS Thin Film Solar Modules

Sebastian Voswinckel, Viktor Wesselak, Sven Münter, Lukas Gerstenberg

Institute for Renewable Energy Technologies/ University of Applied Sciences Nordhausen (Germany)

Abstract

The life time of over 20 years is a unique feature of PV modules. Because of weather exposition and the system design of PV power plants system induced degradation can occur. In case of CIGS PV modules it is called Potential Induced Degradation (PID). The rate of degradation depends on the transferred charge, which can be determined by measuring the leakage currents because of the potential between module connectors and ground. Thereby only the sum of the leakage current can be measured, but there are different leakage current pathways. The main pathways are through the cover glass and the back glass/ material. For a real lifetime prediction the correlation of climate chamber tests and outdoor conditions is necessary. A method for measuring the exclusive leakage current pathway through the cover or the back glass was developed. The encapsulation foil enables the possibility to deactivate the leakage current pathways which is more harmful in relation to PID of CIGS PV modules.

Keywords: CIGS, Potential Induced Degradation, leakage current, transferred charge

1. Introduction

Like all other module technologies, thin film solar modules (TFSM) are exposed to the environmental conditions during lifetime. Because of the repeated long term environmental stress (e.g. temperature changes, UV radiation, moisture ingress, mechanical stress etc.) the material properties may change and loss their functionality. Furthermore, the environmental stress can accelerate the movement of volatile components of materials or semiconductor layers. Especially reactive sodium ions are suspected to move into the semiconductor layers. This can be lead to reversible or irreversible degradation of thin film solar cells (Osterwald et al., 2003). However, because of the module wiring and the inverter concept a potential between module connectors and ground can occur (Schmidt, 2009). The result is a leakage current between these two connection points. In principle this effect can be observed for all module technologies. In this context, the specific effects, strategies for prevention and notations are different for each technology. In case of crystalline silicon the term used is Potential Induced Degradation (PID). In case of TFSM TCO corrosion occurs for superstrate modules and PID can be observed for CIGS modules (substrate modules). Note, the PID effect for CIGS modules differs from the PID effect for cSi modules. In both cases a sodium ion diffusion is suggested to reduce the efficiency. But for CIGS modules a diffusion into the CdS/CIGS interface is supposed (Fjällström et al., 2013) whereas for cSi modules the anti-reflection coating plays the main role (Naumann et al., 2012).

1.1 Module Technology

Thin film solar modules (TFSM) represent a young technology in comparison to crystalline silicon solar modules. There are two main production technologies for TFSM: Superstrate and substrate modules. As shown in Fig. 1, the layer deposition of superstrate modules starts with the front contact on the cover glass. CIGS thin film solar modules are produced in substrate technology. The layer deposition starts with the back contact on the back glass. The CIGS absorber will be deposited by co-evaporation, where the CIGS is formed during the deposition or by a deposition reaction, where a precursor will be deposited and the CIGS formation occurs during a second step (Scheer and Schock, 2011). On top of the CIGS layer a CdS buffer layer will avoid

doi:10.18086/swc.2017.20.10 Available at http://proceedings.ises.org

shunting paths followed by transparent intrinsic ZnO (i-ZnO) and an aluminum doped ZnO (ZnO:Al) layer as front contact. Because of the material consumption of the CIGS the absorber is p-type whereas CdS and the

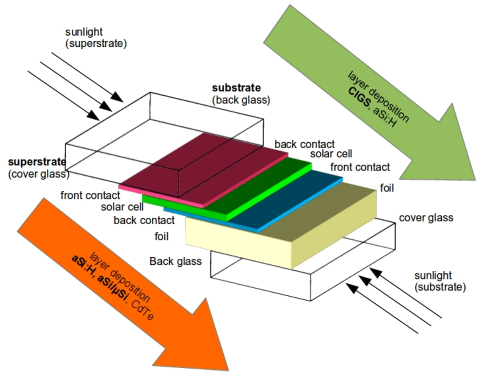

Fig. 1: Order of layer deposition for substrate and superstrate thin film solar modules.

ZnO layers are n-type.

Between the single deposition steps a structuring via mechanical tools or laser will separate the homogeneous layers into single cells. Because of the structuring between the single deposition steps a monolithical series connections as shown in Fig. 2 will occur. These created scribes are specified in order of the structuring step as scribe P1 to P3. The first scribe separates the back contact, P2 the CIGS/ CdS/ i-ZnO layer and P3 the separate the front contact and the CIGS layer again. Following by this a series connection of the solar cells is realized. However, scribe P1 leads to direct connection between CIGS and back glass. For the substrate soda lime glass with a high content of earth alkali ions is used. As indicated in Fig. 2, a fraction of selenium which is part of the absorber formation reacts with the molybdenum back contact to $MoSe_2$. This is the precondition for a low resistant contact on the back side of the cell.

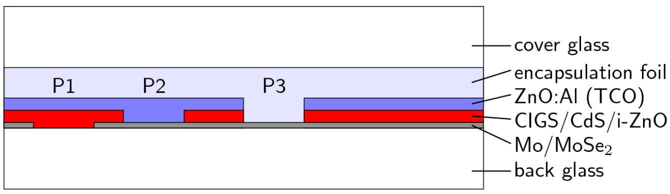

Fig. 2: Simplified illustration of layer order and solar cell connection.

1.2 Potential Induced Degradation of CIGS thin film solar modules

In PV power plants a series connection of PV modules is called module string. The aim of the series connection is to scale up the power of the PV system with ohmic losses as small as possible. This is realized by high system voltages. The system voltage V_{sys} can be measured between the first and the last module in a module string, as shown in Fig. 3. Typical system voltages in Europe achieve up to 1000 V DC, in some cases up to 1500 V DC.

In addition, a voltage between the positive and negative pole of the module string occur. The grounding situation of the module string and the type of inverter influence the amount and sign of this voltage (Schmidt, 2009). For ungrounded systems a voltage of -½ V_{sys} can be measured between the negative pole and ground. In case of the positive pole + ½ V_{sys} can be measured. In dependency of the type of inverter the amount of this voltage can be shifted to higher negative voltages and lower positive voltages or vice versa. Normally only in case of inverters with transformers an external grounding of the module string is possible. For the grounding of the negative pole a voltage of +V_{sys} can be measured between the positive pole and ground, and no voltage between the negative pole occurs. For the grounding of the positive pole the opposite is the case. This voltage is the reason for an accelerated migration of alkali ions and lead to PID. Furthermore, because of this voltage a current flow between module connector and ground can arise, the so called leakage current. The amount of the leakage current depends on the potential between the module connectors and ground. The leakage current is suspected to be an indicator of the progress of PID. However, the conductivity of the module is influenced by temperature and humidity. Following by this, the influence of environmental conditions in relation to PID has to be taken into account.

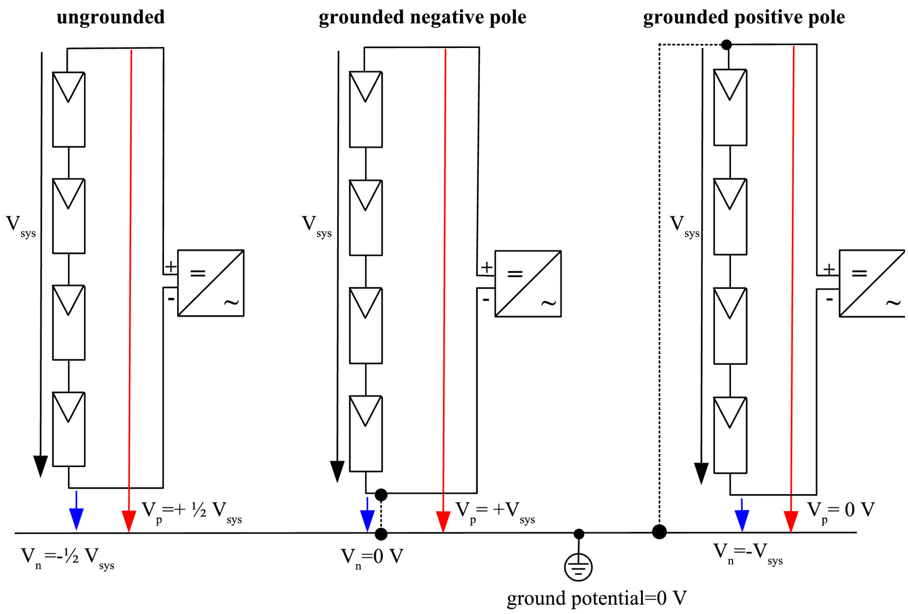

Fig. 3: Potential against ground for different grounding situations.

There are mainly four leakage current pathways in a module. The leakage current from the solar cell through the encapsulation foil and the cover glass is called I_1. The leakage current through the encapsulation foil, the edge sealing and the frame is called I_2. If the leakage current flows through the interface of the encapsulation foil and back glass and the edge sealing it is called I_3. Leakage current I_4 flows from the solar cell through the back glass. From Ohm's law it is known that the current takes the path of least resistance. This depends on the conductivity of the materials and the influence of humidity and temperature. So this lead to the question weather the current through the cover glass is most harmful or one of the others.

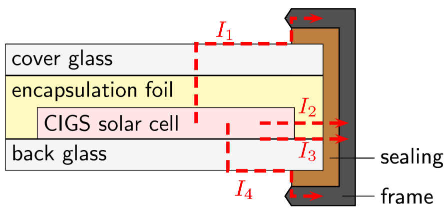

Fig. 4: Simplified illustration of the main leakage current pathways of a CIGS thin film solar module.

The aim of this study is to prove the origin of the leakage current for CIGS photovoltaic modules. The leakage current can take several different pathways. Fig. 1 shows the four main pathways for a CIGS thin film solar module. Especially the leakage current through the cover glass and through the back glass are from special interest. For a correlation of accelerated aging tests in climate chambers with outdoor exposure in the field the knowledge of active leakage current pathway is necessary. Thereby, the path activation depends on the surface and the volume conductivity of the cover and back glass as well on the encapsulation foil. Especially the surface conductivity is influenced by the environmental conditions. Consequently, a method for modeling the active leakage current as a function of environmental conditions will be shown. Therefore, lab tests are performed to correlate the outdoor measured leakage current to indoor measurements.

2. Experimental

2.1 Outdoor Test Facility

On an outdoor test facility six CIGS TFSM with two different encapsulation foils are mounted on individually insulated racks. The semiconductor device of the modules is identical. These are framed glass glass modules. However, for each foil type one module is connected with an external applied voltage of -500 V and -1000 V between module connectors and ground. The remaining two modules are mounted as reference modules, without any applied external voltage. So degradation effects because of metastable defects can be detected and differentiated from the degradation which are investigated in this study. Every ten seconds the leakage current is measured through a shunt resistant. The schematic circuit diagram of the test setup is shown in Fig. 5. Thereby,

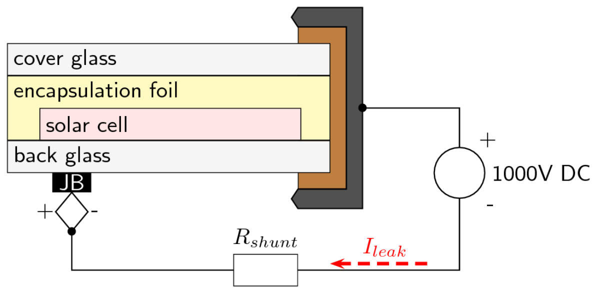

Fig. 5: Standard test setup for accelerated aging tests.

the problem that only the sum of all leakage currents can be measured occurs. But depending on the surface humidity the main leakage current pathway will change. Therefore, in addition climate chamber and water basin tests has to be done to assess the actual pathway. In order to simulate real operating conditions the external applied voltage is switched off during night and irradiations below 50 W/m^2. During the test, the modules are operated near their maximum power points. The climate conditions are measured directly adjacent to the test rack by a weather station. So at the end of the tests for each climate condition the leakage current and the pathway can be classified.

2.2 Water basin tests

For analyzing typical leakage current magnitudes depending on the leakage current pathway three different contacting methods are realized. To measure current I_1 only the cover glass is connected with an external voltage supply. In this case the current has to be overcome the resistant of the encapsulation foil and of the cover glass. However, this electrical contacting method corresponds with a wet surface of the cover glass in the field and a dry back glass surface. This can occur if it starts to rain.

In principle the same method is used to measure exclusively the current I_4 through the back glass. For this purpose only the back glass is connected. In the field this condition arise if there is dew on both sides of the module and sun is rising. The sun is drying the cover glass where the back glass is still wet. Consequently, in the third case both sides are connected to the voltage source.

All setups are realized in a water basin, as shown in Fig. 6. In the first case only the cover glass is wetted, in the second case only the back glass is wetted and for the sum of the currents the whole module is submerged in water. Furthermore, in the field a wide range of temperature for different moisture rates on the module can be observed. So the water basin is heated during the tests. The result is a temperature dependent leakage current, which can be clearly attributed to one leakage current pathway.

Water basin tests are suitable to realize a homogeneous contact on the cover or back glass as well as for the hole module. In climatic chamber tests the contact is often realized by metal plate. A gap between plate and glass can occur. In the gap water vapor can condensate and lead to local reduction of conductivity (Voswinckel et. al., 2015). With a homogeneous water film the contact can be improved and local reductions of conductivity can be neglected. With an external heat source the water can be tempered. Following by this the leakage current behavior for different conditions which correspondent with real operating conditions and accelerated aging tests can be simulated and verified. For accelerated aging tests high temperatures are needed. This leads to evaporation of the water in the basin and to reduction of the water level, which can lead to a lack on electrical conduction. So it is obvious that this test setup is only appropriate for short testing times and the analysis of special operating points. For the analysis of the aging behavior accelerated aging tests in climate chambers are necessary. Note, the typical test duration of an accelerated aging test is between one and four weeks.

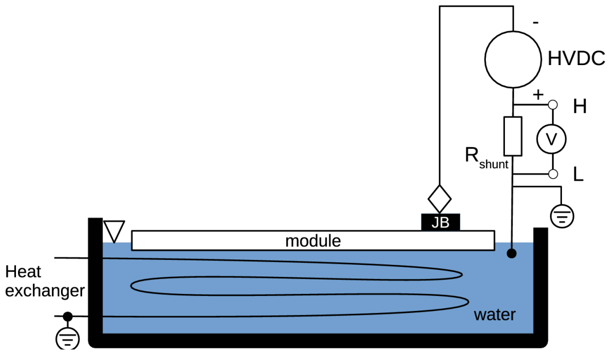

Fig. 6: Water basin test for a separate activation of one leakage current pathway.

2.3 climate chamber tests

According to the outdoor tests the climate chamber tests include two different potentials. In a first step two modules for each encapsulation foil are applied with an external voltage about -500 V. Thereby, one module is connected to module frame and the other is connected over the entire area of the cover glass. Differently from the outdoor tests, the modules are short circuited. This is done, because no irradiation is applied to the modules and no illuminated operation point can be chosen. The climate conditions during this tests are kept constant to 85°C and 85 percent relative humidity. Before and after 500 hour testing the I-V-curves are measured before and after a light soaking for four hours. The light soaking is used to stabilize the module performance before the test and to determine any regeneration effects after the tests. During the climate chamber tests the leakage currents between module connectors and frame respectively the cover glass contact are measured in a ten second interval. Furthermore, before and after the tests electroluminescence images are recorded. The influence of dark soaking in accordance to a possible regeneration or further degradation is measured in a monthly interval after the climate chamber tests. After the first experiment run the tests will be repeated with an external applied voltage of -1000 V.

For verifying the results of the water basin tests climate chamber tests with fluctuating climate conditions are performed. So, modules are connected to an external voltage supply for a bias damp heat test. However, several states of temperature in a range of -5°C and 90°C and relative humidity between 10 and 95 percent are realized. The modules are connected by metal plates on the cover glass and on the back glass. The result is a map of leakage currents for a wide range of temperature and humidity states as well as for different contacting methods.

3. Results

2.1 Degradation rate

Different climatic chamber tests are performed to analyze the degradation behavior regarding PID of CIGS TFSM. On the left side in Fig. 7 the power loss depending different contacting methods and different voltage levels is shown. One module group was contacted with metals blade on the cover glass (front) and the other group on the back glass (back). The encapsulation foil of this test run consist of PVB. The aging time was about 500 h with interruptions for measuring the I-V vurve of the modules. The results are shown for -500 V and -1000 V. It is clear visible that a higher voltage amount leads to a faster transferred charge and a faster degradation rate. However, there is a clear difference between the degradation rate of the front contacted and the back contacted modules. For the back contacted modules less transferred charge is needed to induce a power loss regarding to the front contact. The back contact corespondent with water on the backside of the module. This can occur in case of dew, if the dew on the front side is dried because of sunshine, or rain.

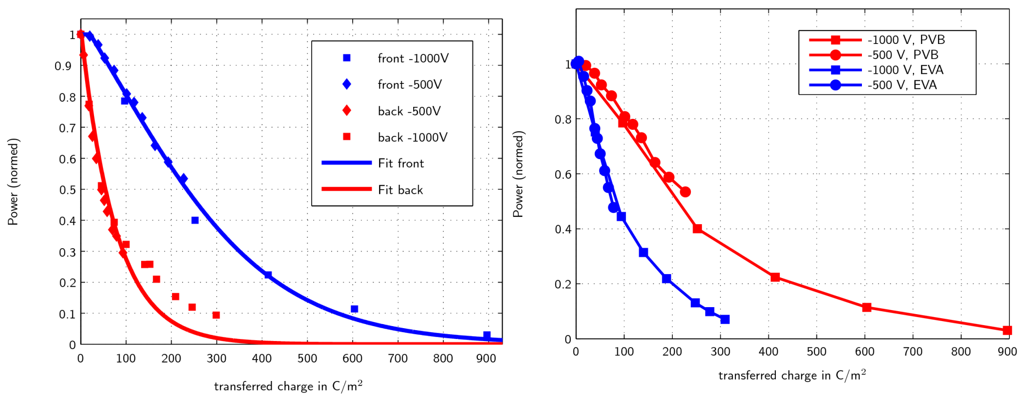

Fig. 7: Power loss as a function of transferred charge for different contact methods (left) and encapsulation foils (right).

The power loss depending on the transferred charge for different evaluated foil types is shown in Fig. 7 (right). Modules with a PVB and a EVA encapsulation foil are tested with an external voltage about -500 V and -1000 V. For the same test conditions and voltages there are clear differences regarding to power loss and transferred charge between these foil types. This indicates that there are differences in conductivity. The Foil EVA shows a faster degradation rate with higher power losses at lower transferred charges. The results show that there is a clear dependency if the leakage current flows through the back or the cover glass. The current through the back glass is more harmful than his counterpart through the cover glass. Furthermore, a clear dependency of the used encapsulation foil exists. The degradation rate can be reduced by a decrease of the conductivity of the encapsulation foil. This leads to less transferred charge and less power loss.

2.2 Leakage current pathway

Two module types with different encapsulation foils are tested. The first one is standard PVB and the second one is an EVA foil. The results of the water basin tests confirm the result of the climatic chamber tests.There is a clear difference depending on the encapsulation foil. The measured and modeled leakage current values are shown in Fig. 8. It is clear visible, that the leakage current I_1 through the cover glass for PVB is more dominant than I_4 through the back glass. In contrast, for EVA I_4 is more dominant. Nevertheless, the magnitude of I_4 for both modules is in the same range. In addition, the activation energy of the currents through the back glass is also the same for both foils, for the cover glass it is quite different. This fact is no surprise, because for both modules the same back glass is used. Whereas, in case of I_1 the material properties of the different encapsulation foils has been taken into account. Additionally, climate chamber tests are performed. Therefore, the modules are connected by a metal plate on the back glass. The results of the leakage currents measured in the water basin correspond with leakage currents in climate chamber well. However, there are some states in the climate chamber with dew on the module. In that case, the main current flow through the cover glass for PVB. In contrast to that, for EVA the main current flow through the back glass at the same condition (water on the cover glass). A comparison with former bias damp heat tests show qualitatively comparable results. In a first approach, outdoor measured leakage currents can be correlate qualitative to these results.

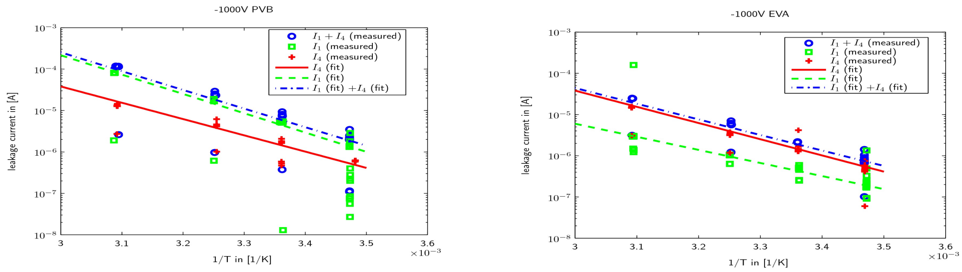

Fig. 8: Measured and modeled leakage currents through the cover glass (I_1) and the back glass (I_4) of a CIGS module with PVB (left) and EVA (right) encapsulation foil.

The Arrhenius plots in Fig. 8 can be used to extract the activation energy. The results are shown in Tab. 1. For the leakage current pathway I_4 through the back glass the same activation energy occur. The lack of differences between the two module types is because of the use of the same type of back glass. However, the estimated activation energy is typicall for soda lime glass. Regarding the leakage current pathway through the cover glass clear differences occur. The activation energy for the module with a EVA encapsulation foil is lower than for the module with PVB foil. For the latter the activation energy is also in the typicall range as for soda lime glass. This indicates, that in case of EVA the encapsulation foil limit the activation energy whereas in case of PVB the cover glass is the limiting factor.

Tab. 1: Activation energy for the leakage current pathways (Manz, 2015)

Leakage current pathway	$I_{1, EVA}$	$I_{1, PVB}$	I_4
Activation energy	0,63 eV	0,82 eV	0,78 eV

2.3 Outdoor relevance

Considering the Arrhenius equation, high temperatures lead to high degradation rates. Following by this, also

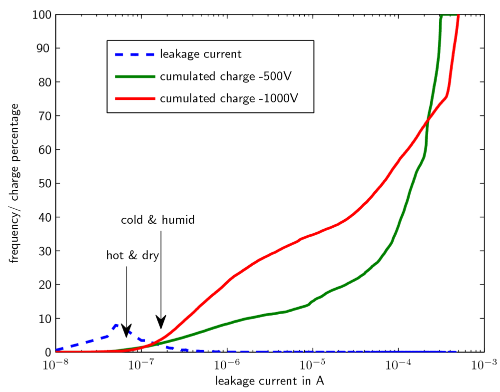

Fig. 9: .Leakage current frequency (dashed) and cumulated transferred charge (solid) in dependency of leakage current.

high leakage currents must occur. This relation is well proven by climatic chamber and water basin tests (Manz, 2015). It seems reasonable to suppose that especially the hot and humid climate regime has to considered to prevent PID of CIGS TFSM. This assumption could be true for tropic climatic regions. But for moderate climates like in central Europe the opposite is the case. Fig. 9 shows the frequency of the leakage currents (dashed) and the cumulated transferred charge (solid) for the corresponding leakage current amount over one year in Nordhausen/ Germany. Most leakage currents occur for hot and dry conditions up to leakage currents amounts in the range of 10^{-7} A. But this lead only to a transferred charge less than one percent of the hole year. Also the cold and humid regime shows a high frequency of leakage currents. The cumulation of the transferred charge to the hot and dry regime leads to three percent of the hole transferred charge. Nearly 96 percent of the transferred charge occurs during dew and rain. This conditions are infrequent but the leakage current arise up to two or three magnitudes of orders in comparison to hot and dry and cold and humid states.

4. Summary

Accelerated aging tests regarding PID observe normaly only one leakage current path. Uncontrolled condensation can occur and can falsify the measurement. The results show that for realistic life time predictions the knowledge of the active leakage current pathway for the whole operating time is necessary. So in case of CIGS thin film solar modules more than simple climatic chamber tests are necessary to predict their lifetime.

Leakage current pathways for two different encapsulation foils of CIGS thin film solar modules are investigated. The results show that there is a difference of the dominating pathway if the glass surface is wet. For PVB a wet cover glass surface leads to a dominating current through this part of the modules. Whereas for EVA a wet cover glass surface do not lead to a dominating leakage current through it. As expected, for both encapsulation materials the leakage through the back glass shows a comparable magnitude. However, the results are compliant to climate chamber and outdoor measurements. As a result, these measurements can be used to identify the active leakage current pathway in the field. In combination with weather measurements this will enable a correlation of accelerated aging tests and outdoor measurements regarding the transferred charge. Last but not least, the encapsulation foil is generally suitable to influence the active leakage current pathway.

There is a clear difference regarding the amount and the consequences of the leakage currents through the cover and the back glass. The leakage current of the back glass can be over a magnitude lower than the current through the cover glass. But the power loss followed by the leakage current through the back glass needs much less transferred charge. There is a factor of up to 20 between the relevant charge which is needed to damage the module. To carry out the relevant active leakage current pathway a homogeneous contact of the glass plates is necessary (Voswinckel et al., 2015). For analyzing the amount of the leakage current a water basin is suitable. For climatic chamber tests at high temperatures metal plates are more suitable. However, this can lead to non connected areas.

5. References

Osterwald, C. R., Mcmahon, T. J., Adelstein, J., and J. Pruett, 2003. Accelerated Stress Testing of Thin-Film Modules with SnO_2:F Transparent Conductors. National Center for Photovoltaics and Solar Program Review Meeting Colorado.

Fjällström, V., Salom, P. M. P., Hultquist, A., Edoff, M., Jarmar, T., Aitken,B. G., Zhang, K., Fuller, K., Kosik Williams, C., 2013. Potential-induced degradation of $CuIn_{1-x}Ga_xSe_2$ thin film solar cells," IEEE J. PV, Vol. 3, No. 3, pp. 1090–1094.

Scheer, R. and Schock, H.-W., 2011. Chalcogenide Photovoltaics, Wiley-VCH, Weinheim.

Schmidt, H., 2009. Do Thin-Film Modules need special Inverters? 5th User Forum Thin Film Photovoltaics, Würzburg.

Naumann, V., Hagendorf, C., Grosser, S., Werner, M., Bagdahn, J., 2012. Micro structural root cause analysis of potential induced degradation in c-Si solar cells. Energy Procedia, Vol. 27, pp. 1–6.

Manz, P., 2015. "Investigation of Leakage Currents as an indicator of ageing effects (PID) occuring at CIGS photovoltaic modules," Master's thesis, University of Applied Sciences Nordhausen.

Voswinckel, S., Wesselak, V., Fokuhl, E., Schmidt, C., Watzlawik, K., 2015, Dos and Don'ts of Leakage Current Measurement. EU PVSEC, Hamburg.