SHUNT DETECTION IN AMORPHOUS SILICON MODULES BY CURRENT/VOLTAGE-MEASUREMENTS

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ABSTRACT: This work presents a novel method to determine the parallel resistance of individual solar cells in an amorphous silicon based photovoltaic module. The method does not require accessing to the contacts of every cell. Therefore, it is suitable for measurements on encapsulated modules without disassembling and possibly damaging the module. The used setup measures only the current/voltage characteristics of the module. The determination of the parallel resistance exploits the dependence of the photoconductivity of intrinsic amorphous silicon on the illumination intensity. The experiments, in agreement with the simulation, show that shunts which are independent of the illumination, e.g. the interconnection shunts due to laser scribing, are the limiting factor for the operation of the proposed setup.
Keywords: amorphous silicon, module, shunts, Rose factor

1 INTRODUCTION

Requirements on photovoltaic modules demand a stable performance over 20 years. However, the output power of a module might degrade. The degradation especially concerns amorphous silicon (a-Si) based solar modules, as they suffer from a light induced degradation [1]. One of the figures of the degradation is a decreasing shunt resistance (also called parallel resistance R_p) of the module and of the individual cells. The effect of a reduced R_p, even if it only concerns one or few cells, is detrimental on the entire module performance [2,3]. Therefore, the comparison of shunt resistances of every individual solar cell in a photovoltaic module is useful to figure out the reasons for module degradation.

However, once a module is encapsulated, the contacts of an individual cell are not accessible anymore. Removing the encapsulation would damage the cells and the module irreversibly. Therefore, electrical measurements are only possible at the two terminals of the whole module. Some non-intrusive and damaging free techniques were proposed to investigate the individual cell performances, especially the parallel resistance [2, 4-6]. The two-terminal technique presented in [2] investigated the shunt resistance of crystalline silicon solar cells. However, the authors did not prove it for a-Si modules. The laser scanning method in [4] is more accurate, determines the photocurrent besides the parallel resistance and is suitable for thin film solar modules. However, it requires a relatively expensive laser setup and a complex high frequency measurement system. Electroluminescence [5] and lock-in thermography [6] require sophisticated and costly camera setups with energy consuming cooling systems. The goal of this work is to develop a simple and low cost method, which measures the parallel resistance of any individual cell in encapsulated a-Si modules.

In this paper, we propose a new technique to extract the parallel resistance of individual solar cells in a-Si based photovoltaic modules. The technique does not require access to the contacts of the actual cell and only requires measurements of current/voltage (*I/V*) characteristics of the whole module. Therefore, the new method is suitable for measurements on laminated modules without disassembling and possibly damaging them.

2 MEASUREMENT TECHNIQUE

2.1 Setup

Figure 1 presents our experimental setup to determine the parallel resistance R_p of an individual cell in an a-Si module. The required hardware consists of a homogeneous light source, a set of optical neutral density filters and an *I/V* measurement system. The module is composed of *M* series-connected solar cells. The light source exposes the module to a constant and uniform illumination. The spectrum and the intensity are close to one-sun illumination (1000 W/m^2). A neutral density filter with an optical transmission *T* shades one cell *m* with $1 \leq m \leq M$. The filter reduces the light intensity and nearly conserves the light spectrum. The optical transmission *T* corresponds to the illumination ratio of the shaded cell, whereas the remaining *M* - 1 cells see the full illumination. Sequential measurements yield the *I/V* characteristics of the module for *m* = 1…*M* with *M* - 1 cells being 100 % illuminated at a time, and only cell *m* facing the reduced illumination intensity under the filter. This method exploits the dependency of the photoconductivity and the parallel resistance of a-Si solar cells on the illumination intensity [7,8] to deduce the parallel

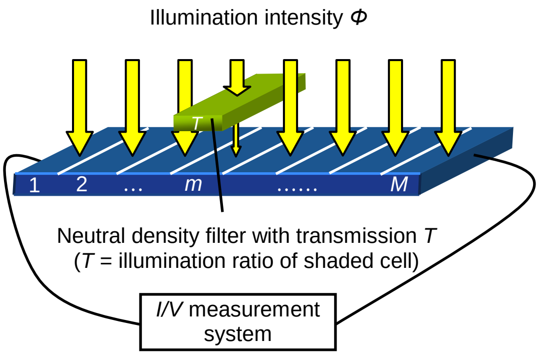

Figure 1: Experimental setup to determine R_p of each cell in a module. The setup consists of a light source, neutral density filters and an *I/V* measurement system. The module is composed of *M* series-connected solar cells. The neutral density filter (optical transmission *T*) shades cell *m* ($1 \leq m \leq M$). The remaining *M* - 1 cells see the full illumination. Sequential shading of one cell after the other and recording the corresponding *J/V* characteristics of the module yield R_p.

resistances of the shaded cells. Therefore, our method is able to localize shunts in an encapsulated module without disassembling it. Furthermore, the setup is suitable for automated industrial applications. The next part of this paper explains how to exploit the photoconductivity dependency on the illumination intensity to obtain the parallel resistance of each individual cell from the measured *I/V* characteristics of the entire module.

2.2 Theoretical background

Amorphous silicon based solar cells are deposited from a homogeneous gas phase. Therefore, the material and thus the parallel resistance R_p are homogeneously distributed over the whole area of the solar cell. Assuming the parallel resistance of a-Si based solar cells to be mainly caused by the leakage through the intrinsic layer, R_p is inversely proportional to the photo-conductivity σ_{ph} of a-Si. For intrinsic a-Si layers, Wronski and Daniel proved the power law [7]

$$\sigma_{ph} \sim \Phi^{\gamma} \qquad (1)$$

relating σ_{ph} to the illumination intensity Φ by the Rose factor γ of the photoconductivity, which is typically $0 < \gamma < 1$. Therefore, the parallel resistance R_p of the a-Si cell is

$$R_p \sim \Phi^{-\gamma} \qquad (2a)$$

and

$$R_p(\Phi_1) = R_p(\Phi_2)\left(\frac{\Phi_1}{\Phi_2}\right)^{-\gamma} \qquad (2b)$$

at two different illumination intensities Φ_1 and Φ_2. This assumption is valid for a certain range of intensities close to one-sun illumination [8].

The measurement setup tests an a-Si module composed of *M* cells connected in series. When the module is fully exposed to the light intensity Φ_1 without any shading, the parallel resistance $R_{p,module}$ of the complete module is

$$R_{p,module} = \sum_{i=1}^{M} R_{p,i}(\Phi_1) \qquad (3)$$

i.e. the sum of the parallel resistances $R_{p,i}(\Phi_1)$ of each individual cell with $1 \leq i \leq M$. When cell *m* is exposed to reduced intensity $\Phi_2 = T\,\Phi_1$ through the neutral density filter, and the remaining *M* - 1 cells are fully illuminated by Φ_1, the photocurrent of cell *m* is the smallest in the module. Therefore it limits the current in the whole module and cell *m* is negatively biased. A previous work investigated the correlation between partial shading and shunts in a module. It showed that the shunt resistance decreases when the shading ratio of a solar cell increases [9]. Our measurement technique combines this effect with the dependence of R_p on Φ. This is illustrated in a simulation in the following part.

2.3 Simulation

Figures 2a and 2b show the simulated parallel resistance $R_{p,module}$ of a module when one cell is partially shaded and sees a fraction *T* of the full illumination through the neutral density filter. The simulation implements the dependence of R_p on light intensity according to eq. (2a) into the one-diode model [10]. The simulated module consists of five solar cells connected in series. All solar cells have identical area, series resistance, ideality factor, reverse saturation current and Rose factor γ. The parallel resistances are $R_{p,1}$ = 1 kΩcm^2, $R_{p,2} = R_{p,4} = R_{p,5}$ = 2 kΩcm^2 and $R_{p,2}$ = 3 kΩcm^2. In Figure 2a, cell 2 with corresponding $R_{p,2}$ is shaded. Assuming $\gamma = 0$, the shaded cell limits $R_{p,module}$. For $\gamma > 0$ (e.g. $\gamma = 0.5$), the increase of $R_{p,2}$ results in an increasing $R_{p,module}$ and leads to a minimum shunt at a certain illumination ratio T_{min} and an increase of $R_{p,module}$ at low illumination intensities. Figure 2b shows the same behavior when cells 1, 2 and 3 are sequentially shaded and $\gamma = 0.5$. At low *T* the increase of $R_{p,module}$ is more pronounced while shading a cell *m* with a large $R_{p,m}$ than a cell with a small one.

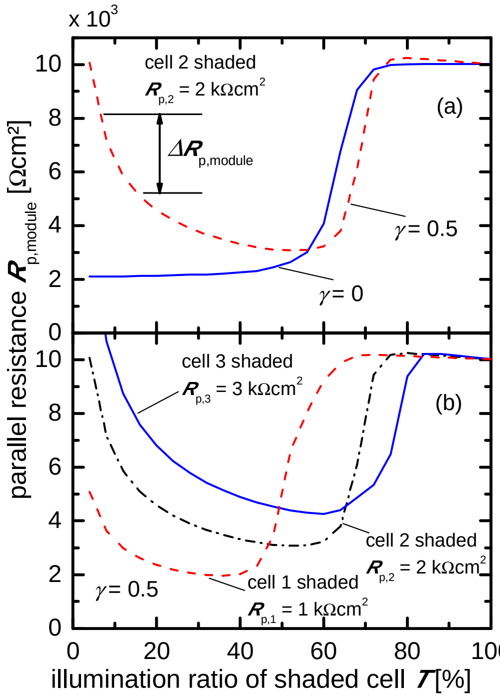

Figure 2: Simulated $R_{p,module}$ when one cell is partially shaded and sees the illumination ratio *T* of the full illumination. The simulation uses one-diode model and R_p dependency on light intensity according to eq. (2a). The module consists of five solar cells in series with $R_{p,1}$ = 1 kΩcm^2, $R_{p,2} = R_{p,4} = R_{p,5}$ = 2 kΩcm^2 and $R_{p,3}$ = 3 kΩcm^2. a) Cell 2 is shaded. Assuming $\gamma = 0$, the shaded cell limits $R_{p,module}$. For $\gamma > 0$, $R_{p,2}$ increases when *T* decreases and overcompensates the decrease of $R_{p,module}$. The change $\Delta R_{p,module}$ is proportional to $R_{p,m}$. b) Cells 1, 2 and 3 are sequentially shaded and $\gamma = 0.5$. At low *T* the increase of $R_{p,module}$ is more pronounced while shading a cell with a large $R_{p,m}$ than one with small $R_{p,m}$. This allows for a comparison of different $R_{p,m}$.

To deduce $R_{p,m}$, we consider the variation $\Delta R_{p,module} = R_{p,module}(\Phi_1) - R_{p,module}(\Phi_2)$ when the shaded cell is exposed to reduced illuminations Φ_1 and Φ_2 corresponding to the transmissions T_1 and T_2 of the neutral density filters both below T_{min}. The parallel resistance $R_{p,m}$ of the shaded cell dominates $R_{p,module}$ in this range. Therefore the previous expression simplifies to

$$\Delta R_{p,module} \approx R_{p,m}(\Phi_1) - R_{p,m}(\Phi_2). \qquad (4)$$

Inserting eq.(2b) into eq.(4) results in

$$\Delta R_{\mathrm{p,module}} = R_{\mathrm{p,m}}(\Phi_2)\left(\frac{\Phi_1}{\Phi_2}\right)^{-\gamma} - R_{\mathrm{p,m}}(\Phi_2) \qquad (5)$$

and

$$R_{\mathrm{p,m}}(\Phi_2) = \Delta R_{\mathrm{p,module}}\left(1-\left(\frac{\Phi_1}{\Phi_2}\right)^{-\gamma}\right). \qquad (6)$$

Thus, $\Delta R_{\mathrm{p,module}}$ is proportional to $R_{\mathrm{p,m}}$, which allows a direct estimation of $R_{\mathrm{p,m}}$. This comparison assumes γ to be constant for all cells in the module and $\gamma > 0$ for low illumination intensities. In the next part of this work we present some experimental results and confirm the limits of the assumptions taken in the simulation.

3 EXPERIMENTAL RESULTS

This part aims to experimentally investigate the behavior of the module when one cell is shaded. Here we prove that the method is only operational in case $\gamma > 0$. Therefore, our experiments first extract γ of a solar cell and module by shading the complete device by a neutral density filter. The inverse slope of the *I/V* characteristics under negative bias voltage yields the experimental value of R_p [10].

Figure 3a displays the dependence of the parallel resistance $R_{\mathrm{p,cell}}$ of one a-Si solar cell on illumination intensity Φ. The model according to eq. (2a) with γ = 0.91 fits the measurement over two orders of magnitude. Figure 3b shows the results of similar measurements on a commercially available mini-module consisting of five solar cells. The parallel resistance $R_{\mathrm{p,module}}$ of the module shows different dependencies on Φ in two ranges. While for the range close to full illumination intensity fitting the measurement data results in γ = 0.28, the range of lower Φ shows γ = 0.03, i.e. $R_{\mathrm{p,module}}$ is almost independent of Φ and constant. We conclude that under this illumination regime, light independent shunts are dominating the shunt behavior of the module. Under full illumination, these shunts are negligible compared to the parallel resistance induced by the intrinsic a-Si layer. A possible source of the shunts is the interconnection between the solar cells after laser scribing.

Figure 4 shows the measured parallel resistance $R_{\mathrm{p,module}}$ of two different types of commercially available mini modules A and B when different cells are shaded. Module A consists of 5 and module B of 12 solar cells. We sequentially shade different solar cells, measure the *I/V*-characteristics and extract R_p of the module. Both examples do not show any increase of $R_{\mathrm{p,module}}$ at low T which corresponds to a Rose-factor $\gamma \approx 0$ at lower light intensities as shown in the simulation in section 2. In this case illumination independent shunts are dominating. Therefore, extracting the parallel resistances of every solar cell in the module is not possible. Only in cases where the shunts in the intrinsic layer are the dominant shunting component, the proposed measurement technique is applicable.

4 CONCLUSION

This work proposes a measurement technique to extract the shunt resistance of every individual solar cell in an encapsulated a-Si module. We show that illumination independent shunts, e.g. the interconnection shunts due to laser scribing, limit the operation of the setup. The technique is simple and cheap and does not require accessing to the contacts of the cell. Thus, it avoids disassembling and possibly damaging the module. Furthermore, the setup is suitable for several automated industrial applications and for field-inspection measurements.

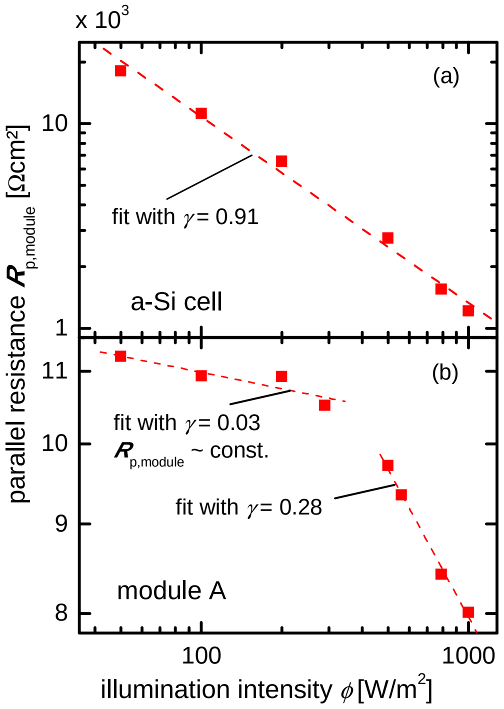

Figure 3: a) Dependence of $R_{\mathrm{p,cell}}$ on illumination intensity Φ derived from *J/V*-measurement on a-Si solar cell. Modeling data according to Eq. (2a) with γ = 0.91 agree with measurements over two orders of magnitude (standard error < 5 %). b) Dependence of $R_{\mathrm{p,module}}$ on Φ derived from measurement on module. Modeling data according to eq. (2a) fits measurement with γ = 0.28 in a range close to full illumination and γ = 0.03 at lower Φ. Shunt in module A is therefore determined by two components: leakage through intrinsic layer with $\gamma > 0$ and illumination independent shunts with $\gamma \approx 0$.

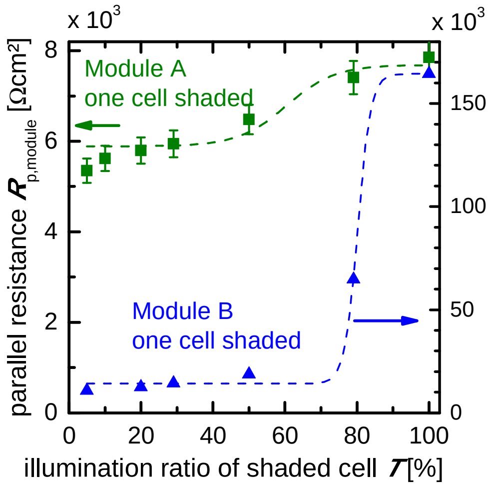

Figure 4: Measured $R_{p,module}$ of two different types of commercially available mini-modules when different cells are shaded. The dashed lines are a guide to the eye and remind on the proposed model in section 2.3. Both examples do not show an increase of $R_{p,module}$ at low T due to small γ at lower light intensities which is due to dominating shunts related to series interconnection of the solar cells.

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