Parameter variation of the one-diode model of a-Si and a-Si/µc-Si solar cells for modeling light-induced degradation

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Abstract. For analyzing the long-term behavior of thin film a-Si/µc-Si photovoltaic modules, it is important to observe the light-induced degradation (LID) in dependence of the temperature for the parameters of the one-diode model for solar cells. According to the IEC 61646 standard, the impact of LID on module parameters of these thin film cells is determined at a constant temperature of 50°C with an irradiation of 1000 W/m² at open circuit conditions. Previous papers examined the LID of thin film a-Si cells with different temperatures and some others are about a-Si/µc-Si. In these previous papers not all parameters of the one-diode model are examined. We observed the serial resistance (Rs), parallel resistance (Rp), short circuit current (Isc), open circuit voltage (Uoc), the maximum power point (MPP: Umpp, Impp and Pmpp) and the diode factor (n). Since the main reason for the LID of silicon-based thin films is the Staebler Wronski effect in the a-Si part of the cell, the temperature dependence of the healing of defects for all parameters of the one-diode model is also taken into account. We are also measuring modules with different kind of transparent conductive oxides: In a-Si thin film solar cells fluorine-doped tin oxide (FTO) is used and for thin film solar cells of a-Si/µc-Si boron-doped zinc oxide is used. In our work we describe an approach for transferring the parameters of a one-diode model for tandem thin film solar cells into the one-diode model for each part of the solar cell. The measurement of degradation and regeneration at higher temperatures is the necessary base for optimization of the different silicon-based thin films in warm hot climate.

1. Introduction
Silicon-based thin film solar cells have a transparent conductive oxide of doped zinc or tin oxide as front contact. Amorphous silicon-based (a-Si) solar cells consist of a thin film p-i-n structure of amorphous silicon (a-Si). Micromorphous thin film solar cells consist of a tandem structure of an amorphous and a microcrystalline silicon thin film (a-Si/µc-Si): each has a p-i-n structure. In the presentation of our work we want to show the electrical behavior of a compound of these different kinds of thin film cells under different climate conditions.

The Staebler - Wronski effect describes the degradation of amorphous silicon (a-Si) solar thin film cells. The a-Si solar cell degradation depends strongly on operating temperature. [1]. Because of their amorphous layer, light-induced degradation is also observed in amorphous/microcrystalline tandem (a-Si/µc-Si) solar cells. [2]
All current-voltage-(I-V) curves can be well described by the extended single-diode model, as seen in Fig. 1. For a tandem solar module, like a-Si/μc-Si, one single-diode model must be selected for each of the two solar cells.

![One-diode-model of a solar module.][3]

In our work we are observing the dependence of the serial resistance ($R_s$), the parallel resistance ($R_p$), the short circuit current ($I_{sc}$), the open circuit voltage ($V_{oc}$) and the diode factor ($n$) on light-induced degradation and the procedure of annealing of thin-film silicon-based solar cells connected with zinc oxide as described by the Staebler-Wronski effect.

In this equivalent circuit the serial resistance describes, among other ohmic loses, the internal losses of electrical energy through the recombination of electron-hole pairs at the dangling bonds, which are caused by the Staebler-Wronski effect [4]. This recombination in dangling bonds increases during the light-induced degradation [5]. The creation of these dangling bonds is reversible [6]: As described by the Staebler-Wronski effect (SWE), the amount of dangling bonds reduces at higher temperatures. Consequently the probability of recombination of electron-hole pair reduces with higher temperatures. The efficiency at standard test conditions (STC) and the fill factor decrease with increasing amount of dangling bonds and vice versa.

2. Materials and Methods

Solar cells of a-Si and a-Si/μc-Si are degraded under controlled conditions at different constant temperatures and constant irradiation of 1000W/m². At fixed times the efficiency of the modules is measured at 25°C, 1000W/m² and a spectrum of AM 1.5, so called standard test conditions (STC). Consequently comparable values are received. The key parameters $n$, $V_{oc}$, $I_{sc}$, $R_s$, and $R_p$ are extracted of the measured I-V-curves.

The samples are placed under such a light-soaking bench (LSB) for several days. The sun simulator has an irradiation of 1000W/m². The modules are degraded usually at 50°C. For our measurements the LSB is set to a constant temperature of 70°C, 50°C and 30°C. The mini modules are retained in regular time intervals from the LSB, cooled down to 25°C and measured again at STC. Afterwards they are put back to the LSB for further light soaking.

The diode factor was calculated by the measured I-V-curve for $V>V_{mp}$ with elementary charge ($e$), Boltzmann constant ($k$) and the temperature of the solar module ($T$):

$$N_n = \frac{e}{kT} \frac{dV}{d[I_{dark}]}$$  \hspace{1cm} (1)

with

$$I_{dark} = I_{sc} - I - \frac{V - IR_s}{R_p}$$  \hspace{1cm} (2)
N is the number of measured solar cell: for tandem solar cell (two solar cells) is N=2.

3. Results

3.1. Degradation of a-Si solar cells at different temperatures
As it was already reported by Staebler and Wronski [1], the efficiency and the fill factor of amorphous thin film solar cells decrease in the first 100 hours in dependence of the constant operating temperature. Two components of the fill factor are Voc and Isc. During the light-induced degradation Voc and Isc are decreasing: The lower the degradation temperature the lower the stabilized Voc and Isc. This decreasing effect is shown in figure 2 and 3.

![Figure 2. Open circuit voltage Voc of a-Si during light-induced degradation normed at its initial value (Voc₀).](image1)

![Figure 3. Short circuit current Isc of a-Si during light-induced degradation normed at its initial value (Isc₀).](image2)

![Figure 4. Serial resistance Rs of a-Si during light-induced degradation normed at its initial value (Rs₀).](image3)

![Figure 5. Parallel resistance Rp of a-Si during light-induced degradation normed at its initial value (Rp₀).](image4)
The different resistances $R_s$ (figure 4) and $R_p$ (figure 5) have got an opposite trend: $R_s$ increases, while $R_p$ decreases. The impact of the variation of these parameters is a function of the decreasing temperature: The higher the temperature the higher is the impact of the light-induced degradation.

3.2. Degradation of a-Si/µc-Si solar cells at different temperatures

The degradation of a-Si/µc-Si is caused by the degradation in the a-Si solar cell. The degradation is proportional to the thickness of the intrinsic layer of the a-Si layer [7]. To eliminate the different thickness in the intrinsic layers caused by production fluctuations, the solar cells were first degraded at 50°C and afterwards we degraded them at a lower temperature. All of the values were normed of their initial value before the degradation at 50°C.

![Figure 6](image6.png)
**Figure 6.** $R_s$ of a-Si/µc-Si after stabilization at a degradation temperature at 50°C and during light-induced degradation at 30°C normed at its initial value ($R_{s0}$)

![Figure 7](image7.png)
**Figure 7.** $R_p$ of a-Si/µc-Si after stabilization at a degradation temperature at 50°C and during light-induced degradation at 30°C normed at its initial value ($R_{p0}$).

The serial resistance increases during the degradation at a temperature of 50°C at a factor of 1.22 of the initial value. Afterwards the samples were degraded at 30°C: the serial resistance increases further (figure 6). It stabilizes at a factor of 1.34 +/- 0.04.

![Figure 8](image8.png)
**Figure 8.** Open circuit voltage $V_{oc}$ of a-Si/µc-Si after stabilized at a degradation temperature at 50°C and during light-induced degradation at 30°C normed at its initial value ($V_{oc0}$)

![Figure 9](image9.png)
**Figure 9.** Short circuit current $I_{sc}$ of a-Si/µc-Si after stabilized at a degradation temperature at 50°C and during light-induced degradation at 30°C normed at its initial value ($I_{sc0}$).
This stabilized factor is higher than if the samples would have been degraded at a constant temperature of 30°C. The increasing effect of Rs was already observed under field test conditions [8].

The parallel resistance Rp decreases. After a small increasing in the first hours (figure 7), Rp decreases with a high fluctuation.

Figure 8 shows Voc during the procedure of degradation. Before the samples were degraded at 30°C, Voc increases at the degradation of 50°C. Voc decreases at a degradation temperature of 30°C.

As already shown for a-Si solar cells, Isc decreases with lower temperatures for a-Si/µc-Si solar cells.

![Diagram](image-url)

**Figure 10.** Diode factor n for a tandem solar module (N=2). After 600h the degradation temperature was decreased from 70°C to 30°C

The diode factor decreases stronger with lower degradation temperatures. The diode factor is calculated for one tandem solar cell, composed of one a-Si and one µc-Si solar cell. The diode factor stabilizes at about 200h of degradation, independent of the degradation temperature.

### 3.3. Degradation of a-Si/µc-Si solar cells at humid conditions

Samples of non-encapsulated a-Si/µc-Si solar cells were exposed to dark and high humidity conditions. We observed a decreasing efficiency (figure 11). This decreasing effect is lower than the decreasing effect described by the Staebler-Wronski effect. It is stabilized in less than 200h. The humidity air does not have any contact to the silicon layers of the solar cell. Because the solar modules are not encapsuled, the zinc oxide is in direct contact to air and its high humidity. By the absorption of humidity by the TCO the serial resistance increases [9]. By this increasing of Rs the ohmic loses in the TCO increases. By this increasing loses the efficiency of the solar cells decreases.

![Diagram](image-url)

**Figure 11.** Efficiency (Eff) degraded at humidity conditions normed at its initial value
4. Conclusions

The investigation of light induced degradation of micromorph solar modules under different degradation temperature shows, that the serial resistance in the equivalent circuit increases at lower temperatures because of the light-induced degeneration of the Staebler Wronski effect. The average degradation temperature plays a central role for the equivalent circuit of micromorphous solar modules and its light-induced degradation behavior.

Also it was shown, that humidity air has a decreasing effect of non-encapsulated solar cells: The humidity affects the zinc-oxide and decreases the efficiency of the solar cell: By increasing the serial resistance the ohmic loses is higher in the zinc oxides. Encapsulating the solar cells with a back glass can decrease the decreasing effect.

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References

[1] Staebler D and Wronski C R 1977 Appl. Phys. Lett. 31 292
[2] Weicht J A, Hamelmann F U and Behrens G 2013 Proc. EU PVSEC 28th (Paris, France 30. September – 4 November 2013) 2542
[3] Quaschning V 1966 Simulation der Abschattungsverluste bei solarelektrischen Systemen (Berlin, Köster)
[4] Chan D S and Phang J C 1987 IEEE Transact. Electron Devices 34 286
[5] Kolodziej A 2004 Opto-electronics Review 12 21
[6] Crandall R S 1991 Phys. Review B 43 4057
[7] Meillaud F, Shah A, Droz C, Vallat-Sauvain E and Miazza C 2006 Solar Ener. Mater. Solar Cells 90 2952
[8] Weicht J A, Hamelmann F U, A. Domnik and Behrens G 2014 Proc. 40th IEEE PVSC (Denver, Colorado, USA 8-13 June 2014)
[9] Yaklin M A, Schneider D A, Norman K, Granata J E and Staiger C L 2010 Proc. 40th IEEE PVSC (Honolulu, Hawaii, USA 20-25 June 2010)