Outdoor degradation of thin film amorphous silicon based PV modules

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Abstract. One of the main problems in thin film silicon based modules is the deterioration of their performance upon exposure to light. The presented work focuses on a methodology for evaluation of thin-film photovoltaic module degradation behavior under real operating conditions. An outdoor degradation of double junction a-Si:H/a-Si:H modules was investigated using automated measurement setup for a period of two years. A deterioration of the module’s maximum power was observed due to the well known Staebler-Wronski effect, which main causes are the decrease of open circuit voltage and the fill factor of the module. The obtained results can be correlated to the technology and construction of the thin film silicon based modules.

1. Introduction
One of the main problems in thin film silicon based modules is the deterioration of their performance upon exposure to light. The degradation of the electric parameters of the a-Si thin film modules over the time is observed upon exposure to solar radiation and in conditions of electric current flow which is manifested as decreasing of module power and, respectively, its efficiency. When the amorphous silicon layer is exposed to light or when an electric current is injected into the layer, a degradation effect takes place. The weaker bonds within the amorphous silicon network are broken and, thereby, new dangling bonds are created. Usually, after a time of about 1000 hours of light exposure, amorphous silicon layers “stabilize”. It is, however, often observed that degradation still continues, albeit at a lower rate, even after 1000 hours of light exposure.

In practice, for present state of the art the p-i-n amorphous silicon solar cells one finds degradation in the range 10% to 30% for cells of i-layer thickness between 200 nm and 400 nm and cells of thicker i-layers have higher relative degradation. The use of tandem (double junction) solar cells is one way to reduce the effect of light-induced degradation because the top cell in a tandem structure can be kept very thin, and therefore shows little degradation.

The presented work focuses on a methodology for evaluation of thin-layer photovoltaic module degradation behaviour under real operating conditions. An outdoor measurements of six double junctions a-Si:H/a-Si:H modules have been carried out at the Central Laboratory of Solar Energy and New Energy Sources, located in Sofia, Bulgaria. The degradation of module performance, initially due to the well-known light-induced degradation described by Staebler and Wronski [1] has been investigated. The module performance parameters have been determined by outdoor measurements for
a long period of time (two years) under varying conditions of solar irradiance and air temperature in order to estimate the degradation effects.

2. Experimental set-ups

2.1 Selection of module types
The measurements are focused on thin film modules, in particular, p-i-n - type double junction (a-Si:H/a-Si:H) structure. They are rated by the manufacturer at 40Wp. Typical thickness of the i-layer of the thin top cell in a tandem structure is 100-120 nm and for the bottom cell i – layer is 400-500 nm. The modules are glass/glass laminates of size 1245x635mm, and 0.79 m² module area.

Six PV modules, labelled M 1 to M 6, have been deployed outdoors at the beginning of June 2008. During the whole measurement period the modules were mounted on a fixed south facing open rack at a fixed 45° tilt all the year round.

2.2 Outdoor electrical characterizations.
A major problem in thin-film photovoltaic modules is the degradation of their parameters with time at operation in real conditions. In amorphous semiconductors under solar radiation and at electric current flow degradation of the fundamental electric parameters with time is observed, which is manifested as a reduction of module power and, respectively, its conversion factor. The investigation of the performance of single- and multi-junction a-Si thin film modules at outdoor conditions are the object of many papers [2, 3, 4 and 5]. In real conditions test the modules are put under the continuous influence of solar radiation and temperature.

The especially designed experimental setup which was developed for to perform long-term electrical measurements is presented in figure 1. The unit MUX-1 switches over the modules from standby generation state in the maximum power point, to measurement mode for tracing the I-V curves of the modules, at a specified interval (i.e. every 30 minutes). In I–V curve tracing mode, the modules are consequently connected by unit MUX-2 for measurement by the Agilent 34970A measurement system. The data acquisition software is based on the LABVIEW package for laboratory automation.

![Automated measurement setup.](image)

The accumulated experimental data are processed with especially developed software. In order to process the data correctly filters of random fluctuations have been employed. Usually the parameters of solar radiation are measured and then one proceeds with the measurement of the modules load characteristics. This approach allows obtaining various functional dependencies by processing the results of the database. For example:
- The generated power $P_{\text{max}}$ as a function of time, using solar radiation and ambient temperature as a parameter;
- The short circuit current $I_{\text{sc}}$ as a function of time at fixed values of solar radiation and for a certain temperature range;
- The degradation of the fill factor (FF) with time, FF being determined at a fixed value of solar radiation and fixed temperature range.

An advantage of the proposed methodology provides an objective measurement and processing of large amounts of data. Measurements are made in real conditions, following all environmental parameters (solar radiation, air temperature, spectral density of solar radiation). The PV modules are kept in generation mode and the current magnitude can be set. The developed measurement system allows assessing the degradation at different types of thin-film PV modules experimentally.

3. Results and discussion
A set of 6 thin film amorphous Si modules (M1…M6) are measured for a two-year period. With our developed software, the dependence of electrical parameters with time can be plotted, so that one can see the different degradation effects. In figure 2 the degradation of $P_{\text{max}}$ for all modules can be seen. One can choose the desired ambient temperature and irradiance range using the sliders on the left side of the figure.

![Figure 2. Degradation of $P_{\text{max}}$.](image)

It should be noted that the degradation of $P_{\text{max}}$ is more pronounced in the first 120 days. This cannot be seen for module M4, as it was exposed to solar radiation 6 months before it was connected with the other 5 modules to the measurement system. From the collected data during the investigated long-term period it is possible to estimate the deterioration of the $P_{\text{max}}$ as a function of the time. The light-induced degradation of $P_{\text{max}}$ at different solar radiation is shown in figure 3 and table 1. The most severe degradation was observed after the first 3 months of outdoor exposure.

From the accumulated in the database results one can assess maximum power output $P_{\text{max}}$.
deterioration at various solar radiation values. The light-induced degradation of Pmax at different light intensities is shown in figure 3 and table 1. After the first 3 months of outdoor exposure, the rate of degradation for year is between 2 to 5%.

The power output degradation due to illumination is the manifestation of the Staebler-Wronski effect. The drop in performance is ascribed to the creation of additional metastable defects in the absorber layer, which act as extra trapping and recombination centres. As a result of trapping, the space charge distribution in the intrinsic a-Si:H is changes in such a way that internal electric field

| Radiation (W/m²) | Pmax (W) | After 1 year (W) | After 2 years (W) |
|------------------|---------|-----------------|------------------|
| 1000 (13:30 h)   | 45      | 41              | 39.3             |
| 900 (12 h)       | 41.3    | 38.1            | 35.8             |
| 750 (11 h)       | 37.8    | 33.7            | 32.9             |
| 300 (9 h)        | 15.7    | 14.2            | 13.8             |

Figure 3. Pmax at different light intensities.

Figure 4. Degradation of open-circuit voltage Voc.

The experimental data about the stability of the electrical parameters demonstrate a decrease of the open circuit voltage Voc shown in figure 4. The same behaviour is observed under different intensities of solar radiation. It is most probably that the defects and microvoids are forming conductive paths causing increased leakage current. The open-circuit voltage Voc depends on the value of photogenerated current density, but it depends also on the diode reverse saturation current J0, also [6]. Therefore, Voc can decrease if the diode factor n increases (indicating a diode of a lower quality) [6]. It
should be noted that short circuit current $I_{sc}$ does not change upon the same conditions, even it values increase – figure 5 (start day 1.07.2008). The measurements of $I_{sc}$ in August 2008 and the same month in 2010 showed that this parameter remains constant value (figure 6).

![Figure 5. Degradation of $I_{sc}$](image)

![Figure 6. Short circuit current vs. irradiance for module M1.](image)

The most significant degradation is obtained for the value of the fill factor FF shown in figure 7. The measured value is a very sensitive experimental indication of the quality of a solar cell and it should be used as a complementary quantity, in addition to $V_{oc}$, to characterize solar cell quality. The difference of the fill factors between the initial and the degraded state can be explained by the effect of light induced degradation. The most common effects encountered are:
- collection problems due to the low $i$-layer quality or to defects at the $p/i$ and $i/n$ interfaces;
- high series resistance due to unsatisfactory contact layers;
- low parallel (shunt) resistance;
- high diode reverse current due to leakage paths and bad quality diodes.

One possible reason for this is the decrease in carrier collection caused by light induced defects which leads to degradation of the FF.
Shunt resistance $R_{sh}$ represents the ohmic shunts through the diode due to pinholes and defects within the i-layer. Figure 8 shows $R_{sh}$ (shunt resistance) for M1 determined from I-V characteristics using the one-diode model. The values in blue show the initial values of $R_{sh}$ at different irradiance, and in red are the values after 2 years.

Figure 8. Shunt resistance $R_{sh}$ vs solar irradiance. I-V curves have been taken down in August 2008 and August 2010, respectively.

Figure 9. Series resistance $R_s$ vs solar irradiance. I-V curves have been taken down in August 2008 and August 2010, respectively.

It can be seen that $R_{sh}$ changes only slightly in the irradiance range 400 W/m$^2$–1000 W/m$^2$, $R_{sh}$ degrades by 50% after 2 years of outdoor exposure. One explanation is that the defects and microvoids formation directly affect shunt resistance. Most likely, this is caused by generated defects in the i-layer, which influence the diode quality factor. The shunt resistance $R_{sh}$ have no effect on short circuit current, but lead to strong decrease in $U_{oc}$, which is clearly seen in our case.

Series resistance $R_s$ is calculated from the load characteristics of module M1, applying the one diode model. Usually, $R_s$ represents the contact resistance due to the TCO- layer and the insufficiently
doped p- and n-layers. The estimated value reveals that $R_s$ depends on the solar irradiance level, but does not show light-induced degradation effect – figure 9).

4. Conclusions
The behaviour of double junction (a-Si:H/a-Si:H) PV modules at outdoor conditions has been investigated for two years and deterioration of their performance upon exposure to sunlight observed. It was found that the $U_{oc}$ is decreasing during this period. No change in $I_{sc}$ was observed. Using the one diode model, $R_{sh}$ and $R_s$ were estimated. It was found that $R_{sh}$ reduces its value with 50% during these two years while no significant changes have been observed for $R_s$. The methodology used on the experimental data in the database, enables us to study the degradation effect of module’s performance, and to correlate the results with the production technology and construction of the thin-film silicon modules.

5. References
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