Light-Induced Degradation of Thin Film Silicon Solar Cells

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Abstract. Silicon-wafer based solar cells are still domination the market for photovoltaic energy conversion. However, most of the silicon is used only for mechanical stability, while only a small percentage of the material is needed for the light absorption. Thin film silicon technology reduces the material demand to just some hundred nanometer thickness. But even in a tandem stack (amorphous and microcrystalline silicon) the efficiencies are lower, and light-induced degradation is an important issue. The established standard tests for characterisation are not precise enough to predict the performance of thin film silicon solar cells under real conditions, since many factors do have an influence on the degradation. We will show some results of laboratory and outdoor measurements that we are going to use as a base for advanced modelling and simulation methods.

1. Introduction
Thin-film silicon in p-i-n structure is already used for commercial solar cells for decades [1]. Amorphous silicon (a-Si) uses very thin absorbing layers of just a few 100 nm thickness, the deposition processes are well known from flat panel display industry and scaleable to large areas of some square meters, which allows low production costs [2]. However, the resulting efficiencies are low compared to other solar cell technologies (5-7%). Using tandem or triple junction solar cells in combination with microcrystalline silicone offers the potential for efficiencies up to 10-15%, which makes this technology more competitive [3].

A major disadvantage of amorphous silicon is the light-induced degradation (LID) that occurs during illumination of the cells [4]. The so-called Staebler-Wronski-effect reduces the efficiency by breaking weak silicon-hydrogen bonds in the absorbing layer, leading to an increasing density of defects [5]. This effect depends very much on the quality of the intrinsic a-Si layer, the thickness of the layer, the operation temperature, the intensity of the light and other parameters [6]. The standard test for the LID uses an illumination of 1000 W/m² at 50°C for 1000 hours at open circuit conditions, which is different from real life operation of the solar cells [7].

In this paper we show results of a-Si cells and modules produced on industrial deposition systems, in order to find a suitable trade-off between material quality, deposition time and stable solar cell efficiency. The transparent conductive layer (fluorine doped tin oxide or boron doped zinc oxide) enables higher efficiencies with advanced light scattering, but also shows an influence on the LID of the amorphous silicon.

We also show long term measurements of industrial thin-film silicon modules under outdoor conditions. We will discuss the need for advanced models in order to get reliable simulations for the performance of thin-film silicon solar cells under different climate conditions. The LID is reduced in tandem structures due to the stable microcrystalline layer, but the series connection of the subcells makes the LID of the amorphous part still important for the cell efficiency.
2. Method
The results presented in this paper have been measured in the lab on thin film silicon solar cells produced by production sized deposition systems (1.4 square meter glass substrates) by Applied Materials and Oerlikon. The outdoor measurements were performed on full size commercial modules. A Wacom steady state solar simulator with selfmade liquid cooled samples stage was used for IV-curve measurement under standard-test conditions (1000 W/m², AM 1.5, 25°C). Measurements of external quantum efficiency (EQE) were performed on a taylor made system with monochromator and additional bias illumination for tandem cells. Light induced degradation was done in a light soaking bench with controllable substrate temperature.

The outdoor characterisation of the full size modules was performed with the Sol.Connect monitoring system provided by Papendorf SE. The weather station with calibrated reference cells and pyranometers for the measurement of solar irradiation was bought from EKO Instruments. A taylor made database is logging all relevant parameters of the stations every minute: IV-curves of up to 10 modules, module temperatures, irradiation detected by pyranometer and reference cell, diffuse and direct irradiation, wind speed and direction, humidity, rain, air temperature. A detailed description of this system can be found elsewhere [8].

The modelling and simulation is not topic of this paper, the work is still in progress. First results are already published [9, 10].

3. Results
The outdoor performance of PV modules shows differences from the expected performance, usually the modules are labelled with a peak power value (in Wp) and a temperature coefficient. With the knowledge of irradiation (in W/m²) and module area the efficiency can be calculated. Some results are shown for amorphous (a-Si), amorphous/microcrystalline tandem (a-Si/µc-Si) and polycrystalline (c-Si) modules. In summer the irradiation is up to 1000W/m² at noon (figure 1), the module temperature reaches 60°C at that time. The efficiency is not constant during the day, it is lowered at high irradiation due to thermal effects, and lowered in the morning and in the evening by the weak light behaviour.

![Figure 1. Efficiency of different Si-modules on a sunny summer day in Germany.](image)
On a dark winter day the irradiation is as low as 20 W/m², even with low module temperatures of below 10°C the efficiency of the c-Si module is reduced by about 50%, while the a-Si thin film module shows no significant reduction (see figure 2). This effect shows the advantage of thin film silicon at low light conditions [11]. A precise simulation of the performance of PV-modules is difficult; taking the Staebler-Wronski effect in account makes things even worse [7].

Since the amorphous part of a-Si/µc-Si tandem cells is mostly relevant for light induced degradation, single junction a-Si cells are investigated in detail about the factors influencing the light induced degradation (LID). Figure 3 shows the degradation of single junction a-Si cells on ZnO:B front contact with different i-layer thickness as a function of time. The 390 nm i-layer cell has the highest initial efficiency of 10.86 %, but also the highest degradation of 33.6% and thus the lowest stable efficiency of 7.2% (see table 1). Highest stable efficiency shows the thinnest i-layer cell (310 nm) with degradation from 10.55% to 7.34% (LID: 30.4%). Increasing i-layer thickness makes no sense the goal in production must be thinnest possible i-layer. It can be seen that the degradation does not change much after 300 h, for the following experiments the time was limited to 312 h.

Figure 2. Efficiency of different Si-modules on a cloudy winter day in Germany.

Figure 3. Degradation of a-Si cells with different i-layer thickness.
Table 1. Efficiency of cells with different i-layer thickness during LID.

| i-layer  | Initial | 312 h | 1000 h | Degradation |
|----------|---------|-------|--------|-------------|
| 310 nm   | 10.55   | 7.53  | 7.34 % | 30.4%       |
| 350 nm   | 10.77   | 7.46  | 7.25 % | 32.7%       |
| 390 nm   | 10.86   | 7.29  | 7.21 % | 33.6%       |

With industrial large area deposition, homogeneity of the films becomes an important issue. With a deposition area of 1.4 m² thickness variations between the center and the corners of about 10% cannot be avoided. Cells from different positions of the substrate show different results (figure 4). The results from two different runs with 270 nm i-layer are almost equal, but the difference between the middle position and the corner position are significant, the LID is 25% at the corner and just 20% in the middle. Such effects are resulting in a reduced performance of full size modules compared to small cells produced in a lab.

Figure 4. LID on different positions of a 1.4 m² substrate.

Figure 5. LID for i-layer with different deposition rates on different positions.
Another important factor is the deposition rate of the intrinsic layer. The stability to light exposure can be improved by a small growth rate, which gives the amorphous silicon a higher material quality. Unfortunately, for cost efficient production highest possible growth rates are required. For commercial use of amorphous silicon a trade off between deposition rate and LID has to be defined. In figure 5 the development of the efficiency during LID can be seen for low (400 W rf power) and high growth rate (650 W) for three different positions on the substrate. Please note that the area of highest efficiency is in the middle for high growth rate, while it is at the corner for low growth rate, with a degradation of just 15%.

Another influence is given by the front contact TCO of the substrate. The different morphology of the ZnO:B shows an influence on the LID. In figure 6 the LID results for identical a-Si layers on different ZnO:B substrates are plotted. For a similar sheet resistance of about $8 \, \Omega_{\text{sq}}$ the level of boron doping was changed with the deposition time, thin ZnO layers are highly doped (11 minutes deposition time, 2.8 sccm diborane flow), while thick layers are slightly doped (17 minutes, 1.6 sccm) with an increased surface roughness. The lowest LID can be found for the thicker, low doped TCO’s.

![Figure 6. LID for a-Si mini modules on different ZnO:B substrates.](image)

For this set of samples the possible regeneration by dark annealing was studied (figure 7). After the degradation for 312 h at 50°C with 1000 W/m² the samples were heated in an oven for 88 h at 80°C.

![Figure 7. Regeneration by dark annealing of a-Si mini modules.](image)
The efficiency was measured, and the samples were once more heated for 90 h at 100°C. It can be seen, that the degradation could be partly healed with this dark annealing steps. For a complete healing even larger times, or higher temperatures are needed. Some other cell layers do have an influence on the degradation, as the buffer layer between p-doped silicon and intrinsic silicon. But since this influence is small, it is not shown here. The silicon p-layer also affects the LID, as described in [12].

Finally in figure 8 the development of degradation normalised on the initial values for tandem a-Si/µc-Si mini modules produced in a factory line are shown. The degradation has been performed under different, but stable temperatures. It can be seen, that the degradation compared to the standard test at 50°C is significantly lower at 80°C, and higher at 20°C. This shows that for regions with higher temperature and solar irradiation a better performance of the modules than in central Europe can be expected.

![Figure 8. Degradation of a-Si/µc-Si mini modules at different temperatures.](image)

![Figure 9. Temperature dependent performance of a-Si/µc-Si tandem modules for different degradation temperatures.](image)

If the results of degradation at different temperatures with resulting different stable efficiencies are combined with the temperature dependent performance of such modules, the calculations result in the plots on figure 9. Here we have the normal temperature coefficient for the modules for several different degradation temperatures. This may give first impression about the real life performance of
tandem modules. However, still the changing temperature during LID is not taken into account in this case. More work is needed for dynamic simulations.

4. Conclusions
The Staebler-Wronski-effect in a-Si solar cells and modules produced by industrial deposition equipment can be influenced by many factors during deposition. The degradation can be reduced mainly by the right choice of TCO substrate and i-layer thickness and a low deposition rate for the intrinsic silicon. Other factors such as the p-layer structure and the buffer layer also have a minor influence on the LID. All these results for a-Si can be used for the amorphous part of tandem junction thin film silicon cells. However, progress in the reduction of the LID does usually have the disadvantage of lower deposition rates, more raw material consumption and a lower production line output.

The temperature dependence of the LID and the ability for regeneration at high temperatures makes a prediction about the performance of a-Si containing solar cells difficult. In difference to standard test conditions with a stable irradiation and constant cell temperature, modules are facing changing light and temperature during degradation. The usual models are more or less good for central European climate conditions, but will differ reasonable for hotter or colder climate regions.

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