Investigation of light-induced degradation of tandem photoconverters on a-Si:H/μc-Si:H

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Abstract. Photo-induced degradation of tandem a-Si: H/μc-Si: H photoconverters under standard light flux densities of 1000 W/m² (AM1.5G) have been investigated. Spectral and current-voltage characteristics of solar modules produced with standard and modified recipes are presented and analyzed. This research is dedicated to the optimization of crystallization level in intrinsic layer of lower (microcrystalline) cascade.

1. Introduction

Solar cells based on the a-Si:H/mc-Si:H (micromorph) thin-film technology became more widespread in recent years [1]. Record efficiency for one-cascade a-Si:H photoconverters is 10.1%, for double-cascade tandems a-Si:H/mc-Si:H – 12.3% under standard light flux conditions AM1.5G. Thin-film technology allows to produce one of the lowest costs of watt for solar modules on the market [2,3,4]. This is achieved primarily due to the low production cost because of the relatively simple production technology and low raw materials consumption.

Main disadvantage of micromorph technology is photoinduced (light) degradation – a decrease of photoelectrical characteristics under the light exposition [5]. This process is closely connected with the Staebler-Wronski effect – effect of decrease in the photoconductivity of a-Si:H films under continuous light impact [6]. Typical decrease in the efficiency of micromorph cells is 10 to 30% and depends on the number of subelements, thickness and chemical compound of photoactive layers [7,8].

Improvement in the efficiency of micromorph modules can be achieved by two ways – increasing the initial efficiency and reducing the degradation of the modules.

In this article the micromorph modules degradation is researched. Photoconverters in question were produced on TEL Solar (formerly Oerlikon Solar) installation based on a standard recipe (sequence of steps to produce solar cell) and modified one by TF TE Ioffe R&D Center (TFTC). This research is dedicated to the optimization of crystallization level in intrinsic layer of lower (microcrystalline) cascade.

2. Methodic of the experiment

1100x1300mm glass with high optical transmission is used as a top substrate. Different layers are sequentially deposited on the top substrate: front transparent conduction oxide (TCO) layer (ZnO), a-Si:H, mc-Si:H and back TCO contact. A polymeric reflector at the back is used to increase the...
operating current. PECVD (Plasma Enhanced Chemical Vapor Deposition) under high pressure method is used to obtain TCO layers - Boron doped ZnO layers with a light scattering degree up to 25-27% and optical transparence (400-1000nm) over 85%. When ZnO layer thickness is 1600-1700 nm, the electrical resistance of the front contact is 16-18 Ohm/□ (Ohm per square), for back layer – 13-15 Ohm/□.

Photocascades are deposited by a PECVD method. It uses a mixture of silane and hydrogen, as well as doping gases trimethylboron (for p-layers) and phosphine (for n-layers). In addition, methane additive is added to the gas mixture to increase the transparency of p-layer of top cascade. CO2 is added to the gas mixture with the reflectors deposition.

Each of the cascades is a p-i-n diode and current flow between them is provided by the recombinative junctions. The pin configuration is used instead of the classical pn-junction due to special material properties of used a-Si:H and mc-Si:H materials. These materials are characterized by a large number of structural defects that serve as traps for electrons and holes, whose presence reduces the diffusion length of charge carriers. Unlike classical crystalline semiconductors a small diffusion length leads to the inability to use any significant thickness of photovoltaic structures and, as a consequence, produce the essential values of the photocurrent. To overcome this fundamental limitation pin-diode circuit is applied, where undoped i-layer is inserted between the doped layers. In this i-layer the absorption of light and separation of charges takes place. Charge transfer is carried out not by the diffusion mechanism, but by the drift in an electric field formed by an energy barrier in the pin-junction. The drift length depends on the electric field, which is determined by the structural parameters: the thickness of the i-layer, the degree of doping of p- and n-layers, the band gap value, the quality of the deposited layers – all parameters of pin-structure deposition process.

Usage of the two cascade scheme can lead to the growth of the cell efficiency by increasing the spectral sensitivity of solar cells, which is achieved with materials with different band gaps as absorbers, as well as with reducing thermalization of photocarriers losses due to the separation of absorption of light in two cascades. In order to ensure separation of photoconverter into individual cell and electrically connect them laser scribing is used - the removal of layers deposited material on a strictly limited area with laser beam. By implementing such a sequence of operations monolithic electrical connection of individual cells is performed in the composition module.

Schematic representation of the structure and electron micrograph of researched cells are presented in Fig. 1 [9].

![Figure 1](image_url)

**Figure 1.** Micromorph solar cell: (a) schematic structure (b) electron micrograph [9].

Optimization of crystallization level (degree) in intrinsic layer of lower (microcrystalline) cascade is performed in this research. This parameter has an optimum value in the range of 55-60% [10, 11], which corresponds to the maximum value of the stabilized power. Increase in crystallinity degree
relating to this range leads to an increase of the absorption coefficient in the red and near infrared range and, consequently, to an increase in a short-circuit current, however, negatively affects the open circuit voltage due to increase in number of cracks in the material. Crystal grain boundaries are insufficiently passivated, there is a large number of defects, resulting in increased surface recombination and reduced load voltage. Moreover, there is evidence [12,13] that too high a degree of crystallinity of the microcrystalline silicon layer results in a dark material degradation due to the diffusion of oxygen atoms and water molecules to the grain boundaries, which reduces the open circuit voltage over time. Reduction of the crystallinity degree results in a reduction of the coefficient of absorption in the red and near infrared range and, consequently, reduction of the short circuit current, as well as increase in the level of photo-induced degradation, due to the increase of the volume fraction of the amorphous phase.

The crystallinity level is determined by Raman scattering and calculated as follows: \((I_{520} + I_{510}) / (I_{520} + I_{510} + I_{480})\), where \(I_{520}\) and \(I_{510}\) is the intensity of Raman lines at frequencies at 520 and 510 cm\(^{-1}\), corresponding to the thermal lattice vibrations of the silicon crystallites, \(I_{480}\) - the intensity of the Raman band at a frequency at 480 cm\(^{-1}\), corresponding to the thermal vibrations of the amorphous matrix. The ratio of intensities of these peaks is taken as the degree of crystallinity of the material. As part of the research optimal characteristics are obtained with a degree crystallinity of i-layer at level of 52-53%. In this paper we compare the photovoltaic characteristics of cells with a crystallinity degree of the i-layer in the lower cascade at 66-68% (basic recipe) to the photovoltaic characteristics of cells with a crystallinity degree of the i-layer in the lower cascade at 52-53% (modified recipe). In addition to the crystallinity level there is optimization of the deposition rate and area uniformity of deposition. Comparison of these parameters for two recipes is given in Table 1.

| Recipe     | Deposition rate, A / s | Area non-uniformity thickness, % | Crystallinity level, % |
|------------|------------------------|---------------------------------|------------------------|
| Base       | 4,4                    | 18,5                            | 67                     |
| Modified   | 5,6                    | 7,9                             | 53                     |

Thus, we obtained in the recipes with modified i-layers of the lower cascade a lesser crystallinity degree and better thickness uniformity over the area of the glass.

In the research \(100 \times 100\) mm test samples is cut from the full-size modules, in which by the method of laser scribing photoactive part \(60 \times 66\) mm is obtained with an open surface area of \(37.95\) cm\(^2\). It consists of 10 photovoltaic cells of equal size, connected in series. There is a custom solar module \(10 \times 10\) cm on fig. 2.
Contacts of the test sample are obtained by gluing strips with silver paste. Then the side with the contacts is covered with the laminating film contacts based on the ethylene vinyl acetate, and after that the test cells are subjected to a heat treatment at a temperature 150°C for 25-30 min to polymerize the film.

Research of the degradation of solar cell is set up using the installation of the light soaking benchmark (LSB), where modules are continuously exposed to the light. In practice, modules degradation tests are carried out with the illumination 600-1000 W/m² and a temperature no more then 50-60°C and a total exposure not less than 1000 hours [14]. Since it is very important to maintain a certain temperature to saturate the solar cells, the heat they emit should be scattered evenly. For this purpose an aluminum plate with water cooling is used as the sample holder.

The degraded samples are further investigated with continuous type sun simulator (SUS) and with a system for the study of the external quantum efficiency (EQE). Degradation tests last for about 1000 hours. In the first 100 hours the intervals between measurements are small, since the curve degradation is sufficiently sharp. After that measurements are made with a period of 100 hours or more.

3. Experimental results

The research carried out with the following samples: i305, i738 - two standard recipes, i748, i754, i755 - three different recipes created (modified) in the TFTC.

Average initial parameters obtained with the continuous type solar simulator shown in Table 2.

| Cell ID | Voc [V] | Isc [mA] | Jsc [mA/cm²] | FF [%] | Eta [%] | Rs [Ω] | Rp [kΩ] |
|---------|---------|----------|---------------|--------|---------|--------|---------|
| i305    | 13.33   | 45.18    | 11.5          | 68.77  | 10.55   | 35.58  | 17.54   |
| i738    | 12.98   | 42.96    | 10.93         | 67.29  | 9.58    | 40.54  | 16.30   |
| i748    | 13.61   | 42.30    | 10.76         | 71.44  | 10.46   | 33.52  | 10.77   |
| i754    | 13.72   | 41.97    | 10.68         | 72.24  | 10.58   | 32.16  | 10.08   |
| i755    | 13.52   | 40.96    | 10.42         | 69.11  | 10.37   | 38.04  | 9.13    |

Figure 2. Mini-module: photo (b) and scheme (a).
The table shows that the initial parameters of the optimized recipes are slightly above ones of base recipes. However, the uniformity of the modified recipes is much better. For example, the standard deviation of the efficiency for the new prescription i754 is 0.21 and for the i305 - 0.81, which is nearly four times higher (see. Table 3). Thus, the total efficiency of the full-scale module (1300 × 1100 mm) is higher.

| Table 3. Average parameters of the elements i305 and i754 before degradation. |
|---------------------------------|-----------------|-----------------|-----------|----------|----------|-----------|
|                                | Voc [V]         | Isc [mA]        | Jsc [mA/cm²] | FF [%]   | Eta [%]  | Rs [Ω]    | Rp [kΩ]   |
|---------------------------------|-----------------|-----------------|-----------|----------|----------|-----------|
| i754                            | 13.72           | 41.97           | 10.68     | 72.24    | 10.58    | 32.16     | 10.08     |
| stddev                          | 0.08            | 1.03            | 0.26      | 1.35     | 0.21     | 0.67      | 5.66      |
| i305                            | 13.33           | 45.18           | 11.50     | 68.77    | 10.55    | 35.58     | 17.54     |
| stddev                          | 0.17            | 0.38            | 0.10      | 4.87     | 0.82     | 6.47      | 15.02     |

Then mini-modules of these parties are subjected to degradation tests. The results are shown in Table 4.

| Table 4. Parameters of the samples after degradation. |
|---------------------------------|-----------------|-----------------|-----------|----------|----------|-----------|
|                                | Voc [V]         | Isc [mA]        | Jsc [mA/cm²] | FF [%]   | Eta [%]  | Rs [Ω]    | Rp [kΩ]   |
|---------------------------------|-----------------|-----------------|-----------|----------|----------|-----------|
| i305                            | 13.30           | 43.83           | 11.15     | 62.73    | 9.21     | 45.62     | 7.98      |
| i738                            | 13.15           | 41.40           | 10.54     | 61.10    | 8.45     | 56.54     | 26.28     |
| i748                            | 13.50           | 41.83           | 10.64     | 64.02    | 9.18     | 47.23     | 10.93     |
| i754                            | 13.60           | 41.30           | 10.51     | 65.85    | 9.39     | 46.75     | 12.40     |
| i755                            | 13.51           | 41.44           | 10.55     | 65.14    | 9.26     | 47.37     | 9.03      |

After the degradation average values of the optimized recipes appear still with less current and higher voltage, but the fill factor and conversion efficiency have increased significantly in comparison with the standard recipes. Figure 3 shows a comparison of the average current-voltage curves for the recipes i305 - standard and i754 - modified.
Studies of external quantum efficiency are shown in Figure 4: the dashed lines are for the i305, solid - for the i754. It can be seen that the lower mc-Si cell substantially does not degrade, compared with a top, a-Si.

Figure 3. Average current-voltage characteristics of the test samples after degradation.

Figure 4. Study of the external quantum efficiency of the samples.

Degradation process itself is described in Table 5 and represented in fig.5.
Table 5. Degradation of the samples.

| Glass No. | $\Delta P_{\text{max}}$, % | $\Delta V_{\text{o}}$, % | $\Delta I_{\text{sc}}$, % | $\Delta F_{\text{F}}$, % | $\Delta R_{\text{s}}$, % |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| i305      | 14.9            | 1.3             | 2.6             | 11.5            | 38.4            |
| i738      | 17.0            | 0.2             | 3.4             | 14.0            | 59.7            |
| i748      | 11.8            | 1.3             | 0.5             | 10.2            | 39.1            |
| i754      | 11.0            | 0.4             | 1.5             | 9.2             | 48.5            |
| i755      | 11.4            | 0.7             | 0.8             | 10.0            | 45.4            |

From Table 4 and Figure 5 it can be concluded that the modules of the new recipes degrade much less than the old samples - 11-11.8% for the old versus 15-17% for new samples.

4. Conclusion

We investigated the photoinduced degradation of the solar cells based on the tandem structure of a-Si:H/μc-Si:H with a standard illumination – 1000 W/m² AM1.5. During the tests the spectral and current-voltage characteristics of samples specially produced with the standard and modified in the TFTC recipes measured.

To sum up, while maintaining (or even slightly increasing) the original characteristics of the modules with respect to the basic recipe, the degradation of the modified samples when exposed to sunlight reduced significantly.

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