LONG TERM STABILITY OF THIN-FILM SILICON CELLS AND MODULES

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ABSTRACT: The long term stability of thin-film silicon solar cells and modules based on amorphous (a-Si:H) and microcrystalline silicon (µc-Si:H) is an important issue for their development and application. In-diffusion and absorption of chemical species can affect the performance of transparent conductive oxide films, metallic contact layers or the silicon films forming the p-i-n single or tandem cell structure. Therefore, the solar cells and solar modules are exposed to damp heat tests (temperature, T = 85°C, relative humidity, RH = 85%) of up to 1500 h to characterize their long term behaviour under harsh environmental conditions. The investigated thin-film silicon devices with different back contact assemblies are prepared in superstrate configuration on fluorine doped tin oxide or sputtered aluminium doped ZnO coated glass substrates. The degradation of the non-encapsulated cells and non-encapsulated modules was studied as a function of the exposure time with the focus on the back contact stability.

Keywords: stability, damp heat test, µc-Si :H, a-Si:H, module

1 MOTIVATION

The long term stability of thin-film silicon solar cells and modules depends on the stability of the individual layers, on the stability of contacts between these layers and on the degree the solar cell is exposed to various aging stresses like high temperatures, strong and frequent variation of temperature, exposure to environmental gases etc. In particular for microcrystalline silicon (µc-Si:H), where the microstructure can change from a more porous-like structure to a more compact material (a-Si:H) [1, 2], and for ZnO layers [3] various phenomena are reported. Although solar cells usually are protected against environmental gases by encapsulation, the long term stability of non-encapsulated thin-film silicon cells and modules is still an important issue for their development and application. Costs and effort for module encapsulation, materials applied and back end assembly strongly depend on the stability of non-encapsulated devices. In order to investigate the long-term stability of solar cells and solar modules, damp heat tests (temperature (T) = 85°C, relative humidity (RH) = 85%) were carried out and the performance of the solar cells was studied as a function of exposure time. Within these investigations in particular the stability of the back contact realized by different deposition methods and designs of µc-Si:H solar cells and modules was addressed.

2 EXPERIMENTS

All investigated µc-Si:H single p-i-n diodes and solar modules were prepared in superstrate configuration on fluorine doped tin oxide (FTO) or sputtered aluminium doped ZnO (AZO) coated glass substrates. The absorber layer of a-Si:H and µc-Si:H p-i-n diodes is between 300 - 500 nm and 1 - 1.4 µm, respectively. µc-Si:H diodes on AZO substrates with different back contact materials (Ag, ZnO/Ag) were fabricated. The µc-Si:H diodes were prepared close to the transition region from microcrystalline crystalline to amorphous silicon growth, where the maximum cell efficiency is achieved. For more details regarding the ZnO sputtering and PECVD processes see Ref. [4] and [5], respectively. Damp heat tests were performed for more than 150 samples. However, it has to be mentioned that the storing conditions (time, temperature and humidity), handling procedures and contaminations prior to the stability test can affect the degradation behavior in the climatic exposure test cabinet.

3 RESULTS

The back contact design can have a significant influence on the device performance due to e.g. their optical reflectivity, cost of the cell and module and on the long term stability. Silver is an attractive back contact material since it has a high reflectivity. However, a surprising result is observed in damp heat treatment when the back contact consists of a single 700 nm Ag layer. The FF of diodes with an Ag back contact drops after 20 - 100 h of damp heat exposure time due to adhesion problems of the silver layer on the silicon (not shown, [3]). The silver layer starts to peel off and the series resistance increases. The increase of the series resistance of the cell also affects the shape of the dark IV characteristics. After 20 h damp heat testing, the dark IV curve differs significantly from their exponential behavior due to carrier injection limitaions (fig. 1, top). A contrary behavior is observed for the red response of µc-Si:H solar cells measured under low illumination intensity. This is demonstrated in the lower part of Fig. 1. In the long wavelength region the quantum efficiency increases with time and reaches values which even exceed the quantum efficiency of samples with a ZnO/Ag back contact. For λ = 750 nm the quantum efficiency increases by more than 50%. This result demonstrates that a simple Ag back contact leads to strong optical losses, likely due to surface plasmon absorption losses [6-8]. When the metal layer locally peels off, these optical losses disappear. To account for this effect, a ZnO layer was embedded between the silicon and silver layer. Consequently, the adhesion is highly improved and the optical losses are also significantly reduced. After 2000 h of damp heat testing no significant degradation is observed for thin-film silicon solar cells based on a-Si:H and µc-Si:H single pin structures employing both types of TCOs (SnO_2 and ZnO) and a-Si:H/µc-Si:H tandem cells when our standard ZnO/Ag-back contact (d_{TCO} = 80 nm, d_{Ag} = 700 nm) is applied [9]. The investigations have shown that in addition to the reduced peeling effects, ZnO/Ag double layers also have optical advantages, because a direct interaction between silver and silicon is avoided and a higher reflectivity at the back contact is obtained. A similar long term stability is also observed for cells with Al or TCO/Al contact. However, in this case, the lower reflectivity of the reflector limits the efficiency in particular of µc-Si:H solar cells [6].

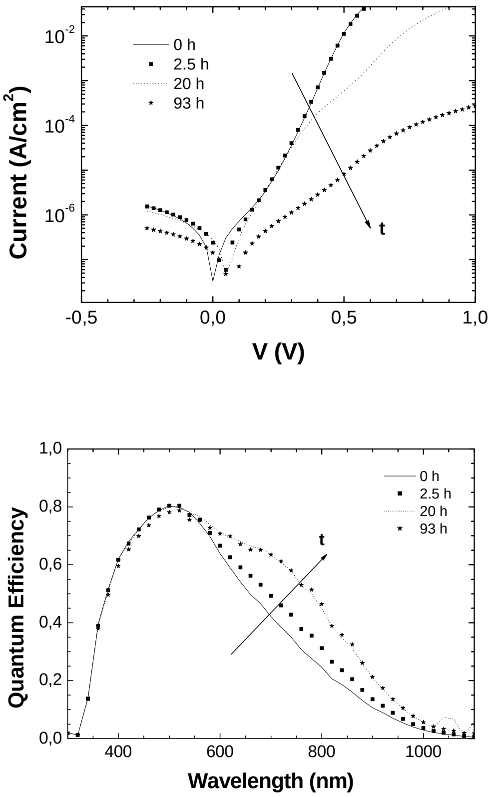

Figure 1: Dark IV characteristics (top) and quantum efficiency (bottom) measured at reverse bias (-0.5V) of µc-Si:H diodes with an Ag back contact deposited on AZO for different exposure times.

While for solar cells the TCO/Ag back contact is optimized with respect to a high reflectivity and good stability, for thin-film silicon modules other aspects also have to be considered. Laser patterning of the ZnO/metal layer stack for integrated series connection requires thinner metal layer to achieve a reliable process and a flake-less back contact line [10]. Therefore, µc-Si:H solar cells with a 80 nm sputtered ZnO layer and an Ag layer with different thickness produced by thermal evaporation were realized. The solar cell parameters measured under AM 1.5 illumination conditions are summarized in table 1. Stated is the relative abatement normalized to the initial value. Furthermore, the FF behavior as a function of the exposure time is plotted in fig. 2 for cells with an Ag-layer thickness of 100 nm (open symbols) and 600 nm (closed symbols). For thermal evaporated Ag back layer a distinct decrease in the efficiency with increasing damp heat testing time is observed, mainly caused by a decrease of the FF. All other solar cell parameters show only a slight dependency on the testing time. This result indicates that stable back contacts using evaporated Ag can only be achieved when a layer thickness between 600 – 700 nm is applied. However, this thickness is not favourable from the perspective of the line scribing process of the back contact.

Ag layer thickness	$\Delta\eta$	ΔFF	ΔV_{oc}	ΔJ_{sc}
100 nm	-0,25	-0,22	-0,02	-0,02
150 nm	-0,27	-0,25	-0,02	-0,01
200 nm	-0,22	-0,20	-0,02	-0,01
250 nm	-0,09	-0,08	-0,01	-0,01
300 nm	-0,10	-0,08	-0,01	-0,01
600 nm	-0,04	-0,02	-0,01	-0,01
700 nm	-0,04	-0,01	-0,01	-0,01

Table 1: Relative degradation of µc-Si:H solar cells with TCO/Ag back contact and different Ag layer thicknesses after 1500 h damp heat testing. The layer thickness of the thermally evaporated Ag was varied between 100 nm and 700 nm.

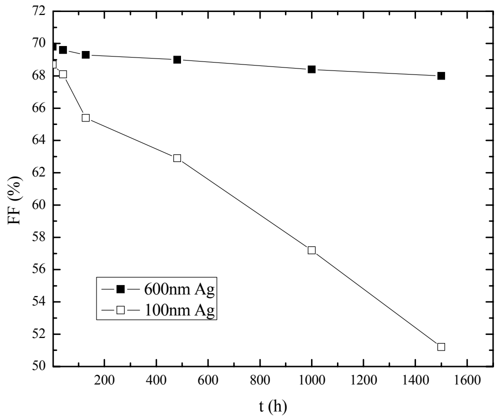

Figure 2: FF of a µc-Si:H solar cells with different evaporated Ag-layer thickness as a function of the exposure time.

For industrial applications the back contact has to be realized by sputtering to achieve a high throughput. Therefore, the long term stability of samples with a sputtered Ag-layer using different deposition conditions is investigated. Fig. 3 shows the long term stability of cells with a 200 nm thick Ag-layer prepared at various pressure of the Ar sputtering gas. In particular for films prepared at high pressure (49 µbar) a reduced stability is

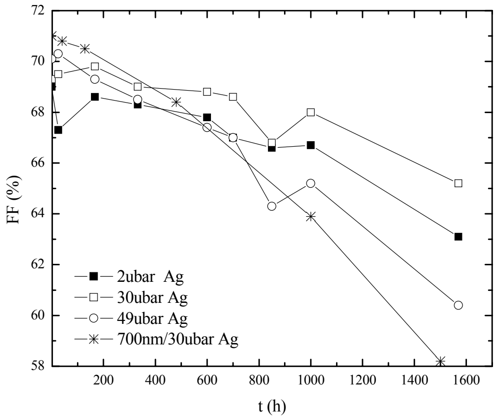

Figure 3: FF of µc-Si:H solar cells with sputtered Ag-layer using different pressure and Ag layer thickness. A 200 nm sputtered Ag is used as a metal reflector when not otherwise mentioned.

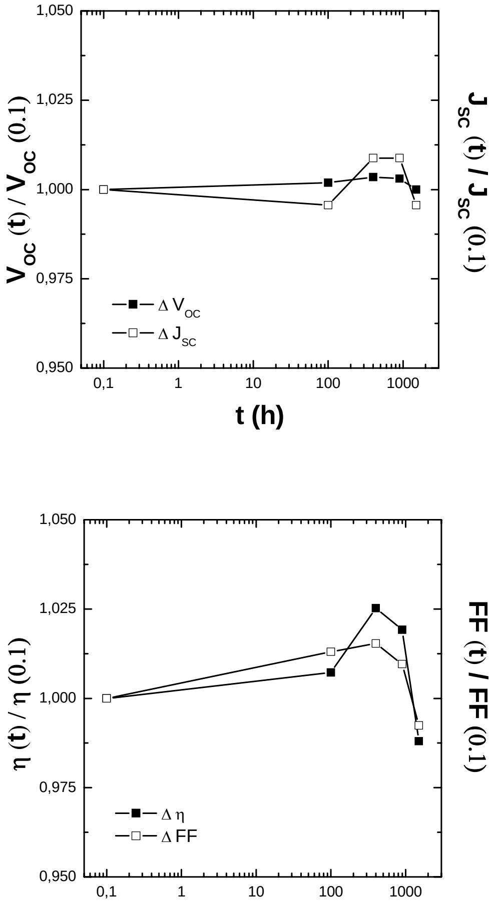

Figure 4: Relative solar cell parameters: V_{OC} and I_{SC} (top) and efficiency and FF (bottom) of a µc-Si:H module with an initial efficiency of 8.32 %.

between 5 µbar and 30 µbar. Additionally, a sample with a thicker Ag sputtered back contact is plotted Samples with a thicker sputtered Ag layer exhibit a found. A decline of the FF after damp heat testing between 1% and 4% is in the scattering regime of the data. A weak degradation is observed for a pressure reduced long term stability. Sputtering can result in a too dense film which is likely to relax during the testing procedure. The stability behavior of cells with sputtered metal layer is opposite to the behaviour of evaporated Ag films. Surprisingly, the thickness dependence was not observed for cells with a sputtered Ag-back contact (d_{Ag} > 200 nm) using our small area system although similar process parameters were applied. Therefore, the long term stability depends strongly on the deposition conditions and methods used. Further work is necessary to clarify these observations.

Therefore, special design rules have to be considered to realize modules with high long term stability [10]. Taking all the requirements into account, non-encapsulated microcrystalline silicon thin-film module with an Ag layer prepared in the large area sputtering system show a fill factor decrease by less than 3% after more than 1500 h damp heat testing. This is demonstrated in Fig. 4 which exhibits the module parameters scaled to the initial (t = 0.1 h) conditions: open circuit voltage (Voc) and short circuit current (Isc) (top) and module efficiency (η) and fill factor (FF) (bottom) are plotted as a function of the exposure time. The initial efficiency of the investigated µc-Si:H module was 8.32%. In this case a ZnO/Ag/ZnO back contact layer stack was applied, which is optimized with respect to a high reflectivity, flake-free line scribing process by laser ablation and high long term stability. The degradation of all solar module parameters with a modified ZnO/Ag/ZnO back contact system is less than 2%. This result shows that it is possible to achieve inherent stability of non-encapsulated thin-film silicon modules when the thin-film silicon absorber layers are sandwiched between ZnO-layers.

The back contact patterning is achieved by an ablation of the underlying silicon film. Therefore, the ZnO front contact in this area is exposed to the ambient. Although no significant degradation during damp heat testing was observed, the ablated area of a non-covered ZnO layer was enhanced by several scribing line steps. Figure 5 shows a microscopic view of the modified interconnection area of a µc-Si:H module with a zinc-oxide substrate. The image was taken from the film side. The left line with a width of around 50 µm corresponds to the TCO ablated area. The middle line with a width of around 75 µm represents the connection between the front TCO and the back contact of neighboring cell stripes. On the right side is shown the ablated area of the back contact with a width of 425 µm realized by 10 line scribing steps. In comparison to the standard line width (75 µm) the scribed line is a factor of around 6 broader.

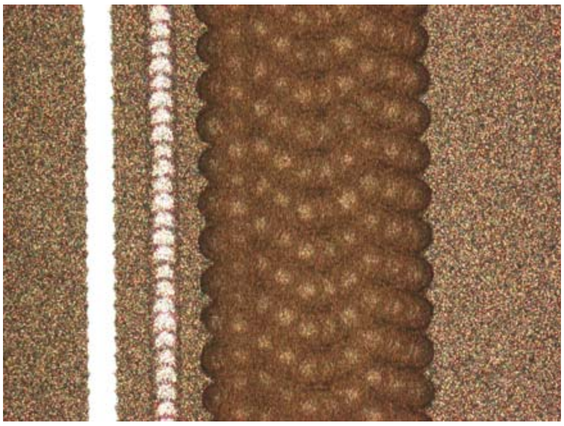

Figure 5: Interconnection area of a thin-film silicon module. The standard line width of the back contact line was enhanced from 75 µm to 425 µm.

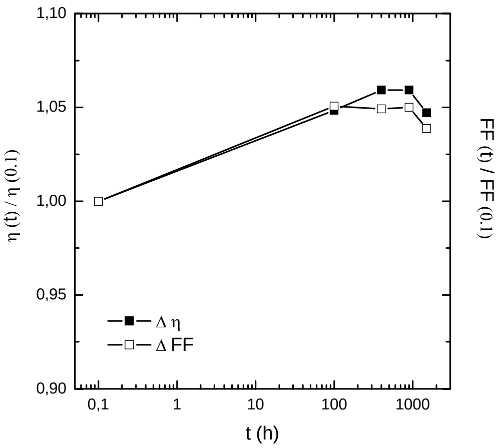

Figure 6: Relative efficiency and FF behavior of a µc-Si:H module with a 6 time thicker back contact line (425 µm).

Also in this case, we have not found a significant degradation of the cell performance (fig. 6) during damp heat testing. The lower value at 0.1h which represents the initial value is caused by a shunt effect of one cell stripe of the module, which is annealed during the testing procedure. This result indicates that laser patterning of the ZnO/Ag/ZnO back contact, which is the most critical laser scribing step, has no adversely effect on the stability of the module. Although ZnO slightly degrades during temperature and moisture exposure, thin-film silicon modules with a non-covered ZnO region of around 0.425 mm are nearly stable. Since laser patterning leads also to an altering of the surface topology, possible variation of the surface can likely contribute to the device stability. Thus, the high inherent stability of non-encapsulated thin-film silicon solar modules regarding damp heat testing enables the possibility of low cost encapsulation techniques.

CONCLUSIONS

The long term stability of thin-film silicon cells and modules was investigated by means temperature and moisture exposure. The results have shown that in particular the ZnO/Ag back contact system leads to a high cell stability and the ZnO/Ag/ZnO layer stack to a outstanding module stability. Thus, the high inherent stability of non-encapsulated thin-film silicon solar cells and modules regarding damp heat testing recommends these types of devices for various applications and offers the possibility of low cost encapsulation techniques.

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