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High stabilized efficiency single and multi-junction thin film silicon solar cells

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Abstract

We present the study of high efficiency single and multi-junction solar cells, focusing on the stability against degradation under illumination. In both single and multijunction solar cells, the thickness of the a-Si:H absorber layer was varied over a wide range up to 790 nm. While single junction a-Si:H solar cells show reduced stability against prolonged light illumination with an increase in layer thickness, themultijunction solar cells are significantly more stable. In these cells the total thickness of the a-Si:H absorber layers (first and second sub-cells) can be significantly increased up to 790nm while keeping the degradation level low (below 13%) after 1000 hrs of light soaking. The possible origins of an improved stability against degradation are addressed in the paper.

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*Keywords:*amorphous silicon, microcrystalline silicon, multijunction solar cells, light induced degradation

1. Introduction

Silicon thin film solar cells are known to suffer from degradation due to prolonged illumination. This degradation process, known as Staebler-Wronski effect [1], is considered as a major limiting factor for high efficiency devices and usually is associated with the stability of amorphous silicon (a-Si:H) absorber layers. It is widely accepted that that degradation kinetics in a-Si:Hsingle junction solar cells demonstrates a thickness dependency andan improved stability of a-Si:H solar cells could be achieved for thinner absorber layers [2-4]. A combination of sub-cells with

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amorphous/microcrystalline silicon (μc-Si:H) absorber layers or its alloys in multijunction solar cells allows for more efficient utilization of the sun spectrum. Various combinationsof thin-film silicon solar cells with a-Si:H, a-SiO_X:H, a-SiGe:H and μc-Si:H, absorber layershave been reported in multi-junction devices [5-9].Microcrystalline silicon is generally more stable against prolonged illumination [10], whereas the presence of a-Si:H absorber layers can reduce the efficiency of multijunction devices considerably under illumination.

Here we present the study of high efficiency single junction (a-Si:H absorber) and multi-junction (a-Si:H and μc-Si:H absorbers) solar cells, focusing on the stability against degradation under illumination. In the case of multijunction devices, a wide range of device architectures is considered: a-Si:H/μc-Si:H and a-Si:H/a-Si:H tandem solar cells, a-Si:H/μc-Si:H/μc-Si:H and a-Si:H/a-Si:H/μc-Si:H triple junction solar cells and a-Si:H/a-Si:H/μc-Si:H/μc-Si:H quadruple junction cells. Moreover, in order to obtain more insights into the degradation behavior, the total thickness of the a-Si:H absorber layers in both single and multijunction solar cells was varied over a wide range up to 790 nm. In the case of a-Si:H single junction solar cells, 300 nm was found to be an optimal absorber layer thickness resulting in high stabilized efficiency of 9.8% (12% relative degradation). Further increase in the thickness of the absorber layer results in the reduction of stabilized efficiency and stronger degradation (up to 30% in the case of 700 nm thick absorber layer). In contrast, in the case of multijunction solar cells, the total thickness of the a-Si:H absorber layers (first and second sub-cells) can be significantly increased up to 790nm while keeping the degradation level low (below 13%). The details of degradation behavior upon illumination and stability issues in single- and multijunction solar cells are compared and discussed in this contribution.

2. Experimental details

Single and multi-junction solar cells were prepared by PECVD at deposition temperatures of 185°C or below. In the case of multi junction devices, we have prepared a-Si:H/μc-Si:H and a-Si:H/a-Si:H tandem solar cells, a-Si:H/μc-Si:H/μc-Si:H and a-Si:H/a-Si:H/μc-Si:H triple junction solar cells and a-Si:H/a-Si:H/μc-Si:H/μc-Si:H quadruple junction cells. The matching of the current in the sub-cells of the multijunction devices was achieved by variation in the thickness of the absorber layer and by implementation of doped microcrystalline silicon oxide (μc-SiO_x:H) layers. Additional details on the preparation of solar cells can be found elsewhere [4, 9, 11, 12]. Table 1 presents an overview of individual layer thicknesses for multijunctionsolar cells studied here. The performance of the solar cells was evaluated by current-voltage (*J-V*) measurements under AM 1.5 illumination (intensity of 1000 W/m^2, class A spectrum). Degradation of solar cells was performed at 55 °C in open circuit condition with an intensity of 1000 W/m^2 (class B spectrum) over a period of 1000 hours.

Table 1.Layer sequence and thickness of multijunction solar cells, together with efficiency (η) in initial and stabilized (after 1000 hrs of light soaking) states and relative degradation in efficiency. A-D tandem junction, E-F triple junction and G quadruple junction cells.

	Junction 1		Junction 2		Junction 3		Junction 4		η	η	Δ η
		Thickness[nm]		Thickness[nm]		Thickness[nm]		Thickness[nm]	ini. [%]	stab. [%]	[%]
A	a-Si:H	350	μc-Si:H	1800					13.1	11.8	-10
B	a-Si:H	160	μc-Si:H	650					10.6	10.1	-5
C	a-Si:H	110	a-Si:H	400					11.3	9.6	-12
D	a-Si:H	90	a-Si:H	400					10.5	9.2	-13
E	a-Si:H	90	a-Si:H	700	μc-Si:H	1800			13.6	11.7	-13
F	a-Si:H	160	μc-Si:H	1200	μc-Si:H	1600			11.2	11.0	-3
G	a-Si:H	80	a-Si:H	400	μc-Si:H	1600	μc-Si:H	2300	13.2	12.6	-4

3. Results and discussion

The performance of solar cells was investigated in the initial state and after 1000 hrs of light soaking. Figure 1 shows the J-V characteristics of the a-Si:H single junction solar cells with absorber layer thickness varied up to 700 nm. In the case of both initial and stabilized conditions, it is evident that an increase in the i-layer thickness results in increasing short circuit current density Jsc (Fig. 1(d)) and decreasing both open circuit voltage V_{OC} and fill factor FF (Figs. 1 (c) and 1(b) respectively). The efficiency η in the initial state (Figure 1 (a)) increases with i-layer thickness up to 300 nm, following an increase in the short circuit current density J_{SC} with increasing absorber layer thickness. The highest initial efficiency of 11.4% is obtained. When the i-layer thickness is further increased up to 700 nm the efficiency remains on the same level. In the degraded state the performance is reduced mainly due to reduction in fill factor *FF*, while the open circuit (V_{OC}) values remain nearly unchanged (Fig. 1(b)). Due to the trade off between increasing J_{SC} and decreasing *FF* with absorber layer thickness, the highest stabilized efficiency (9.8%)is obtained for the solar cell with 300nm thick a-Si:H layer.

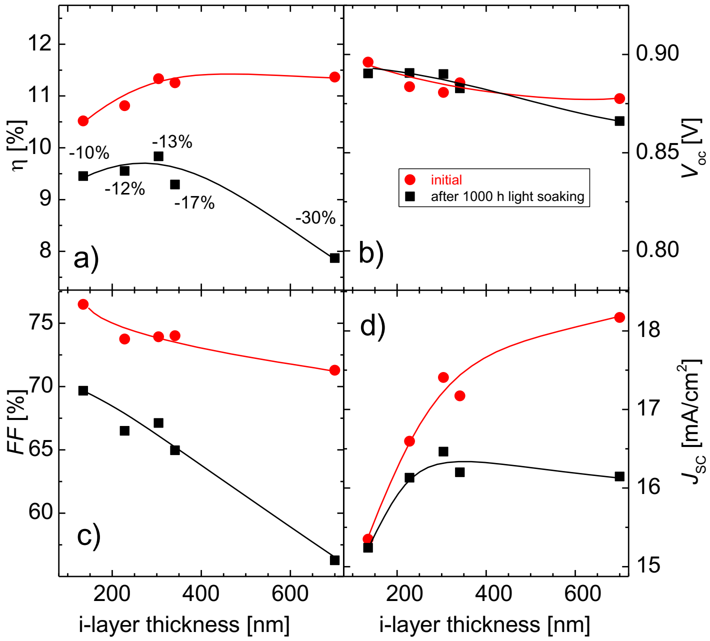

Fig. 1.*J-V* parameters of a-Si:H single junction solar cellversus the a-Si:H i-layer thickness: (a) efficiency η, (b) open circuit voltage V_{OC}, (c) fill factor *FF*, and (d) short circuit current density J_{SC} in the initial state (red) and after 1000 hrs of light soaking (black). The numbers shown in (a) denote relative degradation in efficiency after 1000 hrs of light soaking.

Figure 2 presents *J-V* characteristics of multijunction solar cells in the initial state and after 1000 hrs of light soaking. It is evident that the highest initial efficiencies are obtained for the solar cells containing μc-Si:Habsorber layers (cells A, E and G). Note a significant difference in the initial efficiency for a-Si:H/μc-Si:H tandem cells (cells A and B). This is because these cells were optimized for high efficiency (cell A) and high voltage (cell B) applications [11, 12].The highest initial efficiency of 13.2% is achieved for a-Si:H/a-Si:H/μc-Si:H triple junction solar cell.It is evident that V_{OC} and J_{SC} remain the most stable parameters upon light induced degradation while the*FF* values (Fig 2(c))are affected much more in some cases. The most significant degradation in *FF* is observed in the case of a-Si:H/a-Si:H solar cells (cells C and D) with a total absorber layer thickness around 500 nm. a-Si:H/μc-

Si:H tandem solar cells (cells A and B) are significantly more stable again light-induced degradation, especially cell B with thinner absorber layers. Triple junction a-Si:H/a-Si:H/μc-Si:H solar cell (cell E), having the highest total a-Si:H absorber layer thickness of 790nm show significant degradation, similar to that of a-Si:H/a-Si:H solar cells. a-Si:H/μc-Si:H/μc-Si:H and a-Si:H/a-Si:H/μc-Si:H/μc-Si:H solar cells (cells F and G respectively) show very little degradation. In terms of performance, the quadruple junction solar cell G shows the best stabilized efficiency of 12.6% after 1000 hrs of light soaking.

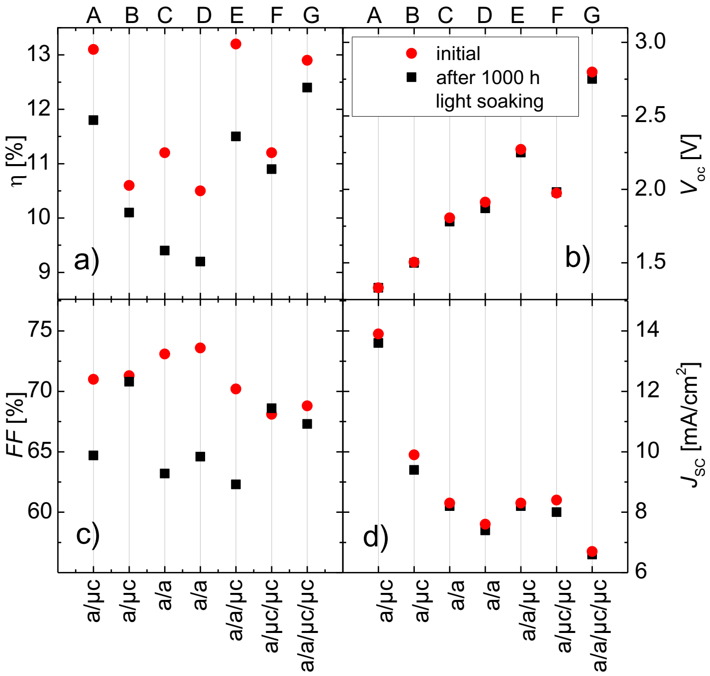

Fig. 2. *J-V* parameters of multijunction solar cell: (a) efficiency η, (b) open circuit voltage V_{OC}, (c) fill factor *FF*, and (d) short circuit current density J_{SC} in the initial state (red) and after 1000 hrs of light soaking (black). Bottom x-axis denotes the sub-cell type of each multijunctionsolar cell (a – amorphous silicon, μ – microcrystalline silicon). Top x-axis denotes each cell listed in Table 1.

In the following, we summarize the results of light induced degradation for the single and multijunction cells discussed above. Figure 3 shows the relative degradation in efficiency ($\Delta\eta=(\eta_{ini} - \eta_{stab})/\eta_{ini}$) after 1000 hrs of light soaking, plotted as a function of total thickness of a-Si:H absorber layers in solar cells. It is clear that all multijunction solar cells (even tandem cells C and D containing only a-Si:H absorber layers) are significantly more stable against prolonged illumination. Note that a-Si:H/a-Si:H solar cells (cells C and D) with a thickness above 500 nm show similar efficiency degradation as 300 nm thick a-Si:H single junction solar cell. In the case of single junction solar cells degradation increases with increasing a-Si:H layer thickness, as previously reported elsewhere [2-4]. The effect is commonly related to a stronger electric field present in thinner solar cells, which improves carrier collection making thinner a-Si:H single junction solar cells less sensitive to light induced degradation. Multijunction solar cells show less pronounced trend as a function of a-Si:H layer thickness. It is evident that a-Si:H/a-Si:H and a-Si:H/a-Si:H/μc-Si:H/μc-Si:H solar cells (cells D and G), having nearly same total thickness of a-Si:H layers, show 4 times difference in relative degradation (16% and 4%, respectively).Remarkably, triple junction a-Si:H/a-Si:H/μc-Si:H solar cell (cell E) with a total a-Si:H absorber layer thickness of 790nm shows similar degradation (around 13%) as 300 nm thick a-Si:H single junction solar cell. Overall, our results demonstrate that while light induced degradation is increased with absorber layer thickness in the case of single junction a-Si:H solar cells, multijunction devices with significant total thickness of a-Si:H layers are much more stable against prolonged illumination.

Several reasons could be considered to explain improved stability of multijunction solar cells relative to single junction devices:

- the incident photon flux is distributed between sub-cells, so each of sub cells receives lower illumination in comparison to a single junction cell, which would reduce light induced degradation
- high energy photons, which are more efficient in light induced degradation [13], are filtered by the top cell of a multijunction device and therefore do not contribute in light induced degradation in the rest of device. The top cell is usually quite thin, for example, in the case of quadruple junction solar cell G it is only 80 nm thick, therefore relatively low light induced degradation is expected. Additional External Quantum Efficiency measurements [9] indicate that the 400 nm thick middle a-Si:H sub cell degraded even less than the 80 nm thick top a-Si:H cell, supporting the view that filtering of high energy photons can reduce light induced degradation.
- the effect of light induced degradation in a multijunction device may be partly 'hidden' by a photocurrent mismatch of the individual sub cells. In the case of single junction solar cells, *FF* is the most affected PV parameter upon degradation, while in the case of multijunction solar cells *FF* is strongly influenced by the current mismatch conditions and increases in general for an increased current mismatch [14, 15].

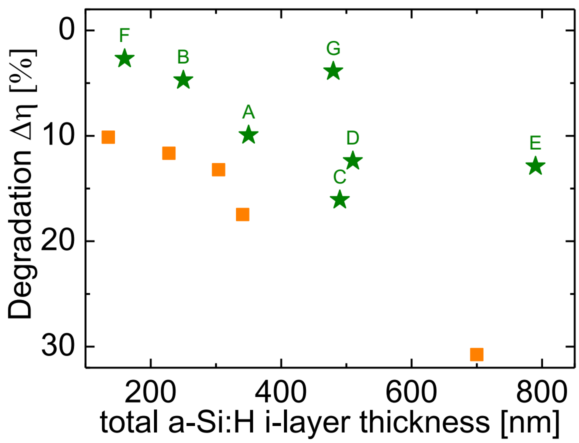

Fig. 3. Relative degradation in efficiency (Δη) of single junction (yellow square) and multijunction (green star) solar cells plotted *vs.* total thickness of a-Si:H absorber layer. A-G denotes cells listed in Table 1.

4. Summary

The effects of light induced degradation in high efficiency single- and multijunction thin film silicon solar cells were investigated. Our results demonstrate that in all cell configurations, the open circuit voltage is quite stable after 1000 hrs of light soaking. In the case of multijunction solar cells J_{SC} is only weakly changed upon light soaking, while in single junction cells the changes are stronger and tend to become more pronounced with increasing thickness of the absorber layer. The fill factor remains the most sensitive parameter influenced by light induced degradation. In the case of multijunction cells, the degradation in *FF* is substantially reduced.We have shown that multijunctionsolar cells with significant total thickness of a-Si:H layers (up to 790 nm) are much more stable against prolonged illumination compared to a-Si:H single junction devices; the possible origins of an improved stability were discussed. Quadruple junction solar cell demonstrated an excellent stability against light-induced degradation: a maximum stabilized conversion efficiency of 12.6% was obtained, which corresponds to a very low degradation of 4%.

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