

A-SiO:H THIN FILMS WITH INCREASED LIGHT INDUCED DEGRADATION STABILITY FOR THIN FILM SILICON SOLAR CELLS

Sven Holinski*, Dietmar Borchert, Stefan Hohage, Britt-Marie Meiners, Petra Schäfer, Tobias Westrich
Fraunhofer Institute for Solar Energy Systems, Laboratory- and Servicecenter Gelsenkirchen, Auf der Reihe 2, 45884
Gelsenkirchen, Germany

* Corresponding author e-mail: sven.holinski@ise.fraunhofer.de, phone: +49 209 155 3920, fax: +49 209 12090 93

ABSTRACT: Silicon based multi-junction thin film solar cells suffer from light-induced degradation (LID) due to the Staebler-Wronski effect. The top-absorber in such a cell is usually made out of intrinsic amorphous silicon (i)a-Si:H which suffers most from LID. Intrinsic amorphous silicon oxide (i)a-SiO:H promises an increased LID stability. We deposited (i)a-SiO:H absorber layers with different ratios of CO_2/SiH_4 by radio frequency plasma enhanced chemical vapour deposition (RF-PECVD). The (i)a-SiO:H absorber layers were characterized regarding to their electrical and optical properties. The defect density N_d has been determined by the constant photocurrent method (CPM). It was found that (i)a-SiO:H has an increased LID stability compared to a-Si:H. The measurement results were then transferred into the simulation software Advanced Semiconductor Analysis (ASA). We carried out simulations for the initial and light soaked state of solar cells with a reference (i)a-Si:H absorber layer and the new (i)a-SiO:H absorber layer. The cells showed after light soaking nearly equal efficiency.

Keywords: a-SiO:H, Amorphous Silicon, Multijunction Solar Cell, Thin Film Solar Cell

1 INTRODUCTION

To increase the efficiency of stacked silicon thin film solar cells it is necessary to overcome the problem of LID [1]. One approach is to develop new absorber materials with better LID stability. A promising absorber material is a-SiO:H, because it shows less LID due to the Staebler-Wronski effect [2], while having a higher bandgap than a-Si:H [3].

For further increase in the efficiency of stacked silicon thin film solar cells one needs to use a wide bandgap absorber material in the top cell of the layer stack. A wider bandgap of the absorber increases the open-circuit voltage V_{oc} of the cell [4]. Simulations done by Yunaz et al. [5] showed that only a top-cell with at least a bandgap of 2.0 eV would provide high enough V_{oc} values for efficiencies of over 20% in a triple-junction silicon thin film solar cell.

These triple-junction cells including an a-SiO:H top cell reach stabilized efficiencies close to 12% on laboratory scale [6].

2 EXPERIMENTAL DETAILS

We deposited (i)a-SiO:H films on Schott AF32 eco glass substrate (100x100x1.1 mm) by RF-PECVD at 13.56 MHz. We used SiH_4 , H_2 and CO_2 as process gases. We evacuated the process chamber to a base pressure of $\sim 5 \times 10^{-8}$ mbar before starting the deposition processes. The deposition conditions are listed in table 1.

The film thickness was kept constant at 300 nm and was measured by reflectometry and spectroscopic ellipsometry. The spectroscopic ellipsometry data (J.A. Woollam, M2000) were fitted with a Tauc-Lorentz model [7] using the WVASE software. The Tauc bandgap $E_{g,\text{Tauc}}$ [8] was determined from Varian Carry 500 spectrophotometer data for transmission and reflectance in the UV-VIS range.

The defect density N_d and Urbach energy E_u [9] were determined by constant photocurrent method (CPM) [10]. The defect density N_d was calculated from CPM measurements using the “absorption coefficient at a single energy” method [11].

The thin films were light soaked for totally 100 hours with 100 mW/cm² by a SOL2 solar simulator from Dr. Hönle AG to investigate the metastable changes related to the Staebler-Wronski effect. During the degradation the temperature was kept constant at 25 °C.

The defect density was recorded by CPM at different stages of degradation. Before the degradation experiment the samples were annealed in air at 160 °C for 30 minutes to set up an initial state.

At last we transferred the recorded measurement values before and after degradation of the (i)a-SiO:H absorber layer with the highest bandgap ($r_c = 1.2$) and the reference (i)a-Si:H absorber layer into the simulation software “Advanced Semiconductor Analysis” (ASA) [12] and simulated a single junction solar cell with the layer stack shown in fig. 1.

Table I: Deposition conditions of (i)a-SiO:H films

Paramter	Value	Unit
Substrate temperature T	195	°C
Deposition pressure p	0.5	mbar
Power density P	15	mW/cm ²
SiH_4 flow r_x	210	sccm
H_2 flow r_y	1050	sccm
CO_2 flow r_z	21-252	sccm

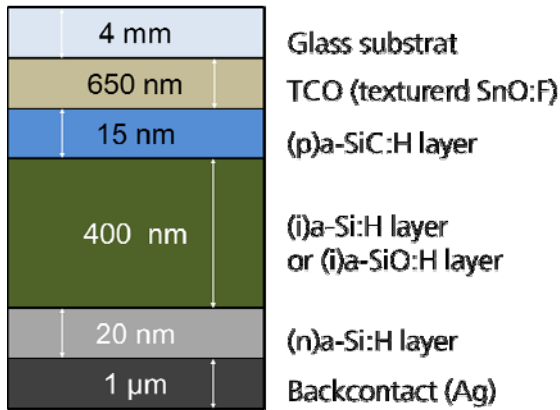


Figure 1: Layer stack for the ASA simulations

3 MEASUREMENT RESULTS

3.1 Optical properties of (i)a-SiO:H absorber layers

Fig. 2 shows the dependency on the bandgap $E_{g,Tauc}$ of the ratio r_c . It was observed that the bandgap increases linearly with the CO_2/SiH_4 ratio r_c . The bandgap increased from $E_{g,Tauc} = 1.78$ eV for the reference (i)a-Si:H layer to $E_{g,Tauc} = 1.91$ eV for the (i)a-SiO:H layer with $r_c = 1.2$.

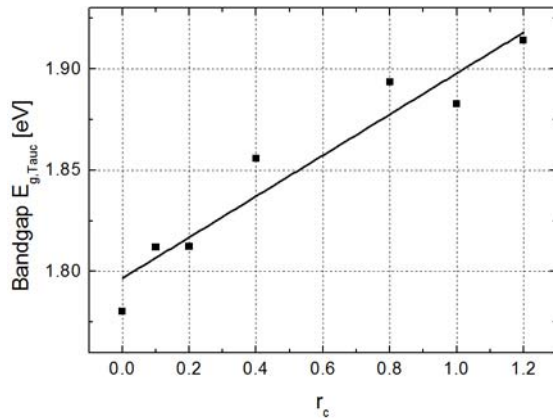


Figure 2: Variation of bandgap $E_{g,Tauc}$ with r_c

The optical constants (n , k) were derived from the spectroscopic ellipsometry measurement data. Fig. 3 shows exemplary the measurement data of the optical constants for the (i)a-Si:H reference layer and two (i)a-SiO:H layers with $r_c = 0.4$ and $r_c = 1.2$. The reference layer showed the highest refraction index n and also the highest extinction coefficient k . By increasing the CO_2/SiH_4 ratio the optical constants of the (i)a-SiO:H layer were lowered.

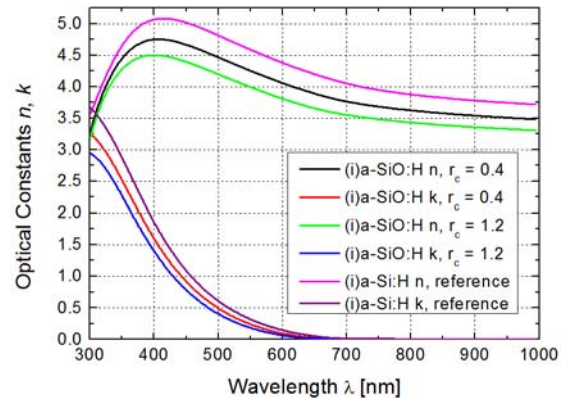


Figure 3: Optical constants for different r_c values

3.2 Defect characterization of (i)a-SiO:H thin films

The obtained CPM spectra for various (i)a-SiO:H films with increasing r_c are plotted in Fig. 4. Because of the increasing bandgap the CPM spectra are shifted to lower energies for the layers with higher bandgaps. We also observe a decrease of steepness of the linear part of the curves with higher ratios of r_c . This means that the Urbach energy increases and the density of states (DOS) for the extended tail states also increases. One can see that the values for the absorption coefficient α at the characteristic energy of 1.2 eV, where one can read the defect density N_d , increase. This means that the defect density N_d for the layers with higher ratios of r_c increases.

This behavior is confirmed by dark con

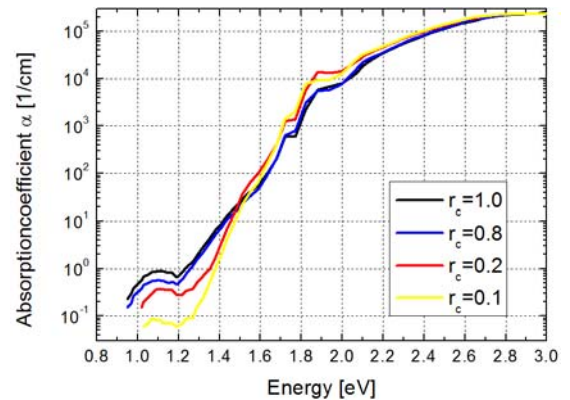


Figure 4: CPM spectra for various (i)a-SiO:H films with increasing r_c

Fig. 5 displays the effect of the increasing ratio r_c on the Urbach energy E_u . The Urbach energy E_u shows a linear dependency on the CO_2/SiH_4 ratio r_c . A higher Urbach energy indicates less sharp band edges which results in a poorer material quality.

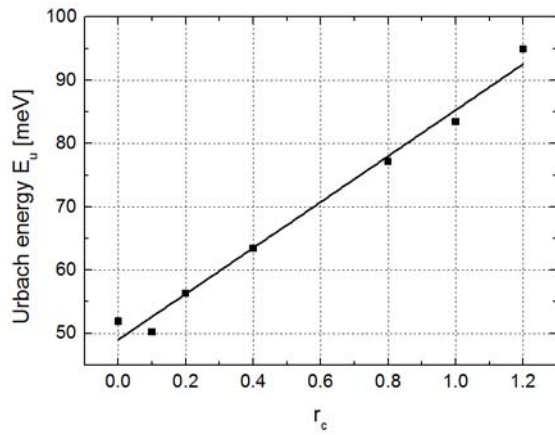


Figure 5: Urbach energy as a function of r_c

As can be seen from Fig. 6 the defect density N_d increases with higher r_c ratios. The defect density for the reference (i)a-Si:H sample was $N_d = 1.04 \times 10^{15} \text{ cm}^{-3}$. For the (i)a-SiO:H film with $r_c = 1.2$ the defect density reached $N_d = 2.65 \times 10^{16} \text{ cm}^{-3}$.

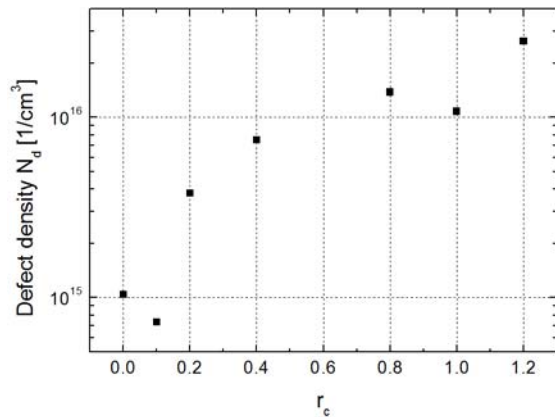


Figure 6: Variation of defect density N_d with r_c

3.3 Light induced degradation in (i)a-SiO:H thin films

The changes of the defect density N_d for different values of light soaking time in dependency of r_c were investigated and are shown in Fig. 7.

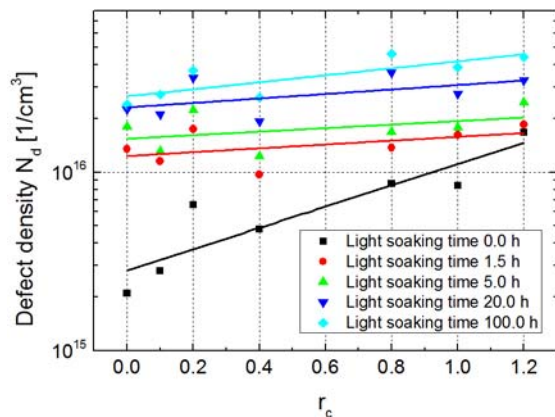


Figure 7: Variation of defect density N_d for different light soaking times with increasing r_c

The (i)a-SiO:H layers show a smaller increase in the defect density N_d with the time than the reference (i)a-Si:H layer. The reference (i)a-Si:H absorber layer showed an

increase in the defect density of a factor of 11.4 after 100 h of light soaking, while the (i)a-SiO:H layer with the highest r_c showed an increase of defect density N_d of a factor of 2.6. This means that the (i)a-SiO:H layers are less sensitive to light induced degradation related to their higher initial defect density N_d . The results are summarized in table 2.

Table II: Defect density N_d quotients after degradation for different CO_2/SiH_4 ratios r_c

CO_2/SiH_4 (r_c)	N_d 100 h light soaked / N_d initial
0.0	11.4
0.1	9.7
0.2	5.7
0.4	5.5
0.8	5.4
1.0	4.6
1.2	2.6

4 SIMULATION RESULTS

Fig. 8 shows the IV-curves for a single junction solar cell with an (i)a-SiO:H absorber layer ($r_c = 1.2$) and for a cell with the reference (i)a-Si:H absorber for the initial state and after 100 h of light soaking

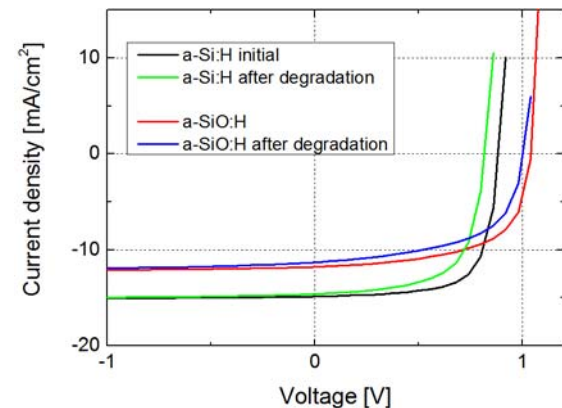


Figure 8: IV-curves for (i)a-SiO:H absorber layer and reference (i)a-Si:H absorber for the initial and degraded state

Both cell types show a loss of V_{oc} and fill factor after degradation, whereas the current density remains unchanged. The loss in fill factor for the cell with the reference (i)a-Si:H absorber layer is higher. The reference cell shows a LID of 20.7 %, while the (i)a-SiO:H cells has 15 % of LID. The simulated cell results are summarized in table 3.

Table III: Cell results for cells with (i)a-SiO:H and (i)a-Si:H absorber layers

	a-SiO:H initial / degraded	a-Si:H initial / degraded
Voc (V)	1.041 / 1.000	0.882 / 0.816
Jsc (mA/cm^2)	11.77 / 11.31	14.86 / 14.61
Fill factor (%)	62.1 / 58.45	71.3 / 64.87
Efficiency (%)	7.6 / 6.61	9.34 / 7.74
LID loss (%)	14.98	20.67

5 SUMMARY

We deposited (i)a-SiO:H absorber layers with different ratios of $r_c = \text{CO}_2/\text{SiH}_4$. We observed a linear increase of the bandgap for higher r_c ratios, but also an increase of the Urbach energy E_u and the defect density N_d in comparison to the reference (i)a-Si:H absorber layer. After 100 h of light soaking the (i)-SiO:H layer showed less LID in comparison to the reference (i)a-Si:H layer. Simulations of a standard a-Si:H PIN solar cell and a a-SiO:H PIN cell using the ASA software reveal a difference in the LID of 5.7 %.

6 ACKNOWLEDGEMENT

This work was supported by the European Union – European Fond for regional development “Investments for the Future” and the government of Northrhine-Westphalia under contract number 64.65.69-EN-2001A (ALPS).

7 REFERENCES

- [1] S. Inthisang, K. Sriprapha, S. Miyajima, A. Yamada, and M. Konagai, “Hydrogenated Amorphous Silicon Oxide Solar Cells Fabricated near the Phase Transition between Amorphous and Microcrystalline Structures,” *Jpn. J. Appl. Phys.*, vol. 48, no. 12, p. 122402, 2009.
- [2] D. L. Staebler and C. R. Wronski, “Reversible conductivity changes in discharge-produced amorphous Si,” *Appl. Phys. Lett.*, vol. 31, no. 4, p. 292, 1977.
- [3] M. Shiratani, S. Inthisang, T. Krajangsang, I. A. Yunaz, A. Yamada, M. Konagai, and C. R. Wronski, “Fabrication of high open-circuit voltage a-Si_{1-x}O_x:H solar cells by using p-a-Si_{1-x}O_x:H as window layer,” *Phys. Status Solidi C*, vol. 8, no. 10, pp. 2990–2993, 2011.
- [4] E. Schiff, “Low-mobility solar cells: a device physics primer with application to amorphous silicon,” *Solar Energy Materials and Solar Cells*, vol. 78, no. 1-4, pp. 567–595, 2003.
- [5] I. A. Yunaz, A. Yamada, and M. Konagai, “Theoretical Analysis of Amorphous Silicon Alloy Based Triple Junction Solar Cells,” *Jpn. J. Appl. Phys.*, vol. 46, no. No. 47, pp. L1152, 2007.
- [6] S. Inthisang, B. Janthong, P. Sichanugrist, and M. Konagai, “Fabrication of Novel Structure aSiO:H/a-Si:H/ μ c-Si:H Triple-Junction Solar Cells,” in *26th European Photovoltaic Solar Energy Conference and Exhibition: Proceedings : CCH Congress Centre and International Fair, Hamburg, Germany : conference 5-9 Sept 2011 : exhibition 5-8 Sept 2011*, Munich: WIP-Renewable Energies, 2011, pp. 2392–2394.
- [7] G. E. Jellison and F. A. Modine, “Parameterization of the optical functions of amorphous materials in the interband region,” *Appl. Phys. Lett.*, vol. 69, no. 3, p. 371, 1996.
- [8] J. Tauc, “Optical properties and electronic structure of amorphous Ge and Si,” *Materials Research Bulletin*, vol. 3, no. 1, pp. 37–46, 1968.
- [9] F. Urbach, “The Long-Wavelength Edge of Photographic Sensitivity and of the Electronic Absorption of Solids,” *Phys. Rev.*, vol. 92, no. 5, p. 1324, 1953.
- [10] M. Vaněček, J. Kočka, J. Stuchlík, and A. Tříska, “Direct measurement of the gap states and band tail absorption by constant photocurrent method in amorphous silicon,” *Solid State Communications*, vol. 39, no. 11, pp. 1199–1202, 1981.
- [11] N. Wyrsh, F. Finger, T. J. McMahon, and M. Vanecek, “How to reach more precise interpretation of subgap absorption spectra in terms of deep defect density in a-Si:H,” *Journal of Non-Crystalline Solids*, vol. 137-138, pp. 347–350, 1991.
- [12] M. Zeman, O. Isabella, S. Solntsev, and K. Jäger, “Modelling of thin-film silicon solar cells,” *Solar Energy Materials and Solar Cells*, vol. 119, pp. 94–111, 2013.