

CHARACTERIZATION OF MICROSTRUCTURE AND INTERFACES IN CADMIUM TELLURIDE THIN FILM SOLAR CELLS

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INTRODUCTION

In the superstrate configuration of CdTe thin film solar cells a thin n-type CdS layer is deposited on a TCO coated float glass. Afterwards a typically 4 to 5 µm thick p-type CdTe absorber layer and the thin metallic back contact are produced. CdS with a bandgap of about 2.4 eV absorbs already a part of the solar light with wavelength smaller than 500 nm and restricts therefore the quantum efficiencies in the short wavelength range. For limitation of these undesirable losses the CdS film should be as thin as possible to achieve a higher photo induced current. Simultaneously a minimum CdS layer thickness is necessary to maintain the properties of the pn junction for a preferably high open circuit voltage. Shunts between the CdTe absorber layer and the TCO layer must be avoided. Therefore for high solar cell efficiencies the thickness of CdS layer must be optimized to obtain a thin but compact layer without porosity. In addition a thermal CdCl₂ activation treatment is necessary for improvement of CdTe layer quality. In the frame of our work we like to investigate mainly the effect of CdS layer thickness and of subsequent activation treatment on microstructure, interfaces and solar cell parameters.

EXPERIMENTAL

The CdS and CdTe films were deposited by closed space sublimation (CSS) using an in-line vacuum equipment installed by Roth & Rau AG at Fraunhofer Institute for Electron Beam and Plasma Technology FEP. For the present experiments a commercial available 3.2 mm clear float glass substrate coated with fluorine doped tin oxide (AGC; IS9) was used. The CdS layer thickness was varied between 70 and 150 nm. The CdTe layers with thickness between 4.0 and 5.0 µm were deposited with a high dynamic deposition rate of about 320 nm·m⁻¹. The substrate temperature was kept nearly constant at 520°C. For the activation step the surface of CdTe layers was wetted with a saturated CdCl₂/methanol solution. The thermal treatment was carried out in a separate muffle furnace in air atmosphere. For the samples with varied CdS layer thickness a constant treatment at 390°C for 20 min was applied. In addition for a constant CdS layer thickness of about 100 nm the treatment temperature was varied between 390 and 430°C in steps of 10 K. Microstructure and interfaces of the solar cells were investigated on cross sections prepared by an ion beam preparation technique (Cross Section Polisher, SM-09010, Jeol). The cross sections and layer surfaces were investigated by high resolution field emission scanning electron microscopy (FE-SEM, SU 8000, Hitachi). The imaging was carried out with low angle backscattered electrons using the atomic number and channelling contrast. These results were supplemented by investigations of surface roughness of TCO and CdS layers using atomic force microscopy (AFM, Explorer, Topometrix). IV-curves of the solar cells were measured under AM 1.5 G illumination.

RESULTS AND DISCUSSION

FTO COATED FLOAT GLASS

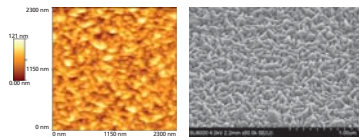


Fig. 1a: AFM FTO coated float glass Fig. 1b: FE-SEM FTO coated float glass

In the frame of this study all experiments were carried out on a commercial available clear float glass coated with fluorine doped tin oxide (FTO) as TCO layer and a high resistance tin oxide as buffer layer on top. The total layer thickness amounts to about 500 nm, whereas the typical sheet resistance was 10 ohms per square. AFM and FE-SEM micrographs of the FTO coated float glass show faceted crystallites with the typical morphology of tetragonal cassiterite phase (Fig. 1a and b). The mean lateral grain size of the FTO crystallites was estimated to 65 nm.

In addition roughness values are calculated from the AFM micrograph. The value for arithmetic average roughness value (Ra) is 12.7 nm and for maximum peak to valley roughness height (Rt) 120 nm, respectively.

EFFECT OF CdS LAYER THICKNESS AT A CONSTANT SUBSEQUENT CdCl₂ ACTIVATION TREATMENT

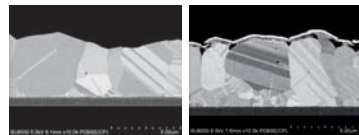


Fig. 2a: FE-SEM cross section before activation treatment Fig. 2b: FE-SEM cross section after activation treatment at 390°C

CdS layers with thickness of 70, 100 and 150 nm were deposited by CSS on FTO coated clear float glass. Ion prepared cross sections of solar cells were then investigated by FE-SEM before and after constant CdCl₂ treatment at 390°C for 20 min. The results show no significant effect of this treatment on the grain structure of the CdTe absorber (Fig. 2a and b). The CdTe layers have already before the treatment a typical block microstructure with large lateral crystallite sizes of about 2 µm. Therefore no appreciable driving force for further grain growth is present. This result is in accordance with former investigations which have shown that a pronounced recrystallisation and grain growth during activation treatment occurs only for crystallite sizes smaller than 1 µm. Within the grains twins are visible before and also after the treatment. At the surface of CdTe layer and especially on grain boundaries a darker contrast occurs. This contrast can be explained by NP etching which is linked with a tellurium enrichment and a slightly oxidation, which is more pronounced on grain boundaries.

Differences between the samples could be observed by high resolution FE-SEM investigations of the interfaces FTO / CdS / CdTe. It can be recognized that before the activation treatment the thin 70 nm CdS layer is not completely closed, because of the relative high roughness of the FTO layer. In contrast a thickness of 100 nm was sufficient for the formation of a nearly completely dense CdS layer. In addition with increasing layer thickness the lateral grain size of CdS was increased from 80 to 160 nm. After activation treatment no considerable change of CdS grain structure could be observed for the applied activation treatment, but some agglomerated porosity is visible at the CdS/CdTe interface for the 70 nm and 100 nm layers, whereas nearly no porosity could be recognized for the 150 nm layer.

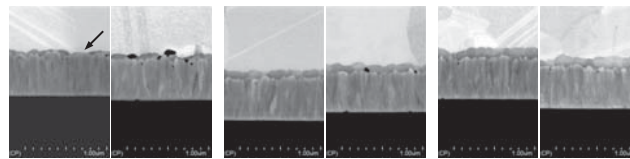


Fig. 3a: 70 nm CdS (left before; right after treatment) Fig. 3b: 100 nm CdS (left before; right after treatment) Fig. 3c: 150 nm CdS (left before; right after treatment)
FE-SEM micrographs of cross sections at interfaces FTO / CdS / CdTe on the left before activation treatment and on the right after activation treatment for solar cells with varied CdS layer thickness

CdS layer thickness in nm	Uoc in mV	Isc in mA/cm ²	FF in %	η in %
70	526	21.8	63.9	7.3
100	812	18.4	64.7	9.7
150	796	19.1	68.7	10.5

Table 1: Effect of CdS layer thickness on cell parameters (constant: CdCl₂ activation treatment at 390°C for 20 min)

The open circuit voltage is reduced for the 70 nm layer which can be explained by voids within the layer and the observed high porosity on interface, whereas the short circuit current density is relative high because of lower CdS absorption. In contrast with increasing layer thickness the open circuit voltage, the fill factor and the efficiencies are raised.

EFFECT OF TEMPERATURE OF CdCl₂ ACTIVATION TREATMENT AT A CONSTANT CdS THICKNESS

The effect of the temperature of CdCl₂ activation treatment was investigated for temperatures between 390 and 430°C, a constant activation time of 20 min and constant CdS layer thickness of 100 nm. In respect of CdTe grain structure no significant effect of activation treatment can be observed up to the highest applied activation temperature of 430°C (Fig. 5). Differences can be observed in high resolution micrographs of the interfaces FTO / CdS / CdTe and by imaging of CdS layer surface after chemical removal of CdTe layer and careful quantitative microstructure analysis (Fig. 4a-c). At 420°C a start of CdS grain growth can be detected. In comparison to the as deposited state the mean grain size is significant increased from 105 nm to 119 nm. A further more distinct growth of CdS crystallites was evaluated for activation treatment at 430°C. For this treatment the mean lateral grain size is increased to 133 nm. This growth and agglomeration of CdS crystallites is linked with the formation of voids within the CdS layer, which can be seen in the ion-prepared cross-section of the complete solar cell as well as on surface topography of CdS film. Simultaneously an increase of mean arithmetic roughness value (Ra) from 9.1 nm for the as deposited state to 11.9 nm after treatment at 430°C were detected by AFM (Fig. 6).

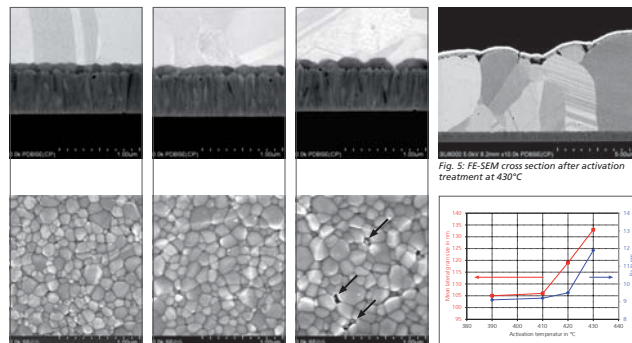


Fig. 4a: 390°C FE-SEM micrographs of CdS layer surfaces on the bottom and of cross sections at interfaces FTO / CdS / CdTe on the top after CdCl₂ activation treatment at different temperatures Fig. 4b: 420°C Fig. 4c: 430°C Fig. 5: FE-SEM cross section after activation treatment at 430°C Fig. 6: Effect of activation temperature on mean lateral grain size and roughness (Ra) of CdS layers

Temperature of CdCl ₂ activation in °C	Uoc in mV	Isc in mA/cm ²	FF in %	η in %
390	812	18.4	64.7	9.7
420	809	18.3	64.3	9.5
430	777	18.8	65.6	9.6

Table 2: Effect of temperature of CdCl₂ activation treatment on cell parameters (constant CdS thickness of 100 nm; treatment time 20 min)

The IV characteristic is nearly unchanged for activation temperatures between 390 and 420°C. At 430°C the open circuit voltage is declined from 809 mV to 777 mV, whereas the short circuit current density is slightly increased. These results can be explained by the observed voids within the CdS layer, which are the reason for partially disturbance of pn junction.

SUMMARY AND CONCLUSIONS

The applied cross section ion preparation technique in combination with high resolution FE-SEM investigations enables a detailed characterization of microstructure and interfaces within CdTe solar cells and is therefore very useful for optimization of process parameters. The results have shown that roughness of the underlying TCO FTO layer is an important issue for further minimizing of CdS layer thickness and thus lower absorption in the short wavelength range. A minimizing of layer thickness to values below 100 nm calls therefore for TCO's layers with very smooth layer surface. For the used FTO coated float glass with average roughness value (Ra) of 12.7 nm and maximum peak to valley roughness height (Rt) of 120 nm, a CdS layer thickness of about 150 nm was necessary to achieve solar

cells with homogeneous efficiencies above 10%. Higher efficiency can be expected for thinner but compact CdS layers on smoother TCO's. The investigations have further revealed that grain growth of CdS layer is a crucial issue during CdCl₂ activation treatment procedure. For higher treatment temperatures a pronounced CdS grain growth occurs which is linked with void formation within the CdS layer, a decreased open circuit voltage and only a slightly increased short circuit current density. The CdCl₂ activation treatment has to be therefore well adapted on the grain boundary structure and layer thickness.

CONTACT

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ACKNOWLEDGEMENT

THIS PROJECT WAS FUNDED BY THE EU AND THE FREE STATE OF SAXONY:
14549/2533



Europa fördert Sachsen.
EFRE
Europäischer Fonds für regionale Entwicklung

