LIGHT SCATTERING AND TRAPPING IN DIFFERENT THIN FILM PHOTOVOLTAIC DEVICES

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ABSTRACT: Light trapping in different thin film technologies is investigated in the context of the European integrated project ATHLET since it allows for thinner devices and thus for reduction of costs for absorber material preparation as well as for advanced multi-junction solar cells. In silicon technology, rough interfaces are typically introduced by roughening of substrates, transparent conducting oxides (TCOs) and/or reflectors at the back side to scatter the light into the absorber material. Well known rough TCOs, plasma-textured poly-Si as well as rough Cu(In,Ga)Se$_2$ (CIGS) absorbers are used as source for light scattering in microcrystalline silicon solar cells and compared regarding their surface roughness. The results prove that CIGS and poly silicon solar cells provide efficient light scattering by the surface features of the rough absorber.

Keywords: Light Trapping, Thin Film Solar Cell, Si-Films, CIGS

1 INTRODUCTION

Light trapping is an important feature of silicon thin film solar cells. Also for other thin film technologies light trapping attracts increasing attention since it allows for thinner devices, and costs for absorber material preparation have to be reduced. In silicon technology, typically, rough interfaces are introduced to scatter the light into the absorber material. This can be achieved by roughening of substrates, transparent conducting oxides (TCOs) and/or reflectors at the back side. In chalcopyrite or crystalline film silicon devices, rough features are introduced during growth or by post deposition texturing of the absorber material, respectively. However, the effectiveness of the different types of roughness for light trapping is not known in detail. This paper addresses the comparison of different light scattering features that are involved in the European integrated project, called ATHLET. We will compare the different types of roughness, namely well known rough TCOs, plasma-textured poly-silicon as well as rough CIGS absorbers. To be comparable for all these types of rough substrates we prepared hydrogenated microcrystalline silicon (μc-Si:H) solar cells in substrate configuration on top of the rough layers with a rough back contact.

We investigated the surface structure, the light scattering behavior the corresponding reflectors and performance of microcrystalline hydrogenated silicon solar cells on top of the reflectors.

2 EXPERIMENTAL

2.1 Sample preparation

As substrates for the light trapping investigation we applied CIGS absorber layers grown by an evaporation method [1], plasma-textured poly silicon [2] and as reference two often applied surface textured ZnO films, namely as-grown textured boron doped zinc oxide (ZnO:B) prepared by low pressure chemical vapor deposition (LPCVD) [3] and sputtered and texture-etched aluminum doped ZnO:Al [4]. Details on sample preparation are given in the respective references. These rough layers were used as substrates for μc-Si:H solar cells. The cells consist of the previously mentioned rough substrates, 200 nm evaporated silver film and 80 nm aluminum doped ZnO as part of the back reflector, p-i-n doped silicon films and an 80 nm aluminum doped ZnO front contact. Silver finger contacts were applied to support the conductivity of the thin TCO front contact.

All silicon and ZnO layers were co-deposited in 30x30 cm² reactors by plasma-enhanced CVD [5] and non-reactive RF sputtering from ceramic ZnO targets (1 wt% Al$_2$O$_3$) [4]. All silver films were thermally evaporated in a 10x10 cm² system. The approximately 1.2 μm thick solar cell is then illuminated through the n side.

Table I: RMS roughness data of the bare rough samples, samples with Ag and with Ag/ZnO coating, and photo current of the solar cells extracted from QE

Substrate	RMS roughness [nm]	Surface angle α [°]	J_{ph} [mA/cm²]
CIGS absorber (EMPA)	65		
+ 200 nm Ag	-	18	16.7
+ 80 nm ZnO	-		
LPCVD ZnO:B (EPFL)	80	44	
+ 200 nm Ag	74		16.4
+ 80 nm ZnO	77		
RF-sputtered, texture-etched ZnO:Al (Jülich)	130	26	18.7
+ 200 nm Ag	115		
+ 80 nm ZnO	117		
Plasma-textured poly-Si (IMEC)	240	39	13.1
+ 200 nm Ag	202		(at -0.5V)
+ 80 nm ZnO	200		

2.2 Characterization

We investigated the surface structures by atomic force microscopy (AFM) and statistical analysis. For roughness values given in Table I a measurement error of about 5 nm was estimated. Optical reflectivity spectra were taken of the rough silver layers with and without the additional ZnO:Al film and of the solar cells on areas with only ZnO:Al front contact without silver fingers. The reflectance spectra show some artifacts at about 900 nm that must be ignored. Cell performance was evaluated by spectral response measurements to get quantum efficiency and to extract the cell current via AM1.5 spectrum.

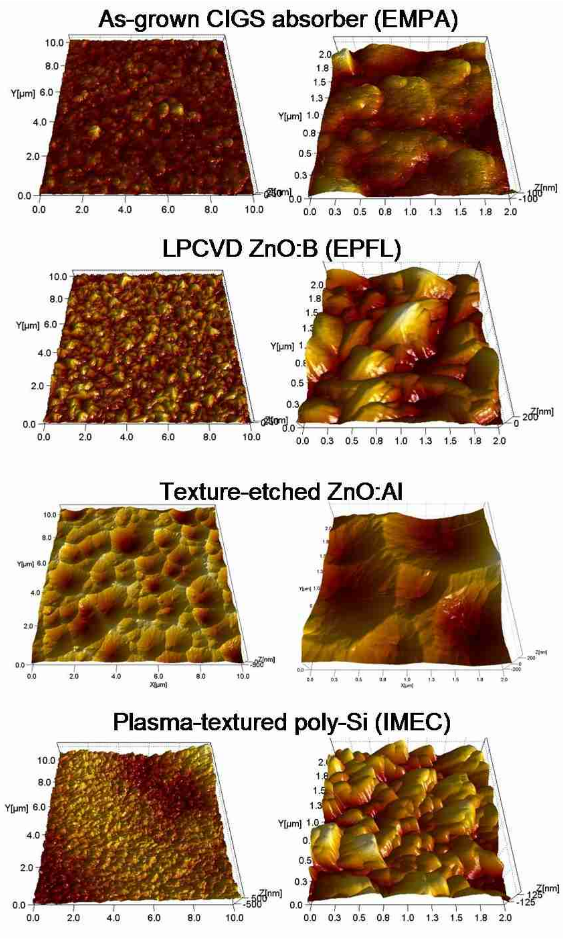

Figure 1: AFM surface images of the rough substrates before Ag layer deposition

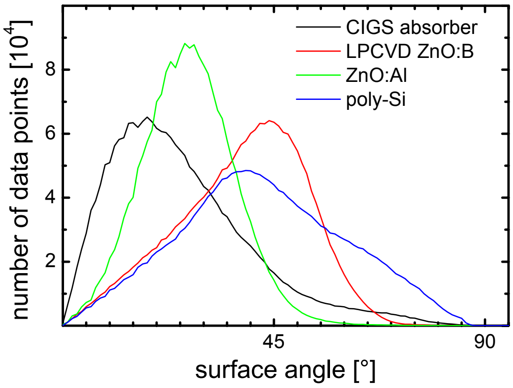

Figure 2: Histogram of the local surface tilt angle for the different substrates: CIGS (black), LPCVD ZnO (red), texture-etched ZnO:Al (green) and plasma-textured poly silicon (blue)

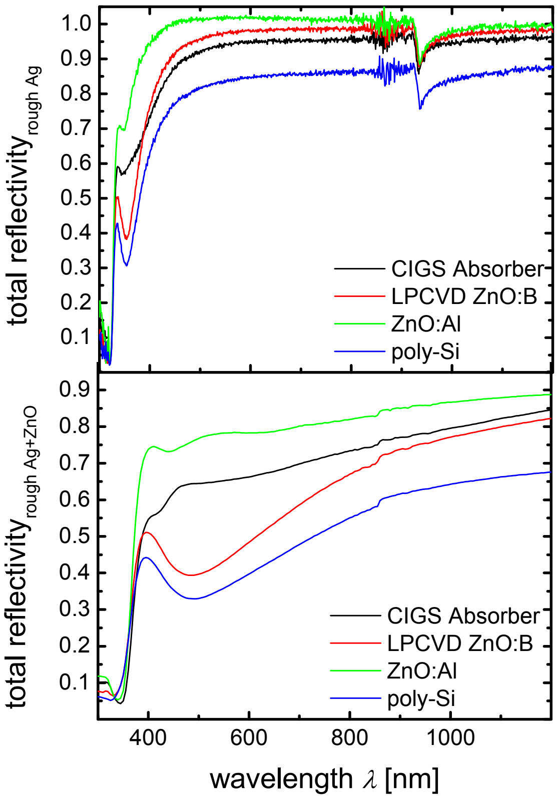

Figure 3: Reflectivity of rough Silver layers without (top) and with an additional 80 nm ZnO film

3 RESULTS AND DISCUSSION

3.1 Surface characteristics of rough samples

Figure 1 shows the AFM surface images of the rough surfaces. The type of substrate is indicated in the figure. The corresponding statistical roughness data are provided in Table I. The data exhibit different lateral and vertical feature sizes. The roughness increases from CIGS via LPCVD and texture-etched ZnO films to the plasma-textured poly silicon film. The lateral features are largest for texture-etched ZnO:Al, followed by CIGS, LPCVD ZnO:B and plasma-textured poly silicon. Thus, the local tilt angles of the surfaces are different. These AFM data were evaluated by a self-made software [6] and the local tilt angles of the surface relative to the substrate are illustrated in Figure 2. The maxima of the distribution of surface tilt angles α are given in Table I. The CIGS absorbers and the texture-etched ZnO:Al films exhibit small values of α and also are similar in lateral surface feature size. The other two samples LPCVD ZnO:B and textured poly silicon structures consist of laterally smaller and sharp features leading to much steeper angles around 40°.

3.2 Optical reflector performance

After coating of the rough samples with silver and ZnO we performed reflectivity measurements as shown in Figure 3. The reflectivity of the rough silver shows severe minima at about 350 nm for bare silver that shift up to 500 nm after coating with the ZnO layer. These absorption peaks are discussed in literature to be propagating or localized surface plasmons [7,8,9]. Additionally, the low reflection of the rough Ag/ZnO reflector is related to strong absorption by light trapping inside the ZnO:Al layer that also enhances parasitic absorption at the rough Ag/ZnO interface. This effect is more pronounced for samples with steeper surface angles α. Here the light scattering into larger angles is much more effective [10] and the small sharp features may enhance localized plasmonic effects to cause additional absorption.

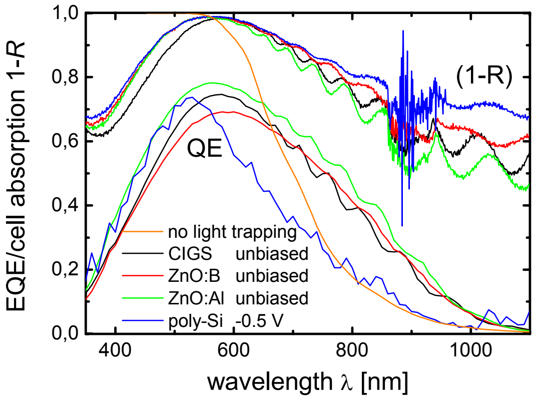

Figure 4: External quantum efficiency and total cell absorption (1-R) of μc-Si:H solar cells on different rough substrates: CIGS (black), LPCVD ZnO (red), texture-etched ZnO:Al (green) and plasma-textured poly silicon (blue). Additionally, we show absorption of 2.4 μm silicon corresponding to no light trapping and ideal front side anti-reflection and back side reflector

3.3 Solar cells

Standard p-i-n solar cells were prepared in substrate configuration and illuminated through the n side. The cell performance in terms of efficiency was strongly limited by the fact of a non-optimized process for substrate configuration and for μc-Si:H growth on these different rough substrates. However, there were a few solar cells with acceptable fill factor, open circuit voltage and current (not shown), proving that the deposition process worked well. Spectral response measurements of the solar cells on different rough substrates were taken and the corresponding quantum efficiency QE is given in **Figure 4**. The figure also contains cell absorption data calculated from total cell reflection. The absorption of 2.4 μm silicon corresponds to a cell with no light trapping, no parasitic absorption and ideal front side antireflection and back side reflector. The calculated photocurrent is given in Table I. Note that the electrical properties of the μc-Si:H cell on the poly-silicon substrate were poor, so the photocurrent could only be collected at reverse bias. The different and partially poor QE of the solar cells especially in the blue region is attributed to imperfect homogeneity of the antireflective front contact and of n-layer thickness. It may also be limited by the quality of μc-Si:H, grown on rough substrates [11]. However, reverse bias did not significantly change the QE data for the cells on ZnO and CIGS.

At about 550 nm the cell absorption is nearly 100% caused by an effective antireflection effect of the transparent front contact. Below this wavelength, strong primary reflection occurs. The amount of secondary reflection in the NIR depends on light trapping and parasitic absorption inside the cells. In the long wavelength region, the QE reveals severe light trapping in cells prepared on CIGS and the two kinds of ZnO. The light absorption is strongly enhanced as compared to the absorption calculated for light passing twice the silicon thickness (no light trapping, ideal reflector). For both rough ZnO one would expect enhanced red response, since the surface features are known to provide good light trapping in silicon thin film solar cells when applied at the front contact. For surface features provided by the CIGS itself, the provided light trapping is an important message, since cost reduction drives CIGS development to thinner cells moreover in combination with appropriately chosen CIGS composition (for bandgap tailoring) advance multi-junction solar cells are under development [12,13]. The μc-Si:H cell on plasma-textured poly silicon substrate behaves strongly different. The QE is comparable to the curve calculated for no light trapping. However, the cell absorption is highest within this series. This hints to very strong parasitic absorption losses. This can be explained by the low reflectivity of the reflector as shown in Figure 3. However, the reflectivity measurement of the reflector was performed in air and reflectivity might change in the real cell structure, where the silicon is directly attached to the ZnO. From the roughness one would expect light trapping effect. Thus one can directly study the light trapping effect in the poly silicon cells itself. From another publication that studies the effect of plasma texturing on optical performance [2], one can extract a light trapping effect, if the QE values are compared to the case of no light trapping in analogy to **Figure 4** (not shown). This comparison reveals even in the un-textured cells a significant light trapping effect. However, the light trapping ability in the poly-silicon cells still can be improved by adjusted surface texturing and even more important by reduction of parasitic absorption [2].

4 CONCLUSIONS

Light trapping in silicon thin film solar cells is very important. It might also be important for CIGS technology if the absorber thickness is reduced for cost reasons. The rough CIGS absorber already provides light scattering to enhance the optical performance, even though, it is not important due to the strong absorption of CIGS, but with tailored bandgap and thickness the concepts are attractive for applications in multi-junction (tandem) solar cells. In this context a-Si as top cell and CIGS as intermediate or bottom cell are suitable. By our approach a judgment of light trapping in poly silicon cells is not possible. Other publications indicate a light trapping effect even in the un-textured cells. That means that light trapping is available in different thin films PV technologies and will be an important factor to boost the efficiency, even for material systems that did not require light trapping so far.

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