A comparison of the vacuum evaporated CdTe for substrate and superstrate solar cells

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ABSTRACT: The structural properties of CdTe layers grown on different substrates were characterized for their application in “substrate” and “superstrate” type solar cells. $CdCl_2$ treated CdTe layers in substrate configuration have large grains up to 10 µm with well defined shape and the (111) preferred orientation is retained. Na has a strong influence on the crystallization and electronic properties of the CdTe layers. As-deposited and $CdCl_2$ treated CdTe layers on alkali free glass have small but more compact grains, the layers are always (111) oriented. The solar cells in substrate configuration exhibit low efficiency, but in superstrate configuration high efficiency cells were obtained: 11% with evaporated Sb_2Te_3 and 12% with Cu/Au contacts.

Keywords: CdTe-1: Substrates-2: Thin Film-3

1. INTRODUCTION

CdTe/CdS is one of the most promising solar cell for low cost and high efficiency conversion of solar energy into electricity. Solar cells with efficiencies of 10 to 16% have been obtained with CdTe grown by close space sublimation, electrodeposition, spray pyrolysis, vacuum evaporation and RF sputtering methods [1]. In the most common superstrate configuration metal back contact/CdTe/CdS stacked layers are grown on transparent conducting oxide (TCO) coated glass substrate and the cell is illuminated from the glass substrate side.

It is known that a “$CdCl_2$ treatment”/annealing in air is very important for high efficiency cells. These treatments are necessary for the recrystallization and p-type conductivity conversion of CdTe layers, as well as for the intermixing of CdS-CdTe. An optimum annealing condition is required for the formation of an appropriate $CdTe_{1-x}$-S_x intermixed interface. It is desirable to separately control the CdTe recrystallization and intermixing. This is difficult in superstrate configuration because the CdS layer is already present during the recrystallization of CdTe. However, this can easily be performed in the substrate configuration: i.e. TCO/CdS/CdTe/metal-contact/glass. In this configuration the light is incident from the top TCO side (and not from the glass substrate) [2-3]. The advantage of this configuration is that it extends the possibility to first recrystallize the CdTe layer and then activate the junction by independently controlling the CdS-CdTe intermixing. The efficiency and stability of solar cells depend on the CdTe-back contact. Earlier, we used Cu-Au back contacts in the superstrate configuration. Now we have used vacuum evaporated Sb_2Te_3 as a back contact for substrate and superstrate solar cells. We have evaluated different materials that may form a good contact with CdTe in substrate configuration. The paper presents a comparative study of the photovoltaic and structural properties of CdTe layers grown on different back-contact substrates.

2. EXPERIMENTAL DETAILS

2.1 Superstrate configuration

Commercially available fluorine doped SnO_x (FTO) coated soda lime glass substrates are used for the growth of superstrate solar cells. CdS layers are grown in a high vacuum evaporation chamber at a substrate temperature of 150 °C. The optimum thickness of the CdS is about 500 nm. CdS layers are then annealed in vacuum at 450 °C. The CdTe layers are subsequently grown by evaporation of CdTe (6 nine pure) source material, at a substrate temperature of 300 °C with a growth rate of 4 µm/h. The typical thickness of CdTe layer is in the range of 3 to 4 µm. An optimized $CdCl_2$ treatment at 430 °C is applied on the CdTe/CdS stacks [5-6]. The surface of the CdTe layer is etched in a bromine-methanol solution prior to the deposition of Cu/Au layers or Sb_2Te_3 for back contacting on CdTe.

2.2 Substrate configuration

For the growth of solar cells in this configuration the choice of an appropriate metal or semiconductor surface is critical, because this layer has to form a low resistance Ohmic contact with CdTe. We have evaluated Cu-Au, Mo, Te-Mo, Sb_2Te_3-Mo as back contact layers on glass substrates.

First a layer of 0.5 µm thick molybdenum is deposited with a DC magnetron sputtering system either on a soda lime or alkali free glass. Thin layer of Sb_2Te_3 or Te were deposited in an ultra high vacuum chamber with a substrate temperature of 200 °C. CdTe layers are grown at 300 °C in the same chamber without breaking the vacuum. For the $CdCl_2$ treatment, vacuum evaporation is used for the deposition of $CdCl_2$ layers on CdTe and the stacks are annealed at 430 °C for 30 minutes in air.

After washing CdTe in water, CdS is then deposited in a high vacuum chamber at a substrate temperature of 150 °C. Before evaporation, the fluxes of CdS and CdTe are controlled by an UHV ionization gauge (Balzers IMG-U2), and after evaporation, the thicknesses are measured with a profilemeter (Dektat 3030). The CdTe thickness is about 3 to 4 µm and CdS is about 0.5 µm thick in a standard deposition. After the growth of CdS layers, the CdS/CdTe stack is annealed in air at 430 °C or given a $CdCl_2$ treatment by annealing at 430 °C.

For the front contact a layer of ZnO:Al is deposited on the CdS surface by RF sputtering at room temperature.

3. STRUCTURE PROPERTIES OF CdTe

We have previously shown [4-5] that the growth and morphology of CdTe depend strongly on the substrate on which it is grown. After the $CdCl_2$ treatment a large increase in the grain size is observed. The $CdCl_2$ acts like a sintering flux in CdTe as small grains grow and coalesce together, but it also causes the widening of grain boundaries. Wider grain boundary regions are not desired because they may affect the parallel conduction across the grain boundaries as well as they may also cause the shunting of solar cells by providing a conducting link between the top and bottom electrodes. For high efficiency and stability large grained and compact CdTe is required.

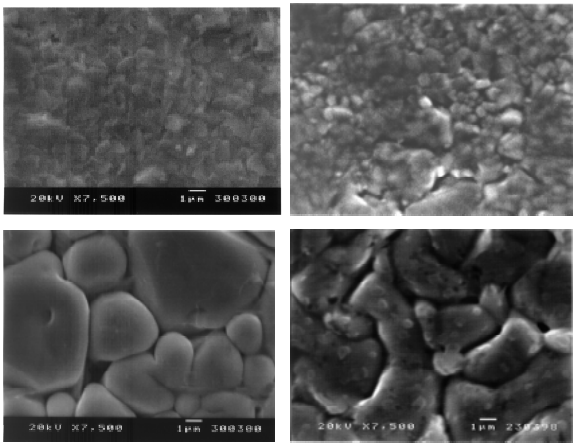

Figure 1: SEM images of CdTe surfaces. Top; as-deposited CdTe on Mo/glass (left) and on CdS/FTO (right). Bottom; $CdCl_2$ treated CdTe on Mo/glass (left) and on CdS/FTO substrate after $CdCl_2$ treatment (right). The substrate is soda lime glass.

As shown in figure 1 the as deposited CdTe layer on Mo is compact and it consists of grains of 0.5 µm to 2 µm size. The morphology is rough due to irregular shape and size of grains. This condition is similar to the as deposited CdTe on CdS/FTO/glass, even if in this later case the shape and size of grains are more randomly distributed. After $CdCl_2$ treatment, the CdTe layer on Mo/ glass has grains with well defined shape but different grain size ranging from 3 µm to 10 µm. $CdCl_2$ treated CdTe on CdS/FTO/glass is very different, with grains of random shape and size of 1 µm to 10 µm.

The layers on Sb_2Te_3/Mo/glass (see figure 2) exhibit a different microstructure. In the as deposited case the grains have homogeneous shape and size of about 1 to 2 µm, and they are very compact. After $CdCl_2$ treatment, the grains enlarge up to 8 µm with wide grain boundaries.

In figure 2 are also shown CdTe layers grown on Sb_2Te_3/Mo, but on *alkali free glass* substrates. The morphologies of CdTe, grown under identical conditions, on alkali free and soda lime glasses are substantially different. On alkali free glass, in the as-deposited case the grains have a size of about 0.1 µm-0.5 µm and they are homogeneous in shape. After $CdCl_2$ treatment, the layers are very compact (narrow grain boundaries) and the size of grains is much smaller compared to the other treated layers on soda lime substrates (1 to 5 µm).

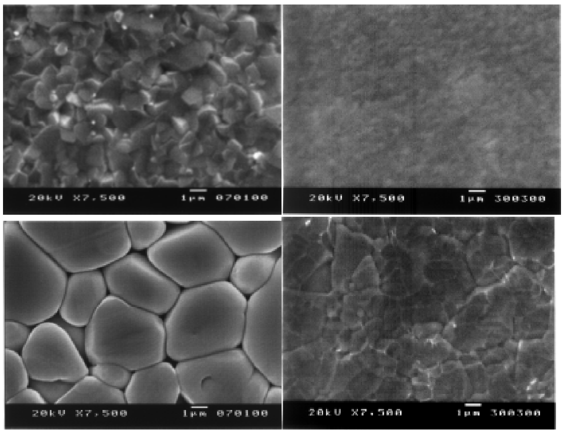

Figure 2.SEM of as-deposited (top) and $CdCl_2$ treated (bottom) CdTe layers on soda lime (left) and alkali free (right) substrates. The layers are grown on Sb_2Te_3/Mo coated substrates.

The influence of substrate on the growth of CdTe is also evident from the X-ray diffraction (XRD) measurements. As shown in figure 3, CdTe in the substrate configuration has a pronounced (111) preferred orientation, which is not the case for CdTe in superstrate configuration. Even after the $CdCl_2$ treatment, CdTe layer in substrate configuration is still (111) oriented. While in the superstrate configuration the (111) preferred orientation is almost lost. In figure 4 are shown the XRD patterns of CdTe grown on alkali free glass. A comparison with figure 3 clearly indicates that the sodium has a very strong influence on the orientation. The as-deposited layer has a strong (111) orientation and the $CdCl_2$ treatment does not change this preferred orientation.

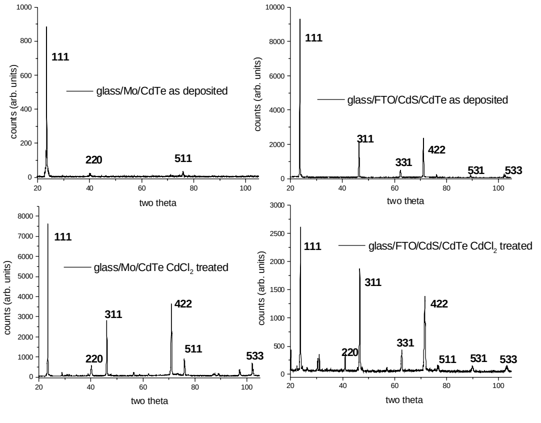

Figure 3: X-Ray diffractograms of CdTe on Mo/glass (left) and CdTe on CdS/FTO/glass (right): as-deposited (top), treated (bottom) conditions. The substrate is soda lime glass.

This is in contrast to that on soda lime substrates. From these results, together with the SEM observations, it is clearly evident that the sodium has a strong influence on the recrystallization of CdTe grains. It has been reported that the efficiency of superstrate cells on alkali free glass is higher than those on soda lime glass, a higher I_{sc} of the cells on Corning glass was attributed to a better transparency of the alkali free glass [6]. We believe instead, that this difference is more to be attributed to a different growth and orientation of CdTe. In addition the electrical influence of sodium in CdTe should be considered. As described by Altosaar [7], Na on Cd site is an acceptor, while it may also form a complex donor-acceptor pair (Na_{Cd}-Cl_{Te}) after the $CdCl_2$ treatment. Therefore the carrier concentration of CdTe on soda lime and alkali free glass will be different due to the doping effects of Na

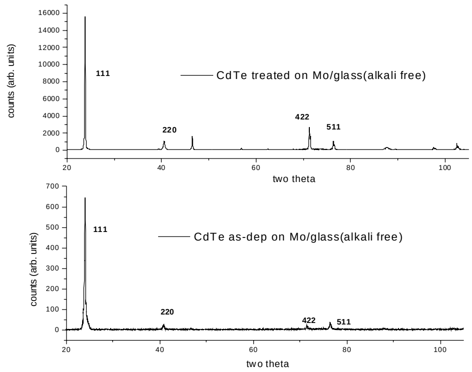

Figure 4: X-ray diffractograms of CdTe on Mo/glass: as-deposited (bottom) and treated (top). The substrate is alkali free glass.

In figure 5, the diffractograms of CdTe grown on Sb_2Te_3/glass are shown. It is clearly seen that the $CdCl_2$ treatment has a different effect on this layer; in the as-deposited case the CdTe is (111) oriented and almost no other peaks are present. For the $CdCl_2$ treated layer the (111) orientation is completely lost, and the (311) and (422) peaks are the stronger. Once again the observations suggest that the growth of CdTe is affected by the substrate. Therefore different back contacts provide different template for the growth of CdTe and the microstructure of the layer is influenced.

4. JUNCTION FORMATION WITH CdS

Heat treatment of the CdS/CdTe stack is necessary for interfacial intermixing and junction activation. In case of the superstrate solar cells, CdS-CdTe interdiffusion already takes place during the deposition of CdTe on CdS at 300 °C. However, in the substrate configuration CdS is grown at a low temperatures of 150 °C. Therefore high temperature annealing is still required for an optimum intermixing even if the CdTe is already recrystallized in $CdCl_2$. The intermixing and photovoltaic properties are better when CdS/CdTe substrate cells are annealed in presence of $CdCl_2$.

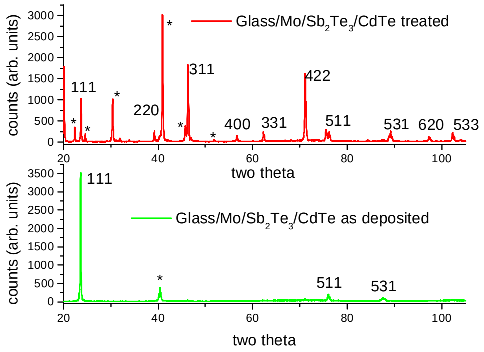

Figure 5: X-Ray diffractograms of CdTe on Sb_2Te_3/Mo/glass: as-deposited (bottom) and $CdCl_2$ treated (top). The substrate is soda lime glass.

5. SOLAR CELL PERFORMANCE

One of the difficult task in processing a CdTe solar cell in substrate configuration is to have a stable back contact. Different back contacts, such as Cu/Mo, Mo, Sb_2Te_3/Mo were evaluated. Solar cells with Cu/Au contact were shorted because of the diffusion of Cu in CdTe during its growth and recrystallization. Cells on Mo or Sb_2Te_3 also exhibited poor performance (<2%), as shown in figure 7 the V_{oc} is in the range of 300 mV to 400 mV and the cells have a low FF. However high efficiency cells are obtained in superstrate configuration. Fig 7 shows I-V curves of solar cells with evaporated Sb_2Te_3 back contact (V_{oc}=751 mV, I_{sc}=24.8 mA/cm^2, F.F.=59% η=11%) and Cu-Au back contact (V_{oc}=795 mV, I_{sc}=23 mA/cm^2, F.F.=67% η=12%). The cells with Cu-Au back contact exhibit higher V_{oc} and F.F. but they have long term stability problem during migration of Cu.

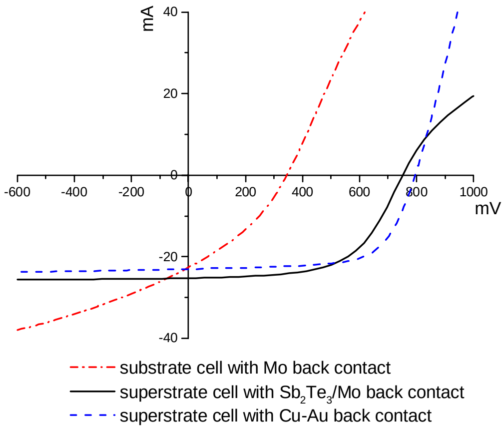

Figure 7. I-V performance of superstrate and substrate solar cells. The efficiency of Sb_2Te_3 contacted cell is 11%.

6. CONCLUSIONS

A comparative study of the structural properties of CdTe layers on different substrates have been performed. The development of substrate type solar cell requires an appropriate substrate. Despite of large grain size of CdTe on Mo/glass and Sb_2Te_3/Mo/glass, the cell efficiencies are rather low (<2%). With Cu/Mo contacts the cells are shunted. In contrast to this, the same back contact materials when used in superstrate configuration yield high efficiency cells e.g. 11% and 12% cells with evaporated Sb_2Te_3 and Cu/Au contacts. It has been observed that Na has a influence on the microstructure and orientation of CdTe layers. Na may affect the carrier concentration in CdTe by substitutional doping at cation vacancy site or forming a donor-acceptor pair. The structure and electronic influence on Na on the efficiency of solar cells should be investigated further.

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