DEVELOPMENT OF HIGH EFFICIENCY FLEXIBLE CdTe SOLAR CELLS

A.Romeo, M. Arnold, D.L. Bätzner, H. Zogg and A.N. Tiwari*
Thin Films Physics Group, Laboratory for Solid State Physics, Swiss Federal Institute of Technology,
Technopark, ETH-Building, Technoparkstr.1, CH-8005 Zurich
Tel: +41-1-4451474, Fax: +41-1-4451499
E-mail: romeo@phys.ethz.ch

*also at Center for Renewable Energy Systems and Technology,
Electronic and Electrical Engineering Department Loughborough University,
Loughborough Leicestershire, LE11 3TU, UK
Telephone: +44-1509-227031
E-mail: a.n.tiwari@lboro.ac.uk

ABSTRACT: Polycrystalline thin film solar cells of II-VI compound semiconductors are important because of their low cost, high efficiency and stable performance. Flexible and lightweight solar cells are interesting for a variety of terrestrial and space applications that require a very high specific power (ratio of output electrical power to the solar module weight). Moreover, light modules are advantageous in terms of transport and mounting.
We have previously described the development of flexible CdTe/CdS solar cells on polyimide substrates with a novel method; efficiencies of 8.6 % were reported. Further improvements in the processing have now increased the solar cell efficiency to 11%. The CdTe solar cell is fabricated in a "superstrate" configuration where the light passes through the polyimide substrate. Absorption of the incident light and possible degradation of polyimide under UV and particle irradiation are the major limitations of this configuration. To overcome these a new approach is introduced here. The CdTe/CdS/TCO stacks are grown on a NaCl/glass substrate. After the solar cell has been processed, a polymer layer is spin coated on top and the flexible solar cells are detached from the glass by dissolving the NaCl buffer layer. Solar cells of 7.3% efficiency have been obtained.

Keywords: CdTe, Flexible Cells, Space Cells

1. INTRODUCTION

Polycrystalline CdTe thin film solar cells have shown long-term stable performance [1] and high efficiency up to 16.5% under AM 1.5 illumination [2]. If produced in large volume, e.g. more than 60 MW/year, their cost could be lower than 1 Euro/Wp [3]. Only a few micron thick layers are needed for the solar cell, therefore devices with high specific power (ratio of output power to the weight) are expected if the glass is substituted with a lightweight substrate (the glass substrate represents more than 98 % of the total weight of the cells).

It has been shown that CdTe has the highest stability under proton and electron irradiation [4][5] compared to the other photovoltaic devices, which makes CdTe cells very interesting for space applications. High specific power is an important issue for space solar cells: if satellites are lighter they are easier and cheaper to launch in orbit.

One approach to maximize the specific power is to substitute the glass substrate with a flexible thin substrate, such as metal or polymer foils. Moreover, this gives flexibility to the solar panel that can be adapted to any kind of shape and is easy to deploy in space.

In the last years, terrestrial photovoltaics has moved towards the direction of building integration of modules. Flexible cells give much more possibilities for integration in buildings, and can be applied in smart cards, consumer electronics, solar cars and boats, etc. In this paper we present two different processes for the fabrication of lightweight flexible CdTe solar cells:

- A "superstrate configuration" process is based on the introduction between the glass and the stacks of a transparent polyimide layer, followed by a lift-off from the glass.
- A "substrate configuration" process is based on the application of a polyimide on the back of the cell and followed by a lift-off from the glass.

2. FABRICATION OF SOLAR CELLS

We have developed a solar cell fabrication process in which all the layers are grown by vacuum evaporation [6]. Commercially available soda-lime glass coated with fluorine doped tin oxide (FTO) was used as substrates. CdS layers were grown in a high vacuum evaporation (HVE) chamber with a substrate temperature of 150°C and subsequently annealed at 450°C for recrystallization. Without breaking the vacuum CdTe was then deposited at a substrate temperature of 300°C. In a standard deposition CdS thickness is about 0.5 μm and CdTe thickness is between 3 to 4 μm.

Vacuum evaporation was used for the deposition of 600 nm $CdCl_2$ activation layers on CdTe. The stacks were annealed at 430 °C for 30 minutes in air. For the electrical back contact the surface of the CdTe was etched with a Br-methanol solution followed by the deposition of Cu/Au stacks and a short annealing at 200 °C in air.

Solar cells in the efficiency range of 11 to 12% are routinely obtained. In figure 1 is shown an I-V characteristic of a 12.5% solar cell (with open circuit voltage (Voc) of 800 mV, short current density (Jsc) of 23.2

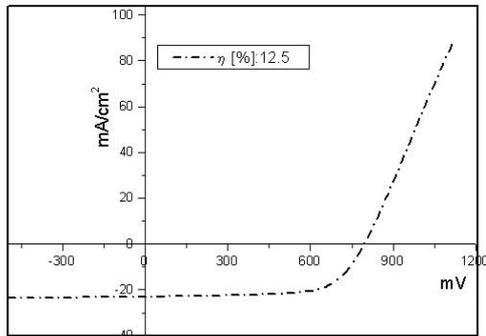mA/cm^2 and fill factor (f.f.) of 67.5 %) under AM1.5 illumination.

Figure 1: I-V of a standard CdTe solar cell on glass with a 12.5% efficiency under AM1.5 illumination, fabricated with a high vacuum evaporation process.

3. STRUCTURE OF CdTe SOLAR CELLS

The CdTe solar cell can be fabricated in a superstrate or a substrate configuration (see figure 2).

High efficiency CdTe solar cells are generally grown in a superstrate configuration where the CdTe/CdS stacks are deposited on transparent conducting oxide (TCO) coated glass substrates. Efforts to develop flexible CdTe solar cells were, until recently, not successful, because for such solar cells in the superstrate configuration the choice of an appropriate substrate is crucial; the substrate should be optically transparent and should withstand high temperature, during deposition and processing.

Most of the CdTe solar cell fabrication processes require temperatures of about 450 to 550 °C, while most of the transparent polymers are not stable at such high temperatures. However, some polyimides are stable at temperatures of up to 450 °C with an optical transparency sufficient for solar cell applications.

Moreover, if the thickness of the polyimide film is reduced, the absorption loss in the substrate can be minimized further.
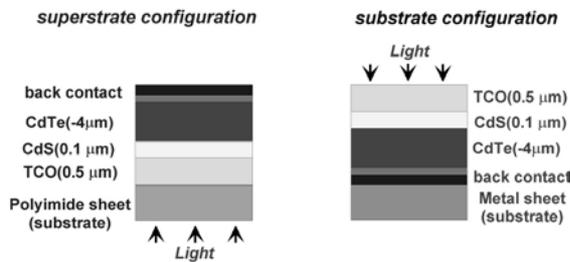

Figure 2: Schematics of superstrate (left) and substrate configuration (right) solar cells, respectively on polyimide and on metal sheets.

4. SUPERSTRATE CONFIGURATION FLEXIBLE CdTe CELLS

Commercially available polyimide films such as Kapton and Upilex can withstand high temperatures (~450°C), but they are dark yellow and they strongly absorb visible radiation (Figure 3). Therefore, CdTe solar

cells on 50- to 100-μm-thick-polyimide films will yield a low current due to a large optical absorption loss in the substrate.

We have developed a process in which, instead of using a commercially available foil, a "specific" type of polyimide film, thin and transparent in order to minimize the absorption loss, is prepared in-house

The left part of figure 2 shows the schematics of solar cell processing. A thin buffer layer of NaCl was evaporated on a glass substrate, then a polyimide layer was spin-coated and cured at about 430°C. The thickness of the polyimide film can be controlled by the spin-coating process, we have used about 10 μm-thin polyimide films.

As shown in figure 3, the average transmission of the polyimide film is more than ~75% for wavelengths above 600 nm. There is a strong absorption of photons in the wavelength range of 400 to 600 nm.
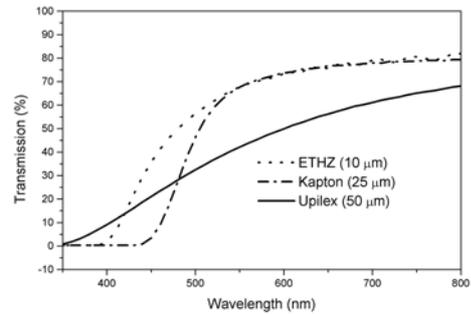

Figure 3: Transmission spectra of different polyimide layers, transparency is strongly depending on the polyimide thickness.

A TCO on the top of the polyimide (either ZnO:Al or ITO) is deposited with RF sputtering, followed by the standard HVE CdS and CdTe deposition and post deposition treatment, as described in section 2. After processing the device is rinsed in water in order to dissolve the NaCl layer and the solar cell is detached from the glass.
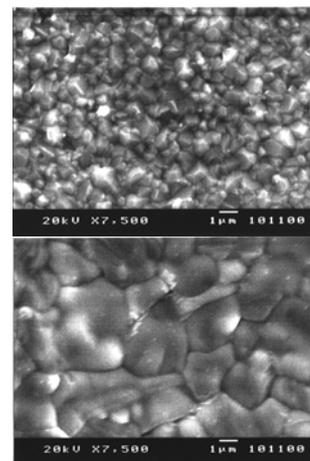

Figure 4: As-deposited (top) and CdCl$_2$ (bottom) treated CdTe/CdS/TCO layers on polyimide, the morphology is compact and crack free.

The morphology of CdTe on polyimide is similar to that on glass substrates [6]. As shown in figure 4, the as-

deposited CdTe layer is homogeneously compact with grains of up to ~1 μm size. The CdCl$_2$–annealed layers are crack-free and consist of large grains of up to ~5 μm.

The solar cells grown on this polyimide exhibit efficiencies of 8.6% (see figure 5) with ZnO:Al [7] and 11% with ITO as front contact under AM1.5 illumination, we believe that this is the highest reported efficiency of a flexible CdTe solar cell.

The reason for a lower efficiency with the ZnO:Al is that this contact result to be less stable to the fabrication process and its electrical properties are changed after processing. Earlier we have reported [6] that solar cells on ZnO: Al coated glass substrates exhibit ~3% efficiency because of a very low fill factor ~30%, low current density, and high series resistance; while the same process on ITO or FTO /glass yields 11 to 12% efficiency solar cells.

In figure 5 it is shown, in the case of ITO as front contact, that high values of open circuit voltage (842 mV) and fill factor (70.9 %) are obtained. However the Jsc is lower (18.5 mA/cm^2) than the ones of CdTe/CdS solar cells on glass (see figure 1) because of the absorption loss in the polyimide.
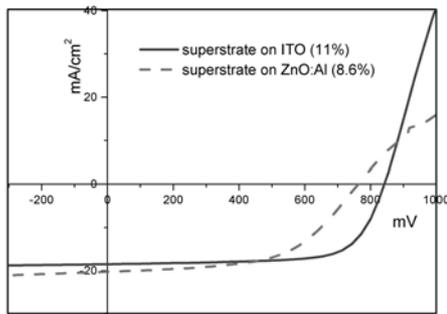

Figure 5: I-V performance of flexible solar cells in superstrate configuration with ITO and ZnO:Al as front contact under AM1.5 illumination.

This effect is seen with quantum efficiency measurements as shown in figure 6. The lower response from 500 to 820 nm is attributed to the absorption loss due to the polyimide.
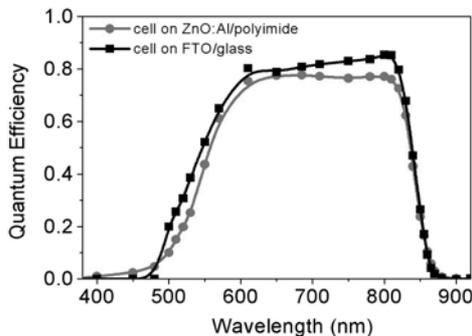

Figure 6: Quantum efficiencies of a superstrate configuration flexible cell (8.6%) compared with a cell on glass (12.5%), a lower response of the flexible solar cell is measured.

5. SUBSTRATE CONFIGURATION FLEXIBLE CdTe CELLS

Substrate configuration is the most suitable for flexible solar cells from application point of view. The flexible substrate is at the back of the cell and has to be stable at high temperatures and compatible with the material deposited on it but does not have to be transparent.

The substrate configuration is more favorable for flexible solar cells on metal foils, but this kind of solar cells has, apart from some interesting exceptions [8-9], exhibited low efficiencies of around 5% [10-11].

It is generally known that for a conventional CdTe/CdS superstrate cell, a CdCl$_2$ annealing treatment is applied which controls the junction activation, recrystallization, and intermixing of CdS into the CdTe.

In a substrate cell the CdCl$_2$ treatment will be applied either only on the CdS or in both layers. In the first case, a complete recrystallization of the CdTe is not obtained [12]; in the second case, CdCl$_2$ tends to diffuse impurities into the ohmic contact changing its properties [12]. In both cases the intermixing is difficult to control. Another reason for low efficiency is that most of the metal foils do not form an efficient ohmic contact with CdTe and it is difficult to incorporate an additional buffer layer as ohmic contact to increase the cell efficiency [10-11].

In the second process, presented hereby, the different stacks are not deposited on the polyimide substrate but directly on a thin layer of NaCl, deposited by vacuum evaporation on soda lime glass. After processing the cell, a polyimide or a metal foil can be laminated on the back of the device and the front glass can be removed by dissolving the NaCl in water. The result is a solar cell in substrate configuration.

In this way no polyimide layer is present during processing and there is no absorbing layer, except of TCO, between the incident light and the photovoltaic layers.

The fabrication process is similar to the standard one, presented in section 2, apart from the prior deposition of NaCl. The CdS and CdTe layers are grown by HVE and the back contacting is done using the standard procedure.

However we registered difficulties for the NaCl/TCO stacks to withstand the CdCl$_2$ activation process. Attempt of using the standard amount of CdCl$_2$ resulted in low efficiencies, due to the instability of the NaCl/TCO layers which causes the pinholes. An optimum amount of CdCl$_2$ for this type of cells was found to be around 200 nm. If from one side this gives a good quality of the layer, from the other side it is not sufficient for a complete recrystallization of the CdTe stack near the junction with CdS [6].

The structural properties of CdTe on CdS/TCO/NaCl stacks are similar to that on glass substrates. As shown in figure 7, the as-deposited CdTe layer is very compact with grains sizes similar to the ones shown in figure 3. The CdCl$_2$ –annealed layers are crack-free and consist of large grains of up to ~6 μm.

It is interesting to observe that the presence of NaCl on the substrate is not affecting the morphology of the CdTe layers. TCO is a good barrier for NaCl, however more investigations have to be performed.
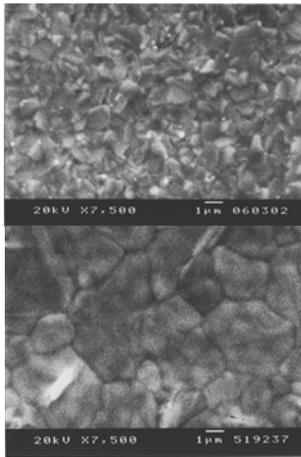
Figure 7: As-deposited (top) and CdCl$_2$ (bottom) treated CdTe layers on CdS/TCO/NaCl stacks, the morphology is similar to the one shown in figure 4.
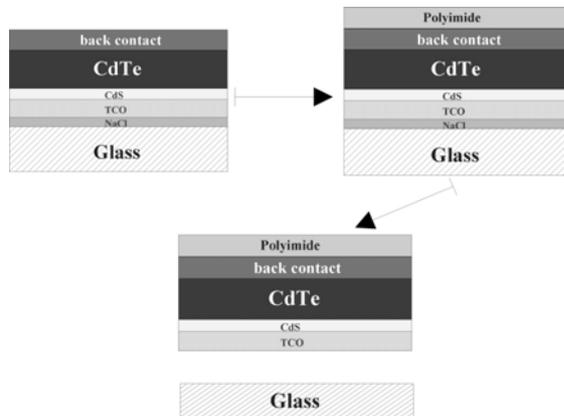

Figure 8: Schematics of the flexible cell process in substrate configuration: after the polyimide is deposited on top, the cell is rinsed in water (in order to dissolve NaCl) and lifted-off from the glass.

The schematics of the whole fabrication process is shown in figure 8. One advantage of such a process is that glass is the substrate during all the fabrication steps, avoiding temperature issues as in the case of polyimide or diffusion issues like in the case of metal sheets. Another advantage is that in the substrate configuration the polyimide is at the back of the cell avoiding absorption losses and possible degradations on the transparency due to UV or electrons and protons irradiations, which are important for space applications.

As shown in figure 9, cells in this configuration have efficiencies of 7.3% with a tin oxide fluorine doped front contact and of 6% with a zinc oxide aluminum doped front contact under AM1.5 illumination. Fill factor has very low values (49 % and 40 %) related to the low stability of the TCO on NaCl layer, which means that the electrical properties of the front contact tend to degrade after processing.

Despite lower values of open circuit voltage (692 mV and 743 mV respectively for FTO and ZnO:Al as front contact) and fill factor the current density is higher than in the superstrate case (21.6 mA/cm^2 and 20.3 mA/cm^2 respectively for FTO and ZnO:Al as front contact) because of the absence of the polyimide on the front of the cell.

The lower efficiencies obtained are also to be attributed to the different CdCl$_2$ activation applied to avoid pinholes. We believe that with an optimization of NaCl/TCO stacks higher efficiencies will be obtained.
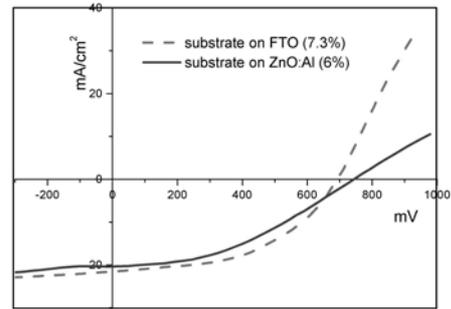

Figure 9: I-V performance of flexible solar cells in substrate configuration with FTO and ZnO:Al as front contact under AM1.5 illumination.

6. CONCLUSIONS

Lightweight and flexible CdTe/CdS solar cells in the superstrate and substrate configuration have been developed on polyimide films. A spin-coated polyimide layer is used as a substrate. In order to reduce the absorption loss in the substrate, the polyimide thickness is decreased from ~50 to ~10 µm. Deposition of CdTe/CdS layers and CdCl$_2$ annealing treatment were performed at temperatures below 450 °C.

Solar cells of 11% efficiency were obtained on ITO-coated polyimide with a "lift-off" method, which, to our knowledge, results to be the highest efficiency reported for a flexible CdTe solar cell. A comparison of the quantum efficiency and optical transmission measurements suggests that thinner polyimide layers will increase the short circuit current.

A novel process for flexible substrate CdTe solar cells has been presented. The substrate configuration gives the opportunity to eliminate the limitations of the polyimide at the front of the cell. Unlike other flexible CdTe-substrate-cell-processes the one presented here keeps the superstrate fabrication process, maintaining all the properties of the high efficiency process.

Up to now 7% efficiency flexible substrate solar cells have been prepared, but with further optimization we believe that the efficiency can be further enhanced.

ACKNOWLEDGMENTS

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