Invited Paper

Flexible CdTe Solar Cells and Modules: Challenges and Prospects

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ABSTRACT

Thin film CdTe/CdS solar modules are currently the most promising photovoltaic technology for cost efficient solar electricity production. Solar modules on glass substrate with more than 10% efficiency are already available on the market. Substituting a flexible substrate material for the rigid and heavy glass will further reduce production costs due to manufacturing advantages and will allow novel applications due to product advantages. In this paper we are presenting the development of CdTe/CdS thin film solar cells with ZnO based TCO on commercially available polyimide. The polyimide is coated with Al doped ZnO as front electrical contact followed by a highly transparent and resistive ZnO buffer layer. Highest efficiency of 12.4% was achieved on 7.5 µm thin polyimide with 823 mV open circuit voltage, 19.6 mA/cm^2 short circuit current density and 76.5% fill factor. Using 12.5 µm thick polyimide as substrate reduces the current density of the device by approximately 5%. No cracks in the layers or adhesion problems of the solar cell structure on the polyimide are observed even when rolled to small radius of curvatures (few mm).

Keywords: polyimide, CdTe, flexible, high efficiency, aluminum doped zinc oxide (ZnO:Al)

1. INTRODUCTION

The direct energy band gap of CdTe (1.45 eV at room temperature) and the high absorption coefficient (10^5 cm^{-1}) for photons with energies above the band gap are ideal for highly efficient solar energy conversion to electricity. The theoretically achievable cell efficiency under AM1.5G illumination is more than 28% [1]. Furthermore, the simple phase diagram of this binary semiconductor and the fact that CdTe evaporates congruently facilitate simple manufacturing techniques for cost efficient solar module production. The material is chemically and thermally robust which is not only important for the solar cell processing but also for the stability of the final product. Various studies of the Brookhaven National Laboratory, USA, showed that CdTe solar modules are environmentally safe and do not bear health hazard (see for instance [2]). Rigid glass based CdTe modules with more than 10% efficiency are already available on the market and the production costs of 0.93 $/Wp by First Solar are the lowest compared to any other photovoltaic technology [3].

Highly efficient CdTe solar cells and modules are developed in superstrate configuration which means that light has to pass through the substrate material accounting for a transparent substrate material. The substrate is covered with a transparent conductive oxide (TCO) as front electrical contact. Common TCO materials are fluorine doped tin oxide (FTO), cadmium stannate (CTO), tin doped indium oxide (ITO), and aluminum doped zinc oxide (ZnO:Al). Subsequently, CdS is deposited as n-type semiconductor onto the TCO followed by the p-type CdTe absorber and a back electrical contact. The certified record efficiency for CdS/CdTe solar cells on glass is 16.5% on cell level achieved by NREL, USA, using a complex process to minimise various optical and electrical losses and process temperatures above 600°C [4] and 10.8% on module level achieved by BP Solar, USA [5]. Even though the CdTe solar technology has already been successfully transferred from the research laboratory to the market, there are still challenges and major problems to be solved for further cost reduction and novel applications. Among the open problems are (i) increasing the transmittance of the substrate-TCO stack whilst maintaining high conductivity using simple processing techniques; (ii) reducing the CdS thickness well below 100 nm for minimization of absorption loss, without adversely affecting the fill factor and cell voltage; (iii) reduce the self compensation effect of the polycrystalline CdTe material to increase the net acceptor density; (iv) increase the raw material utilization by reducing the CdTe layer thickness; (v) formation of an low resistive ohmic and stable back contact onto p-type CdTe by an all-vacuum deposition process; (vi) development of highly efficient CdTe solar cells in substrate configuration.

Solving the abovementioned challenges will help to further increase the conversion efficiency and to reduce the production costs. Substituting a flexible substrate for the rigid glass will further increase the low cost potential of this

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technology. Flexible CdTe solar cells and modules offer several advantages on the production of the device as well as on the final product in terrestrial and space applications.
Cost effective and fast roll-to-roll deposition process is possible with the use of a flexible substrate material. Also faster heating and cooling are applicable for thin flexible substrate material and there is no need for cost intensive robotics handling of fragile and heavy glass. This approach will not only lower the production cost but also the energy pay back time significantly.
Due to the light-weightiness and flexibility of the final product new markets become attractive. The building integrated architecture will enter new dimensions for energy production on roofs and facades with not flat surfaces or complex shapes. Advanced products will be possible for the portable source of power as well as for any mobile application.
Flexible CdTe solar cells have been already developed in the superstrate and in the substrate configurations. Efficiencies of 3.5%-7.8% have been reported for the substrate configuration using molybdenum foil as substrate material [6-8]. The major limitation for the development of flexible CdTe solar cells in the substrate configuration is the formation of an ohmic back contact to the p-type CdTe. The highest efficiency of 7.8% was obtained with an all sputtering process using nitrogen doped ZnTe as buffer layer for tunneling enhancing between the molybdenum back contact and the CdTe layer.
On the other hand, the main limitation in the superstrate configuration is the availability of a flexible material with high transmission between 300 nm and 900 nm and thermal stability up to 450°C. Polyimide (PI) was identified as being currently the most promising material. The highest reported efficiencies of flexible CdTe solar cells in superstrate configuration on PI are 10.7% by sputtering [9] and 11.4% by high vacuum evaporation [10].
Broadly, the deposition methods can be categorized in high temperature methods (>550°C) such as close space sublimation (CSS) or vapor transport deposition (VTD) and modifications of those and in low temperature methods (<450°C) such as sputtering, electro deposition (ED) or high vacuum evaporation (HVE) of which the latest one is used in our laboratory. We are focusing on the development of flexible CdTe solar cells in superstrate configuration on commercially available PI material from Upilex® and substituting ZnO:Al for ITO as front electrical contact. Because of the limited thermal stability properties of the PI the CdTe solar cells needs to be processed by a low temperature deposition method.
We already demonstrated 11.4% efficiency on ITO in combination with intrinsic zinc oxide (i-ZnO) which is introduced between the ITO and the CdS layer [10]. This highly resistive transparent layer (HTR) turned out to be necessary in order to reduce the CdS thickness and increase the reproducibility of the process [11]. In this paper we present results on aluminum doped zinc oxide (ZnO:Al) in combination with i-ZnO, for 12.4% efficiency flexible solar cells.

2. EXPERIMENTAL

CdTe/CdS solar cells were grown by high vacuum evaporation on glass and polyimide (PI) substrates. To prevent alkali diffusion from the glass substrate we used borosilicate glass for the results presented in this paper. As transparent conductive oxide (TCO) material we used aluminum doped zinc oxide (ZnO:Al) followed by a highly resistive intrinsic ZnO layer. The ZnO layers were deposited by radio frequency magnetron sputtering. During the sputter process the substrate was heated to 300°C. The thickness of the whole TCO including the intrinsic layer is 1.6 µm. The CdS was grown by high vacuum thermal evaporation at a substrate temperature of 160°C and subsequently vacuum annealed at 420°C for 30 min. Without breaking the vacuum the CdTe was evaporated at 300°C substrate temperature. A post-deposition activation treatment of the CdS/CdTe stack was performed by depositing 400 nm of $CdCl_2$ onto the CdTe surface and annealing the stack in air at 420°C for 20 min. The standard back contact formation starts with a CdTe surface etching in dilute bromine-methanol solution followed by the evaporation of a Cu/Au bilayer and an annealing of the finished device at 215°C to enhance the formation of a Cu_xTe buffer layer.
The finished solar cells were characterized by current voltage (J-V) and spectral response (SR) measurements according to the international standards IEC 60904-1 Ed. 2 and IEC 60904-8 Ed. 2. The SR measurements were done using a 900 W halogen lamp, a beam chopper running at 360 Hz, and a dual grating image monochromator. Before each SR measurement the monochromatic beam was carefully calibrated with a silicon reference solar cell produced and calibrated at ISE Freiburg. From SR measurements the external quantum efficiency (EQE) and the short circuit current density under AM1.5 (Jsc[AM1.5]) was calculated with reference spectrum IEC 60904-4 Ed.2.
Electrical resistance of the TCO was quantified by measuring the sheet resistance via four probe measurement and direct side to side resistance measurement via beforehand deposited metalic contacts to determine the resistance of the TCO in

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the finished cell. Film thicknesses were measured using a quartz crystal deposition monitor, a profilometer and SEM cross-section images.

3. RESULTS

Under optimized processing conditions the CdTe/CdS solar cells were grown crack free on glass and on PI substrates. Figure 1 shows a photograph of the front (a) and backside (b) of a completed CdTe/CdS device on 7.5 µm thick PI.

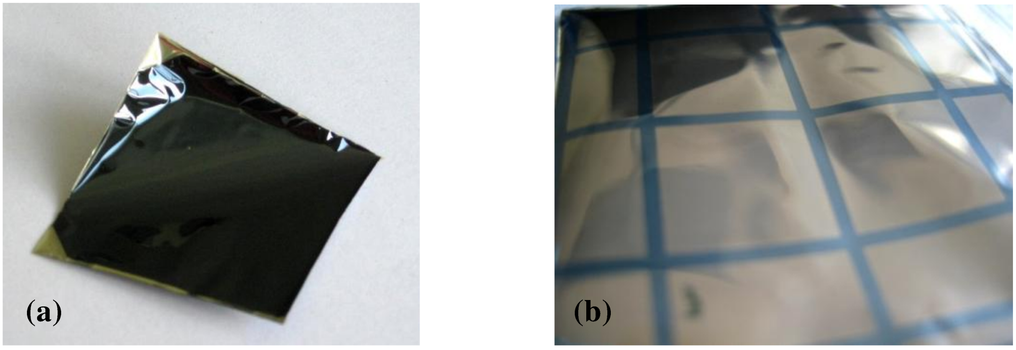

Fig. 1 Photograph of a finished CdTe/CdS device on 7.5 µm PI. The front side is shown in picture a). At the corners the metal contacts are visible which establish electrical contact to the ZnO:Al. The non coated boundary part which was shaded during the process by the frame was cut away to reduce deformation. Picture (b) shows cells with 1 cm^2, 0.5 cm^2 and 0.25 cm^2 area.

The surface of the PI is flat apart from the boundary region where stress occurred between the coated and non coated PI which was shaded by the frame used for the processing. In scanning electron microscope (SEM) cross-section and top view images no difference in grain size and morphology of the CdTe cells grown on PI and glass was visible (see [11]). The sheet resistance of the ZnO:Al was found to be 5.5 $\Omega/\square$ before the CdS/CdTe deposition on glass and on PI. After the complete cell processing the sheet resistance increased to 8 $\Omega/\square$ on glass and 20 $\Omega/\square$ on PI. In air annealing experiments of ZnO:Al/i-ZnO bilayer on PI we observed the same increase in sheet resistance combined with an increase in maximum direct transmittance from 75.4% to 78.5% in the range between 450-850 nm (fig. 2a).

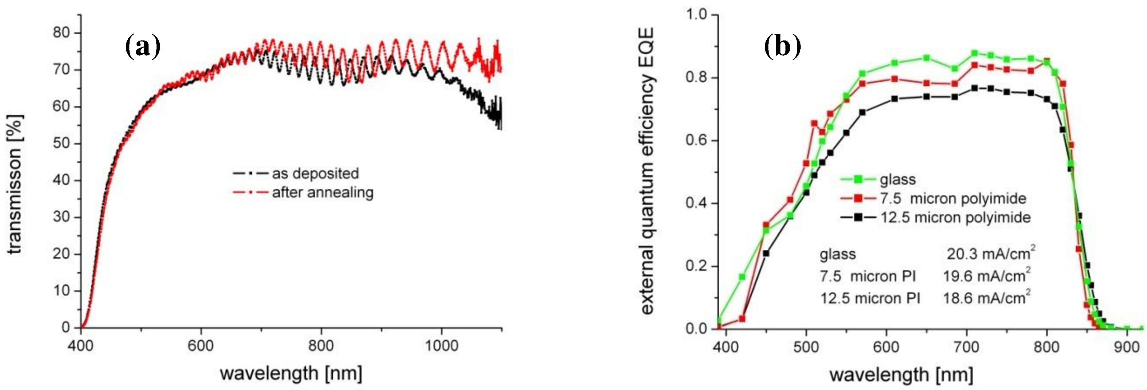

Fig.2 Direct transmission of ZnO:Al/i-ZnO bilayer on 7.5 µm PI before and after annealing in air a) and quantum efficiency of identically processed CdTe/CdS solar cells on different substrates b). On glass the best results so far were obtained using ITO as TCO material using the same CdS layer thickness.

For the annealing experiments the same temperatures and heating ramps as for the $CdCl_2$ treatment were used. An increase in sheet resistance after air annealing was also observed by others [12] and is attributed to reduced carrier concentration and mobility. Figure 2a shows the transmission curves of a ZnO:Al/i-ZnO TCO on PI before and after air annealing. We believe that the larger increase in sheet resistance observed on PI than on glass is due to incomplete protection of the ZnO layers from oxygen and or water by the PI in comparison to the 100 times thicker glass. On the

other hand the incomplete protection leads most probably to an increase in transparency during the $CdCl_2$ annealing as we observed in annealing experiments of the individual layer.
Furthermore, the growth of the ZnO layers on PI may be significantly influenced by the substrate material. ITO films on polymer substrates are reported to have better transparency than layers on glass manly due to better <100> orientation [13]. If a similar effects occur for ZnO:Al is currently under investigation. Thermal stability of ZnO:Al layers can be optimized by changing the sputtering conditions and deposition temperature.
Solar cells were identically processed on 7.5 µm and 12.5 µm thick PI as well as on 1 mm thick glass with ZnO:Al as TCO and 130 nm thick CdS. The external quantum efficiency measurement (fig 2b) illustrates the influence of the substrate material on the spectral response and the current density of the solar cell. A current density of 20.3 mA/cm^2 was obtained on glass with the 1.6 µm thick TCO bilayer. With 7.5 µm polyimide as substrate material the current density is 19.6 mA/cm^2 which is slightly lower as compared to the glass substrate resulting from parasitic light absorption in the PI over the whole spectrum.

Table 1. PV parameters of CdTe/CdS solar cells on ZnO:Al TCO. The TCO was optimized for the 7.5 µm PI. With other TCO structures we obtained already higher efficiencies on glass [14] whereas on PI the ZnO:Al lead to the highest efficiency achieved so far.

substrate	*Voc [mV]*	*Jsc [mA/cm^2]*	*FF [%]*	*η [%]*
7.5 µm PI	823	19.6	76.5	12.4
12.5 µm PI	801	18.6	68.1	10.1
1mm glass	806	20.3	73.1	12.0

We conclude that the rather small current density difference between the cells on glass and on PI illustrated in figure 2b and table 1 originates from the above mentioned annealing effect, which increases the TCO transmittance on PI cells but does not have an effect on glass. The exact mechanism of the responsible reactions has still to be identified.
It is also possible that among other effects the gain in Voc and FF between these cells compared to earlier results [10] may originate from a better protection of the CdS/CdTe junction region by the thick and dense ZnO bilayer.
Solar cells on 12.5 µm PI show similar PV performance as the cells on 7.5 µm PI with marginally reduced Jsc by 5% due to lower transmission of the substrate. The yield (defined as percentage of cells that are within 10% of the maximum efficiency on one substrate) is 90% on the 12.5 µm PI and over 95% on the 7.5 µm PI.
With the above mentioned process solar cells with 12.4% efficiency were grown on PI foil. Figure 3 shows the current voltage characteristic and quantum efficiency of such a high efficiency solar cell. To our best knowledge this is the highest efficiency for flexible CdTe solar cells reported so far. In table 1 the best results achieved on glass and PI with ZnO:Al as TCO are summarized.

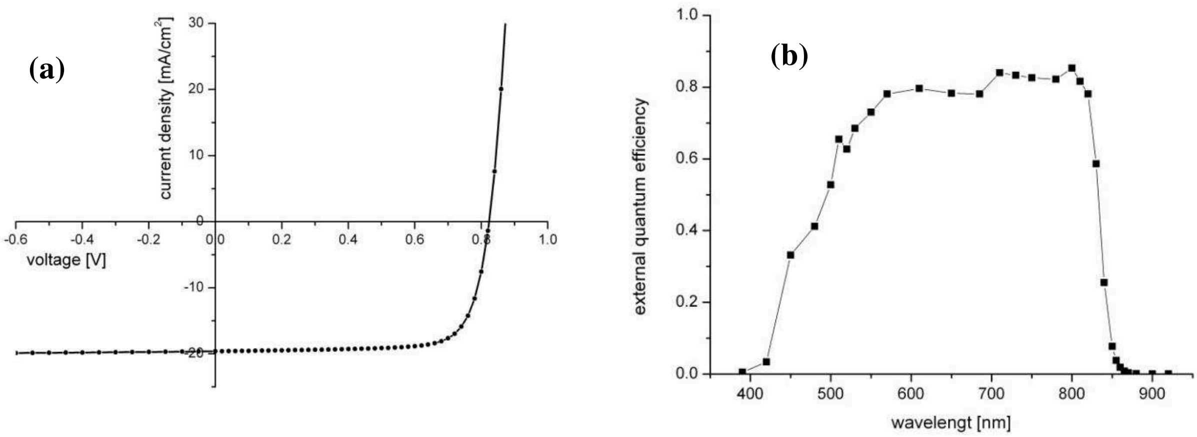

Fig. 3. J-V characteristics (a) and external quantum efficiency (b) of a 12.4% efficient flexible CdTe solar cell on polyimide foil. The PV parameters are given in table 1.

Compared to the previously reported record of 11.4% [10] the device presented here has a lower current density but higher Voc and FF. This originates from lower transmission of the used TCO but better electrical properties and better protection of the junction region as explained above.

4. CONCLUSION

Flexible CdTe solar cells with more than 12% efficiency on 7.5 µm PI and with more than 10% on 12.5 µm PI are reproducibly obtained with the modified deposition process. The best device so far was grown on ZnO:Al/i-ZnO bilayer TCO with 12.4% efficiency. Replacing the 7.5 µm thin PI with 12.5 µm PI reduces the current density by 5%. The results show that the aluminum doped zinc oxide is chemically and thermally stable and suitable for the low temperature process. The ZnO:Al/i-ZnO bilayer is a very promising TCO for flexible CdTe/CdS cells on PI. However, further optimization of the TCO is still an important task for further transmittance and conductivity improvement. No cracks in the layers or adhesion problems of the solar cell structure on the polyimide are observed even when rolled to small radius of curvatures (few mm). The results presented in this paper show that flexible CdTe solar modules are a promising technology for cost effective roll-to-roll manufacturing.

REFERENCES

[1] B. E. McCandless and J. Sites, 'Cadmium Telluride Solar Cells' in Handbook of Photovoltaic Science and Engineering, Edited by A. Luque and S. Hegedus, John Wiley & Sons, Ltd, 2003
[2] Vasilis M. Fthenakis, 'Lifecycle impact analysis of cadmium in CdTe PV production', Renewable and Sustainable Energy Reviews 8 (2004) 303–334
[3] First Solar corporate overview Q1 2009
[4] X. Wu et al., 'High-Efficiency CTO/ZTO/CdS/CdTe Polycrystalline Thin-Film Solar Cells', Proc. of 17th EU-PVSEC, 2001, pp. 531
[5] D. Cunningham et al., 'Large area Apollo(R) module performance and reliability', Proc. of 28th IEEE PVSC, pp. 13-18 (2000)
[6] J.P. Enriquez et al., 'CdTe/CdS solar cells on flexible molybdenum substrates', Solar Energy Mat. Solar Cells, 82 (2004) 307-314
[7] V.P. Singh et al., 'Thin film CdTe-CdS heterojunction solar cells on lightweight metal substrates', Solar Energy Mat. Solar Cells,59 (1999) 145-161
[8] I. Natulionis et al., 'Cadmium telluride solar cells on molybdenum substrates', Proc. of MRS 668 (2001) H8.23.1-6
[9] Al Compaan et al., presented at 34th IEEE PVSC, Philadelphia, 2009
[10] A. Romeo et al., 'High-efficiency flexible CdTe solar cells on polymer substrates', Solar Energy Materials & Solar Cells 90 (2006) 3407–3415
[11] J. Perrenoud et al., 'Flexible CdTe Solar Cells with High Photovoltaic Conversion Efficiency', Proc. of 34th IEEE PVSEC, Philadelphia, 2009
[12] T. Minami et al., 'Preparations of ZnO:Al transparent conducting films by d.c. magnetron sputtering', Thin Solid Films 193-194 (1990) 721-729
[13] J. Herrero et al., 'Transparent films on polymers for photovoltaic applications', Vacuum 67 (2002) 611-616
[14] S. Buecheler et al., 'Low temperature processed CdTe thin film solar cells with reduced CdS thickness', Proc. of E-MRS conference, Strasbourg, France, 2009

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