Flexible CdTe Solar Cells and Modules: Recent Progress

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Broadly, the CdTe solar cell processing is categorized according to the deposition temperature of CdTe layer 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 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 [1]. In this contribution we present results on aluminum doped zinc oxide (ZnO:Al) in combination with i-ZnO, for 12.4% efficiency flexible solar cells and the interconnection to flexible solar modules.

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.

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. A current density of 23.3 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 for high energy photons.

Table 1. PV parameters of CdTe/CdS solar cells on ZnO:Al TCO. * With anti reflection coating.

substrate	*Voc [mV]*	*Jsc [mA/cm²]*	*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	826	23.3	76.0	14.7
1mm glass	821	25.0*	75.0	15.4

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 1 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.

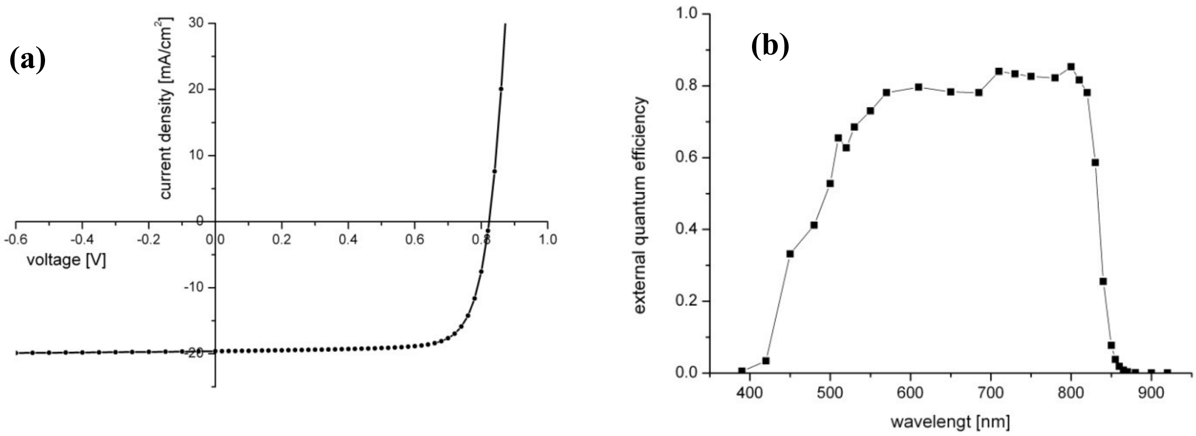

Fig. 1. J-V characteristics (a) and external quantum efficiency (b) of a 12.4% efficient flexible CdTe solar cell on polyimide foil. The PV parameters are given in table 1.

Compared to the previously reported record of 11.4% [1] 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.

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 here show that flexible CdTe solar modules are a promising technology for cost effective roll-to-roll manufacturing.

The process has been upscale to 32 cm^2 and flexible modules on PI were fabricated. The interconnection of cells was done using laser scribing. The loss of active area due to interconnection was about 15%. Further the series resistance increased as the back to front contact connection showed high resistivity. The homogeneity of CdS and CdTe varied by 10% on the sample. Nevertheless the module reached 7.5% total area efficiency (Jsc=16.7 mA/cm^2, Voc= 8.35 V (11cells), FF=59%). An efficiency of 10% should be possible with the current process.

A. Romeo et al., 'High-efficiency flexible CdTe solar cells on polymer substrates', Solar Energy Materials & Solar Cells 90 (2006) 3407–3415