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Influence of proton irradiation and development of flexible CdTe solar cells on polyimide

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

ABSTRACT

CdTe/CdS solar cells of ~10% efficiency, developed with a vacuum deposition method were irradiated with high-energy protons of different fluences. The V_{oc} and f.f. of irradiated cells *increase* or decrease depending on the fluence. The normal soda lime glass substrate darkens under the irradiation; therefore low Isc is measured. Measurements suggest that CdTe solar cells are *highly stable* under proton flux. Flexible and lightweight solar cells were developed in a superstrate configuration on polymer substrates. 8.6 % efficiency cells with Voc~770 mV and Isc of 20.3 mA/cm^2 were achieved.

INTRODUCTION

There is a recent interest to reduce the cost of solar modules for space applications. Polycrystalline thin film solar cells of II-VI and I-II-VI compounds are potentially important because of their low cost, high efficiency and stable performance. One of the important requirements for space application is the stability of solar cells against high-energy proton and electron irradiation. Recent investigations on $Cu(In,Ga)Se_2$ (called CIGS) solar cells have proven that their stability against high energy radiation is superior to Si or III-V solar cells [1-2]. CdTe/CdS solar cells are also expected to exhibit good stability for space applications [3]. CdTe solar cells with an efficiency of 10% to 16 % have been developed in the "superstrate configuration" with a variety of deposition processes [4-6]. We have developed 12% efficiency (AM1.5) solar cells with a vacuum deposition process [6]. To determine the radiation tolerance of solar cells on glass substrates were irradiated with high-energy protons; this paper will describe the photovoltaic properties of irradiated solar cells.

Development of flexible and lightweight solar cells are interesting for terrestrial and space applications that require a very high specific power (defined as the ratio of output electrical power to the solar module weight). Thin film solar cells on polymer films can yield more than 2-kW/kg specific power.

CIGS solar cells of about 10 to 12.8% efficiency have been developed on polymer substrates [7-8]. However, CdTe solar cells on polymer substrates have not been reported up to now, although solar cells of about 10 to 16% have been obtained on glass substrates. CdTe solar cells on metal foils exhibit an efficiency of ~5% [9-10]. Here, we describe an approach for the development of flexible CdTe solar cells on polymer films.

EXPERIMENTAL DETAILS AND RESULTS

PROTON IRRADIATION STABILITY MEASUREMENTS

Proton irradiation experiments were performed at the Paul Scherrer Institute (Villigen, CH). Solar cells were irradiated through the (1 mm thick) glass substrates with protons of different energies (5 to 15 MeV) and fluences (10^{11} to 10^{13} cm^{-2}). These fluences are higher than the typical fluence on the earth orbits, as protons are "trapped" by the magnetic field of the earth. Three sessions of irradiation experiments were performed. It is known that high-energy particles (electrons and protons) can change the structural, electrical and optical properties of solids by causing a displacement damage or through ionization effects [1-3][11]. Incident particles on polycrystalline material can create dislocations and/or displace atom from their lattice sites, creating electronic traps into the band gap, and so altering the electronic characteristics of the crystal. The displacement damage depends on the non-ionizing energy loss, which is the energy and momentum transfer to lattice atoms (depending on the mass and energy of the incident quanta) [11]. In the case of SiO_2 (glass) not only the displacement damage but also the ionization effects are important. These effects cause a darkening of the glass that is proportional to the fluence of irradiation (as shown in figure 1). For these measurements and also for the cell development soda lime glass (1 mm thick) was used. It should be mentioned that there is a certain type of glass (CeO_2 doped glass) which remains highly transparent under space conditions. Such a glass is generally used to cover Si and GaAs solar cells in space.

To investigate the influences of proton irradiation the I-V measurements were performed before and after the irradiation. The initial efficiency was in the range of 8 to 10 % under AM 1.5 illumination. Table 1 gives the change in the PV performance of cells irradiated with different energies and fluences.

As it has been already observed [3], one should expect some degradation of the cells because the proton bombardment may change the characteristics of CdTe. For high fluence (10^{13} cm^{-2}) a small degradation in Voc and f.f. was observed. For the medium fluence (10^{12} cm^{-2}), increase in the Voc and f.f. are measured presumably due to passivation of some defects in CdTe layers. Such an improvement in the PV properties of cells has not been reported, more work is needed to explain this observation. It is observed that the Isc of irradiated cells "appear to decrease" with increasing fluence. However it should be emphasized that the measurement of low Isc is not due to any degradation of the semiconductor or heterojunction, but the darkened glass is responsible for the absorption of photons during the measurements, therefore there is a decrease of Isc. Solar cells grown on "space quality glass" would not have problems of glass darkening.

The superstrate configuration of CdTe solar cells has certain advantages and disadvantages: the glass substrate, depending on thickness, will influence the energy and fluence of protons reaching to the CdTe/CdS. For a scientific curiosity we irradiated the cells from the CdTe side and found no degradation due to CdTe/CdS, of course darkening of the glass was observed also in this case [13]. These measurements have shown that CdTe solar cells are stable against proton irradiation. These results give a good perspective for the application of CdTe solar cells in space.

FLEXIBLE CdTe SOLAR CELLS

High efficiency CdTe solar cells are generally grown in a "superstrate configuration" where CdTe/CdS stacks are deposited on transparent conducting oxide (TCO) coated glass substrates. Efforts for developing flexible CdTe solar cells were, up to now, based on the "substrate configuration"; such solar cells were grown on metal foils and they exhibit low efficiency ~5% due to non-compatibility of the CdTe with metal substrates. Their photovoltaic performance is poor because of inefficient ohmic contact on CdTe [9-10].

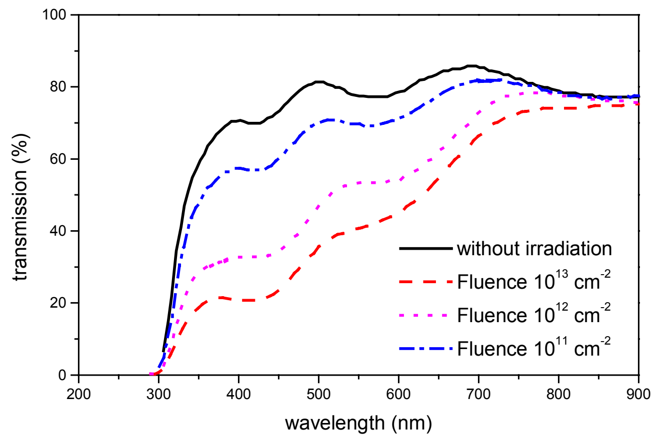


Figure 1. Transmission of proton irradiated and not-irradiated glass.

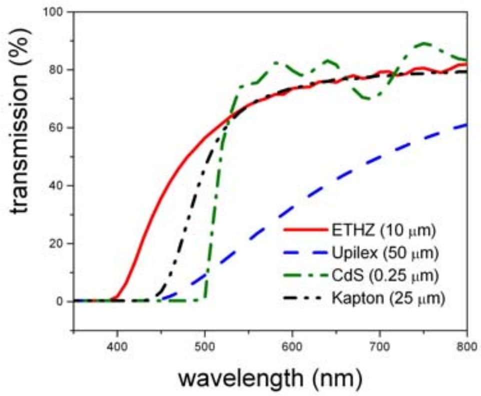
Table 1. Change in the PV parameters due to incident proton irradiation. The actual energy and fluence reaching to the CdTe/CdS may differ due to stoppage from the glass substrate [11].

	Fluence 10^{13} cm^{-2}			Fluence 10^{12} cm^{-2}			Fluence 10^{11} cm^{-2}		
Energy (MeV)	ΔVoc (mV)	Δf.f. (%)	ΔIsc (mA/cm^2)	ΔVoc (mV)	Δf.f. (%).	ΔIsc (mA/cm^2)	ΔVoc (mV)	Δf.f. (%)	ΔIsc (mA/cm^2)
15	-20	-2.5	-6	+35	+3	-4	0	0	-1
10	-20	-2.5	-7	+35	+3	-4.5	0	0	-1
5	-20	0	-6.5	+25	+2	-5	0	0	-1

For flexible solar cells in a superstrate configuration the choice of an appropriate substrate is crucial because the substrate should be optically transparent and should withstand the high temperature deposition/processing of solar cells. Most of the solar cell fabrication processes require temperatures of about 450 to 550 °C but transparent polymers are not stable at such high temperatures. However, some of the polyimides are stable at high temperature (up to ~500 °C) and their optical transparency could be sufficient for CdTe/CdS solar cell application. As shown in figure 2 the thickness of polyimide can strongly influence the transmission spectra, 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 is prepared in-house. One of the advantages is that the thickness of the polyimide film can be reduced to minimise the absorption loss in the substrate. The solar cell fabrication process is schematically shown in figure 2. A thin buffer layer of NaCl was evaporated on a glass substrate (which permits to lift off the cell from the glass), 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 2, the average transmission of the polyimide film is more than ~75% for wavelengths above 550 nm. There is a strong absorption of photons in the wavelength range of

400 to 550 nm, which coincides to the high absorption region of CdS window layer. Due the band gap of ~2.4 eV the CdS window layer absorbs photons of wavelength shorter than 515 nm.



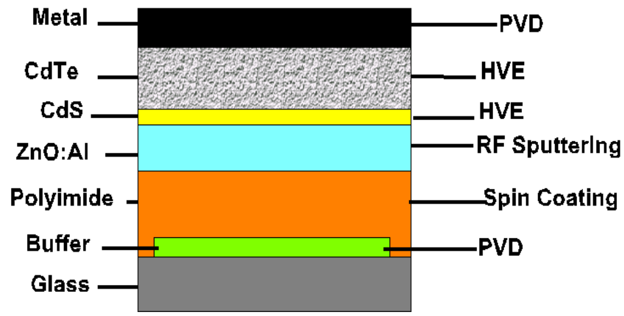


Figure 2. Transmission spectra of polyimide films and CdS with different thickness (left) and schematic structure of the flexible solar cell (right).

For the front electrical contact with CdS, transparent and conducting ZnO: Al layers with an average transmission of about 80% and sheet resistance of ~20 Ω/☐ were grown by RF magnetron sputtering. CdTe/CdS solar cells were developed with a process in which all the layers are grown by evaporation methods [12]. After the complete processing, flexible CdTe/CdS/ZnO: Al/polyimide stack was removed from the glass substrate by dissolving the NaCl buffer layer in water. The structural properties of CdTe on polyimide are similar to that on glass substrates. As shown in figure 3, 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 as-deposited layers have a (111) preferred orientation but a loss in orientation for the $CdCl_2$ annealed is observed, similar to the CdTe on glass (see figure 4). The solar cells were grown on 3 x 3-cm substrates and scribed to smaller area for measurements. No antireflection coating was applied. Figure 5 shows the I-V characteristic of an 8.6% efficiency cell on a flexible polyimide film under AM1.5 illumination. The solar cell (see fig. 5) has an area of 0.13 cm^2 and exhibits V_{oc} = 763 mV, I_{sc} = 20.3 mA/cm^2, f.f. = 55.7%. We believe that this is the highest reported efficiency of a flexible CdTe solar cell.
A comparison of the quantum efficiency measurements of a 12% efficiency cell on SnO_x: F/glass and an 8.6% efficiency cell on polyimide indicates a slight difference (see fig. 5). The solar cell on polyimide has a slightly lower response in the wavelength range of 500 to 820 nm due to the absorption loss in the polyimide film substrate.

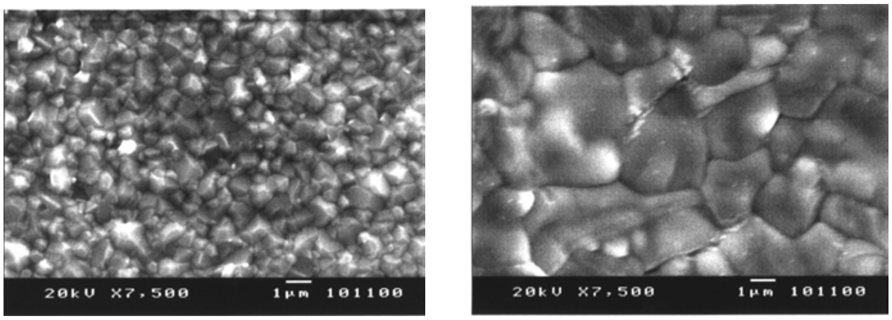


Figure 3. SEM pictures of as-deposited (left) and $CdCl_2$ annealed CdTe layer (right).

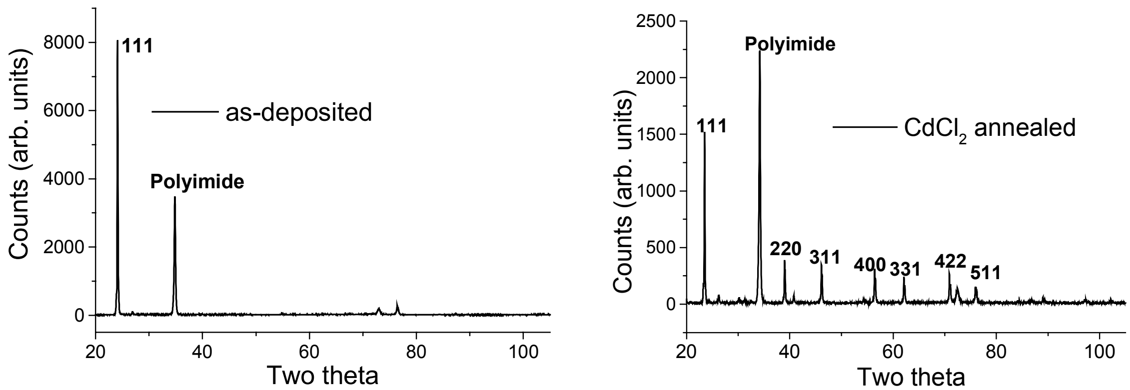


Figure 4. X-ray of as-deposited (left) and $CdCl_2$ annealed (right) CdTe on flexible substrate.

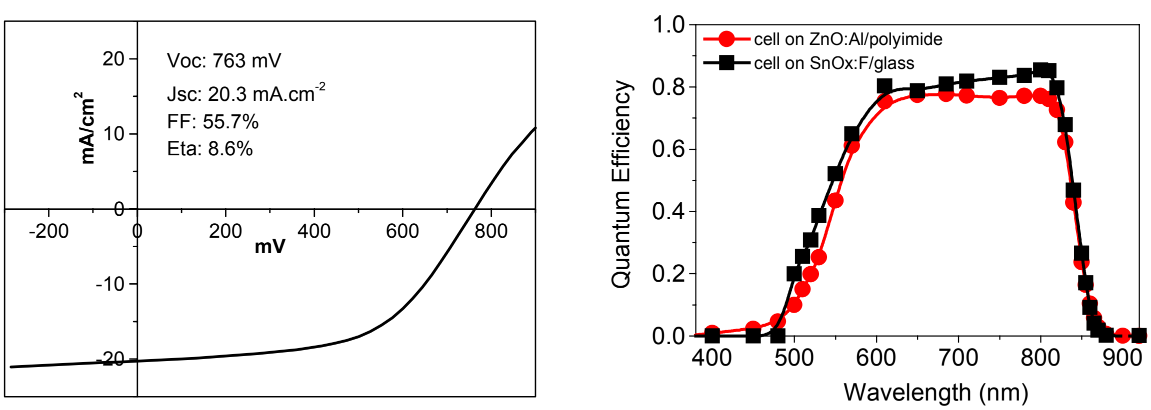


Figure 5. I-V characteristic of 8.6% efficiency CdTe solar cell on polyimide measured under AM1.5 illumination (left). Comparison of the absolute quantum efficiency of an 8.6 % cell on polyimide with another 12 % efficiency cell on SnOx: F/glass substrate (right).

To understand the reasons for lower efficiency of CdTe solar cells on ZnO: Al/polyimide, it is important to mention that the ZnO: Al, despite of good opto-electronic properties, does not yield efficient CdTe/CdS solar cells. Earlier we have reported [12] 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 SnO_x: F/glass yields 11 to 12% efficiency solar cells. In the present work we have used ZnO: Al front contact on polyimide because of the non-availability of other TCO deposition equipment in our laboratory. We believe that solar cells of more than 12% efficiency can be easily developed by replacing ZnO: Al with other TCO front contacts.

CONCLUSIONS

For the first time proton irradiation stability test on CdTe/CdS solar cells have been described. Despite of the very high fluences used (which are exceeding some orders of magnitude the proton fluences that are actually in space), only for a high fluence (10^{13} cm^{-2}) a minor degradation has been measured. CdTe cells have shown a high stability against proton irradiation that is very promising for space application. Lightweight and flexible CdTe/CdS solar cells in the superstrate configuration have been developed for the first time. A spin coated polyimide layer is used as a substrate. Solar cells of 8.6% efficiency were obtained on ZnO: Al coated polyimide with a "lift-off" method. We believe that replacing ZnO: Al with other transparent conducting front contacts will further increase the efficiency of solar cells.

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