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Potential of CdTe thin film solar cells for space applications

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ABSTRACT: There is a recent interest to reduce the cost of solar modules for space applications. Polycrystalline thin film solar cells of CdTe 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. CdTe solar cells of 10 to 12% efficiency were irradiated with high-energy protons of different energy (5 to 15 MeV) and fluence (10^{11} cm^{-2} to 10^{13} cm^{-2}) to determine their radiation tolerance. A comparison of the photovoltaic performance of various cells show that the Voc and f.f. of irradiated cells increase or decrease depending on the fluence. Irradiation can create or passivate the electronic defects in CdTe layers. Quantum efficiency measurements indicate that high fluence (10^{13} cm^{-2}) can affect the carrier collection efficiency. Flexible CdTe/CdS solar cells were prepared using a novel polymer substrate. The choice of an appropriate substrate is essential for good performance. An efficiency of 8.6% for flexible cells was obtained. Our measurements show that the CdTe solar cells are highly stable under proton flux and further developments of lightweight and flexible cells will make them attractive for space applications.

Keywords: CdTe - 1: Space Cells - 2: Radiation Damage: - 3.

1. INTRODUCTION

Polycrystalline CdTe thin films solar cells have shown long term stable performance and high efficiency up to 16.4% under AM 1.5 illumination [1]. If produced in large volume, e.g. more than 60 MW/year, their cost could be lower than 1 Euro/W [2]. Only a few micron thick materials are needed for the solar cell, therefore high specific power (ratio of output power to the weight) solar cells are expected. These features make thin film CdTe solar cells attractive for space applications. However, a number of requirements should be satisfied for these cells to be used in space condition. A high concentration of protons and electrons as well as a relevant ultraviolet component of the light are present in space which may change the PV characteristics of solar cells. In addition there is a high thermal stress (from -100 °C to 80 °C). The solar cells must be stable under proton, electron and UV irradiation, and under strong temperature changes.
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 solar cells are also expected to exhibit good stability but not much was reported up to now [3].
The high specific power is an important issue for space solar cells: if satellites are lighter they are easier and cheaper to put in orbit. CdTe thin films solar cells are lighter and have higher specific power than silicon cells [4]. 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.
We have developed ~12% efficiency (AM1.5) CdTe solar cells on glass substrates with a vacuum deposition process [3]. Lightweight and flexible CdTe solar cells of 8.6% have also been developed on polyimide films [5]. These solar cells in the "superstrate configuration" offer certain advantages for encapsulation and cost, but there are some disadvantages related to the absorption of photons and creation of color centers in the substrate or window layers.
CdTe solar cells developed in our laboratory were irradiated with 3 MeV electrons [6] and high-energy protons of different energy (5 to 15 MeV) and fluence (10^{11} cm^{-2} to 10^{13} cm^{-2}) through the front and the back side of solar cells to determine their radiation tolerance. The results of proton irradiation are described in this paper to show that CdTe solar cells are suited for space application.

2. STRUCTURE OF CdTe SOLAR CELLS

The CdTe solar cell can be developed in the "superstrate" or "substrate" configuration (see figure 1).

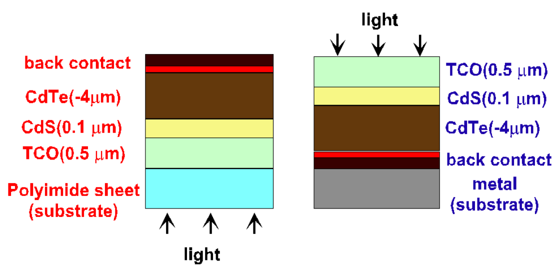


Figure 1: Superstrate (left) and substrate (right) configurations for CdTe/CdS thin film solar cells.

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 to develop flexible CdTe solar cells were, until recently [5] 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 the high temperature deposition and processing. Most of the solar cell fabrication processes require temperatures of about 450 to 550 °C, while transparent polymers are not stable at such high temperatures. However, some of the polyimides are stable at temperatures of up to 500 °C and their optical transparency could be sufficient for CdTe/CdS solar cell application. Moreover, the thickness of the polyimide film can be reduced to minimize the 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, the solar cells grown on that polyimide exhibit 8.6% efficiency (see figure 2); with further optimization cells with more than 12% efficiency should be easily achieved. CdTe solar cells on flexible polyimide can offer specific power up to 3 kW/kg. The stability of polyimide substrate against UV and particle irradiation is a considerable problem, however.

The substrate configuration is more favorable for flexible solar cells on metal foils but that kind of solar cells have, up to now, exhibited low efficiency ~5%. 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; in the second case $CdCl_2$ tends to diffuse impurities into the ohmic contact changing the properties [7]. In both cases the intermixing is difficult to control [8-9]. 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 a buffer layer to increase the cell efficiency.

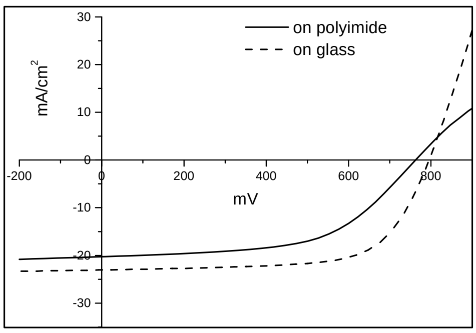


Figure 2: I-V characteristics of 8.6% and 12.4% efficiency CdTe/CdS solar cells on polyimide and soda lime glass, respectively, measured under AM1.5 illumination.

3. DEVELOPMENT OF SOLAR CELLS

We have developed a solar cell fabrication process in which all the layers are grown by vacuum evaporation [3]. Commercially available tin oxide doped with fluorine coated soda-lime glass were used as substrates. CdS layers were grown in a high vacuum evaporation 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 $CdCl_2$ layers on CdTe. The stacks were annealed at 430 °C for 30 minutes in air. For electrical back contact the surface of the CdTe was etched with a Br-methanol solution followed by the deposition of Cu/Au stack and a short annealing at 300 °C was applied. Solar cells in the efficiency range of 10 to 12.4% are routinely obtained, see figure 2 for the typical I-V characteristic of a 12.4% efficiency cell.

4. EFFECTS OF HIGH ENERGY IRRADIATION

The superstrate configuration of CdTe/CdS solar cells has the advantage that the glass substrate itself encapsulates the solar cell. We have grown solar cells on 1 mm thick glass but they can also be grown on very thin (50-100 µm) “cover glasses” while a low cost encapsulation or lamination can be applied to protect the back of the modules. This is an important aspect to increase the specific power of CdTe/CdS solar modules.

The glass substrate, depending on thickness, will influence the energy and fluence of charged particles reaching to the CdTe/CdS stack. For this reason we tested the irradiation stability of CdTe/CdS solar cells through the glass and also through the back side.

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 [10-13]. Incident particles on polycrystalline material can create dislocations and/or displace atoms from their lattice sites, creating electronic traps into the band gap, and so altering the electronic characteristics of the semiconducting layers. The displacement damage depends on the non-ionizing energy loss (NIEL), which is the energy and momentum transfer to lattice atoms, depending on the mass and energy of the incident quanta [13]. For glass not only the displacement damage but also the ionization effects are important. When a particle hits an atom of any insulating material the ionized atom moves from its original site to be trapped at another site. This creates a field inside the material and gives rise to color centers causing a darkening of the glass that is proportional to the fluence of irradiation as shown in figure 3 (proton irradiated soda lime glass coated with FTO layer). Therefore, CdTe superstrate solar cells on soda lime glass substrates may apparently exhibit lower efficiency due to the browning of the glass but not necessarily because of any degradation in the semiconductor layer. However, space quality CeO_2 doped glass which are used to protect the Si and GaAs cells in space, remain transparent even after proton or electron irradiation. The CdTe superstrate solar cells should be grown on such type of glass substrates for space application. Due to the non availability of CeO_2 glass to us, we have used 1 mm thick soda lime glass substrate.

5. PROTON IRRADIATION EXPERIMENTS

In order to investigate the stability of CdTe solar cells against high energy protons the cells were exposed to proton flux from the glass side (front wall illumination). The cells were also exposed from the gold back contact side (back illumination) to study the material properties of CdTe while excluding the influence of glass.

Proton irradiation experiments were performed at the Paul Scherrer Institute, Villigen, Switzerland.

The cells were irradiated 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 expected for any installation in the earth orbits, as protons are “trapped” by the magnetic field of the earth.

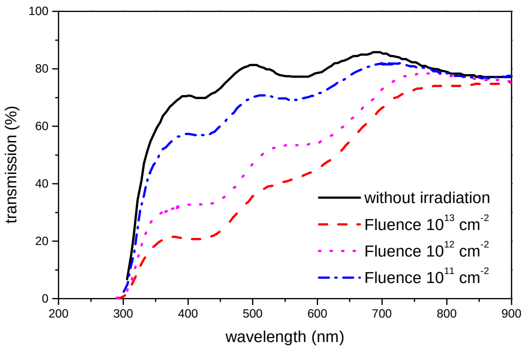


Figure 3: Transmission of non-irradiated glass and 10 MeV proton irradiated glass with different fluences.

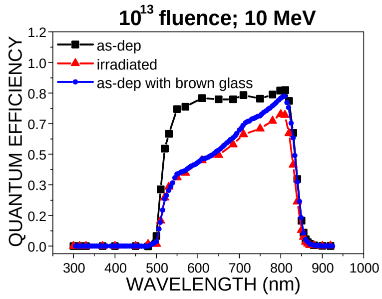
5.1 Front wall irradiation

To investigate the influences of proton irradiation the I-V measurements were performed before and after the irradiation. The initial efficiency of solar cells was in the range of 10% to 12% under AM 1.5 illumination. As it has been already observed [5-6], one should expect some degradation of the cells because the proton bombardment may change the characteristics of CdTe. A fluence of 10^{11} cm^{-2}, irrespective of energy, did not cause a significant change in PV parameters. However, as shown in table 1, for high fluence (10^{13} cm^{-2}) a small degradation in Voc and f.f. were 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 the CdTe layers. Measurements of the carrier concentration and diffusion length are necessary to explain these observations.

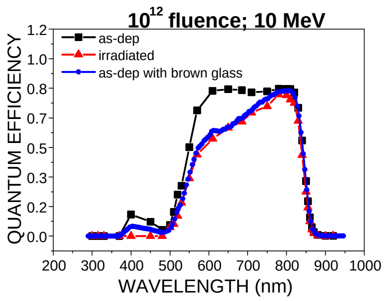
The Isc of irradiated cells apparently decreases with increasing fluence, but the measurement of low Isc is not due to any degradation of the semiconductor or heterojunction, instead it is attributed to the darkening of the glass which, as already mentioned, is proportional to the proton fluence. This effect is clearly shown in figure 4, where the quantum efficiencies of the irradiated and as-deposited cells are compared. The figures include quantum efficiency of the non irradiated sample normalized for the darkening of the glass. It is clearly observed that the 5-15 MeV protons of 10^{12} cm^{-2} fluence do not cause any significant change in the Isc (and quantum efficiency). However, for the 10^{13} cm^{-2} fluence a decrease in Isc is expected because of a low response in the red region due to a loss in carrier collection.

Table 1: Change in the I-V parameters of the cells irradiated through the soda lime glass substrate.

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



Less carrier collection



Passivation of defects

Figure 4: Comparison of the quantum efficiency of front wall irradiated and as-deposited cells.

5.2 Back wall irradiation

As already discussed, the presence of a 1 mm thick glass substrate will alter the energy and fluence of protons because of absorption and scattering effects. Even though in superstrate cells the radiation will be incident on the glass, to make a complete analysis of the test and also for scientific curiosity some CdTe/CdS solar cells were irradiated from the back contact side. It must be mentioned that the browning of the glass in this case is much lower because of the absorption in CdTe but the effect still persists to cause current loss. The I-V parameters of as-deposited and postirradiated cells are shown in table 2.

Table 2: Degradation for cells irradiated from the back side.

	Fluence 10^{13} cm^{-2}			Fluence $10^{12}cm^{-2}$		
MeV	ΔVoc mV	Δf.f. %	ΔIsc mA/cm^2	ΔVoc mV	Δf.f. %	ΔIsc mA/cm^2
15	-20	-2.5	-6	-20	-1/0	-2
10	-15	-4	-5	-20	+1	-3
5	-10	-3	-5	-5	-1	-3

Apparently degradation seems to occur but actually it is lower than what the table shows. This is because some of the loss is due to the browning of the glass (it corresponds to maximum loss in current of about 30%), however the Voc decreases by a maximum of 2.5% and fill factor by a maximum of 6%. From Monte Carlo simulations we have observed that the irradiation through a glass and directly on the sample are very different not only for the loss of absorbed protons but also for the shape and distribution of energies of the flux, so the two tests can not be compared directly.

These results confirm the high stability of CdTe solar cells, only at very high fluence a modest degradation is indicated.

6. CONCLUSIONS

Proton irradiation stability tests on CdTe/CdS solar cells from the top and the bottom side have been described. Despite of the very high fluences used, which are exceeding some orders of magnitude to the proton fluences that are actually encountered in space application, only for a high fluence (10^{13} cm^{-2}) a minor degradation has been measured. For a scientific curiosity we irradiated the cells from the CdTe side and found minor degradation due to CdTe/CdS, darkening of the glass was observed also in this case [13]. These and other measurements have shown that CdTe solar cells are stable against proton and electron irradiation.

Lightweight and flexible CdTe/CdS solar cells in the superstrate configuration have been developed on polyimide films. CdTe solar cells can be grown on very thin $Ce0_2$ doped (50-100 µm) space quality cover glass. Solar cells of 10 to 15% have the potential to yield specific power of up to 3 kW/kg.

These results give a good perspective for the application of CdTe solar cells in space.

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