RADIATION HARDNESS OF CdTe/CdS SOLAR CELLS

D. L. Bätzner, A. Romeo, M. Döbeli[1], H. Zogg, A. N. Tiwari

Thin Film Physics Group, Laboratory for Solid State Physics, ETH Zurich, Technoparkstr. 1,
8005 Zurich, Switzerland
[1]Institute for Particle Physics, ETH Zurich

ABSTRACT: The performance stability of CdTe/CdS thin film solar cells against radiation damage caused by protons and electrons has been investigated. High vacuum evaporated superstrate configuration cells of 10 - 12.5 % were developed on soda-lime glass.The irradiation experiments were performed under extremely damaging conditions. The subsequent characterisation confirms that CdTe/CdS solar cells are highly suitable for space application. A minor degradation is measured at high fluences for low energy protons of 650 keV and fluences of some $10^{16}cm^{-2}$ for 3 MeV electrons.

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

1. INTRODUCTION

The main power source for most satellites are solar cells. Usually the solar power generators consist of high efficiency Si and III-V cells made of mono-crystalline materials. Not only the beginning of lifetime efficiency but also the stability against particle irradiation in space is an important factor for the long term suitability of solar cells in space. It is known that the efficiency of mono-crystalline solar cells depends on the proton and electron irradiation, which changes the electrical properties of the cells and causes degradation. Thin film solar cells have the potential for low cost production on flexible substrates, high specific power (1.5 - 3 kW/kg) and stable performance [1].

Investigation of the thin film solar cell materials $CuInSe_2$ (CIS) or $CuInGaSe_2$ (CIGS) [2] show a superior electron and proton irradiation hardness. Unlike the conventional mono-crystalline cells, micro-crystalline cells are not so sensitive against irradiation damage because of favourable carrier compensation effects in defect rich and ionic-like poly-crystalline materials.

In a preliminary study [3] the excellent stability of CdTe/CdS solar cells against high energy protons was shown. In this work the stability of CdTe/CdS solar cells irradiated with low energy protons and high energy electrons is described.

2. EXPERIMENTAL DETAILS AND RESULTS

The CdTe/CdS solar cells were developed with a vacuum evaporation process on soda-lime glass [4] yielding cell efficiencies in the range of 10 - 12.5 % (AM1.5).

The particles that have to be considered for irradiation damage to solar cells are protons and electrons, which get trapped in the earth magnetic field, the Van Allen belt. Protons have a nearly isotropic, omnidirectional high fluences depending on the orbits, altitude and their energy. For 1 MeV protons in circular geostationary orbit with an inclination of 60° a fluences of $5 \cdot 10^{12}cm^{-2}$ per year has to be expected [5]. For 1 MeV electrons the concentration is highest in an orbit of about 5 earth radii distance where annual fluence is some $10^{12}cm^{-2}$.

Many space applications, e. g. communications satellites operate in geostationary orbits, where proton irradiation is the dominating degradation factor. The most important parameter for the damage in solar cells is the non ionisation energy loss (NIEL). For protons the NIEL is higher for lower energies (up to a threshold) where as for electrons the NIEL rises with energies as can be seen in Fig. 1. Therefore our investigation is focused on low energy protons of 650 keV, 1 MeV and 2.2 MeV with fluences ranging from $10^{11}cm^{-2}$ up to $10^{14}cm^{-2}$ as well as high energy electron irradiation at an energy of 3 MeV for high fluences of $3 \cdot 10^{16}cm^{-2}$ to $2 \cdot 10^{17}cm^{-2}$. In a previous paper [3] we already investigated CdTe/CdS cells irradiated with high energy protons of 5, 10 and 15 MeV.

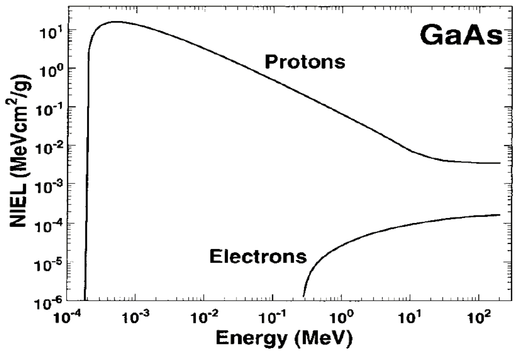

Figure 1: The non ionisation energy loss NIEL in a GaAs solar cell (taken from [6]).

Proton irradiation was performed at the ionbeam accelerator at the ETH Zürich. Electron irradiation was performed at the DYNAMITRON electron accelerator at the Strahlenphysik of the University Stuttgart. All particle irradiations were perpendicular on the non covered cell surface with monochromatic beams. Generally for radiation damage tests proton fluences in the range of $10^{10}cm^{-2}$ to $10^{12}cm^{-2}$ and electron fluences of $10^{12}cm^{-2}$ to $10^{14}cm^{-2}$ are used. However, we have tested cells under rather high fluences to find the onset of degradation. The solar cells where characterised before and after irradiation using the standard electro-optical measurements, i.e. IV-characteristics under AM1.5 irradiance, CV-characteristics at 100 kHz and room temperature as well as quantum efficiency measurements.

2.1 Low Energy Proton Irradiation

The relative efficiency as a function of the proton fluence can be seen in Fig. 2 for 3 energies. Most damaging are protons of 650 keV, where as the damage at 1 MeV and 2.2 MeV protons is comparably small.

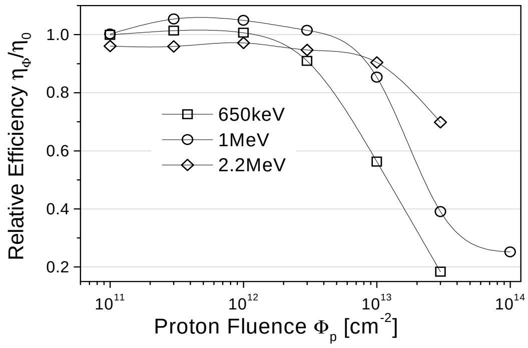

Figure 2: Relative efficiency vs. proton fluence for irradiation with different energies.

Especially for the 2.2 MeV protons irradiation with $3{\cdot}10^{12}$cm^{-2} fluence the efficiency is still 70% of the initial value. As shown in Fig. 3 and Fig. 4 the changes in the photovoltaic parameters depend on energy and fluence.

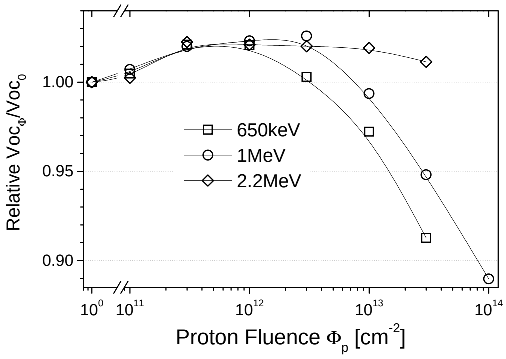

Figure 3: Relative V_{oc} vs. proton fluence for 3 energies. For medium fluences V_{oc} increases after irradiation.

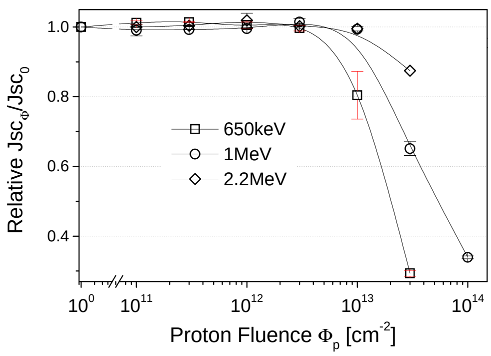

Figure 4: Relative J_{sc} vs. proton fluence for three energies.

Decrease in V_{oc} and J_{sc} are only measured for high fluences, above $3{\cdot}10^{12}$/cm^2. For smaller fluences the V_{oc} even increases by up to 20 mV in absolute value. In case of the irradiation with 2.2 MeV protons the V_{oc} shows more sustained increase over the whole measured fluence range. Together with the *FF* (Fig. 5) this yields a slight increase in efficiency as observed for 650 keV and mainly for 1 MeV proton irradiation at low to medium fluences. For 1 MeV and 2.2 MeV protons at high fluences, > 10^{13}cm^{-2}, the decrease in J_{sc} and efficiency is partly due to glass darkening, which is explained in section 3.1 and in [3].

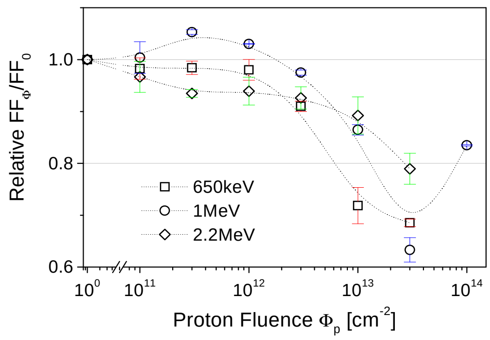

Figure 5: Relative *FF* vs. proton fluence for low energies.

2.2 High Energy Electron Irradiation

The CdTe cells have been irradiated with high energy electrons of 3 MeV and fluences of $3{\cdot}10^{16}$cm^{-2},$7{\cdot}10^{16}$cm^{-2} and $2{\cdot}10^{17}$cm^{-2}. The V_{oc} and *FF* slightly decrease and remain to 85% - 90% of their initial value, see Fig. 6.

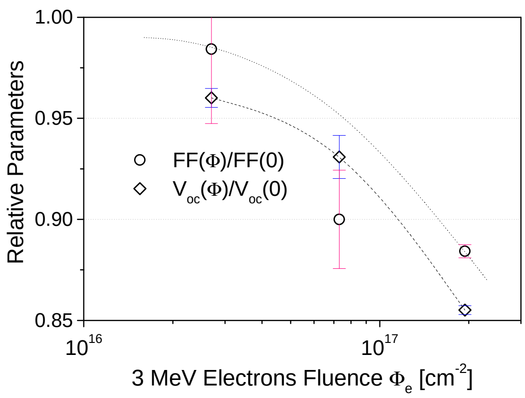

Figure 6: Apparent, relative V_{oc} and *FF* of 3 MeV electron irradiated cells vs. the electron fluence.

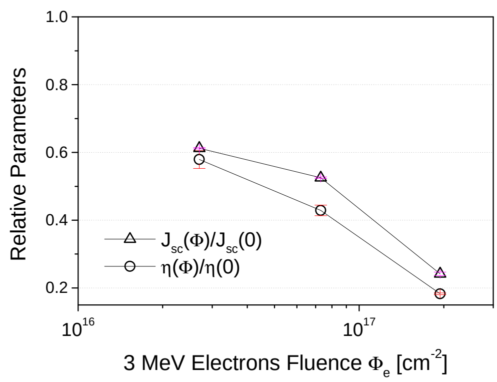

Figure 7: Apparent, relative efficiency and J_{sc} of 3 MeV electron irradiated cells vs. the electron fluence. Both are decreased due to darkening of the glass substrate.

The apparent efficiency decrease down to 20% of the initial value is caused by a comparable decrease in J_{sc} as can be seen in Fig. 7. It should be clarified that this decrease in J_{sc} is caused by the severe browning of the soda lime glass which reduces transmission and therefore the current almost by a factor of 2.

3. DISCUSSION ON PERFORMANCE STABILITY

3.1 Glass substrate and cover glasses

CdTe/CdS solar cells were processed on soda-lime glass in the superstrate configuration. Due to the ionisation energy loss of irradiated particles in soda-lime glass colour centres are created, which reduce the transmission of the glass drastically [5], especially in the blue part of the spectrum as can be seen in Fig. 8.

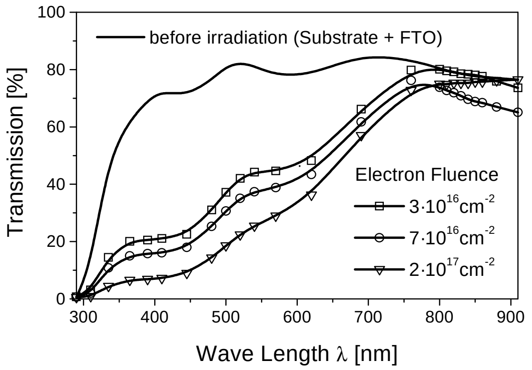

Figure 8: Transmission of non irradiated and particle irradiated soda-lime substrate with $SnO:F_2$ (FTO) front contact.

The current loss due to this reduced transmission was calculated for the cells by integrating the product of the spectral response with the transmitted AM1.5 spectrum. The glass, which was irradiated with $2{\cdot}10^{17}cm^{-2}$ electrons of 3 MeV for example, reduces the current to 52% of the initial value. Especially for the 3 MeV electron irradiated cells, a correction of the current and efficiency data is therefore important, as can be seen in Fig. 9. Additionally a decreased J_{sc} causes a decrease in V_{oc}, which explains the largest part of the measured V_{oc} decrease. The darkening of the substrate glass can be avoided by using a space grade glass which is doped with CeO_2. It is commonly used as cover glass for Si and III-V solar power generators in space [5]. Superstrate CdTe solar cells can be directly grown on such cover glass.

For the low energy proton irradiation (0.65 MeV - 2.2 MeV) up to $10^{13}cm^{-2}$ fluence, no transmission loss in the substrate glass was observed. A Monte-Carlo simulation of the proton distribution and collisions in the semiconductor layers of the investigated solar cells was carried out using the computer program TRIM [7] with the full collision cascade model. The transmission trough the cells of 650 keV protons is less than 0.5%. For 1 MeV protons more than 99% and for 2.2 MeV protons more than 99.9% are transmitted into the glass substrate. Since the 650 keV protons get stopped completely in the cell layers, the substrate glass should remain transparent irrespective of fluence. On the other hand, higher energy protons penetrated through the cell layers and created colour centres in the glass, which reduces transmission similar to electrons [3]. The CeO_2 doped cover glasses without transmission loss are used to protect the cells against particle irradiation in space. They effectively reduce the fluence of more damaging low energy protons depending on the glass thickness. For example, a silica fused cover glass of 0.5 mm thickness would limit the differential proton fluence for all energies to below $4{\cdot}10^{10}cm^{-2}a^{-1}$ in an orbit of 5100 km above the earth [8].

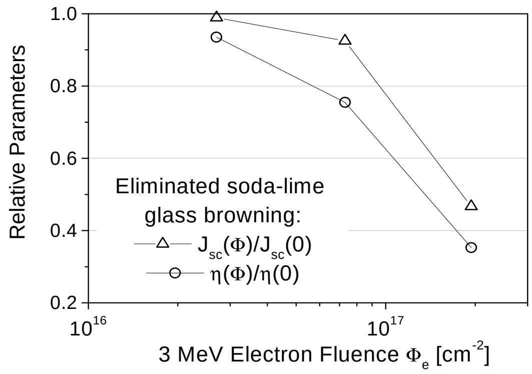

Figure 9: Efficiency and current of 3 MeV electron irradiated cells corrected for transmission loss in the glass.

3.2 Simulated defect generation

The protons loose their energy to the largest part through ionisation but also by creating defects such as vacancies. The Monte-Carlo simulation of the proton distribution and collisions mentioned above, yield the vacancy generation per incident proton, see Fig. 10.

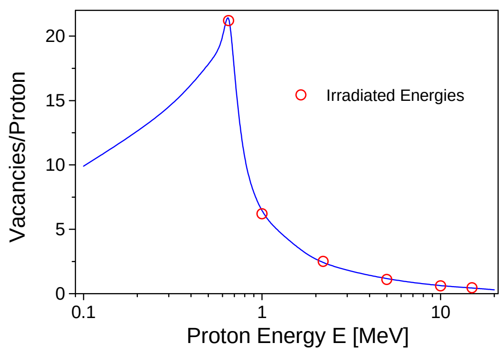

Figure 10: Simulated vacancy generation per proton vs. energy for the CdTe/CdS cells [7].

The irradiation creates intrinsic defects, which change the carrier concentration and diffusion length in the semiconductor material. Depending on the nature of the defects there may be an increase of the effective carrier concentration N_A, e.g. by either creating an acceptor or compensating a donor in CdTe, or it may decrease N_A by adding a donor or compensating an acceptor. Assuming that fluence increases the density of recombination centres N_r linearly, an expression for the voltage decrease ΔV_{oc} can be calculated [2]

$$\Delta V_{oc}(\Phi) = \frac{nkT}{q}\ln\left(1 + \frac{\gamma \cdot \Phi}{N_r(0)}\right) \qquad (1)$$

with the diode quality factor n, the thermal voltage kT/q the initial recombination centre density $N_r(0)$, the fluence Φ and the recombination centre introduction rate γ. For CIGS cells an exponential decrease of N_A was found experimentally [2]. For the CdTe/CdS solar cells the relation between introduction of defects, recombination centres and the change in N_A, is not so clear. In Fig. 3 both increase and decrease in V_{oc}, as well as a dominating logarithmic decrease for high fluences, can be seen. From capacitance measurements a change in the effective carrier concentration N_A can be deduced. Since the CV-measurements taken at room temperature exhibit systematic limits for the calculation of N_A, no reasonable quantitative analysis can be given by now. This will be subjects of ongoing research.

3.3 Change in effective diffusion length L_p

There are two degradation causes for the measured J_{sc}. The first is a strong transmission loss in the blue due to glass browning, the second is due to changes in the semiconductor (SC) materials and junctions. Apart from the obvious transmission loss due to darkened glass, the minor decrease in current can be explained by a decrease of the effective diffusion length L_p. It is possible to calculate L_p from the quantum efficiency using a standard procedure [9] taking only the near IR spectral part around the band edge (800 - 840 nm). Since the transmission is not significantly reduced due to irradiation in this spectral range a comparison of the estimated diffusion lengths is valid. In case of the proton irradiation with 650 keV where no glass browning is to be expected, a decrease in L_p is calculated, see Fig. 11.

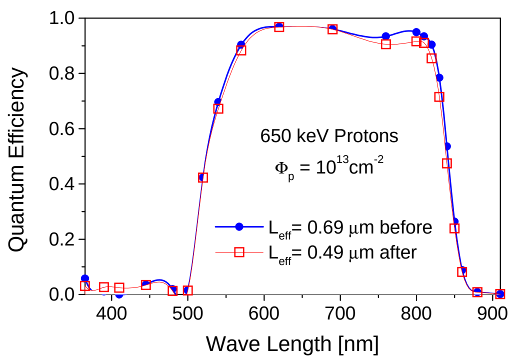

Figure 11: Measured quantum efficiency before and after proton irradiation (650 keV, 10^{13}cm^{-2}). The decrease in L_p can be seen as decreased QE around 800 nm.

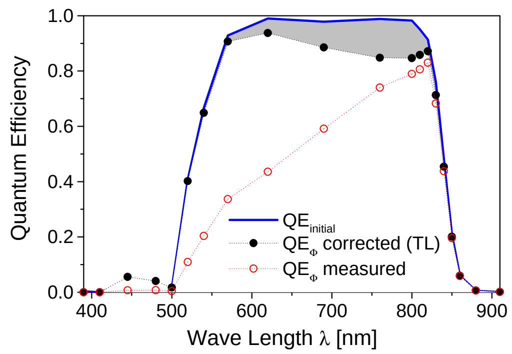

Figure 12: Measured quantum efficiencies of a cell before and after 3 MeV electron irradiation with $2{\cdot}10^{17}$cm^{-2} fluence. The gray area shows the cell material related decrease in J_{sc}, which is corrected for glass browning.

In case of the electron irradiation with 3 MeV, transmission loss (TL) in the used soda-lime glass substrate effects QE as well. The dotted line in Fig. 12 resembles the initial QE decrease only due to TL. Therefore, the current loss due to damage in the SC materials is the gray area in Fig. 12.

4. CONCLUSIONS

CdTe/CdS solar cells are stable under high fluences of particles. Their irradiation hardness is superior to mono-crystalline materials reviewed in literature. The apparent degradation observed was mainly due to transmission loss of the glass substrate caused by the creation of colour centres in the glass. This could be avoided by using space qualified CeO_2 doped silica fused glass. For space missions in the typical orbits of communications satellites no *End Of Lifetime* degradation is expected. On the contrary, for medium proton fluences of around 10^{12}cm^{-2} even a slight increase in performance can be expected. Variation in *FF* and V_{oc} can be explained by structural modification of prime defects causing changes in N_A by donor and acceptor generation or compensation. The observed reduction of diffusion length is responsible for the decrease in J_{sc}. Ongoing monitoring of the cells revealed a substantial degradation recovery for both kinds of irradiation.

5. ACKNOWLEDGEMENTS

We gratefully acknowledge K. Weinert and A. Jasenek from the IPE, University of Stuttgart for organising and conducting electron irradiation at the DYNAMITRON in Stuttgart.

6. REFERENCES

[1] A. Romeo, D. L. Bätzner, H. Zogg, A. N. Tiwari, 17th EC PVSEC (2001) VD3.2
[2] A. Jasenek, U. Rau, J. Appl. Phys. **90** (2001) 650-658.
[3] A. Romeo, D. L. Bätzner, H. Zogg, A. N. Tiwari, MRS Symp. Proc. **668** (2001) H3.3.1
[4] A. Romeo, A. N. Tiwari, H. Zogg, M. Wagner, J. R. Günter, 2nd World Conf. PVSEC (1998) 1105-1108.
[5] G. La Roche, Solargeneratoren für die Raumfahrt, Physikalische Technik und Raumfahrt, Vieweg (1997).
[6] S. R. Messenger, G. P. Summers, E. A. Burke, R. J. Walters, M. A. Xapsos, Prog. in PV **9** (2001) 103-121.
[7] J. F. Ziegler, J. P. Biersack, U. Littmark, The Stopping and Range of Ions in Solids, Pergamon Press (1985).
[8] G. P. Summers, E. A. Burke, P. Shapiro, S. R. Messenger, R. J. Walters, IEEE Trans. Nucl. Sci. **40** (1993) 1372-1379.
[9] P. A. Basore, IEEE PVSEC (1993) 147-152.