Presented at the 29th PVSC, New Orleans (2002)

HIGH ENERGY IRRADIATION PROPERTIES OF CdTe/CdS SOLAR CELLS

D. L. Bätzner, A. Romeo, M. Döbeli[1], K. Weinert [2], H. Zogg, A. N. Tiwari

Thin Film Physics Group, Laboratory for Solid State Physics, ETH (Swiss Federal Institute of Technology) Zurich, Technoparkstrasse1, CH - 8005 Zürich, Switzerland; http://www.tfp.ethz.ch
[1]Paul Scherrer Institute c/o Institute of Particle Physics, Swiss Federal Institute of Technology Zurich, Switzerland
[2]Institute of Physical Electronics, University Stuttgart, Germany

ABSTRACT

The irradiation hardness of CdTe solar cells was investigated for extremely high fluence of protons (up to 10^{14} cm^{-2}) and electrons (up to 10^{18} cm^{-2}) since the degradation onset occurs at very high fluences. One general degradation characteristic for CdTe cells was calculated using a damage dose formulation, allowing a comprehensive comparison with other cell technologies. CdTe cells show an excellent radiation stability, superior to monocrystalline cells and also slightly superior to other thin film cells. Changes in the cell parameters are quantitatively correlated to recombination centres. For proton irradiation, a passivation of recombination centres at low and medium fluences is observed causing even an increases the efficiency. The damage recovery of CdTe cells shows an exponential time dependence.

INTRODUCTION

Satellites are almost entirely powered by solar cells. Usually these power generators are made of high efficiency monocrystalline Si and III-V cells. The stability against particle irradiation in space is an important factor for the long term suitability of space cells. The cell efficiency decreases under proton and electron irradiation, because the semiconductor properties get changed by introduction of defects. Investigations of polycrystalline thin film cells like $CuInSe_2$ (CIS), Cu(In,Ga)Se_2 (CIGS) [1] and CdTe [2] show they are less sensitive to defect generation and consequent power losses than monocrystalline cells. Additionally, CdTe cells have the potential for low cost production on flexible substrates, high specific power and stable performance in space. In a preliminary study the excellent stability of CdTe solar cells against high energy protons was demonstrated [3]. In this work the stability of CdTe cells irradiated with low energy protons and high energy electrons is presented.

EXPERIMENTAL DETAILS AND RESULTS

CdTe solar cells were developed on SnO_2:F coated soda-lime glass substrates in superstrate configuration using a low temperature vacuum evaporation method [3,4] yielding efficiencies of 10 - 12.5 % under AM1.5 spectrum. The low temperature process allows to process flexible CdTe solar cells on polyimide substrates with efficiencies of around 11 % [8]. Since the irradiation experiments had to be conducted with CdTe cells on soda-lime glass substrates, the cells were irradiated from the uncovered back side with a perpendicular, monochromatic beam, thus avoiding measurement deviations due to shifted polychromatic spectra. The thin back contact layer (40 nm) influences the particle energy negligibly at the applied energies and is comparable to TCO or anti-reflex coating effects.

The most damaging particles in geostationary orbits are protons and electrons. The fluences depend on the orbit altitude and are highest for electrons at about 5 earth radii (10^{12} cm^{-2} y^{-1} at 1 MeV). For protons an integrated nearly isotropic and omnidirectional fluence is <10^{12} cm^{-2} y^{-1} [5]. Protons are dominant in geostationary orbits where most satellites operate. The damage in solar cells is caused mainly by non ionising energy loss (NIEL) of the incident particles [6]. This loss depends on cell material and is different for electrons and protons. The NIEL of protons is highest at energies of some keV but decreasing with energy, whereas the NIEL of electrons increases with energy becoming significant at >100 keV, see Fig. 1. The irradiation conditions

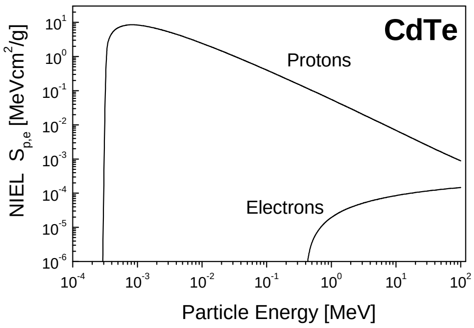

Fig. 1. The non ionisation energy loss NIEL in CdTe (by courtesy of S.Messenger, NRL, USA).

were chosen such that a substantial damage purposely occurs in order to study the damage mechanism and possible recovery in CdTe. Therefore the cells were irradiated with proton energies of 650 keV, 1 MeV and 2.2 MeV with fluences of 10^{11} cm^{-2} to 10^{14} cm^{-2}, as well as electron energies of 1 MeV and 3 MeV with fluences of $2{\cdot}10^{16}$ cm^{-2} to $8{\cdot}10^{17}$ cm^{-2}. These fluences are higher than usually applied for radiation stability measurements of solar cells in order to get to the limit of the extreme radiation resist-

ance. The proton irradiation was conducted with the PSI / ETH tandem accelerator at the Institute of Particle Physics at The ETH Zurich, the electron irradiation was performed with the DYNAMITRON electron accelerator at the Institute of Radiation Physics in collaboration with the Institute of Physical Electronics, University of Stuttgart. Before and in subsequent time intervals after the irradiation the cells were characterised using I-V (AM1.5), quantum efficiency and C-V characteristics. The cell parameters labelled as relative are normalised to their respective initial values.

Proton irradiation

The efficiencies do not change for low fluences of 10^{11} cm^{-2} and a slight increase for medium fluences is measured, as shown in Fig. 2. Only at an already high

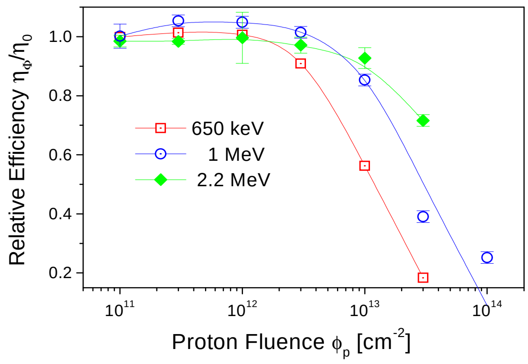

Fig. 2. Relative efficiency, i.e. efficiency after irradiation normalised to initial efficiency, *vs* the proton fluence for irradiation with different energies.

threshold fluence of 1 - 3·10^{12} cm^{-2}, a degradation onset is measurable. As expected from the NIEL, lower proton energies cause higher damage. At a fluence of 10^{13} cm^{-2} the relative efficiency of cells irradiated with 650 keV protons is still 56%, with 1 MeV protons 83% and with 2.2 MeV protons 92%. The efficiency increase for medium fluences is due to an increase in V_{OC} of up to 20 mV. At higher fluences the V_{OC} starts to decrease as a result of increased recombination centre density N_r. The decrease in efficiency is mainly caused by reduced J_{SC} at higher fluences. As verified with QE measurements, the effective diffusion length decreases due to the increase in N_r.

CdTe cells are very stable against proton irradiation since any significant damage happens only for fluences above some 10^{12} cm^{-2}. The fast damage recovery, described below, yet upgrades the stability properties.

Electron irradiation

The relative efficiencies of electron irradiated cells are shown in Fig. 3. They stay at 95 % for a high fluence of 3·10^{16} cm^{-2} and degrade down to 30 % and 10 % for 1 Mev and 3 MeV, respectively at a fluence of 3·10^{17} cm^{-2}. The performance degradation is dominated by the degradation of J_{SC}. Fill factor and V_{OC} are only little affected and stay both above 85 % (relative) for all applied irradiation conditions. In case of 1 MeV electron irradiation the loss in V_{OC} is even less than 3 %. In contrast to proton irradiation no increase of any cell parameter was measured. By an extrapolation of the damage characteristics the onset of degradation fluences is almost 10^{16} cm^{-2}.

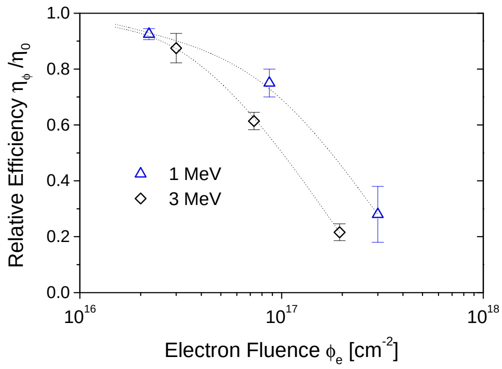

Fig. 3. Relative efficiency of 1 MeV and 3 MeV electron irradiated cells *vs* the fluence.

As mentioned earlier the experiments had to be conducted with soda-lime glass substrates, since radiation resistant glass was not available. Radiation induced glass browning influenced the current measurement, however all data presented in this paper are corrected for any transmission loss as previously reported [2].

THE DISPLACEMENT DAMAGE DOSE APPROACH

For a reliable degradation prediction it is necessary to know the degradation characteristics for each particle and energy over a sufficient fluence range. However a description of one general degradation characteristic can be obtained by applying the displacement damage dose (Dd) formalism [6]. In a first step the particle fluences $\Phi_{p,e}(E)$ are converted to displacement damage doses $D_{p,e}(E)$ using the NIEL $S_{p,e}(E)$ that contains the material specific information

$$D_{p,e}(E) = \Phi_{p,e}(E) \cdot S_{p,e}(E) \qquad (1)$$

The indices p and e denote protons and electrons, respectively. In case of an energy spectrum an integral form of Eq. (1) must be used. The degradation curves for different energies and particles now coincide if plotted against the D_p and D_e, as shown in Fig. 4. As demonstrated for other materials [6] this formalism is also applicable to CdTe. To match the electron degradation curves usually a correction function for an effective D_e has to be applied, which is not the case for the tested CdTe cells [8]. With the scaling factor R_{EP} of 3.29 in our case the characteristics for electrons can be matched to the proton characteristics. The effective damage dose D_s for electrons and protons can be defined as

$$D_S = D_p + \frac{D_e}{R_{EP}} \qquad (2)$$

Relative efficiencies plotted *vs* D_S yield the general degradation characteristics as shown in Fig. 5. For any specific

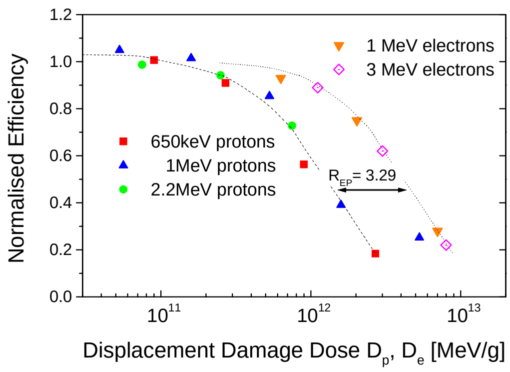

Fig. 4. Degradation curves of protons and electrons *vs* the respective displacement damage doses D_e and D_p. The correlation factor R_{EP} scales electron to proton doses.

space mission, the effective Dd can be calculated according to Eq. (2) with the proton dose D_p and the electron dose D_e, which can be received from existing algorithms [6], and the end of life (EOL) performance can be deduced from Fig. 5.

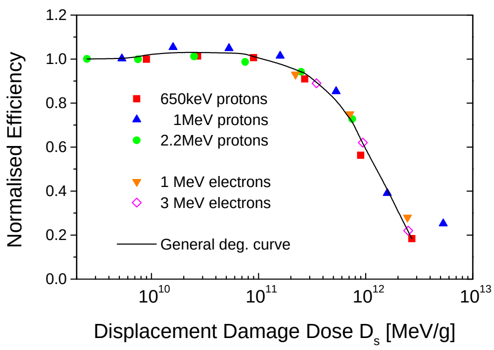

Fig. 5. Generalised degradation characteristics *vs* the displacement damage dose D_S for all particle irradiations.

A model for cell degradation due to particle damage

A Monte-Carlo simulation in ‘full collision cascade mode’, supplied by the computer program SRIM2000 [7] was applied for a more detailed study of the proton damage including spatial scattering distribution, vacancy generation, transmitted particles and recoil energies for given cell layers and energies.

The energy loss of electrons in the cell can be estimated to be a few keV, with an assumed stopping power of 2 MeV*g^{-1}*cm^2, indicating that almost all electrons are transmitted through the cell.

The transmission of protons though the cell is less than 0.5 % at 650 keV, but already higher than 99.9 % at 2.2 MeV. As shown in Fig. 6 the Monte-Carlo simulation indicates that most of the 650 keV protons are stopped in the pn-junction and CdS layer. Since the 2.2 MeV protons are mainly transmitted, the energy loss distribution is more uniform throughout the cell layers. Degradation is determined by the particle energy loss due to vacancy generation, which is much for low energy than for high energy protons as obtained from simulation. The introduced defects result in an increased recombination centre density

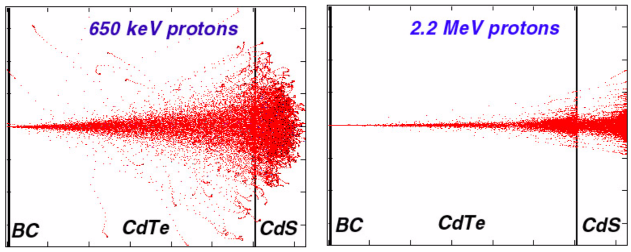

Fig. 6. Monte-Carlo simulation of proton scattering distribution in the CdTe/CdS cells [7].

N_r, which changes the cell parameters V_{OC} and J_{SC} strongly due to a modified transport. At medium proton fluences a significant increase in V_{OC} (20 mV) indicating that N_r is decreased because of recombination centres passivation. Presumably the protons are trapped as they are slowed down saturating free bonds in the absorber material, i.e. a hydrogen-passivation by ion implantation. As the passivation saturates, N_r starts to increase again by defect generation at higher fluences. This increase in N_r allows a higher current through the device, which appears to be a ’shunting’ of the cell. In a first approximation this current is proportional to N_r. The logarithmic dependence of V_{OC} on current allows a precise calculation of the V_{OC} loss, as presented in detail elsewhere [8]. The rate of defect generation decreases with increasing proton energy as predicted by the SRIM simulation. The fluence threshold for maximum passivation is shifted towards higher fluences for higher energies since less defects are introduced. The increased recombination current causes a loss in J_{SC}. The introduced recombination centres decrease the effective diffusion length, which is calculated from quantum efficiency measurements [2]. Using these relations the current loss can be described mathematically [8].

COMPARISON OF DIFFERENT CELL TECHNOLOGIES

The irradiation stability of different cell technologies can be compared conveniently with the damage dose formalism since only one general curve characterises the materials. CdTe cells are compared to GaAs/Ge and CIS solar cells with data taken from literature [6], see Fig. 7. Thin films (CdTe, CIS, CIGS) show generally higher radiation hardness than monocrystalline materials (Si, GaAs). Each cell technology has a specific R_{EP} scaling D_e to D_p, therefore care has to be taken interpreting Fig. 7. While the efficiency R_{EP} of CdTe cells was determined to be 3.29 for GaAs/Ge cells a value of 2.54 is reported [6] signifying that electrons are less damaging to CdTe than to GaAs/Ge cells. Additional comparison of literature data proved that the damaging fluence onset for polycrystalline thin film cells is typically 2-3 orders of magnitude higher than for monocrystalline material. Especially CdTe cells show a sustained stability for higher doses, which is even superior to other thin film

solar cells. In case of proton irradiation the performance increases slightly for intermediate fluences. The degrada-

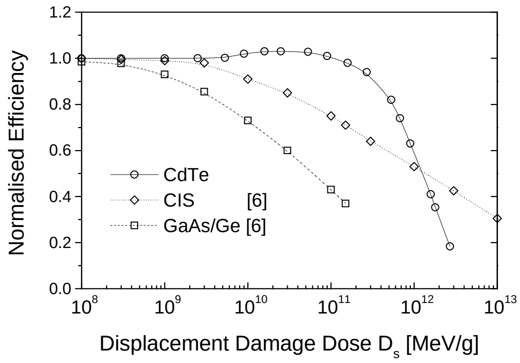

Fig. 7. Comparison of degradation characteristics of different cell technologies.

tion characteristics is somewhat steeper and meets for example the CIS curve in Fig. 7 at a dose above 10^{12} MeV/g (hardly ever reached in a space mission), which degrades performance of CIS cells to 50 % but of GaAs/Ge to below 10 % (extrapolated) of the initial value.

RECOVERY OF DEGRADED CELLS

The performance recovery of CdTe cells was studied at room temperature, however recovery will be faster at elevated temperature, because temperature influences the defect mobility and self compensation mechanisms in semiconductors. The current loss is the major degradation factor, therefore it also determines the recovery, which follows an exponential dependence

$$\frac{\eta_\Phi(t)}{\eta_0} = 1 - c_1 - c_2 \cdot \exp(-c_3 \cdot t) \qquad (3)$$

where η_0 is the initial efficiency, $\eta_\Phi(t)$ the recovered efficiency at time t, c_1 a possible residual damage, $c_1 + c_2$ the initial damage after irradiation and c_3 a time constant that determines the recovery speed, as shown in Fig. 8. The recovery mechanism depends on temperature, but only slightly on irradiation energy or fluence. The time constant c_3 is 0.058/day at room temperature, which gives a reco-

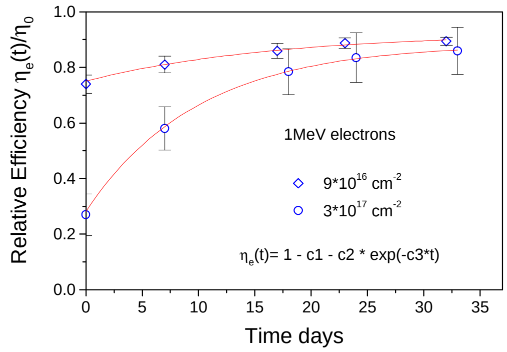

Fig. 8. Performance recovery of CdTe cells after irradiation with different electron fluences.

very half-life period of approximately 12 days. After 1 month more than 80% of the damage is recovered. During irradiation experiments in the laboratory the fluences are typically introduced in few minutes (protons) to a few hours (electrons), however the same fluences will be collected in space during years, depending on the orbit. Further the cells in space get heated to 100°C or more, strongly accelerating the performance recovery. As the recovery rate is much shorter than the damage generation rate, radiation damage in geostationary orbits will be recovered immediately resulting in excellent stability.

CONCLUSIONS

CdTe/CdS solar cells are very stable under high fluences of protons and electrons. Their radiation hardness is superior to monocrystalline cells and slightly superior to thin film cells of other materials. For space missions in the typical orbits of communications satellites no EOL degradation for CdTe solar cells is expected because of the low fluences that are below the onset of cell degradation. The recovery of CdTe/CdS solar cells is very fast and proceeds exponentially in time. Any possible irradiation damage in space is expected to be recovered immediately without causing permanent damage.

Solar cell performance degradation was successfully described with the damage dose formulation and simulation of recombination mechanisms, which explains the gain and loss in the cell parameters.

ACKNOWLEDGEMENTS

We thank S. Messenger for discussion and contribution of the NIEL data, G. Agostinelli for providing valuable ideas, U. Rau for discussion and The European Space Agency ESA for support.

REFERENCES

[1] A. Jasenek, U. Rau, *J. Appl. Phys.* **90**, 650-658 (2001).

[2] D. L. Bätzner, A. Romeo, H. Zogg, A.N. Tiwari, *17th European PVSEC*, Munich, OA9.3 (2001).

[3] A. Romeo, D. L. Bätzner, H. Zogg, A.N. Tiwari, *Mat. Res. Soc. Symp. Proc.* Vol. **668**, H3.3.1 (2001).

[4] A. Romeo, A. N. Tiwari, H. Zogg, M. Wagner, J. R. Günter, *2nd World PVSEC*, Vienna 1105-1108 (1998).

[5] G. La Roche, *Solargeneratoren für die Raumfahrt,* Vieweg (1997).

[6] S.R. Messenger, G.P. Summers, E.A. Burke, R.J. Walters, M.A. Xapsos, *Prog. in PV* **9**, 103-121 (2001).

[7] J.F. Ziegler, J.P. Biersack, U. Littmark, *The stopping and range of ions in solids,* Pergamon Press (1985).

[8] D.L. Bätzner, A. Romeo, M. Döbeli, K. Weinert, H. Zogg, A.N. Tiwari, to be published

Presented at the 29th PVSC, New Orleans (2002)

HIGH ENERGY IRRADIATION PROPERTIES OF CdTe/CdS SOLAR CELLS

D. L. Bätzner, A. Romeo, M. Döbeli[1], K. Weinert [2], H. Zogg, A. N. Tiwari

Thin Film Physics Group, Laboratory for Solid State Physics, ETH (Swiss Federal Institute of Technology) Zurich, Technoparkstrasse1, CH - 8005 Zürich, Switzerland; http://www.tfp.ethz.ch
[1]Paul Scherrer Institute c/o Institute of Particle Physics, Swiss Federal Institute of Technology Zurich, Switzerland
[2]Institute of Physical Electronics, University Stuttgart, Germany

ABSTRACT

The irradiation hardness of CdTe solar cells was investigated for extremely high fluence of protons (up to 10^{14} cm^{-2}) and electrons (up to 10^{18} cm^{-2}) since the degradation onset occurs at very high fluences. One general degradation characteristic for CdTe cells was calculated using a damage dose formulation, allowing a comprehensive comparison with other cell technologies. CdTe cells show an excellent radiation stability, superior to monocrystalline cells and also slightly superior to other thin film cells. Changes in the cell parameters are quantitatively correlated to recombination centres. For proton irradiation, a passivation of recombination centres at low and medium fluences is observed causing even an increases the efficiency. The damage recovery of CdTe cells shows an exponential time dependence.

INTRODUCTION

Satellites are almost entirely powered by solar cells. Usually these power generators are made of high efficiency monocrystalline Si and III-V cells. The stability against particle irradiation in space is an important factor for the long term suitability of space cells. The cell efficiency decreases under proton and electron irradiation, because the semiconductor properties get changed by introduction of defects. Investigations of polycrystalline thin film cells like $CuInSe_2$ (CIS), Cu(In,Ga)Se_2 (CIGS) [1] and CdTe [2] show they are less sensitive to defect generation and consequent power losses than monocrystalline cells. Additionally, CdTe cells have the potential for low cost production on flexible substrates, high specific power and stable performance in space. In a preliminary study the excellent stability of CdTe solar cells against high energy protons was demonstrated [3]. In this work the stability of CdTe cells irradiated with low energy protons and high energy electrons is presented.

EXPERIMENTAL DETAILS AND RESULTS

CdTe solar cells were developed on SnO_2:F coated soda-lime glass substrates in superstrate configuration using a low temperature vacuum evaporation method [3,4] yielding efficiencies of 10 - 12.5 % under AM1.5 spectrum. The low temperature process allows to process flexible CdTe solar cells on polyimide substrates with efficiencies of around 11 % [8]. Since the irradiation experiments had to be conducted with CdTe cells on soda-lime glass substrates, the cells were irradiated from the uncovered back side with a perpendicular, monochromatic beam, thus avoiding measurement deviations due to shifted polychromatic spectra. The thin back contact layer (40 nm) influences the particle energy negligibly at the applied energies and is comparable to TCO or anti-reflex coating effects.

The most damaging particles in geostationary orbits are protons and electrons. The fluences depend on the orbit altitude and are highest for electrons at about 5 earth radii (10^{12} cm^{-2} y^{-1} at 1 MeV). For protons an integrated nearly isotropic and omnidirectional fluence is <10^{12} cm^{-2} y^{-1} [5]. Protons are dominant in geostationary orbits where most satellites operate. The damage in solar cells is caused mainly by non ionising energy loss (NIEL) of the incident particles [6]. This loss depends on cell material and is different for electrons and protons. The NIEL of protons is highest at energies of some keV but decreasing with energy, whereas the NIEL of electrons increases with energy becoming significant at >100 keV, see Fig. 1. The irradiation conditions

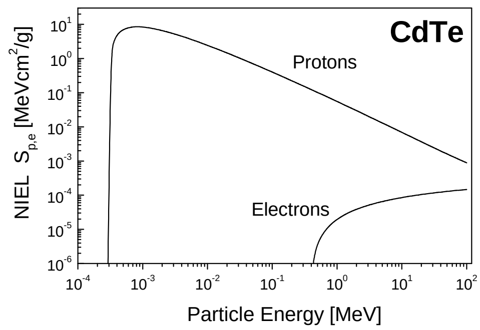

Fig. 1. The non ionisation energy loss NIEL in CdTe (by courtesy of S.Messenger, NRL, USA).

were chosen such that a substantial damage purposely occurs in order to study the damage mechanism and possible recovery in CdTe. Therefore the cells were irradiated with proton energies of 650 keV, 1 MeV and 2.2 MeV with fluences of 10^{11} cm^{-2} to 10^{14} cm^{-2}, as well as electron energies of 1 MeV and 3 MeV with fluences of $2 \cdot 10^{16}$ cm^{-2} to $8 \cdot 10^{17}$ cm^{-2}. These fluences are higher than usually applied for radiation stability measurements of solar cells in order to get to the limit of the extreme radiation resist-

ance. The proton irradiation was conducted with the PSI / ETH tandem accelerator at the Institute of Particle Physics at The ETH Zurich, the electron irradiation was performed with the DYNAMITRON electron accelerator at the Institute of Radiation Physics in collaboration with the Institute of Physical Electronics, University of Stuttgart. Before and in subsequent time intervals after the irradiation the cells were characterised using I-V (AM1.5), quantum efficiency and C-V characteristics. The cell parameters labelled as relative are normalised to their respective initial values.

Proton irradiation

The efficiencies do not change for low fluences of 10^{11} cm^{-2} and a slight increase for medium fluences is measured, as shown in Fig. 2. Only at an already high

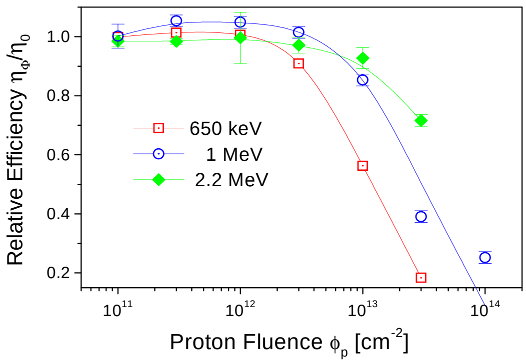

Fig. 2. Relative efficiency, i.e. efficiency after irradiation normalised to initial efficiency, *vs* the proton fluence for irradiation with different energies.

threshold fluence of 1 - 3·10^{12} cm^{-2}, a degradation onset is measurable. As expected from the NIEL, lower proton energies cause higher damage. At a fluence of 10^{13} cm^{-2} the relative efficiency of cells irradiated with 650 keV protons is still 56%, with 1 MeV protons 83% and with 2.2 MeV protons 92%. The efficiency increase for medium fluences is due to an increase in V_{OC} of up to 20 mV. At higher fluences the V_{OC} starts to decrease as a result of increased recombination centre density N_r. The decrease in efficiency is mainly caused by reduced J_{SC} at higher fluences. As verified with QE measurements, the effective diffusion length decreases due to the increase in N_r.

CdTe cells are very stable against proton irradiation since any significant damage happens only for fluences above some 10^{12} cm^{-2}. The fast damage recovery, described below, yet upgrades the stability properties.

Electron irradiation

The relative efficiencies of electron irradiated cells are shown in Fig. 3. They stay at 95 % for a high fluence of 3·10^{16} cm^{-2} and degrade down to 30 % and 10 % for 1 Mev and 3 MeV, respectively at a fluence of 3·10^{17} cm^{-2}. The performance degradation is dominated by the degradation of J_{SC}. Fill factor and V_{OC} are only little affected and stay both above 85 % (relative) for all applied irradiation conditions. In case of 1 MeV electron irradiation the loss in V_{OC} is even less than 3 %. In contrast to proton irradiation no increase of any cell parameter was measured. By an extrapolation of the damage characteristics the onset of degradation fluences is almost 10^{16} cm^{-2}.

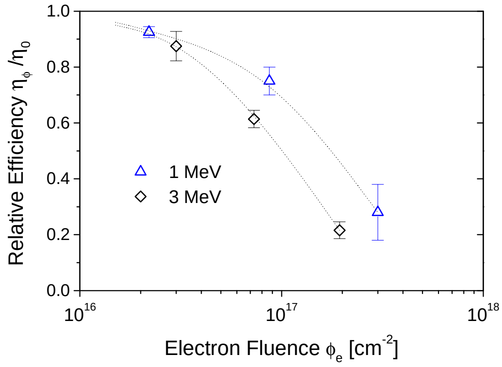

Fig. 3. Relative efficiency of 1 MeV and 3 MeV electron irradiated cells *vs* the fluence.

As mentioned earlier the experiments had to be conducted with soda-lime glass substrates, since radiation resistant glass was not available. Radiation induced glass browning influenced the current measurement, however all data presented in this paper are corrected for any transmission loss as previously reported [2].

THE DISPLACEMENT DAMAGE DOSE APPROACH

For a reliable degradation prediction it is necessary to know the degradation characteristics for each particle and energy over a sufficient fluence range. However a description of one general degradation characteristic can be obtained by applying the displacement damage dose (Dd) formalism [6]. In a first step the particle fluences $\Phi_{p,e}(E)$ are converted to displacement damage doses $D_{p,e}(E)$ using the NIEL $S_{p,e}(E)$ that contains the material specific information

$$D_{p,e}(E) = \Phi_{p,e}(E) \cdot S_{p,e}(E) \qquad (1)$$

The indices p and e denote protons and electrons, respectively. In case of an energy spectrum an integral form of Eq. (1) must be used. The degradation curves for different energies and particles now coincide if plotted against the D_p and D_e, as shown in Fig. 4. As demonstrated for other materials [6] this formalism is also applicable to CdTe. To match the electron degradation curves usually a correction function for an effective D_e has to be applied, which is not the case for the tested CdTe cells [8]. With the scaling factor R_{EP} of 3.29 in our case the characteristics for electrons can be matched to the proton characteristics. The effective damage dose D_s for electrons and protons can be defined as

$$D_S = D_p + \frac{D_e}{R_{EP}} \qquad (2)$$

Relative efficiencies plotted *vs* D_S yield the general degradation characteristics as shown in Fig. 5. For any specific

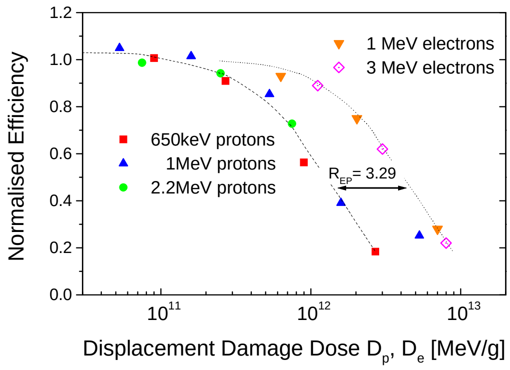

Fig. 4. Degradation curves of protons and electrons *vs* the respective displacement damage doses D_e and D_p. The correlation factor R_{EP} scales electron to proton doses.

space mission, the effective Dd can be calculated according to Eq. (2) with the proton dose D_p and the electron dose D_e, which can be received from existing algorithms [6], and the end of life (EOL) performance can be deduced from Fig. 5.

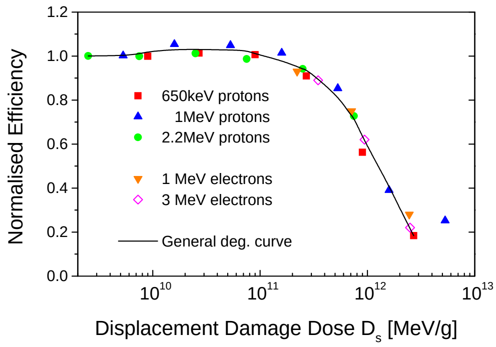

Fig. 5. Generalised degradation characteristics *vs* the displacement damage dose D_S for all particle irradiations.

A model for cell degradation due to particle damage

A Monte-Carlo simulation in ‘full collision cascade mode’, supplied by the computer program SRIM2000 [7] was applied for a more detailed study of the proton damage including spatial scattering distribution, vacancy generation, transmitted particles and recoil energies for given cell layers and energies.

The energy loss of electrons in the cell can be estimated to be a few keV, with an assumed stopping power of 2 MeV*g^{-1}*cm^2, indicating that almost all electrons are transmitted through the cell.

The transmission of protons though the cell is less than 0.5 % at 650 keV, but already higher than 99.9 % at 2.2 MeV. As shown in Fig. 6 the Monte-Carlo simulation indicates that most of the 650 keV protons are stopped in the pn-junction and CdS layer. Since the 2.2 MeV protons are mainly transmitted, the energy loss distribution is more uniform throughout the cell layers. Degradation is determined by the particle energy loss due to vacancy generation, which is much for low energy than for high energy protons as obtained from simulation. The introduced defects result in an increased recombination centre density

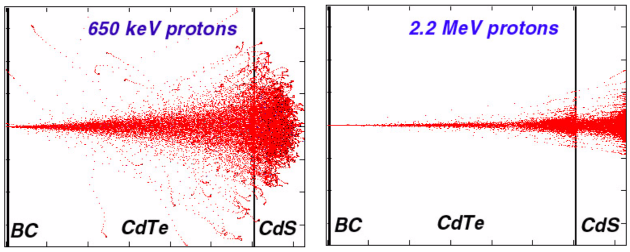

Fig. 6. Monte-Carlo simulation of proton scattering distribution in the CdTe/CdS cells [7].

N_r, which changes the cell parameters V_{OC} and J_{SC} strongly due to a modified transport. At medium proton fluences a significant increase in V_{OC} (20 mV) indicating that N_r is decreased because of recombination centres passivation. Presumably the protons are trapped as they are slowed down saturating free bonds in the absorber material, i.e. a hydrogen-passivation by ion implantation. As the passivation saturates, N_r starts to increase again by defect generation at higher fluences. This increase in N_r allows a higher current through the device, which appears to be a ’shunting’ of the cell. In a first approximation this current is proportional to N_r. The logarithmic dependence of V_{OC} on current allows a precise calculation of the V_{OC} loss, as presented in detail elsewhere [8]. The rate of defect generation decreases with increasing proton energy as predicted by the SRIM simulation. The fluence threshold for maximum passivation is shifted towards higher fluences for higher energies since less defects are introduced. The increased recombination current causes a loss in J_{SC}. The introduced recombination centres decrease the effective diffusion length, which is calculated from quantum efficiency measurements [2]. Using these relations the current loss can be described mathematically [8].

COMPARISON OF DIFFERENT CELL TECHNOLOGIES

The irradiation stability of different cell technologies can be compared conveniently with the damage dose formalism since only one general curve characterises the materials. CdTe cells are compared to GaAs/Ge and CIS solar cells with data taken from literature [6], see Fig. 7. Thin films (CdTe, CIS, CIGS) show generally higher radiation hardness than monocrystalline materials (Si, GaAs). Each cell technology has a specific R_{EP} scaling D_e to D_p, therefore care has to be taken interpreting Fig. 7. While the efficiency R_{EP} of CdTe cells was determined to be 3.29 for GaAs/Ge cells a value of 2.54 is reported [6] signifying that electrons are less damaging to CdTe than to GaAs/Ge cells. Additional comparison of literature data proved that the damaging fluence onset for polycrystalline thin film cells is typically 2-3 orders of magnitude higher than for monocrystalline material. Especially CdTe cells show a sustained stability for higher doses, which is even superior to other thin film

solar cells. In case of proton irradiation the performance increases slightly for intermediate fluences. The degrada-

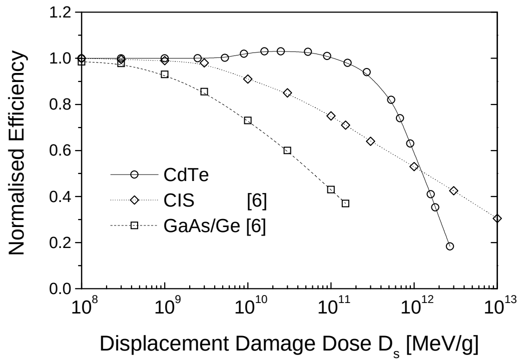

Fig. 7. Comparison of degradation characteristics of different cell technologies.

tion characteristics is somewhat steeper and meets for example the CIS curve in Fig. 7 at a dose above 10^{12} MeV/g (hardly ever reached in a space mission), which degrades performance of CIS cells to 50 % but of GaAs/Ge to below 10 % (extrapolated) of the initial value.

RECOVERY OF DEGRADED CELLS

The performance recovery of CdTe cells was studied at room temperature, however recovery will be faster at elevated temperature, because temperature influences the defect mobility and self compensation mechanisms in semiconductors. The current loss is the major degradation factor, therefore it also determines the recovery, which follows an exponential dependence

$$\frac{\eta_\Phi(t)}{\eta_0} = 1 - c_1 - c_2 \cdot \exp(-c_3 \cdot t) \qquad (3)$$

where η_0 is the initial efficiency, $\eta_\Phi(t)$ the recovered efficiency at time t, c_1 a possible residual damage, $c_1 + c_2$ the initial damage after irradiation and c_3 a time constant that determines the recovery speed, as shown in Fig. 8. The recovery mechanism depends on temperature, but only slightly on irradiation energy or fluence. The time constant c_3 is 0.058/day at room temperature, which gives a recovery half-life period of approximately 12 days. After 1 month more than 80% of the damage is recovered. During irradiation experiments in the laboratory the fluences are typically introduced in few minutes (protons) to a few hours (electrons), however the same fluences will be collected in space during years, depending on the orbit. Further the cells in space get heated to 100°C or more, strongly accelerating the performance recovery. As the recovery rate is much shorter than the damage generation rate, radiation damage in geostationary orbits will be recovered immediately resulting in excellent stability.

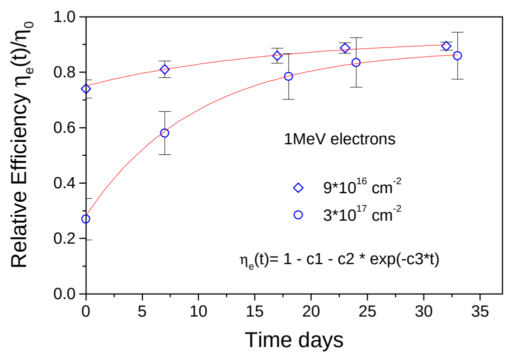

Fig. 8. Performance recovery of CdTe cells after irradiation with different electron fluences.

CONCLUSIONS

CdTe/CdS solar cells are very stable under high fluences of protons and electrons. Their radiation hardness is superior to monocrystalline cells and slightly superior to thin film cells of other materials. For space missions in the typical orbits of communications satellites no EOL degradation for CdTe solar cells is expected because of the low fluences that are below the onset of cell degradation. The recovery of CdTe/CdS solar cells is very fast and proceeds exponentially in time. Any possible irradiation damage in space is expected to be recovered immediately without causing permanent damage.

Solar cell performance degradation was successfully described with the damage dose formulation and simulation of recombination mechanisms, which explains the gain and loss in the cell parameters.

ACKNOWLEDGEMENTS

We thank S. Messenger for discussion and contribution of the NIEL data, G. Agostinelli for providing valuable ideas, U. Rau for discussion and The European Space Agency ESA for support.

REFERENCES

[1] A. Jasenek, U. Rau, *J. Appl. Phys.* **90**, 650-658 (2001).

[2] D. L. Bätzner, A. Romeo, H. Zogg, A.N. Tiwari, *17th European PVSEC*, Munich, OA9.3 (2001).

[3] A. Romeo, D. L. Bätzner, H. Zogg, A.N. Tiwari, *Mat. Res. Soc. Symp. Proc.* Vol. **668**, H3.3.1 (2001).

[4] A. Romeo, A. N. Tiwari, H. Zogg, M. Wagner, J. R. Günter, *2nd World PVSEC*, Vienna 1105-1108 (1998).

[5] G. La Roche, *Solargeneratoren für die Raumfahrt,* Vieweg (1997).

[6] S.R. Messenger, G.P. Summers, E.A. Burke, R.J. Walters, M.A. Xapsos, *Prog. in PV* **9**, 103-121 (2001).

[7] J.F. Ziegler, J.P. Biersack, U. Littmark, *The stopping and range of ions in solids,* Pergamon Press (1985).

[8] D.L. Bätzner, A. Romeo, M. Döbeli, K. Weinert, H. Zogg, A.N. Tiwari, to be published

HIGH ENERGY IRRADIATION PROPERTIES OF CdTe/CdS SOLAR CELLS

D. L. Bätzner, A. Romeo, M. Döbeli[1], K. Weinert [2], H. Zogg, A. N. Tiwari

Thin Film Physics Group, Laboratory for Solid State Physics, ETH (Swiss Federal Institute of Technology) Zurich, Technoparkstrasse1, CH - 8005 Zürich, Switzerland; http://www.tfp.ethz.ch
[1]Paul Scherrer Institute c/o Institute of Particle Physics, Swiss Federal Institute of Technology Zurich, Switzerland
[2]Institute of Physical Electronics, University Stuttgart, Germany

ABSTRACT

The irradiation hardness of CdTe solar cells was investigated for extremely high fluence of protons (up to 10^{14} cm^{-2}) and electrons (up to 10^{18} cm^{-2}) since the degradation onset occurs at very high fluences. One general degradation characteristic for CdTe cells was calculated using a damage dose formulation, allowing a comprehensive comparison with other cell technologies. CdTe cells show an excellent radiation stability, superior to monocrystalline cells and also slightly superior to other thin film cells. Changes in the cell parameters are quantitatively correlated to recombination centres. For proton irradiation, a passivation of recombination centres at low and medium fluences is observed causing even an increases the efficiency. The damage recovery of CdTe cells shows an exponential time dependence.

INTRODUCTION

Satellites are almost entirely powered by solar cells. Usually these power generators are made of high efficiency monocrystalline Si and III-V cells. The stability against particle irradiation in space is an important factor for the long term suitability of space cells. The cell efficiency decreases under proton and electron irradiation, because the semiconductor properties get changed by introduction of defects. Investigations of polycrystalline thin film cells like $CuInSe_2$ (CIS), $Cu(In,Ga)Se_2$ (CIGS) [1] and CdTe [2] show they are less sensitive to defect generation and consequent power losses than monocrystalline cells. Additionally, CdTe cells have the potential for low cost production on flexible substrates, high specific power and stable performance in space. In a preliminary study the excellent stability of CdTe solar cells against high energy protons was demonstrated [3]. In this work the stability of CdTe cells irradiated with low energy protons and high energy electrons is presented.

EXPERIMENTAL DETAILS AND RESULTS

CdTe solar cells were developed on SnO_2:F coated soda-lime glass substrates in superstrate configuration using a low temperature vacuum evaporation method [3,4] yielding efficiencies of 10 - 12.5 % under AM1.5 spectrum. The low temperature process allows to process flexible CdTe solar cells on polyimide substrates with efficiencies of around 11 % [8]. Since the irradiation experiments had to be conducted with CdTe cells on soda-lime glass substrates, the cells were irradiated from the uncovered back side with a perpendicular, monochromatic beam, thus avoiding measurement deviations due to shifted polychromatic spectra. The thin back contact layer (40 nm) influences the particle energy negligibly at the applied energies and is comparable to TCO or anti-reflex coating effects.

The most damaging particles in geostationary orbits are protons and electrons. The fluences depend on the orbit altitude and are highest for electrons at about 5 earth radii (10^{12} cm^{-2} y^{-1} at 1 MeV). For protons an integrated nearly isotropic and omnidirectional fluence is <10^{12} cm^{-2} y^{-1} [5]. Protons are dominant in geostationary orbits where most satellites operate. The damage in solar cells is caused mainly by non ionising energy loss (NIEL) of the incident particles [6]. This loss depends on cell material and is different for electrons and protons. The NIEL of protons is highest at energies of some keV but decreasing with energy, whereas the NIEL of electrons increases with energy becoming significant at >100 keV, see Fig. 1. The irradiation conditions

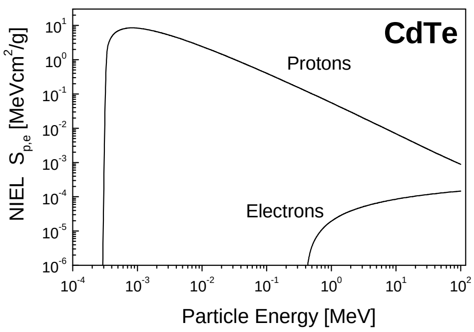

Fig. 1. The non ionisation energy loss NIEL in CdTe (by courtesy of S.Messenger, NRL, USA).

were chosen such that a substantial damage purposely occurs in order to study the damage mechanism and possible recovery in CdTe. Therefore the cells were irradiated with proton energies of 650 keV, 1 MeV and 2.2 MeV with fluences of 10^{11} cm^{-2} to 10^{14} cm^{-2}, as well as electron energies of 1 MeV and 3 MeV with fluences of $2 \cdot 10^{16}$ cm^{-2} to $8 \cdot 10^{17}$ cm^{-2}. These fluences are higher than usually applied for radiation stability measurements of solar cells in order to get to the limit of the extreme radiation resist-

ance. The proton irradiation was conducted with the PSI / ETH tandem accelerator at the Institute of Particle Physics at The ETH Zurich, the electron irradiation was performed with the DYNAMITRON electron accelerator at the Institute of Radiation Physics in collaboration with the Institute of Physical Electronics, University of Stuttgart. Before and in subsequent time intervals after the irradiation the cells were characterised using I-V (AM1.5), quantum efficiency and C-V characteristics. The cell parameters labelled as relative are normalised to their respective initial values.

Proton irradiation

The efficiencies do not change for low fluences of 10^{11} cm^{-2} and a slight increase for medium fluences is measured, as shown in Fig. 2. Only at an already high

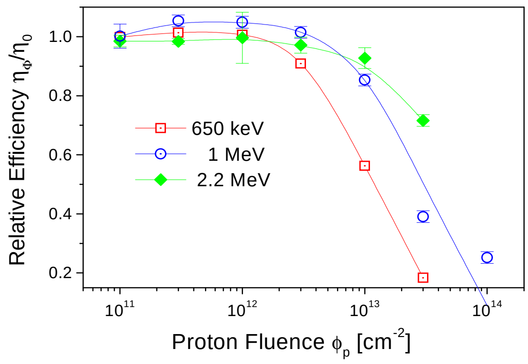

Fig. 2. Relative efficiency, i.e. efficiency after irradiation normalised to initial efficiency, *vs* the proton fluence for irradiation with different energies.

threshold fluence of 1 - 3·10^{12} cm^{-2}, a degradation onset is measurable. As expected from the NIEL, lower proton energies cause higher damage. At a fluence of 10^{13} cm^{-2} the relative efficiency of cells irradiated with 650 keV protons is still 56%, with 1 MeV protons 83% and with 2.2 MeV protons 92%. The efficiency increase for medium fluences is due to an increase in V_{OC} of up to 20 mV. At higher fluences the V_{OC} starts to decrease as a result of increased recombination centre density N_r. The decrease in efficiency is mainly caused by reduced J_{SC} at higher fluences. As verified with QE measurements, the effective diffusion length decreases due to the increase in N_r.

CdTe cells are very stable against proton irradiation since any significant damage happens only for fluences above some 10^{12} cm^{-2}. The fast damage recovery, described below, yet upgrades the stability properties.

Electron irradiation

The relative efficiencies of electron irradiated cells are shown in Fig. 3. They stay at 95 % for a high fluence of 3·10^{16} cm^{-2} and degrade down to 30 % and 10 % for 1 Mev and 3 MeV, respectively at a fluence of 3·10^{17} cm^{-2}. The performance degradation is dominated by the degradation of J_{SC}. Fill factor and V_{OC} are only little affected and stay both above 85 % (relative) for all applied irradiation conditions. In case of 1 MeV electron irradiation the loss in V_{OC} is even less than 3 %. In contrast to proton irradiation no increase of any cell parameter was measured. By an extrapolation of the damage characteristics the onset of degradation fluences is almost 10^{16} cm^{-2}.

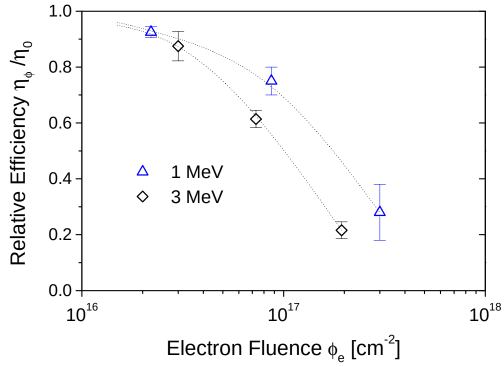

Fig. 3. Relative efficiency of 1 MeV and 3 MeV electron irradiated cells *vs* the fluence.

As mentioned earlier the experiments had to be conducted with soda-lime glass substrates, since radiation resistant glass was not available. Radiation induced glass browning influenced the current measurement, however all data presented in this paper are corrected for any transmission loss as previously reported [2].

THE DISPLACEMENT DAMAGE DOSE APPROACH

For a reliable degradation prediction it is necessary to know the degradation characteristics for each particle and energy over a sufficient fluence range. However a description of one general degradation characteristic can be obtained by applying the displacement damage dose (Dd) formalism [6]. In a first step the particle fluences $\Phi_{p,e}(E)$ are converted to displacement damage doses $D_{p,e}(E)$ using the NIEL $S_{p,e}(E)$ that contains the material specific information

$$D_{p,e}(E) = \Phi_{p,e}(E) \cdot S_{p,e}(E) \qquad (1)$$

The indices p and e denote protons and electrons, respectively. In case of an energy spectrum an integral form of Eq. (1) must be used. The degradation curves for different energies and particles now coincide if plotted against the D_p and D_e, as shown in Fig. 4. As demonstrated for other materials [6] this formalism is also applicable to CdTe. To match the electron degradation curves usually a correction function for an effective D_e has to be applied, which is not the case for the tested CdTe cells [8]. With the scaling factor R_{EP} of 3.29 in our case the characteristics for electrons can be matched to the proton characteristics. The effective damage dose D_s for electrons and protons can be defined as

$$D_S = D_p + \frac{D_e}{R_{EP}} \qquad (2)$$

Relative efficiencies plotted *vs* D_S yield the general degradation characteristics as shown in Fig. 5. For any specific

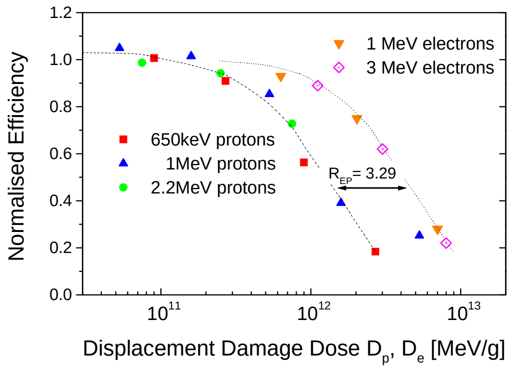

Fig. 4. Degradation curves of protons and electrons *vs* the respective displacement damage doses D_e and D_p. The correlation factor R_{EP} scales electron to proton doses.

space mission, the effective Dd can be calculated according to Eq. (2) with the proton dose D_p and the electron dose D_e, which can be received from existing algorithms [6], and the end of life (EOL) performance can be deduced from Fig. 5.

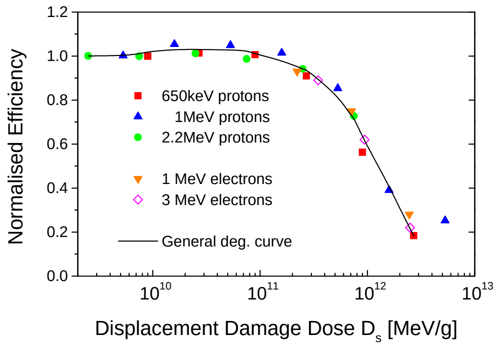

Fig. 5. Generalised degradation characteristics *vs* the displacement damage dose D_S for all particle irradiations.

A model for cell degradation due to particle damage

A Monte-Carlo simulation in ‘full collision cascade mode’, supplied by the computer program SRIM2000 [7] was applied for a more detailed study of the proton damage including spatial scattering distribution, vacancy generation, transmitted particles and recoil energies for given cell layers and energies.

The energy loss of electrons in the cell can be estimated to be a few keV, with an assumed stopping power of 2 MeV*g^{-1}*cm^2, indicating that almost all electrons are transmitted through the cell.

The transmission of protons though the cell is less than 0.5 % at 650 keV, but already higher than 99.9 % at 2.2 MeV. As shown in Fig. 6 the Monte-Carlo simulation indicates that most of the 650 keV protons are stopped in the pn-junction and CdS layer. Since the 2.2 MeV protons are mainly transmitted, the energy loss distribution is more uniform throughout the cell layers. Degradation is determined by the particle energy loss due to vacancy generation, which is much for low energy than for high energy protons as obtained from simulation. The introduced defects result in an increased recombination centre density

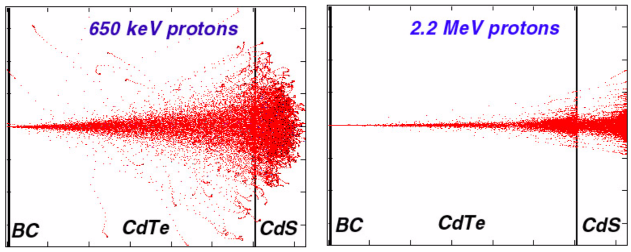

Fig. 6. Monte-Carlo simulation of proton scattering distribution in the CdTe/CdS cells [7].

N_r, which changes the cell parameters V_{OC} and J_{SC} strongly due to a modified transport. At medium proton fluences a significant increase in V_{OC} (20 mV) indicating that N_r is decreased because of recombination centres passivation. Presumably the protons are trapped as they are slowed down saturating free bonds in the absorber material, i.e. a hydrogen-passivation by ion implantation. As the passivation saturates, N_r starts to increase again by defect generation at higher fluences. This increase in N_r allows a higher current through the device, which appears to be a 'shunting' of the cell. In a first approximation this current is proportional to N_r. The logarithmic dependence of V_{OC} on current allows a precise calculation of the V_{OC} loss, as presented in detail elsewhere [8]. The rate of defect generation decreases with increasing proton energy as predicted by the SRIM simulation. The fluence threshold for maximum passivation is shifted towards higher fluences for higher energies since less defects are introduced. The increased recombination current causes a loss in J_{SC}. The introduced recombination centres decrease the effective diffusion length, which is calculated from quantum efficiency measurements [2]. Using these relations the current loss can be described mathematically [8].

COMPARISON OF DIFFERENT CELL TECHNOLOGIES

The irradiation stability of different cell technologies can be compared conveniently with the damage dose formalism since only one general curve characterises the materials. CdTe cells are compared to GaAs/Ge and CIS solar cells with data taken from literature [6], see Fig. 7. Thin films (CdTe, CIS, CIGS) show generally higher radiation hardness than monocrystalline materials (Si, GaAs). Each cell technology has a specific R_{EP} scaling D_e to D_p, therefore care has to be taken interpreting Fig. 7. While the efficiency R_{EP} of CdTe cells was determined to be 3.29 for GaAs/Ge cells a value of 2.54 is reported [6] signifying that electrons are less damaging to CdTe than to GaAs/Ge cells. Additional comparison of literature data proved that the damaging fluence onset for polycrystalline thin film cells is typically 2-3 orders of magnitude higher than for monocrystalline material. Especially CdTe cells show a sustained stability for higher doses, which is even superior to other thin film

solar cells. In case of proton irradiation the performance increases slightly for intermediate fluences. The degrada-

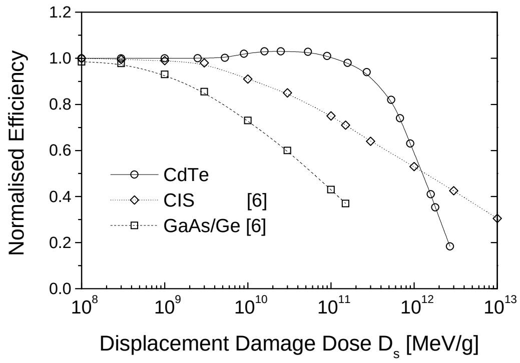

Fig. 7. Comparison of degradation characteristics of different cell technologies.

tion characteristics is somewhat steeper and meets for example the CIS curve in Fig. 7 at a dose above 10^{12} MeV/g (hardly ever reached in a space mission), which degrades performance of CIS cells to 50 % but of GaAs/Ge to below 10 % (extrapolated) of the initial value.

RECOVERY OF DEGRADED CELLS

The performance recovery of CdTe cells was studied at room temperature, however recovery will be faster at elevated temperature, because temperature influences the defect mobility and self compensation mechanisms in semiconductors. The current loss is the major degradation factor, therefore it also determines the recovery, which follows an exponential dependence

$$\frac{\eta_\Phi(t)}{\eta_0} = 1 - c_1 - c_2 \cdot \exp(-c_3 \cdot t) \qquad (3)$$

where η_0 is the initial efficiency, $\eta_\Phi(t)$ the recovered efficiency at time t, c_1 a possible residual damage, $c_1 + c_2$ the initial damage after irradiation and c_3 a time constant that determines the recovery speed, as shown in Fig. 8. The recovery mechanism depends on temperature, but only slightly on irradiation energy or fluence. The time constant c_3 is 0.058/day at room temperature, which gives a recovery half-life period of approximately 12 days. After 1 month more than 80% of the damage is recovered. During irradiation experiments in the laboratory the fluences are typically introduced in few minutes (protons) to a few hours (electrons), however the same fluences will be collected in space during years, depending on the orbit. Further the cells in space get heated to 100°C or more, strongly accelerating the performance recovery. As the recovery rate is much shorter than the damage generation rate, radiation damage in geostationary orbits will be recovered immediately resulting in excellent stability.

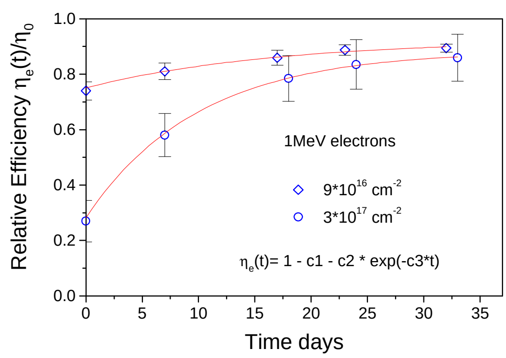

Fig. 8. Performance recovery of CdTe cells after irradiation with different electron fluences.

CONCLUSIONS

CdTe/CdS solar cells are very stable under high fluences of protons and electrons. Their radiation hardness is superior to monocrystalline cells and slightly superior to thin film cells of other materials. For space missions in the typical orbits of communications satellites no EOL degradation for CdTe solar cells is expected because of the low fluences that are below the onset of cell degradation. The recovery of CdTe/CdS solar cells is very fast and proceeds exponentially in time. Any possible irradiation damage in space is expected to be recovered immediately without causing permanent damage.

Solar cell performance degradation was successfully described with the damage dose formulation and simulation of recombination mechanisms, which explains the gain and loss in the cell parameters.

ACKNOWLEDGEMENTS

We thank S. Messenger for discussion and contribution of the NIEL data, G. Agostinelli for providing valuable ideas, U. Rau for discussion and The European Space Agency ESA for support.

REFERENCES

[1] A. Jasenek, U. Rau, *J. Appl. Phys.* **90**, 650-658 (2001).

[2] D. L. Bätzner, A. Romeo, H. Zogg, A.N. Tiwari, *17th European PVSEC*, Munich, OA9.3 (2001).

[3] A. Romeo, D. L. Bätzner, H. Zogg, A.N. Tiwari, *Mat. Res. Soc. Symp. Proc.* Vol. **668**, H3.3.1 (2001).

[4] A. Romeo, A. N. Tiwari, H. Zogg, M. Wagner, J. R. Günter, *2nd World PVSEC*, Vienna 1105-1108 (1998).

[5] G. La Roche, *Solargeneratoren für die Raumfahrt,* Vieweg (1997).

[6] S.R. Messenger, G.P. Summers, E.A. Burke, R.J. Walters, M.A. Xapsos, *Prog. in PV* **9**, 103-121 (2001).

[7] J.F. Ziegler, J.P. Biersack, U. Littmark, *The stopping and range of ions in solids,* Pergamon Press (1985).

[8] D.L. Bätzner, A. Romeo, M. Döbeli, K. Weinert, H. Zogg, A.N. Tiwari, to be published