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Effect of 8 MeV electron irradiation on the performance of CSS grown CdTe/CdS solar cells

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Abstract
The results of investigations carried out on the effect of electron irradiation on the electrical properties of CdTe/CdS solar cells prepared by close spaced sublimation (CSS) are presented in this paper. The solar cells were characterized using current–voltage (*I*–*V*) measurements under dark and air mass (AM) 1.5 illumination conditions. They were also characterized by capacitance measurements at various frequencies. The cells were exposed to graded doses of electrons up to 100 kGy. The effect of electron irradiation on the solar cell parameters such as short circuit current (I_{sc}), open circuit voltage (V_{oc}), fill factor (FF), conversion efficiency (η), saturation current (I_o) and ideality factor (n) were studied. Only small changes in the cell parameters were observed after electron irradiation. Since the observed changes in the cell parameters were not remarkable up to an electron dose of 100 kGy, CdTe/CdS solar cells seem to be stable under electron irradiation.

1. Introduction

Polycrystalline thin film CdTe solar cells are one of the important candidates for large scale photovoltaic applications because of their low cost, high efficiency and stable performance [1]. CdTe/CdS solar cells have been used for large area terrestrial applications [2]. CdTe has the advantage of a nearly ideal band gap (1.45 eV) for absorbing the maximum amount of solar spectrum with minimal losses. Being a direct band gap material, the absorption coefficient is large enough ($>10^5$ cm^{-1}) to require only 1–2 μm (compared to $\sim$10 μm for Si) of the absorber material. Compared to typically encountered grain sizes in thin films, CdTe has a short absorption length resulting in reduced recombination at grain boundaries, a major problem encountered in other polycrystalline materials. As a result, a large fraction of the carriers are generated within the depletion layer during illumination, allowing more efficient collection [3]. The photovoltaic devices fabricated from polycrystalline CdTe show higher efficiency than single crystalline CdTe solar cells. Also, devices fabricated from II–VI compounds are less sensitive to grain boundaries than solar cells made from III–V or group IV materials [4].

Thin films of CdTe and CdS can be grown by a variety of deposition techniques such as spray-pyrolysis (SP), vacuum evaporation (VE), chemical bath deposition (CBD), electrodeposition (ED), radio frequency (RF) sputtering, close spaced sublimation (CSS), screen printing (SP) and metal organic chemical vapor deposition (MOCVD) [3, 5–9]. CdTe solar cells with an efficiency of 10% to 16% have been developed in the superstrate configuration by a variety of deposition techniques [3]. However, the best CdTe-based thin film solar cells have been fabricated using the CSS method and efficiencies close to 16.5% have been reported for thin film solar cells fabricated using this technique [10].

It is possible to deposit CdTe on thin metallic or polymer substrates to yield high specific power (ratio of output power to weight) CdTe/CdS solar cells. This will make it an attractive candidate for space applications where solar cells of high specific power are preferred. One of the important requirements for space or satellite applications, other than high specific power and efficiency, is the stability against particle irradiation. In particular, high energy electrons and protons are of major concern in space applications. The high energy particles incident on crystalline material can create dislocations and/or displace atoms from their lattice sites, creating electronic traps in the band gap. This in turn will reduce the carrier concentration, mobility and lifetime, which result in a gradual deterioration in solar cell performance over a period of time [11, 12]. Therefore, it is essential to investigate and understand the physical aspects and fundamental limitations of these solar cells under irradiation. The stability of CdTe/CdS solar cells against high energy electron irradiation is investigated and the results are presented.

2. Experimental section

The CdTe/CdS solar cells used in the present work were prepared by CSS on soda lime glass substrates coated with cadmium stannate (cadmium tin oxide—CTO) and zinc tin oxide (ZTO). The typical structure of the cell is glass/CTO/ZTO/CdS/CdTe/graphite. The area of the solar cells used was 1.158 cm^2. The current–voltage characteristics of solar cells in dark and under illumination were measured at room temperature using a computer-controlled Keithley 236 source/measure unit. Simulated solar cell illumination under AM 1.5 condition was provided by a tungsten–halogen lamp at an intensity of 100 mW cm^{-2}. The intensity of the light source was adjusted to 100 mW cm^{-2} using a light intensity meter (CEL Suryamapi model SM 201). Capacitance measurements of the devices at various frequencies were made under dark condition using a Keithley 3322 LCZ meter. Solar cells were irradiated at room temperature with 8 MeV electrons at various doses ranging from 0.1 kGy to 100 kGy using a Microtron accelerator. The doses were estimated using a Fricke dosimeter. The cells were irradiated from the back contact side to minimize the darkening of glass due to electron irradiation.

3. Results and discussion

Current–voltage (*I*–*V*) characteristics of CdTe/CdS solar cells under AM 1.5 illumination condition, irradiated with 8 MeV electrons are shown in figure 1.

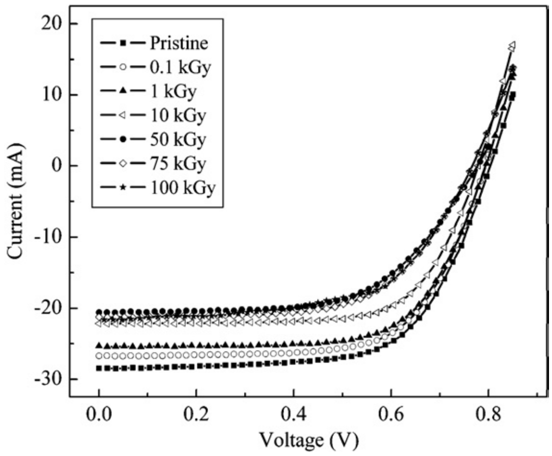

Figure 1. *I*–*V* characteristics of the CdS/CdTe solar cell at various doses of 8 MeV electrons under AM 1.5 illumination condition.

In a solar cell, the junction current is approximated by [13, 14]

$$\mathrm{I} = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] - I_\mathrm{L} \tag{1}$$

where I_0 denotes the dark saturation current of the CdS/CdTe junction, n is the diode ideality factor and I_L is the photo generated current in the CdTe layer.

Short circuit current density J_{sc} for solar cells is dependent on band-gap energy E_g, optical absorption coefficient α and minority carrier diffusion length L of the solar cell materials [15].

The open circuit voltage, V_{oc}, of solar cells is mainly dependent on band-gap energy and is related to the diode saturation current by [16]

$$V_{oc} = \left(\frac{nkT}{q}\right)\ln\left[\left(\frac{I_{sc}}{I_0}\right) + 1\right]. \tag{2}$$

The fill factor (FF) of a solar cell is defined as [14]

$$FF = \frac{I_m \cdot V_m}{I_{sc} \cdot V_{oc}} \tag{3}$$

where I_m and V_m are the current and voltage at the maximum power point on the *I*–*V* curve.

The fill factor of a solar cell is a function of diode ideality factor n, open circuit voltage V_{oc}, series resistance R_s and the shunt resistance R_{sh} [17].

The energy conversion efficiency of a solar cell can be written as [14]

$$\eta = \frac{I_m \cdot V_m}{P_{in} \cdot A} \tag{4}$$

where P_{in} is the incident solar power density and A is the area of the solar cell.

From the *I*–*V* characteristics of the cells, optoelectronic parameters such as short-circuit current I_{sc}, open circuit voltage V_{oc}, power conversion efficiency η and fill factor FF were determined. The parameters for the unirradiated CdTe/CdS solar cell under AM 1.5 illumination condition are $\eta = 13.01\%$, $V_{oc} = 800$ mV, $I_{sc} = 28.37$ mA and FF = 66.43%.

Figure 2 shows the changes in the solar cell parameters, normalized to their values prior to irradiation as a function of electron dose.

From the figure, it can be seen that there is a marked reduction in the values of short circuit current and efficiency after irradiation. Only a small reduction in the values of V_{oc} and FF were observed after irradiation. The overall radiation response is primarily controlled by the degradation of I_{sc}, which in turn decreases the efficiency of the cells as a function of electron dose. The radiation-induced defects are more likely to act as recombination centers. It is known that for low irradiation doses, the degradation is due to the introduction of non-radiative recombination centers which decreases the

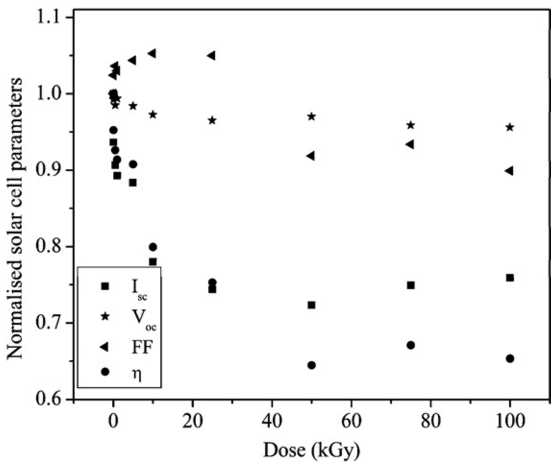

Figure 2. Normalized cell parameters of the CdTe/CdS solar cell under AM 1.5 illumination condition as a function of electron dose.

minority carrier diffusion length [18]. An increase in the values of FF was observed up to a dose of 25 kGy. The normalized values of FF, V_{oc}, I_{sc} and efficiency remain at 90%, 96%, 76% and 65% respectively after irradiation at a dose of 100 kGy. It was observed that the glass substrate of the solar cell turned brown after irradiation and the darkening increased with electron dose. Irradiation induces not only displacement damage, but also ionization damage in glass, giving rise to color centers. This results in the increased absorption of photons in the glass itself. Therefore, the decreased efficiency exhibited by the CdTe solar cells prepared on soda lime glass substrates after irrdaition may be mainly due to the effect of radiation on glass. The use of space quality CeO_2 doped glass, which remains transparent even after irradiation, would overcome this problem.

The *I–V* characteristics of solar cells in the dark are as important as their characteristics in the light, since the behavior of the cells under dark condition largely determines the voltage output and fill factor.

The forward *I–V* characteristics follow the double exponential law [5, 19]:

$$I = I_{01}\exp\left(\frac{qV}{n_1\kappa\,\mathrm{T}}\right) + I_{02}\exp\left(\frac{qV}{n_2\kappa\,\mathrm{T}}\right) \qquad (5)$$

where I_{01} and I_{02} are the saturation currents, $n_1$and n_2 are the ideality factors, k is the Boltzmann constant, q is the charge and T is the temperature.

The first term on the right-hand side of the equation dominates at large forward bias voltages ($V > 0.4$ V) and the second term at lower bias voltages. Figures 3(*a*) and (*b*) show the forward and reverse dark *I–V* characteristics respectively of 8 MeV electron irradiated CdTe/CdS solar cells.

The shunt resistance was determined from the slope of the reverse current in a linear range [20]. The device series resistance in the dark was determined from the inverse of the slope of *I–V* characteristics in the higher forward bias region [20, 21]. The values of I_{01}, I_{02}, n_1 and n_2 are determined from the forward dark *I–V* characteristics [20, 22] as a function of dose and summarized in table 1.

From the table, it can be seen that there is no significant change in the values of I_{01} and n_1 after irradiation. An increase

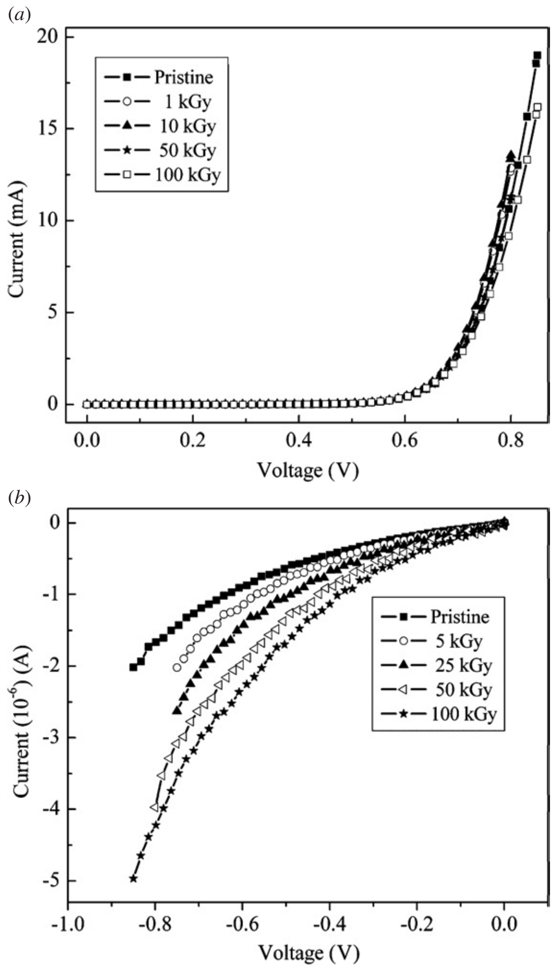

Figure 3. (*a*) Forward *I–V* characteristics of the CdS/CdTe solar cell under dark condition at various doses of 8 MeV electrons. (*b*) Reverse *I–V* characteristics of the CdS/CdTe solar cell under dark condition at various doses of 8 MeV electrons.

Table 1. The values of the cell parameters estimated from the forward dark *I–V* characteristics at different doses.

Dose (kGy)	I_{01} (10^{-9} A)	n_1	I_{02} (10^{-8} A)	n_2
0	2.65	1.91	7.95	3.13
0.5	1.54	1.81	8.68	3.12
1	1.76	1.83	8.15	3.07
5	1.87	1.84	8.63	3.02
10	1.59	1.81	8.79	3.10
25	1.87	1.84	11.8	3.28
50	1.77	1.84	11.1	3.22
100	1.87	1.84	13.8	3.37

in the values of I_{02} was observed after irradiation, which becomes significant above 10 kGy. An increase in the values of n_2 was also observed above a dose of 10 kGy. The increase in I_{02} means that the concentration of recombination centers in the space charge region becomes higher and consequently the carrier life time decreases [23].

Figure 4 shows the series resistance of the solar cells under the dark condition as a function of dose.

It can be observed from the figure that the series resistance decreases with dose up to 10 kGy, and then it increases up to a dose of 100 kGy. The increase in the series resistance might

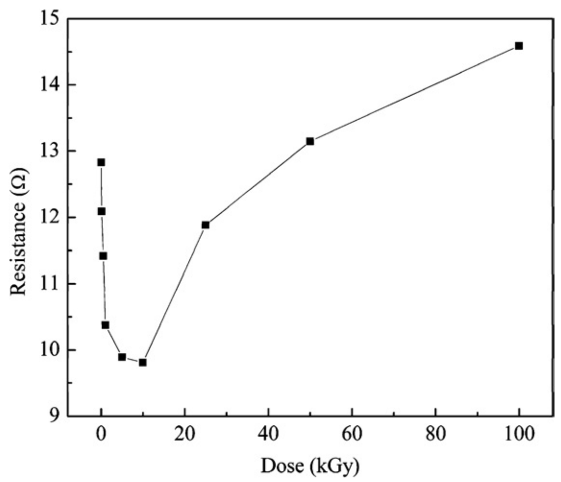

Figure 4. Series resistance of the CdTe/CdS solar cell as a function of dose.

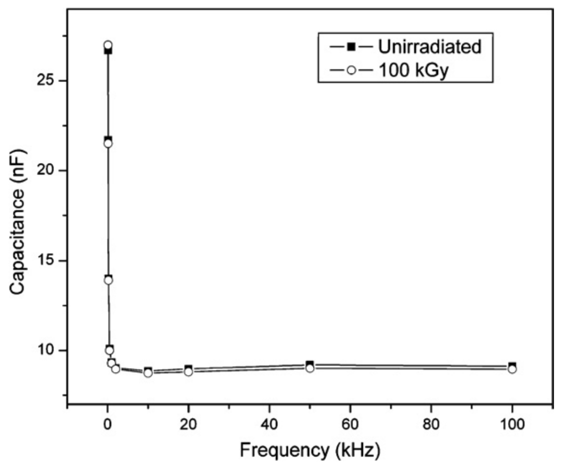

Figure 5. Variation of capacitance with frequency at 1 V for an unirradiated and electron irradiated CdTe/CdS solar cell.

be a result of carrier removal. Degradation in the solar cell properties were observed only above 10 kGy (table 1 and figure 4). The observed degradation in the solar cell parameters may be due to the decrease in the minority carrier diffusion length due to the introduction of radiation-induced defects.

Figure 5 shows the variation of capacitance with frequency, at 1 V, for the irradiated CdTe/CdS solar cells, measured under dark condition.

As the frequency increases the capacitance decreases and reaches a steady value at frequencies above 1 kHz. Increasing the frequency from 100 Hz to 100 kHz causes a decrease in capacitance from 26.7 to 9.13 nF for an unirradiated sample and 26.7 to 8.65 nF for the sample irradiated at a dose of 100 kGy. The decrease in capacitance with frequency indicates the presence of relatively slow deep levels at or near the CdTe/CdS interface [24]. The difference in the decrease in capacitance with frequency for unirradiated and irradiated samples is negligible, indicating that the irradiation has not contributed significantly to the concentration of deep level defects at the interface.

Radiation exposure rates in the laboratory are usually many orders of magnitude greater than the natural space radiation rates. In space, the damage and annealing processes occur simultaneously with the annealing rate much closer to the damage rate than in the laboratory [25]. Therefore, degradation of CdTe/CdS solar cells will be much lesser in space environment than the degradation observed in the laboratory. Hence, one can infer that the CSS grown CdTe/CdS thin film solar cells are stable against electron irradiation and are better suited for space applications.

4. Conclusion

The following conclusions can be drawn from the studies on the effect of 8 MeV electron irradiation on the properties of CdTe/CdS solar cells under dark and illumination conditions.

(1) A small reduction in the values of short circuit current, open circuit voltage, fill factor and efficiency of the devices was found after irradiation with electrons. The reduction observed in I_{sc} as well as efficiency is attributed to the darkening of the glass substrate due to radiation damage.
(2) An increase in the values of I_{02} and n_2 was observed after irradiation, the increase being significant after an electron dose of 10 kGy.
(3) Capacitance variation with frequency indicates that irradiation does not contribute significantly to the increase of deep level defects in the interface.
(4) The CSS grown CdTe/CdS thin film solar cells are stable against electron irradiation and are better suited for space applications

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