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Joseph J. Loferski

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HAL Id: jpa-00242721
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Submitted on 1 Jan 1966

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THE EFFECTS OF ELECTRON AND PROTON IRRADIATION ON THIN FILM SOLAR CELLS (1)

By JOSEPH J. LOFERSKI,
Division of Engineering Brown University, Providence, R. I., U. S. A.

Résumé. — On passe en revue les raisons de l'intérêt porté aux effets de l'irradiation sur les cellules solaires. L'étude de ces effets : a) permet d'estimer la durée de vie utile des cellules dans les champs de radiation spatiaux, b) renseigne sur la nature de l'effet photovoltaïque dans chaque espèce de cellule, et c) peut fournir des données fondamentales sur l'effet de l'irradiation sur le matériau constituant. On indique les détériorations par les radiations dans GaAs, CdS et CdTe, ainsi que les renseignements publiés sur la détérioration par les radiations des cellules à couches minces. D'après les publications, seuls les protons agissent pour détériorer les cellules. Cette observation concorde, en gros, avec la théorie de la détérioration par les radiations.

Abstract. — The reasons for interest in irradiation effects on solar cells are reviewed. It is shown that studies of these effects (a) permit estimates of the useful life of solar cells in space radiation fields, (b) provide information about the nature of the photovoltaic effect in specific kinds of cells and (c) can lead to fundamental information about radiation effects in the parent material. Studies of radiation damage in GaAs, CdS and CdTe are reviewed. Published data on damage to thin film cells is also reviewed. According to the literature, only protons have been shown to produce damage in the cells. This observation is shown to be in rough agreement with radiation damage theory.

Introduction. — Considerable effort has been devoted to investigations of the effects of high energy radiation on solar cells. The main reason for such research is the fact that the principal use for photovoltaic cells thus far has been to provide power on space vehicles intended for long periods of operation in an environment which includes the high energy electrons and protons of the earth's radiation "belts" [1, 2].

The electrons in these radiation belts exhibit energies up to about 2 MeV with a maximum flux of about $10^7$ electrons/cm²s. The proton energies range from the lowest energies measured by detectors on space vehicles (a few keV) up to energies of tens of BeV. The proton flux increases exponentially on the low energy end of the scale. Typical fluxes reported have been about $3 \times 10^8$ pro-
tons/cm² with energies between 0.5 and 1.0 MeV and about \(10^{15}\) protons/cm²s with energies between 1 and 80 MeV. Often satellites are expected to function for periods as long as ten years. If a satellite orbit were confined to regions of maximum flux levels, the integrated flux over such a ten year period would be about \(4 \times 10^{15}\) electrons/cm² with an effective energy of about 1 MeV and \(4 \times 10^{13}\) protons/cm² with energies between 1 and 80 MeV. In addition the satellite would have been irradiated by about \(10^{17}\) protons/cm² with energies between 0.5 and 1.0 MeV. To be sure it is easy to shield against these low energy protons but their presence must still be taken into account. All indications are that the changes produced in the cells are cumulative and therefore it is prudent to assume that the changes in cell characteristics which will result after 10 years are about the same as those which would result from an equivalent integrated flux delivered at a much higher rate.

Measurement of such changes have been made on silicon cells and the dependence of their sensitivity to radiation has been studied as a function of various material and device parameters. One result of these studies was the discovery that the useful life of cells in which the thin diffused skin was made by diffusing an n-type impurity into a p-type wafer was about ten times as long as that of cells made the other way around [3]. It should be emphasized that the rates of degradation are such that it is possible to design silicon photovoltaic systems which should operate successfully for periods up to ten years. Therefore, when some other kind of photovoltaic cell is being considered for space applications it is imperative to examine the effects of irradiation on these cells and to compare their performance to that of the silicon cells.

Another reason for studying the effects of radiation on photovoltaic cells is that such studies provide experimental data which can be used to test the models devised to explain the behavior of such cells. The radiation induces changes in various parameters of the cell and from these changes it is possible to deduce the significance of the roles played by these various parameters. For example, radiation induced changes can be used to determine the depth of the active region of a cell by correlating changes in spectral response with changes in diffusion length. Irradiation by protons of very low energy and, therefore, low range, can help to establish relative contributions to the photovoltaic effect from various regions of the cells. Irradiation by electrons whose energy is too low to produce bulk damage in the cells can help to evaluate the role played by surface effects on the properties of cells. By careful interpretation of radiation experiments, it should be possible to distinguish between collection mechanisms which demand large minority carrier lifetimes and those which depend on built-in electric fields, i.e. on space charge regions.

A third reason for studying these radiation effects is the possibility of extracting fundamental information about the radiation damage process in the semiconductors from which the cells are made. For example, the first accurate measurements of radiation damage thresholds in Ge, Si, GaAs and InP involved measurement of the changes of photovoltage in photovoltaic cells made from these materials. Annealing of radiation damage can be studied by monitoring the annealing of solar cell parameters which in turn can be related to more fundamental parameters of the material.

It is clear that there is adequate motivation for studying the effects of radiation damage on thin film photovoltaic cells. In the balance of this paper, we will review the results of radiation damage studies on single crystal solar cells in order to indicate the radiation tolerance which thin film cells must equal or exceed and to show how these studies have fitted in with the model of the silicon cell. Secondly we shall review the information about radiation damage in those materials which are the principal candidates for thin film cells, namely, GaAs, CdS and CdTe. Finally, we shall review the meagre information available about the effects of radiation on thin film cells and we shall discuss the implications of the experiments.

**Effects of radiation on silicon photovoltaic cells.**

— When silicon crystals are irradiated by electrons, protons or neutrons, the primary defects, namely, vacancies and interstitial atoms tend to form complexes with chemical impurities present in the crystal in minute amounts. Numerous energy levels are associated with these complexes; for example recently Konopleva et al. have found as many as twelve energy levels associated with defects resulting from "annealing" of "primary" damage in neutron irradiated silicon, the annealing having been performed at room temperature [4]. Vavilov et al. who studied the defects resulting from electron irradiation found numerous discrete levels after annealing [5]. Both shallow and deep levels are produced. The details of the level scheme are not essential to our discussion. The net effect is to increase the number of recombination centers (and thus reduce minority carrier lifetime \(\tau\)) and to introduce carrier removal sites which cause an increase of resistivity in both n- and p-silicon. For silicon of the resistivity and quality required for solar cells, it is found that the lifetime \(\tau\) will have decreased by one or two orders of magnitude before any observable change will have occurred in the conductivity. This is because \(\tau\) is controlled by about \(10^{12}\) defects per cc whereas \(\sigma\) in material of the resistivity range used in cells is determined by \(10^{16}\) to \(10^{16}\) impurities per cc.

In order to predict the behavior of a silicon cell
subjected to various types and energies of radiation, it is necessary to study the operation of such cells. They consist of a thin region (\(\sim 1 \mu\) thick) onto which the light is incident, produced by diffusion of an appropriate impurity into a wafer whose resistivity lies between 0.5 and 1.0 ohm cm. Studies of spectral response and of the electron voltaic effect have shown that the active region of these silicon cells, where the active region is defined as the sum of the minority carrier diffusion lengths on the two sides of the cell, is of the order of 100 \(\mu\). Since the diffused skin is \(\sim 1 \mu\), this means that the conversion of optical energy into electrical energy occurs mainly in the base, or long diffusion length region of the cell. Changes in this diffusion length produced by radiation will be reflected in reductions in power output of the cells. On the other hand, it is known that the thin diffused region has a very short diffusion length (< 1 \(\mu\)) since the fabrication of blue-sensitive photovoltaic cells requires that the junction depth be less than 1 \(\mu\).

Radiation damage studies have supported this model of the single crystal photovoltaic cell. One can expect three categories of damage behavior. First of all, if the range of the particles is greater than the thickness of the active region and if the particles are of sufficient energy to produce displacements, the base diffusion length will decrease as a result of the irradiation. This reduction manifests itself in a reduction of red response of the cells. If the current-voltage \((I-V)\) characteristics of the cell exposed to sunlight or its equivalent are observed after successively higher irradiations, it is found that the short circuit current \(I_s\) of the cell decreases rapidly with increasing flux while the open circuit voltage \(V_{oc}\) decreases more slowly. Such a behavior is consistent with the following considerations. If the absorption constant of the light \(\alpha \ll 1/L\) where \(L\) is the diffusion length, then \(I_s \propto L\). Now \(L^2 = D\tau \) so \(I_s \propto \tau\). Furthermore \(\tau\) is inversely proportional to the concentration of recombination centers \(N_v\) which for low flux rates can be assumed to be proportional to the integrated flux \(\Phi\) received by the cell. It can be shown that [6]

\[
\frac{I_{so}}{I_s} \propto \Phi
\]  

(1)

where \(I_{so}\) is the initial value of \(I_s\).

On the other hand, if \(\alpha > 1/L\), then solving the ambipolar diffusion equation for this situation leads to the result that

\[
[I_{so} - I_s]^{2} \propto \Phi.
\]  

(2)

If the cell is exposed to light of mixed wavelengths, its behavior will lie between these limits and this agrees with the observations. The reason for the slower degradation of \(V_{oc}\) is that

\[
V_{oc} \propto \ln \frac{I_s}{I_0} \propto \ln \tau
\]  

(3)

where \(I_0\) is the reverse saturation current of the junction. It is reasonable to expect that if the irradiation is allowed to proceed, the resistivity of the base material will eventually begin to change. When this happens, the barrier height between the \(n\) and \(p\) regions will begin to decrease and \(V_{oc}\) should change more rapidly than would be permitted by its dependence on \(\tau\). Recent experiments with penetrating particles have led to a number of interesting results. It was shown by Flicker et al. that the electron bombardment radiation damage thresholds of \(n\)- and \(p\)-type silicon differ by a substantial amount i.e. 150 keV in \(n\)-Si and 220 keV \(p\)-Si and that the shape of the introduction rates are different. The experiments of Carter and Downing confirmed this difference in shape of the introduction rate curves and extended the measurements to 20 MeV. They showed that the Mott-Rutherford scattering equation made a reasonably good fit to the \(n\)-Si data up to 20 MeV whereas it was extremely poor in the case of \(p\)-Si. Recently Flicker and Patterson calculated the divacancy production rate in silicon and showed that the resulting curve fitted the experimental data for \(p\)-Si extremely well over the energy range 0.250 to 20 MeV. These experiments support the view that the formation of stable defects which affect lifetime in \(n\)-Si begins with single vacancy-interstitial pairs whereas lifetime controlling stable defects in \(p\)-Si require the divacancy as the basic building block [7] [8].

Another interesting result of the experiments with penetrating particles was the discovery by Smits et al. [9] that whereas protons of energy 10 to 100 MeV produced damage at a rate that was in agreement with predictions based on Rutherford scattering of protons by atoms i.e. \(L\) should be proportional to \(E_p^{1/2}\) where \(E_p\) is the proton energy, protons of higher energy introduced defects at a considerably higher rate than that predicted by Rutherford scattering. The second category of radiation damage behavior is that induced by particles whose range is much less than the dimensions of the active region of the cells. The particles must of course be capable of producing damage at reasonable rates. This requirement eliminates electrons as particles for production of this type of damage but leaves low energy (< 1 MeV) charged particles. An example of the phenomena encountered in this case is provided in the recently published paper of Wysocki et al. which describes the results of irradiating \(p/n\) and \(n/p\) Si solar cells with protons of energies between 185 and 530 keV. Protons of these ener-
gies have ranges between 1.2 and 4.8 μ in Si. It was found that $V_{oc}$ decreased far more rapidly with $I_a$ than did $I_s$. Furthermore, the behavior of $I_s$ exhibited a peculiar behavior. Its value decreased very slightly during the early stages of irradiation but it dropped rapidly after attainment of a certain integrated flux. This flux was a function of proton energy; the lower the energy of the protons, the higher the flux at which this rapid decrease began. This behavior was explained by the observation that these low energy protons changed $L$ in close proximity to the junction, i.e. within a few microns of the junction, while $L$ remained unchanged throughout most of the active region. The "transmission" coefficient of a low $L$ region near the junction for carriers produced deeper in the active region can be calculated. The transmission turns out to be surprisingly high until the value of $L$ has dropped to an exceedingly low value at which point a rapid decrease of short circuit current should occur. Furthermore since $V_{oc}$ depends on $I_a$ close to the junction, the lowered value of $L$ in this region has a strong effect on $L$. We have extended these experiments to protons of even lower energies like 25 keV; their range is less than 0.5 μ so that they are stopped in the diffused skin. Such low range protons can produce a surprisingly substantial reduction in $I_a$. The amount of this reduction yields an estimate of the contribution to the photovoltaic effect from this diffused skin region. It was found that for commercial 10% efficient $n/p$ Si cells, 25 keV protons removed about 30% of the power produced by a cell exposed to sunlight. In summary, low energy protons can be used to probe various depths of the photovoltaic cell and the results of such bombardment experiments ought to yield information which should prove useful in elucidating the mechanism of the photovoltaic effect in the irradiated cells.

The third category of radiation damage behavior is that encountered when the cells are exposed to radiation which cannot produce bulk displacements. This means low energy electrons (for Si, this means $E < 150$ keV) or certain other ionizing radiations (X-rays, γ-rays, u-v). Very little work has been reported with radiation of this kind. At Brown University, R. F. Santopietro and Loferksi studied the effects of sub-threshold (<150 keV) electrons on the surface recombination velocity of silicon solar cells. It was concluded that low energy electron bombardment increased $s$ on the surface of a $p/n$ Si cell whereas it decreased $s$ for an $n/p$ Si cell. The changes amounted to about 5% of the short circuit current produced by sunlight but to large changes in the response to strongly absorbed light (3 600 Å). Such low energy electron irradiation helps to assess the role of the surface in the behavior of a photovoltaic cell. Cells which have a larger surface to volume ratio than do single crystal cells would seem to be likely candidates for high sensitivity to such ionizing radiation.

To summarize this section, the effects of penetrating, short range and ionizing radiation on Si photovoltaic cells have been reviewed. The possibility of using these various kinds of radiation to test models of photovoltaic cells was emphasized.

Effects of radiation on GaAs, CdS and CdTe. —

The amount of information on the effects of radiation on the materials used in thin film photovoltaic cells is not very extensive. First consider the case of GaAs. The threshold for radiation damage by electrons has been measured in this material. The parameter involved was the short circuit current of a photovoltaic cell. As we have already pointed out, $I_s$ is dependent on minority carrier lifetime. Bauerlein reported observing two thresholds for damage in GaAs one at 233 keV and another at 256 keV [11]. He attributes the first of these to the energy needed to displace a gallium atom and the second to the displacement threshold of the heavier arsenic atom. Experiments by Loferksi and Wu based on observations of changes in the recombination radiation spectra (which also depend on minority carrier lifetime) of GaAs crystals have led to the conclusions that the threshold for damage is about 290 keV [12]. Only one threshold was observed in the recombination radiation experiments. The reason for the difference between these two experimental threshold determinations is not known at this time, but in any event the threshold lies below 300 keV.

Auckerman studied the effects of gamma and proton bombardment on the electrical conductivity of GaAs [13]. He found that the material approached intrinsic carrier concentrations as irradiation proceeded. It is reasonable to assume that electron and proton bombarded gallium arsenide will experience similar changes in resistivity, i.e. it will tend to become intrinsic. This was confirmed in subsequent experiments by Vitovskii et al. [14], who studied the effects of 1 MeV electron bombardment on GaAs single crystals. In a more recent paper Vodop'yanov and Kurdiani [15] studied effects of fast neutron bombardment on GaAs crystals. In agreement with previous authors, they found that the resistivity increased with increasing flux. They also reported that annealing returned the carrier concentration to pre-irradiation values, but the mobility remained low. In their samples, the mobility prior to irradiation was typically $3 \times 10^{19}$ cm$^2$/Vs at 300 °K whereas after irradiation by about $10^{19}$ neutrons/cm$^2$ and subsequent annealing, the mobility was 34 cm$^2$/Vs.

Threshold determination in CdS have been performed by Kulp [16] and Kulp and Kelley [17]. In these experiments changes in recombination radiation spectra were used as the damage index. The
procedure consisted of selecting CdS crystal which had various luminescence spectra. When a crystal lacking a red luminescence band was irradiated by electrons whose energy exceeded 115 eV, a new red luminescence band manifested itself in the cathodoluminescence spectrum. Companion experiments showed that the introduction of excess sulfur into crystals lacking the red luminescence led to the appearance of the red band in the material. From these experiments, Kulp concluded that interstitial sulfur was responsible for the red luminescence and, therefore, the threshold for displacement of sulfur was identified with the 115 keV threshold for this process. This corresponds to 8.7 eV transferred to the sulfur atom. The experiments were performed at 300 °K.

In a second group of experiments it was found that two new bands appeared in the spectrum of pure CdS crystals irradiated at 77 °K. With the help of parallel experiments involving the introduction of interstitial Cd into such crystals, it was established that the new bands involved interstitial Cd and Cd vacancies in CdS. Kulp found that $2 \times 10^{16}$ el/cm$^2$ of energy 300 keV caused a factor of two change in the intensity of these bands. Note, however, that these experiments were performed at 77 °K. Room temperature experiments by Kulp showed a different behavior, but changes in the luminescence spectrum were also observed at 300 °K. In this case, it was found that $3 \times 10^{17}$ e/cm$^2$ of 320 keV energy produced readily observable changes in the luminescence spectrum. The energy required to displace the cadmium atom amounted to 7.3 eV as contrasted to 8.7 eV required to displace sulfur atoms. From these experiments one concludes that electrons of energy in excess of 115 keV can cause displacements of at least one species of the ions comprising the CdS crystal and that 300 keV electrons can displace both species of atoms.

Unfortunately, little data on changes of conductivity of CdS during irradiation has been published. According to Woodbury and Aven, F-doped and Cl-doped CdS exhibited an increase in resistivity when irradiated by 1.5 MeV electrons, i.e. the Fermi level moves toward the middle of the forbidden energy gap [18]. However, they found that an In-doped sample exhibited a decrease in resistivity during irradiation.

In the case of CdTe, no radiation damage threshold measurements have as yet been reported. From the behavior of CdS, it would be reasonable to assume that the energy needed to displace the Cd and Te atoms ought to be about 8 eV for each of them. This would mean a damage threshold somewhat in excess of 300 keV for CdTe. Auckerman reported that neutron bombardment changes p-CdTe into n-CdTe. On the other hand, Woodbury and Aven reported that the carrier concentration in n-CdTe decreased when the crystals were irradiated by 1.5 MeV electrons. Of course these two pieces of information are not necessarily in conflict, since neither author indicates the final value of the Fermi level after long irradiation. Unfortunately the authors of these papers did not indicate how large a flux is needed to produce a specified change in $\rho$.

**Effects of proton and electron bombardment on thin film cells.** — Very little data has appeared in the literature on the effects of radiation on thin film solar cells. The principal sources of information on this topic are the "Proceedings of the Photovoltaic Specialists Conferences " of 1963, 1964 and 1965. Even in these publications, there is very little information relevant to this topic. Usually, the authors have been concerned with demonstrating that thin film cells are far more radiation resistant than single crystal cells. It had even become fashionable to publish curves which show some parameter of a silicon or gallium arsenide cell as a function of flux and to plot the same parameter for thin film cells on the diagrams. In general, the thin film cells do not exhibit any degradation whereas the silicon and gallium arsenide cells exhibit large decays. This sort of comparison may in fact be meaningless, since the pre-irradiation solar energy conversion efficiencies of the thin film cells used in these studies have been about 2 to 3 % whereas those of the single crystal cells were 10 % or more. If one were to compare the thin film cells to low efficiency single crystal cells, it is possible that much of the "superiority" of the thin film cells might melt away. Furthermore, it should be pointed out that the radiation damage studies have often been conducted on cells covered by various kinds of plastic encapsulants. In some instance where "damage" was observed, it depended only on the kind of encapsulant used. This was true in the case of electron irradiations reported by H. W. Brandhorst and R. E. Hart [19]. They irradiated a number of samples with 0.6, 1.0 and 2.5 MeV electrons up to a maximum dose of about $10^{17}$ el/cm$^2$. Cells encapsulated in Tedlar and H-Film did not exhibit any degradation whereas cells encapsulated in Mylar decayed ; the rate of decay was independent of electron energy.

These same authors reported results of irradiation by protons of 2, 5, 7 and 10 MeV for doses up to $10^{14}$ per cm$^2$. The short circuit current $I_s$ and open circuit voltage $V_{oc}$ each decreased by about 10 % after the cells had been exposed to about $10^{14}$ protons per cm$^2$. The damage was independent of plastic encapsulant. Furthermore, the ranges of these protons (greater than 100 $\mu$ for all energies) was larger than the thickness of the plastic. This encourages the view that their "damage" was characteristic of the CdS. However, the lack of a
dependence on energy of the bombarding particles raises questions about such an interpretation.

More recently Hui and Corra [20] described low-energy proton bombardment of bare CdS cells whose maximum efficiencies were between 3 and 4 %. They used protons of three energies 50, 100 and 400 keV supplied by the Van de Graaff machine at Brown University. The ranges of these protons in CdS are about 0.8, 1.2 and 4 μ respectively, i.e. the protons were stopped within the cadmium sulfide. They found that the degradation of both $I_s$ and $V_{oc}$ is energy dependent; the degradation associated with 50 keV proton irradiation is smaller than that associated with either 100 or 400 keV protons. A flux of $10^{18}$ protons/cm$^2$ of energy 100 keV caused a reduction of 20 % in $I_s$ and 20 % reduction in $V_{oc}$. This is to be contrasted with the previously reported degradation of encapsulated CdS cells irradiated by 2, 5, 7 and 10 MeV protons. In that case, the response dropped about 10 % after exposure to $10^{15}$ protons/cm$^2$. Of course, the cells studied by Hui and Corra were of a later generation and higher efficiency than those studied by Brandhorst and Hart. Furthermore, the low energy proton experiments were performed on unencapsulated cells, so that in general it is difficult to make any significant conclusions from comparison of the two sets of data.

Recent experiments at Brown University were aimed at examining the effects of low energy electrons on the properties of commercial CdS (2) cells which had no plastic encapsulant. These had sunlight conversion efficiencies between 3 and 4 %. They were irradiated in vacuum and their $I-V$ characteristics were measured after exposure to various integrated fluxes of electrons. It was found that no change in characteristics of these cells was observable even after exposure to $10^{18}$ 425 keV electrons. As noted above, electrons of this energy should be capable of displacing both Cd and S atoms in CdS. Not only was no permanent, stable bulk damage observed, but there was no indication of reversible effects which could be attributed to changes in surface properties, in spite of the high surface to volume ratio.

To summarize the work on bare CdS thin film cells, $10^{13}$ protons/cm$^2$ of 100 keV caused a degradation of 20 % in $I_s$ while $10^{18}$ electrons/cm$^2$ of 425 keV caused no change whatever. A rough estimate of relative effectiveness of low energy protons and electrons in producing damage in a device whose active region is about 2 μ can be made by referring to the behavior of GaAs cells. Here it has been reported that $5 \times 10^{10}$ protons/cm$^2$ of 325 keV produced about the same degradation as $7 \times 10^{16}$ electrons/cm$^2$ of 800 keV, i.e. a factor of $1.4 \times 10^8$ more electrons than protons were needed to produce equivalent damage. If this same ratio is required in CdS, a few times $10^{10}$ electrons/cm$^2$ of energy below 1 MeV would be needed to produce a 20 % degradation. Unfortunately such exceedingly high fluxes are difficult to obtain in reasonable periods of time.

As for CdTe thin film cells, the only published information on degradation of these cells consists of a brief reference in a paper by L. D. Massie and J. F. Wise [21]. They found that up to $10^{17}$ roentgens of Co-60 γ-rays and $2 \times 10^{14}$/cm$^2$ 5 MeV electrons produced no changes in cell response, whereas exposure to 2.4 MeV protons did cause degradation. To be specific a 15 % decrease in $I_s$, occurred after exposure to $10^{18} - 2.4$ MeV protons/cm$^2$. This degradation rate is comparable to that observed in CdS cells irradiated by 50 keV protons by Hui and Corra.

The literature does not contain any information concerning radiation damage in GaAs thin film cells.

Discussion of damage experiments on thin film cells.— In the few cases where radiation damage on thin film cells has been reported, protons of energies ranging from 50 keV to 10 MeV were the damage producing particles. The fluxes required to produce measurable damage were a factor of 10$^{3}$ greater than those needed to damage Si or GaAs cells. This is consistent with the idea that collection of carriers in thin film cells depends on the existence of a wide space charge region rather than on large minority carrier diffusion lengths like those needed in single crystal cells. If this is so, there are a few questions which arise with respect to the irradiation experiments. As indicated above, separate experiments have indicated that the resistivity of CdS crystals increases when radiation defects are introduced into the material. If the protons, especially low range protons, are introducing such radiation defects in the vicinity of the junction, the width of the space charge region ought to increase and the cell characteristics ought to improve. No such improvement of the characteristics of any thin film cells has ever been reported.

Furthermore, the defect concentration in the thin films from which the cells are fabricated has been assigned values ranging from $10^{16}$/cc to $10^{20}$/cc. Now the width of the space charge region is controlled by these impurities, so that the number of defects produced by irradiation must be comparable to the initial defect concentrations if damage is to be observed. To estimate the concentration of displacements produced by protons of energy 100 keV, we can utilize the expressions given by Seitz and Koehler [22]. For a thick target (one in which the particles are stopped), the number of primary displacements per incident proton $\eta_\nu$ is given by

$$\eta_\nu \simeq n_0 R_1 \frac{\eta}{E}$$
where $n_0$ is the density of host lattice atoms, $R_i$ is the range of the incident particle of energy $E$ and

$$\eta = 4\pi a_0^2 \frac{M_1 Z^2_1 Z^3_2 R^2_H}{M_2} \frac{E_D}{E_D}$$

where $a_0$ is the Bohr radius, $R_H$ is the Rydberg, $M_1$ and $M_2$ are the masses of the proton and the host lattice atom, $Z_1$ and $Z_2$ are the atomic numbers of the proton and host atom respectively and $E_D$ is the threshold energy for displacements. Assuming that the average atomic weight in CdS is 120; average atomic number 50 and $E_D = 10$ eV, we find that

$$\eta_p \sim 12/\text{incident proton}.$$  

The average number $v$ of secondaries plus primaries produced after each primary collision is given by the relation

$$\bar{v} = \frac{1}{2} \left( \frac{T_m}{T_m - E_D} \right) \left[ 1 + \ln \frac{T_m}{E_D} \right]$$

where $T_m$ is the maximum energy transferred to a struck atom by a proton and is in turn given by

$$T_m = \left[ \frac{4 M_1 M_2}{(M_1 + M_2)^2} \right] E.$$  

If we put this information together we find that the total number of displaced atoms per incident proton is given by

$$N_T = \frac{\eta_p}{v}.$$  

In our case, this turns out to be about 25. Hui and Corra found a 20% decrease in $I_v$ after about $10^{13}$ protons/cm$^2$. These $10^{13}$ protons/cm$^2$ would produce a total of $2.5 \times 10^{14}$ displaced atoms over a distance equal to the range of the particles which is about 1 $\mu$ for 100 keV protons. Thus, $10^{13}$ protons/cm$^2$ of 100 keV energy would produce about $10^{18}$ displacements per cc. This concentration is in the range needed to match the assumed concentration of defects in the CdS prior to irradiation.

Finally, the lack of sensitivity to electron irradiation indicates that the surfaces of the crystallites comprising the cells do not play any significant role in the photovoltaic response of thin film cells, in spite of the large surface to volume ratio. It might also be remarked that the lack of sensitivity to electrons of energies known to produce bulk damage in CdS and CdTe crystals is regrettable since this precludes the use of these cells in experiments designed to study effects to electron bombardment with the help of thin film cells.

Acknowledgement. — The author wishes to thank Mr. Fred Shirlond of the Clevite Corporation and Mr. James C. Schaefer of the Harshaw Chemical Co., Cleveland, Ohio for help in obtaining “bare” CdS cells for the electron irradiation studies at Brown.

REFERENCES

[8] See Ref. [7].