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PROTON-INDUCED DAMAGE TO SILICON SOLAR CELL ASSEMBLIES
A STATE-OF-THE-ART SURVEY

First Quarterly Report

by

M. J. Barrett and R. H. Stroud

July 10, 1968

JPL Contract 952246

with

EXOTECH INCORPORATED
525 School Street, S. W.
Washington, D. C. 20024

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ABSTRACT

The literature concerning proton-induced radiation damage to silicon solar cells and their coverslides is collected and reviewed. A summary of the state-of-the-art is presented, in which it is observed that the localized damage in the cell depends on the proton energy at the point being considered. Hence, it may be nonuniform across the thickness of the cell. Equations are available to allow computation of the effect of this damage on the electrical characteristics and are discussed.

Contents

I Introduction

Protons and electrons in space are the principle causes of the performance degradation of solar cell assemblies. Protons above a certain energy generate effects similar to those of electrons since they completely penetrate the assembly and deposit damage more or less uniformly throughout the material. A review of these effects may be found* in reference 13.

When the proton energy is sufficiently low, the proton range and the assembly thickness are of comparable magnitude. This leads, under certain conditions, to strong shielding by a coverslide, heavy localized damage to the cell junction, and/or a non-uniform damage density in the cell. An effort was made to collect and review the literature relating to proton damage and cell response. In this quarterly report, the result of the review is presented as section VI and each item is accompanied by a summary.

By a review of the studies listed, it is possible to outline the processes by which protons damage solar cell assemblies. Such an outline is provided in sections II through V.

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* References, in alphabetical order, are presented in the Bibliography.

II. Coverslide-Related Effects

A. Shielding

All material in front of the junction shields it and the base region of the solar cell and generally reduces the damage by a spectrum of protons as encountered in space. The principal materials acting as a shield in a typical solar cell assembly are shown in Figure 1. The coverslide should completely cover the solar cell.[30] Serious effects due to very low energy protons occur when this rule is violated.[6] [15]

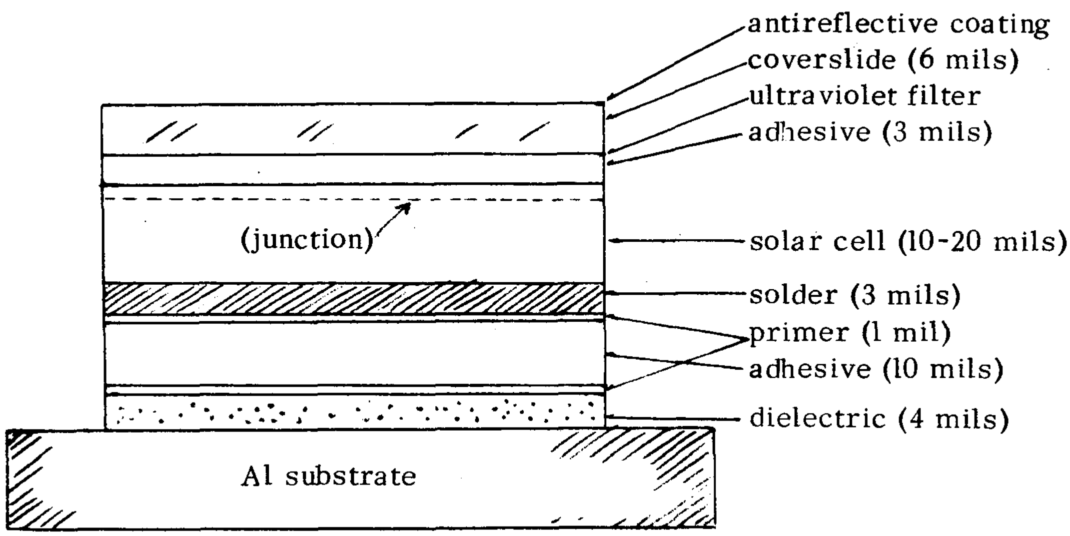

Figure 1. Typical solar cell stack representing current technology

If a proton, incident on a coverslide-solar cell assembly, has an energy E_0, it will penetrate a distance R, measured in grams/cm^2, into the assembly, in the same direction as it entered. R is known as the proton range and is presented graphically[24] in Figure 2. Various authors[13][26] have considered analytical forms for $R(E_0)$ in intervals of interest, and generally take

$$R = R_0 \, (E_0)^n \qquad (1)$$

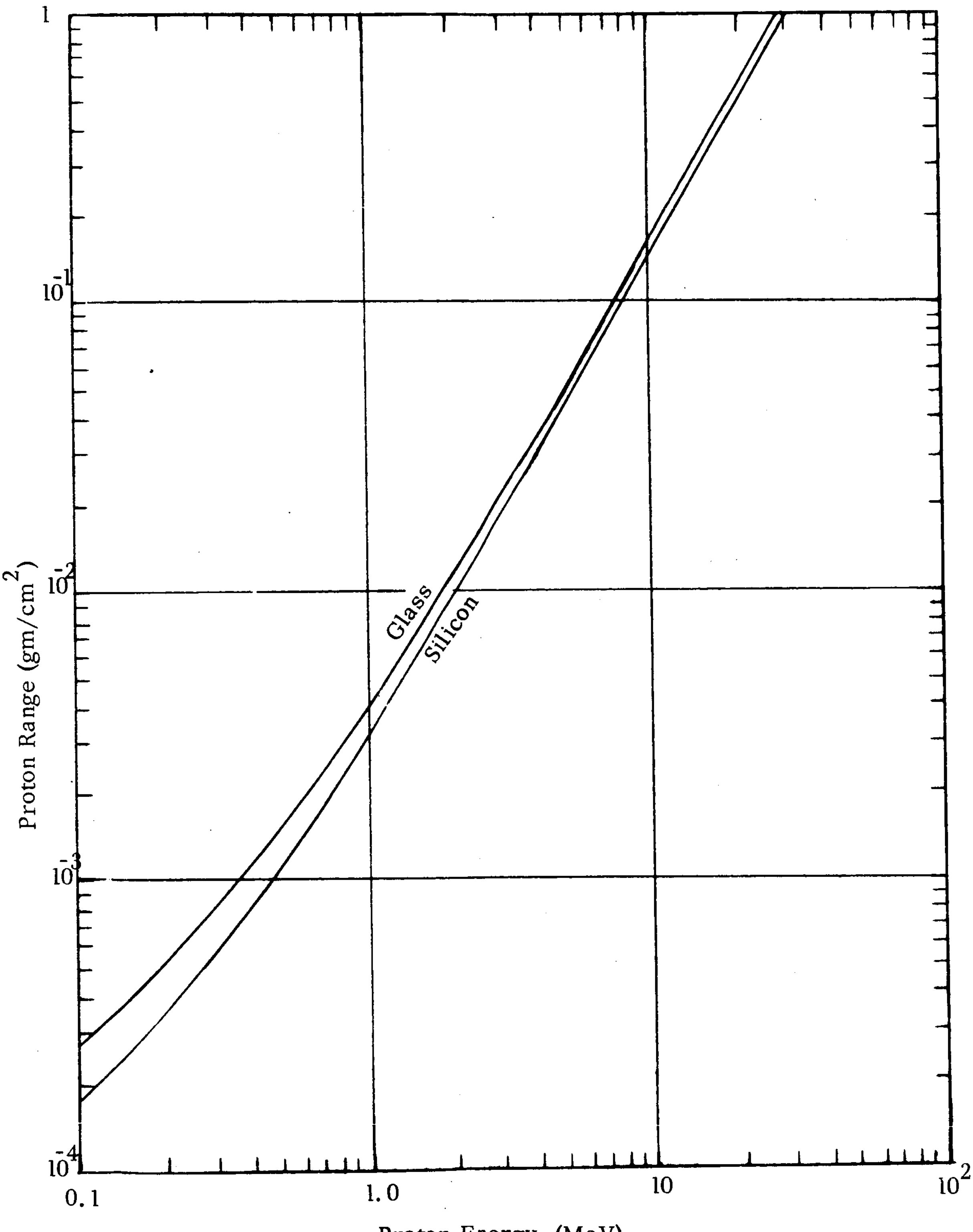

Figure 2. Proton range-energy relationship in silicon and pyrex glass for protons from 0.1 to 30 MeV.[24]

From the figure, it is apparent that n is not constant and, as a result, R_o changes. The slope n varies from about 1.33 for energies below 1 MeV to about 1.75 for energies in the range 1-10 MeV.

A coverslide of thickness t will remove protons of energy E_o and incident angle θ with the normal if their range R is less than the path length $t/\cos\theta$ through the coverslide. It will also reduce the energy of a transmitted proton to E given by (13)

$$E = \left[E_o^{\,n} - \frac{t}{R_o \cos\theta} \right]^{1/n} \tag{2}$$

where R_o may be taken as 2.72 mg/cm^2 when n is 1.75.

The proton spectrum striking the solar cell due to a monoenergetic, unit flux incident isotropically on the coverslide can be obtained. (9)(13) The result is

$$\Phi(E) = \frac{nt\ E^{n-1}}{R_o (E_o^n - E^n)^2} \qquad \text{For} \quad E_o \quad < E^n \tag{3}$$

Superposition of this result yields the proton spectrum $\Phi(E)$ incident on the solar cell due to an isotropic fluence $\Phi(E_o)$ in space penetrating a shield of thickness t, expressed in mass per unit area.

$$\Phi(E) = \int_E^{\infty} \frac{nt\ E^{n-1}}{R_o (E_o^n - E^n)^2} \quad \Phi(E_o)\, d\, E_o \tag{4}$$

Carosella (10) has programmed a calculation of Φ (E) for silica shields and an incident isotropic proton flux. His results show that, for typical spectra of the form E_o^{-x}, where x varies from 3 - 5 in the magnetosphere, the transmitted spectra show a maximum at an energy which increases as the shield thickness t increases and is typically around 1-5 MeV.

B. Transmission of Light

1. Coverslide Darkening

When irradiated, glasses tend to darken. Fused silica, such as Corning 7940, is almost always chosen for the coverslide since it is considerably more resistant than other coverslide materials to radiation darkening.[9][22][28] The spectral transmission of this material before and after electron radiation is shown in Fig. 3.[22] Similar effects are observed after proton irradiation since the darkening response is primarily a function of the ionization dose produced in the material. If, indeed, the short-wavelength (blue) end of the optical band utilized by the solar cell is partially absorbed by radiation darkening, the solar cell output will be reduced. The reduction will increase with the darkening and with the importance of the blue end of the spectrum to the cell. For example, a cell which has a significant blue response should be more sensitive to this type of coverslide darkening than is one with its response more in the long wavelength (red) region.

Absorption of light in the bulk material reduces the solar cell output. Darkening of the bulk material can also increase its surface reflectivity, although this has not been measured. Finally, darkening can increase the temperature of the assembly, thereby reducing the solar cell efficiency.[9]

2. Surface Erosion

Large fluences of protons at extremely low energies, comparable to those of the solar wind, can degrade the anti-reflective coating. A 45 percent transmission loss was observed at 0.7 microns after 5×10^{17} protons/cm^2 of 2 keV energy.[15] This loss is related to the anti-reflective coating since irradiation of the uncoated side of the coverslide caused no loss.

No loss of effective transmittance was observed after 10^{16} (1.5 MeV) electrons/cm^2 on uncoated 20 mil Corning 7940 fused silica but fused silica coated with blue-reflective and anti-reflective coatings had a 3 percent loss of short circuit current of a solar cell.[28]

Coverslide erosion is not restricted to that produced by radiation. Collision of meteoroids may cause erosion, penetration and/or puncture. On covered cells this results in a loss of light transmission.[9]

3. Adhesive Darkening

The adhesive used is susceptible, in some degree, deterioration and darkening by protons, electrons, and ultraviolet radiation. While the magnitude and details of the darkening depend on the particular adhesive in use, generally the short wavelength transmission suffers the most.[8]

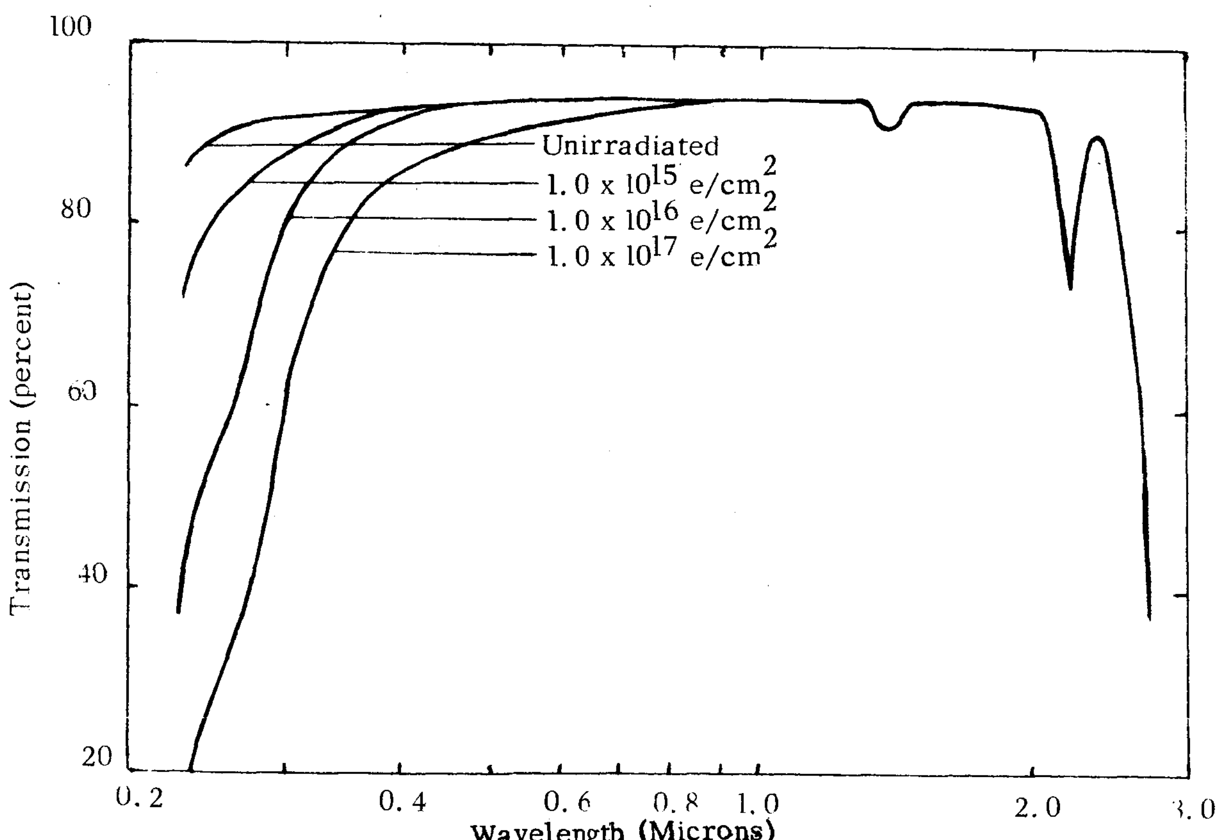

Figure 3. Spectral transmission of a sample of synthetic fused silica before and after irradiation by 1.2 MeV electrons.[22]

III. Effects on Silicon

A. Proton Interactions with Silicon

1. Energy Dependence

To dislodge a silicon atom from its lattice position in a crystal, a proton must transfer to it energy that exceeds the lattice binding energy. In a scattering collision, the partition of the kinetic energy of the proton must conserve momentum; this requires that the initial proton energy be considerably greater than the energy transferred. For a silicon binding energy of 12.9 eV, the minimum energy a proton can have if it is to dislodge an atom is 90 eV. Somewhat arbitrarily, a threshold proton energy of 100 eV may be used in calculations, since the probability of dislodgment rises gradually as the energy transferred to the silicon rises above its binding energy.

Up to about 10 MeV kinetic energy, Rutherford scattering is the mechanism for energy transfer to the nucleus. The cross section for this interaction, multiplied by the density of atoms in the lattice, is therefore equal to the number of silicon atoms dislodged per centimeter of track by the proton. The moving silicon atoms can collide with neighboring atoms and dislodge them. This cascade effect must be taken into account in a calculation of η, the number of dislodged atoms per centimeter of proton track. The damage density, or defects per cubic centimeter, is the product $\eta\Phi$, where Φ is the proton fluence.

Several expressions, discussed by Vavilov[36], exist for the average number ν of silicon atoms dislodged per initial displacement, due to this cascade effect. Ionization competes with atomic displacement for the kinetic energy of the silicon atom, and it appears to provide a maximum value of the order of 10^3 for ν when the primary silicon atom has a recoil energy greater than 30 keV.[36]

Calculations of the Rutherford scattering cross section frequently assume a point charge for the silicon nucleus. The actual nucleus covers a finite volume, and Lafond has shown this leads to a lower estimate of η, particularly at high energies.[17] This is observable in Figure 4.

Above about 10 MeV, nuclear interactions add to the number of nuclei displaced and the proton interacts either by elastic scattering or a nuclear reaction with silicon atoms. One nuclear reaction has been found to yield 6×10^{-3} atoms of aluminum per incident 22 MeV proton.[29] The additional interaction mechanism augments η for energies above the threshold. The energy dependence of η as calculated by several authors is shown in Figure 4. The inflection in the curve, near 10 MeV, represents the increase due to nuclear interactions.

2. Distribution of Defects

The principal effect of the proton interactions discussed above is to dislodge atoms, leaving a lattice position vacant and the atom at a nearby interstitial position (Frenkel defect). The linear density of defects, η, is determined by the proton energy, which decreases with depth of penetration. For example, consider a solar cell about 10 mils thick. To penetrate through a silicon crystal of this thickness, a proton must have an energy* no less than 5.3 MeV. If the solar cell has been shielded by about 6 mils of fused silica, the initial energy of a penetrating proton must have been no less than 7.2 MeV. Below these energies for bare and shielded cells respectively, the base region damage density is strongly dependent on distance from the surface.

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* The energies were calculated from the range formula $R = 16.41\, E^{1.64}$ microns, given by Marcinkowski et al.[26]

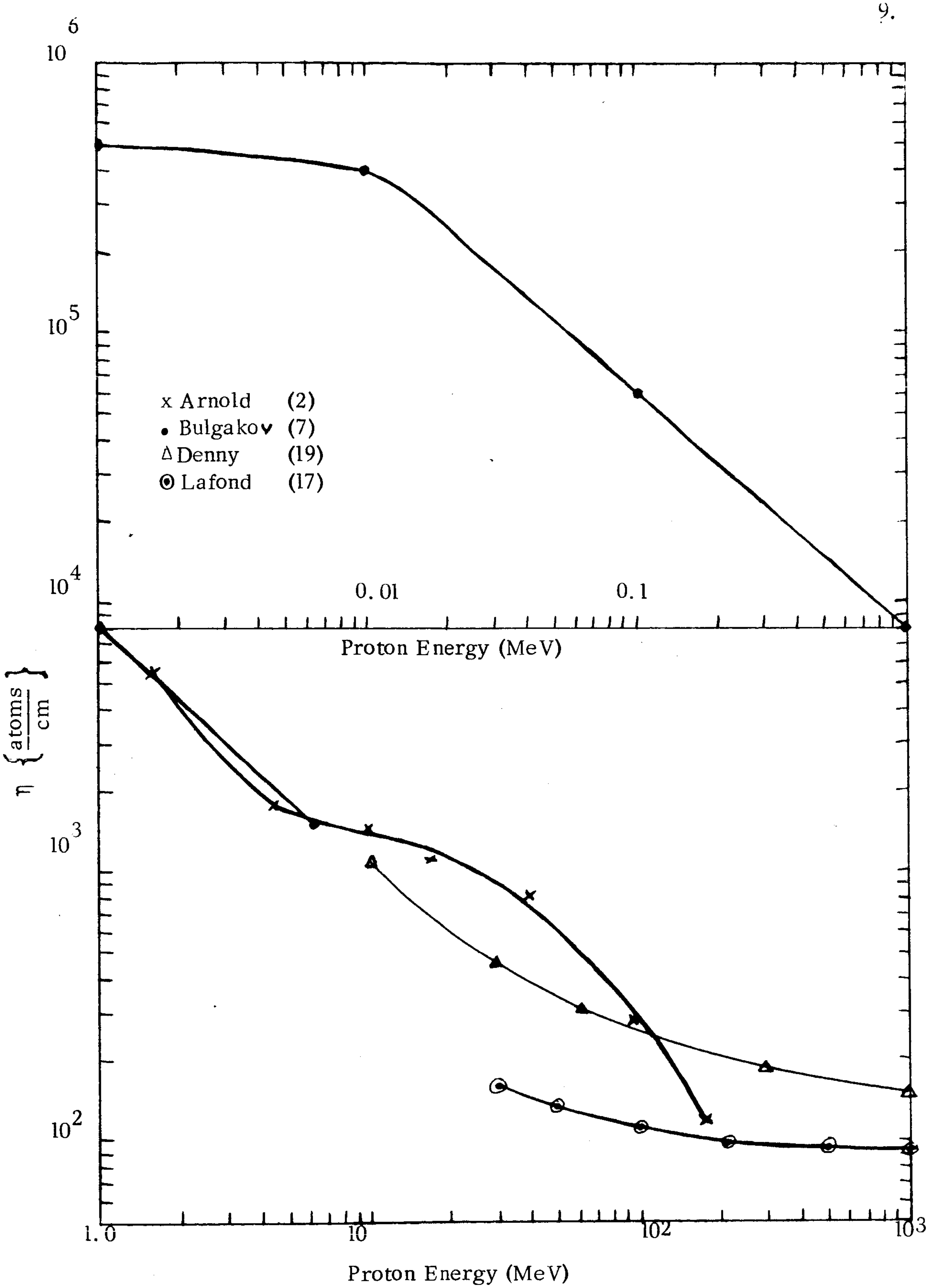

Figure 4. Number of displacements η per centimeter of proton track for energies from 10^{-3} to 10^3 MeV.

To obtain a better understanding of the distribution of damage caused by protons, consider a 10 MeV proton normally incident on an assembly consisting on a 6 mil coverslide and a 10 mil solar cell. * Range calculations indicate that this proton penetrates the coverslide with a residual energy of 8.85 MeV, and emerges from the back of the cell with a residual energy of 5.8 MeV. From Figure 4, it appears that the damage (atomic displacements) in this example is about 1.3 times greater at the back of the cell than at the front.

It can be seen from these examples that the uniformity of damage increases with increasing proton energy and that the energy range of 5-10 MeV is where the transition occurs between strongly nonuniform damage and nearly uniform damage to the base region.

Silicon solar cells are constructed with the diode junction typically about 0.5 microns below the surface. This is the range of a proton of about 72 keV. Since a proton does its greatest damage near the end of its track, one would expect the defects introduced by protons of this energy to have a unique effect on the cell, due to their concentration near the junction. This, has, indeed, been shown to be in the case.[25]

The proton energy spectrum should therefore be considered in three parts, with regard to damage effects. Above some energy in the range 5-10 MeV, uniform damage to solar cells is experienced. Below this, non-uniform damage is experienced. At a very low energy, about 100 keV, significant junction damage is experienced (on bare cells).

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* For simplicity, the slight shielding by the adhesive is neglected here.

B. Stabilization of Defects

1. Recombination Centers

Frenkel defects are not stable. The defect may recombine or the vacancy site may wander through the crystal. When the vacancy combines with impurity atoms (notably oxygen) and/or other vacancies, a stable configuration results. Often such a configuration provides an energy level for carrier recombination and is then termed a recombination center. This leads to the well-known equation for the reduction of the minority carrier diffusion length L in an irradiated crystal[34]

$$\frac{1}{L^2} = \frac{1}{L_o^2} + K\Phi \qquad (5)$$

where L_o is the diffusion length in the crystal before exposure. K is the local damage coefficient for the fluence Φ and is proportional to η. The product $K\Phi$ is proportional to the number of recombination centers and their effective cross section for recombination, which is affected to some extent by the density of minority carriers generated by light.[13][19]

Thus, K combines the effects of radiation, as given by η, with the subsequent response of the crystal in forming centers, and the action of these centers on the carriers diffusing to the cell junction. It is dependent on the energy spectrum of the fluence, on properties of the crystal such as polarity and resistivity, on temperature, and on light intensity.

The energy dependence of K for proton irradiation has been the subject of considerable study. It would seem that K varies with proton energy much as the displacement density η does.

This assumption must be used with caution ; for example, it does not hold for electron damage.[11] However, Arnold[2] states that in the proton damaged cell the number of recombination centers introduced is directly proportional to the number of lattice displacements. Experimentally, one can measure changes in $1/L^2$ for a fluence of a given energy to determine K. Although this can be done where the proton energy changes insignificantly across the sample, it is not easily accomplished for low proton energies. The "measured" value of diffusion length in a crystal irradiated with protons below 5 MeV will be an effective diffusion length for the effect being measured, while the actual diffusion length may vary greatly with location in the crystal. One such empirical damage coefficient K is intended to produce an effective L such that the short-circuit current can be predicted for a proton-irradiated cell, given the relationship of L to short-circuit current in a uniformly-damaged cell (p. VI-4 of ref. 13).

2. <u>Dependence on Crystal Purity</u>

Impurity atoms used to dope a silicon crystal will reduce its resistivity. Within limits, increased electrical resistivity of silicon provides increased radiation resistance.[34] Cherry and Slifer,[12] using short circuit current and maximum power as criteria, found that sensitivity to 1 MeV electrons(penetrating radiation) decreased with increasing base resistivity to a least 25 ohm-cm and resistance to 4.5 MeV proton damage increases to at least 10 ohm-cm. Within a group of n/p silicon cells that Statler[31] irradiated with 4.6 MeV protons the 10 ohm-cm cells had a short circuit current degradation of 16 percent per decade of integrated flux and a power degradation of 20 percent per decade while 1 ohm-cm cells had short circuit current and power degradations of 20 percent per decade and 23 percent per decade, respectively.

The damage coefficient is consistently lower in 10 ohm-cm cells as compared to 1 ohm-cm cells.[13]

There is a lack of a significant dependence of the decrease in minority carrier diffusion length on dopant material. Even the oxygen content of the crystal seems to have negligible effect on the damage resistance.[33] This is consistent with neutron degradation studies on arsenic, phosphorus, gallium and boron doped cells by Curtis[16] in which no dependence of the lifetime degradation rate on impurities was observed.

3. Annealing

To remove recombination centers and return a solar cell to its initial efficiency, two courses of action have been proposed. Lithium atoms in the base region have been shown to combine with the defect and reduce the recombination cross section.[35] A second approach is to heat the cell, dissociating the recombination centers and thereby annealing the solar cell. At room temperature, about 5% of the centers are annealed.[34] Typically, temperatures over 200 degrees C are required for a more significant percentage, but it appears that low energy proton damage (below 10 MeV) is partially annealed at temperatures near 150 degrees C.[21] With high energy proton damage to an n/p cell, a temperature of 300 degrees C is required for significant annealing.[4] The difference in annealing temperature indicates that some recombination centers induced by low energy protons are of a different character from those induced by high energy protons.

The recovery due to annealing is never complete. After irradiation of 10 ohm-cm n/p silicon solar cells by protons ranging from 0.2 to 1.9 MeV, Downing[20] observed a slow 20 to 90 percent recovery in short circuit current but none in open circuit voltage after a matter of days at room temperature.

Hulten,[23] et al., noticed very little recovery in p/n cells irradiated by 22 MeV protons after 3 months at room temperature. The same cells recovered approximately 2 percent of their initial maximum power after 3.5 days at 130 degrees F. After 240 MeV proton irradiation they regained 4 percent power recovery after 3 weeks at room temperature.

IV. Effects on Solar Cells

A. Photovoltaic Current Effects

When the damage is uniform, the short circuit current I_{sc}, varies approximately as the logarithm of the diffusion length in the damaged base region.[18][32] Figure 5 shows this to be true for 10 MeV proton damage to 10 ohm-cm n/p silicon cells measured under tungsten illumination and under sunlight. Lower energy proton irradiation creates non-uniform damage. In order to relate the current to the diffusion length for non-uniform damage the continuity equation may be employed.[1]

$$D \frac{d^2 n}{dx^2} - \frac{n}{\tau} = G(x) \qquad (6)$$

where n is the number of minority carriers per cm^3, D is their diffusion coefficient, τ is their lifetime, and G(x) is their rate of production by photons per cm^3 at depth x. Since L^2 equals the product of the diffusion coefficient D and the lifetime τ, the term n/τ becomes, under non-uniform damage, a function through L^2 of depth in the cell. Thus, L varies from its value at the surface (as calculated with Eq. 5 and the damage coefficient K for the proton energy being used) to lower values as the proton energy decreases with depth of penetration.

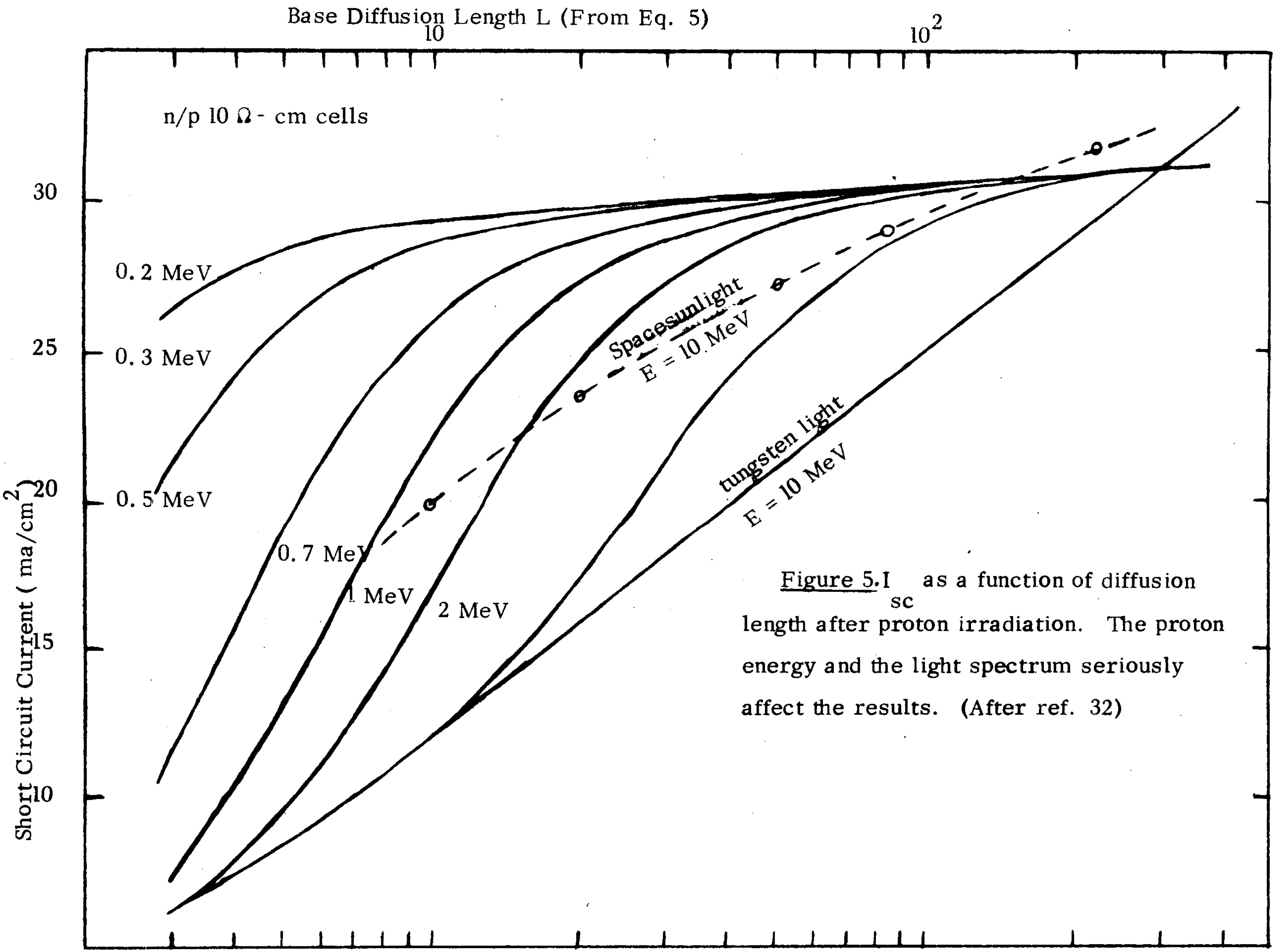

Figure 5.I_{sc} as a function of diffusion length after proton irradiation. The proton energy and the light spectrum seriously affect the results. (After ref. 32)

Figure 5 plots short-circuit current density versus that value of L in the base region where the proton has its initial energy, and makes apparent that the greater is the non-uniformity of L with depth x, the greater will the short-circuit current deviate from a logarithmic dependence on L.

The net current density j moving across a plane is given by

$$j = q\ D\ \frac{dn}{dx} + q\ \mu\ E\ n \tag{7}$$

where q is the electronic charge, μ the mobility, and E the electric field. Frequently, the electric field is negligible.[32] In such a case, Eqs. 6 and 7 can be combined to yield.

$$\frac{1}{q}\ \frac{dj}{dx} - \frac{nD}{L^2\ (x)} = G\ (x) \tag{8}$$

and a solution to this equation gives the current I_L at the junction due to the photovoltaic process. Both sides of the junction contribute to the current and Eq. 8 can be used both for the base region and for the thin region in front of the p/n junction.

In the application of this model consideration must also be given to the dependence of G (x) on the wavelength of incident light λ. The actual value of G (x) becomes the integral from λ_1 to λ_2 of $G(x, \lambda)$ where λ_2 represent the end points of the incident spectrum.[14] Figure 5 includes a comparison of the response, for uniform damage by 10 MeV protons, under tungsten light (solid line) and under a sun simulator (dashed line). It is evident that the spectrum used to measure the solar cell characteristic in space must match that of space sunlight. Photons of very short wavelengths, for example, generate electron-hole pairs near the surface while longer wavelength act in the base region and far infrared wavelengths pass through the cell without affecting it.[3]

Consequently, tungsten light will emphasize the damage in the cell more than sunlight.

The solar cell equation may usually be written as

$$I = I_L - I_o \left[e^{(V + IR)/V_o} - 1 \right] \tag{9}$$

where I is the current through the load, I_L the photovoltaic current across the junction, I_o the diode saturation current, V the voltage across the external load, and R the internal cell resistance.[13] V_o is a constant that appears to be unaffected by radiation. When R is quite small, of the order of an ohm or less as in present solar cells, the short circuit current I_{sc} approaches the photovoltaic current I_L across the junction.

Taking I_{sc} as a criterion for radiation damage, the non-uniformity of damage will affect the solar cell spectral response. Figure 6 shows the relative I_{sc} spectral response for n/p cells before and after 100 and, 500 keV protons irradiation as measured by Lodi.[25] The degradation due to the 100 keV irradiation is in the short wavelength region as expected since the proton range is approximately equal to the junction depth.

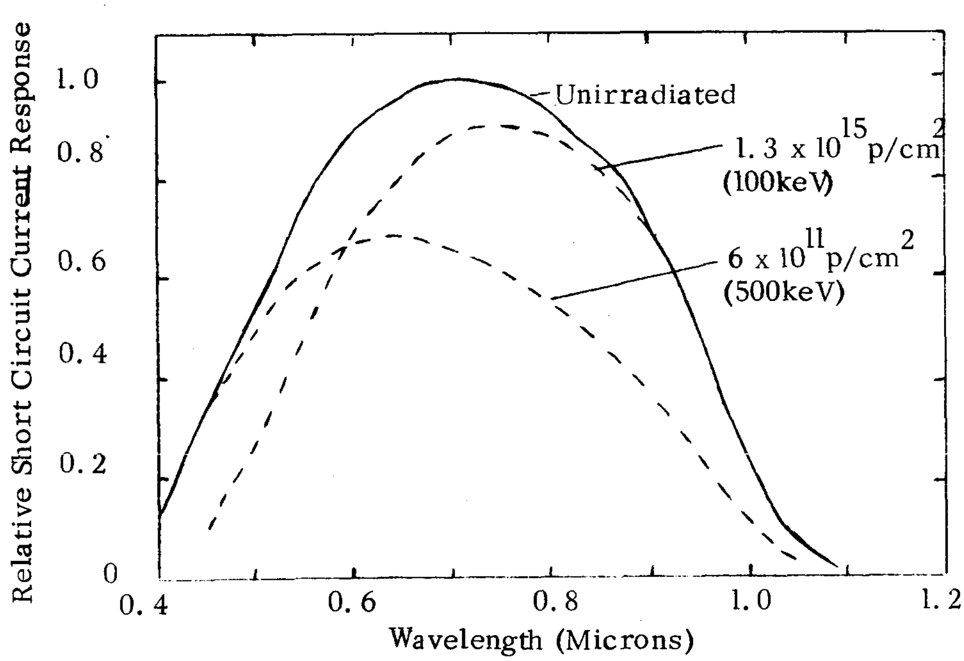

Figure 6. Relative spectral response before and after irradiation by 100 and 500 keV protons.[25]

The degradation due to the 500 keV irradiation, however, occurs in the base region which is more sensitive to the longer wavelengths. Carriers in the back of a cell are more affected by radiation damage because they must diffuse farther. Therefore thin cells should show relatively less base damage than thicker ones because these cells are less dependent on the deeply penetrating red and infrared photons. Martin, et. al.,[27] in a study of n/p silicon cells ranging in thickness from 3.4 to 11.8 mils irradiated with 1 MeV electrons found this to be the case.

B. Diode Effects

I_o, the saturation current, will also vary when the damage is concentrated near the junction. Using the I-V measurements of Lodi,[25] I_o can be calculated from the solar cell equation for fluence of 100 and 500 keV protons that were used. The cell resistance is assumed negligible and I_o is computed using the measured values of I_{sc} and V_{oc} in Eq. 9. The result, displayed in Figure 7, shows I_o, increases with increasing 100 keV proton fluence while for 500 keV protons it remains comparatively constant.

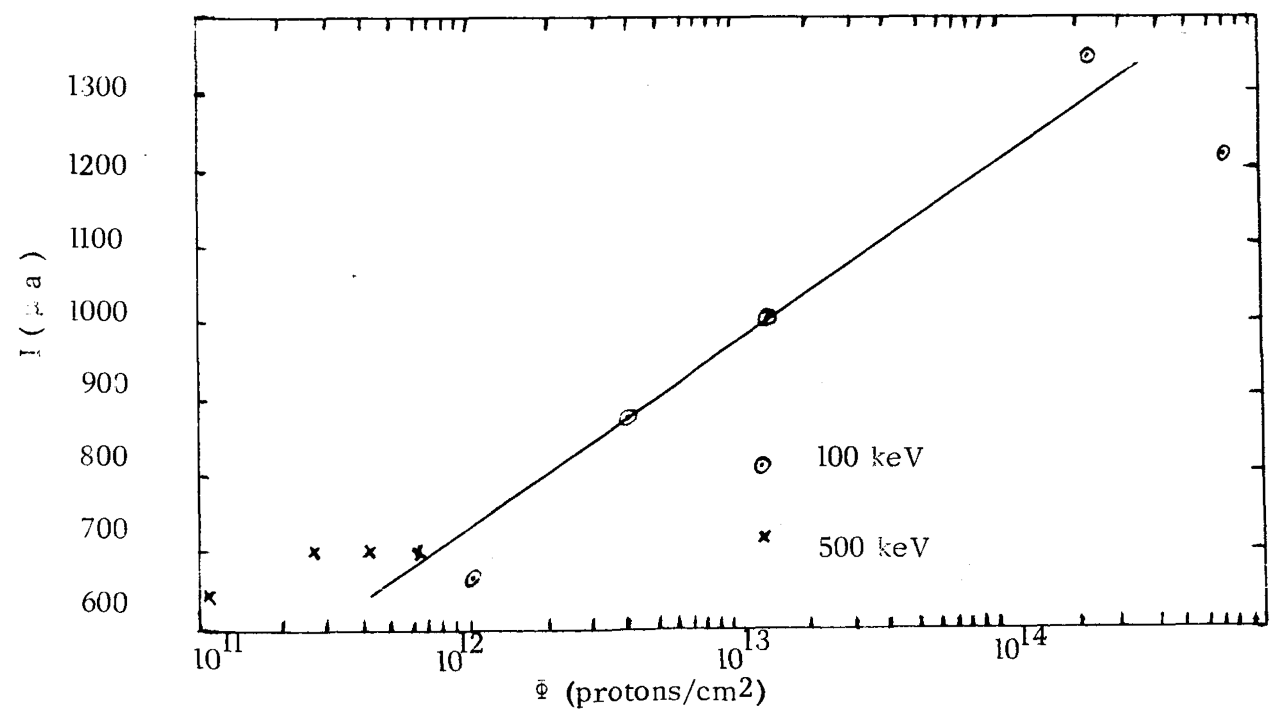

Figure 7. I_o versus Φ for 100 and 500 keV protons.[25]

C. Cell Resistivity

The series resistance in the solar cell equation includes terms for the resistance of the surface layer of the cell for current flow from junction to collecting grid and the relatively small resistance of the base region. Under proton irradiation, the resistivity of both n and p type silicon increases. Bulgakov[7] gives an expression for the increase in resistivity in terms of the defect density and the energy level characteristics of the silicon.

Increasing resistivity tends to straighten out the IV curve, decreasing the maximum power obtainable but not affecting the short circuit current or the open circuit voltage as greatly. The results of two experiments which exhibit this behavior are shown in Figure 8. In Figure 8a, low energy protons are incident on the front surface of a p/n solar cell.[5] The proton range is insufficient to allow junction damage, and the damage appears to be an increase in resistivity of the surface layer, as well as bulk damage in that region. The similar results in Figure 8b are due to low energy protons incident on the back of a n/p cell. This effect has been ascribed to the formation of a high resistance layer at the back of the bulk region.

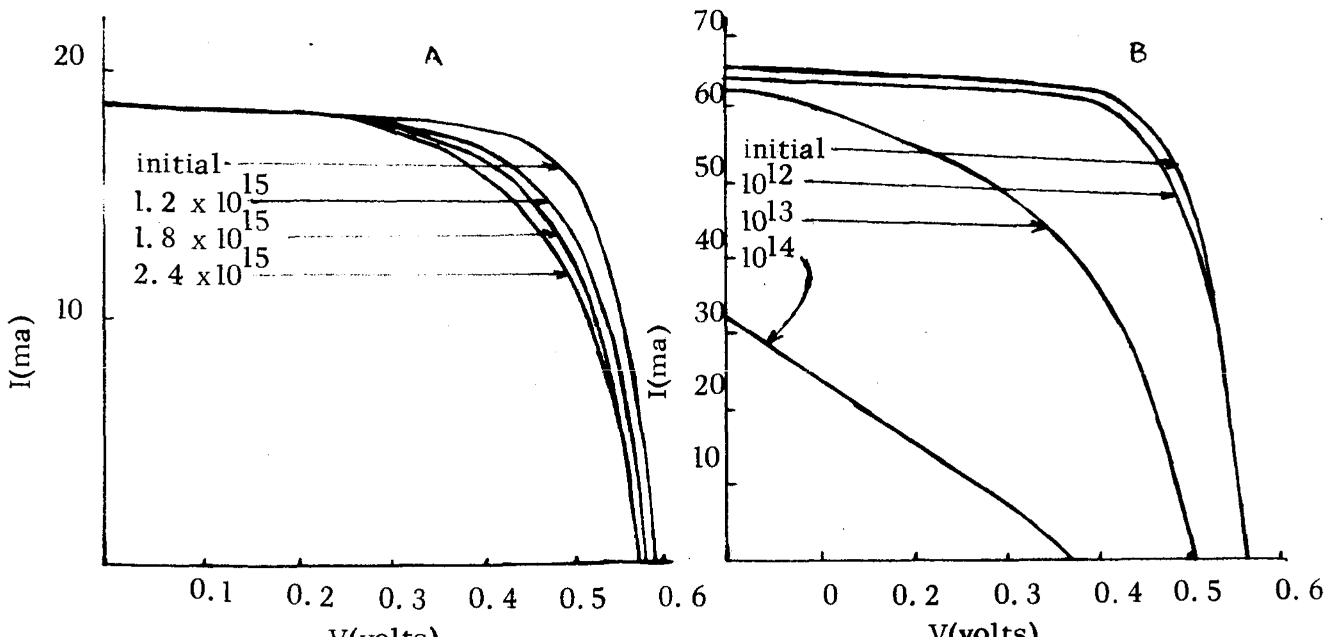

Figure 8. I-V curves for low energy proton irradiated cells.

V. Summary

When solar cells are irradiated by protons, some of which have a range less than the combined thickness of the coverslide and solar cell, the concentration of recombination centers and consequently the local value of the minority carrier diffusion length will vary with depth through the cell. In order to calculate the effect of proton damage in this case, it appears necessary to consider at least three effects:

1. Diffusion of minority carriers in the base region to the p/n junction through a region with a varying valve of local minority carrier diffusion length (L). This local valve of L may also be a function of the local concentration of charge carriers, which depends on the spectrum and intensity of the illumination.

2. Damage which increases the resistivity of the surface layer above the junction and possibly changes the recombination velocity at the front surface.

3. Damage to the junction itself, which strongly affects the open circuit voltage.

In addition, one must consider the effect of coverslide darkening and changes in optical properties of the adhesive and filters on the intensity and spectral distribution of light actually reaching the solar cell.

This quarterly report reviews the state of knowledge relating to low energy proton damage which will provide a basis for developing analytical techniques to predict solar cell performance.

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Results of the bombardment of n/p and p/n silicon solar cells by 185, 325, 450, 530 keV protons are given. I_{sc}, V_{oc}, P_{max}, spectral response, and diffusion length are considered. It was shown that an important parameter in low energy proton irradiation is the junction depth, where major changes occur. Carrier collection from the base region is substantial when the proton energy is sufficiently low for the damaged region to be thin. As a result, the junction characteristic and the open-circuit voltage are most affected.

2. Arnold, D. M. et. al. Proton Damage in Semiconductor Devices. NASA Contractor Report NASA CR-40. April 1964.

The objective of this study is to interpret observed changes in transistor electrical characteristics in terms of fundamental changes in the semiconductor crystal structure and, in so doing, to predict the effects of proton bombardments. Emphasis is placed on lattice displacements, but transmutations and ionization are also considered. Proton and neutron displacement production rates are calculated. These are used in conjunction with neutron irradiation data and an assumed similarity of defect clusters to determine the effects of protons on transistors. Reasonable agreement with experiment is obtained.

3. Beatty, M. E., G. F. Hill. Effect of 40 MeV Protons on Semiconductors as Determined With an Improved Method of Measuring Diffusion Length of Minority Carriers. NASA Technical Note D-2817. June 1965.

The minority carrier diffusion length L is determined with an infrared monochromatic light source. In this way the surface effects are minimized, and the lifetime in the base region is obtained for values as short as 10^{-10} second.

The theoretical expression for the minority carrier diffusion length as related to the short circuit current I_{sc} as a function of incident light wavelength was determined. Therefore by using light of a particular wavelength it is possible to obtain L.

The data are tabulated and given as functions of the 40 MeV proton fluence.

4. Beatty, M. E., G. F. Hill, Annealing of High Energy Proton Damage in Silicon. In Proc. of the 6th Photovoltaic Specialists Conference, Vol. III. March 1967.

Studies of n-and p-type silicon irradiated with 22, 40, and 158 MeV protons and annealed at 100 degrees, 200 degrees, and 300 degrees C show that proton damage is very complex and more difficult to anneal than electron damage. After 12 hrs. of annealing, around 10% of the p-type silicon defects are annealed at 200 degrees C and 25% at 300 degrees C. Annealing becomes less successful with increasing proton damage or decreasing proton energy, and n-type silicon shows more annealing than p-type.

5. Brown, R. R. Surface Effects in Silicon Solar Cells. IEEE Trans. on Nuclear Science NS-14; No. 6, 260-5, Dec. 1967.

Protons from 0.5 to 27.5 keV were used to irradiate n/p, p/n, and lithium doped p/n silicon solar cells at 10 degrees C. Changes of I_{sc} and V_{oc} for p/n cells irradiated with 27.5 keV protons were consistent with classical degradation of minority carrier lifetime in surface and bulk regions. Changes in the lithium-doped cells were consistent with those observed in the conventional p/n cells indicating no improvement in low energy proton radiation resistance. No appreciable recovery was observed at 10 degrees C. The 27.5 keV proton irradiation of n/p cells did not produce classical damage but relatively large, partially recoverable changes in P_{max} at high exposure levels were observed. Similar changes in P_{max} occured in p/n cells for protons at insufficient energy to penetrate the n region substrate. Larger changes in V_{oc} occured in n/p cells at high exposure than in p/n cells and a definite dependence on energy was observed. Surface damage I_{sc} of p/n cells at 0.6 keV (borosilicate layer) was not significant. Changes in I_{sc} for n/p cells irradiated with energies of 5.5, 16.3, and 27.5 keV are approximately equivalent indicating that changes associated with the n surface region of n/p cells are not strongly energy dependent.

The threshold energy for surface effects in p/n cells is approximately 0.45 keV which correlates with the borosilicate layer and in n/p cells approximately 4 keV which correlates with the silicon oxide thickness of the protective over-coating. Surface effects observed in the n region of the n/p cells show a significant dependence on proton penetration depth in the n region.

6. Brown, W. D. ATS Power Subsystems Radiation Effects Study. Phase I/Final Report on NASA Contract NAS5-3823. Feb. 1968.

Experiments using 150 keV, 270 keV, and 1 MeV protons show serious damage in covered solar cells after exposure to 10^{13} protons/cm^2. The damage is due to gaps (uncovered areas of the solar cell) around the perimeter of the cell and between the bus bar and the coverglass. Gaps as small as 2 mils are enough to cause significant degradation.

7. Bulgakov, Y. V., T. I. Kolomenskaya High-Resistance Regions in Silicon Irradiated with Protons , Soviet Physics Semiconductors, Vol. 1, September 1967.

The electrical resistivity of n-and p-type silicon increases when bombarded with electrons or fast protons. This is due to the generation of capture centers for the electrical carriers. Experimentally, the resistivity is shown to be a function of the density of states above the valence band, their degeneracy, and the increase in states due to defects introduced by the bombarding particles.

8. Campbell, F. J. Effects of Radiation on Transmittance of Glasses and Adhesives. Presented at the 17th Annual Power Sources Conference, May 1963.

The effects on spectral transmittance of various specimens were measured after exposure to 10^{13}, 10^{14}, 10^{15}, and 10^{16} (1 MeV) electrons/cm^2 in air, a single dose at 4×10^{11} (4. 5 MeV) protons/cm^2, and ultra violet radiation from a 360 watt mercury vapor lamp to the equivalent of 630 hours in space sunlight. The samples consisted of several variations of blue and blue-red thin, multilayer filters deposited on microsheet and fused silica and several radiation-shielding, high-density glasses. Three adhesives were also exposed. Spectral transmittance was measured over the range of wavelengths from 0. 35 to 1. 2 microns.

It is evident that optical degradation occurs most predominantly at shorter wavelengths going to almost zero beyond 0. 8 microns. The exception to this is the blue-red filter specimen.

9. Campbell, F. J. Status of Solar Cell Cover Material Radiation Damage. <u>In</u> Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-2. 1. Jan. 1966.

The most immediate effect of radiation on shielding materials is the production of color absorbing defects in the molecular structure resulting in a decrease of transmission in the ultra violet region. Transmission of shielding samples was calculated as the ratio at I_{SC} of the covered cell to I_{SC} of the bare cell as measured using tungsten light at 100 mw/cm^2 on silicon solar cells at room temperature. Sapphire, fused silica, and some high density shielding glasses suffered little or no decrease in wide band transmission at doses of 2.7×10^{15} electrons (1. 2 MeV)/cm^2.

Ultraviolet exposure caused a slight decrease in broad band transmittance of blue reflective filters and a greater decrease in blue-red filters.

Experiments on Corning 7940 fused silica shields with blue filters showed a 2 to 3 percent loss after ultraviolet exposure and a 3 to 4 percent loss after exposure to 10^{15} electrons (1.5 MeV)/cm^2 but no change in either case when uncoated. It was also found that silicon type adhesives, while not as strong as epoxy, are less affected by ultraviolet and electron irradiation.

Composite systems studied include 1) 20 mils of Corning 7940 fused silica with no coating, 2) 20 mils of Corning 7940 fused silica with a blue-reflective coating, and 3) 27 mils of Corning 0211 microsheet glass with no coating. These samples were irradiated with 2 MeV electrons to a total flux at $10^{15}/cm^2$. Differential losses in P_{max} and I_{SC} above that of unfiltered cells was 3 percent greater in samples with blue filters and 15 to 20 percent greater with microsheet.

10. Carosella, C. A. Shielding of Solar Cells Against Van Allen Belt Protons. NRL Progress Report. August 1967.

A computer program has been written for determining the time needed to reduce the output power of a shielded solar cell by 25 percent when the cell is subjected to damage from protons in the Van Allen radiation belts. First, the change in omnidirectional differential spectrum of protons due to shields of various thickness is calculated. Then the damage to the solar cell is determined by multiplying the new flux spectrum by the damage per particle at each energy for the solar cell and integrating the results over all energies. The time required to reduce the output power of a 1 ohm-cm, n/p, blue-sensitive solar cell by 25 percent has been calculated as a function of shield thickness for nine fused silica shields ranging in thickness from 10 to 1000 milligrams per square centimeter. The data of lifetime T in seconds versus shield thickness R fits the equation $T = 4.8 \times 10^3 R^{2.05}$ for thicknesses between 10 and 200 milligrams per square centimeter. Above 200 milligrams per square centimeter, lifetime increases at a slower rate with increasing shield thickness.

11. Carter, J. R., and R. G. Downing. Effects of Low Energy Protons and High Energy Electrons on Silicon. U. S. National Aeronautics and Space Administration, Washington, D. C. NASA Contract Report 404. March 1966.

Hall coefficient measurements indicate that the radiation induced defect introduction rate rises slowly for the $E_c - 0.17$ eV and $E_c - 0.4$ levels and rapidly for the $E_v + 0.3$eV level with increasing electron energy above 1MeV. The results are related to silicon solar cells and it is found that the defect introduction rate for $E + 0.3$ eV level and the damage rate of an n/p solar cell have identical energy dependence.

Other results indicate that the recombination centers in high energy irradiated n/p silicon solar cells are associated with double displacement defects.

Under proton irradiation in the 0.2 to 1.9 MeV range, I_{SC}, Voc, and P_{max} degradation rates increase considerably as compared to those for high energy (penetrating)protons with a peak power degradation at approximately 2 MeV.

Experiments using the damage coefficient K as a criterion of sensitivity were conducted on boron and aluminum doped silicon to determine the effects of dopant material on radiation response. The results of bombardment by 1 MeV electrons on 1 ohm-cm and 10 ohm-cm cells indicate no significant difference in radiation sensitivity.

12. Cherry, William R., and Luther W. Slifer. Solar Cell Radiation Damage Studies with 1 MeV Electrons and 4.6 MeV Protons. U.S. National Aeronautics and Space Administration, Washington, D.C. NASA Technical Note D-2098. Feb. 1964.

n/p silicon solar cells with base resistivities ranging from less than 1 ohm-cm to 25 ohm-cm, two drift field n/p silicon cells, and a 1 ohm-cm p/n silicon cell were irradiated 1 MeV electrons and 4.6 MeV protons. Using a standard reflector flood tungsten bulb the percent changes in I_{SC} and P_{max} caused by 10^{16} electrons/cm^2 and 3×10^{11} protons/cm^2 were determined and compared. The results show a decrease in sensitivity to 1 MeV electrons with increasing base resistivity up to at least 25 ohm-cm. Radiation resistance to 4.6 MeV protons increases at least to 10 ohm-cm but beyond this no improvement is evident. In both cases the 1 ohm-cm p/n cell displays a lower radiation resistance than the 1 ohm-cm n/p cell while the data indicate that the drift field cells are superior to non-drift field cells under 1 MeV electron bombardment.

13. Cooley, W.C., M.J. Barrett. Handbook of Space Environmental Effects on Solar Cell Power Systems. Report on contract NASw-1345. Jan. 1968.

This handbook provides a review of research data and analytical methods for evaluation of silicon solar cell power systems for earth satellites which have orbits passing through the magnetosphere and for spacecraft exposed to solar flares and micrometeoroids. The methods are limited to uniform damage effects, although some information is given regarding nonuniform damage.

14. Crowther, D. L., et. al. An Analysis of Nonuniform Proton Irradiation Damage in Silicon Solar Cells. IEEE Trans. on Nuclear Science NS-13: No. 5, 37-49. Oct. 1966.

One ohm-cm n/p uniform silicon solar cells were irradiated with 0.22, 0.32, 0.5, 1.0, and 3.0 MeV protons. Measurements consisted of the initial diffusion length measured with a Co^{60} source and short circuit current degradation measured under tungsten illumination. The results show that the damage constant rises less rapidly with decreasing proton energy below 1 MeV than at high energies. With the aid of an N-layer solar cell model the damage constant was fitted to the data yielding the equation

$$K(E) = \begin{cases} K_o e^{-1.08 E} & \text{if } E \le 0.962 \text{ MeV} \\ K_o e^{-1.08 E} (E/.962)^{-0.85} & \text{if } .962 \le E \le 2.98 \text{ MeV} \end{cases}$$

where K_o equals 1.92×10^{-5} and E is the proton energy in MeV. The measurements were taken under artifical light; the calculated values of the proton damage coefficient from this expression are expected to be a factor of 2.3 higher than would be measured in space sunlight.

15. Curtin, Denis J. "Solar Cells at Synchronons Altitude" Symposium Summary (Preliminary) Report, Communications Satellite Corporation. March 15, 1968.

Among the topics discussed at this symposium was radiation damage to solar arrays. The unusually large degradation of solar arrays which have regions of the solar cell unprotected by the coverslide was attributed to a shunting effect resulting from a marked change in the junction characteristics of the affected region from low energy protons. Results of experiments (by Art Wilbur of Ames Research Center) on the transmission loss of coverglasses due to very low energy protons showed a loss of 45% at 0.7 microns after 5×10^{17} (2 keV) protons/cm^2 due to degradation of the anti-reflective coating. Other areas of discussion included possible remedies for present array degradation, definition of the radiation environment, and a compilation of satellites and flight results.

16. Curtis, Orlie L. Jr. Neutron-Induced Lifetime Degradation in Silicon. (Northrop Nortronics, Newbury Park, Calif.). pp855-83 of Lattice Defects and Their Interactions. Hasiguti, R. R. (ed.). New York, Gordon and Breach Science Publishers, 1967.

Effects of dopont impurities and oxygen on the degradation of the carrier lifetime of silicon by neutrons was investigated. Arsenic, phosphorus, gallium, and boron were utilized over a wide range of carrier concentration in materials grown by different techniques. No dependence of the rate of lifetime degradation on impurity was observed. The reason for the wide variation in degradation rates reported in the literature for neutron-irradiated silicon are injection level effects and annealing effects, with injection-level effect being more important. In In all cases the lifetime was strongly dependent upon injection level. To obtain exponential photoconductivity decays, excitation levels as low as 0.01% were required. Following room-temperature irradiation the samples were stored in dry ice. Measurements were performed after total time at room temperature of about 2 hours. For the conditions of these measurements the number of neutrons/cm^2 required to reduce the lifetime 1 μ sec. in initially perfect samples varied from 8.2 x 10^{10} for 0.5 - ohm-cm n-type material to 2.1 x 10^{11} for 60-ohm-cm n-type material. For p-type material the required dose values of 1.1 x 10^{11} to 3.3 x 10^{11} correspond to the restivity range 0.6 to 38 ohm-cm.

17. DeLafond, Y. G., D. Devillers, F. Cambou. Comment Delivered at the Symp. on the Physics of Semiconductors. July 1964.

Calculations are presented for the displacement density of results of atoms in a silicon crystal due to proton bombardment. Elastic scattering and nuclear interacting are treated separately for proton energies up to 10^5 MeV. A comparison is made between results obtained for elastic scattering under the assumption of a point nucleus and the assumption of a Yukawa distribution of the nuclear charge, showing the latter tends to reduce the elastic scattering cross section by 30-50% for proton energies above 10 MeV.

18. Denney, J. M., et. al. Charged Particle Radiation Damage in Semiconductors, IV: High Energy Radiation Damage in Solar Cells. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS 5-1851. TRW 8653-6017-KU-000. Jan. 1963.

Radiation damage produced in silicon by 95.5 MeV protons is experimentally described by measurements of I_{SC} deterioration, changes in I-V characteristics, changes in minority carrier diffusion length, and comparative analysis of the photovoltaic and proton-voltaic effects. It is shown that because of the dependence of the minority carrier diffusion length on minority carrier density, the damage coefficient, K, obtained in silicon can vary by a factor of about two in p-type silicon exposed to 95.5 MeV protons. It is concluded that the damage coefficient obtained by the proton-voltaic effect at this energy is too large by these ratios for the description of solar cell deterioration under sunlight.

19. Denney, J. M., G. W. Simon, R. G. Downing. Charged Particle Radiation Damage in Semiconductors, III: The Energy Dependence of Proton Damage in Silicon. TRW Space Technology Labs., Redondo Beach, Calif., Report on Contract NAS 5-1851. TRW 8653-6005-KU-001. Feb. 1963.

Changes in the defect density calculated in a previous paper are presented. The changes are due to two modifications of the previous theory: 1) a more detailed and accurate calculation, using the theory of LeCouteur, of the number of slow nucleons emitted; and 2) a calculation of the changes in the recoil energy of the target nucleus during the evaporation process, a phenomenon previously neglected. The defect density calculated by the new method was found to be 10 to 25 percent higher than that determined before.

20. Downing, R. G. Low Energy Proton Degradation in Silicon Solar Cells. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-7. January 1966.

Ten ohm-cm, 1 cm by 1 cm n/p silicon solar cells were bombarded with protons of energies from 0.2 MeV to 1.9 MeV and 1 ohm-cm by 1 cm p/n silicon solar cells with 0.5 MeV protons. Both had junction depths of 0.5 microns and initial efficiencies of 8 to 10 percent. Only enough data to ensure correlation was taken for the p/n cells. Measurements consisted of the cell I-V characteristics observed under the STL sun simulator and unfiltered tungsten light. The experiment shows that at low energies the short circuit current density degradation rate varies considerably with energy from 10.5 to 15.5 ma/cm^2 per decade of fluence as opposed to 6.5 to 7 ma/cm^2 per decade of fluence for penetrating radiation. The degradation rate of the V_{oc} is approximately 120 mv. per decade of fluence while that observed with penetrating electrons and protons is on the order of 40 to 50 mv/decade. The maximum sensitivity of V_{oc} seems to lie between 1.5 and 2 MeV and the shift from the 40 to 50 mv/decade region to that of higher degradation occurs between 2 and 6.7 MeV. It appears that the greatest degradation of P_{max} is approximately 45 percent per decade between 1.9 and 0.5 MeV. For penetrating radiation it ranges from 15 to 20 percent per decade.

Post irradiation measurements indicate that considerable room temperature annealing occurs for low energy proton irradiated cells. Although none was observed in V_{oc} recovery of 20 to 90 percent I_{sc} was observed in times of the order of days.

21. Faraday, B. J., R. L. Statler, and R. V. Tauke. Thermal Annealing of Proton-Irradiated Silicon Solar Cells. Proceedings of the IEEE. Jan. 1968.

Solar cells made from 1.5 and 10 Ω - cm p- type silicon were irradiated by 4.6 MeV protons at room temperature to fluences ranging from 10^{10} to 10^{12} p/cm^2. The resulting damage was observed to anneal in two stages as the annealing temperature increased: The first between 50 degrees and 150 degrees C and the second between 350 degrees and 450 degrees C. This differs markedly from the annealing reported for 1 MeV electron damage, where practically no recovery is observed below 350 degrees C. Annealing of the 10 Ω - cm cells was slightly more complete than annealing of the 1.5 Ω - cm cells, although in both cases over 85 percent recovery was obtained after annealing near 500 degrees C.

22. Haynes, G. A., and W. E. Miller. Effects of 1.2 and 0.30 MeV Electrons on the Optical Transmisssion Properties of Several Transparent Materials. U. S. National Aeronautics and Space Administration, Washington, D. C. NASA Technical Note D-2620. March 1965.

The optical transmission of several materials was measured before and after irradiation with 1.2 and 0.3 MeV electrons. Spectral transmission tests were made for the range from 0.25 to 2.7 microns. The maximum fluence used was 2.7 x 10^{15} e/cm^2. In the cases of materials commonly used for solar cell shields the fluence was increased to 10^{17} e/cm^2. The transmission measurements were made using a solar cell at room temperature illuminated with tungsten light at an intensity of 100 mw/cm^2. The transmission was obtained from the ratio of I_{sc} of the covered cell to I_{sc} of the uncovered cell.

Sapphire, synthetic fused silica, and some radiation shielding glasses are almost totally undamaged for fluences up to 2.7 x 10^{15} e/cm^2. Other substances that did degrade did so mainly in the ultraviolet and visible region. Materials which suffered severe damage did so at low exposures. It is possible that bleaching by ultraviolet light may significantly reduce the degree of radiation damage.

23. Hulten, W. C., W. C. Honoker, J. L. Patterson. Irradiation Effects of 22 and 240 MeV Protons on Several Transistors and Solar Cells. NASA Technical Note D-718. April 1961.

The solar cells used were 1 cm x 2 cm, p/n, nominally 8 percent efficient, and with no coatings or coverglasses, the same as those used on the Scout micrometeroid satellite. Two out of four cells in each test had simulated windows of 1/16 inch thick commercial grade fused quartz spaced approximately 1/16 inch from the cell surface. Under 22 MeV irradiation of 1.95 x 10^{13} protons/cm^2 the quartz window was visibly darkened. Although the window gave some protection to the cell for this energy the darkening approximately nullified the effect. 240 MeV protons did not darken the quartz and hence the percentage reduction of I_{sc}, V_{oc}, and P_{max}, obtained with and without the windows were the same.

Annealing studies showed that the 22 MeV irradiated cells changed little after 3 months at room temperature but the 240 MeV irradiated cells had a 4 percent power recovery after 3 weeks. After 3.5 days at 130 degrees all of the cells showed a power recovery of approximately 2 percent.

24. Janni, J. F. Calculations of Energy Loss, Range, Pathlength, Straggling, Multiple Scattering, and the Probability of Inelastic Nuclear Collisions for 0.1 to 1000 MeV Protons. Air Force Weapons Laboratory. Technical Report No. AFWL-TR-65-150. Sept. 1966.

Theoretical calculations of the proton range in a large number of materials have been made by integration of the energy loss as determined from the Bethe Equation. Proton energies between 0.1 and 1,000 are considered. The energy loss and range calculations have been compared with the available experimental data and the mean deviation is usually within 1.0 percent.

25. Lodi, Edward. Lockheed Low-Energy Proton Damage Experiments. In Transcript of the Photovoltaic Specialists Conference. Vol. I, Section B-4. July 1963.

Irradiation of p/n and n/p oxygen-free silicon solar cells by 100 and 500 keV protons shows that at 500 keV degradation of I_{sc} is **similar** to that for high energy proton irradiation. At 100 keV, however, V_{oc} degrade more rapidly than Isc. This is due to damage to the junction characteristics since in silicon the range of 100 keV protons is approximately equal to the junction depth of the solar cell. For n/p cells the 500 keV effects were much the same. At 100 keV they displayed a similar trend but the degradation of V_{oc} saturated and with sufficient integrated flux increased.

26. Marcinkowski, A. Range-Energy Relation for Low Energy Protons in Si and Ge. (Inst. of Nuclear Research, Warsaw); Rzewuski, H.; Werner, Z. Nucl. Instrum. Methods, 57: 338-40 (Dec. 1967).

The range-energy relations for protons of energy between 0.8 and 2.0 MeV in Si and Ge were determined. For the measurement of the proton energy a 100 channel pulse-height analyzer and silicon semiconductor detector were used. The range energy relations for Si and Ge were assumed to be of the form $R(\mu m) = a\ E^{x}$ (MeV) and the parameters a and x were calculated using a least-squares fit. The following analytical expressions were obtained:

$$R_{Si}\ (\mu\ m) = 16.41\ E^{1.64}\ (\text{MeV}) \text{ and } R_{Ge}\ (\mu\ m) = 7.52\ E^{2.05}\ (\text{MeV}).$$

27. Martin, J.H., R.L. Statler, E.L. Ralph. Radiation Damage to Thin Silicon Solar Cells. Advances in Energy Conversion Engineering, 1967. pp. 289-96.

The effect of 1 MeV electron radiation and operating temperature on 2 ohm-cm and 10 ohm-cm base resistivity n/p silicon solar cells of 3.7-12 mills thickness was studied. The current-voltage curves were determined using an OCLI solar simulator for temperatures from 13 degrees C to 54 degrees C and radiation levels from 1.3×10^{19} to 5.1×10^{21} electrons/cm^2.

Results showed that irradiation raises the temperature coefficient of V_{OC} in all cells. 10 ohm-cm cells have a greater rise than 2 ohm-cm cells and thick cells are more affected than thin.

Measurements of V_{OC} and I_{SC} showed that V_{OC} decreased for all cells with increasing doses but that thin 10 ohm-cm resistivity cells were more resistant to radiation damage than the others. At 5×10^{21} electrons/ cm^2 10 ohm-cm cells began to produce more power than 2 ohm-cm cells.

Thin 10 ohm-cm cells deliver constant power for a longer time in a radiation environment than do the 2 ohm-cm cells but in low raidation environments the 2 ohm-cm cells are superior due to higher initial maximum power. While the thicker cells of a given base resistivity yield higher power initially they behave similarly regardless of wafer thickness, after extensive irradiation.

28. Reynard, D.L. Proton and Electron Irradiation of n/p Silicon Solar Cells, Locheed Aircraft Corp., Sunnyvale, Calif., Report LMSC 3-56-65-4. April 12, 1965.

One ohm-cm and 10 ohm-cm n/p cells were irradiated by 0.5, and 0.8, 1.0, and 2.0 MeV electrons and 0.5, 1.0, and 2.7 MeV protons.

Covered 10 ohm-cm cells were also included but only irradiated by 2.0 MeV electrons so the energy loss in passing through the cover would be small compared to the initial energy. The three covers tested were: 1) 20 mil Corning 7940 with no surface coatings, 2) 20 mil Corning 7940 with OCLI blue-reflective and anti-reflective coatings, and 3) 26 mil Corning 0211 with no coatings. Data consisted of I-V curves measured under illumination by an OCLI Solar Simulator.

There was no loss of effective transmittance after 10^{16} (1.5 MeV) electrons per cm^2 due to cover #1 but cover #2 caused a 3 percent loss of short circuit current. Microsheet caused 15-20% power loss over equivalent fused silica. The 10 ohm-cm cells retain short circuit current generating capabilities better but the 1 ohm-cm cells are equal or better with respect to V_{OC}, or P_{max}. The 10 ohm-cm cells offer no great advantage over 1 ohm-cm cells for the types used in the experiment although they may be slightly superior because of recent improvements in cell design and manufacturing techniques.

29. Robertson, J.B., R.K. Franks, T.E. Gilmer, Jr. Proton Bombardment of High-Purity Single-Crystal Silicon NASA Technical Note D-3989, May 1967.

Bombardment of high-purity silicon with 22 MeV protons has produced Al^{27} at a rate of 6×10^{-3} atoms per proton in a thick target. The production of aluminum in the crystals eliminated the study of damage in impurity-free silicon but, in return, provided for a study of defect interactions with aluminum. Three new infrared absorption bands were observed in the irradiated silicon with mean peaks at 8.9, 14.2, and 21.0 microns. The 20.5 micron absorption band, which has been reported in neutron irradiated silicon, was found in proton irradiated silicon.

30. Stanley, A.G. Effects of Low Energy Proton Irradiation on Silicon Solar Cells. Lincoln Laboratory, Massachusetts Institute of Technology. March 1968.

Although solar cells in the synchronous orbit covered with 6 mil silica coverslides should be protected from low energy protons, it was shown that they suffered a loss of maximum power from 4 to 34 percent after irradiation by 5×10^{13} protons/cm^2 at 400 keV. The power loss was accompanied by a decrease in V_{OC} but little change in I_{SC}.

An examination of the covered solar cells revealed four unprotected regions: 1) the front contact consists of a silver-titanium alloy of insufficient thickness to stop all of the low energy protons, 2) the coverslide usually leaves a few mil peripheral region around the cell, 3) there is sometimes a gap between the contact and the coverslide, and 4) the sides of the cell are unprotected.

Qualitative results are given for 3 cells irradiated by 200, 300, and 400 keV protons to a fluence of 9.3×10^4 protons/cm^2 and a fourth with a 1/16 inch tantalum shield over the contact bar irradiated with 400 keV protons.

31. Statler, R. L. Radiation Damage in Silicon Solar Cells from 4.6 MeV Proton Bombardment. U. S. Naval Research Lab., Washington, D. C. NRL Report 6333. Nov. 15, 1965.

The degradation of thc I-V characteristics, diffusion length, and spectral response resulting from irradiation by 4.6 MeV protons was measured in 1 ohm-cm p/n silicon solar cells, 1 ohm-cm, 10 ohm-cm and 25 ohm-cm n/p cells, and n/p drift field cells. The p/n cells were in all cases less radiation resistant than the n/p cells used in this study. Within the group of n/p cells used the 10 ohm-cm cells has an I_{sc} degradation at 16 percent per decade of integrated flux and a power degradation of 20 percent per decade while the 1 ohm-cm cells had I_{sc} and a power degradations of 20 percent per decade and 23 percent per decade, respectively, showing a greater radiation resistance in the 10 ohm-cm cells. The drift field cells were superior to the 25 ohm-cm cells. Comparision of the 25 ohm-cm cells to the standard n/p solar cells on the basis of arbitrary power output is not valid because the 25 ohm-cm cells are initially less efficient.

32. Tada, H. Y. A Theoretical Model for Low-Energy Proton Irradiated Silicon Solar Cells. In Proc. of the 5th Photovoltaic Specialists Conference, Vol. II, Section D-8. January 1966.

Effects of low-energy protons on silicon solar cells were theoretically investigated. A model has been generated for low carrier injection levels and the solution is presented in a closed form in terms of physical and geometrical parameters. Both I_{SC}, and V_{OC} calculated from the theory were compared with experimental results. The computed I_{SC} agrees with the observed decay slope if the magnitude of the degradation is less than 6 percent for proton energies greater than 0.5 MeV. According to the theory, experimental values of the energy dependent damage constant at moderately high proton energies can be extrapolated back to about 0.5 MeV on the basis of the energy dependence of the Rutherford scattering cross section for a reasonable estimate of short circuit current degradation. A sharp decay of V_{OC} at low proton energies is also demonstrated by the theory.

33. Tauke, R. V. and B. J. Faraday, 'Proton-Irradiation Study of Pulled and Float-Zoned Silicon Solar Cells'. Proc. IEEE 55, 234 , February, 1967.

A comparison of the photovoltaic properties of pulled and float-zone silicon n-on-p solar cells exposed to 4.6 MeV protons at 30 degrees C showed that differences in the residual oxygen impurity did not play a major role in the radiation-induced damage.

34. Weller, J. F., and R. L. Statler, Low Energy Proton Damage to Solar Cells, Presented at the IEEE Summer General Meeting, Toronto, Canada, June 19, 1963. (Conference Paper CP 63-1184)

The effects of 4.66 and 4.80 MeV protons on various silicon n/p and p/n, oxygen free and oxygen rich solar cells were studied. Results show that with 4.66 MeV protons it takes approximately 10 times the fluence to produce equivalent damage in 1 ohm-cm n/p silicon cells compared to p/n cells, whereas with 1.0 MeV electrons, it takes 30 to 80 times the fluence. Measurements at P_{max} indicate that higher base resistivity cells are more radiation resistant. Measurements of the spectral response show that there is little surface damage in the n/p cells and that n/p cells suffer less bulk degradation than the p/n cells

Comparing the oxygen-free and oxygen-rich cells of the same configuration and base resistivity gave no obvious difference in the damage rate. Room temperature annealing of cells occurred and, qualitatively, the n/p cells annealed more than the p/n, and higher resistivity cells annealed more than those of lower resistivity.

35. Wysocki, J. J. Lithium-Doped Radiation-Resistant Solar Cells. IEEE Trans. on Nuclear Sci. NS-13 (6): 168-173 Dec. 1966.

Photovoltaic measurements indicate that lithium in the n region of silicon p/n solar cells interacts with 1 MeV electron and 16.8 MeV proton radiation induced damage to produce a center which preserves the minority carrier lifetime. The lithium was the dominant impurity in the base region of these cells.

The diffusion length degradation from 10^{14} e/cm^2/hr 1 MeV electrons was measured for the lithium cells and standard cells and it was found that the decay in both cases was comparable. The bombardment, however, was periodically interrupted at which times the diffusion length increased substantially in the lithium cells but not in the standard cells. This recovery was also evident in other cell characteristics such as the maximum power output. The recovery of the lithium cells to 16.8 MeV proton induced damage was similar to that observed for 1 MeV electrons.

In general it was found that when lithium cells are irradiated at a low rate at room temperature they degrade only slightly. Under high rate irradiation the degradation is comparable to standard cells but the lithium cells are "self healing". It is estimated that lithium cells may be 10 times more damage resistant to 16.8 MeV protons than 1 ohm-cm standard n/p cells. it is obvious that a new center is involved in the lithium cells although the nature and formation mechanism of this center are not yet established.

36. Vavilov, V. S. Effects of Radiation on Semiconductors. Consultants Bureau, New York, 1965.

An early comprehensive text in which the formation of secondary structural defects as a result of elastic collision cascades is considered. A theoretical evaluation of the number of atoms displaced by a particle is given, along with a comparison of various theories on the energy dependence of this process. The basic processes of light absorption, ionization, recombination, and radiation effects are reviewed.

VII. New Technology

No reportable items of new technology have been identified during performance of this work.