RADIATION DAMAGE IN HIGH-VOLTAGE SILICON SOLAR CELLS

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During the past several years, the NASA Lewis Research Center has conducted a program to achieve high open-circuit voltage V_{OC} in silicon solar cells. To date, three cell designs have been developed under this program and air-mass-zero (AMO) open-circuit voltages of approximately 645 millivolts have been achieved. Although the program has been directed primarily toward demonstrating increased V_{OC}, the effects of the particulate space radiation environment on cell performance are an ever present concern. Hence, we have determined the performance, after exposure to 1-MeV-electron irradiations, of the three cell designs emerging from this program.

EXPERIMENTAL PROCEDURE

The salient features of the cells are given in table I. The ion-implanted and high-low emitter (HLE) cells have thermally grown silicon dioxide (SiO_2) on their front surfaces; the diffused cells have no front-surface oxide. The oxide on the HLE cells was formed by using a temperature-time schedule that results in a net positive charge, in the oxide, near the oxide-silicon interface (ref. 1). The positive oxide charge induces an accumulation layer at the silicon surface and thus establishes the n^+n high-low emitter junction.

Preirradiation AMO parameters are listed in table II. Diffusion lengths were measured by an X-ray excitation technique with 250-keV X-rays (ref. 2); the AMO-current-voltage measurements were obtained with a xenon-arc solar simulator. Spectral response data were obtained by using a filter-wheel solar simulator (ref. 3). Both X- and electron irradiation result in changes in oxide charge (refs. 4 and 5). Therefore, only one of each pair of oxide-coated cells was exposed to X-irradiation for diffusion length measurement. However, all cells were exposed to 1-MeV-electron irradiations to a maximum fluence of 10^{15} cm^{-2}.

RESULTS AND DISCUSSION

A typical data plot used to determine the diffusion-length damage coefficient is shown in figure 1. Table III summarizes the damage coefficients obtained for each cell design. Comparison with previous damage coefficient evaluations (ref. 6) indicates that the damage coefficients obtained for the present high-V_{OC} cells are typical of 0.1-ohm-cm p-type silicon.

Plots of normalized short-circuit current I_{SC} and V_{OC} as a function of 1-MeV-electron fluence are shown in figures 2 and 3, respectively. Data for a 10-ohm-cm cell are included for comparison. This cell showed a decrease in output typical of that resistivity. In general, performance degradation under irradiation was highest for the HLE cells, with the greatest degradation being noted for the X-rayed HLE cell. For the ion-implanted cells, there was no measurable difference between the X-rayed and non-X-rayed cell performance. Both diffused and ion-implanted cell designs degraded at approximately the same rate. The I_{sc} and V_{oc} degradation data for the HLE cells appear to be anomalous because the diffusion-length damage coefficient K is approximately the same for all cell designs. However, K is largely a measure of the degradation occurring in the cells base region. Hence, in attempting to understand the observed increased degradation of the HLE cells, we must consider damage occurring in the emitter and oxide in addition to that occurring in the base region.

The sources of I_{sc} degradation are clarified by plots of the normalized short- and long-wavelength spectral response shown in figures 4 and 5. Since significant I_{sc} degradation of the HLE cells occurs at both long- and short-wavelengths, we concluded that I_{sc} degradation of the HLE cells occurs in both p-type base and n-type emitter. On the other hand, I_{sc} degradation of the ion-implanted and diffused cells occurs predominantly at long wavelengths and therefore predominantly in the base region. This tends to explain the observed, relatively higher I_{sc} degradation in the HLE cells despite the approximate equality of K values for all cell designs.

Calculations are in progress to determine the cell region in which V_{oc} degradation occurs. Preliminary results indicate that V_{oc} degradation occurs predominantly in the emitter region for the HLE cells and in the base region for the ion-implanted and diffused cells.

For the HLE cells, one source of the increased I_{sc} and V_{oc} degradation under irradiation is the use of a relatively deep (10 μm), n-type emitter. The damage coefficient for n-type silicon is an order of magnitude greater than that for p-type silicon (ref. 7). Since about 75 percent of the incoming optical radiation is absorbed in the 10-micrometer-wide HLE n-region, the increased susceptibility of n-type silicon to radiation damage is reflected in the increased degradation noted for the HLE cells under 1-MeV-electron irradiation. Thus, a large loss in the blue spectral response would be expected and was observed.

Another source of increased degradation of the HLE cells is the use of a charged oxide. It has been established that ionizing radiation affects the charge state of SiO_2 (refs. 4 and 5). Hence, so that the effects of the X-irradiation on the charged oxide cells could be explored, an additional HLE cell was exposed to 250-keV X-rays for 5 minutes, and its performance parameters were determined as a function of time after irradiation for times to 54 days (fig. 6). At this time, V_{oc} had degraded by 2.3 percent and I_{sc} by approximately 7 percent. These results clearly show that the X-irradiation causes performance degradation over and above that caused by electron irradiation. Since X-rays do not damage the silicon but are known to damage the oxide (refs. 4 and 5), the performance degradation shown in figure 6 is clearly attributable to oxide degradation.

The I_{sc} degradation shown in figure 6 is insufficient to account for the difference in total short-circuit-current degradation between the X-rayed and non-X-rayed cells after irradiation by 1-MeV electrons (fig. 2). One source of the added I_{SC} degradation could be synergism between the effects of X- and electron irradiations. Another possible source of the added degradation could be a difference in the quality of the silicon constituting the emitters of the two HLE cells of figure 2.

CONCLUSIONS

The results of the NASA Lewis Research Center program to achieve high V_{OC} in silicon solar cells show that cells with a relatively deep n-type emitter (high-low emitter (HLE) design) are more susceptible to radiation damage than other high-V_{OC} cell designs. Use of diffused or ion-implanted junctions leads to high-V_{OC} cell designs that are less susceptible to radiation damage. These latter two types of cells show degradations that are typical of the 0.1-ohm-cm material from which they are fabricated. Furthermore, exposure to ionizing radiation causes oxide degradation and decreased cell performance in cells that depend on a charged oxide to achieve significant cell properties. Hence, the combination of a charged oxide and a relatively deep n-type emitter is not recommended for incorporation into a cell designed for use in the particulate radiation environment of space.

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TABLE I. - TYPES OF HIGH-OPEN-CIRCUIT-VOLTAGE CELLS

[Base resistivity ≈ 0.1 ohm-cm; all cells n on p.]

	Ion implanted	High-low emitter	Diffused
Oxide	SiO_2	SiO_2 + charge near interface	None
Oxide depth, μm	0.1	0.01	----
n-layer depth, μm	0.2 - 0.3	10	1.5 - 2
Cell thickness, μm	300	260	200

TABLE II. - PRE-ELECTRON-IRRADIATION AMO CELL PARAMETERS

Cell type	Open-circuit voltage, V_{oc}, mV	Short-circuit current, I_{sc}, mA/cm^2	Maximum power, P_{max}, mW/cm^2	Fill factor, percent	Pre-irradiation diffusion length, L_0, μm	X-irradiated	
						Yes	No
Ion implanted	636	34.4	14.4	65.8	---		X
	636	35.5	14.5	64.1	158	X	
Diffused	626	20.3	9.3	73.3	279	X	
	623	19.8	9.2	74.4	158	X	
HLE	634	31.2	13.5	68	---		X
	640	28.6	14	76.5	47	X	

TABLE III. - DIFFUSION-LENGTH DAMAGE COEFFICIENTS

(a) Present data

Cell type	Diffusion-length damage coefficient, K
Ion implanted	$8x10^{-10}$
Diffused	$9x10^{-10}$
HLE	$10x10^{-10}$

(b) Previous data - 0.1-ohm-cm cells

Research	Diffusion-length damage coefficient, K
Srour, et al. (ref. 6), 1974	$7x10^{-10}$ to $8x10^{-10}$
Lewis data (unpublished), 1973	$9x10^{-10}$

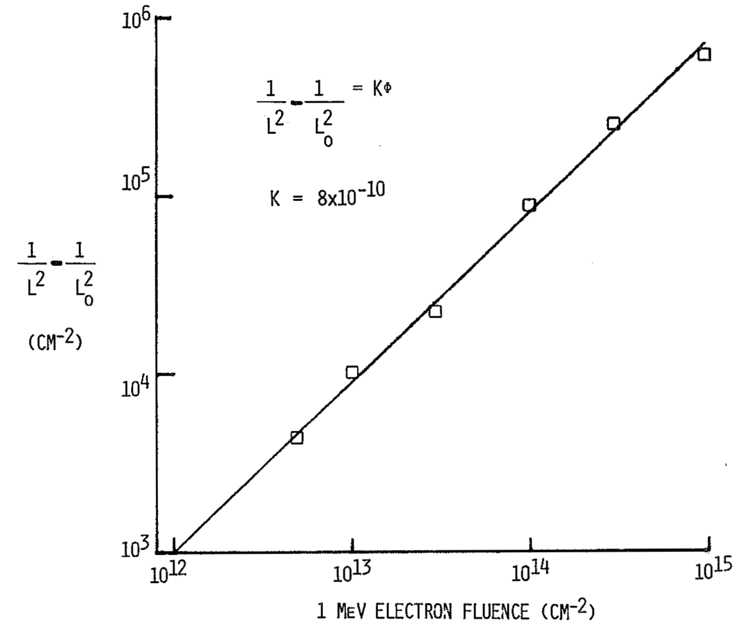

Figure 1. - Diffusion length as function of fluence for ion-implanted cell.

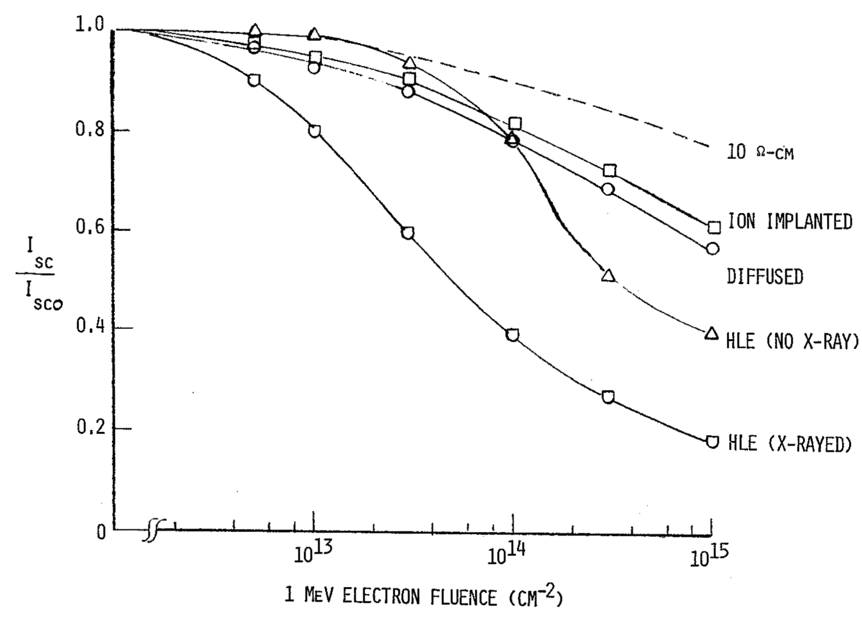

Figure 2. - Normalized I_{sc} versus electron fluence.

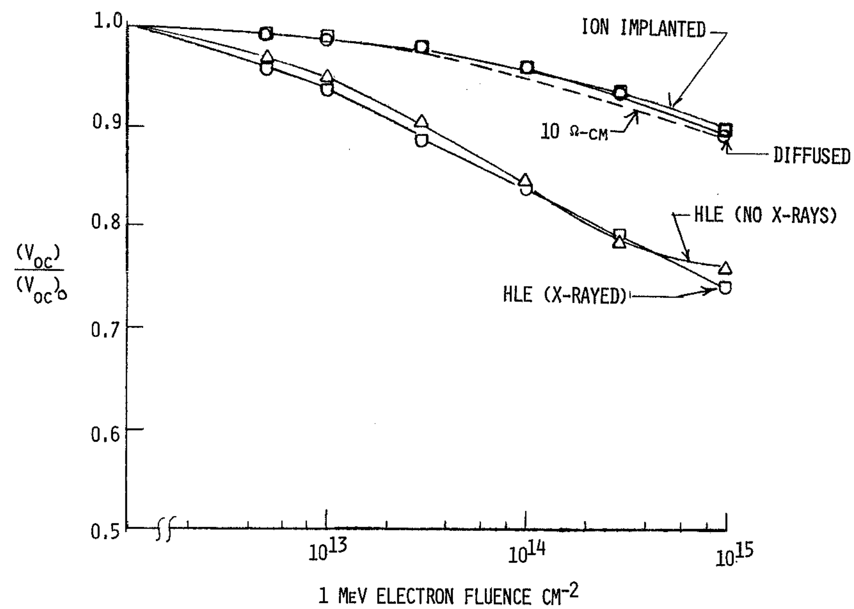

Figure 3. - Normalized V_{oc} electron fluence.

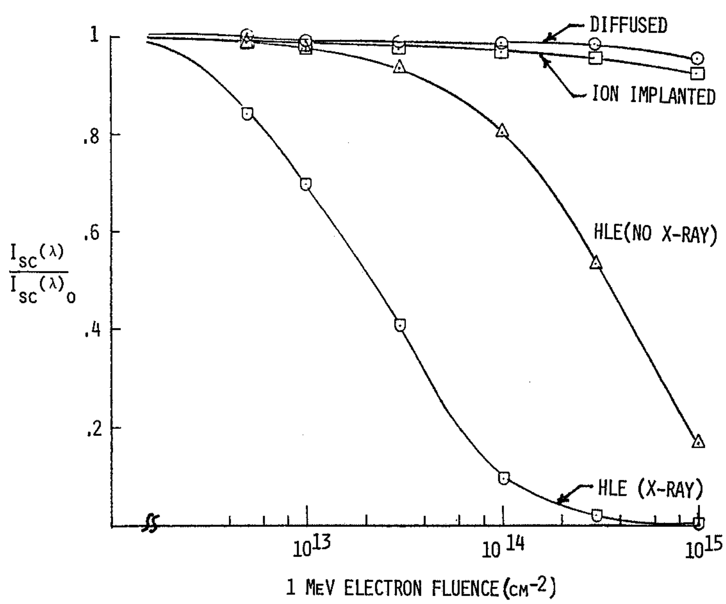

Figure 4. - Normalized spectral response at short wavelength. Wavelength, 0.45 micrometers.

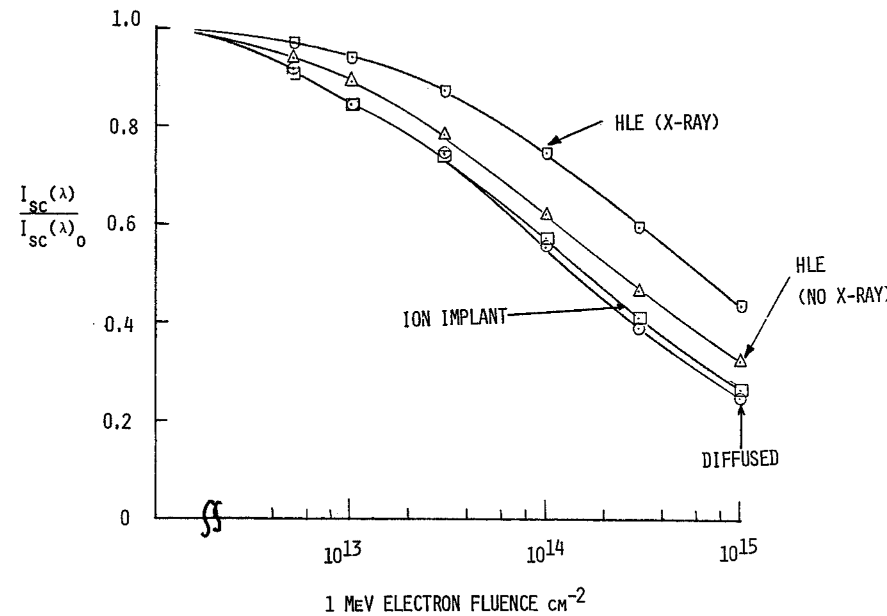

Figure 5. - Normalized spectral response at long wavelength (0.9 μm) after irradiation with 1-MeV electrons.

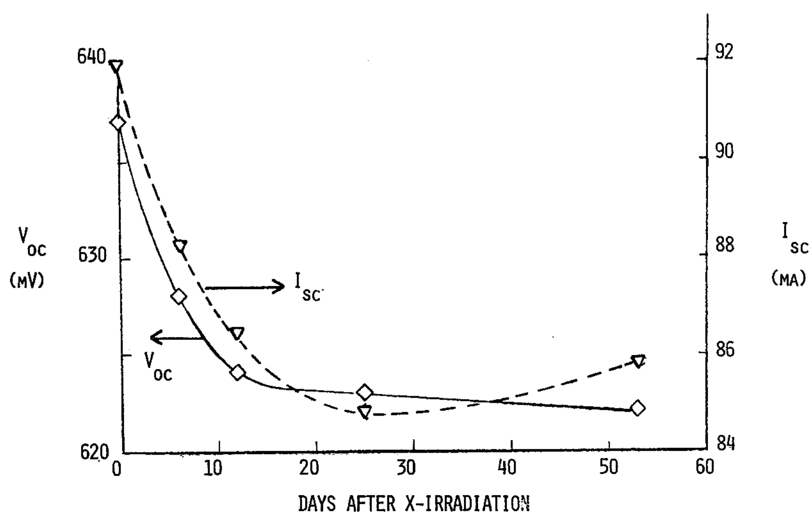

Figure 6. - Voltage and current decay in HLE cell exposed to x-irradiation only.