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EFFECTS OF UNIFORM DAMAGE

TO SILICON SOLAR CELLS

Second Quarterly Report

by

M. J. Barrett and R. H. Stroud

October 10, 1968

JPL Contract 952246

with

EXOTECH INCORPORATED
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Washington, D. C. 20024

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ABSTRACT

A theoretical analysis of published data on silicon solar cells has been performed. Reasonable values of the photovoltaic current density at the cell junction have been obtained as a function of the minority carrier diffusion length L in the base region. The calculation was performed on a computer with a numerical technique which appears applicable to a nonuniform profile of L across the base region, as occurs after low-energy proton damage.

The junction characteristics of the cells were also shown to be affected by radiation, light and temperature in ways that can be described by simple mathematical functions.

Contents

I. Introduction

In the previous quarterly report, the results of a survey of published efforts on proton radiation damage to solar cells were presented. During the current reporting period, the effects of damage are studied further for the special case where it is uniform across the solar cell. Uniform damage, of course, can be caused by fast protons or by electrons. To allow development of a mathematical model that may be generalized to include nonuniform damage, a computer-oriented approach has been devised.

Equations which were introduced in the previous report will form the basis of the model that is developed herein. These equations describe the reduction in minority carrier diffusion length L due to radiation, the resulting decrease in short-circuit current, and the changes in the other parameters of the solar cell equation due to radiation.

The analysis of a decrease in short-circuit current, due to a uniform reduction in L, is presented as section II of this report. The study of the more general behavior of the solar cell, and the further effects of radiation, is presented as section III of this report. For the sake of completeness, the effects of temperature and light intensity are included in the mathematical development.

II. The Short-Circuit Current

A. The Difference Equation

The short-circuit current I_{sc} approximates the photovoltaic current I_L for silicon solar cells with typically negligible resistance.[1] The photovoltaic current is simply the photovoltaic current density j multiplied by the area of the solar cell that is exposed to the light source. This is somewhat less than the actual front surface area, inasmuch as the front contact typically covers 10% of the total surface. The continuity equation implies that j is also proportional to the light intensity U for a given spectrum.

The equations necessary for determination of j are the continuity equation

$$\frac{1}{q}\frac{dj}{dx} - \frac{n}{\tau(x)} + G(x) = 0 \qquad (1)$$

the current equation

$$j = q\ D\ \frac{dn}{dx} + q\ \mu\ E\ n \qquad (2)$$

the damage equation

$$\frac{1}{L^2} = \frac{1}{L_0^2} + K\ \Phi \qquad (3)$$

the diffusion relation

$$L^2 = \tau\ D \qquad (4)$$

and the Einstein relation

$$q\ D = \mu\ k\ T \qquad (5)$$

(The symbols are defined in the Glossary)

Combining the continuity and current equations eliminates j. Furthermore, it may be assumed that D and E are constant through the region being considered. The resulting expression may be written as a difference equation

$$D\left[n_{k+1}-2n_k+n_{k-1}\right]+\mu Eh\left[n_k-n_{k-1}\right]-n_k h^2/\tau_k+G_k h^2=0 \qquad (6)$$

where the continous differential equation is approximated by using discrete values of n for points of the independent variable x spaced a distance h apart. (Thus, n_k is the magnitude of n at a distance k h from the junction.)

Grouping the expressions gives a formula for progression in the solution of n_k. After elimination of μ by the Einstein relation and τ by the diffusion relation, the formula becomes

$$n_{k+1}=(2-qEh/kT+h^2/L_k^2)\,n_k+(qEh/kT-1)n_{k-1}-G_k h^2/D \qquad (7)$$

Radiation damage affects the solution to this formula principally by decreasing L_k^2 according to the damage equation

$$\frac{1}{L_k^2}=\frac{1}{L_o^2}+K\ \Phi\ (x_k) \qquad (8)$$

where the particle fluence to which an incremental volume of the cell (at depth x_k) is exposed becomes an integral over all particle energies. When there are several types of particles (electrons, protons, alpha particles, etc.) there will be a sum of several integrals.

The assumptions are made here that any change in D is negligible, and that the migration of the damage-induced recombination centers from their points of formation is also a negligible effect. These assumptions allow a solution of Eq. 8 to be applied directly to Eq. 7 and the carrier density n_k to be developed.

The field E will be shown below to be proportional to temperature T. As a result, temperature enters into Eq. 7 only by increasing the diffusion coefficient in accordance with the Einstein relation. The increase in D reduces the magnitude of the negative term and leads to an increase in current with increase in temperature. The trend is in agreement with the positive temperature coefficient normally observed for the short circuit current. However, the current of solar cells not operated near short-circuit generally has a negative temperature coefficient because of diode characteristics discussed in the next section.

To solve Eq. 7, it is necessary to have values for n_0 and n_1. We assume the boundary conditions that the carrier density vanishes at the junction and at the cell surface. This assumption was also made by Bullis and Runyan,[2] but other boundary conditions have been assumed.[3] We guess n_1 and calculate all the higher values of n_k. We iterate this guessing of n_1 until we arrive at a satisfactory value for the carrier density at the cell surface.

The accuracy of the initial guess for n_1 is of importance in determining how often the calculation must be iterated before obtaining a zero carrier density at the contact surface of the cell. If the guess for n_1 is too small, then the values of n_k determined via Eq. 7 will change sign in the cell. If it is too large, the n_k at the back of the cell will fail to be zero.

Iterating on n_1 leads to as close an estimate as is desired. One possible technique for convergence is to compare each n_k with n_{k-1} and if there is a sign change then stop, increase the estimate for n_1 by a nominal 10% and repeat. When there is no sign change, decrease the estimate for n_1 by a nominal 5% and repeat until a sign change occurs. Then increase by 1% until there is no sign change. Such a convergence routine can obviously be carried to any level of accuracy in the estimate of n_1 for the solar cell in question, by taking advantage of this sign change.

The current equation relates n_1 to the current from the base into the junction. Evaluating this as a difference equation at k equal zero, we have

$$j = q D n_1 / h \qquad (9)$$

since the boundary condition requires that n_o vanishes. This j is the calculated photovoltaic current I_L in amperes per square centimeter, for the solar cell. For a cell with negligible internal resistance, the short-circuit current I_{sc} is j times that portion of the surface area not covered by the contact bar and grid.

Equation 7 is simplified in the base region since the electric field E is negligible in a uniformly-doped crystal. The electric field is dependent on the impurity concentration, N, through the relationship[4]

$$E = \frac{-kT}{q} \frac{1}{N} \frac{dN}{dx} \qquad (10)$$

When there is no impurity concentration gradient in the base region, Eq. 7 reduces to

$$n_{k+1} = (2 + h^2/L_k^2)\, n_k - n_{k-1} - G_k h^2/D \qquad (11)$$

The current density calculation so far has considered only the solar cell base region contribution. In order to determine the contribution by the surface region, the same procedure may be used. Since the surface region is heavily doped, and, consequently, has a relatively short minority carrier lifetime,[5] this contribution to the total photovoltaic current density is small and often neglected. The electric field does not vanish in this region because of the dopant gradient which is the result of diffusing phosphorus into the crystal to form the p/n junction. The magnitude of the photovoltaic current contributed by the surface layer is not significantly changed unless the electric field is on the order of 10^3 volts/cm.

Calculations by Tada [6] using penetrating radiation indicate that either the field is generally small enough or exists over a region of the surface layer small enough to be neglected.

B. Computer Calculations

In the solution of the difference equation the contribution to G(x) from different parts of the incident light spectrum must be considered. The source term is due to light within a range of wavelengths

$$G(x) = \int_{\lambda_1}^{\lambda_2} G(x, \lambda)\, d\lambda \qquad (12)$$

where λ_1 and λ_2 are the minimum and maximum wavelengths of sunlight to which the solar cell responds. These are normally taken as 0.4 and 1.1 microns.

Since no simple, closed form has been reported for the integral, G(x) may best be calculated using Simpson's Rule. The integrand is given by

$$G(x, \lambda) = \alpha(\lambda) H(\lambda) \left(\frac{\lambda}{2\pi\hbar c} \right) [1 - R(\lambda)] e^{-\alpha(\lambda) x} \qquad (13)$$

Values of the absorption coefficient $\alpha(\lambda)$ [7] and the spectral irradiance $H(\lambda)$ [8] for space sunlight* are given in Table 1. The spectral irradiances are calculated for a sunlight intensity of 140 milliwatts per cm^2. The resultant G(x) is illustrated in Figure 1 for x up to .025 cm of silicon. $R(\lambda)$, the fraction of the incident light reflected at the surface, is usually on the order of two or three percent for solar cell assemblies.

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*Spectral irradiance may be defined as the differential of solar energy flux per unit wavelength. This is frequently depicted by Johnson's curve.

Table 1

Absorption Coefficient of Silicon and Sunlight Intensity as a Function of Wavelength.

λ in microns, $\alpha(\lambda)$ in cm^{-1} (Ref. 7)
$H(\lambda)$ in $watts/cm^2-\mu$ (Ref. 8)

λ	$\alpha(\lambda)$	$H(\lambda)$
0.40	7.50×10^4	0.1540
0.45	2.58×10^4	0.2200
0.50	1.18×10^4	0.1980
0.55	7.00×10^3	0.1950
0.60	4.65×10^3	0.1810
0.65	3.33×10^3	0.1620
0.70	2.42×10^3	0.1440
0.75	1.69×10^3	0.1270
0.80	1.12×10^3	0.1127
0.85	7.95×10^2	0.1003
0.90	3.80×10^2	0.0895
0.95	1.80×10^2	0.0803
1.00	7.30×10^1	0.0725
1.05	2.08×10^1	0.0665
1.10	4.40×10^0	0.0606

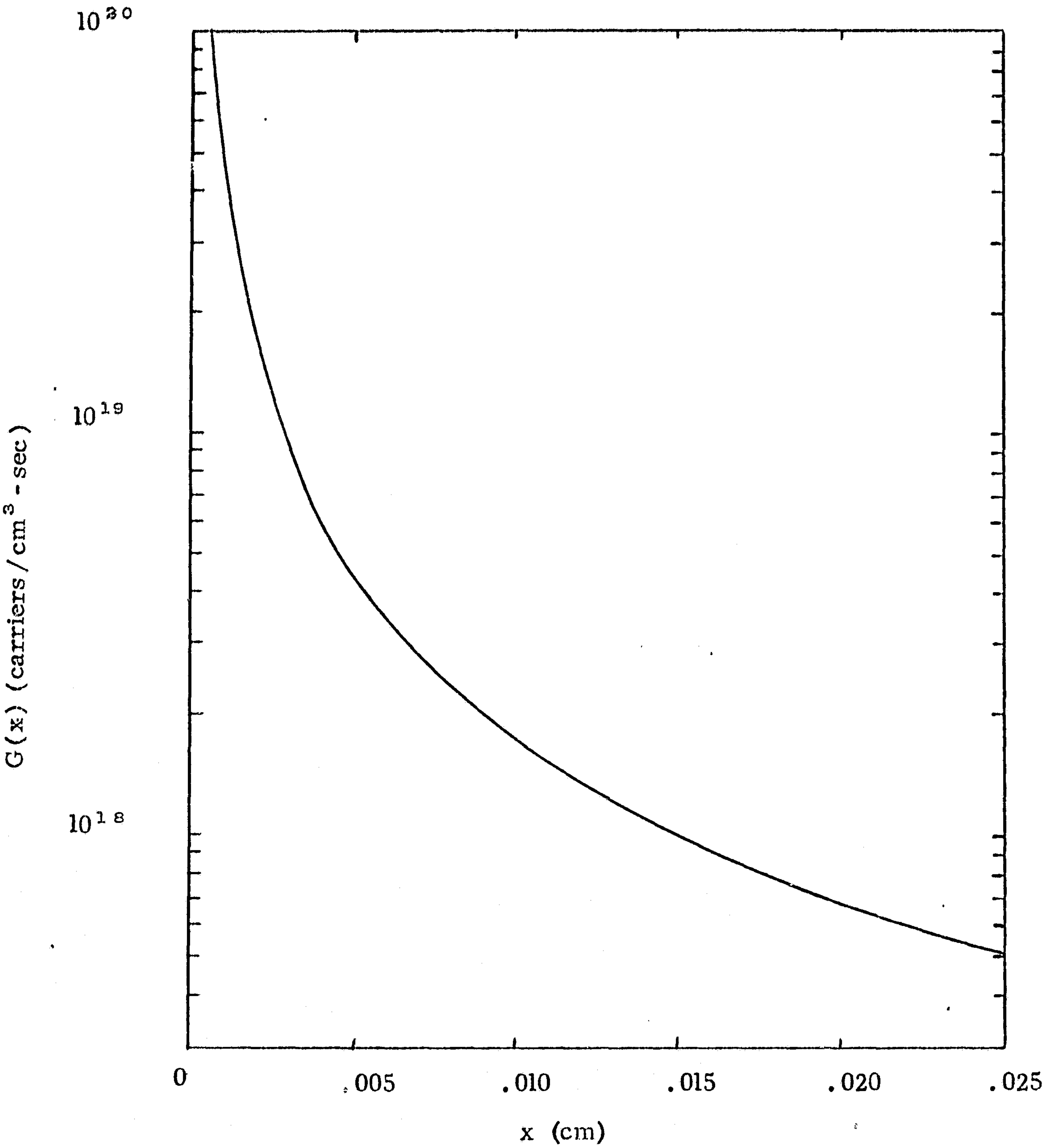

Figure 1. Computed values of the number of minority carriers / cm^3 - sec produced in silicon by space sunlight as a function of depth x of penetration. Values from Table 1 were used in equation 11 and reflection was neglected.

The difference equation yields a solution that usually depends on the mesh interval h. When h is made smaller and smaller, the solutions tend to the solution of the corresponding differential equation. Thus, the calculated value of j depends on the selection of h. We have performed several calculations, with different mesh sizes, of the sample cell described by Tada [6]. The results, seen in Figure 2, should extrapolate to his result for h going to zero.

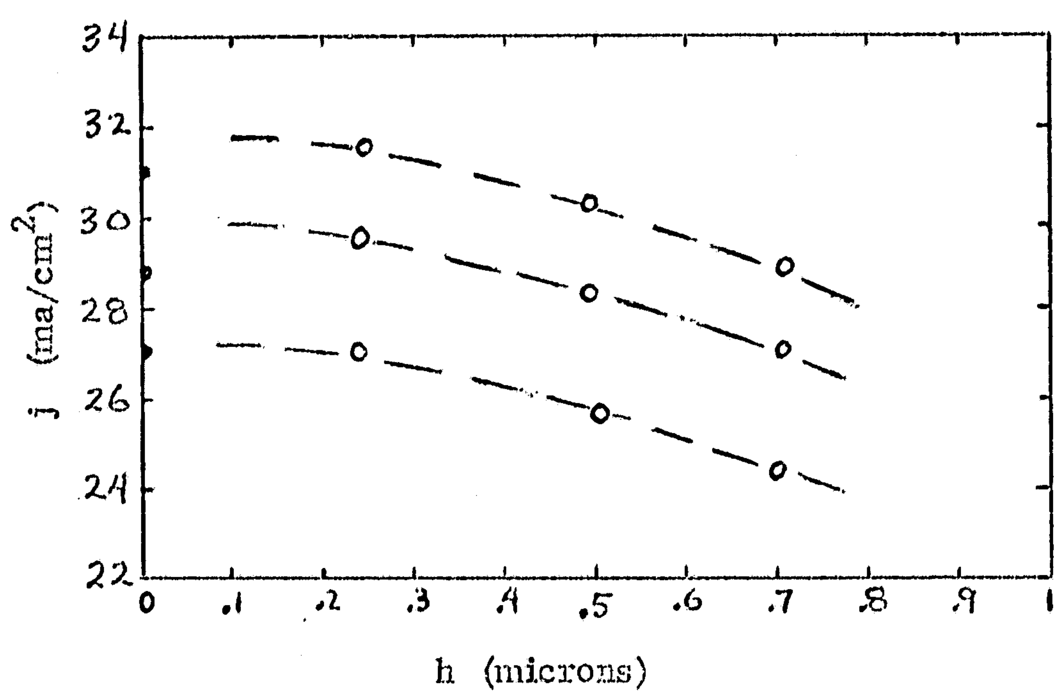

Figure 2. Calculated values of short-circuit current density versus mesh interval h, for three cells with different base minority carrier diffusion lengths L.

The minority carrier concentration for a 10 mil n/p solar cell was computed for various values of diffusion length. Figure 3 shows the results of the calculations with the base divided into 500 increments. Figure 4 shows a plot of the short-circuit current density versus diffusion length for these calculations.

The mathematical technique developed here has only been applied to solar cells where the minority carrier diffusion length is uniform across the base. As is obvious from Eq. 7, the technique is applicable to a situation where L is not constant across the base. This situation will be explored further in future work.

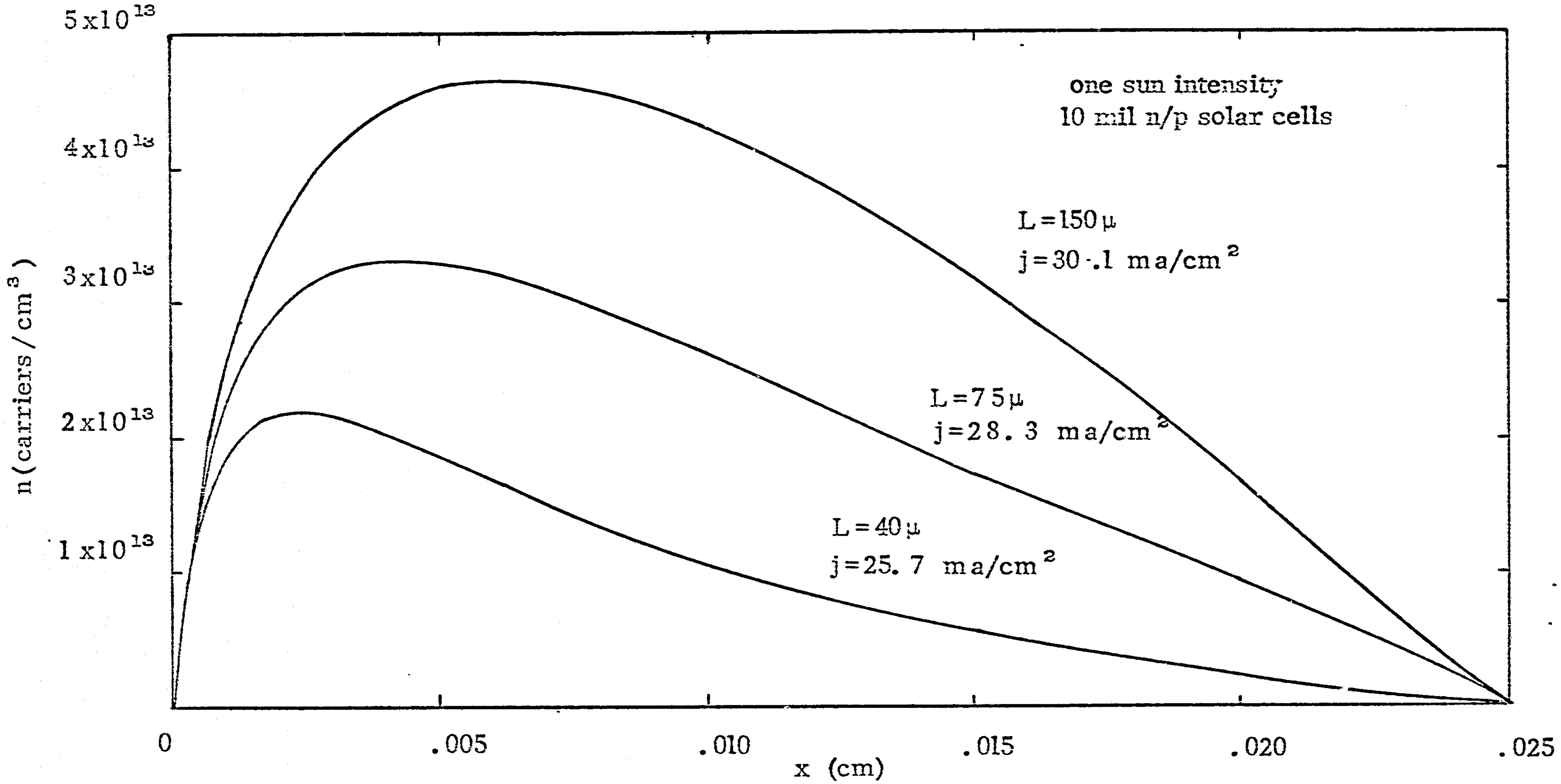

Figure 3. Minority carrier concentration (electrons / cm^3) as a function of distance from the junction in three solar cells with different values of L. These concentrations were computed using 500 intervals, and the photovoltaic current from base into junction, on each curve, was computed with Eq. 9.

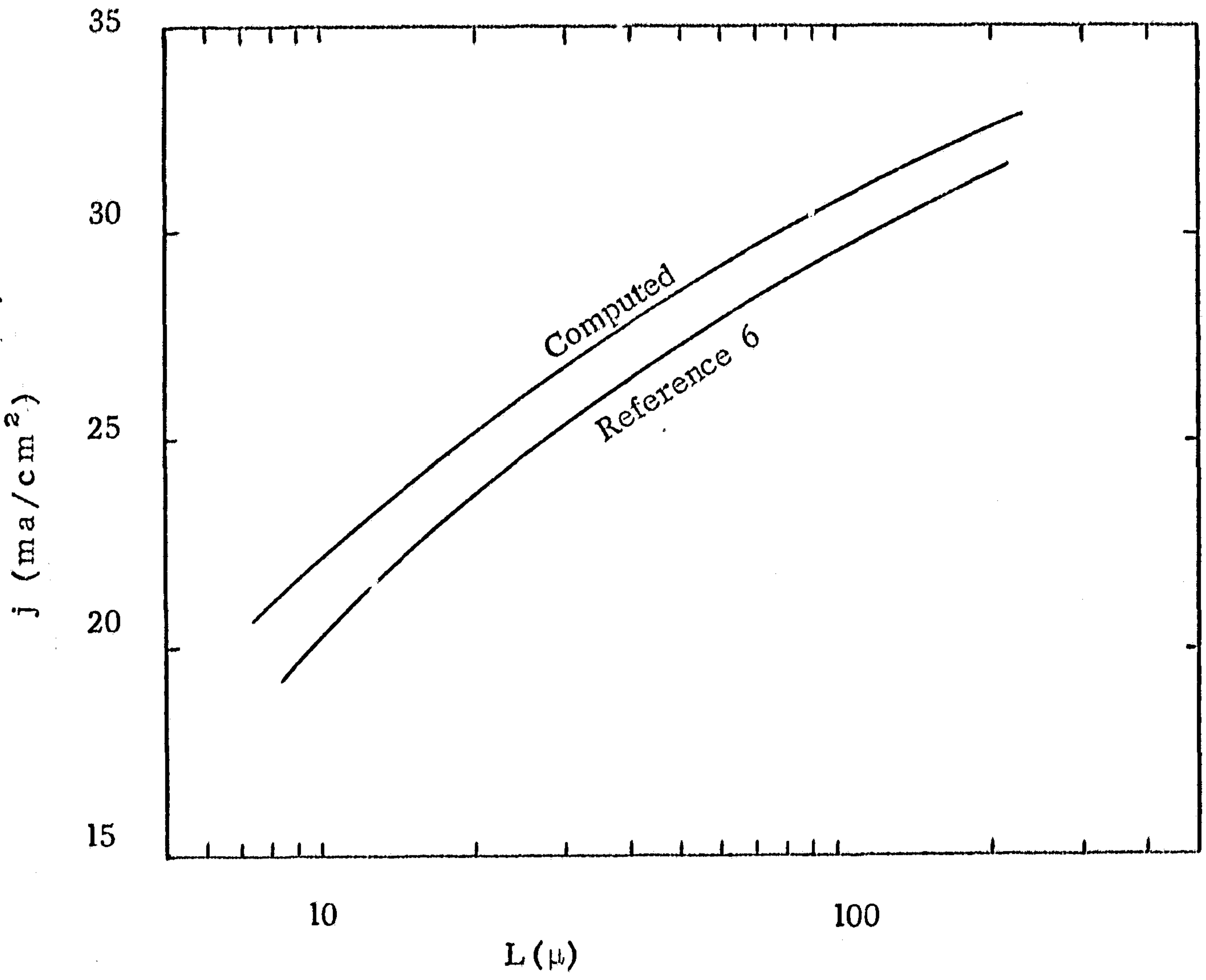

Figure 4. A comparison of computed values of photovoltaic current, versus L, with reported data from Reference 6. For the computation, the base region of a 10 mil cell was divided into 500 intervals.

III. Junction Characteristics

A solar cell is frequently regarded as a current source coupled with a diode, and the solar cell equation may be derived in this manner. The back-saturation current I_o is given theoretically as

$$I_o = [q\, D_p\, p_o\, /\, L_p + q\, D_n\, n_o\, /\, L_n] \tag{14}$$

and the characteristic voltage V_o is frequently written as

$$V_o = AkT/q \tag{15}$$

(The terms have their usual meanings, as listed in the Glossary).

These expressions are misleading as to the dependences of I_o and V_o on the radiation exposure, temperature and light intensity on a solar cell. For example, Eq. (14) suggests that I_o can be computed from the diffusion length for an irradiated cell, but the computation does not agree with experiment. Likewise, the inference of Eq. (15) that V_o is proportional to temperature is not borne out by experiment.

When the I - V curve is determined experimentally for a silicon solar cell, the parameters I_o and V_o can be estimated by a simple technique. This is seen from the solar cell equation,

$$I = I_L - I_o\, [e^{(V+IR)/V_o} - 1] \tag{16}$$

with the observation that the series resistance R is small and can be neglected for a first approximation. Then, for short-circuit conditions (V equal zero), I_L approximately equals the short-circuit current I_{sc}.

Now, when I is measured for voltages close to open-circuit conditions, the expression in the brackets approaches e^{V/V_o}. Thus, a plot of $I_{sc} - I$ versus V has a slope, on a semilogarithmic graph, that tends to $1/V_o$ as the open-circuit voltage is approached.

A series of such plots is shown in Figures 5 and 6. The data are those reported by Reynard[9] for 10 ohm-cm n/p cells under various temperatures, with a solar simulator as the light source, and before and after exposure to 5.2×10^{15} electrons (at 1 MeV) per square centimeter. It is apparent from these plots that V_o is independent both of temperature and penetrating radiation exposure. The surprising lack of temperature dependence within normal operating limits is borne out by Kennerud[10], whose measurements show A to vary as the reciprocal of T.

Plots of $I_{sc} - I$ are not useful in determining I_o to any degree of accuracy. A straight-line extrapolation of the plot from V_{oc} back to the abscissa should yield an intercept that is I_o but only a slight error in slope will result in a large error in the intercept. Rather, it is convenient to solve the solar cell equation directly. Given the short-circuit current I_{sc} and the open-circuit voltage V_{oc}, the solution is

$$I_o \cong I_{sc} \, e^{-V_{oc}/V_o} \tag{17}$$

when the internal resistance of the cell can be neglected.

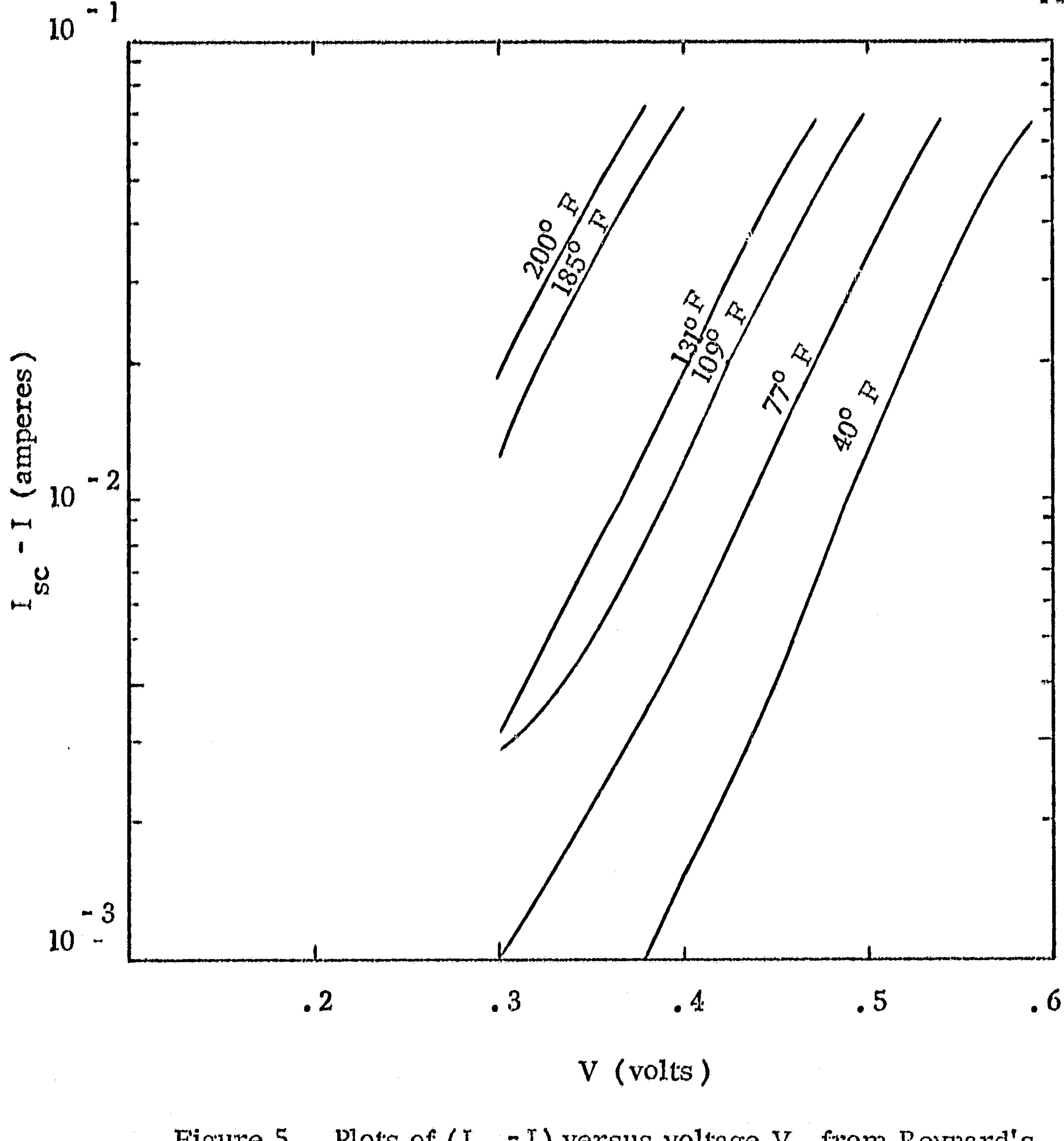

Figure 5. Plots of (I_{sc} - I) versus voltage V, from Reynard's laboratory data, using a sun simulator (Ref. 9). Note the slopes of the curves, for various temperatures, are essentially identical near open - circuit.

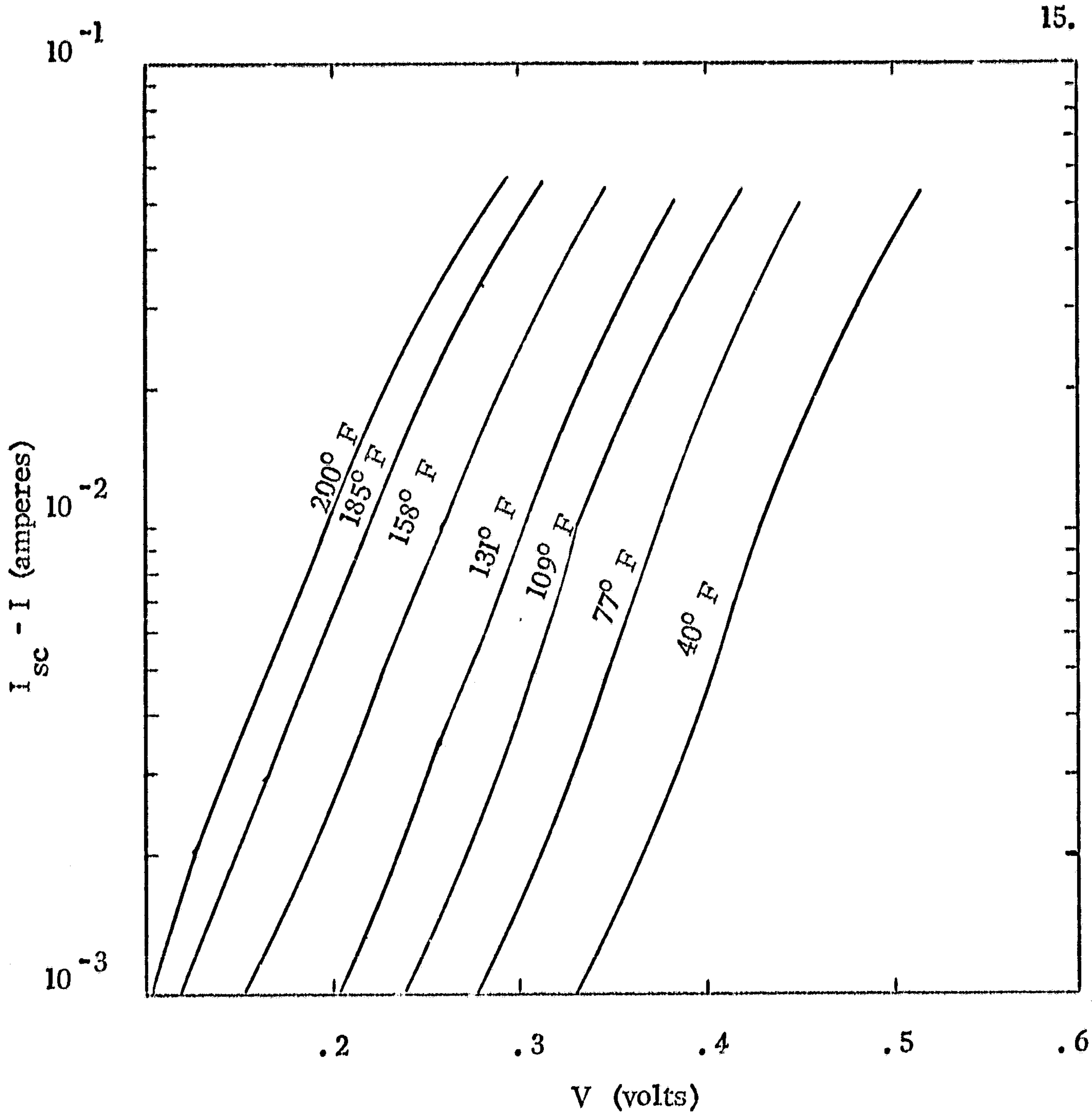

Figure 6. The same presentation as Figure 5, after the cells had been exposed to 5.2×10^{15} electrons / cm^2. The slopes of the curves near open-circuit voltage again appear independent of temperature and are essentially unchanged from the slopes of Figure 5.

Given the I - V curve for a solar cell, V_o and I_o may be computed by these methods. Analyzing published data, we find that I_o tends to increase with radiation exposure (as was shown in our first quarterly report [11]), with temperature, and with light intensity. The temperature dependence, seen in Figure 7 for the data of Reynard, is exponential and independent of radiation history. The light intensity dependence, seen in Figure 8 for the data of Brown [12] and of Wolf and Rauschenbach [1], is logarithmic.

In conclusion, it appears that the junction characteristics of a solar cell for an arbitrary radiation exposure, light intensity, and temperature can be evaluated if the junction characteristics were given for the cell under specified values of these parameters.

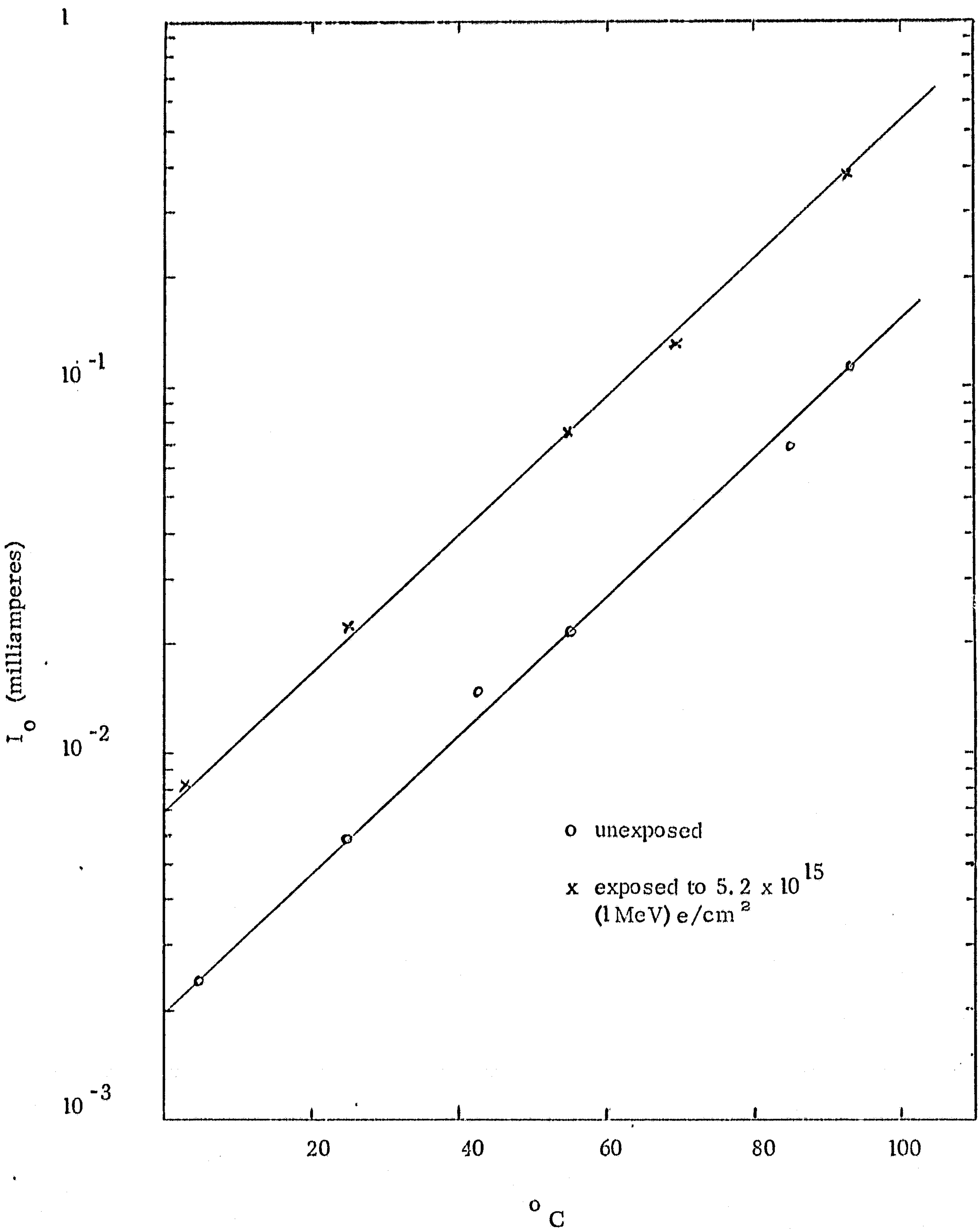

Figure 7. Plots of the reverse saturation current I_o versus temperature. Eq. 17 was used with the laboratory data of Reynard (Ref. 9).

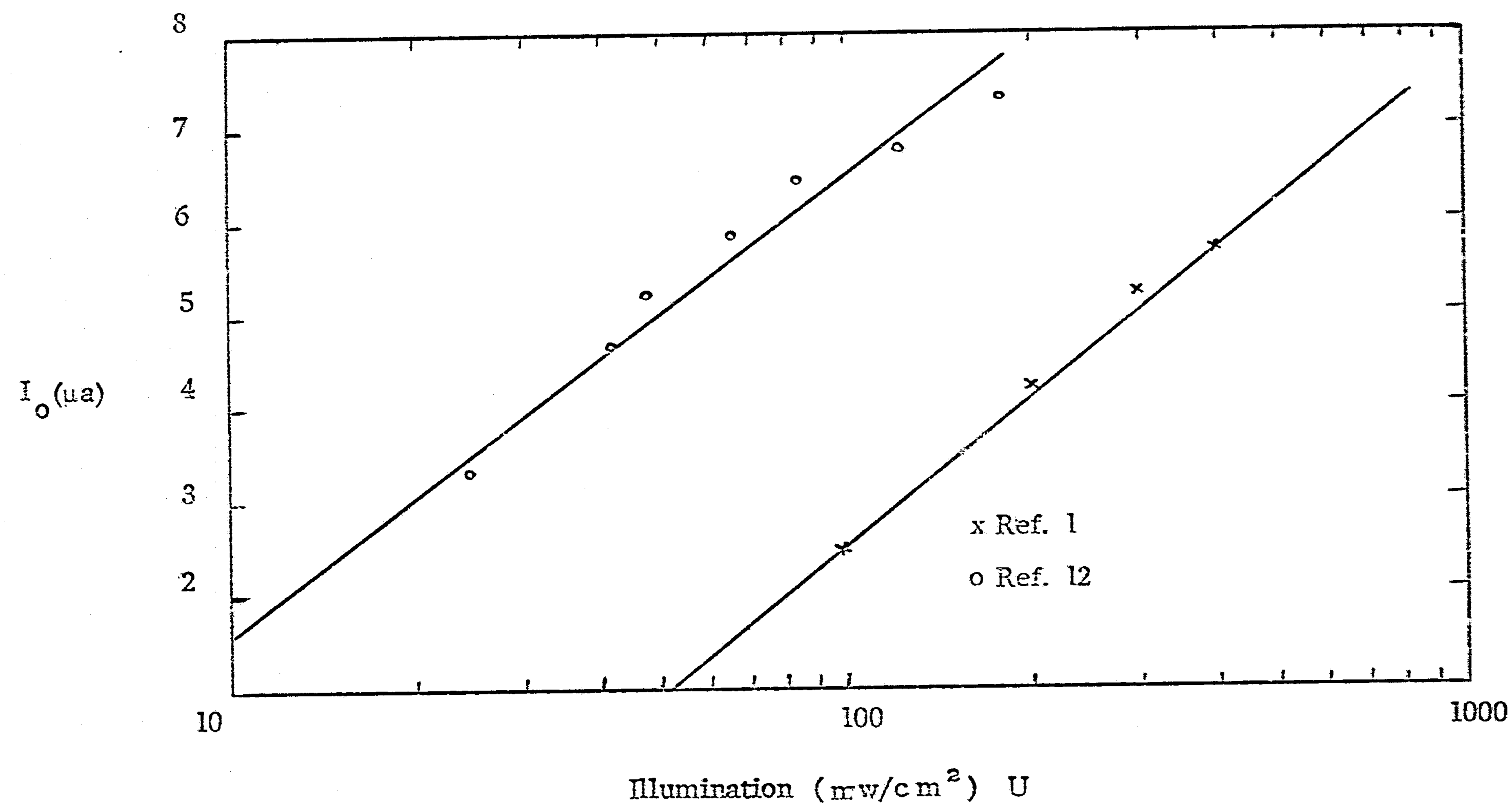

Figure 8. Plots of reverse saturation current I_o versus illumination intensity U. Laboratory data (Refs. 1 and 12) were analyzed using Eq. 17.

IV. Conclusions and Recommendations

While the reduction in minority carrier diffusion length in the base of the solar cell is the most significant permanent effect to solar cells in space, effects to the diode properties should also be considered. It appears that the solar cell equation (Eq. 16) is the most appropriate basis for an analysis of these effects. Efforts to understand solar cell operation therefore should be concentrated on the specific problems of how radiation (Φ), light (U), and temperature (T) affect the photovoltaic current (I_L) and the diode properties (I_o and V_o), and the internal resistance (R) of the solar cell.

Our analysis of some of these relations has been described in this report. The conclusions we have reached which appear to have the most significance are:

(1) Changes in the photovoltaic current may be calculated from the change in minority carrier diffusion length induced by radiation. Sample calculations are in fair agreement with previous work (Figure 4).

(2) The photovoltaic current is proportional to the light intensity. This follows from the continuity equation.

(3) The diode characteristic V_o is unaffected both by temperature and by radiation exposure.

(4) The logarithm of the diode characteristic I_o is proportional to the temperature, and the constant of proportionality is unaffected by radiation exposure (Figure 7).

(5) The diode characteristic I_o is also affected by the light intensity. In the range around an intensity of one sun, I_o is proportional to the logarithm of the light intensity (Figure 8).

These conclusions can be fitted into a theoretical framework for solar cell performance in space. While this is being done under continuance of this project, it is recommended that some effort be made to determine if there are underlying physical explanations for the relations discovered, or if they are merely useful approximations.

V. Glossary

A	An empirical parameter in the solar cell equation (see Eqs. 15 and 16)
c	Speed of light (cm/sec)
D	Diffusion coefficient of carriers in silicon (cm^2/sec.)
E	Electric field (volts / cm)
G(x)	Rate of production of minority carriers per cm^3 at depth x in silicon due to space sunlight
H(λ)	Spectral irradiance at wavelength λ (watts / cm^2-μ)
$\hbar$	Planck's constant (joule-sec)
h	Increment thickness (cm)
I	Current through the load (amperes)
I_L	Photovoltaic current across the junction (amperes)
I_o	Diode reverse-saturation current (amperes)
I_{sc}	Short-circuit current (amperes)
j	Photovoltaic current density (amp/cm^2)
K	Damage coefficient for radiation in silicon (dimensionless)
k	Boltzmann's constant (joule/molecule-°K). Also used as a subscript to denote a parameter measured at a depth k h into a cell, where k is an integer.
L	Minority carrier diffusion length (cm)
L_o	Minority carrier diffusion length before irradiation (cm)
N	Concentration of impurity atoms in a silicon lattice (atoms/cm^3)
n	Minority carrier concentration (in p-type material, electrons/cm^3)

n (subscript)	Referring to electrons or n-type silicon
p (subscript)	Referring to holes or p-type silicon
q	Electronic charge (coulombs)
R	Solar cell internal resistance (ohms)
$R(\lambda)$	Fraction of incident photons of wavelength λ reflected by cell surface.
T	Absolute temperature (^{o}K)
V	Voltage across a load
V_o	Characteristic voltage of a solar cell (defined by Eq. 15)
$\alpha(\lambda)$	Absorption coefficient in silicon for light of wavelength λ (cm^{-1})
λ	Wavelength of light (cm or microns)
μ	Minority carrier mobility (cm^2/ volt - sec)
τ	Mean lifetime of minority carriers in the conduction band (sec)
Φ	Radiation fluence to which the solar cell has been exposed (particles / cm^2)

VI. References

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VII. New Technology

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