THE USE OF MULTIPLE EBIC CURVES AND LOW VOLTAGE ELECTRON

MICROSCOPY IN THE MEASUREMENT OF SMALL DIFFUSION LENGTHS

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Diffusion length measurements were made in highly doped and radiation damaged III-V semiconductors using the technique of charge collection microscopy (sometimes known as electron beam induced current (EBIC)). EBIC curves were plotted while using the SEM on a line scan mode. Values of the currents read from these curves were then equated to expressions obtained from the solution of the diffusion equation for a thick sample. An extended generation function was used in order to account for the finite volume of the induced minority carriers. The surface recombination velocity was either treated as an unknown in a system of two integral equations, or measured directly using low accelerating potentials for the electron beam.

With the emergence of III-V compounds in the field of photovoltaics, it has become increasingly more important to have accurate methods for determining small (1 to 10 μm) diffusion lengths L. A reliable determination of the values of L is necessary in device modeling, radiation damage studies, and device fabrication since it is quite important to be able to assess the damage to the electronic properties of materials subject to certain processes.

Figure 1 shows the configuration that has been used to make these measurements. The depicted geometry was chosen to permit direct measurements to be made on finished solar cells. The contacts used were ohmic ones made with evaporated thin films of gold. The current amplifier had fast response, low noise, low input imped ance, and the gain was calibrated. The leads were shielded, and the circuit ground was separated from the SEM ground.

When energetic electrons impinge on semiconducting material, electron hole pairs are created. The required ionization energy is a function of the bandgap (ref. 1). In GaAs it takes 4.5 eV of incoming radiation energy to create a minority carrier. If one assumes no surface recombination, and point generation of minority carriers, the collected current follows a simple exponential decay form:

$$I_{cc} = I_o e^{-x/L} \tag{1}$$

where

I_o maximum current collected (PN junction)
L   diffusion length
X   distance from PN junction

However, the surface recombination can be very large in III-V's, and its effect (ref. 2) cannot be neglected in the measurement of L. Increasing the accelerating potential for the electron beam minimizes the effect of surface recombination velocity S. Unfortunately, this approach diminishes the resolution of this technique, since for small L's the electron range then becomes comparable to the

value of L. Figure 2 shows that at 30 kV - the most commonly used accelerating potential in routine SEM operation - the electron range R_e is about 3 μm.

For these reasons low accelerating potentials have been used to obtain the charge collection microscopy curves used in these measurements and calculations. The integral solution of the two-dimensional diffusion equation with semi-infinite thickness and an extended generation function (ref. 3) in the form of a three-dimensional gaussian distribution have been used here. Figure 3 shows an experimental EBIC plot of the ratio of collected current to maximum current (in the depletion region). At any x_0, this ratio can be expressed as (ref. 4)

$$\frac{I_{cc}(x_0)}{I_0} = \frac{2}{\pi} \int_0^\infty \frac{u\,du}{(u^2+1)} \left\{ \exp\left(-\frac{u^2\sigma^2}{2L^2}\right) - 0.57 \exp\left(\frac{\sigma^2}{2L^2} - \sqrt{u^2+1}\,\frac{z_0}{L}\right) \right.$$

$$\left. \times \frac{\eta}{\eta + \sqrt{u^2+1}} \; \mathrm{erfc}\left[\frac{\sigma}{\sqrt{2}L}\left(\sqrt{u^2+1} - \frac{z_0}{L}\frac{L^2}{\sigma^2}\right)\right] \right\} \sin\left(u\,\frac{x_0}{L}\right) \tag{2}$$

where

$$z_0 = 0.3\,R_e$$

$$\sigma = \frac{R_e}{\sqrt{15}}$$

$$\eta = \frac{LS}{D}$$

As can be seen one can measure or assume reasonable values for all the variables in equation (2) except for the surface recombination velocity S, an unknown whose effect is not negligible. Hence, two different approaches that allow the determination of S were undertaken, so that equation (2) could be solved numerically, and the value of L could be extracted from the integral form.

Assume two different accelerating potentials (E_1 and E_2) for the electron beam impinging on the same semiconductor. In functional form, the normalized current at a given x_0 can be rewritten as

$$\frac{I_{cc1}(x_0)}{I_{o1}} = \int f(L,E,S,x_0,\ldots) \tag{3}$$

$$\frac{I_{cc2}(x_0)}{I_{o2}} = \int f(\ldots,E_2,\ldots) \tag{4}$$

Figure 4 shows two of the experimentally obtained EBIC curves at the different potentials. The same x_0 is used, so one can assume the same value for the diffusion length. This applies even in the case of graded doping or other nonuniformities. At the same x_0, one can also assume that S will be the same, even for different values of the recombination across the surfaces of the samples analyzed. This allows the treatment of equations (3) and (4) as two integral equations with two unknowns.

The value for S can then be obtained by using an iterative process, where an initial value for S is guessed. Holding S constant in equation (3), an L is found that satisfies the condition

$$\left| I_{cc(calculated)} - I_{cc(measured)} \right| \leq \text{TOLERANCE} \qquad (5)$$

This value for L is then used in equation (4), where S is next varied to satisfy equation (5). This process is repeated as necessary until an L and an S are found which satisfy both equations (3) and (4). Numerical integration was done using the Romberg method where the upper limit was increased until the last two computed integrals differed by a negligible value. The roots (values of L and S) were searched by using the Regula Falsi Method. The integral form for the complementary error function was used. Figure 5 shows a flowchart for the numerical calculations performed here.

The second method uses less computer time but requires a more sophisticated SEM. It makes use of the result (ref. 5)

$$\frac{\partial}{\partial z} \ln I_{cc} \bigg|_{z \to 0} = \frac{S}{D} \qquad (as\ E \to 0) \qquad (6)$$

which allows a more direct determination of the value of S while the sample is inside the SEM specimen chamber. In order to use equation (6) and obtain accurate values, one must have low voltage capabilities and the ability to vary the beam accelerating potential without changing the total beam current. Figures 6 and 7 show the determination of S/D for the devices that were analyzed here. The GaAs diode was P on N. The N region was silicon doped, with a carrier concentration of about 1×10^{18}. The junction was very abrupt. The InP solar cell had a P-type base, doped at about 1×10^{17}. The cell had been subject to $10^{12}/cm^2$ 10 MeV proton irradiation.

Figures 8 and 9 show the measured values for diffusion length, as a function of distance from the PN junction, for the same devices. The spread in the data points from the different accelerating voltages (which ideally, would coincide for a given x_0) has been used to assign a value to the uncertainty. The reported value has been chosen as the L that is reached asymptotically as x_0 gets farther from the junction, since other workers (ref. 6) have observed that the measured value of L is more reliable if a larger x_0 is used.

In summary, accurate evaluations of diffusion lengths for heavily to moderately doped III-V semiconductors and/or radiation damaged solar cells have been made possible by using the experimental and numerical techniques described.

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6. Luke, K.L.; von Roos, O.; and Cheng, L.: Quantification of the Effects of Generation Volume, Surface Recombination Velocity, and Diffusion Length on the Electron-Beam-Induced Current and its Derivative: Determination of Diffusion Lengths in the Low Micron and Submicron Ranges. J. Appl. Phys., vol. 57, no. 6, Mar. 15, 1985, pp. 1978-1984.
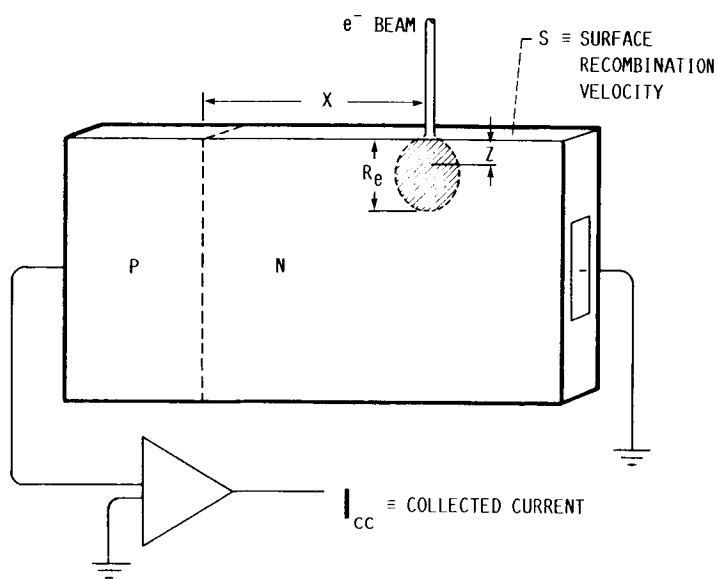
FIGURE 1. - EXPERIMENTAL SETUP FOR CHARGE COLLECTION MICROSCOPY.
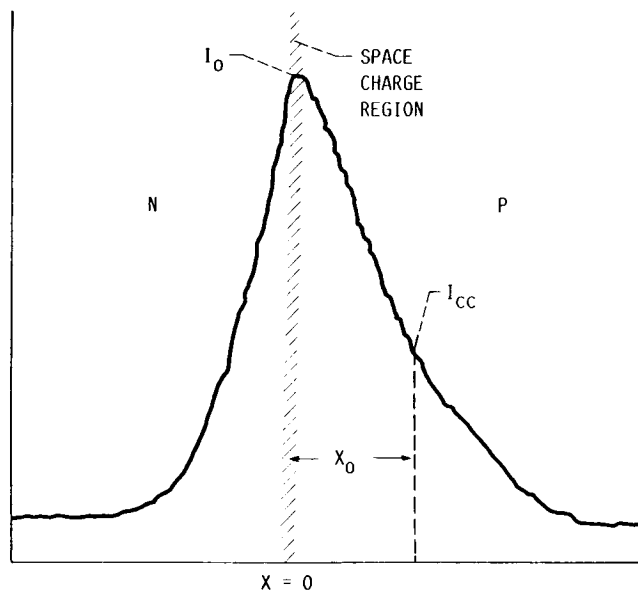

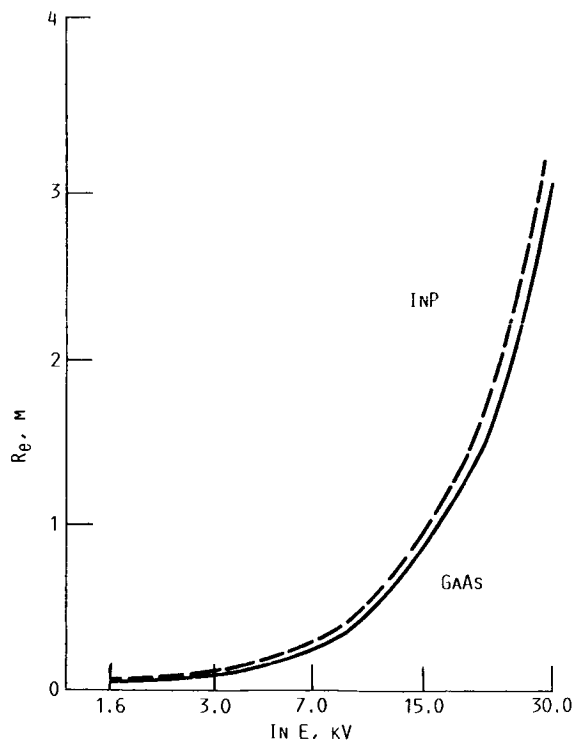FIGURE 3. - EBIC PLOT FOR A PN JUNCTION.

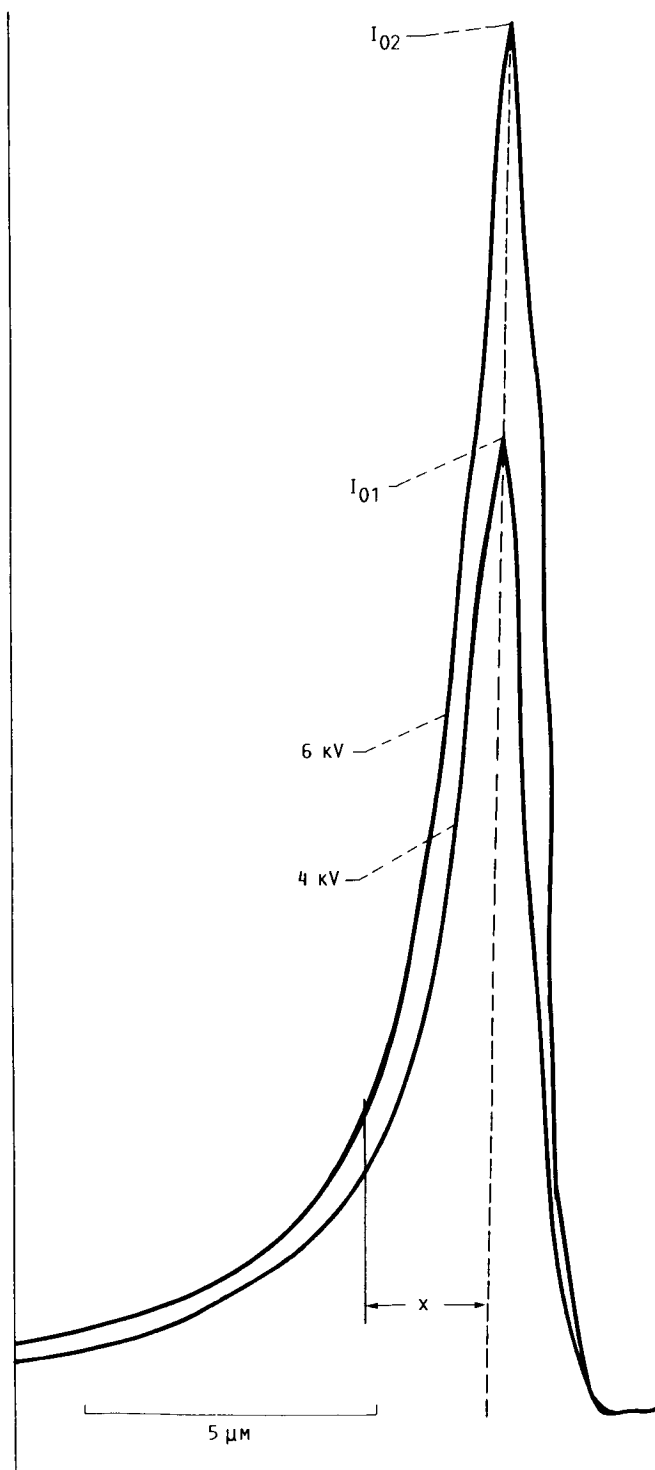FIGURE 2. - ELECTRON RANGE AS A FUNCTION OF
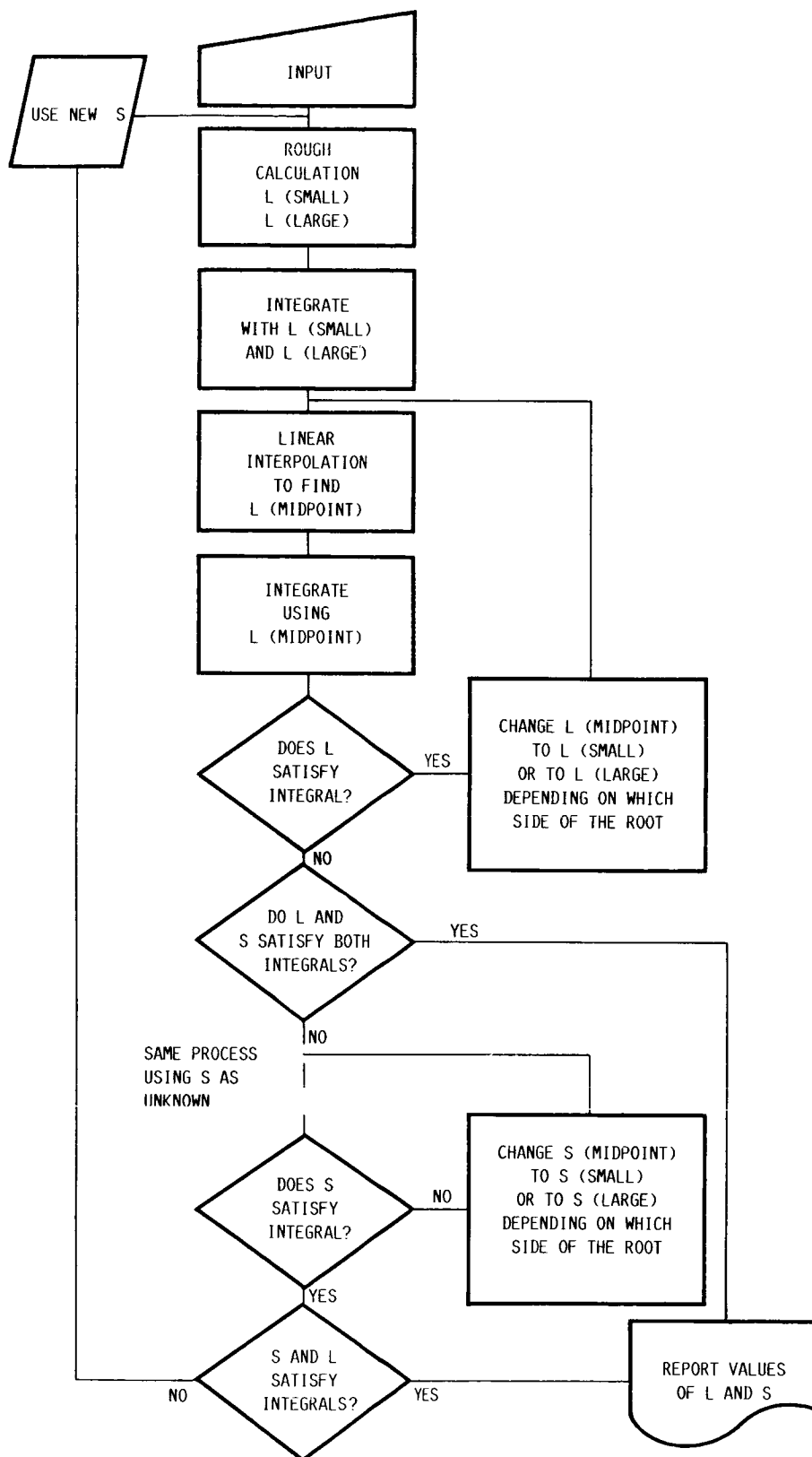ACCELERATING VOLTAGE.

FIGURE 4. - EBIC CURVES AT 4 AND 6 kV.

INPUT

USE NEW S

ROUGH
CALCULATION
L (SMALL)
L (LARGE)

INTEGRATE
WITH L (SMALL)
AND L (LARGE)

LINEAR
INTERPOLATION
TO FIND
L (MIDPOINT)

INTEGRATE
USING
L (MIDPOINT)

DOES L
SATISFY
INTEGRAL?

YES

CHANGE L (MIDPOINT)
TO L (SMALL)
OR TO L (LARGE)
DEPENDING ON WHICH
SIDE OF THE ROOT

NO

DO L AND
S SATISFY BOTH
INTEGRALS?

YES

NO

SAME PROCESS
USING S AS
UNKNOWN

DOES S
SATISFY
INTEGRAL?

NO

CHANGE S (MIDPOINT)
TO S (SMALL)
OR TO S (LARGE)
DEPENDING ON WHICH
SIDE OF THE ROOT

YES

S AND L
SATISFY
INTEGRALS?

NO

YES

REPORT VALUES
OF L AND S

FIGURE 5. - FLOWCHART FOR NUMERICAL CALCULATIONS. USER INPUTS X_0, NORMALIZED
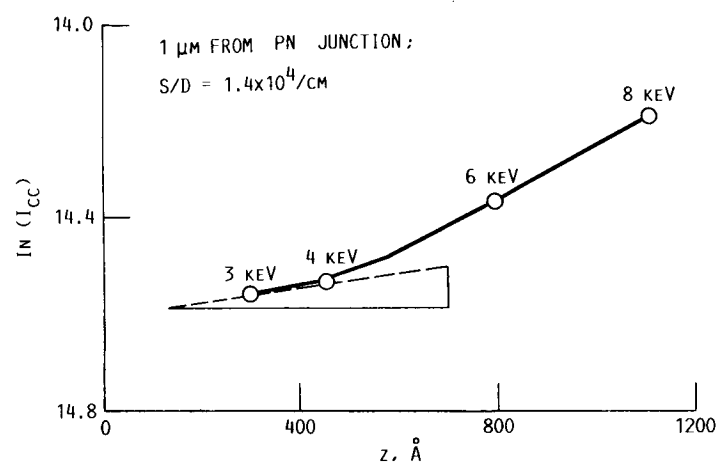CURRENTS, AND ELECTRON BEAM POTENTIALS FOR TWO CURVES.
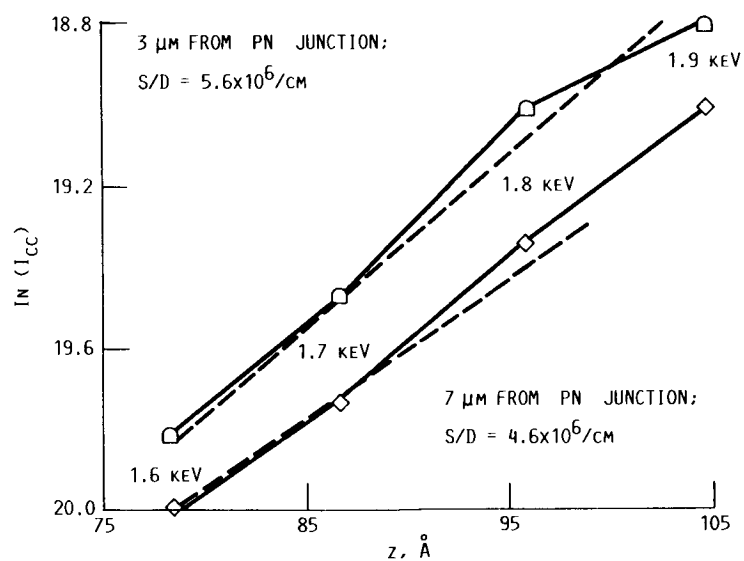
FIGURE 6. - DETERMINATION OF S/D FOR AN InP CELL.

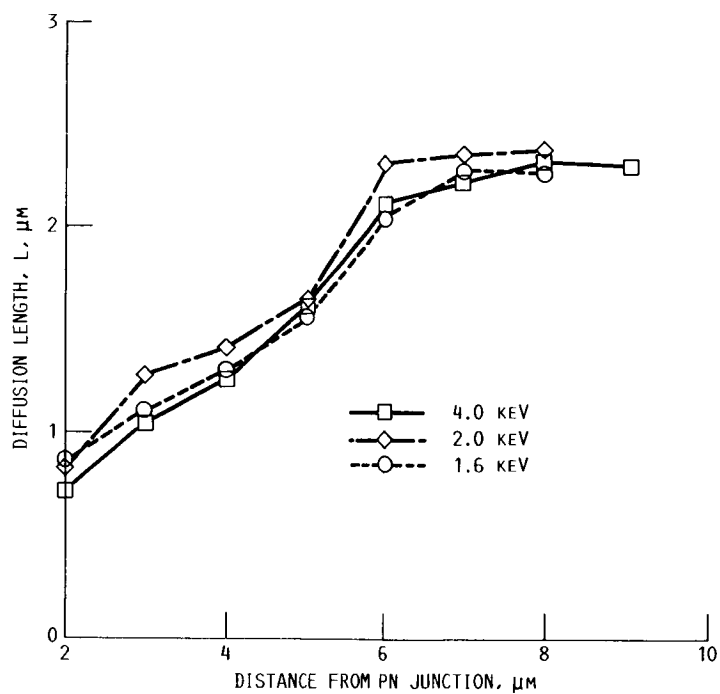
FIGURE 7. - DETERMINATION OF S/D FOR A GaAs DIODE.

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FIGURE 8. - VALUES OF DIFFUSION LENGTHS IN THE GaAs DIODE.
N TYPE; $N_A = 1 \times 10^{18}/cm^3$; $L = 2.3 \ \mu m \pm 0.15 \ \mu m$.

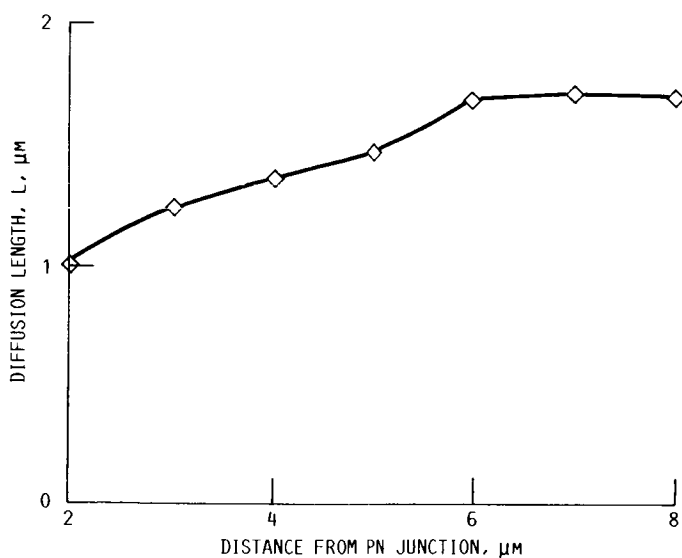FIGURE 9. - VALUES OF DIFFUSION LENGTHS IN AN IRRADIATED InP
SOLAR CELL. P TYPE; $N_A \equiv 10^{17}/cm^3$; (AFTER $10^{12}/cm^2$ 10 MeV
PROTON IRRADIATION). $L = 1.7 \ \mu m \pm 0.15 \ \mu m$.