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# Diffusion Length Damage Coefficient and Annealing Studies in Proton-Irradiated InP

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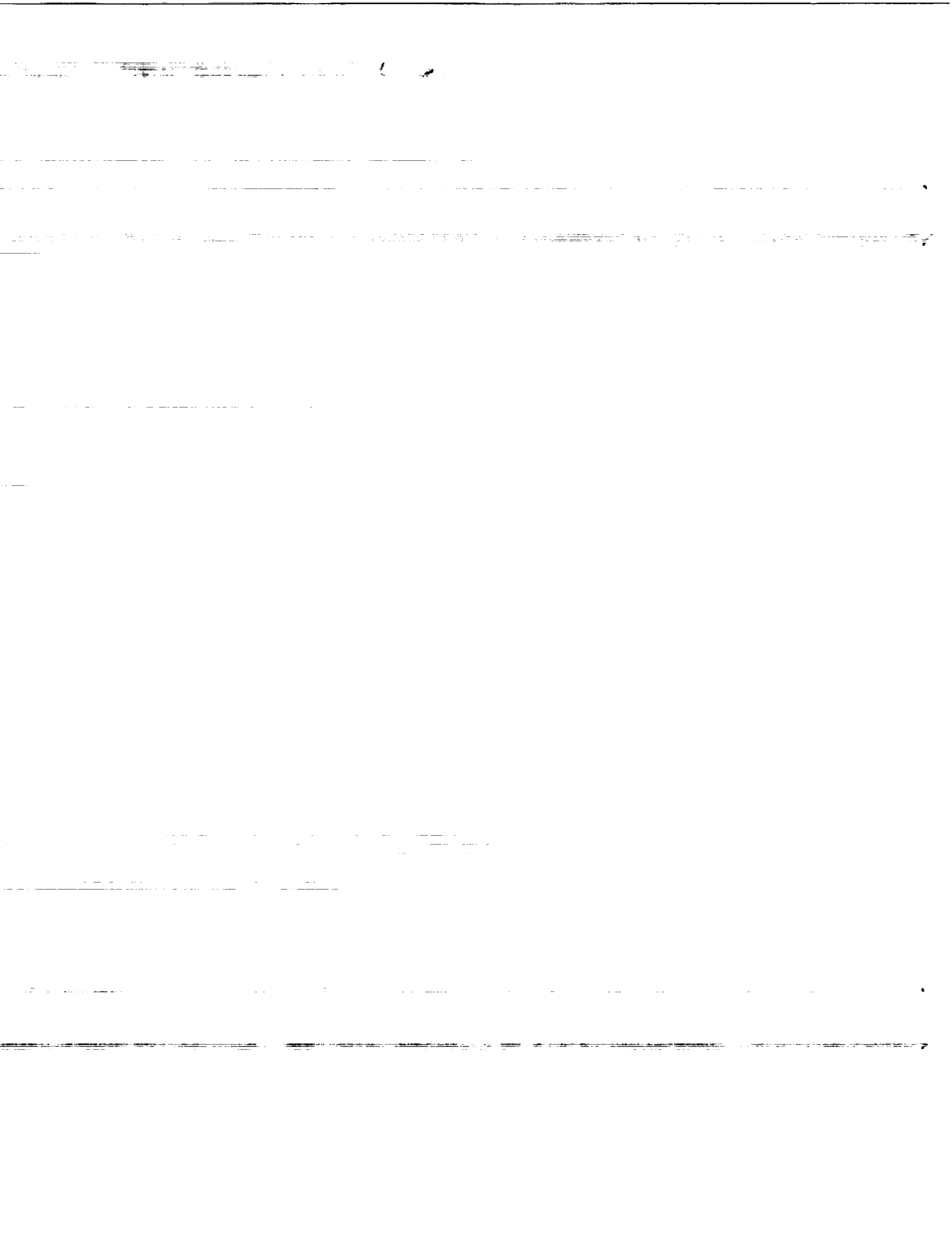


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# DIFFUSION LENGTH DAMAGE COEFFICIENT AND ANNEALING STUDIES

## IN PROTON-IRRADIATED InP

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### SUMMARY

We report on the measurement of the diffusion length damage coefficient ( $K_L$ ) and the annealing characteristics of the minority carrier diffusion length ( $L_n$ ) in Czochralski-grown zinc-doped indium phosphide (InP), with a carrier concentration of  $1 \times 10^{18} \text{ cm}^{-3}$ . In measuring  $K_L$  irradiations were made with 0.5 MeV protons with fluences ranging from  $1 \times 10^{11}$  to  $3 \times 10^{13} \text{ cm}^{-2}$ . Pre- and post-irradiation electron-beam induced current (EBIC) measurements allowed for the extraction of  $L_n$  from which  $K_L$  was determined. In studying the annealing characteristics of  $L_n$  irradiations were made with 2 MeV protons with a fluence of  $5 \times 10^{13} \text{ cm}^{-2}$ . Post-irradiation studies of  $L_n$  with time at room temperature, and with minority carrier photoinjection and forward-bias injection were carried out. The results showed that recovery under air mass zero (AMO) photoinjection was complete.  $L_n$  was also found to recover under forward-bias injection, where recovery was found to depend on the value of the injection current. However, no recovery of  $L_n$  after proton irradiation was observed with time at room temperature, in contrast to the behavior of 1 MeV electron-irradiated InP solar cells reported previously.

### I. INTRODUCTION

Indium phosphide (InP) is recognized as a prime candidate for space solar cells. In addition to its near optimum bandgap, other qualities of InP include its superior radiation resistance as compared to Si and GaAs (refs. 1 to 8), the cells currently used in space. Figure 1 (ref. 1)

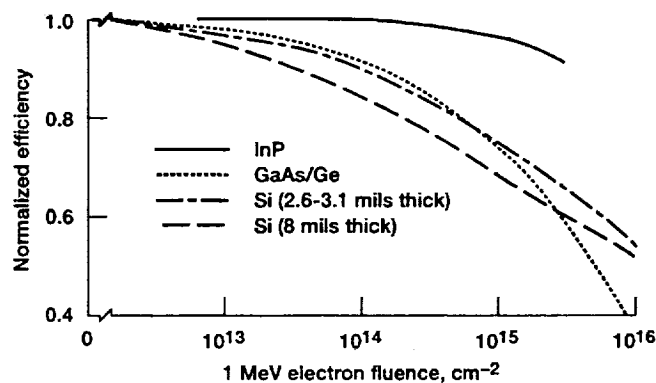


Figure 1.—Normalized efficiency ( $\eta/\eta_0$ ) after 1 MeV electron irradiation.  $\eta_0$  = pre-irradiation efficiency,  $\eta$  = post-irradiation efficiency. (Reproduced from [1]).

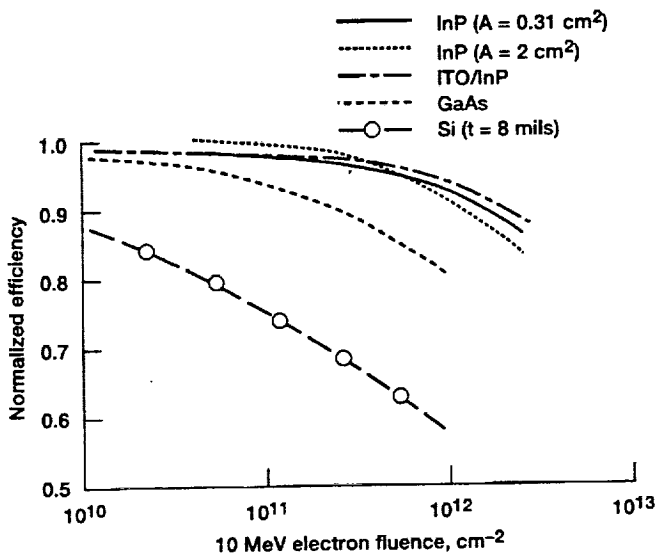


Figure 2.—Normalized efficiency ( $\eta/\eta_0$ ) after 10 MeV proton irradiation.  $\eta_0$  = pre-irradiation efficiency,  $\eta$  = post-irradiation efficiency,  $A$  = cell area,  $t$  = cell thickness. (Reproduced from [1]).

shows the performance of InP solar cells as compared to GaAs and Si under 1 MeV electron irradiation, and figure 2 (ref. 1) shows a similar comparison of the normalized efficiencies under 10 MeV proton irradiation. As can be seen, in both cases the radiation resistance of InP solar cells is superior to that of GaAs and Si solar cells.

Another remarkable property exhibited by InP solar cells is their ability to anneal after irradiation. Annealing has been observed at elevated temperatures (ref. 9), at room temperature (refs. 10 and 11), and under minority carrier injection (ref. 12). Since annealing occurs under forward bias and photoinjection conditions, one would expect the cells to have more radiation resistance if illuminated while being irradiated, and this has indeed been shown to be the case (ref. 13). It has also been shown that power obtained from InP solar cells could be increased through periodic forward bias annealing and that the recovery of InP cells under periodic forward bias annealing at 90 °C is significantly greater than that of GaAs (ref. 14).

Due to these remarkable characteristics, much interest has been shown in InP solar cells by the space photovoltaic community.

An important parameter in characterizing the behavior of solar cells under irradiation is the damage coefficient. Solar cell damage coefficients are parameters obtained from a study of the minority carrier diffusion length and lifetime as a function of radiation fluence. There are two types of radiation damage coefficients, the lifetime damage coefficient,  $K_T$ , and the diffusion length damage coefficient,  $K_L$ . Experimental values for the dam-

age coefficients are useful for predicting solar cell performance in specified radiation environments. Yamaguchi et al. (ref. 8) have calculated  $K_L$  for both p- and n-type InP under 1 MeV electron irradiation. Hakimzadeh (ref. 15) was the first to report experimentally obtained values of  $K_L$  in p-type InP materials. Later, Jain et al. (ref. 16) calculated  $K_L$  in the base of  $n^+p$  solar cells. In their work values for the base diffusion length were obtained from a fit of the experimentally obtained current-voltage characteristics to computer simulations.

In this work the results obtained by Hakimzadeh (ref. 15) are summarized. We report on the measurement of  $K_L$  versus 0.5 MeV proton fluence, and the annealing characteristics of the minority carrier (electron) diffusion length ( $L_n$ ) after 2 MeV proton irradiation. Throughout this work the specimens used were gold-contacted zinc-doped (Czochralski-grown) InP Schottky barriers. Schottky barriers were used to minimize the effect of processing. The technique used to measure  $L_n$  in this work was a previously reported electron-beam induced current (EBIC) technique (refs. 15 and 17 to 22). Further details of the measurement technique and specimen preparation can be found in references 15, 17, and 18.

In measuring  $K_L$ , The specimens were irradiated with 0.5 MeV protons at fluences ranging from  $1 \times 10^{11}$  to  $3 \times 10^{13} \text{ cm}^{-2}$  using a 1.7 MV Tandetron accelerator. The low energy of the protons and the corresponding fluences were chosen carefully based on previously reported results (ref. 23) to ensure a measurable damage in the value of  $L_n$  in these highly doped specimens. During irradiation the beam current was kept at a constant low level (2 nA) to prevent the specimen temperature from rising above room temperature. Pre- and post-irradiation measurements of  $L_n$  led to the calculation of  $K_L$  as a function of fluence. The technique used for calculating  $K_L$  from experimental data is described in Section II.

In studying the annealing behavior of  $L_n$  the specimens were irradiated with 2 MeV protons at a fluence of  $5 \times 10^{13} \text{ cm}^{-2}$  using a Van de Graaff accelerator. With this accelerator we were not able to obtain proton energies below 2 MeV. Hence, higher fluences were used to ensure a measurable change in the value of  $L_n$ , again based on previously published data (ref. 23). During irradiations, the beam current was kept at a constant low level (1 nA) to prevent the specimen temperature from rising above room temperature. The results are presented in Section III.

## II. TECHNIQUE USED TO CALCULATE $K_L$

$K_T$ , the lifetime damage coefficient, is obtained from the equation:

$$\frac{1}{\tau_\phi} = \frac{1}{\tau_o} + K_r \phi \quad (1)$$

where  $\tau_\phi$  is the minority carrier lifetime after irradiation at a fluence  $\phi$ , and  $\tau_o$  is the minority carrier lifetime prior to irradiation. The minority carrier lifetime,  $\tau$ , can also be expressed as (refs. 24 and 25):

$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i} = \sum_i N_{T_i} \sigma_i v_{th} \quad (2)$$

where  $N_{T_i}$  and  $\sigma_i$  are the concentration and capture cross-section of the  $i$ th defect, respectively,  $v_{th}$  is the thermal velocity, and  $\tau_i$  is the contribution to minority carrier lifetime of the  $i$ th defect. Using equation (2) one can therefore obtain:

$$\Delta \left( \frac{1}{\tau} \right) = \frac{1}{\tau_\phi} - \frac{1}{\tau_o} = \left[ \sum_j \left( \frac{N_{T_j}}{\phi} \right) \sigma_j v_{th} \right] \phi \quad (3)$$

where the summation is over all the radiation-induced defects and  $K_r$  is the term in square brackets (ref. 1). Hence,  $K_r$  will be a constant if the defect introduction rate,  $N_{T_j}/\phi$ , is constant. This rate is dependent on the bombarding particle's type and energy. A similar expression can be derived for  $K_L$  by using equation (2) together with the following equation:

$$L_n^2 = D_n \tau \quad (4)$$

where  $D_n$  is the minority carrier (electron) diffusion coefficient. The resultant expression is (refs. 1 and 26):

$$\Delta \left( \frac{1}{L_n^2} \right) = \frac{1}{L_n^2} - \frac{1}{L_{no}^2} = \left[ \sum_j \left( \frac{N_{T_j}}{\phi D_n} \right) \sigma_j v_{th} \right] \phi = K_L \phi \quad (5)$$

where  $L_{no}$  and  $L_n$  are the minority carrier diffusion lengths before and after irradiation, respectively, and  $K_L$  is the diffusion length damage coefficient. Hence, if the defect introduction rate is a constant and  $D_n$  is a constant,  $K_L$  will also be a constant for a specified particle type and energy. Depending on the dopant concentration of the solar cell at hand, carrier removal may be significant, in which case  $D_n$  will vary with fluence.

### III. RESULTS

#### A. Diffusion Length Damage Coefficient, $K_L$

The specimens were irradiated with 0.5 MeV protons at various fluence levels, as shown in table I. After each irradiation,  $L_n$  was measured by the EBIC technique (refs. 15 and 17 to 22). Figure 3 shows a typical plot of  $L_n$  versus cumulative fluence,  $\phi$ . It can be seen that  $L_n$  decreases with increasing  $\phi$  for  $\phi \leq 3 \times 10^{12}$  protons/cm<sup>2</sup>. For larger values of  $\phi$ ,  $L_n$  is seen to increase with radiation. We have considered carrier concentration as a possible explanation for this. The density of the carriers removed can be found from:

$$\Delta p = R_c \phi \quad (6)$$

where  $\Delta p$  is the density of the carriers removed (cm<sup>-3</sup>),  $R_c$  is the carrier removal rate (cm<sup>-1</sup>) at a given proton

TABLE I.—0.5 MeV PROTON IRRADIATIONS

Irradiation number	Fluence, protons/cm <sup>2</sup>	Total cumulative fluence, protons/cm <sup>2</sup>
1	1 × 10 <sup>11</sup>	1 × 10 <sup>11</sup>
2	2 × 10 <sup>11</sup>	3 × 10 <sup>11</sup>
3	7 × 10 <sup>11</sup>	1 × 10 <sup>12</sup>
4	2 × 10 <sup>12</sup>	3 × 10 <sup>12</sup>
5	7 × 10 <sup>12</sup>	1 × 10 <sup>13</sup>
6	2 × 10 <sup>13</sup>	3 × 10 <sup>13</sup>

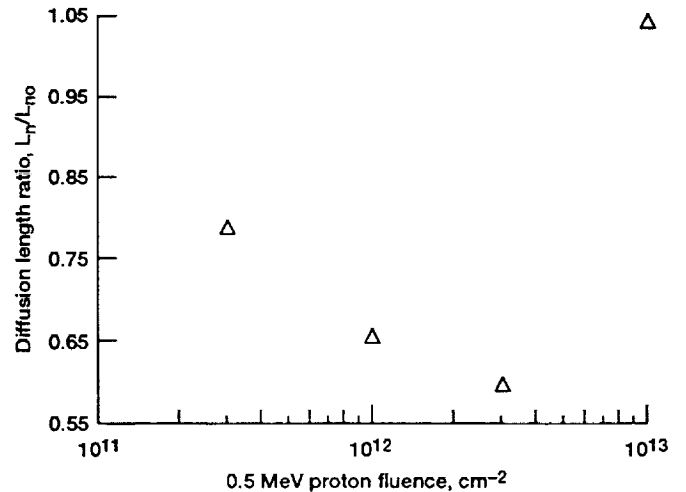


Figure 3.—Typical plot of  $L_n/L_{no}$  as a function of cumulative fluence,  $\phi$  (0.5 MeV protons).  $L_{no}$  is the diffusion length prior to irradiation, and  $L_n$  is their diffusion length after irradiation. (Specimen number 8).

energy and fluence,  $\phi$ . Recently published data (ref. 27) show  $R_c$  to be  $8.4 \times 10^3 \text{ cm}^{-1}$  for 0.5 MeV proton-irradiated InP. For a fluence of  $3 \times 10^{12} \text{ cm}^{-2}$ , therefore,  $\Delta p = 2.5 \times 10^{16} \text{ cm}^{-3}$ . This value of  $\Delta p$  is small as compared to the doping concentration of the specimens used, namely  $1 \times 10^{18} \text{ cm}^{-3}$ . Hence the increase of  $L_n$  for larger values of  $\phi$  cannot be attributed to carrier removal alone.

In this work we concentrated on the lower  $\phi$  regions. For these regions  $\log[\Delta(1/L_n^2)]$  versus  $\log(\phi)$  was plotted (fig. 4). Ideally more experimental points should be taken in these regions. However, for small deltas in  $\phi$ , the delta in the measured value of  $L_n$  would be very small and would likely fall within an estimated 15 percent experimental uncertainty of the EBIC technique (ref. 15).

Since in these low  $\phi$  regions carrier removal is insignificant then  $D_n$  can be assumed to be a constant. If the carrier introduction rate is also constant then  $K_L$  is constant and all points in figure 4 should lie on a straight line with a slope of 1. This is because from equation (5) we have:

$$\log \left[ \Delta \left( \frac{1}{L_n^2} \right) \right] = \log \phi + \log K_L \quad (7)$$

or  $y = mx + b$  where  $m = 1$ . It can be seen from figure 4 that in most cases only the first two points seem to lie on a straight line with a slope approximately equal to 1. At

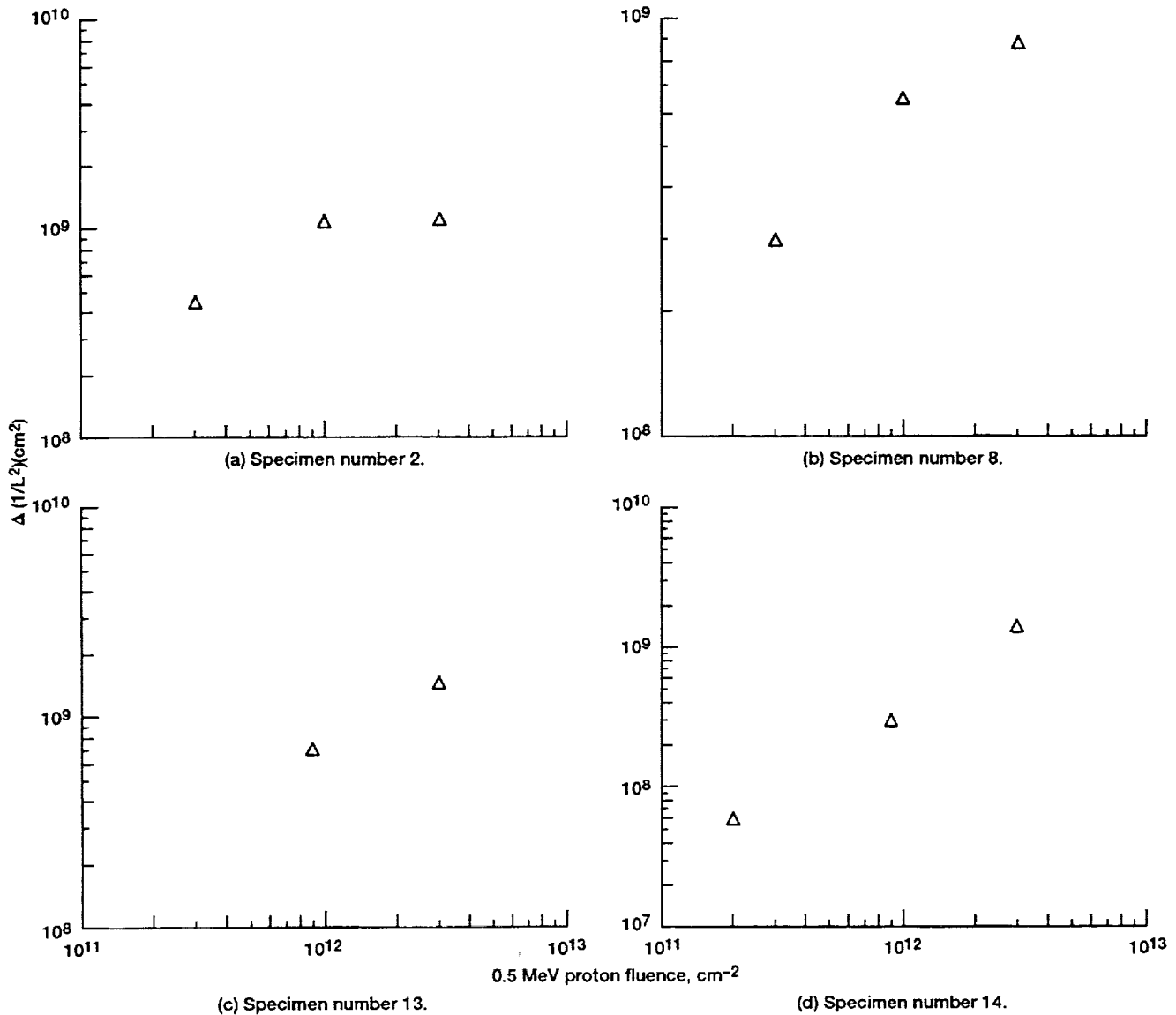


Figure 4.—Plots of  $\log [\Delta(1/L_n^2)]$  versus  $\log(\phi)$ , where  $\phi$  is the cumulative proton fluence, for four specimens. Specimens were irradiated with 0.5 MeV protons.

higher fluences, the data deviate from this straight line, which is an indication that  $K_L$  is no longer constant. Hence, only the first two points were used to calculate  $K_L$  using  $K_L = \Delta(1/L_n^2)/\phi$ . A plot of  $K_L$  versus  $\phi$  for four specimens is shown in figure 5.

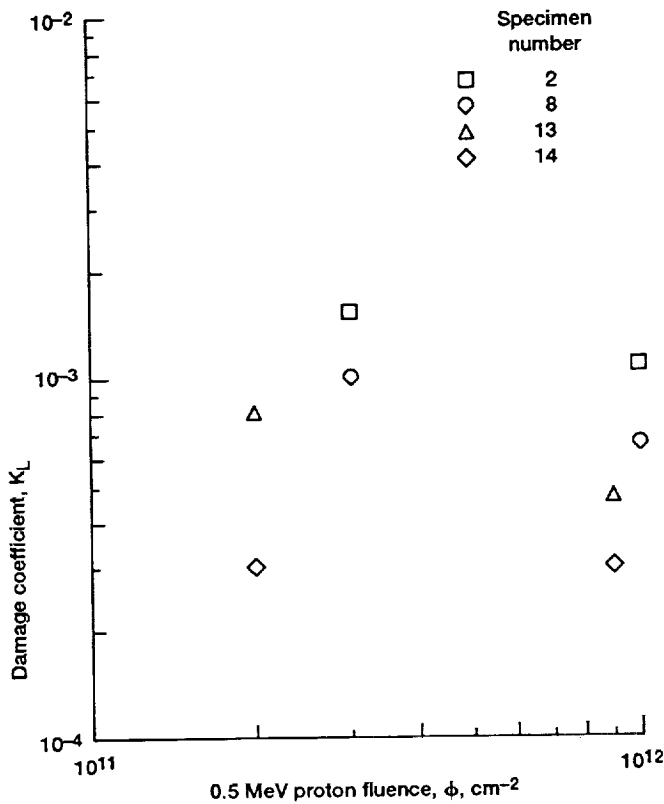


Figure 5.—Plot of  $\log(K_L)$  versus  $\log(\phi)$ , where  $\phi$  is the cumulative proton fluence.

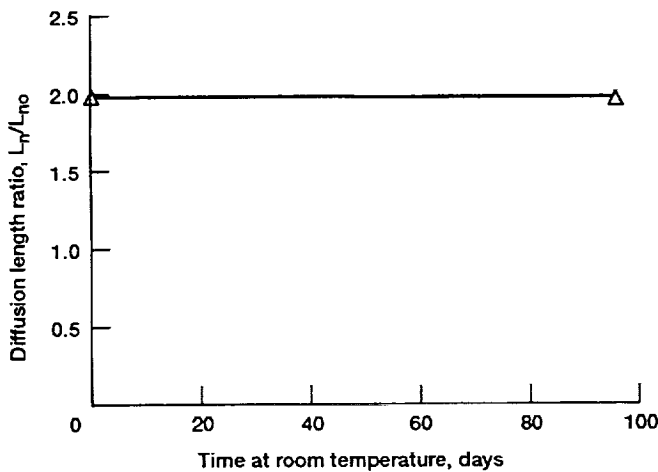


Figure 6.—Room temperature (300 K) annealing after 2 MeV proton irradiation with a fluence of  $5.0 \times 10^{13} \text{ cm}^{-2}$ .  $L_{no}$  = diff. length prior to irradiation ( $= 0.39 \mu\text{m}$ ),  $L_n$  = diff. length after irradiation. Note: in this specimen the high fluence caused significant carrier removal. (Specimen number 31).

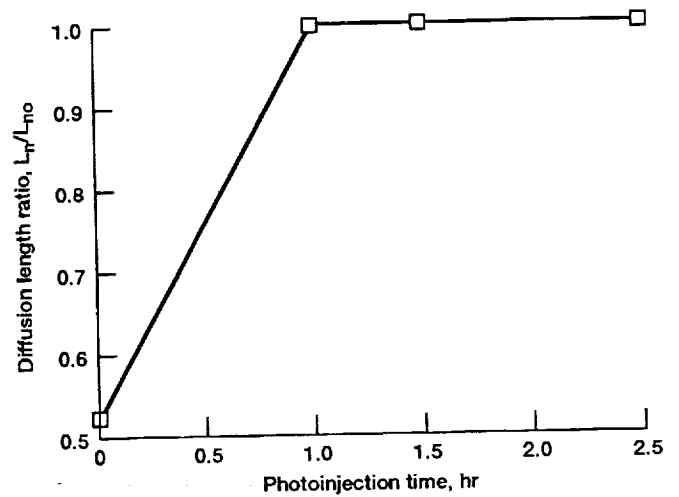


Figure 7.—Recovery of  $L_n$  due to photoinjection of minority carriers, using an AMO solar simulator at  $137.2 \text{ mW cm}^{-2}$ .  $L_{no}$  = diff. length prior to irradiation ( $= 0.38 \mu\text{m}$ ), and  $L_n$  = diff. length after irradiation.  $L_n = 0.2 \mu\text{m}$  prior to annealing, i.e. at time zero. (Specimen number 20).

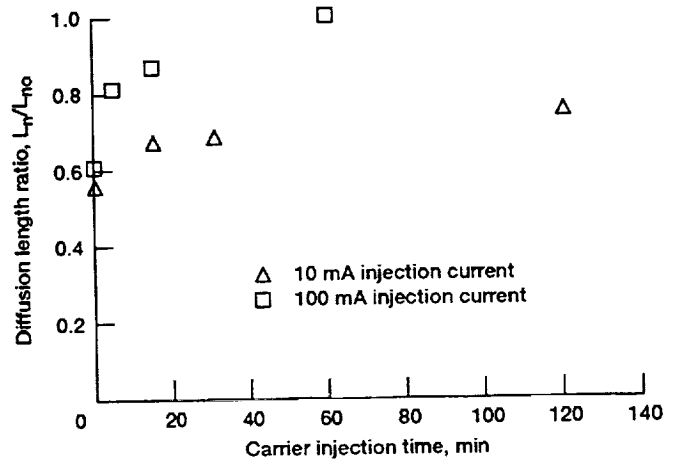


Figure 8.—Recovery of  $L_n$  under an applied forward bias, after 2 MeV proton irradiation with a fluence of  $5 \times 10^{13} \text{ protons/cm}^2$ .  $L_{no}$  is the pre-irradiation diff. length and  $L_n$  is the post-irradiation diff. length. The gold Schottky area in both cases  $= 4.6 \text{ mm}^2$ .

### B. Annealing Behavior of $L_n$

To study the annealing behavior of  $L_n$ , a number of specimens were irradiated with 2 MeV protons. As can be seen from figure 6,  $L_n$  did not appear to anneal with time at room temperature.

Photoinjection of the specimens was achieved at room temperature using an Air Mass Zero (AM0) solar simulator. Figure 7 shows the recovery of  $L_n$  due to photoinjection.

Figure 8 shows the recovery of  $L_n$  due to room temperature forward-bias injection. It can be seen from

this figure that a larger recovery of  $L_n$  is obtained with an increase in the injection current density.

#### IV. SUMMARY AND CONCLUSIONS

The diffusion length damage coefficient,  $K_L$ , of zinc-doped InP was measured as a function of 0.5 MeV proton fluences ranging from  $2 \times 10^{11}$  to  $1 \times 10^{12}$   $\text{cm}^{-2}$ , and found to range in value from  $\approx 3.0 \times 10^{-4}$  to  $\approx 1.5 \times 10^{-3}$ . Yamaguchi et al.'s results (ref. 8) for 1 MeV electron-irradiated solar cells have shown that for zinc-doped InP with a dopant concentration of  $1 \times 10^{18}$   $\text{cm}^{-3}$ , similar to the present specimens,  $K_L$  is  $\approx 6.3 \times 10^{-10}$ . In their work the electron fluences ranged from  $3 \times 10^{14}$  to  $2 \times 10^{16}$   $\text{cm}^{-2}$ . Comparing their results with ours indicates that  $K_L$  for 0.5 MeV proton irradiation is several orders of magnitude larger than that for 1 MeV electron irradiation of higher fluence.

Experimental values for the damage coefficient are very useful for predicting solar cell performance in specified radiation environments. We have, for the first time, measured values of  $K_L$  in proton-irradiated InP.

Annealing studies were carried out on 2 MeV proton-irradiated InP specimens. Minority carrier injection, in the form of AM0 photoinjection and forward-bias injection, led to the recovery of  $L_n$ . This is in agreement with previously published results which show that the maximum power is recovered with minority carrier injection in 1 MeV electron-irradiated solar cells (ref. 12). It was also found that in the case of forward-bias injection, the recovery is dependent on the value of the injection current. This is again in agreement with the effect seen on the maximum power recovery in 1 MeV electron-irradiated solar cells (ref. 12). It was found that  $L_n$  did not anneal with time at room temperature. This is in contrast to previously published results (ref. 10) which show that the radiation damage in 1 MeV electron-irradiated InP solar cells anneals with time at room temperature.

A knowledge of the annealing characteristics of  $L_n$  is beneficial in modelling the performance of solar cells. To our knowledge these are the first reported experimental results on the annealing characteristics of  $L_n$  in proton-irradiated p-type InP materials.

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