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

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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 1×10^{18} cm^{-3}. In measuring K_L irradiations were made with 0.5 MeV protons with fluences ranging from 1×10^{11} to 3×10^{13} 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 5×10^{13} 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 (AM0) 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)

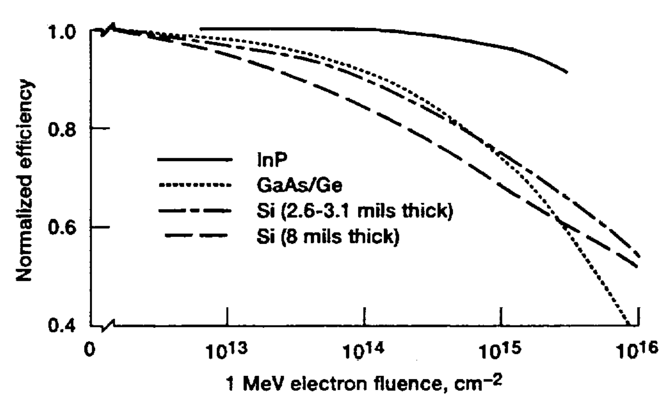

Figure 1.—Normalized efficiency (η/η_o) after 1 MeV electron irradiation. η_o = pre-irradiation efficiency, η = post-irradiation efficiency. (Reproduced from [1]).

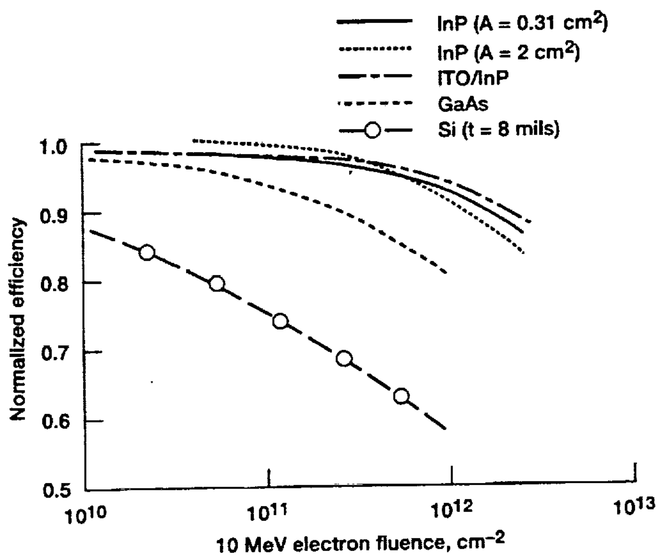

Figure 2.—Normalized efficiency (η/η_0) after 10 MeV proton irradiation. η_0 = pre-irradiation efficiency, η = post-irradiation efficiency, A = cell area, t = cell thickness. (Reproduced from [1]).

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_τ, and the diffusion length damage coefficient, K_L. Experimental values for the damage 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 1×10^{11} to 3×10^{13} 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 5×10^{13} 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_τ, the lifetime damage coefficient, is obtained from the equation:

$$\frac{1}{\tau_\phi} = \frac{1}{\tau_o} + K_\tau \phi \qquad (1)$$

where τ_ϕ is the minority carrier lifetime after irradiation at a fluence ϕ, and τ_o is the minority carrier lifetime prior to irradiation. The minority carrier lifetime, τ, can also be expressed as (refs. 24 and 25):

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

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

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

where the summation is over all the radiation-induced defects and K_τ is the term in square brackets (ref. 1). Hence, K_τ will be a constant if the defect introduction rate, N_{T_j}/ϕ, 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:

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

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

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

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, ϕ. It can be seen that L_n decreases with increasing ϕ for $\phi \leq 3\times10^{12}$ protons/cm^2. For larger values of ϕ, 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:

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

where Δp is the density of the carriers removed (cm^{-3}), R_c is the carrier removal rate (cm^{-1}) at a given proton

TABLE I.—0.5 MeV PROTON IRRADIATIONS

Irradiation number	Fluence, protons/cm^2	Total cumulative fluence, protons/cm^2
1	1×10^{11}	1×10^{11}
2	2×10^{11}	3×10^{11}
3	7×10^{11}	1×10^{12}
4	2×10^{12}	3×10^{12}
5	7×10^{12}	1×10^{13}
6	2×10^{13}	3×10^{13}

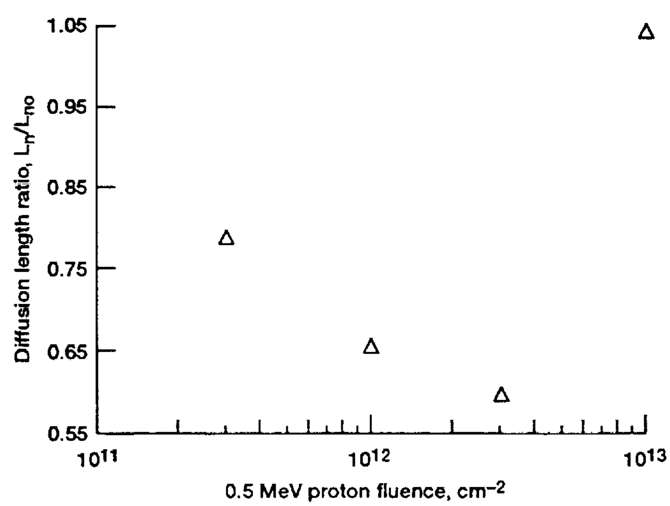

Figure 3.—Typical plot of L_n/L_{no} as a function of cumulative fluence, ϕ (0.5 MeV protons). L_{no} is the diffusion length prior to irradiation, and L_n is ther diffusion length after irradiation. (Specimen number 8).

energy and fluence, ϕ. Recently published data (ref. 27) show R_c to be 8.4×10^3 cm^{-1} for 0.5 MeV proton-irradiated InP. For a fluence of 3×10^{12} cm^{-2}, therefore, $\Delta p = 2.5\times10^{16}$ cm^{-3}. This value of Δp is small as compared to the doping concentration of the specimens used, namely 1×10^{18} cm^{-3}. Hence the increase of L_n for larger values of ϕ cannot be attributed to carrier removal alone.

In this work we concentrated on the lower ϕ 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 ϕ, 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 ϕ 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:

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

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

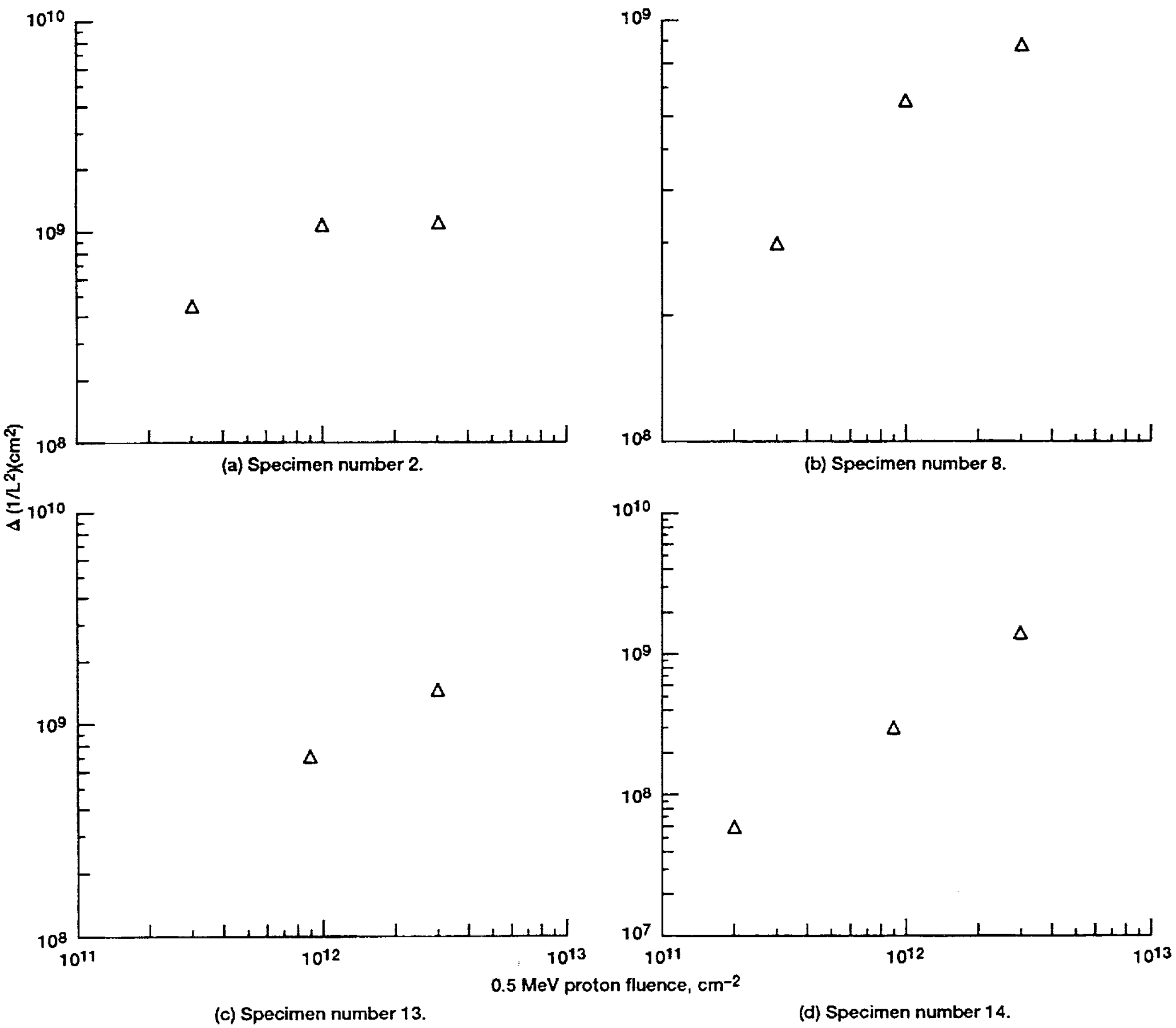

Figure 4.—Plots of log [Δ (1/L^2)] versus log (ϕ), where ϕ is the cumlative proton fluence, for four specimens. Specimens were irradiated with 0.5 MeV protons.

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 ϕ for four specimens is shown in figure 5.

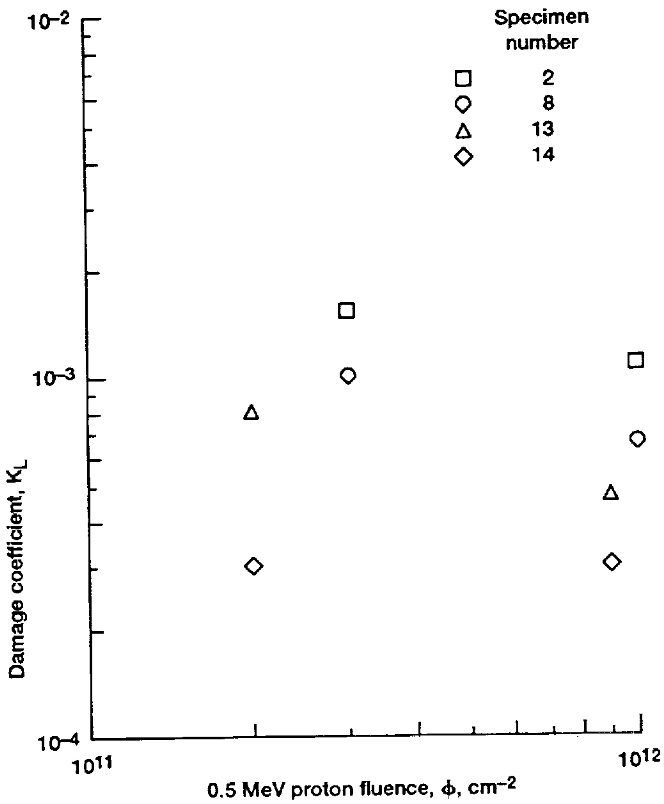

Figure 5.—Plot of log (K_L) versus log (ϕ), where ϕ is the cumulative proton fluence.

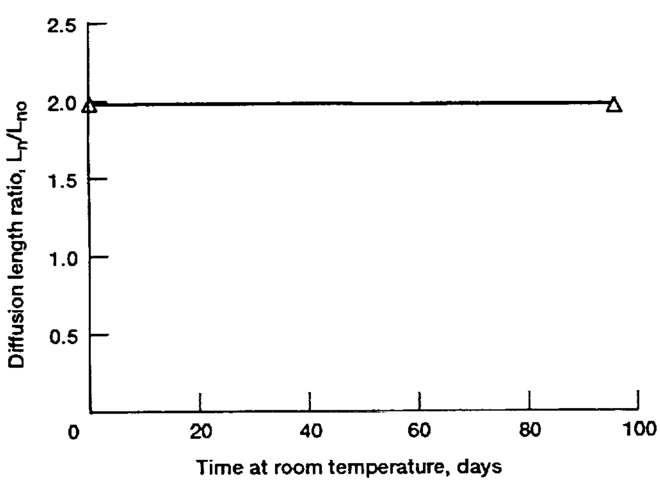

Figure 6.—Room temperature (300 K) annealing after 2 MeV proton irradiation with a fluence of 5.0×10^{13} cm^{-2}. L_{no} = diff. length prior to irradiation (= 0.39 µm), L_n = diff. length after irradiation. Note: in this specimen the high fluence caused significant carrier removal. (Specimen number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

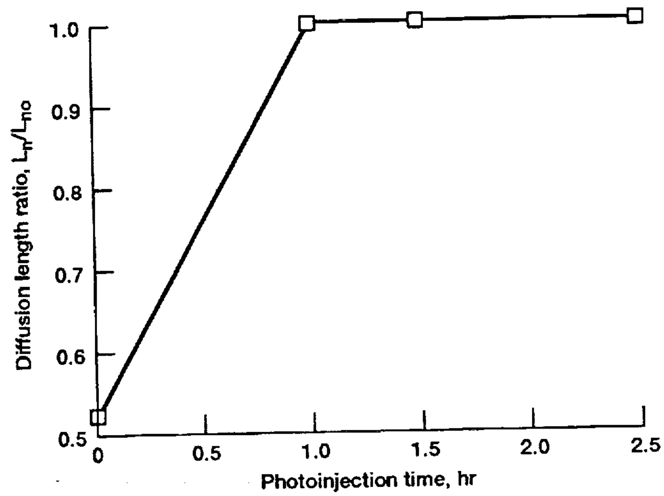

Figure 7.—Recovery of L_n due to photoinjection of minority carriers, using an AMO solar simulator at 137.2 mW cm^{-2}. L_{no} = diff. length prior to irradiation (= 0.38 µm), and L_n = diff. length after irradiation. L_n = 0.2 µm prior to annealing, i.e at time zero. (Specimen number 20).

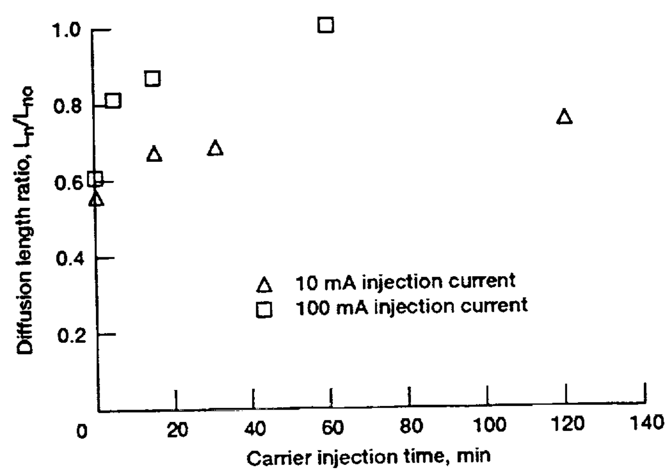

Figure 8.—Recovery of L_n under an applied forward bias, after 2 MeV proton irradiation with a fluence of 5×10^{13} protons/cm^2. L_{no} is the pre-irradiation diff. length and L_n is the post-irradiation diff. length. The gold Schottky area in both cases = 4.6 mm^2.

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 2×10^{11} to 1×10^{12} cm^{-2}, and found to range in value from $\simeq3.0\times10^{-4}$ to $\simeq1.5\times10^{-3}$. 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 1×10^{18} cm^{-3}, similar to the present specimens, K_L is $\simeq6.3\times10^{-10}$. In their work the electron fluences ranged from 3×10^{14} to 2×10^{16} 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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13. ABSTRACT *(Maximum 200 words)*

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