PROTON RADIATION DAMAGE IN BULK n-GaAs

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SUMMARY

Bulk samples of Te-doped n-type GaAs were irradiated using 10 MeV to 24 MeV protons to fluences between 2 x 10^{11} protons/cm^2 and 2 x 10^{14} protons/cm^2. Majority carrier electrical effects were measured using the van der Pauw techniques and it was observed that radiation damage was minimal at the 10^{11} proton/cm^2 fluence. For the higher fluences, carrier removal was proportional to $\Delta E/\Delta x$ for the protons indicating ionization interactions between the protons and atoms. Thermal annealing was observed at 155°C.

INTRODUCTION

Gallium arsenide is of interest for space photovoltaic solar-cells because of its expected increased resistance to space radiation damage and higher solar cell efficiencies than possible for silicon. Proton induced damage to GaAs solar cells, however, has been examined only in a limited number of studies (ref. 1-3). These investigations have been focused primarily on protons with energies $\leq$ 1 MeV with only a few data points at higher energies. Also, the various specialized solar cell structures have been irradiated independent of each other. In contrast to these above mentioned studies, the investigation described in this report has been directed toward evaluating changes in fundamental material properties (as opposed to specific device performance) for higher energy protons. The intent is to begin to identify regimes in which proton radiation effects are significant in determining electrical characteristics of GaAs. This information will hopefully aid in the development of designs for more radiation-resistant solar cells.

Many GaAs solar cell designs are being aimed at high efficiency cell performance in geosynchronous earth orbit ($\sim$ 35,800 km altitude) for 10 or more years. It appears that solar flare protons are the dominant source of radiation in this environment (ref. 4). Solar cells in geosynchronous orbit will also be exposed, to a lesser extent, to trapped electrons in that orbit and to trapped electrons and protons during transfer orbits. The indication is that the solar flare protons with energies > 10 MeV may impinge on cells in synchronous orbits

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with total fluences of nearly 10^{11} protons/cm^2 or more (ref. 5-7). This fluence, however, will depend on the life of the spacecraft beyond 10 years and the particular flare cycle.

The intent of this study was to begin to identify those middle-range energy protons and fluences which are detrimental to GaAs electrical properties. Based on this consideration, and the numbers and energies of solar flare protons found in synchronous orbit, it was decided to investigate proton energies between 10 MeV and 25 MeV and fluences in excess of 1×10^{11} protons/cm^2. These protons were readily available at the NASA Lewis Research Center variable energy cyclotron.

One measure of semiconductor defect production resulting from irradiation is the majority carrier removal (i.e. percent decrease in majority carrier concentration) as a function of radiation fluence (ref. 8). Data of this nature and other majority carrier effects such as mobility and resistivity changes were easily obtained by making pre-irradiation and post-irradiation Hall effect measurements.

In addition to describing more fully the experimental procedures for the above mentioned proton irradiations and Hall measurements for n-type GaAs, this paper will also describe a technique for accurate determination of total proton fluences in irradiated GaAs. Results will be presented linking decreases in mobility and majority carrier concentration to proton energies and fluences as well as data linking 1 MeV electron damage to 10 MeV through 24 MeV proton damage for possible equivalences.

EXPERIMENTAL

Samples used in this study were Czochralski grown n-type bulk gallium arsenide obtained from Metals Research Ltd. (England). The (100) oriented, Te-doped wafers had initial carrier concentrations of about 1×10^{17} electrons/cm^3, resistivities of 2×10^{-2} Ω - cm, and majority carrier mobilities of about 3900 cm^2/V-s. The 0.38 mm (15 mil) thick wafers, polished on both sides, were diced into 8mm x 8mm samples.

Room temperature Hall effect measurements were used to characterize the GaAs before and after irradiation. The Hall measurements were made using the contacts in each of the four corners (ref. 10). The ohmic contacts were made using pure indium. The sample was first etched for 30 seconds in a warm solution of $3H_2SO_4$:$1H_2O_2$:$1H_2O$ to remove oxides from the surface. Dots of pure In were placed in each of the four corners of the sample using a low-power ultrasonic soldering iron in contact with the gallium arsenide (heat-sinked to an aluminum plate) for approximately 1 second. I-V characteristics of all contacts were checked using a transistor curve tracer and were accepted when these characteristics were linear for currents ranging from 0.01 mA to 100 mA. Non-linear Schottky barrier contacts were successfully alloyed further to obtain linear characteristics by applying voltages in excess of the breakdown voltage.

Good ohmic contacts provided for symmetric van der Pauw technique Hall measurements when the applied currents and magnetic fields were reversed. Applied currents ranged from 10 mA to 50 mA and the applied magnetic induction was 10,000 Gauss. Hall data was collected on each sample before and after irradiations.

All irradiations with protons were conducted at the NASA Lewis Research Center variable energy cyclotron facility. Proton energies of 12.5 MeV and 38.8 MeV were obtained from the cyclotron, and scattering foils were used to more evenly disperse the beam over a wider area ($\approx 3 in^2$). Also, in one arrangement, samples were stacked vertically with varying thicknesses of aluminum between them to allow for simultaneous irradiation of different samples with different energy protons all to the same fluence. The result was that irradiations of gallium arsenide were conducted with protons having incident energies of 9.9 MeV, 12.0 MeV, 16.4 MeV, and 24.0 MeV to total fluences ranging between approximately 2×10^{11} protons/cm^2 to 2×10^{14} protons/cm^2. All irradiations reported here were done with the samples in air. To prevent annealing during irradiation, the samples were mounted on a heavy stainless steel plate and the entire apparatus was cooled by a fan. Also, a low proton beam current of 0.2 μA was used.

A direct technique was utilized in this study to measure total proton fluence for each sample. This technique was based on assaying the 39.2 hour half-life Ge-69 isotope, in each irradiated sample, produced by the $Ga^{69}(p,n)\,Ge^{69}$ reaction. Cross sections, $\sigma(E)$, as a function of proton energy were experimentally determined for the above reaction and several others in GaAs. The curve for this cross section is shown in figure 1. This data was obtained using a 15% Ge-Li solid-state detector. The total proton fluence in the GaAs sample could then be determined by

$$\phi_{proton} = \frac{N_{Ge-69}}{[N_{Ga-69}]\sigma(E)} \qquad (1)$$

where N_{Ga-69} = 60% of the Ga atoms in the original sample

N_{Ge-69} = the number of radioactive isotopes produced by the proton radiation; measured by counting the γ-radiation from the Ge-69 isotope.

This method for determining total fluence was believed to be quite accurate since it did not rely on the accuracy of any secondary standards or detectors.

RESULTS AND DISCUSSION

Results presented in this section are for proton irradiations of four samples of Te-doped GaAs labeled A-D. Original Hall data (i.e. before irradiation) and energies of the incident protons for the four samples are shown in table 1. The proton energies listed are the incident proton energies, transmitted proton energies, and average energies. Note that in these irradiations, the protons traveled completely through the 15 mil GaAs samples although their energies did decrease. A 15 mil thick sample of GaAs will stop any protons with energies $\leqq$ 9.4 MeV.

Figure 2 shows the fractional decrease in room temperature Hall mobility as a function of total fluence. It appears that for incident protons having energies $\geqq$ 10 MeV, fluences must be in excess of 10^{13} protons/cm^2 before majority carrier mobility degradation becomes significant.

This same phenomena can be observed for majority carrier removal as shown in figure 3. In fact, if these curves are extrapolated down to the horizontal axis, it appears that noticeable degradation of a GaAs device will not occur below $\sim 10^{11}$ protons/cm^2 for incident proton energies in excess of 10 MeV. This result also demonstrates that as the average energy of the protons increases, their incremental effect in damaging the material decreases. In other words, this supports the tenet that lower energy particles do more damage. This same principle is shown more clearly in figure 4. Here the carrier removal is shown to be a linear function of the proton energy loss per unit distance traveled in the gallium arsenide. The linear nature of this plot suggests that the proton interaction with the gallium and arsenic atoms involves an ionization process.

In an effort to verify that the Hall measurements made in this study were good, it was decided to attempt duplication of 1 MeV electron irradiation results of Look and Farmer (ref. 11). Samples from the same crystal as samples A-D were irradiated with 1 MeV electrons at the NASA Lewis Research Center dynamitron. Total fluences were 4×10^{15} e^-/cm^2, 1×10^{16} e^-/cm^2, and 3×10^{16} e^-/cm^2. As can be seen from figure 5, this data agrees quite well with that of Look and Farmer (ref. 11). Not only does this add validity to our Hall measurements, but it provides some indication of possible equivalence of 9.9 MeV proton damage in GaAs with 1 MeV electron damage in that material. The equivalences in terms of majority carrier removal in n-type GaAs are shown in figure 5. Although the ratios of electrons to protons are not constant (varying between 250 and 326), it appears that a 9.9 MeV proton is approximately equivalent to 300--1 MeV electrons.

Figure 6, a plot of mobility degradation factor as a function of fluence, may provide a clearer picture of equivalence. The mobility degradation factor, b, is defined as follows (ref. 8):

$$b = \frac{\mu_i}{\phi}\left(\frac{1}{\mu_f} - \frac{1}{\mu_i}\right) \tag{2}$$

where $b(cm^2)$ = Mobility degradation factor

$\mu_i(cm^2/V\text{-}s)$ = Initial Hall mobility

$\mu_f(cm^2/V\text{-}s)$ = Final Hall mobility

$\left.\begin{matrix}\phi(p^+/cm^2)\\ \phi(e^-/cm^2)\end{matrix}\right\}$ = Total fluence

In this figure the incremental mobility degradation appears to be about the same for 16.4 MeV protons and 1 MeV electrons. In this case, it appears that 1--16.4 MeV proton does about as much damage as 190--1 MeV electrons.

Low temperature (155°C) annealing of proton and electron damage was briefly examined. Two samples were examined which had been irradiated (1 MeV electrons to 1×10^{16} e^-/cm^2 and 16.4 MeV protons to 6.5×10^{13} p^+/cm^2) to obtain approximately 30% carrier removal. Results of this isothermal annealing in forming gas are shown in figure 7. Percent recovery is defined for this figure as:

$$R = \left(\frac{n_{annealed} - n_{damaged}}{n_{undamaged} - n_{damaged}} \right) \times 100\% \qquad (3)$$

In this definition "n" means majority carrier concentration. Although recovery was not complete after 50 hours of annealing, this data does indicate that annealing was occurring. Thus there is some indication that self-annealing at low temperatures may be feasible especially when particle flux is low such that the permanent damage will occur only in small amounts over the life of the gallium arsenide solar cell.

CONCLUSION

Results of this study indicate that protons with energies between 10 MeV and 25 MeV will probably not adversely affect n-type gallium arsenide for solar cell performance unless the total fluence exceeds 10^{11} protons/cm^2. For proton fluences between 10^{11} protons/cm^2 and 10^{14} protons/cm^2, it appears that the lower energy protons do more damage even for complete penetration through the material. The proton-atom interaction appears to be an ionization process for these radiation conditions. Defects introduced under these conditions appear to be at least partially removed by annealing at 155°C. One might speculate that continuous cell operation at this relatively low annealing temperature would reduce the damaging effects of proton radiation and extend solar cell life.

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TABLE 1 - SAMPLE CHARACTERISTICS

SAMPLE	Original Hall Data			Proton Energies (MeV)		
	ρ_o (Ω-cm)	n_o (e^-/cm^3)	μ_o (cm^2/V-s)	E_{in}	E_{out}	E_{aver}
A		1.08×10^{17}	4248	9.9	1.6	5.8
B	1.74×10^{-2}	9.30×10^{16}	3864	12.0	6.0	9.0
C	1.42×10^{-2}	1.11×10^{17}	3960	16.4	12.0	14.2
D	1.90×10^{-2}	8.35×10^{16}	3938	24.0	20.9	22.5

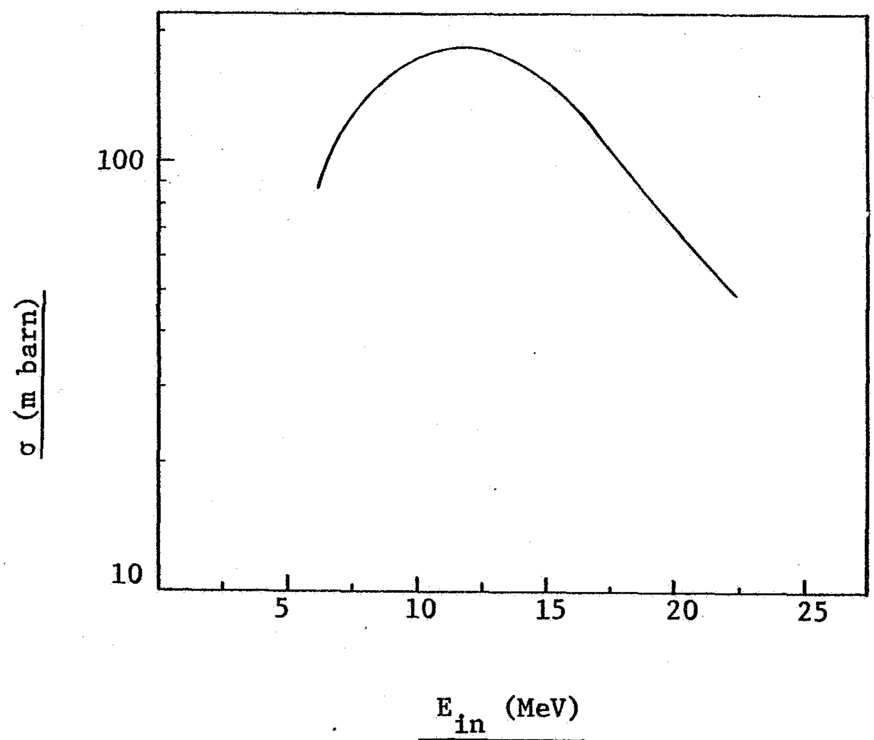

Figure 1. Cross section as a function of incident proton energy for the $Ga^{69}(p,n)Ge^{69}$ reaction

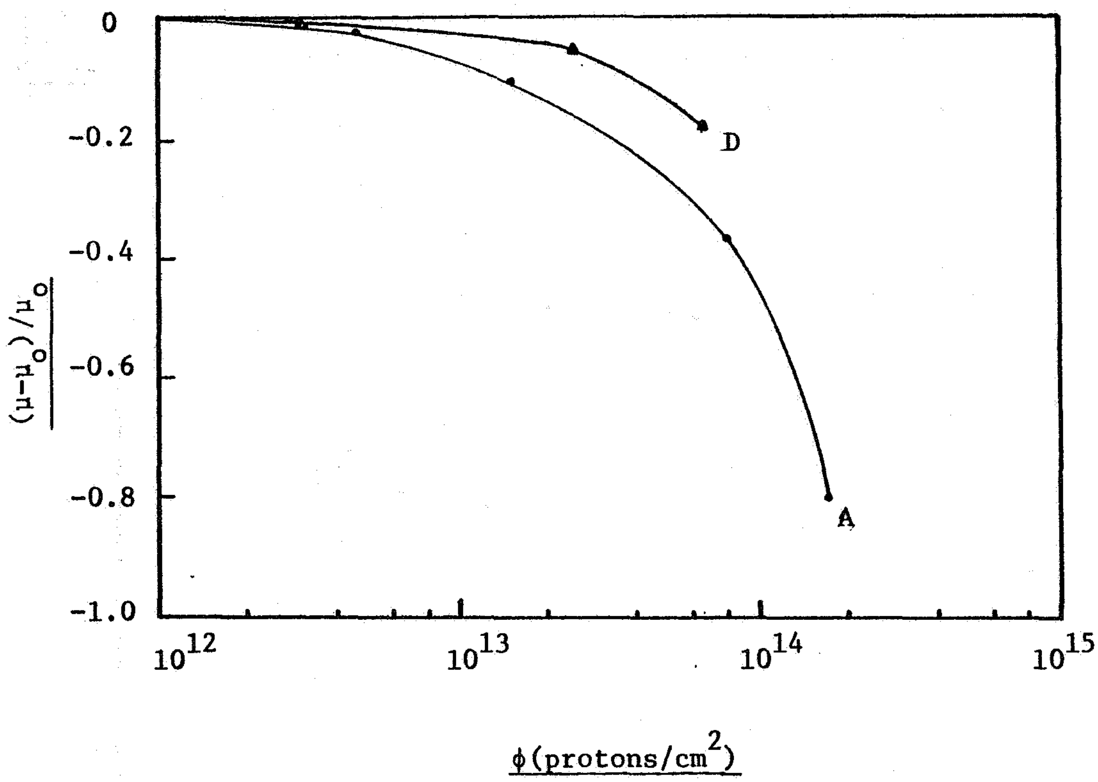

Figure 2. Fractional decrease in room temperature Hall mobility as a function of proton fluence

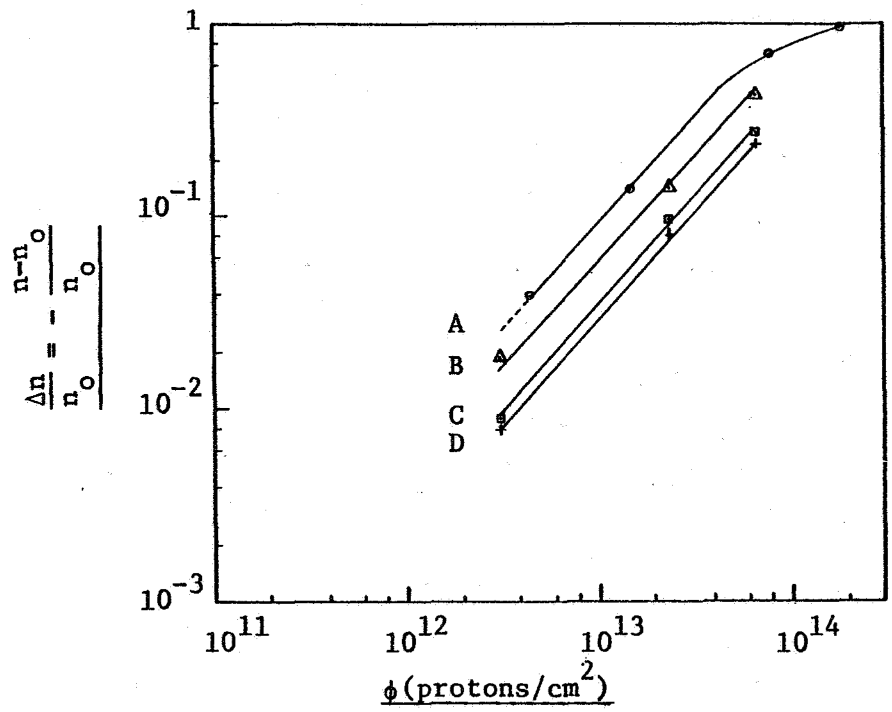

Figure 3. Carrier removal in Te-doped GaAs($n \cong 1x10^{17}$ cm^{-3}) as a function of proton fluence

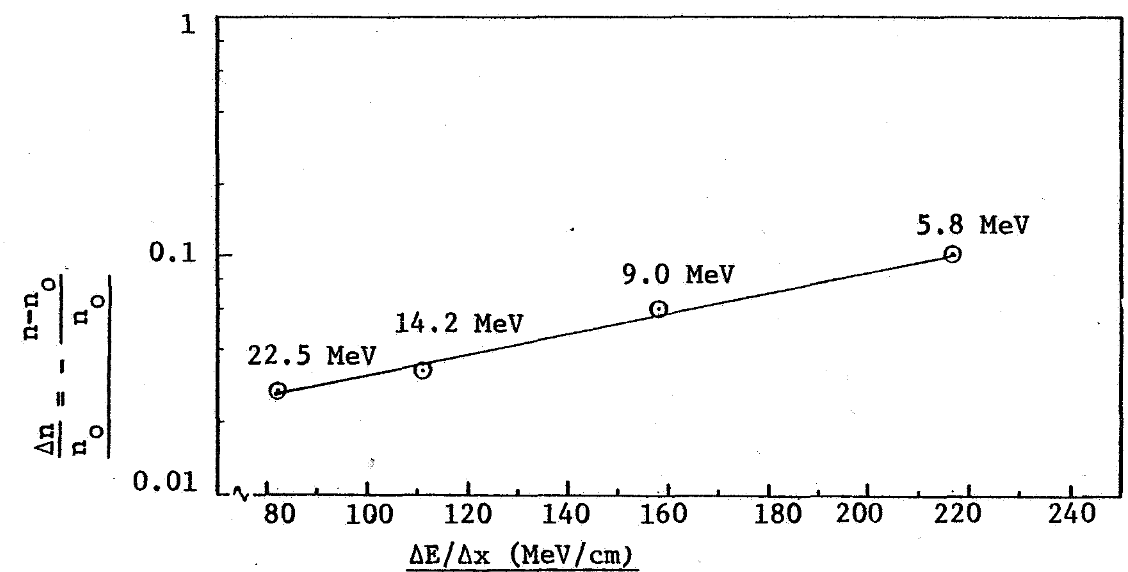

Figure 4. Carrier removal vs. the ratio of the total proton energy loss to the sample thickness. For all samples, $\Delta x = 0.038$ cm and $\phi = 1x10^{13}$ protons/cm^2. Energies listed are average energies.

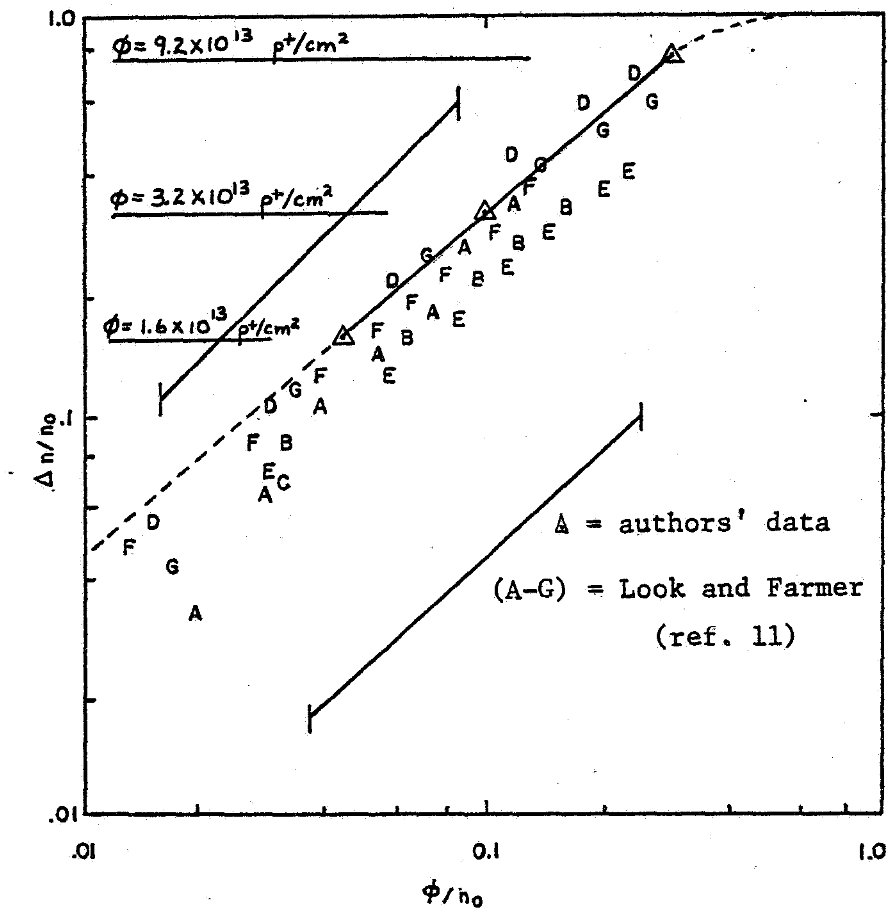

Figure 5. Free carrier removal as a function of fluence for 1 MeV electrons. Horizontal lines indicate equivalent damage produced by 9.9 MeV protons.

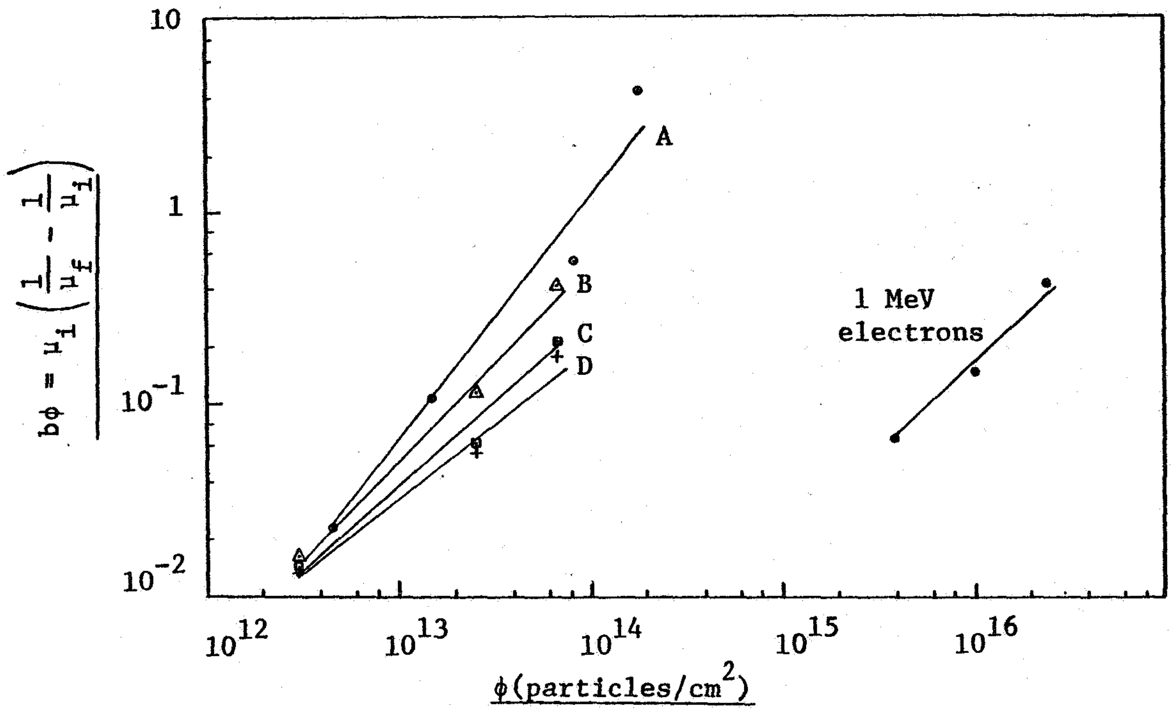

Figure 6. Mobility degradation vs. total fluence. Shown is a comparison of damage for 9.9 MeV, 12.0 MeV, 16.4 MeV and 24.0 MeV protons and 1 MeV electrons.

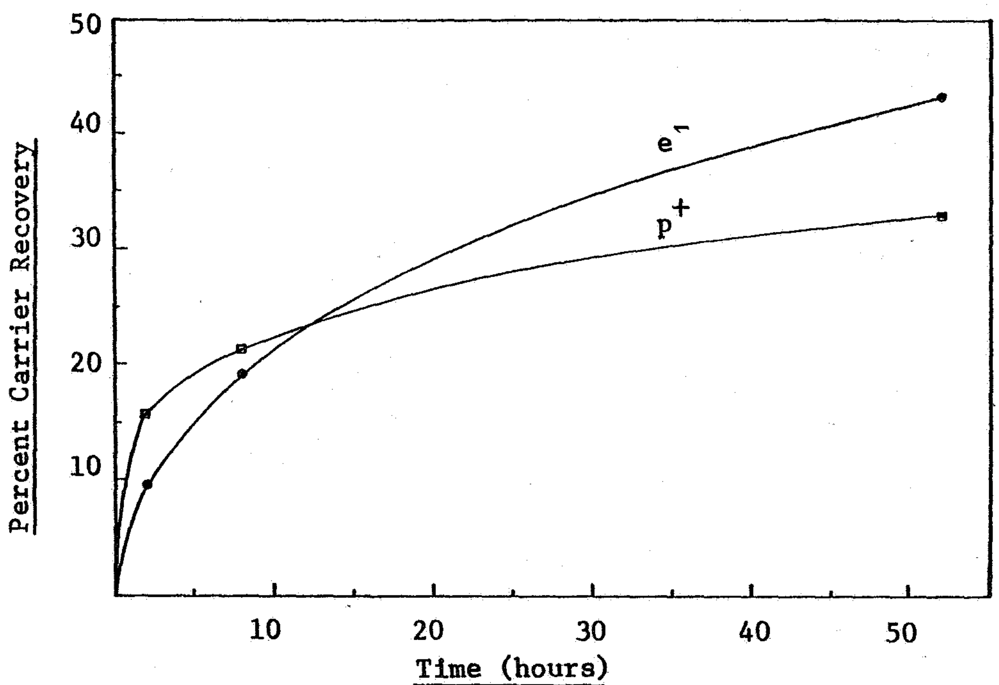

Figure 7. 155°C annealing results for proton and electron irradiated samples. $\Delta n/n_o \approx 0.3$ for both cases.