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RADIATION EFFECTS ON SILICON SOLAR CELLS

Third Quarterly Progress Report Covering the Period June 1, 1962, through August 31, 1962

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1. INTRODUCTION

This report is the third quarterly status report on Radiation Effects in Silicon Solar Cells, Contract No. NAS7-91, and covers the period June 1, 1962, through August 31, 1962. During this period significant experimental results have been achieved on the galvanomagnetic and carrier lifetime measurements. The following specific items will be discussed in this report.

1. The calculation of the theoretical introduction rate of defects by high energy electrons in silicon.
2. Further analysis of the relation between the carrier removal rate and defect introduction.
3. Further discussion of the temperature dependence of the excess carrier lifetimes with particular emphasis on its application to our experimental data.
4. The results of galvanomagnetic studies of irradiated floating-zone refined silicon.
5. Results of detailed analysis of the carrier lifetime in irradiated quartz-crucible grown silicon.

The following sections of this report will discuss each of these items in more detail.

2. THEORY

2.1 CALCULATION OF THE TOTAL DEFECT INTRODUCTION RATE

The total rate at which defects are introduced into silicon by high energy electron irradiation can be calculated from the following assumptions:

1. Energy transfer between a high energy electron and a silicon atom occurs via the coulomb electrostatic interaction.
2. The displacement of atoms can be characterized by a threshold energy, T_d. For energies imparted to the atom less than T_d it is not displaced. For energies greater than T_d it is always displaced.
3. The motion of the primary recoil atoms through the lattice can be characterized by hard sphere scattering for calculating the total number of displacements produced. The probability that

secondary displacements occurred can be evaluated by assuming that the distribution of energies imparted to the secondaries is uniform between zero and the maximum possible energy transfer.

4. The interstitials and vacancies produced are isolated and do not interact to form more complicated defects.
5. No secondary annealing reactions take place.

Obviously assumptions 4 and 5 are not good for silicon irradiated at room temperature. However, this calculation estimates the total number of defects which are produced and affords a comparison with the experimental results whereby one can deduce what fraction of the defects are actually seen in a given experiment.

The calculation of the total number of displaced atoms has been described by Seitz and Koehler[1]. The cross section for displacing an atom from its lattice, σ_d, in which it must receive an energy of at least T_d, is given by the following expression:

$$\sigma_d = \frac{\pi}{4} b'^2 \left[\left(\frac{T_m}{T_d} - 1 \right) - \beta^2 \log \frac{T_m}{T_d} + \pi\alpha\beta \left\{ 2 \left[\sqrt{\frac{T_m}{T_d}} - 1 \right] - \log \frac{T_m}{T_d} \right\} \right]$$

where $b' = \dfrac{2Z_2 e_o^2 c^2}{m_o \gamma \beta^2}$,

$$T_m = 2 \frac{E}{M c^2} (E + 2m_e c^2),$$

E, v are the kinetic energy and velocity of the electron,

$$\beta = v/c, \quad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}},$$

$$\alpha = Z_2/137,$$

Z_2, M_2 are the atomic number and mass number of the target atom, and

e_o, m_o are the charge and mass of the electron.

For large T_m/T_d the formula approaches

$$\sigma_d \approx \pi Z_2^2 \left(\frac{e_o^2}{m_o c^2}\right) \frac{1}{\beta^4 \gamma^2} \left(\frac{T_m}{E_d} - 1\right) .$$

The threshold energy T_d has been chosen at two possible values: 12.9 ev and 25 ev. The absolute threshold for which silicon atoms can be displaced from their lattice has been measured to be 12.9 ev by Lofersky and Rappaport[2]. However, it is probably not true that an atom receiving more than 12.9 ev will always be displaced from its lattice position. Instead, it is quite likely that an ever increasing probability of displacement is associated with increasing energies above this threshold. The value 25 ev has been chosen as an effective threshold for multiple displacement production by high energy electrons. The assumption is that a displacement probability equal to zero for energy < 25 ev and equal to one for energies > 25 ev is a reasonable approximation to the continuously increasing displacement probability curve which has its threshold at 12.9 ev.

The total displacement primary cross section calculated from the above formula for electrons of energy 30 Mev is 75 barns for the 12.9 ev threshold, and 39 barns for the 25 ev threshold. The average total number of displaced atoms in collisions resulting from Rutherford scattering cross section has been given in Ref. 1 by the following formula:

$$\bar{\nu} = \left\{0.885 + 0.561 \log \left(\frac{T_m}{4\, T_d}\right)\right\} \frac{T_m}{T_m - E_d} .$$

Evaluated for 30-Mev electrons on silicon $\bar{\nu} = 4.94$ for the 12.9 ev threshold, and $\bar{\nu} = 4.57$ for the 25 ev threshold.

The total number of displaced atoms, N_d per unit volume per electron/cm^2, is equal to the product of the displacement cross section, σ_d, the average number of total displacements per displacing collision, and the number of atoms per unit volume. N_d is calculated to be 18,5 for the 12.9 ev threshold, and 8.9 for the 25 ev threshold.

It should be noted that this calculated rate at which displacements are produced by high energy electrons is greater by approximately an order of magnitude than the measured rate of introduction of the A centers in pulled silicon. This fact has important implications. In our simplest

analysis we would assume that all the vacancies produced by irradiation would migrate at room temperature to an interstitial oxygen atom, forming the substitutional oxygen or A center. On the other hand, it appears from this fact that only ~10% of the vacancies suffer this fate, and the other ~90% must be accounted for by some other annealing mechanism.

2.2 INTERPRETATION OF CARRIER REMOVAL RATES

The analysis presented in the second quarterly report[3] has been extended. The original analysis assumed that the electron removal rate was equal to the rate at which acceptor centers were populated by electrons. A correction to this analysis should be applied in some cases, particularly at lower temperatures, for the change in occupancy of the original chemical donors by the motion of the Fermi level during irradiation. A revised analysis which includes this correction is performed below.

As shown before, the electron density n is related to the position of the Fermi level, E_f, the bottom of the conduction band, E_c, the effective density of states in the conduction band, N_c, and the temperature, T, by the equation

$$n = N_c \exp\left[-(E_c - E_f)/kT\right]. \tag{1}$$

The fraction of acceptor-like trapping centers which are occupied by electrons, f_T, is given by the Fermi function:

$$f_T = \frac{1}{1 + \alpha_T \exp\left[(E_T - E_F)/kT\right]}, \tag{2}$$

where E_T is the energy of the trapping centers and α_T is a degeneracy factor for the trapping centers, to be discussed later. In a similar manner, the fraction of the donor centers occupied by electrons, f_D, is given by a similar expression,

$$f_D = \frac{1}{1 + \alpha_D \exp\left[(E_D - E_F)/kT\right]}. \tag{3}$$

Charge neutrality requires that the change in density of electrons in the conduction band Δn, due to the radiation is equal to the number of

trapping centers introduced, N_T, times the fraction of them occupied by electrons, fT_2, plus the number of donor centers originally present, N_D multiplied by the change in occupancy fraction, Δf_D,

$$-\Delta n = N_T f_T + N_D \, \Delta f_D \, . \tag{4}$$

The foregoing equations can be solved simultaneously for the number of trapping centers introduced,

$$N_T = -\Delta n \left\{ 1 + \frac{\alpha_D N_C N_D \exp\left[-(E_C-E_D)/kT\right]}{\left\{(n_o+\Delta n) + \alpha_D N_C \exp\left[-(E_C-E_D)/kT\right]\right\}\left\{n_o+\alpha_D N_C \exp\left[-(E_C-E_D)/kT\right]\right\}} \right\} x \tag{5}$$

$$x \left\{ 1 + \alpha_T \frac{N_C}{(n_o + \Delta n)} \exp\left[-(E_C-E_T)/kT\right] \right\}.$$

From the observed change in electron density, Δn, the initial value, n_o, the total number of traps, N_T, can be calculated. In case the Fermi level is not near the donor center, terms like $(n_o + \Delta n)$ can be neglected by comparison with $\alpha_D N_C \exp\left[-(E_C-E_D)/kT\right]$ and the expression simplifies to equation (6),

$$N_T \approx -\Delta n \left\{ 1 + \frac{N_D}{\alpha_D N_C} \exp\left[-(E_C-E_D)/kT\right] \right\} \left\{ 1 + \alpha_T \frac{N_C}{n_o+\Delta n} \exp\left[-(E_C-E_T)/kT\right] \right\}. \tag{6}$$

Typical values indicate that for room-temperature irradiations and the donor concentrations which are used in these experiments, the correction term in the first brackets of the foregoing equation is not significant and one can usually neglect the effect of the change in occupancy of the donor centers. For data taken at lower temperatures this correction term will be significant.

Utilizing these formulas the defect introduction rate can now be evaluated by two techniques:

1. From the initial rate of change of carriers, in which the Δn term in the brackets can be neglected by comparison with n_o, and

2. From the initial and final carrier densities, taking into account the exact value of the experimentally observed Δn.

As shown in a subsequent section of this report, this analysis has been performed for one of the irradiations and the disagreement between the values of N_T calculated in this way has a significant interpretation. In fact, the entire irradiation curve can be predicted from this formula for comparison with experimental results.

Some more calculations have also been performed of the theoretical temperature dependence of the Hall coefficient for various acceptor concentrations. It was indicated qualitatively in the previous quarterly report[3] that for acceptor concentrations less than the initial donor concentrations the temperature dependence of the Hall coefficient tended to reveal the energy level of the donor, although the freezing out of carriers onto the donor center was achieved at higher temperatures when the compensation was almost complete. When more acceptors were introduced than the original donor concentration, the acceptor energy level was seen in the temperature dependence of the Hall coefficient. Figure 1 is a calculation of the temperature dependence of the electron concentration for various acceptor concentrations and illustrates this point very well. The data in Fig. 1 were calculated from an assumed energy level of the donor at 0.044 ev and of the acceptor at 0.16 ev below the conduction band. The density of states in the conduction band, N_T, was assumed to be $5.55 \times 10^{16} T^{3/2}$ cm^{-3} *. Figure 1 illustrates quite dramatically the the shift of the 0.044 ev slope to higher temperatures as the compensation is increased and the eventual transition to the 0.16 ev slope. This calculation can be summarized by saying that the temperature dependence of the Hall coefficient is most effective at revealing that defect center which would be partially occupied by electrons at absolute zero of temperature. It does not give useful information about deeper levels, because these levels are filled at a higher temperature. It does not give accurate information about the deeper levels because these levels are filled at the

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*The value of N_C reported in the second quarterly progress report is incorrect and should be changed to this number. This density of states corresponds to an effective mass for electron density calculations of $m^* = 1.1\ m_o$.

higher temperature. It usually reveals these deeper levels at all only if their concentration is almost sufficient to use up the available electrons at very low temperatures.

As a result of these calculations it should be borne in mind, therefore, that the observed carrier removal rate is due to all the deep lying acceptor states, but that the temperature dependence of the Hall coefficient reveals mostly the highest acceptor state which is being filled by the irradiation. Hence, in case there are more than one acceptor states introduced, it is not necessarily true that the observed carrier removal rate should be associated only with that level revealed by the temperature dependence measurements.

A further discussion of the degeneracy factors, α_D and α_T is in order. The need for these degeneracy factors in the Fermi function can be derived from the following argument. Consider a metal which can accept an electron in any of g states, but having once accepted a single electron the other g-1 states are no longer available. An example of this is an acceptor center which can accept an electron in either of two equivalent spin orientations, but having accepted one electron the energy state for the other electron would be very much higher, due to coulomb repulsion. In this case, we can calculate the Fermi function by the following argument. The Fermi function is equivalent to the statement that the ratio of the number of states which are full and available to be emptied to the number of states which are empty and available to be filled is equal to $\exp\left[E-E_F/kT\right]$. In our model, if the Fermi function for the state is f, the number of states which are full and available to be emptied is equal to fN. The number of states which are empty and available to be filled is equal to g(1-fN). Hence,

$$\frac{fN}{(1-f)gN} = \exp\left[-(E-E_F)/kT\right] \qquad (7)$$

$$f = \frac{1}{1 + \alpha \exp\left[+(E-E_F)/kT\right]},$$

where $\alpha = 1/g$.

The degeneracy factor $\alpha = 1/g$ is usually due to spin degeneracy of

the electron. For example, a simple hydrogenic donor like phosphorus can have in the un-ionized state one electron. When it is ionized it is capable of accepting an electron in either of two spin states. Hence, the factor g is expected to be 2, and $\alpha = 1/2$ for such a center. The A center represents a similar situation in which an electron can be accepted in either of two spin states. The E center is expected to be different, because in the neutral state the E center already contains an unpaired electron, namely that electron associated with the phosphorus atom. Hence, in accepting another electron, this electron can only be accepted in the spin state opposite to the spin of the electron already present. However, once the A center is negatively charged, it can release an electron equivalently from either of the two spin states. Hence, for the E center α is expected to be 2.

2.3 TEMPERATURE DEPENDENCE OF EXCESS CARRIER LIFETIME

In the experiments which have been performed on the change in carrier lifetime in silicon the following are typical values of carrier and trap densities:

The majority carrier density, $n_o \sim 10^{14}$ to 10^{15}.

Excess carriers, $\Delta n \sim 0.1$ to $0.2\ n_o$.

Recombination centers, $N_T \sim 10^{10}$ to 10^{12}.

Under these conditions the analysis for the case of low trap density should be appropriate and the Shockley-Read formula applicable. The assumption of small excess carrier density is not necessarily applicable, particularly since the excess carrier density can be assumed to be large compared to the minority carrier concentration. The pertinent approximation to the Shockley-Read formula is then given by the equation,

$$\tau = \tau_{po}\left(1 + \frac{n_1}{n_o + \Delta n}\right) + \tau_{no}\left(\frac{p_1 + \Delta n}{n_o + \Delta n}\right). \qquad (8)$$

In case the recombination center is above the center of the energy gap, the further approximation, $n_1 \gg p_1$, can be applied. Usually the ratio of these quantities is much larger than any differences between τ_{po} and τ_{no}.

It is particularly interesting to investigate this equation as a function of excess carrier density Δn. Let us consider first the case of a recombination center well above the center of the gap, so that $p_1 \tau_{no}$ is much smaller than $n_1 \tau_{po}$. In this case the dependence of the lifetime, τ, on injection level and temperature can be seen by the following expression:

$$\tau = (\tau_{po} + \tau_{no} \frac{\Delta n}{n_o + \Delta n}) + \tau_{po} \frac{n_1}{n_o + \Delta n} . \qquad (9)$$

The only appreciable temperature dependence is in the n_1 factor of the second term. At very low injection levels and low temperatures, the lifetime should be τ_{po}. At very high injection levels, $\Delta n \gg n_o$, the low temperature lifetime approaches $\tau_{po} + \tau_{no}$. The higher temperature lifetime is dominated by the second term, $\tau_{po} n_1/(n_o + \Delta n)$.

Hence, if τ_{no} is not too small compared with τ_{po} a study of the dependence of the lifetime on injection level can reveal both the values of τ_{po} and τ_{no}. This type of analysis has previously been applied to interpretations of the lifetime in irradiated silicon by Calkin, et al.,[4] although in these experiments the lifetime measurements were performed on diode structures rather than homogeneous silicon samples.

In the other cases, where the recombination center is below the center of the gap in n-type material, the term $n_1 \tau_{po}$ is neglected by comparison with $p_1 \tau_{no}$, resulting in the expression

$$\tau = (\tau_{po} + \tau_{no} \frac{\Delta n}{n_o + \Delta n}) + \tau_{no} \frac{p_1}{n_o + \Delta n} . \qquad (10)$$

The only significant difference between this expression and the previous one is that the coefficient of the temperature dependent term is now not determined by the low-injection lifetime at low temperatures. It should be noted that the absolute value of n_1 and p_1 are uniquely determined by the position of the defect center in the energy gap and the temperature, and do not depend upon the concentration of these centers. As a result, a study of the temperature dependence of the carrier lifetime is subject to internal consistency checks between the low temperature constant-lifetime, the slope of the temperature dependent region and the position of the

transition between the constant and temperature dependent regions. Analysis of the measurements on carrier lifetime in a sample of quartz-crucible grown silicon in terms of this theory will be described in a later section of this report.

3. GALVANOMAGNETIC MEASUREMENTS

3.1 80°K IRRADIATIONS

3.1.1 One Ohm-Cm Floating Zone Grown Silicon

A sample of 1 ohm-cm P-doped silicon was irradiated with 4.7×10^{15} 38-Mev electrons/cm^2. An initial rate of change of reciprocal Hall coefficient, $\Delta(1/R_H e)\Delta\bar{\Phi} = -0.9$ cm^{-1} was observed. The Hall mobility changed at the rate $\Delta(1/\mu_H)/\Delta\bar{\Phi} = 1.9 \times 10^{-20}$ volt-sec.

3.1.2 Ten Ohm-Cm Floating Zone Grown Silicon

Two samples of 10 ohm-cm P-doped Si and two samples of 15 ohm-cm As-doped Si were irradiated with $\sim 3 \times 10^{14}$ 30-Mev electrons/cm^2. The $\Delta(1/R_H e)/\Delta\bar{\Phi}$'s obtained were approximately -1 cm^{-1}, while the $\Delta(1/\mu_H)/\Delta\bar{\Phi}$'s were approximately 10^{-19} volt-sec. Plots of $1/R_H e$ vs $1/\mu_H$ during irradiation and anneal show identical behavior indicating that the same defects are formed in both types of samples.

3.1.3 Five-Tenths Ohm-Cm Floating Zone Grown Silicon

A sample of 0.4 ohm-cm P-doped Si and a sample of 0.5 ohm-cm As-doped Si were irradiated with 5×10^{15} 30-Mev electrons/cm^2. For these samples identical $\Delta(1/R_H e)/\Delta\bar{\Phi}$'s of -0.54 cm^{-1} were obtained and $\Delta(1/\mu_H)\Delta\bar{\Phi}$'s of 2.4×10^{-20} volt-sec and 2.0×10^{-20} volt-sec were obtained for the P-doped and As-doped samples respectively. Here again the irradiation and anneal characteristics for the two samples were identical.

3.2 300°K IRRADIATIONS

3.2.1 As-Doped Floating-Zone Grown Silicon

Three samples of As-doped silicon with initial room temperature resistivities of 0.5, 1.5, and 15 ohm-cm were irradiated with 30-Mev electrons. The 0.5 ohm-cm sample irradiated with 2.4×10^{16} electrons/cm^2 yielded $\Delta(1/R_H e)/\Delta\bar{\Phi} = -0.35$ cm^{-1} and $\Delta(1/\mu_H)/\Delta\bar{\Phi} = 0.32 \times 10^{-20}$ volt-sec.

The plot of $1/R_H e T^{-3/2}$ vs 1/T after irradiation indicated an energy level at 0.17 ev. The 1.5 ohm-cm sample irradiated with 1.1 x 10^{15} electrons/cm^2 yielded $\Delta(1/R_H e)/\Delta\Phi$ = -0.36 cm^{-1}, $\Delta(1/\mu_H)/\Delta\Phi$ = -0.12 x 10^{-20} volt-sec. The temperature plot yielded an energy of 0.03 ev. The 15 ohm-cm sample irradiated with 2.5 x 10^{16} electrons/cm^2 yielded $\Delta(1/R_H e)/\Delta\Phi$ = -0.11 cm^{-1} and an energy level of 0.26 ev. There was enough scatter in the data that it was not possible to obtain $\Delta(1/\mu_H)/\Delta\Phi$. The other numbers obtained in this experiment are subject to large errors due to difficulties encountered during the run. Further experiments will be performed on these materials.

3.2.2 P-Doped Floating Zone Grown Silicon

Four samples of P-doped silicon were irradiated with 30-Mev electrons. Initial room temperature resistivities were 0.1, 0.4, 5 and 50 ohm-cm. Results are tabulated below.

$\Phi e/cm^2$	Sample	ρ(ohm-cm)	$\frac{-\Delta(1/R_H e)}{\Delta\Phi(cm^{-1})}$	$\frac{\Delta(1/\mu_H)}{\Delta\Phi(v\text{-}sec)}$	E(ev)
1.7 x 10^{16}	SiM-P-.1N1-1	.1	3.8	1.4 x 10^{-20}	.04
5.7 x 10^{15}	SiM-P-.4N2-1	.4	1.8	2.6 x 10^{-20}	.17
7.7 x 10^{14}	SiM-P-5N1-1	5	.94	7.2 x 10^{-20}	.08
8.1 x 10^{13}	SiM-P-50N1-2	50	1.1	20 x 10^{-20}	.37

Comparison of these data with those on pulled Si reported in Ref. 3 is made in Figs. 2 and 3.

3.2.3 Analysis

Extensive analyses were performed on the data from the 50 ohm-cm sample. As the temperature dependence following irradiation indicated the deepest lying level of all the data, it was felt that this sample was the only one which could be expected to compare favorably with models based on a single defect level as presented in Ref. 3.

A. The first method was a direct calculation of N_T, the number of traps introduced by the total irradiation, based on the conduction-electron

population before and after irradiation and an assumed trap level at 0.37 ev below the conduction band as indicated by the $1/R_H e$ vs $1/T$ curve. The applicable formulas were developed in Section 2.2.

For sample SiM-P-50N1-2 considered here

$$\frac{n_o}{n} = \frac{(1/R_H)_o}{(1/R_H)} = \frac{1.3 \times 10^{-5}}{4.6 \times 10^{-7}} \approx 28 \text{ at } T = 290^\circ K$$

$$N_C = 5.55 \times 10^{15}\ T^{3/2} = 2.66 \times 10^{19} \text{ at } T = 290^\circ K$$

$$\alpha = 2$$

$$kT = 0.025$$

$$E_C - E_T = 0.37$$

$$n = \frac{\mu_H}{\mu}\ \left(\frac{1}{R_H e}\right) = 3.6 \times 10^{12}$$

then $N_T = 6.3 \times 10^{14}\ cm^{-3}$.

As the total electron flux received by this sample was 8.1×10^{13} 30-Mev electrons/cm^2 the formation rate of these acceptor sites is

$$\frac{dN_T}{d\Phi} = \frac{6.3 \times 10^{14}}{8.1 \times 10^{13}} = 7.8\ \frac{0.37 \text{ ev acceptors/cm}^3}{\text{30-Mev electrons/cm}^2}\ .$$

In summary, the assumptions that went into this calculation were:

1. $\alpha = 2$
2. $\frac{\mu_H}{\mu} = 1.25$
3. No acceptor levels more than 0.37 ev below the conduction band introduced by irradiation.
4. No donor levels closer than 0.37 ev to the conduction band introduced by the irradiation.

B. Another method to calculate the trap formation rate depends on the initial rate of carrier removal. Using the equation derived in Section 2.2,

$$\frac{dN_T}{d\Phi} = \frac{dn}{d\Phi}\left\{1 + \frac{N_D}{\alpha_D N_C}\exp\left[-(E_C-E_D)/kT\right]\right\}\left\{1 + \alpha_T \frac{N_C}{n_o}\exp\left[-(E_C-E_T)/kT\right]\right\}$$

$$= 1.6\ \frac{0.37\text{ ev acceptors/cm}^3}{30\text{-Mev electrons/cm}^2}\ .$$

C. This great disparity in the two preceding results indicates that a false promise has been made. The fact that initially the Fermi level lies rather high above the 0.37 ev trap level makes it reasonable to assume that each trap formed would be immediately filled and the trap formation rate would then be equal to the initial carrier removal rate. This argument favors the solution in (B). However, if all the acceptor levels formed are at 0.37 ev below the conduction band the analysis of (A) should yield the correct number of defects of this type formed. A look at the assumptions made in this analysis shows that the results might be quite different if there were other trap levels introduced below the 0.37 ev level.

Further contemplation of the type of defect assumed (the E center) discloses that a deeper trap must also be postulated. As the E center is postulated to be the association of a vacancy with a phosphorus donor and is known to be neutral with the Fermi level below it, there must be a deep level associated with the recapture of an electron by the defect to neutralize the charge of the originally ionized phosphorus donor.

Figure 4 shows the results of three different calculations. Plotted in this same figure are experimental data for sample SiM-P-50N1-2 in which n has been calculated from Hall coefficient data using a mobility ratio ($r = \mu_H/\mu_\alpha$) of 1.25. Curve I is a calculation of n vs Φ assuming only traps at 0.37 ev below the conduction band introduced at a rate of 1.5 cm^{-1} per incident electron. Curve II is the same calculation with the assumption now of equal numbers of traps at the 0.37 level and at another level deep below the Fermi level, so that it is always full. The total trap formation rate is still 1.5 cm^{-1} per incident electron. This model represents what might be expected if only the E-center type of defect were being formed. However, it may be seen that a good fit to the data is not achieved until a model is assumed in which three times as many

deep traps as 0.37 ev traps are formed. This result is shown in Curve III.

This analysis indicates the formation of deep lying acceptor states introduced at a rate comparable with the E-center production. Possibly these are acceptor states of the J-C center.

4. LIFETIME MEASUREMENTS

An extensive experiment on excess carrier lifetime was performed on a 7 ohm-cm quartz-crucible grown silicon crystal on June 13, 1962. The techniques which have been described in the previous quarterly report[3] for eliminating the spurious effects observed during earlier experiments were utilized. The lifetime was measured as a function of temperature between room temperature and liquid nitrogen temperature before irradiation and after three successively increasing radiation exposures.

The lifetime was measured by irradiating the sample with a short pulse from the linear accelerator (0.02 μsec). Temperature control was achieved by either passing liquid nitrogen through a back wall of the sample chamber or activating heater coils around the sample chamber. The temperature of the sample was measured by a thermocouple in the center of the sample which also served as a ground contact. The current through the sample was maintained constant by a large series impedance. The voltage between the voltage probes was measured in two ways. The dc value was observed through a special filter circuit on a Hewlett-Packard 425 A voltmeter recorded on a Varian G11 recorder. The transient voltage changes during and after a pulse of irradiation were measured with the standard radiation effects wide-band amplifier and oscilloscope recording system.

The results of this experiment are shown in Fig. 5. Most of the analysis has been performed on the data following the 7.9×10^{11} electrons/cm^2 irradiation because these represent a significant radiation-induced decrease in lifetime and at the same time yield lifetimes in the region where they are accurately measurable. Two important features appear in this curve. The lifetime is observed to decrease rapidly below room temperature and subsequently level off. However, somewhat surprisingly the lifetime increases again drastically as the temperature is lowered to

just above liquid nitrogen temperature. The decrease below room temperature can be understood in terms of the Shockley-Read model. However, the increase at lower temperature is not as easily interpreted.

It has been tempting to attribute such increases observed in lifetimes at low temperatures to carrier trapping. In other words, a minority carrier is trapped at a doubly-charged defect center and remains there for a long time due to the net repulsive coulomb interaction between the center and the majority carrier. The lifetime of the majority carrier in this case is limited by thermal re-ionization of the minority carrier from the trapping center or by eventual recombination in the face of the repulsive interaction. However, in the present experiment we can perform a check on this model. Those carriers which are trapped and those which recombine without trapping should either be observed as an early fast decay component in the conductivity, or else fail to contribute to the conductivity at all if their lifetime is too short.

We have calculated a quantity μ^* which is proportional to the change in conductivity observed per excess carrier produced by the radiation. The number of excess carriers produced were deduced from the accelerator beam monitor. The change in conductivity was deduced from the change in voltage observed across the sample. If all of the carriers are observed at all of the measurement temperatures, then the temperature dependence of μ^* should be identical to the temperature dependence of the sum of the electron and hole mobilities. The data are plotted in Fig. 6 and indicate excellent agreement with the $T^{-2.5}$ dependence deduced from experiments on pure Si.[5]

As a result of this analysis it can be concluded that the conductivity associated with most of the carriers formed by the radiation was observed even at the earliest times after the ionization pulse. Unfortunately, the accuracy of the measurement of absolute conductivity at present is not adequate to rule out the possibility that the holes, which represent only 20% of the total conductivity, might be trapped at a doubly-charged center allowing the electrons to remain free for a long period of time. This possibility would still be somewhat surprising for the following reasons:

1. If a trapping center appeared in competition with the observed

recombination center, one would expect to see, at least in an intermediate temperature range, a combination of two exponential decays. This combination was not observed during this experiment, although an irradiation performed on a 0.5 ohm-cm sample and reported in the last quarterly status report[3] did exhibit such a combination of decay times.

2. The trapping centers responsible for this effect could probably not be the ones introduced by the radiation, because the total number of them in this experiment was less than $10^{12}/cm^3$ for the first irradiation curve in Fig. 5, and yet the excess carriers introduced during the pulsed excitation experiments numbered approximately $10^{14}/cm^3$. It is not likely that this many excess carriers could be trapped at so few trapping centers. However, the fact that the apparent trapping phenomenon appears in the pre-irradiation lifetime studies may indicate that defects originally present in the material, and presumably more numerous than those introduced by the radiation, might be responsible for this trapping.

The high temperature behavior of the lifetime is in general agreement with the Shockley-Read theory. The excess carriers introduced, Δn, are somewhat less than the initial carrier concentration n_o and hence unless τ_{no} is larger than τ_{po}, these measurements may be considered to represent low injection conditions. In this case, assuming a relatively constant lifetime in the intermediate temperature region of about 2.2 μsec, the entire theoretical lifetime curve can be calculated from an assumed ionization energy for the recombination center. It can be seen from the two curves shown in Fig. 5 that an ionization energy of 0.16 ev, which corresponds to the A center, is inconsistent with the data. The slope of the temperature dependence seems to favor such an ionization energy or possibly a lower one, but the position in temperature at which the lifetime increases suggests a higher ionization energy such as 0.22 ev. Of course, one can assume that the center is actually in the lower half of the energy gap and, in this case, the position of the transition and slope do not need to correspond as accurately. However, in this case we are also not dealing with the A center.

The measurements taken after longer irradiations suggest a continuation of the trend seen after the first irradiation. In general, the

lifetimes decrease significantly upon irradiation and they also achieve a minimum as a function of temperature at an intermediate point between room temperature and liquid nitrogen temperature. The last set of measurements, in which lifetimes down to 0.1 μsec were observed, represents less accurate numbers than any of the others because of the extremely short decay times.

It is expected that in the near future another lifetime experiment on this same type of material will be performed with two additional features:

1. The lifetime will be measured as a function of excess-carrier concentration between a few percent of the majority carrier concentration and a few times the majority concentration.
2. Irradiation experiments will be continued beyond the dosage delivered previously and the resulting extremely short lifetimes will be deduced by an indirect technique. In this method, the excess conductivity observed during a longer accelerator pulse will be measured for a known accelerator dose rate. Using the mobility deduced from theoretical considerations and experimental Hall effect measurements, this excess conductivity will be related to an equilibrium electron density from which the mean lifetime of the carriers can be calculated.

5. PERSONNEL

The following personnel have participated in this research program during the month of August:

D. M. J. Compton
J. Harrity
H. Horiye
S. Kurnick
D. K. Nichols
V. A. J. van Lint
E. G. Wikner
M. E. Wyatt

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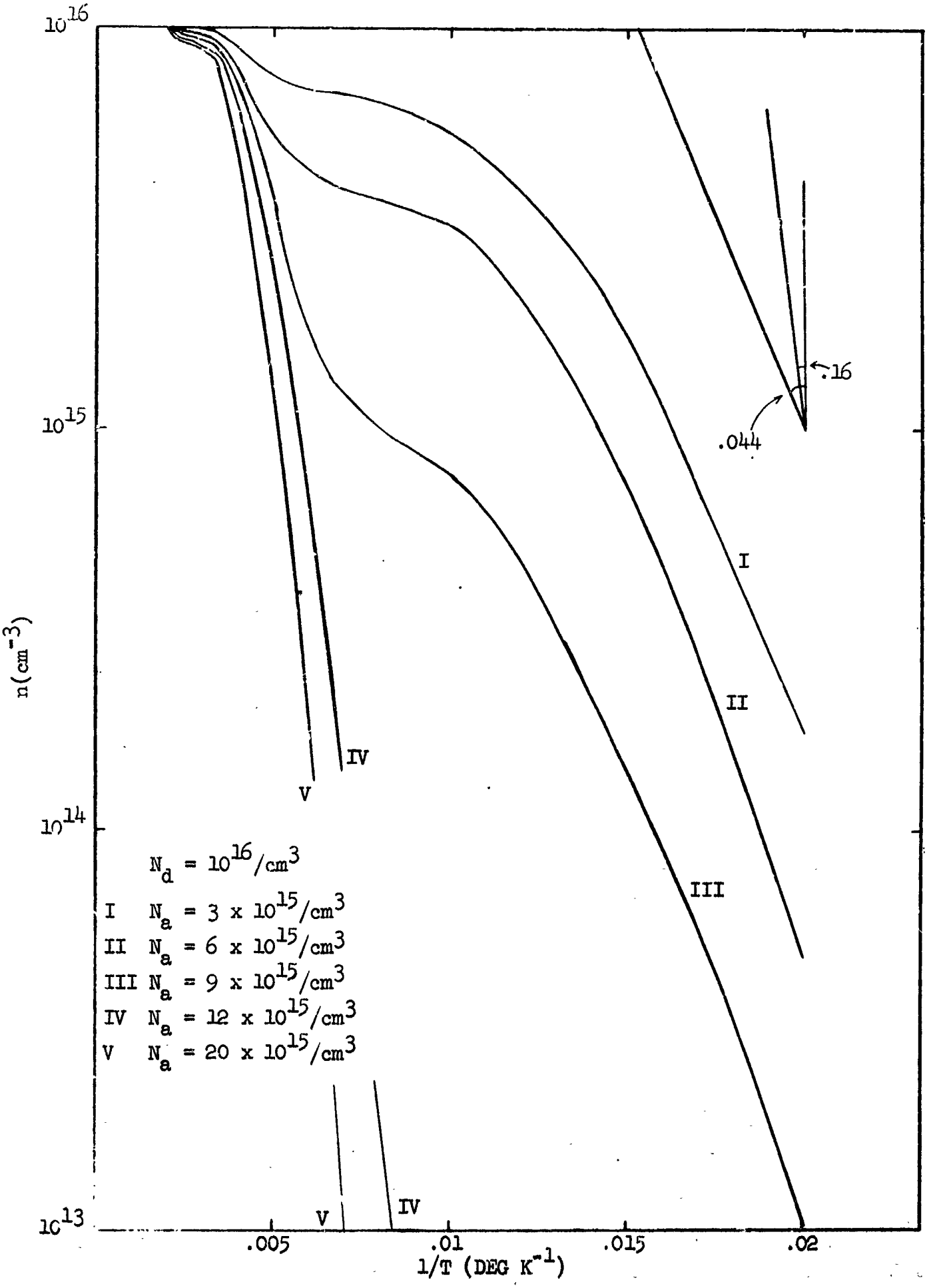

Fig. 1--Electron concentration in silicon.

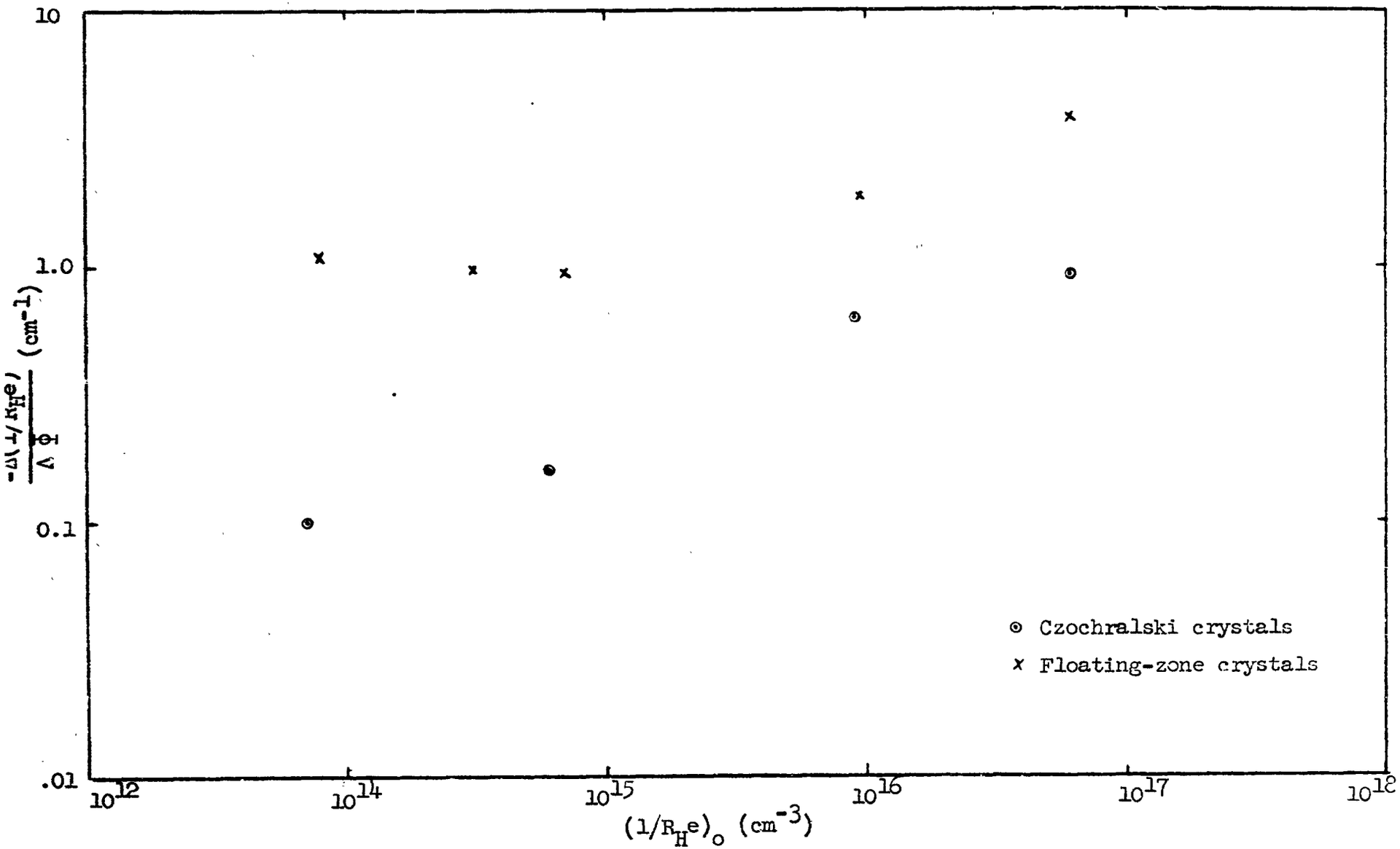

Fig. 2--Carrier removal rate in n-type P-doped Si irradiated at 300°K with 30-Mev electrons.

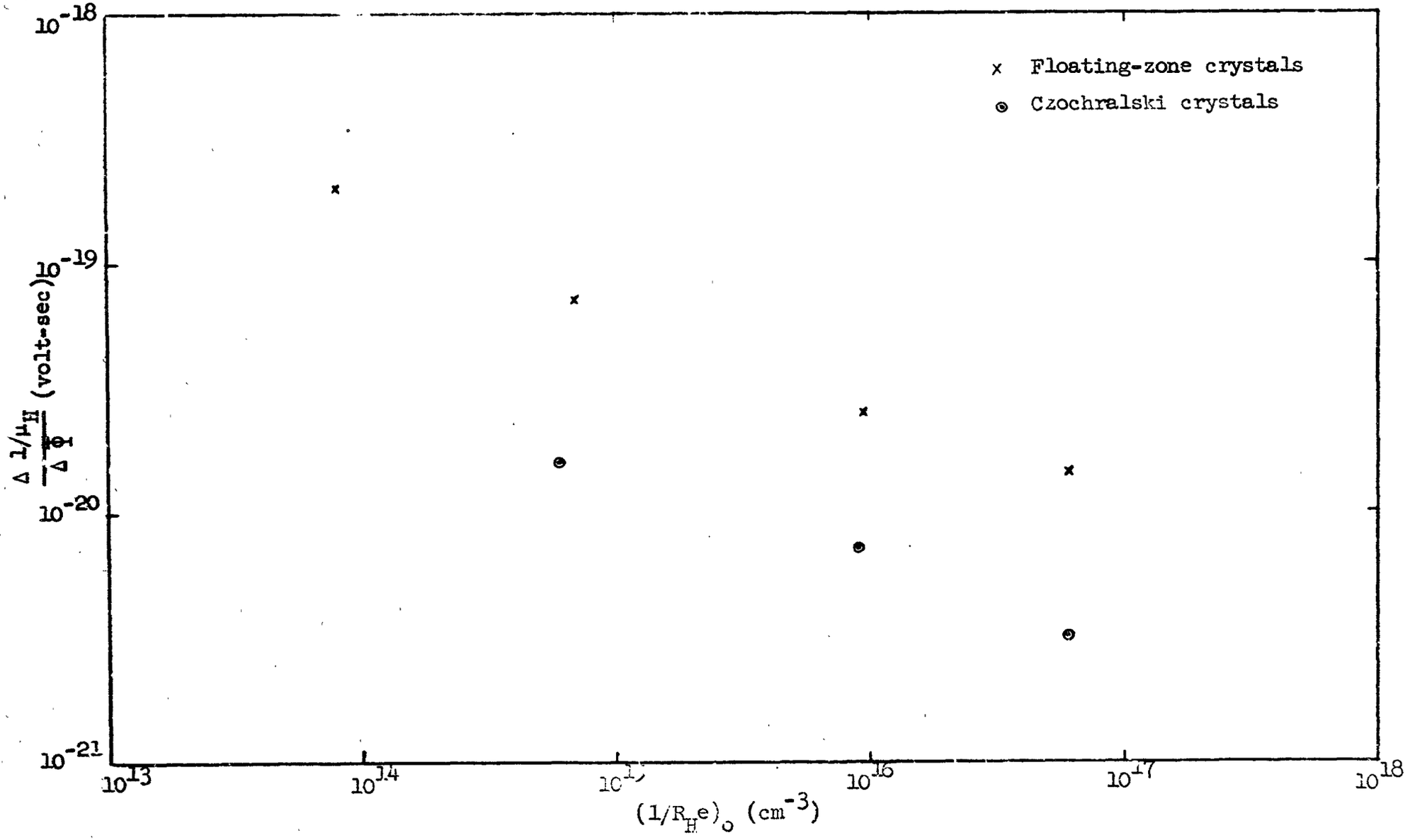

Fig. 3--Mobility changes in n-type P-doped Si irradiated at 300°K with 30-Mev electrons.

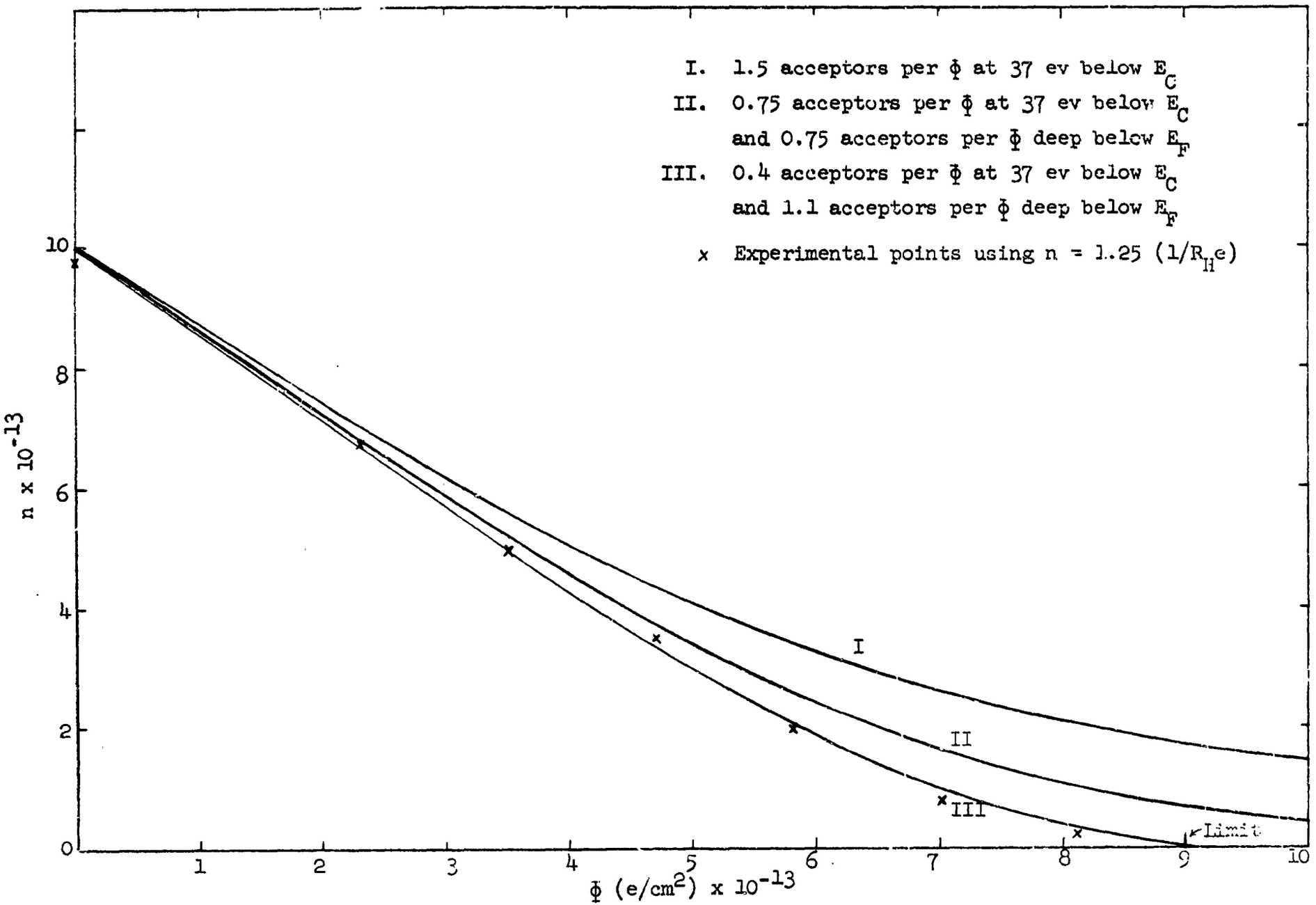

Fig. 4--Calculated carrier removal.

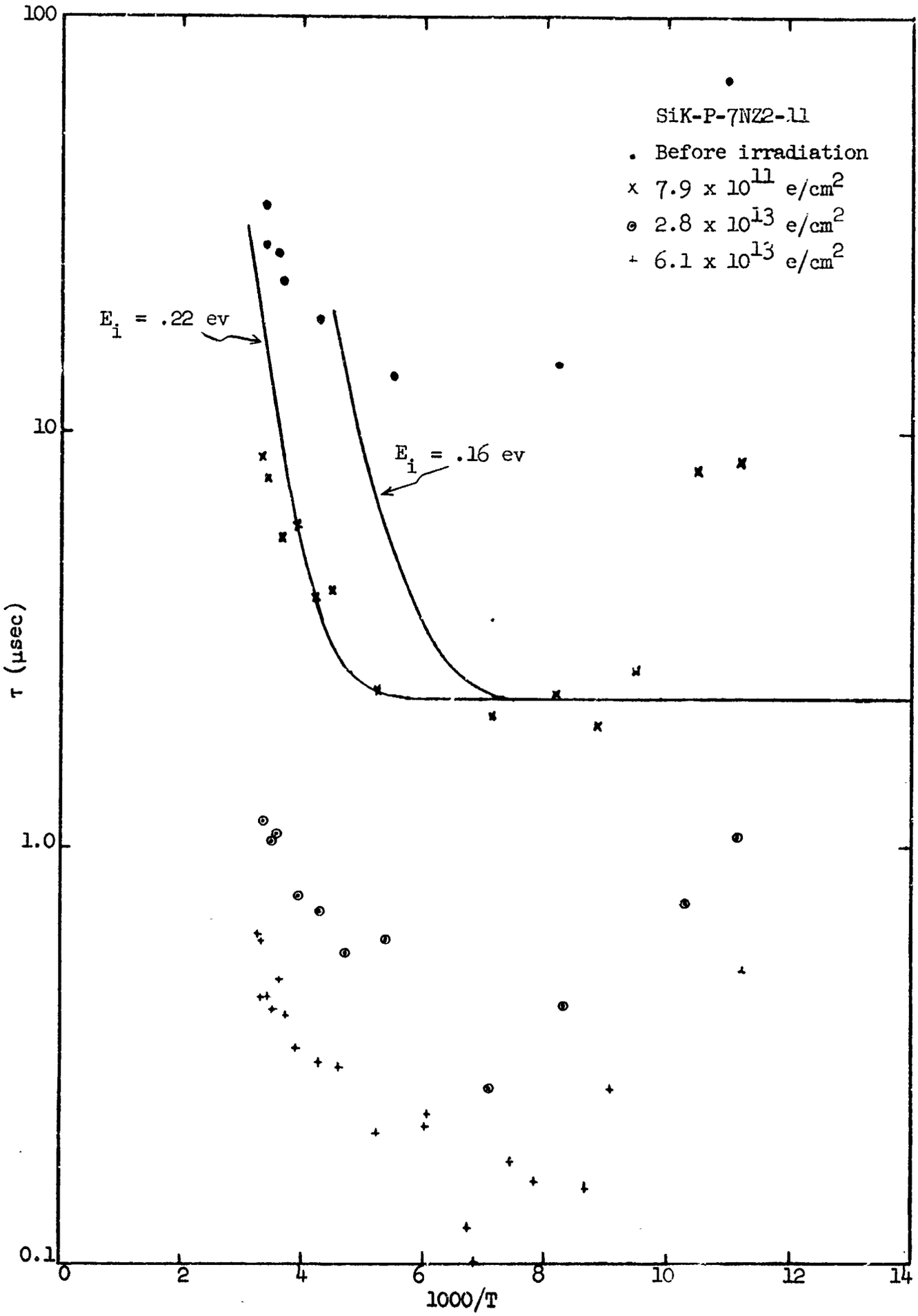

Fig. 5--Lifetime changes in n-type P-doped Si irradiated at 300°K with 30-Mev electrons.

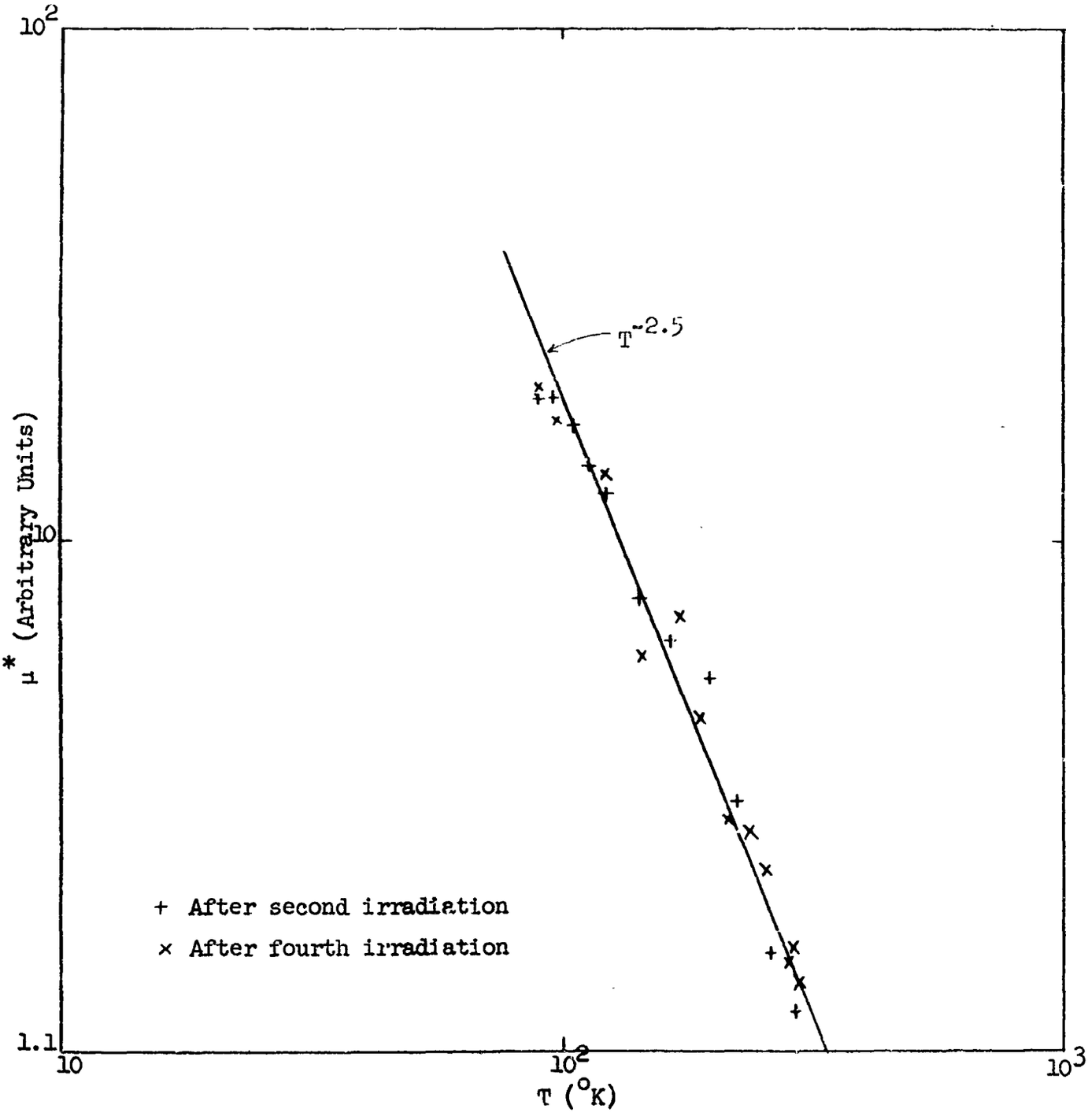

Fig. 6--Temperature dependence of μ^*