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Recombination Lifetimes in Gamma-Irradiated P-type Float Zone Silicon*†

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Photoconductivity decay measurements on boron doped floating zone grown silicon irradiated with Co^{60} gamma rays indicate that the lifetime in this material is controlled by two recombination levels, one located 0.3 ev from the conduction band edge, and one located tentatively 0.17 ev from the valence band edge. The former level, not previously reported, was seen in all materials (ρ = 25 to 1150 ohm-cm) and has a larger capture cross section for holes than for electrons. Its rate of introduction appears to be inhibited by the presence of oxygen. Although the shallow level might possibly arise from the Si-A center (substitutional oxygen), the results of this experiment and previous Hall effect and lifetime measurements suggest that it is nearer the valence band.

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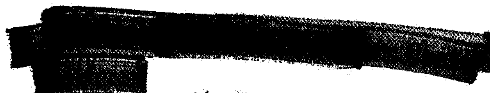
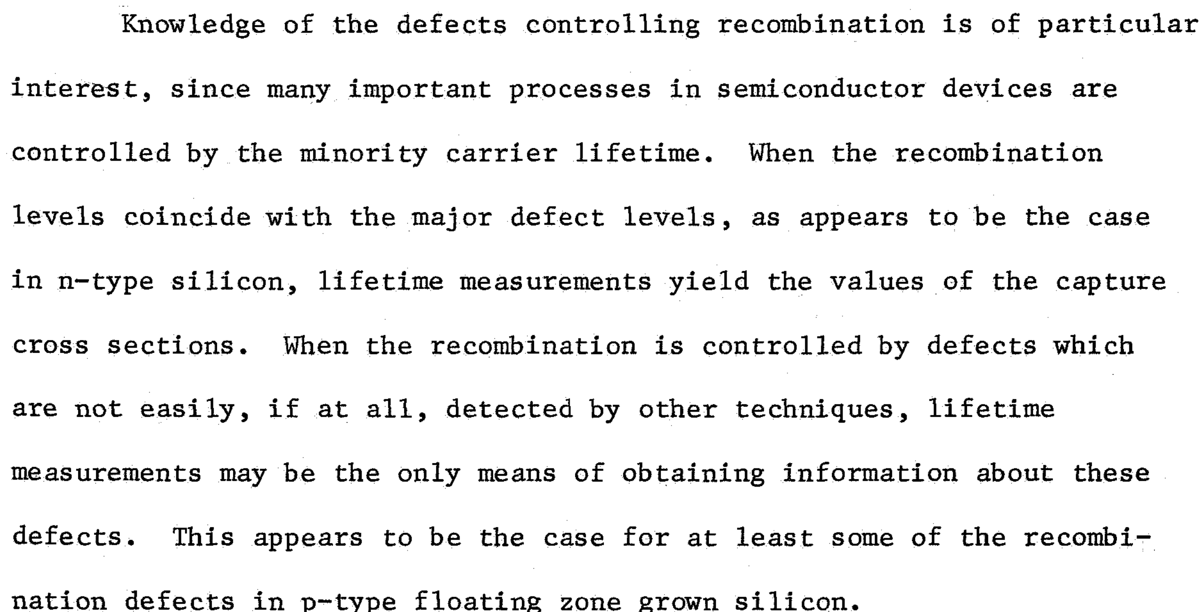


I. INTRODUCTION

Much research has been done in recent years on the defects introduced into silicon by irradiation. Only now, however, can one say that a general picture of the nature of the damage is emerging, since the earlier experiments were usually of an insufficiently broad nature, as well as being too few in number, to permit much correlation between their results. Hall effect,[1-6] photoconductivity and infrared absorption,[7-11] and spin resonance measurements,[12-14] along with lifetime studies,[15-20] have now been performed on electron and gamma-irradiated materials, n- and p-type, crucible grown and floating zone grown. Electron spin resonance studies have been particularly successful in providing detailed models for some of these defects.

Knowledge of the defects controlling recombination is of particular interest, since many important processes in semiconductor devices are controlled by the minority carrier lifetime. When the recombination levels coincide with the major defect levels, as appears to be the case in n-type silicon, lifetime measurements yield the values of the capture cross sections. When the recombination is controlled by defects which are not easily, if at all, detected by other techniques, lifetime measurements may be the only means of obtaining information about these defects. This appears to be the case for at least some of the recombination defects in p-type floating zone grown silicon.



II. THEORY

Recombination of electrons and holes through a single set of monovalent defects was first treated by Hall,[21] and Shockley and Read,[22] who obtained the following solution for the lifetime, valid for steady-state conditions and small excess carrier densities:

$$\tau = \tau_{po} \frac{(n_o + n_1)}{n_o + p_o} + \tau_{no} \frac{(p_o + p_1)}{n_o + p_o} \tag{1}$$

where $\tau_{po} = \sigma_p N v_p$ = lifetime of holes in highly n-type material, τ_{no} = $N v_n \sigma_n$ = lifetime of electrons in highly p-type material, N is the concentration of recombination centers, v_p and v_n are the hole and electron thermal velocities, respectively, σ_p and σ_n are the capture cross sections of the recombination center for holes and electrons, n_o and p_o are the thermal equilibrium concentrations of free electrons and holes, and n_1 and p_1 are usually defined as the thermal equilibrium concentrations of electrons and holes when the Fermi level lies at the recombination center energy level ($n_1 = N_c \exp[(E_R - E_C)/kT]$, $p_1 = N_v \exp[(E_v - E_R)/kT]$, N_c and N_v are the effective densities of states in the conduction and valence bands, and E_R, E_v, and E_c are the energy levels of the recombination center, the energy levels of the valence and conductor band edges, respectively). n_o will be negligible in p-type material except at high temperatures and if no deep-lying acceptors are present, p_o will be given by N_a, the acceptor concentration.

It should be pointed out that the foregoing definition of n_1 and p_1 does not take into account the fact that the (electron) occupied state

of the recombination center contains only one more electron than the unoccupied state. Because of spin degeneracy, the electron that is added to fill the level is assumed to go into an orbital which may or may not already contain another electron. If the orbital contains another electron, then the level can be filled in only one way (spin opposite to that of the other electron), but can be emptied in two ways (losing either a spin-up or spin-down electron) so that the ratio of the degeneracies of the full to the empty level is 2. Likewise, if the orbital does not contain an electron, it can be filled in two ways but emptied only in one, so that the degeneracy ratio, ω, is now 1/2. Thus, a factor of ω should be included in the definition of n_1. If the hole formalism is employed in the foregoing argument, it can be shown that a factor of $1/\omega$ should be used in the definition of p_1.

Sandiford,[23] and Wertheim[24] showed that under conditions of small recombination center concentrations the Shockley-Read result will be valid for transient conditions such as are found in photoconductivity decay experiments. Wertheim also showed that for small enough defect concentrations the net lifetime, τ, in the presence of 2 sets of monovalent defects will be given by

$$1/\tau = \sum_{i=1}^{j} 1/\tau_i \qquad (2)$$

where the lifetime τ_i is the Shockley-Read lifetime for the ith set of defects. This equation most probably applies for $j > 2$, provided none of the centers act as traps for an appreciable fraction of the minority

carriers. Nomura and Blakemore[25] have given a criterion for the concentration of recombination centers for which the Shockley-Read equations are valid. Shockley has shown that the surface recombination is describable as a term in Fig. 2, provided only the fundamental surface decay mode is present.

III. PROCEDURE

A. Measurement

Lifetimes (actually half-decay times) of excess carriers were measured by the photoconductivity decay method. A spark discharge lamp, similar to the one used by Swank,[27] with a half decay time of less than 0.6 microseconds was used to create electron-hole pairs. The light was filtered by silicon filters varying in thickness from 1.5 mm to 7.5 mm, to insure uniform penetration of the exciting light. The 1.5 mm filter was used only when the lifetimes obtained with its use did not differ from those obtained with a much thicker filter, indicating that injection level effects were not present. This was usually the case for the lower resistivity samples.

The samples were connected in series with a current-limiting resistor and a battery, and the transient portion of the sample voltage was amplified by a Tektronix type 1121 amplifier before being passed into a Tektronix type 535A oscilloscope, using Tektronix type L or 1A1 vertical plug-in units. The sweep-delay feature of the type 535A was used to prevent display of at least the first half-decay of the signal, in order to minimize the effects of higher order modes of surface decay

than the fundamental and the effect of the finite decay time of the light pulse. The oscilloscope trace was photographed with a Polaroid camera and the photographs of the traces were measured and plotted on semilog paper to obtain the lifetime. Several different sweep rates were used on each photograph so that the zero signal level could be determined.

Discs 5 mm in thickness were cut from cylindrical boules. Rectangular parallelopipeds with dimensions typically 5 x 5 x 20 mm were cut from the discs. At least two of the larger faces were polished to reduce reflection losses and the other faces were ground. The effective surface recombination lifetimes (defined as the reciprocal of the carrier decay rate due to diffusion into surface recombination centers) were found to be very large. The electrical contacts were made by ultrasonically soldering indium to the samples, and the contacts were found to be ohmic in the temperature region where trapping did not prevent measurement of the lifetime.

Each sample was given a code letter and number, and its pre-irradiation characteristics were measured. The letter designated the boule the sample was cut from and the number was used to distinguish between samples cut from the same boule. The lifetime was measured as a function of position along the sample length, and in those samples where significant variations were found, a region of nearly constant lifetime was selected for measurement. Voltages were chosen such that the excess carrier pulse did not drift out of this region.

The samples were glued onto copper sample mounts with G.E. #7031

insulating varnish, with layers of 1/2 mil mylar between the sample and the mount, and the sample and the copper-constantan thermocouple. The sample mounts were fixed to the bottom of a vacuum dewar, but separated from it by several resistors inbedded in a copper block. The temperature was varied by changing the power dissipated in the heater. For below room temperature measurements a cooling mixture was placed in the dewar.

The samples were irradiated at the U. S. Naval Research Laboratory in Washington, D. C., at approximately room temperature. The exposure rate was approximately 2 x 10^6 roentgens per hour.

The post-irradiation lifetime measurements were done from low to high temperature. On the first sample of each resistivity to be measured, note was taken of the temperature at which annealing first occurred, and measurement of the other crystal(s) of that material was restricted to lower temperatures.

Once the lifetime had been determined for a sample as a function of inverse temperature, the data were plotted on semilog paper, and a smoothed curve drawn through the data points. Each set of points $(10^3/T, \tau_m)$, where τ_m is the measured lifetime, was identified by a code number affixed after the sample number, indicating the total number of measurements taken after irradiation, including that set. Thus E5-0 indicates a pre-irradiation measurement, and E5-2 indicates the second post-irradiation measurement. The value of $\tau_{1/2}$ of the smoothed curve was read from the curve for equally spaced intervals of inverse temperature. If the lifetime was seen to be a strongly varying function of inverse

temperature, the interval chosen was $\Delta(10^3/T) = 0.05$, otherwise an interval of $\Delta(10^3/T) = 0.10$ was chosen. A table was then constructed listing the half-decay time for these values of inverse temperature. This set of points was also given the same code as the original set for which the smoothed curve was drawn. After additional defects had been introduced into the material by irradiation, the lifetime was again measured as a function of inverse temperature, the data plotted, the smoothed curve drawn, and the values of τ_m entered into the table mentioned above.

Using the multilevel lifetime formula Eq. (2), which can be rewritten as

$$1/\tau_m = 1/\tau_{pre} + 1/\tau_\gamma \tag{3}$$

where τ_γ is the lifetime which would be measured if the radiation induced defects were the only recombination centers present, τ_{pre} is the pre-irradiation lifetime, and τ_m is the lifetime measured after irradiation. The set of points $(10^3/T, \tau_\gamma)$ is defined as a data set, and is identified by the sample code followed by the two code numbers of the smoothed curves. Thus E5-2-0 denotes the data set describing the lifetime change caused by defects introduced between the pre-irradiation measurement (the -0) and the second post-irradiation measurement (the -2).

It was noted earlier that the surface states contribute to the lifetime, and hence there are more terms than indicated above in the formula relating pre-irradiation and post-irradiation lifetimes. The pre-irradiation lifetime will be given by

$$1/\tau_{pre} = 1/\tau_{bo} + 1/\tau_{so} \tag{4}$$

where τ_{bo} is the lifetime due to bulk defects present before irradiation, and τ_{so} is the effective pre-irradiation surface lifetime. After irradiation the lifetime will be given by

$$1/\tau_m = 1/\tau_{bo} + 1/\tau_\gamma + 1/\tau_{sf} \quad (5)$$

where τ_{sf} is the effective surface lifetime for the post-irradiation measurement. If the two surface lifetimes are greatly different, and are comparable with the other lifetimes involved, large errors can arise in the measurement of the radiation induced lifetime. In this experiment, the surface lifetimes were much longer than any of the other lifetimes. The errors introduced by considering the two surface lifetimes to be equal is small. The error introduced by the difference in surface decay times is relatively insensitive to moderate changes in the post-irradiation lifetime, if that lifetime is much less than the pre-irradiation lifetime. The error in the radiation induced lifetime due to surface lifetime differences was calculated from the data given by Blakemore and Nomura[28] and was found to be usually 1% or less.

B. Analysis of Lifetime-Temperature Data

The changes in the lifetime due to radiation induced defects were analyzed on an IBM 7094 computer for those cases where measurements could be made over a temperature range large enough to allow meaningful interpretation of computer fits to the S-R theory.

The computer program can be described as a "lesser squares fitting program," in that it adjusts the parameters A_j of the lifetime formula supplied to it, so that the quantity

$$\chi^2 = \sum_{j=1}^{N} \left(\frac{\tau_j - \tau_{\gamma j}}{W_j} \right)^2 \tag{6}$$

is constantly reduced. In the above expression the sum runs over the N data points $(10^3/T_j, \tau_{\gamma j})$, W_j is the estimated probable error of the jth value of $\tau_{\gamma j}$, and τ_j is the lifetime calculated for the temperature of $10^3/T_j$. The W_j were chosen to be equal to $\tau_{\gamma j}/20$, since the error in the lifetime measurement is a percentage error. It was also possible to weight a given temperature region by increasing the density of data points in that region, so that that region contributed more to χ^2 than the other region(s). With the weights as chosen, χ^2 should be equal to the number of points less the number of parameters if the random error is 5%.

For the p-type material used in this experiment, the Shockley-Read equation becomes

$$\tau = \tau_{no}(1 + p_1/N_a) + (n_1/N_a)\tau_{po}, \tag{7}$$

Unless the defect level is very close to the center of the gap, one of the terms $p_1\tau_{n_o}$ and $n_1\tau_{po}$ will be much smaller than the other. Thus, if the defect level in p-type silicon is in the lower half of the gap, the lifetime will be given by

$$\tau = \tau_{no}(1 + p_1/N_A) \tag{8}$$

while if it is in the upper half of the gap, it will be given by

$$\tau = \tau_{no}(1 + \frac{\tau_{po}}{\tau_{no}} n_1/N_A) \tag{9}$$

The simplest approximation to Eqs. (8) and (9) is given by

$$\tau = A_1[1 + (10^3/T)^{-1.5} \exp(A_2 - 11.6(10^3/T)A_3)] \quad (10)$$

where A_1 will be τ_{no}, and A_3 the energy separation of the recombination level from the nearest band edge in electron volts. The factor of 11.6 arises from the conversion 1 ev = 11,600°K. If the level is nearest the valence band, the constant A_2 will be equal to $\ln[N_V(10^3/T)^{3/2}/(N_A\omega)] - \beta$ with $N_V(10^3/T)^{3/2}$ equal to $7.1 \times 10^{19}\,°K^{-1.5}\ cm^{-3}$. The quantity β arises from the assumption that the energy level has a linear temperature dependence

$$E_r = E_{ro} + \beta kT \quad (11)$$

If β is greater than zero, the level will approach the conduction band as the temperature increases.

If the level is nearer the conduction band, A_2 will be given by

$$A_2 = \ln[\omega\tau_{po}N_c(10^3/T)^{1.5}/(N_A\tau_{no})] + \beta \quad (12)$$

where $N_c = 1.73\times10^{20}(10^3/T)^{-1.5}\ cm^{-3}$. The above fit was given the code PFZ-1, since it appeared it would fit p-type float zoned material.

In most cases, it will be possible to determine which energy band the level is nearest, if all three constants can be determined. Previous studies enable us to determine reasonable limits for these quantities. The ratio τ_{no}/τ_{po} or its reciprocal has been determined to be about 20.[15,17] The factor e^{β}, from Hall effect measurements on the Si-A center,[1,3] is about 1/2 so that the product ωe^{β} can range from 4 to 1/4. Thus, if A_2 differs by more than ln4 from $\ln(N_V(10^3/T)^{1.5}/N_A)$, the level most probably lies in the upper half of the gap. If it is within ln4, identi-

fication is more difficult. Since N_V is not known very accurately, and N_A is calculated from the conductivity using published mobilities, there exists an uncertainty of as much as a factor of two in the ratio of N_V/N_A. If $\tau_{po}/\tau_{no} = 20$ and $\omega e^{\beta} = 4$ it will be impossible on the basis of the foregoing discussion to distinguish this level from one in the lower half of the gap with $\omega e^{\beta} = 1/4$. Most previous accounts have tended to neglect these considerations, using $\omega = 1$ and $\beta = 0$.

If the nature of the defect is known from other investigations, then β may be known, and the energy level position known, making it possible to determine β if the experimental errors are small. Alternatively, if the factor ωe^{β} for a given level is known, it may then be possible to determine whether a level indicated by lifetime measurements is indeed the previously discovered level.

In several experiments, it has been determined that the quantities τ_{no} and/or τ_{po} are not constant. Bemski[29] reported temperature dependences of T^n, with $n = 1/2, 2$ and $7/2$ for several of the levels of gold in silicon. By investigating the injection level dependence of the silicon A-center, Galkin, et. al.[15] concluded that the electron capture cross-section was strongly temperature dependent above 250°K. Baicker's[17] injection level curves also indicate a temperature dependence for $\tau_{no} + \tau\tau_{po}$. In view of these findings, a fit designated PFZ-2 was used when it was suspected that τ_{no} and/or τ_{po} were temperature dependent.

In the case of sample E, it seems that either 2 separate levels or a multivalent level control the lifetime. The data sets for this material

were fit by

$$\tau = \frac{P*Q}{P+Q} \tag{13}$$

where P and Q are PFZ-1 fits. The computer fit for Eq. (13) was denoted by PFZ-10.

IV. EXPERIMENTAL RESULTS

The pre-irradiation characteristics of the 9 samples used are listed in Table II, and their radiation histories are given in Table III. Calculations showed that except possibly for the data set U2-2, the Nomura-Blakemore center density criterion was met. Figure 1 shows the variation of the lifetime in sample M3 before (data set M3-0) and after (data set M3-1) an exposure dose of 2×10^6 roentgens. The radiation induced lifetime in sample M3 (data set M3-1-0), obtained from the data sets M3-0 and M3-1 by use of Eq. (3), and for sample M4, is also shown. The parameters used to calculate the theoretical curve shown for the M3-1-0 data set are given in Table IV, and indicate, according to the Shockley-Read theory, a recombination level in the upper half of the forbidden gap, a temperature dependence of $T^{-3/2}$ for the electron capture cross section (or of T for τ_{no}), and a value of 14.6 for the quantity $(\sigma_p/\sigma_n)(e^{-\beta}/\omega)$ indicating that if the capture cross section ratio σ_p/σ_n is about 20, as has been determined previously, that $e^{-\beta}/\omega$ is less than unity. A reasonable consistency would exist if the level is assumed to be in the lower half of the gap with a value of 5.4 for ωe^{β} (ω = 2 and a temperature dependence of 10^{-4}ev/deg for the energy level), but in

view of the results on the other samples, the position near the conduction band is much more probable.

Figure 2 shows the radiation induced lifetime in samples F3 and F4, and the computer results for F4 were anomalous (compared to the F3 data sets), probably as a result of annealing at high temperatures during the post-irradiation measurement. Analysis of the F3 computer determined parameters indicates that the energy level is definitely nearer the conduction band, being between $E_c - 0.23$ ev and $E_c - 0.34$ ev, with τ_{no} and τ_{po} apparently constant. The factor $(\sigma_p/\sigma_n)(e^{-\beta}/\omega)$ has values between 13 and 650, with a mean value of 80. Thus σ_n/σ_p is much less than one, indicating that hole capture is coulomb aided (defect negatively charged before a hole is captured).

The variation of radiation induced lifetime in samples U1 and U2 is shown in Fig. 3. The annealing of the defects at lower temperatures in this material than in the others prevented a better determination of the location of the energy level from the nearest band edge. Again the energy level was definitely located in the upper half of the gap, at about the same separation, with the quantity $(\sigma_p/\sigma_n)(e^{-\beta}/\omega)$ ranging between 24 and 49, and a temperature dependence of T^n for τ_{no}, with n ranging from 0 to 0.66.

In the last boule investigated, the variation of radiation induced lifetime with reciprocal temperature differed greatly from that seen in the other three. Figure 4 shows the data sets for the E samples fit by two Shockley-Read levels according to Eq. (13). One level was presumed to be the level seen in the other samples, and the second level

appeared to be located 0.17 ev from a band edge. The shallow (0.17 ev) level controlled the lifetime. Analysis of the computer parameters showed that this level could be located near either band edge, with ωe^{β} = 3.4 to 5 (ω = 2, temperature dependence of 5 to 8 x 10^{-5} ev/deg, level moving toward midgap with increasing temperature) for a valence band level, or with $\sigma_p/\sigma_n \; e^{-\beta}/\omega$ ranging between 9 and 14 for a conduction band level. If it is assumed that the defect is the A center, Baicker's[17] results on n-type material indicate that for the Si-A center the capture cross section ratio σ_p/σ_n is between 16 and 23, so that ωe^{β} must be greater than unity. However, the spin resonance results of Watkins and Corbett[12] on the A center indicate that ω = 1/2, which is agreement with the previously mentioned Hall effect results of Wertheim,[1] and of Sonder and Templeton,[3] who suggest that ωe^{β} is about 1/4 for the A center. This indicates that if the level lies closer to the conduction band, it is not the A center.

If the introduction rate for the 0.17 ev level observed in the E samples is assumed to hold for the other materials, Eq. (8) predicts that this level will be unobservable in all but the M samples because of their higher resistivities. In the M samples, the 0.3 ev level is expected to control the lifetime except at very low temperatures. If it is assumed that trapping affects the lifetime in the M samples enough so that this behavior is masked, and that a suitable correction for an 0.17 ev level is made according to Eq. (2), the temperature dependence of the M samples appears to be more like that of the U samples.

For a single type of defect, the lifetime-flux product is proportional to the concentration of recombination centers. A calculation of this parameter indicated that, within experimental error, the introduction rates of the recombination centers are constant for material from each boule, except for the U samples. The lifetime-flux product (which for one type of recombination centers is inversely proportional to the center concentration) for the E_c - 0.3 ev level was 700 second-roentgens for the E samples, 70 sec-R for the M samples, 109 sec-R for the F samples, and 47 sec-R for the U samples at fluxes below 10^7 roentgens and 66 sec-R at 10^7 R. The preceding values were calculated at $10^3/T = 3.4$. The lifetime-flux product for the 0.17 ev level in the E samples, using the computer calculated values of τ_{no}, was about 40 sec-R.

This variation of the lifetime-flux product for the E_c - 0.3 ev level among the sample types indicates that any possible dependence of the introduction rate of the defects upon the boron concentration is masked by other factors. The infrared transmission of these samples, in the 9 micron band associated with interstitial oxygen,[30] was measured at room temperature. A correlation between the absorption coefficient of the 9 micron band and the lifetime-flux product indicated that material with a high-lifetime flux product for the E_c - 0.3 ev level contained more oxygen.

V. DISCUSSION

The deeper level seen in this experiment, at E_c - 0.3 ev, has not been previously reported. Hirata, Hirata, and Saito[19] indicate that the

slope of the post-irradiated lifetime in 150 ohm-cm ^{60}Co irradiated material is 0.17 ev. Correction of their data for pre-irradiation lifetime indicates a radiation induced level at approximately 0.3 ev from a band edge, with the ratio σ_n/σ_p greater than one. Since the resistivity of this material is close to that of the F samples, a comparison can be made, and it indicates that the two levels, and hence the defects, are not the same, since the lifetime in sample F is nearly constant for $10^3/T$ greater than 2.9 while the lifetime of the sample of Hirata, et. al. is strongly temperature dependent for $10^3/T$ less than 4.0. This difference in temperature dependences of the lifetime in the two cases is due to the different values of σ_n/σ_p.

Nakano, Nakasima, and Inuishi[18] report a level at $E_v + 0.27$ ev in similar material, but correction of their data for the pre-irradiation lifetime indicates a level less than 0.13 ev from a band edge.

Baicker[17] reported a level 0.18 ev from the valence band edge in 2 ohm-cm p-type float zoned silicon, with injection level measurements confirming the level position. The Hall effect measurements of Vavilov, et. al.[9] also indicate a level near the position ($E_v + 0.19$) ev. The level seen at 0.17 ev in sample E in this experiment appears to be the same as the one seen by Baicker. As mentioned above, the level could be nearer conduction band, and might be the A center, but the valence band assignment seems more probable on the basis of these measurements.

The luminescence data of Spry[31] indicate that the short wavelength recombination luminescence spectra are the same in n- and p-type floating zone grown silicon, indicating that recombination occurs through the same

defects in both materials at low temperatures (77°K and 4°K). Since A centers are known to exist in n-type float zoned silicon, this would argue that either one cannot use the parameters obtained from Hall measurements for lifetime analysis, or that both A centers and defects having a level near the valence band are present, and that at low temperatures the A centers control the recombination, while at higher temperatures the valence band levels dominate.

VI. SUMMARY

Two monovalent recombination levels, one at about E_c - 0.3 ev and one 0.17 ev from a band edge have been seen in ^{60}Co irradiated boron doped floating zone grown silicon. The introduction rates of the defects giving rise to these levels are constant up to doses of 18 x 10^6 roentgens in material containing more than 6 x 10^{13} boron atoms/cm^3. The introduction rate of the E_c - 0.3 ev level defects is inhibited by the presence of oxygen in the lattice. These defects have a larger capture cross section for holes than for electrons. A conclusive assignment of the 0.17 ev level to the A center or to a level near the valence band cannot be made, although a level near the valence band seems somewhat more probable.

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Table I

List of computer fits

Code	Formula
PFZ-1	$\tau = P_o(A_1, A_2, A_3) = A_1 * [1 + (\frac{10^3}{T})^{-1.5} * \exp(A_2 - 11.6 * (\frac{10^3}{T}) * A_3)]$
PFZ-2	$\tau = P_o(A_1, A_2, A_3) * (10^3/T)^{A_4}$ $= P_1(A_1, A_2, A_3, A_4)$

Code	Description
PFZ-1	single S-R level in extrinsic temperature range, constant τ_{n_o}, τ_{p_o}
PFZ-2	same as PFZ-1 except that A_1 now has a temperature dependence of T^{-A_4}

Table II

Pre-irradiation sample characteristics[†]

Sample Code	Resistivity (ohm-cm)	Pre-Irradiation Lifetime (μsec)	Supplier
E3	24	200	D
E4	25	270	D
E5	25	260	D
M3	71	105	M
M4	73	98	M
F3	222	90	D
F4	238	133	D
U1	1160	107	S
U2	1160	125	S

D: Dupont M: Monsanto S: Semi-elements, Inc.

† At room temperature.

Table III

Radiation history of samples used

Data Set*	Total Dose (10^6 Roentgens)
E3-1	4
E4-1	2
E4-2	4
E5-1	2
E5-2	20
F3-1	2
F3-2	4
F3-3	9
F3-4	18
F4-1	2.5
M3-1	2
M4-1	1
U1-1	2.5
U2-1	5
U2-2	10

* Sample is denoted by first letter and number. Second number denotes number of irradiation.

Table IV

Computer results and radiation history

Sample	A_1	A_2	A_3 [a]	A_4	Fit	χ^2	Points	A_{20} [b]
M3-1-0	11.52	10.97	.33	-1.0	PFZ-2	1.20	21	12.65
F3-1-0	35.7	11.07	.311		PFZ-1	.383	12	13.6
F3-2-0	21.1	10.57	.302		PFZ-1	1.09	15	13.6
F3-1-2	50.8	8.10	.236		PFZ-1	1.68	15	13.6
F3-3-0	9.94	11.92	.339		PFZ-1	1.23	14	13.6
F3-4-0	5.38	9.06	.250		PFZ-1	.164	12	13.6
F4-1-0	65.7	13.70	.40		PFZ-1	.40	11	13.6
U1-1-0	38.6	13.20	.355	- .655	PFZ-2	1.33	13	15.4
U2-1-0	15.0	12.57	.328	- .5*	PFZ-2	1.94	14	15.4
U2-2-0	5.66	12.44	.318		PFZ-1	.37	10	15.4
E4-2-0 E3-1-0	P183. Q 9.71	10.8* 10.18	.46* .1784		PFZ-10	2.8	17	11.40
E5-2-0	P 32.8 Q 2.18	7.0 9.79	.30 .170		PFZ-10	.59	13	11.40

* Parameters fixed.

[a] Energy separation from nearest band edge in ev.

[b] $A_{20} = \ln[N_v(10^3/T)^{1.5}/N_a]$.

FIGURE CAPTIONS

Fig. 1 Variation of radiation induced and measured lifetime with reciprocal temperature in 70 ohm-cm p-type float zoned silicon. The parameters for the theoretical curve fit to the data set M3-1-0 are given in Table IV.

Fig. 2 Variation of radiation induced lifetime with reciprocal temperature in 200 ohm-cm p-type float zoned silicon. The parameters for the theoretical curves are given in Table IV.

Fig. 3 Variation of radiation induced lifetime with reciprocal temperature in 1200 ohm-cm p-type float zoned silicon. The parameters for the theoretical curves are given in Table IV.

Fig. 4 Variation of radiation induced lifetime with reciprocal temperature in 20 ohm-cm p-type float zoned silicon. Parameters for the theoretical curves are given in Table IV.

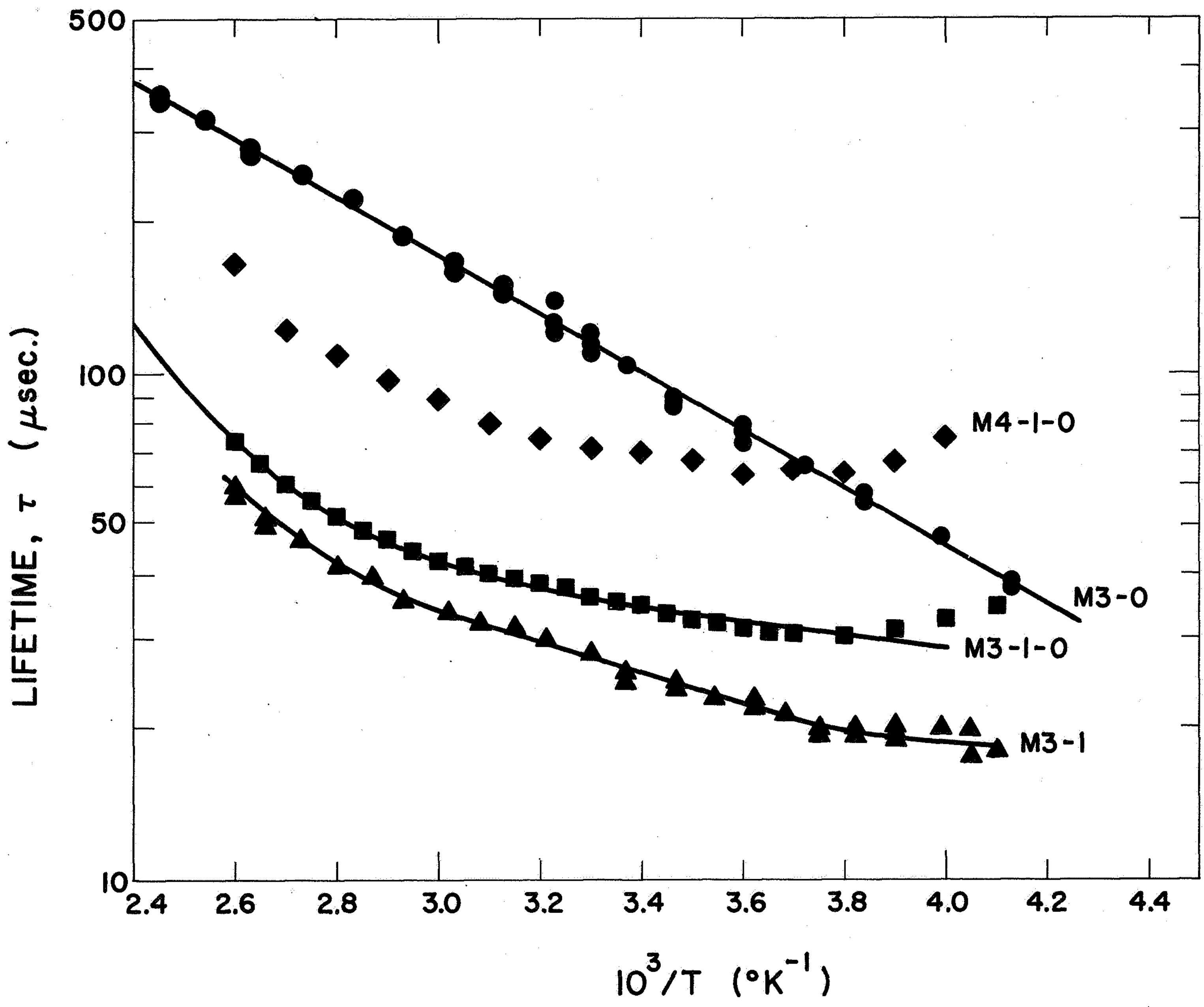

Figure 1

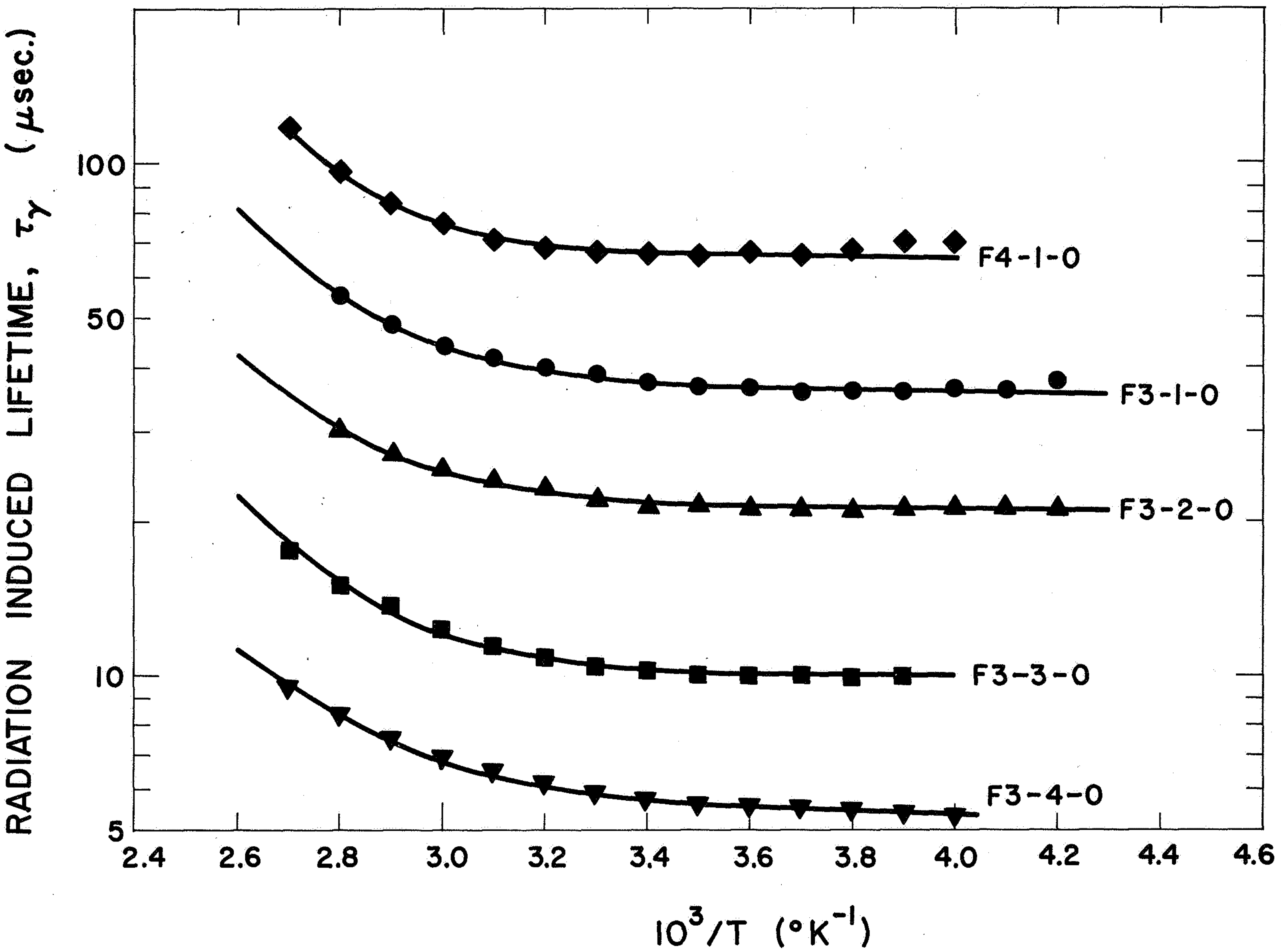

Figure 2

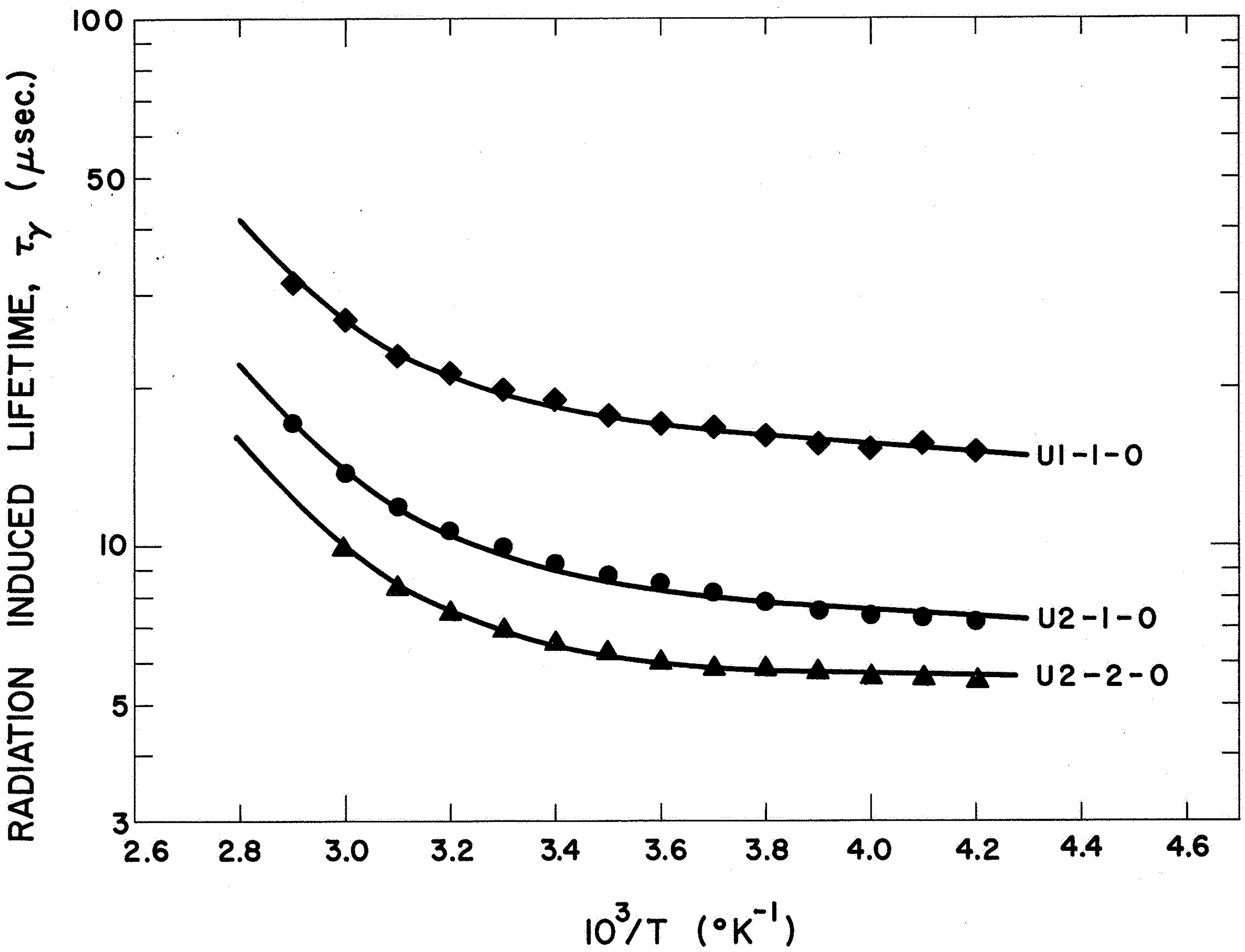

Figure 3

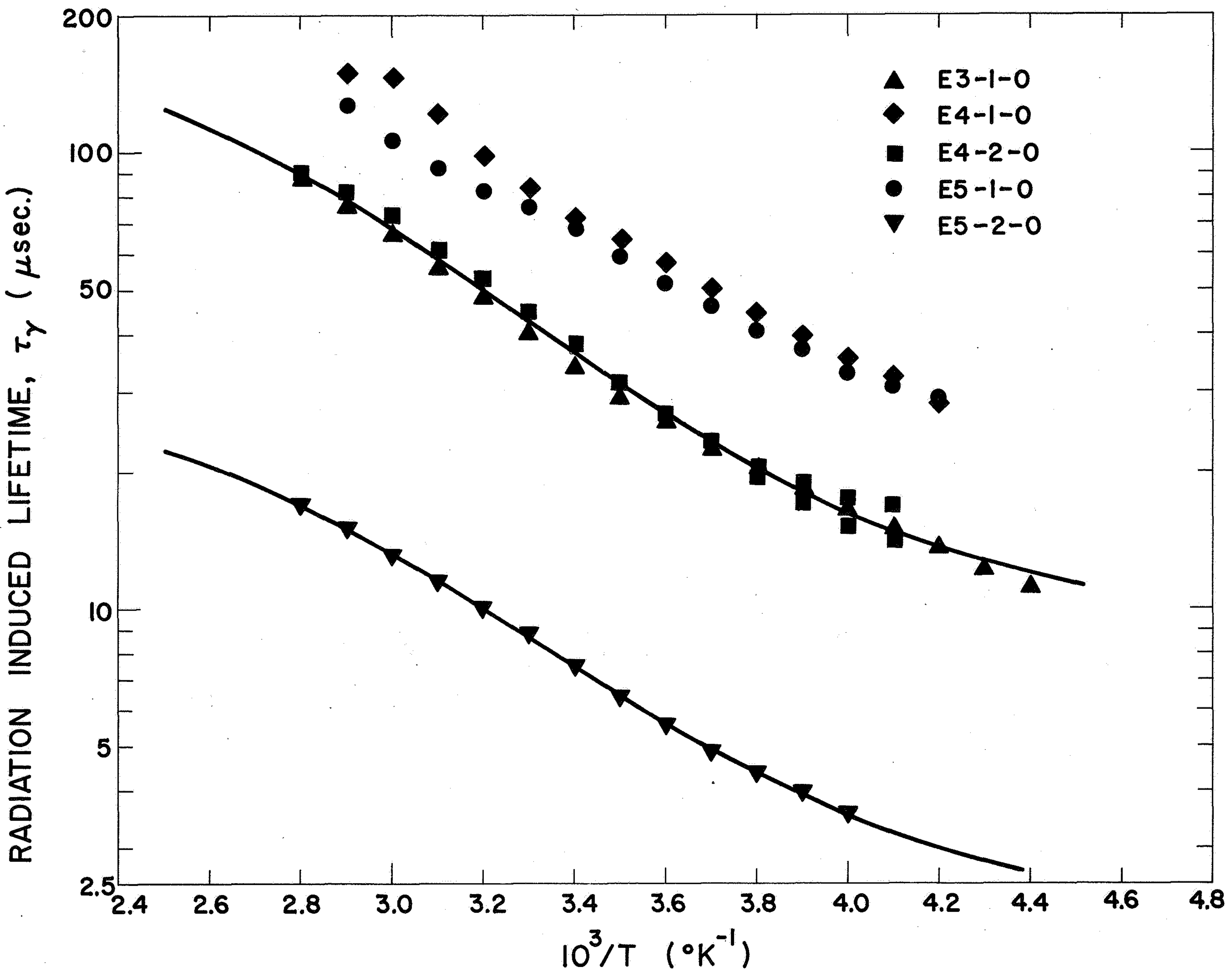

Figure 4