PHYSICAL REVIEW VOLUME 172, NUMBER 3 15 AUGUST 1968

Steady-State Photoconductivity in the Presence of Traps

O. L. CURTIS, JR.
Northrop Corporate Laboratories, Hawthorne, California
(Received 14 March 1968)

An analysis is performed of the dependence of lifetime on excess carrier density when traps are present. Using only realistic assumptions, a relatively simple solution is obtained. Different types of behavior can be obtained, depending on recombination parameters and the concentration and energy-level position of the traps. An especially interesting situation exists in which lifetime versus excess density curve shows no indication of trapping, yet incorrect recombination parameters are obtained if trapping is ignored. Experimental confirmation of the analytical results is presented.

INTRODUCTION

SEVERAL analyses of recombination in the presence of trapping have been performed. In particular, Wertheim[1] considered the problem of trapping in the case of low excess density and Baicker[2] extended the treatment of Haynes and Hornbeck[3] for the transient case to include any injection level. In the latter case it was necessary to assume thermal equilibrium between the traps and the minority carrier band. Unfortunately, this condition is probably not realistic in many instances. Herein we obtain a relationship for the steady-state condition with less restrictive assumptions, specifically avoiding the requirement for thermal equilibrium. The resulting expression is comparatively simple and easy to apply, and its applicability to experimental results is demonstrated.

The Hall[4]-Shockley-Read[5] model has been used extensively to obtain recombination-level parameters from the dependence of low-level lifetime on temperature and majority carrier concentration. Recently, the observation of steady-state photoconductivity as a function of excess density has been shown to be quite useful.[6–8] However, the effect of traps was not considered in these studies.

MATHEMATICAL FORMULATION

This analysis follows closely that of Hall[4] and Shockley and Read[5] for a simple recombination center without trapping. From their treatment it is seen that the rate of electron capture by a recombination center is

$$U_{nr}=c_n\{[n_1/(n+n_1)]N\Delta n+(n+n_1+\Delta n)\Delta N\}\,, \quad (1)$$

where c_n is the electron-capture probability at the recombination center, n is the equilibrium electron concentration, n_1 is the equilibrium electron concentration which would exist if the Fermi level and recombination level coincided, N is the recombination-center density, Δn is the excess electron concentration, and ΔN is the number of recombination centers containing a captured hole. Likewise, for hole capture,

$$U_{pr}=c_p\{[p_1/(p+p_1)]N\Delta p-(p+p_1+\Delta p)\Delta N\}\,, \quad (2)$$

where the definition of the new terms introduced is obvious.

The situation under consideration is one in which separate energy levels act as recombination centers and traps. To be specific, consider only hole trapping. The condition for a trapping level is that recombination at this level is negligible, i.e., that electron capture does not occur. Therefore

$$U_{nt}=0\,, \quad (3)$$

while (assuming the trap lies below the Fermi level)

$$U_{pt}=c_{pt}[N_t\Delta p-(p_{1t}+\Delta p)\Delta N_t]\,. \quad (4)$$

But for steady state, $U_{pt}=0$, since the capture of holes is exactly balanced by their emission. The steady-state electron and hole lifetimes τ_n and τ_p are given by

$$\tau_n=\Delta n/(U_{nr}+U_{nt})=\Delta n/U_{nr} \quad (5a)$$

and

$$\tau_p=\Delta p/(U_{pr}+U_{pt})=\Delta p/U_{pr}\,. \quad (5b)$$

For steady state, $U_{nr}=U_{pr}$. But because of trapping, $\Delta n\neq\Delta p$, so $\tau_n\neq\tau_p$. For the moment, we are considering only hole trapping, so τ_n is of primary interest (1) because of the greater mobility associated with electrons and (2) because of the fact that there are always at least as many electrons as holes. Combining Eqs. (1) and (2) allows the elimination of ΔN, yielding

$$\tau_n=\frac{[(p+p_1+\Delta p)/c_nN][+(n+n_1+\Delta n)/c_pN]}{p+n(\Delta p/\Delta n)+\Delta p}\,, \quad (6)$$

which is identical to the expression obtained from the Hall-Shockley-Read analysis of a simple recombination level. This is so because of the condition that no recombination occurs through the trapping levels and thus their only effect is to modify the ratio $\Delta p/\Delta n$. In the case of no traps and low recombination-center density, $\Delta n=\Delta p$, and the standard equations are obtained.

[1] G. K. Wertheim, Phys. Rev. **109**, 1086 (1958).
[2] J. A. Baicker, Phys. Rev. **129**, 1174 (1963).
[3] J. A. Hornbeck and J. R. Haynes, Phys. Rev. **97**, 311 (1955).
[4] R. N. Hall, Phys. Rev. **87**, 387 (1952).
[5] W. Shockley and W. T. Read, Phys. Rev. **87**, 835 (1952).
[6] O. L. Curtis, Jr., J. Appl. Phys. **36**, 2094 (1965).
[7] C. A. Germano and O. L. Curtis, Jr., IEEE Trans. Nucl. Sci. **NS-13**, 47 (1966).
[8] O. L. Curtis, Jr., and C. A. Germano, IEEE Trans. Nucl. Sci. **NS-14**, 68 (1967).

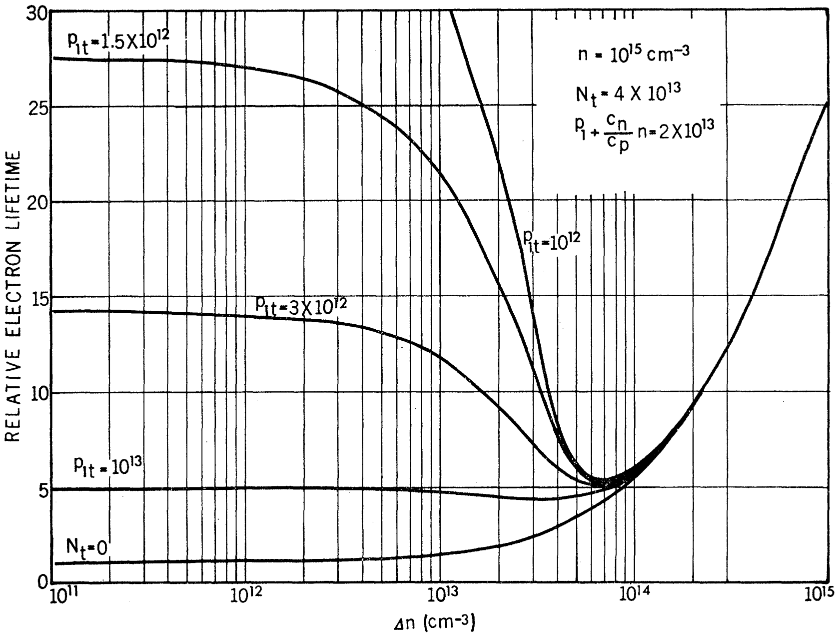

FIG. 1. Examples of the dependence of electron lifetime on excess electron density. It is assumed that the recombination and trapping centers lie below the Fermi level, and $c_p \gg c_n$.

We next assume that the total discrepancy between Δn and Δp is accounted for by trapping, and

$$\Delta p = \Delta n - \Delta N_t. \tag{7}$$

This is an excellent assumption for low recombination-center concentration and is a good approximation whenever trapping is important. Setting Eq. (4) equal to 0,

$$\Delta N_t = \frac{N_t \Delta p}{p_{1t} + \Delta p} \tag{8}$$

or

$$\Delta n = \frac{p_{1t} + N_t + \Delta p}{p_{1t} + \Delta p} \Delta p \quad \text{(hole trapping)}. \tag{9a}$$

Equation (6) gives the electron lifetime, whether or not hole or electron trapping occurs. The hole lifetime is obtained simply by replacing the denominator by $n + p(\Delta n/\Delta p) + \Delta n$. Further,

$$\Delta p = \frac{n_{1t} + N_t + \Delta n}{n_{1t} + \Delta n} \Delta n \quad \text{(electron trapping)}. \tag{9b}$$

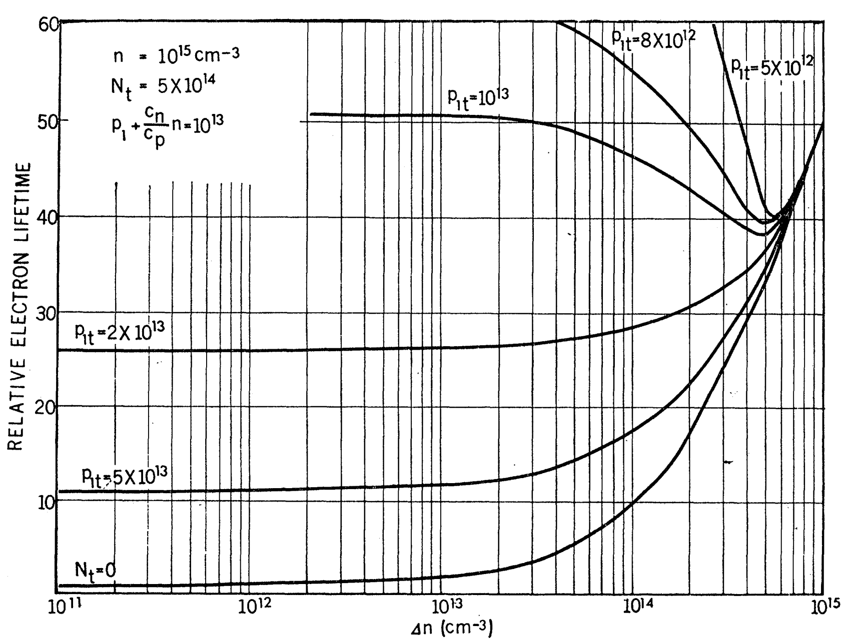

FIG. 2. Examples similar to those shown in Fig. 1, except for a larger trap concentration.

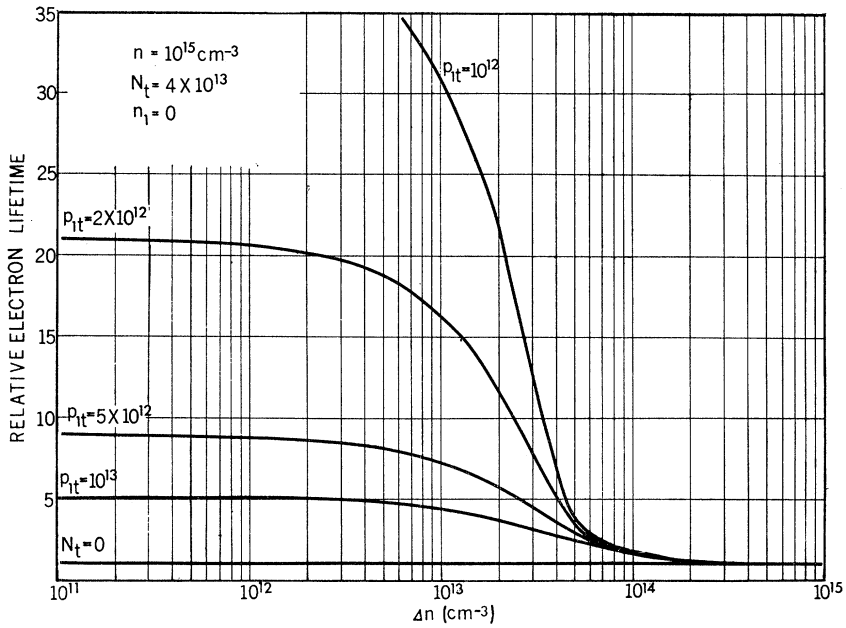

FIG. 3. Examples in which it is assumed that $c_n > c_p$, and again the recombination centers and traps are below the Fermi level. The behavior is similar if the recombination centers are above the Fermi level, except that there is an additional decrease in τ for $\Delta n \gtrsim n$.

This, in principle, solves the problem of the dependence of electron or hole lifetime upon either electron or hole excess density, since either Δn or Δp can be eliminated from Eq. (6) by Eq. (9a). In practice, photoconductivity measurements yield the sum of products of excess hole and electron densities with their respective mobilities. In the case of n-type Si or Ge (electron mobility larger than hole mobility) with hole trapping, the electron concentration can be determined fairly accurately without considering trapping.

ILLUSTRATIVE EXAMPLES

The dependence of electron lifetime on excess electron density in n-type material containing hole traps is illustrated in Figs. 1–3. For these examples the equilibrium electron concentration is 10^{15} cm^{-3}. For Figs. 1 and 2 it is assumed that the recombination level is below the Fermi level and that the hole-capture probability is large compared to the electron-capture probability. In this case Eq. (6) reduces to

$$\tau_n = \frac{p_1 + (c_n/c_p)n + \Delta p}{c_n N[n(\Delta p/\Delta n) + \Delta p]}. \qquad (10)$$

The quantities p_{1t} and N_t have been varied in the two figures. In Fig. 1 the value chosen for N_t is 4×10^{13} cm^{-3}, while the value 5×10^{14} is used in Fig. 2. The lower values of p_{1t} correspond to deeper trapping states; and it is seen that, provided the assumption concerning no electron capture is valid, the deeper the trap the more effective it is in increasing electron lifetime. Other interesting features include the fact that when a minimum occurs it is at $\Delta n \sim N_t$, and where no minimum occurs the presence of trapping may be well camouflaged, showing only a higher lifetime at low excess densities. If trapping is ignored the value of one parameter obtained from such a curve is such that

$$\left(p_1 + \frac{c_n}{c_p} n\right)_{\text{measured}} \approx \left(\frac{p_t + N_t}{p_{1t}}\right)\left(p_1 + \frac{c_n}{c_p} n\right)_{\text{actual}}, \qquad (11)$$

a fact readily seen from Eqs. (9a) and (10).

Figure 3 illustrates the case for electron-capture probability large compared to hole-capture probability, so that

$$\tau_n \approx \frac{n + n_1 + \Delta n}{c_p N[n(\Delta p/\Delta n) + \Delta p]}. \qquad (12)$$

For simplicity, we again assume that the recombination level lies below the Fermi level so the term n_1 drops out. Here the trap concentration is 4×10^{13} cm^{-3} and the trap position, as indicated by the variable p_{1t}, is allowed to take on various values. If the recombination level were above the Fermi level, there would be a further decrease in lifetime at injection levels comparable to or greater than the equilibrium electron concentration. In each of Figs. 1–3, the lowest curve indicates the situation for which either the trap concentration is very small or the trapping level is extremely shallow. Of course, when $N_t = 0$ the value of p_{1t} is immaterial.

EXPERIMENTAL OBSERVATIONS

The data reported here are for 1-Ω cm As- and Sb-doped Ge irradiated with Co^{60} γ rays, and for an unirradiated Al-doped sample of Si. The experimental technique was the same as that used in other studies performed at a single temperature.[7,8] The filter in front of the sample, used to provide uniform excitation, was

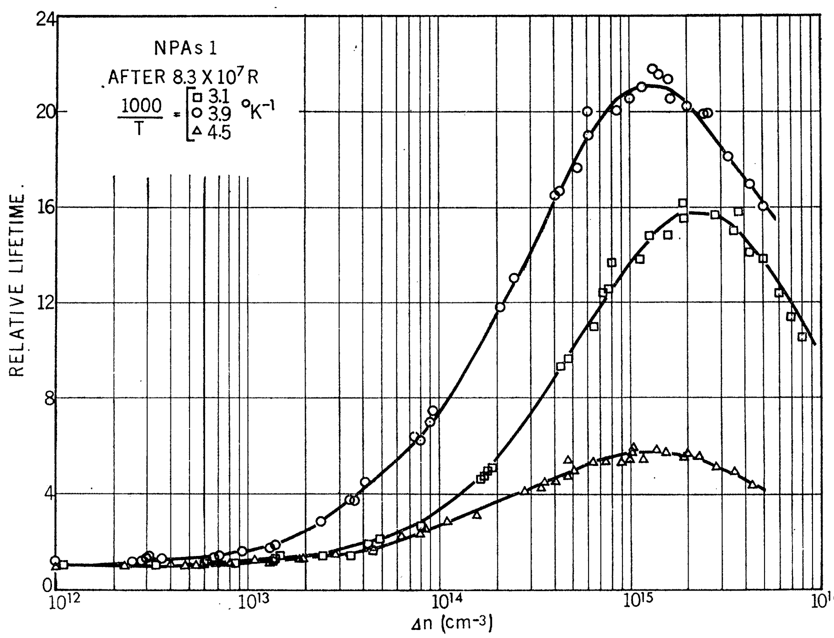

FIG. 4. The dependence of lifetime on excess density at three different temperatures for 1-Ω cm As-doped Ge following γ irradiation.

of the same material as the sample, and maintained at the same temperature.

Figure 4 demonstrates the dependence of lifetime on excess density at various temperatures for a 1-Ω cm As-doped Ge sample, following irradiation with Co^{60} γ rays. The sample was maintained in dry ice during the two weeks required for the irradiation. Data were obtained after ~1 h at room temperature ($1000/T=3.3°K^{-1}$), then at two lower temperatures ($1000/T=3.9$ and $4.5°K^{-1}$). Measurements were then performed at the higher temperature, and the room-temperature measurements were repeated. The behavior was quite surprising at first, since earlier measurements[9] at smaller trap concentrations had shown a break downward in the τ-versus-Δn curve. Evidently, the early portion of the curves corresponds quite closely to the lower curves of Fig. 2. The turnover at higher excess densities is caused by recombination at a shallower level, whose effect is

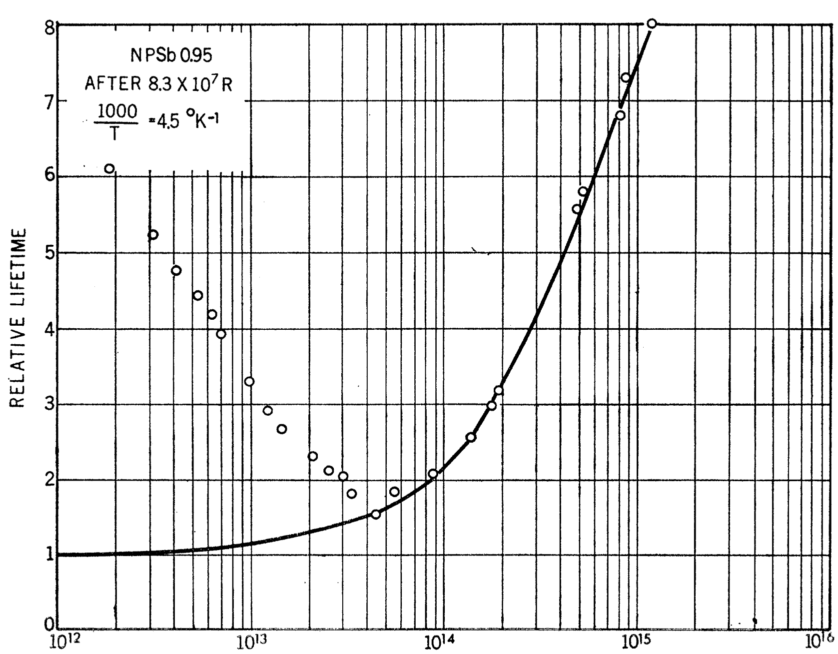

FIG. 5. The dependence of lifetime on excess density at $-51°C$, for 0.95-Ω cm Sb-doped Ge following γ irradiation.

[9] O. L. Curtis, Jr., and J. H. Crawford, Jr., *Radiation Damage in Semiconductors* (Dunod Cie., Paris, 1965), p. 143.

negligible at low excess densities. Curves were fitted to the data using the equation for two simple levels[6,7]:

$$\tau=\left[\frac{bk}{(k+1)n}\,\frac{n+\Delta n}{b+\Delta n}+\frac{c}{(k+1)n}\,\frac{n+\Delta n}{c+\Delta n}\right]^{-1}. \qquad (13)$$

The quantity b is associated with the deep level, dominant at low excess density:

$$b=p_1+(c_pn/c_n). \qquad (14)$$

Referring to the shallow level,

$$c=n_1(1+c_n/c_p), \qquad (15)$$

or, if it is in the lower half of the gap,

$$c=p_1(1+c_n/c_p). \qquad (16)$$

The ratio of lifetimes at low excess density due to the two levels, $(\tau_2/\tau_1)_0$, is k. An illustration of the other type of behavior predicted by Figs. 1 and 2 is shown in Fig. 5 for a Sb-doped sample measured at $1000/T=4.5°\mathrm{K}^{-1}$. The solid curve is again a fit to Eq. (13), assuming no trapping. An example of the behavior exhibited in Fig. 3 (except that the material was p type) is shown in Fig. 6. This 5-Ω cm Al-doped silicon sample was not irradiated, and the dependence of lifetime on excess density reflects the natural trapping and recombination centers. The excess hole density was obtained from the photoconductivity using Eq. (9b) and the relationship

$$\Delta\sigma=e(\mu_p\Delta p+\mu_n\Delta n). \qquad (17)$$

The curve is a fit to the relationships derived with $N_t=1.6\times10^{13}$ cm^{-3} and $n_{1t}=8\times10^{11}$ cm^{-3} ($E_c-E_t \approx 0.30$ eV).

DISCUSSION

That trapping is indeed present in the γ-irradiated, As-doped germanium is demonstrated in Fig. 7, which shows the temperature dependence of lifetime at low excess densities following irradiation and successive ½-h anneals. The behavior at higher temperatures is reasonably consistent with the recombination-level position

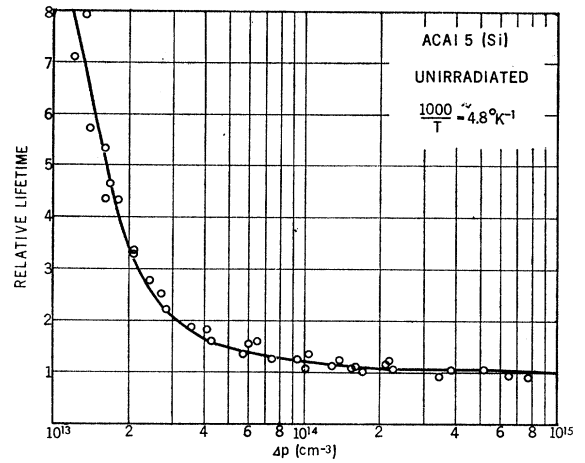

FIG. 6. The dependence of lifetime on excess density for a p-type (Al-doped) Si sample at −65°C. This sample had not been irradiated but exhibited an unusually low lifetime (~2 μsec at room temperature).

determined from the dependence of lifetime on excess density. At lower temperatures the behavior is clearly indicative of trapping, with a trap position (correcting for temperature variation of density of states) at ~0.26 eV above the valence band. The position of this trap is fairly uncertain, and other positions have been quoted.[9,10] However, it is clear that the trap exists, and is important at lower temperatures.

Since the presence of traps is not discernible from the shape of the curves for the As-doped sample, analysis was performed first by ignoring trapping effects. Table I gives the result of this analysis based on application of Eq. (13). The very large apparent variation of c_p/c_n is a manifestation of trapping, and the data at low temperatures are quite consistent with Eqs. (9) and (10). For $c_p/c_n=600$ and $E_t-E_v=0.26$ eV, we obtain $N_t\sim7\times10^{13}$ cm^{-3}. The determination of N_t is crude, since it depends strongly on c_p/c_n, a quantity not well determined in these experiments. The important point is the qualitative agreement between the experiment and theory. The data of Fig. 5 indicate $N_t\sim2\times10^{13}$ cm^{-3}

TABLE I. Recombination parameters for sample NPAs 1.0.

$1000/T$ (°K^{-1})	b (10^{13} cm^{-3})	E_r-E_v (deep level) (eV)	Apparent c_p/c_n	c (10^{16} cm^{-3})	E_c-E_r (shallow level) (eV)	k
4.5[a]	4.5	...	42	1.1	0.12[f]	114
3.9[b]	1.25	...	160	1.31	0.14[f]	48
3.3[c]	1.45	(0.340)	(600)	14.7	0.11[f]	110
3.3[d]	1.33	(0.342)	(600)	14.7	0.11[f]	88
3.1[e]	3.0	0.340	(600)	11.2	0.13[f]	73

[a] Figure 4.
[b] Figure 5.
[c] Initial determination.
[d] Following measurement at $1000/T=3.1°\mathrm{K}^{-1}$.
[e] Figure 6.
[f] Assuming $c=n_1$. If $c=p_1$, the level is 0.02 eV further from the valence band ($E_r-E_v\sim0.14$ eV).

[10] B. G. Streetman, J. Appl. Phys. 37, 3145 (1966).

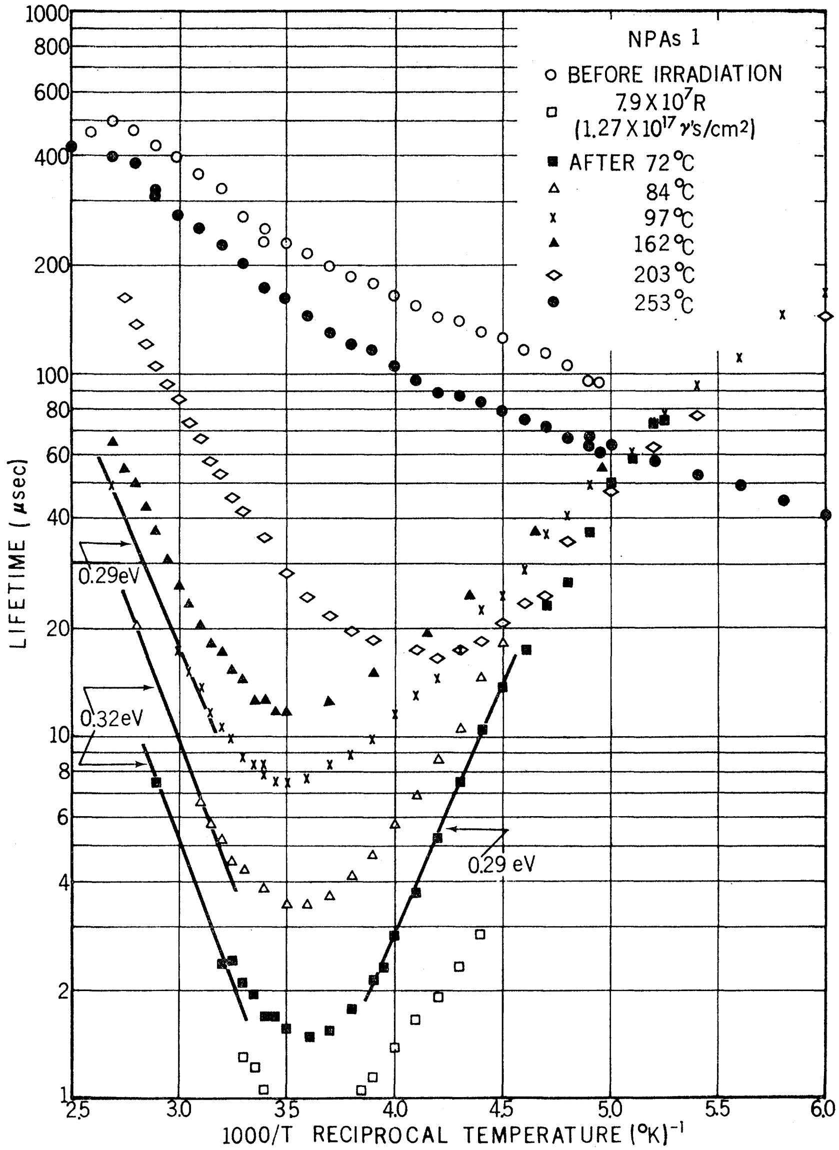

FIG. 7. The dependence of low-excess-density lifetime on temperature for NPAs 1.0 following γ irradiation and successive anneals.

and $E_t - E_v \sim 0.27$ eV. Thus, the major source for the marked difference in behavior between As- and Sb-doped material following irradiation may be the trap concentration. Detailed investigation of this point is under way.

The examples given are not meant to be comprehensive attempts to determine defect parameters. Rather, they are intended to demonstrate the use of the analysis performed. The correspondence between experiment and theory is pleasing.

ACKNOWLEDGMENTS

The author is indebted to C. A. Germano for the experimental data reported herein. This work was supported by Harry Diamond Laboratories and the Defense Atomic Support Agency.