the build-up time, the effect of phonon disturbance can be eliminated and the results can be directly applied to theory. Experiments are in progress and will be reported in the near future.

ACKNOWLEDGMENT

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Recombination Parameters in Low-Resistivity Gamma-Irradiated *n*-Type Germanium*†

J. R. SROUR AND O. L. CURTIS, JR.
Northrop Corporate Laboratories, Hawthorne, California 90250
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Detailed studies of recombination in ~0.2-Ω cm As- and Sb-doped Co^{60} γ-irradiated Ge are reported. The principal experimental techniques used were measurement of the variation of minority-carrier lifetime with temperature (at low excess density) and with excess density (using temperature as a parameter). The temperature dependence of the electron capture probability c_n was obtained for both dopant cases. The hole capture probability c_p was found, in both cases, to be approximately independent of temperature over the range examined. For Sb-doped material at 323°K, the recombination-center energy-level position (neglecting statistical weight) was found to be 0.361 ± 0.005 eV above the valence band, with a possible slight temperature dependence corresponding roughly to one-half the variation of the band gap with temperature. The capture-probability ratio c_p/c_n at this same temperature was 740. For the As-doped case, two different levels appear to dominate the recombination process in annealed and unannealed low-resistivity material. The energy-level positions relative to the valence band (neglecting statistical weight) are 0.327 ± 0.005 and 0.37 ± 0.01 eV at room temperature for the annealed and unannealed samples, respectively. The corresponding capture-probability ratios are 650 and 810. As in the case of Sb doping, the energy level appears to shift with temperature at about one-half the rate of the shift in band-gap energy.

INTRODUCTION

The properties of recombination and trapping centers introduced in *n*-type Ge by Co^{60} γ irradiation have been studied extensively.[1–7] Because of inherent experimental difficulties, however, very little work has been reported on low-resistivity ($\lesssim 0.5$ Ω cm) material. Studies in such material possess the potential of being particularly informative because of the comparative absence of trapping, and the comparative dominance in the expression for minority-carrier lifetime of a term whose only temperature dependence arises from capture-probability variation. Detailed recombination studies on low-resistivity As- and Sb-doped material are reported herein. A primary goal in studying material with high carrier concentration was to investigate in some detail capture-probability temperature dependences, and to obtain reliable information about the capture-probability ratio c_p/c_n. Coupled with data from higher-resistivity samples, this should yield accurate positions for energy levels associated with the radiation-induced defects.

The principal experimental techniques used were measurement of the variation of minority-carrier lifetime with temperature (at low excess density) and with excess density (using temperature as a parameter). In the course of the study, improved techniques were developed for utilizing these concurrent measurements in the determination of recombination parameters.

EXPERIMENTAL

Measurements of minority-carrier lifetime as a function of temperature at low excess density were performed using experimental procedures described previously.[8] The method involves observation of photoconductivity decays. Lifetime as a function of excess density, with temperature as a parameter, was measured using a modification of a method also described elsewhere.[9] The Xe flash lamp previously used for photoexcitation of carriers was replaced by a steady-state light source (R.I. Controls model 5292 high-intensity infrared spot heater). Light to the sample was controlled by a hand-operated shutter, and excess density was varied by using different

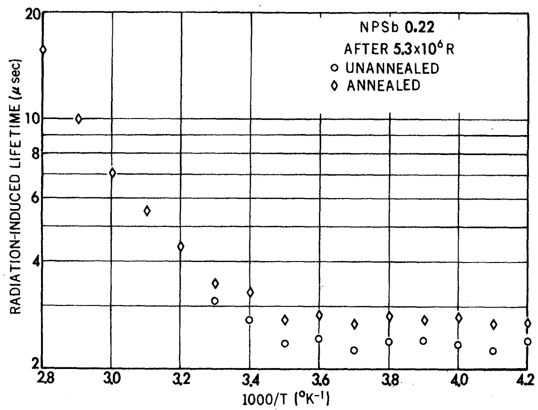

FIG. 1. Radiation-induced lifetime versus reciprocal temperature for 0.22-Ω cm Sb-doped Ge (unannealed and annealed cases). The unannealed case refers to samples that were kept at room temperature for ~1 h (to achieve defect stability) before performing measurements at $1000/T \geq 3.3°K^{-1}$. The annealed case refers to samples that were annealed for $\frac{1}{2}$ h at both 72 and 84°C before performing measurements at $1000/T \geq 2.8°K^{-1}$.

neutral density filters between the light source and the sample. To ensure penetrating radiation, and thus uniform carrier excitation, a Ge filter ~2.5 mm thick was placed between the light source and the sample and was maintained at sample temperature. The primary reason for using a different light source than previously used was to provide more accurate data at low excess densities than previously obtainable. The rf noise associated with the use of a Xe flash lamp becomes an important problem in photoconductivity measurements on low-resistivity material at low excess density.

Samples were cut from As-doped (0.26 Ω cm) and Sb-doped (0.22 Ω cm) single-crystal Ge ingots obtained from Nucleonic Products Co. Ultrasonic soldering techniques were used to prepare Ohmic contacts, which were checked by forward and reverse resistance measurements at both room temperature and dry-ice temperature. In order to measure contact resistances and sample resistivity and homogeneity, potential profiles were obtained for all samples. Samples measured approximately 3×7×30 mm, and all surfaces were lapped. Additionally, samples used for excess-density measurements were etched with CP-4. The sample designation system used in the text, figures, and tables is as follows: NP refers to the manufacturer, Sb and As refer to the dopant, and the numbers give the resistivity in Ω cm.

Samples were electrically connected in a constant-current configuration for the lifetime versus excess-density studies. By measuring the steady-state decrease in voltage (ΔV) across the sample, excess density was then obtained from the expression ($\Delta V \ll V_0$)

$$\Delta n = \sigma_0 \Delta V / e V_0 (\mu_e + \mu_h), \tag{1}$$

where σ_0 is the dark conductivity, V_0 is the dc sample voltage, and the other symbols have their usual meaning. By monitoring the light intensity with a photodiode, and by using the relation

$$\Delta n = g I \tau, \tag{2}$$

where g is the generation rate, I is the measured intensity, and τ is minority carrier lifetime, relative lifetime as a function of excess density was obtained.

After preirradiation measurements of lifetime versus temperature at low excess density, and lifetime versus excess density with temperature as a parameter, irradiations were performed at dry-ice temperature in the Co^{60} source at the Northrop Corp. The total dose given to the samples was $\sim 5.3 \times 10^6$ R (dose rate $\sim 1.5 \times 10^5$ R/h).

Measurements of lifetime as a function of temperature were made for $1000/T \geq 3.3°K^{-1}$ after approximately 1 h at room temperature (to achieve defect stability) for both Sb- and As-doped samples (referred to here as the "unannealed" case). These measurements were repeated for $1000/T \geq 2.8$ after $\frac{1}{2}$-h anneals at 72°C ($1000/T = 2.9°K^{-1}$) and 84°C ($1000/T = 2.8°K^{-1}$) for Sb-doped material ("annealed" case). Because of the large amount of annealing, all As-doped samples were reirradiated to a total accumulated dose of $\sim 1.0 \times 10^7$ R before performing these $\frac{1}{2}$-h anneals so that adequate damage would remain after anneal. This was unnecessary for Sb-doped samples because of the slight annealing that occurred.

Lifetime as a function of excess density was measured successively at $1000/T = 3.3$, 3.6, and $3.9°K^{-1}$. All excess-density measurements were made on samples that were identical to those used in the measurements of lifetime as a function of temperature. Again the measurements at room temperature and below were made after samples had been at room temperature for approximately 1 h (unannealed case); samples were then annealed successively at $1000/T = 2.9$ and $2.8°K^{-1}$ for $\frac{1}{2}$ h (annealed case). Subsequently, lifetime as a function of excess density was measured at $1000/T = 2.9$, 3.1, 3.3, 3.6, and $3.9°K^{-1}$. Prior to this anneal, the As-doped samples were reirradiated as above.

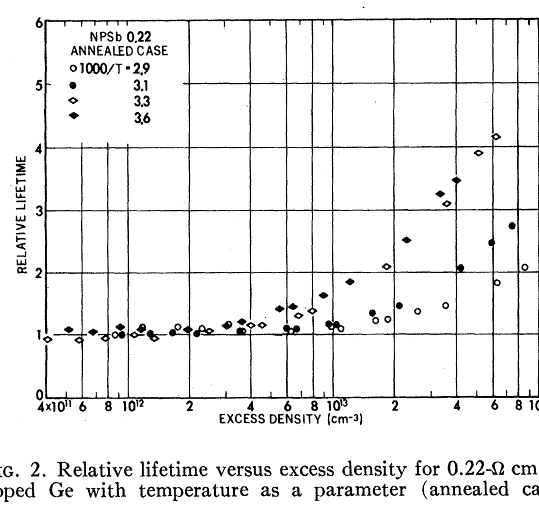

FIG. 2. Relative lifetime versus excess density for 0.22-Ω cm Sb-doped Ge with temperature as a parameter (annealed case).

In addition to the measurements outlined above, an experiment was performed on separate samples to examine dose effects. Samples with nominal resistivities of 0.2, 1, and 5 Ω cm (both As- and Sb-doped) were prepared using the techniques described above. Lifetime measurements were performed for $1000/T \geq 3.3°K^{-1}$ after ~1 h at room temperature on samples with accumulated γ doses of 6×10^4, 2×10^5, 6×10^5, 2×10^6, 6×10^6, and 2×10^7 R. Subsequent to each irradiation, samples were stored at dry-ice temperature until measurements were made. Results of the dose-effects experiment are presented in the final section below.

DATA-ANALYSIS METHODS

Results were analyzed using Hall[10]-Shockley-Read[11] recombination statistics. For n-type material (assuming $\Delta n = \Delta p$), the general expression for minority-carrier lifetime τ, due to a single recombination level, can be written as

$$\tau = \frac{\tau_0(1+\Delta n/b)}{1+\Delta n/n}, \tag{3}$$

where

$$b = [c_p(p+p_1) + c_n(n+n_1)]/(c_p+c_n). \tag{4}$$

In these expressions, all terms have their usual meaning, and the low-excess-density lifetime τ_0 is given by

$$\tau_0 = (p+p_1)/c_nNn + (n+n_1)/c_pNn. \tag{5}$$

The quantity b can be conveniently used in the analysis of measurements of lifetime as a function of excess density. A digital computer was, in most cases, used to perform least-squares fits to the excess-density data. The primary yield of this curve-fitting procedure was values for the parameter b.

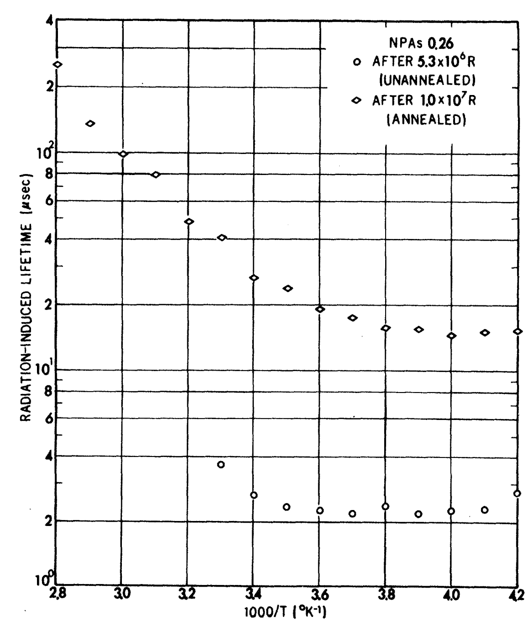

FIG. 3. Radiation-induced lifetime versus reciprocal temperature for 0.26-Ω cm As-doped Ge (unannealed and annealed cases).

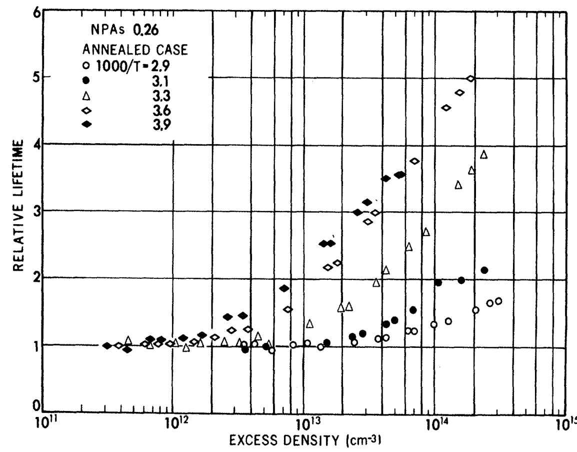

FIG. 4. Relative lifetime versus excess density for 0.26-Ω cm As-doped Ge with temperature as a parameter (annealed case).

RESULTS

In order to separate radiation-induced properties from those present before irradiation, preirradiation lifetime was subtracted reciprocally from measured lifetime to yield the radiation-induced component. This procedure was used both for the temperature-dependence data and the excess-density data.

Figure 1 shows the behavior of lifetime as a function of temperature for Sb-doped material. Typical lifetime as a function of excess-density curves (annealed case) for this material are shown in Fig. 2 for four temperatures. (For clarity, the $1000/T=3.9$ curve is omitted because it approximately overlaps the 3.3 and 3.6 curves.) Data for As-doped material are shown in Figs. 3 and 4. Table I lists b values obtained from fitting curves to the excess-density data. The results for Sb- and As-doped material are now considered separately. As the effective recombination center may be different in low-resistivity material, we will first consider these data independently, and later compare with data from higher-resistivity samples.

Sb-Doped Material

Measurements indicate only slight annealing after successive $\frac{1}{2}$-h anneals at $1000/T=2.9$ and $2.8°K^{-1}$. Furthermore, all measurements show no change in recombination process because of these anneals, so the data will be treated simultaneously.

Consideration of Eq. (4) and b values obtained from excess-density data can yield a conclusion concerning relative magnitudes of the capture probabilities. Since the equilibrium electron concentration n is equal to $1.06\times10^{16}/cm^3$, we conclude that $c_p \gg c_n$ at all of the temperatures studied. Equation (4) then becomes

$$b = p + p_1 + (c_n/c_p)(n+n_1). \tag{6}$$

TABLE I. Values for the parameter b as a function of temperature for Sb- and As-doped Ge. Values with an asterisk are considered less reliable due to fairly scattered data.

	Sb-doped (0.22 Ω cm)		As-doped (0.26 Ω cm)	
$1000/T$ (°K^{-1})	Unannealed (10^{13})	Annealed (10^{13})	Unannealed (10^{13})	Annealed (10^{13})
2.9		6.59		16.01
3.1		2.74		8.53
3.3	1.65	1.48	1.55	3.49
3.6	1.40	1.04	0.52	1.64*
3.9	1.01*	1.19*	0.33	0.87*

Although it seems unusual to include p in this expression because of its very small magnitude relative to n, because of the large c_p/c_n values encountered it becomes an observable correction at the highest temperatures considered here. Usually it will be negligible.

The temperature-dependence data (Fig. 1) can be analyzed using Eq. (5), which contains three significant terms: p_1/c_nNn, $1/c_pN$, and n_1/c_pNn. Figure 1 shows that between $1000/T=\sim3.5$ and 4.2°K^{-1} lifetime is insensitive to temperature. Two of the terms should exhibit a strong temperature dependence, leading to the tentative conclusion that the $1/c_pN$ term dominates, and thus that c_p is approximately independent of temperature. The conclusion is tentative because it is necessary to examine the possibility of temperature-dependence cancellation in either of these terms. (In this discussion we neglect the extremely small temperature dependence of n in this temperature range.) For example, if p_1 and c_n had approximately the same temperature dependence, p_1/c_nNn would be approximately constant and we could not conclusively conclude that the $1/c_pN$ term was dominating.

The temperature dependence of c_n can be obtained from the relation

$$c_n=b/Nn\tau_0, \tag{7}$$

which is obtained from Eqs. (5) and (6).[12] Using the lifetime data of Fig. 1 and the b values given in Table I, relative c_n was calculated as a function of temperature and is plotted in Fig. 5. Because of the small amount of annealing that occurred (Fig. 1), the annealed and unannealed cases are normalized to an equal number of defects N in Fig. 5 (for Sb-doped material). For $1000/T\leq\sim3.6$, we can approximate the temperature variation by $c_n=c_0\exp(-0.07/kT)$, where c_0 is a constant. (This form of the temperature dependence is indicated primarily for comparison purposes, and not necessarily to indicate a physical process.) There is some possibility that the apparent leveling off of c_n at lower temperatures is due to trapping. This might also be the reason for the difference between the b values for the annealed and unannealed cases at low temperatures. The effect of trapping is to increase the observed b values,[13] which would result in an apparently increased c_n. Although trapping was not observed at $1000/T=3.6$ and 3.9 in the temperature-dependence data (Fig. 1), it was observed in preirradiation excess-density data at these temperatures. This is an illustration of the fact that the effects of slow traps are often not observed in transient photoconductivity decay measurements, but they may be effective in steady-state measurements.

We now return to consideration of the temperature-independent region of lifetime in Fig. 1. By inspection of Eq. (6) and consideration of the b value at $1000/T=3.6$, we conclude that $p_1\leq1.04\times10^{13}$ cm^{-3}. This limit restricts the recombination-center energy-level position to $E_r-E_v\gtrsim0.31$ eV. We thus conclude that p_1 cannot possibly have approximately the same temperature variation as c_n, and thus that $p_1/c_nNn\ll 1/c_pN+n_1/c_pNn$ at the lower temperatures. We would observe the temperature dependence of p_1/c_n if this inequality did not hold.

Now consider the n_1/c_pNn term. If $n_1>n$, then this term will dominate, and the lifetime temperature-dependence data would require that n_1 and c_p have approximately the same temperature dependence. In the temperature-independent range, $n_1>n$ requires that $E_c-E_r\leq0.14$ eV. Such a shallow level is relatively ineffective for recombination, and is inconsistent with higher-temperature behavior discussed in the next paragraph. Considering also the fortuitous temperature-dependence cancellation which would be required for this term to be important at low temperatures, it

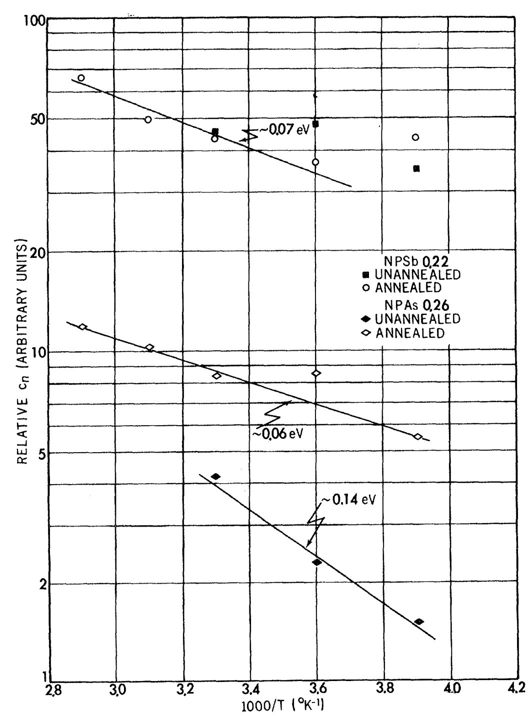

FIG. 5. Relative electron capture probability c_n versus reciprocal temperature for low-resistivity Sb- and As-doped Ge. No comparison should be made between any of the curves with regard to relative magnitude. The curves are plotted on the same figure for convenience only.

TABLE II. Calculation of recombination parameters for Sb-doped material (statistical weight is neglected).

$1000/T$ ($°K^{-1}$)	α Unannealed	α Annealed	c_p/c_n Unannealed	c_p/c_n Annealed	E_r-E_v (eV) Unannealed	E_r-E_v (eV) Annealed
2.9	···	3.6	···	570	···	0.356 ± 0.005
3.1	···	1.97	···	740	···	0.361 ± 0.005
3.3	1.32	1.28	850	920	0.369 ± 0.015	0.375 ± 0.015
3.6	1.0	1.0	760	1020	···	···
3.9	1.0	1.0	1050	890	···	···

seems likely that $n_1/c_pNn \ll 1/c_pN$, and thus that c_p is approximately independent of temperature. The consistency of the analysis below based upon this premise further supports such a conclusion.

It seems evident from Fig. 1 that a temperature-dependent term, n_1 or p_1, is becoming important at higher temperatures. To evaluate this term we find the temperature at which the lifetime is equal to twice the low-temperature plateau value. This occurs at $1000/T \cong 3.1°K^{-1}$. At this temperature, we can write [refer to Eq. (5)]

$$p_1/c_nNn+n_1/c_pNn \cong 1/c_pN. \tag{8}$$

Upon multiplying both sides by c_nNn, Eq. (8) leads directly to the conclusion that $n_1 \leq n$ for $1000/T \geq 3.1$. We can also conclude that $p_1 \leq \frac{1}{2}b$ for the same temperature range, and $c_n/c_p \approx b/2n$ at $1000/T=3.1$. Our conclusions, based on these observations, are that $E_c-E_r \geq 0.18$ eV (from $n_1 \leq n$ at $1000/T=3.1°K^{-1}$), $E_r-E_v \geq 0.36$ eV (from $p_1 \leq \frac{1}{2}b$ at the same temperature), and $c_p/c_n \approx 770$ (from $c_p/c_n=2n/b$). In fact, the energy level must lie near either $E_r-E_v \approx 0.36$ eV above the valence band or ≈ 0.18 eV below the conduction band. The latter possibility is quickly ruled out from the shape of the temperature-dependence curve: Using Eq. (5) and taking into account the variation of c_n with temperature, the position obtained is $E_r-E_v=0.36\pm0.01$ eV.

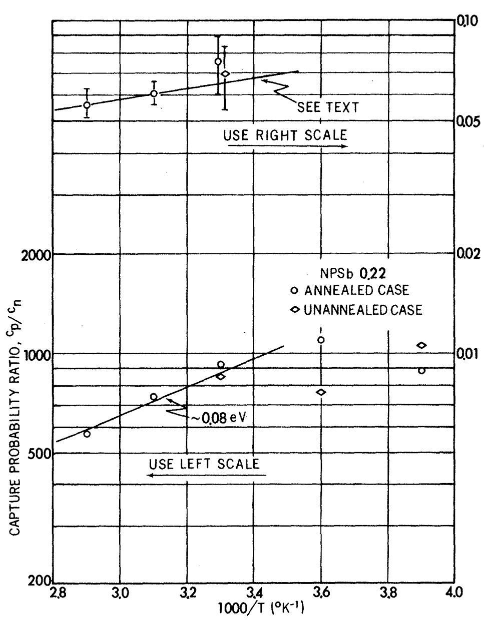

FIG. 6. Capture-probability ratio and recombination-center energy-level position versus reciprocal temperature for 0.22-Ω cm Sb-doped Ge.

Having established that c_p is very nearly temperature independent, and that the plateau lifetime is given by $(c_pN)^{-1}$, a technique becomes available for obtaining more precise parameter values and testing the consistency of the data. When c_p is independent of temperature and a well-defined plateau, $\tau_p=(c_pN)^{-1}$, exists, we can define

$$\alpha(T) \equiv \tau_0(T)/\tau_p. \tag{9}$$

Then

$$\alpha=c_pN[(p+p_1)/c_nNn+(n+n_1)/c_pNn], \tag{10}$$

and thus, from Eq. (6),

$$\alpha=bc_p/nc_n, \tag{11}$$

so that

$$c_p/c_n=\alpha n/b. \tag{12}$$

Rearranging (10) to determine energy-level position,

$$p+p_1=(nc_n/c_p)(\alpha-1-n_1/n)=(b/\alpha)(\alpha-1-n_1/n). \tag{13}$$

In our case n_1/n is a significant correction only at the highest temperature. [An expression similar to Eq. (13) exists when n_1 is the dominant temperature-dependent term.] Table II is a compilation of recombination parameters obtained using this technique for the data of Fig. 1 and Table I, and Fig. 6 is a plot of the results.

As can be observed, the energy levels obtained at the two higher temperatures, where p_1 is large enough to make a major contribution, are in excellent agreement. The temperature dependence of c_p/c_n agrees well with that of c_n, confirming that c_p is very nearly temperature independent. Although the slight differences in energy-level position obtained could be experimental in origin, they could not arise from a very slight temperature dependence of c_p. An 0.01-eV dependence in c_p would produce errors at the various temperatures of only $\sim$0.002 eV; i.e., if there were such a temperature dependence in c_p, this would raise each apparent energy-level value by about 0.002 eV,

TABLE III. Recombination parameters for As-doped material (statistical weight is neglected).

1000/T ($°K^{-1}$)	α Unannealed	α Annealed	c_p/c_n Unannealed	c_p/c_n Annealed	E_r-E_v (eV) Unannealed	E_r-E_v (eV) Annealed
2.9	···	9.3	···	510	···	0.322±0.005
3.1	···	5.2	···	540	···	0.318±0.005
3.3	1.42	2.56	810	650	0.37±0.01	0.327±0.005
3.6	1.0	1.33	1600	710	···	0.335±0.015
3.9	1.0	1.05	2670	1060	···	···

but would not observably affect the temperature dependence of E_r-E_v. However, it is interesting to note that the variation in width of the forbidden gap decreases by roughly twice as great an amount in the same temperature interval.[14] Thus, the actual energy-level position could easily be as strong a function of temperature as indicated here. The line indicated through the points of Fig. 6 corresponds to one-half the band-gap dependence.

In summary, for Sb-doped low-resistivity material, the variation of electron capture probability with temperature was determined and the hole capture probability was found to be nearly independent of temperature. The energy-level position (neglecting statistical weight) determined at $1000/T=3.1°K^{-1}$ was found to be 0.361±0.005 eV above the valence band, with a possible slight dependence on temperature, corresponding roughly to one-half the variation of band gap with temperature. The capture-probability ratio c_p/c_n at this same temperature was 740.

As-Doped Material

Figure 3 indicates approximately no variation of lifetime with temperature for the unannealed case for $1000/T\geq\sim3.5°K^{-1}$. Upon reirradiating to a total dose of 1×10^7 R and annealing for $\frac{1}{2}$ h at both

Using these c_n variations and Eq. (5), fitting curves to the temperature-dependence data of Fig. 3 yields $E_r-E_v=0.37\pm0.01$ eV for the unannealed case and $E_r-E_v=0.33\pm0.01$ eV for the annealed case.

Evidently the procedure used to determine more precisely the recombination parameters for Sb-doped material [Eq. (13)] can be applied as well to the case of As doping. In Table III we have again determined capture-probability ratios and energy-level positions on the premise that the hole capture probability is independent of temperature, and that the plateau value of lifetime is given by $(c_pN)^{-1}$. Results are plotted in Fig. 7. For annealed material the temperature dependence of c_p/c_n is in good agreement with the temperature dependence of c_n, indicating that the assumption of temperature independence of c_p again is well justified. The energy levels are also plotted for this case, and, as before, a slight temperature dependence corresponding to one-half the band-gap temperature dependence appears reasonable. For the

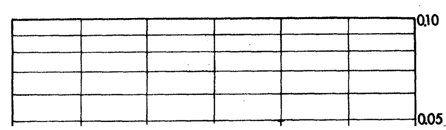

TABLE IV. Recombination-level determination using capture-probability ratios determined from low-resistivity material (As-doped Ge).

	1000/T (°K^{-1})	b (10^{13} cm^{-3})	c_p/c_n	E_r-E_v (eV)
NPAs 1.1 after 8×10^7 R and 84°C anneal, $n=1.6\times10^{15}$	3.9	13.0	510	0.331 ± 0.005
	3.1	5.64	540	0.326 ± 0.005
	3.3	2.63	650	0.324 ± 0.007
NPAs 8.1 after 1.6×10^8 R and 84°C anneal, $n=2.0\times10^{14}$	3.1	7.87	540	0.327 ± 0.005
	3.3	3.34	650	0.318 ± 0.007
NPAs 1.0 after 8×10^7 R, unannealed, $n=1.9\times10^{15}$	3.3	1.45	810	0.341 ± 0.007
NPAs 1.1 after 8×10^7 R, unannealed, $n=1.6\times10^5$	3.3	1.27	810	0.345 ± 0.007
NPAs 9.4 after 1.6×10^8 R, unannealed, $n=1.7\times10^{14}$	3.3	1.94	810	0.336 ± 0.007

unannealed case, the temperature dependence of capture-probability ratio is in reasonable agreement with that for c_n, and the energy-level position at room temperature is determined to be 0.37 ± 0.01 eV above the valence band. For the annealed case, the room-temperature result is 0.327 ± 0.005 eV. These results are in excellent agreement with the curve-fitting results. Thus, the data seem to suggest that the recombination-level position changes upon anneal by about 0.04 eV.

In summary, two different recombination levels appear to dominate the recombination process in annealed and unannealed As-doped material. In both cases, the hole capture probability is very nearly temperature independent, with the temperature dependence of electron capture probability corresponding to an apparent activation energy of ~0.07 and ~0.14 eV for the annealed and unannealed cases, respectively. The energy-level positions are (neglecting statistical weight) 0.327 ± 0.005 and 0.37 ± 0.01 eV at room temperature for the annealed and unannealed samples, respectively. The corresponding capture-probability ratios are 650 and 810. As in the case of Sb doping, the energy level appears to shift with temperature at about one-half the rate of the shift in band-gap energy.

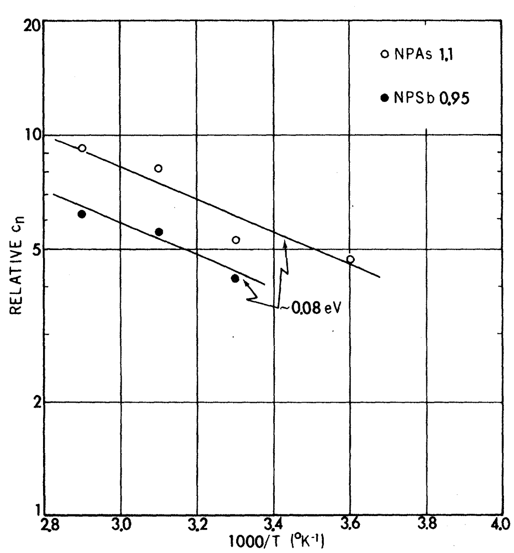

FIG. 8. Relative electron capture probability c_n versus reciprocal temperature for ~1-Ω cm As- and Sb-doped Ge. No comparison should be made between the two curves with regard to relative magnitude. They are plotted on the same figure for convenience only.

COMPARISON WITH DATA FROM HIGHER-RESISTIVITY Ge

As-Doped Material

Data for higher-resistivity As-doped material have been previously presented.[7] In the present discussion only the level effective at low excess densities will be considered. First, we wish to determine if the nature of the recombination center is the same for materials having various carrier concentrations, and if so, to determine what refinements can be introduced into the interpretation of earlier data based on results obtained for low-resistivity material. The close agreement between the energy-level positions obtained in Ref. 7 and that determined here is a strong indication that the annealed As-doped samples are dominated by the same recombination center, irrespective of their resistivity. A further test of this conclusion is to investigate the variation of electron capture probability with temperature, using Eq. (7). Figure 8 shows the result of such an analysis for 1.1-Ω cm material. Comparison indicates that the dependence is very similar to that observed in low-resistivity material, which supports the premise made.

Since we can now feel reasonably assured that recombination parameters are identical in the higher-resistivity annealed specimens, the capture-probability ratios determined from the lower-resistivity samples can be utilized to obtain energy-level position more precisely than was done earlier for the higher-resistivity

TABLE V. Recombination-level determination using capture-probability ratios determined from low-resistivity material (Sb-doped Ge).

Sample	Temp. of meas. ($1000/T°K^{-1}$)	b (10^{13} cm^{-3})	c_p/c_n	E_r-E_v (eV)
NPSb 0.95 ($n=1.95\times10^{15}$ cm^{-3})	3.3	1.61	880	0.337
	3.1	8.91	740	0.315
	3.3	3.84	880	0.313
	2.9	7.19	570	0.356
	3.1	2.53	740	0.351
	3.3	1.53	880	0.340
NPSb 1.0 ($n=1.8\times10^{15}$ cm^{-3})	3.3	1.76	880	0.336
	3.1	3.26	740	0.343
	3.3	3.40	880	0.316
	2.9	5.71	570	0.369
	3.3	1.13	880	0.349
NPSb 4.9 ($n=2.5\times10^{14}$ cm^{-3})	3.3	1.45	880	0.343
	3.2	2.55	800	0.344
	3.3	1.40	880	0.344

case, where an approximate value of capture-probability ratio, 400, was used. With regard to the unannealed specimens,[7] agreement appears less convincing and the data are not sufficient to compare the capture-probability temperature dependence. However, for purpose of comparison of energy-level positions, let us assume that the capture probability for the low-resistivity unannealed samples at room temperature, $c_p/c_n=810$, is valid. Energy-level calculations for both annealed and unannealed cases are shown in Table IV. Again, energy levels are in excellent agreement for the higher-resistivity annealed case with data from low-resistivity samples. However, the unannealed samples show an energy-level position intermediate between the low-resistivity values observed (0.327 and 0.37 eV), possibly indicating that levels at both of these positions are effective.

Sb-Doped Material

Recombination parameters for higher-resistivity Sb-doped Ge have been previously presented.[15] Although the energy-level positions obtained in Ref. 15 tend to be slightly closer to the valence band than for low-resistivity material, the fairly close agreement indicates the possibility that the same level is dominant in each case. As before, to investigate this hypothesis we plot the temperature dependence of c_n for 0.95-Ω cm material (shown in Fig. 8). The similarity to the data of Fig. 5 supports the above viewpoint.

Under the assumption that the recombination level has the same characteristics as obtained for low-resistivity material, we have recalculated energy-level positions based upon capture-probability ratios determined in the present work. These are shown in Table V. Lower-temperature values for NPSb 4.9 are omitted because of the influence of trapping which made the apparent energy levels much shallower. Because of the fact that larger capture-probability ratios were used in compiling this table than were used previously, the calculated energy levels are, in general, slightly deeper than the values given previously.[15] The results cast doubt upon whether the observed energy level is actually the same in materials with different resistivities. However, inspection of the lifetime-versus-reciprocal-temperature curves for the higher-resistivity samples indicates the possibility that trapping may be influencing the lifetime even near room temperature. In Fig. 9 we have plotted calculated energy-level positions as a function of reciprocal temperature for the data of Table V. At the highest temperature, where trapping should be

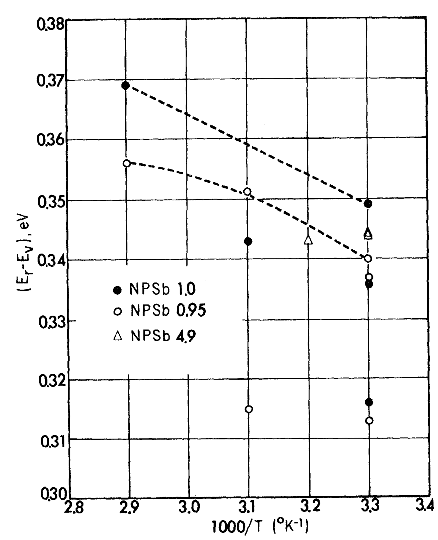

FIG. 9. Calculated recombination-center energy-level positions versus reciprocal temperature for higher-resistivity Sb-doped Ge using capture-probability ratios determined from low-resistivity material.

degradation), when departure from linearity just begins to occur, we can conclude that the $1/c_pN$ and $1/c_nn$ terms are comparable in magnitude. Thus, at that departure point, $N\cong(c_n/c_p)n$. The method would assume, of course, that the c_n/c_p value obtained at lower doses would also apply at this higher-dose transition point. The present data allow the calculation of an upper bound for N. As an example, consider the 0.2-cm As-doped material at room temperature. For this material, $n\cong 9\times 10^{15}$ cm^{-3} and $c_p/c_n\cong 800$. At a dose of 2×10^7 R, Fig. 10 still indicates linearity for this case. We thus conclude that an upper bound for the defect density N at this dose is $\sim 10^{13}$ cm^{-3} for this material. (Similar considerations for higher-resistivity material, where the situation is more complex, yield an even lower upper bound for the rate of defect introduction.) Studies at higher doses than utilized here should in principle yield the introduction rate of defects. However, if carrier removal effects commence before $1/c_nn$ begins to dominate, the method would not apply.

It is interesting to note that the properties of radiation-induced defects obtained in the present case are qualitatively quite similar to those observed in studies of copper in Ge by other workers. Baum and Battey[26] found that the electron capture cross section for a level introduced by copper increased exponentially with temperature ($\Delta E=0.22$ eV). Shulman and Wyluda[27] observed a similar exponential variation ($\Delta E>0.11$ eV) and also found the hole capture cross section to be approximately independent of temperature.

Thus far, we have assumed unity statistical weight in all calculations and discussion, absorbing any deviation from unity in the apparent energy-level position. We have previously made an attempt to include the effects of statistical weight on the assignment of recombination-center energy-level positions,[6,7] but accurate weight assignment depends upon knowledge of the nature of the recombination center being considered, i.e., even more than the knowledge that it is a double acceptor. For a group-III single-acceptor center the spin degeneracy factor is 2, which would result in a shift in apparent energy-level position by ~ 0.02 eV. Because of the complexity of the problem under consideration and because of the lack of an exact description of the center(s) involved, we leave unresolved the problem of statistical weight.

The question then arises as to the nature of the damage that results in the observed recombination centers in Sb- and As-doped material. The present study does not directly yield enough information from which the centers can be attributed to a particular defect or defect complex; detailed annealing kinetics would be necessary to accomplish this. We hope, however, that the detailed information presented here concerning recombination parameters will be helpful to future investigators for this purpose.

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