Recombination and Trapping in Normal and Electron-Irradiated Silicon*

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Both recombination and trapping are observed in normal and irradiated silicon. There combination processes are analyzed on a Shockley-Read model and the energy levels and relative electron and hole capture cross sections of the recombination centers are given. A previously unreported recombination center is produced in p-type silicon by electron irradiation. It is located at $E_v+0.18$ eV and is a net donor. Four samples of n-type silicon were studied, three of which gave agreement with the results of Galkin ($E_r=E_c-0.17$ eV), and the fourth gave agreement with the results of Wertheim ($E_r=E_v+0.27$ eV). A theoretical treatment of trapping in the presence of direct or indirect recombination is presented and shown to give good agreement with the observed trapping behavior. Three distinct trapping levels are seen in n-type silicon.

I. INTRODUCTION

THE nature of the lattice defects which are produced by irradiation of silicon has been the subject of a considerable amount of experimental study in the past several years. Changes have been observed and reported in the majority carrier concentration and mobility,[1–3] in the infrared absorption and photoconductivity,[4,5] in the electron spin resonance spectrum,[6–8] and in the excess-carrier lifetimes.[3,9] The latter effect has been pointed out to be a highly sensitive indicator of radiation damage in semiconductors[10] and has been the subject of considerable theoretical study. The dependence of lifetime on sample temperature and on the concentration of excess carriers can be used to determine both the energy level and the relative electron and hole capture cross sections of the dominant recombination centers.

The two published studies of lifetimes in electron-irradiated silicon[3,9,11] have dealt mainly with n-type material, and are in disagreement on the location of the principal recombination center. The level reported by Galkin *et al.* was 0.16 eV below the bottom of the conduction band, and that reported by Wertheim was 0.27 eV above the top of the valence band. The measurements of Wertheim and Galkin have been extended in the present paper to four different n-type samples. The results in three of the four agree with Galkin, and the fourth agrees with Wertheim.

Three samples of p-type silicon were also studied; the results are in disagreement with the conclusions reached by Wertheim,[3,9] who examined one p-type sample and found a recombination level at $E_c-0.16$ eV. The results on all three p-type specimens indicated a level at $E_v+0.18$ eV.

II. THEORY OF RECOMBINATION

The basis of the modern theoretical studies of the recombination process in semiconductors is the work of Hall[12] and Shockley and Read.[13] Shockley and Read's notation has now become standard, and is used in the present paper.

The original Hall-Shockley-Read papers dealt with recombination via a single species of recombination center under equilibrium generation-recombination conditions. Under these conditions the expression obtained for the lifetime is

$$\tau=\tau_{p0}\left[\frac{n_0+n_1+\Delta n}{n_0+p_0+\Delta n}\right]+\tau_{n0}\left[\frac{p_0+p_1+\Delta n}{n_0+p_0+\Delta n}\right], \quad (1)$$

where n_0 and p_0 are the thermal equilibrium electron and hole concentrations, n_1 and p_1 are the electron and hole concentrations when the Fermi level lies at the recombination center, ($n_1=N_c e^{(E_r-E_c)/kT}$, $p_1=N_v e^{(E_v-E_r)/kT}$), Δn is the excess electron (and hole) concentration, τ_{n0} is the electron lifetime governed by the single level when the Fermi level lies close to the valence band, and τ_{p0} is the hole lifetime when the Fermi level lies near the conduction band.

If the excess carrier concentration is small compared with (n_0+p_0), then

$$\tau_0=\tau_{p0}\left[\frac{n_0+n_1}{n_0+p_0}\right]+\tau_{n0}\left[\frac{p_0+p_1}{n_0+p_0}\right]. \quad (2)$$

In the following discussion n-type material will be considered. Similar expressions are obtained for p-type material by interchange of n and p. Equation (2) simplifies for n-type material to

$$\tau_0=\tau_{p0}(1+n_1/n_0) \quad (3)$$

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[3] G. K. Wertheim, Phys. Rev. **105**, 1730 (1957); **110**, 1272 (1958).
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[5] J. W. Corbett, G. D. Watkins, R. M. Chrenko, and R. S. McDonald, Phys. Rev. **121**, 1015 (1961).
[6] G. D. Watkins and J. W. Corbett, Phys. Rev. **121**, 1001 (1961).
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[13] W. Shockley and W. T. Read, Jr., Phys. Rev. **87**, 835 (1952).

provided the center lies in the same half of the bandgap as the Fermi level, while

$$\tau_0=\tau_{p0}(1+\gamma p_1/n_0) \tag{4}$$

if the center lies in the opposite half of the band gap, where γ is the ratio τ_{n0}/τ_{p0}. Since τ_{n0} and τ_{p0} are inversely proportional to the electron and hole capture cross sections, respectively, of the recombination center, $\gamma\cong\sigma_p/\sigma_n$.

Sandiford[14] and Wertheim[15] have pointed out that these expressions are valid for the lifetime under transient recombination conditions as well, provided the density of recombination centers is small compared with (n_0+p_0). If the injected carrier concentration is not small compared with (n_0+p_0), the lifetime depends on the carrier concentration according to

$$\tau=\frac{\tau_0+(\tau_{n0}+\tau_{p0})\Delta n/n_0}{1+\Delta n/n_0}, \tag{5}$$

where τ_0 is the lifetime in the limit $\Delta n\rightarrow 0$. If more than one independent species of recombination center is present

$$\tau^{-1}=\textstyle\sum_j \tau_j^{-1}, \tag{6}$$

where the τ_j are given by Eq. (5).[16]

There have been, in addition, theoretical papers extending the model to moderately high carrier concentration, trapping, and recombination by a single level[17,18] and recombination via divalent centers.[19]

The present lifetime measurements were analyzed in terms of Eqs. (3) to (5). An activation energy can be determined from the high-temperature dependence of the small injection lifetime. This activation energy is the distance from the recombination center to the nearest band edge. The problem of determining in which half of the band gap the center lies is usually not difficult to resolve. Equation (3) is determined by only two parameters, τ_{p0} and n_1, and if it can be used to obtain a satisfactory experimental fit, then in all probability the center lies in the same half of the gap as the Fermi level. Since Eq. (4) is similar in form to Eq. (3), but contains an extra parameter, γ, it can also be used to obtain a satisfactory experimental fit, but with a value of γ which is near unity. For the usual type of localized charge state in the forbidden gap such a value of γ is highly unlikely; for donor-like levels $\gamma\ll 1$ and for acceptor-like levels $\gamma\gg 1$. Consequently, if a value of γ much different from unity is required to fit Eq. (4) to the experimental results, the evidence is strong that the level lies in the opposite half of the band gap from the Fermi level, and in addition the value of γ indicates the relative electron and hole capture cross sections of the centers.

The dependence of the lifetime on excess carrier concentration was measured in most of the samples that were studied. The principal purpose was a determination of $(\tau_{n0}+\tau_{p0})$ using Eq. (5), but an almost equally important objective was to test the validity of the single recombination level assumption. If a single level is dominant, then $\tau(1+\Delta n/n_0)$ is expected to be linear in $\Delta n/n_0$, whereas two or more contributing levels would cause $\tau(1+\Delta n/n_0)$ to be concave downward.[16]

One additional qualitative note should be made. If there is an assortment of recombination centers, some having donor-like charge states and some acceptor-like, the former will tend to dominate the recombination process in p-type material and the latter will be predominant in n-type. This circumstance follows from the large difference between the capture cross section for a neutral center compared with a charged center.

III. TRAPPING AND RECOMBINATION

The effect of trapping and recombination in silicon has been the subject of some previous work.[20] Hornbeck and Haynes[18] have considered the case of one or more trapping levels and have derived approximate solutions to the transient behavior. Ryvkin and Yaroshetskii[21] have also derived approximate solutions and applied them to a study of gamma-irradiated germanium, and Curtis and Crawford[22] have collected extensive data on recombination and trapping in electron-irradiated germanium. Wertheim[15] has treated the case of a single trap and a single recombination center under the restriction that the filling fraction of the traps is small. This restriction has been relaxed in the present work and the case of a single trap in conjunction with any direct or indirect recombination process was analyzed, beginning with injection levels large enough to fill the traps virtually completely.

We make the assumption that following injection of Δp holes (and the same number of electrons) a condition of quasi-thermal equilibrium is established between the traps and the valence band. The population of the traps and valence band can then be represented by a single quasi-Fermi level F_t. If Δp is large compared with the trap concentration N_t, F_t will lie below the trap level

[14] D. J. Sandiford, Phys. Rev. **105**, 524 (1957).
[15] G. K. Wertheim, Phys. Rev. **109**, 1086 (1958).
[16] A number of typical lifetime vs injection level curves and a complete analysis of unirradiated p-type silicon are given by J. S. Blakemore, Phys. Rev. **110**, 1301 (1958).
[17] K. C. Nomura and J. S. Blakemore, Phys. Rev. **112**, 1607 (1958); **121**, 734 (1961).
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[19] C. T. Sah and W. Shockley, Phys. Rev. **109**, 1103 (1958).
[20] The usual distinction between a trap and a recombination center follows from the position of the center within the band gap and from the relative magnitudes of the electron and hole capture cross sections. In an n-type semiconductor a center will be a hole trap if, after it captures a hole, thermal re-excitation of the hole into the valence band is more probable than subsequent capture of an electron from the conduction band.
[21] S. M. Ryvkin and I. D. Yaroshetskii, Soviet Phys.—Solid State **2**, 1771 (1961).
[22] O. L. Curtis and J. H. Crawford, Jr., Phys. Rev. **124**, 1731 (1961).

E_t and the fractional filling of the traps will be nearly unity.

If a denotes the fraction of the Δp holes which are in the valence band, then the free hole concentration is given by

$$a\Delta p = N_v e^{(E_v - F_t)/kT} = p_t e^{(E_t - F_t)/kT}, \quad (7)$$

where $p_t = N_v e^{(E_v - E_t)/kT}$, and the number of trapped holes is

$$(1-a)\Delta p = N_t \frac{e^{(E_t - F_t)/kT}}{1+e^{(E_t - F_t)/kT}}. \quad (8)$$

Equations (7) and (8) yield a quadratic in $e^{(E_t - F_t)/kT}$ whose solution is

$$e^{(E_t - F_t)/kT} = \frac{(\Delta p - N_t - p_t) + [(\Delta p - N_t - p_t)^2 + 4p_t\Delta p]^{1/2}}{2p_t}, \quad (9)$$

and

$$a = \frac{(\Delta p - N_t - p_t) + [(\Delta p - N_t - p_t)^2 + 4p_t\Delta p]^{1/2}}{2\Delta p}. \quad (10)$$

Letting τ be the lifetime if the hole traps were not present, the recombination rate in the presence of trapping is given by

$$U = -d(\Delta p)/dt = (a/\tau)\Delta p. \quad (11)$$

This equation has been solved with the help of an electronic computer. The results are shown for various values of p_t in Fig. 1. The initial decay, when Δp is large compared with N_t, is a simple exponential with time constant τ. The final decay, when Δp is small compared with N_t, is also a simple exponential of time constant $\tau[(N_t+p_t)/p_t]$. It will be shown in the following section that by means of the solutions shown in Fig. 1 it is possible to determine both N_t and E_t from a single-carrier transient decay measurement made at one temperature.

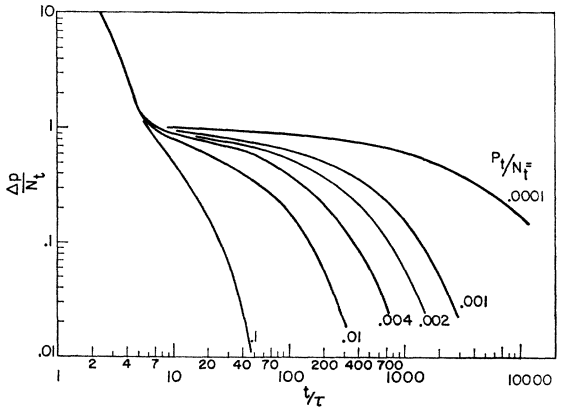

FIG. 1. Decay of excess carriers vs time for the case of a single trapping center in conjunction with any recombination process. The initial portion of the decay curve is a simple exponential with a time constant τ determined by the recombination process.

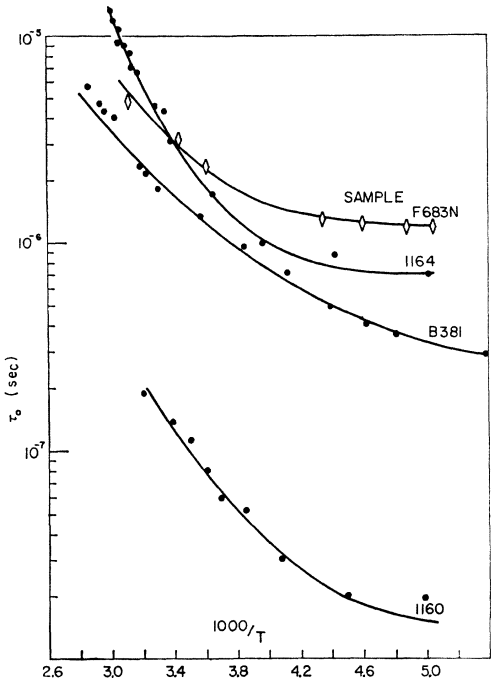

FIG. 2. Small injection lifetimes vs temperature for four n-type samples. The points are experimental; the solid curves are calculated from Eqs. (3) and (4).

The case of two independent sets of traps is somewhat more complicated than the single-trap solutions shown in Fig. 1, but some of the qualitative features of this case can be seen fairly easily. Let E_{t_1} and E_{t_2} be the energy levels of the two traps ($E_{t_2} > E_{t_1}$) and let the initial injection level be sufficiently large so that F_t lies below E_{t_1} at $t=0$. In the initial phases while F_t remains below E_{t_1} the decay occurs very nearly as though the traps at E_{t_2} were absent. There is an initial fast recombination followed by a transition region to trapping primarily in the shallower levels (E_{t_1}). When F_t is between the two trapping levels (and several kT away from both), the decay will approach a simple exponential with a time constant $\tau(1+N_{t_1}/p_{t_1})$. As F_t approaches E_{t_2} a second trapping transition occurs until finally with F_t well above E_{t_2} the decay approaches a third exponential whose time constant is

$$\tau\left[1+\frac{N_{t_1}}{p_{t_1}}+\frac{N_{t_2}}{p_{t_2}}\right].$$

It is also informative to note what happens as the temperature is varied. During the decay the transition from recombination to trapping occurs roughly at $\Delta p = N_t$, and the final decay time constant increases by a factor $(1+N_t/p_t)$. For any given set of traps, as the temperature is raised, p_t increases rapidly until p_t/N_t is not small compared with unity. Under this condition,

TABLE I. Summary of recombination measurements.

Sample No.	Type	Resistivity (ohm-cm)	Dopant	Electron energy (MeV)	Flux (electrons/cm²)	τ_{n0} (μsec)	τ_{p0} (μsec)	E_r
1160	n	3	Arsenic	0.5	1.0×10^{15}	0.30	0.013	$E_c-0.19$ eV
1164	n	3	Antimony	0.5	1.0×10^{15}	1.4	0.07	$E_v+0.27$ eV
B381	n	1	Phosphorus	0.7	2.0×10^{14}		0.27	$E_c-0.18$ eV
F683N	n	1	Phosphorus	0.5	6×10^{14}	20	1.2	$E_c-0.20$ eV
69315[a]	p	2	Boron	0.7	1.0×10^{15}	0.13	1.5–2.0	$E_v+0.18$ eV
N341	p	1	Boron	0.7	4×10^{15}	0.09		$E_v+0.19$ eV
1166	p	1.8	Indium	0.7	1.2×10^{15}	0.3	2.3	$E_v+0.18$ eV
					7×10^{15}	0.06		$E_v+0.18$ eV

[a] Vacuum-floating-zone grown.

the set of traps is relatively unimportant in determining the transient carrier concentration as Fig. 1 indicates. It will be seen in the following section that it is possible by a suitable choice of temperature to observe deep-lying traps having very small concentrations even in the presence of large concentrations of shallow traps. An interesting feature of the analysis is that it is unnecessary to observe the intermediate or final exponential to determine the trap densities and energy levels. The transition region by itself allows a reasonably accurate determination of N_t and E_t.

IV. DISCUSSION

The technique used to measure the excess-carrier lifetime was similar to that used by Wertheim.[8,9] Samples of single-crystal silicon having Ohmic contacts were placed in series with a battery and load resistor and exposed to short bursts of electrons from a 1-MeV Van de Graaff generator. The transient voltage across the sample was measured with an oscilloscope. Whenever the transient was approximately a simple exponential, its amplitude and decay constant were measured; in one case where it was severely nonexponential a series of oscillograms was taken and analyzed using Eqs. (10) and (11) and Fig. 1. The samples were mounted at an angle of 45° to the electron beam to allow illumination during the lifetime and trapping measurements. The sample temperatures were varied over the range from 100 to 400°K.

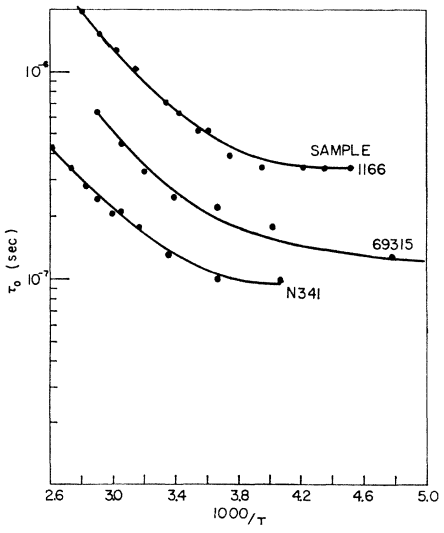

FIG. 3. Small injection lifetimes vs temperature for three p-type samples. The points are experimental; the solid curves are calculated from Eq. (3).

Experimental Results

A total of seven low resistivity samples were studied; their characteristics are given in Table I. The pre-irradiation lifetimes were all in the range from 1 to 22 μsec, and with one exception they were nearly temperature-independent. There are two possible explanations for this; the lifetime may be limited by surface recombination before irradiation, or the dominant recombination levels may be very shallow. The samples all had rough-lapped or sandblasted surfaces (to insure surface stability throughout irradiation) and the surface recombination velocities were known to be high.

The small injection bombardment-limited lifetimes vs temperature are shown in Figs. 2 and 3, and representative lifetime vs injection level in Figs. 4 and 5. In all four figures the lifetime which is shown is the bombardment-limited lifetime, defined by $\tau^{-1}=\tau_{\text{final}}^{-1}-\tau_{\text{initial}}^{-1}$.

Analysis on the basis of a single recombination level is justified by the linearity of the injection level dependence in all cases studied; the results of this analysis are also given in Table I. A comparison of the results on

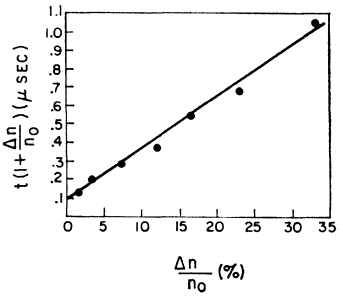

FIG. 4. Lifetime vs injection level for sample 1160. The sample temperature was −67°C.

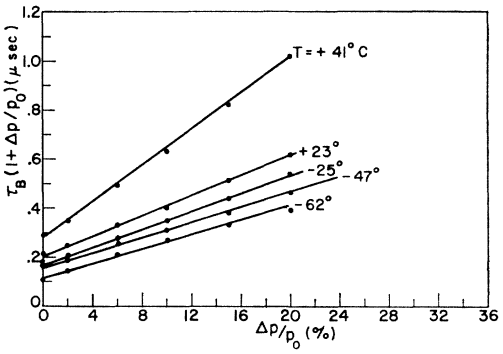

FIG. 5. Lifetime vs injection level for sample 69315 at various sample temperatures.

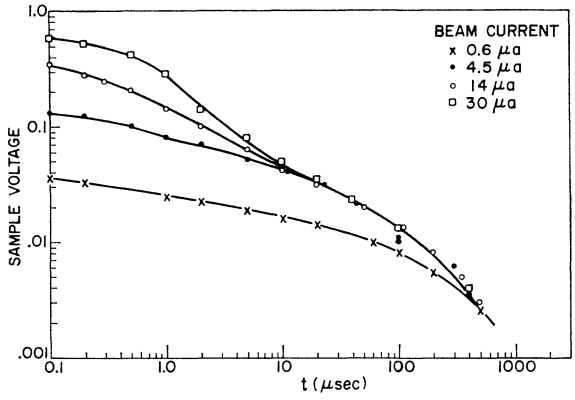

FIG. 7. Decay of the excess conductivity following injection by a short burst of 700-keV electrons in unirradiated sample 1160 at −62°C. Four different beam intensities are shown. The lowest is insufficient to fill all of the traps; at the highest beam all of the traps are filled, and an initial fast recombination can be seen.

n-type silicon with the conclusions of Wertheim and Galkin shows that in three of the four samples the results agreed with Galkin ($E_r=E_c-0.18$ eV) and in the fourth the results agreed with Wertheim ($E_r=E_v+0.27$ eV). In all four cases, as one would expect, the dominant centers were net acceptors.

Analysis of the three p-type crystals leads to the conclusion that $E_r=E_v+0.18$ eV. The only previous lifetime measurements of electron-irradiated p-type silicon, by Wertheim,[9] reported $E_r=E_c-0.18$ eV, and in view of the disagreement between the latter and the present work, the results on the first p-type sample, number 69315, were rather carefully checked. An acceptable (though not excellent) fit to the small injection temperature dependence can be made in this sample using $E_r=E_c-0.18$ eV but only with $\gamma=10$ which is in strong disagreement with the injection level dependence shown in Fig. 5, according to which $\gamma=1/10$.

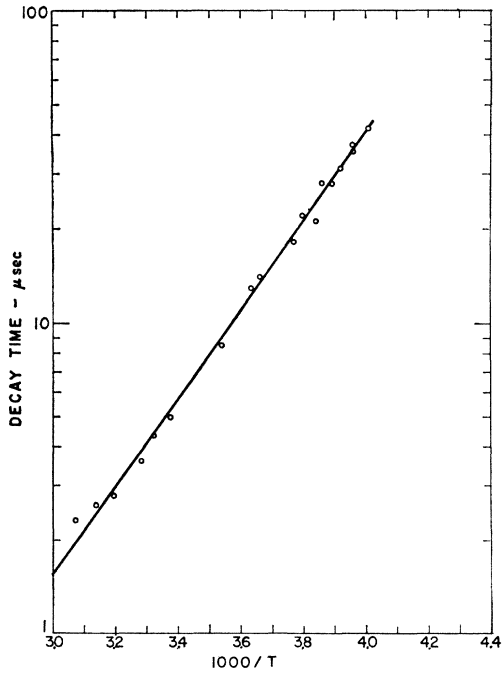

FIG. 6. Decay time of excess carriers in sample 104 (n-type, 200 Ω-cm) following irradiation with 6×10^{14} electrons per cm² at 750 keV, showing an increasing time constant with decreasing temperature characteristic of a trapping process. The decay curves were pure exponentials at all temperatures, indicating a trap concentration large compared with the injection level.

Oue specimen of high-resistivity n-type silicon was also studied: The excess-carrier decay was found to be a pure exponential, whose time constant increased with decreasing temperature as shown in Fig. 6. This behavior is qualitatively what one would expect from a dominant trapping process. Since the decay curve remained a pure exponential at all temperatures, the small injection trapping limit is applicable (Δp and $\Delta n \ll N_t$), the decay constant is given by $\tau(N_t+p_t)/p_t$, and a lower limit of N_t can be estimated. It is $N_t \gg 1.6\times10^{14}$ cm^{-3}.

The linearity of Fig. 6 is quite interesting, and has two possible explanations. One possibility is that the lifetime in the absence of trapping, τ, is nearly independent of temperature (either because the dominant recombination level is very shallow, or because the low-temperature lifetime limit holds at the highest temperature shown, 330°K). In this case the "activation energy" of the figure gives the location of the trap directly, which in this case is $E_v+0.26$ eV. The second possibility is that the high-temperature lifetime limit is reached even at the lowest temperature shown (250°K). In this case the activation energy gives the difference between the relative energy levels of the traps and the recombination centers, each measured from the nearest band edge. The traps in the present sample under this set of assumptions would be deep lying, from $E_v+0.43$ eV to $E_v+0.53$ eV. The latter possibility is considered somewhat more likely in view of the results on other n-type samples, but the first possibility cannot be dismissed altogether.

At low temperatures a number of the samples exhibited evidence of trapping in the form of a slow non-

TABLE II. Summary of trapping measurements for sample No. 1160.

Temperature (°C)	N_{t_1} (cm^{-3})	p_{t_1}/N_{t_1}	ΔE_{t_1} (eV)	N_{t_2} (cm^{-3})	p_{t_2}/N_{t_2}	ΔE_{t_2} (eV)	N_{t_3} (cm^{-3})	p_{t_3}/N_{t_3}	ΔE_{t_3} (eV)
Not irradiated									
−62	2.1×10^{13}	0.0055	0.33	...	...	...	...	...	...
−34	1.4×10^{13}	0.01	0.37	...	...	...	...	...	...
−78	2.4×10^{13}	0.0015	0.32	...	...	...	...	...	...
+27	...	...	...	9×10^{11}	0.03	0.52	...	...	...
Irradiated with 0.7-MeV electrons, $\phi=3.6\times10^{14}$ cm^{-2}									
−75	2.9×10^{13}	0.0003	0.35	...	...	...	1.3×10^{14}	0.03	0.25
−47	2.4×10^{13}	0.0015	0.38	...	...	...	9×10^{13}	0.04	0.29
0	4×10^{13}	0.06	0.36	3.4×10^{12}	0.0003	0.55	...	...	...

exponential tail following the usual fast exponential decay. Sample number 1160 was studied in some detail using a series of oscillograms taken before and after irradiation. By comparing the results with the solutions to Eqs. (10) and (11) shown in Fig. 1 three distinct traps were resolved. One of these, located at $E_v+0.35\pm0.02$ eV, was present before and after irradiation with the same density (roughly 3×10^{13} per cm^3). The second trap is located at $E_v+0.27\pm0.02$ eV and is only present after irradiation, with a density of approximately 1×10^{14} per cm^3. The third trapping center lies near the middle of the bandgap, at $E_v+0.53$ eV±0.02 eV. The concentration was quite low, and hence difficult to determine accurately, but is estimated to be 9×10^{11} per cm^3 before irradiation and 3.4×10^{12} per cm^3 after irradiation. It is not certain whether the difference is real or is due to the large experimental uncertainty at such low signal levels.

Some of the experimental results are shown in Figs. 7–11. In Fig. 7 the decay of the excess conductivity is shown at four different injection levels. The sample is unirradiated, at a temperature of −62°C. At the lowest injection level the carrier concentration is evidently insufficient to fill all of the traps, and no initial rapid decay can be seen. At the higher injection levels the transition from rapid recombination to slow trapping is clear. Figure 8 shows the same unirradiated sample at a temperature of +27°C. At this temperature the 0.35-eV traps are relatively unimportant ($P_t/N_t=0.4$), and the trapping which is apparent following the initial exponential decay is caused by the deeper lying traps at $E_v+0.53$ eV, with a concentration of 9×10^{11} per cm^3.

Figure 9 shows the same sample following irradiation with 3.6×10^{14} electrons per cm^2 at an energy of 700 keV; the sample temperature is −75°C. In Fig. 10 the temperature is −47°C. In both of these, the pre-irradiation centers at 0.35 eV are evident, in addition to which there are approximately 1.1×10^{14} new traps per cm^3 located at $E_v+0.27$ eV. Figure 11 shows the decay at 0°C. At this temperature the 0.27-eV traps are unimportant ($p_t/N_t=1.0$), and the 0.53-eV level can be seen.

The trapping results are summarized in Table II.

CONCLUSIONS

From the radically different behavior of apparently quite similar samples of silicon it appears likely that both recombination and trapping are determined by minor impurity constituents of the crystals. This conclusion is supported by the recent spin resonance experiments in which impurity-vacancy combinations

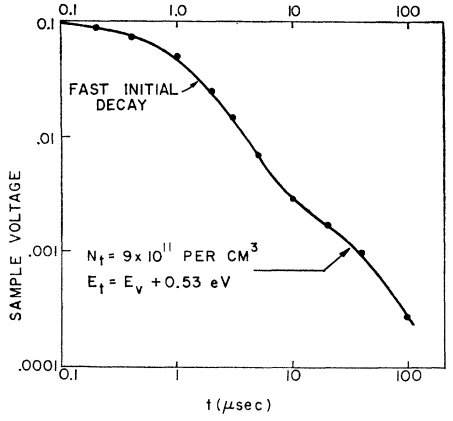

FIG. 8. Decay of excess conductivity in unirradiated sample 1160 at +27°C. At this temperature the 0.35-eV traps are ineffective and a group at 0.53 eV can be seen.

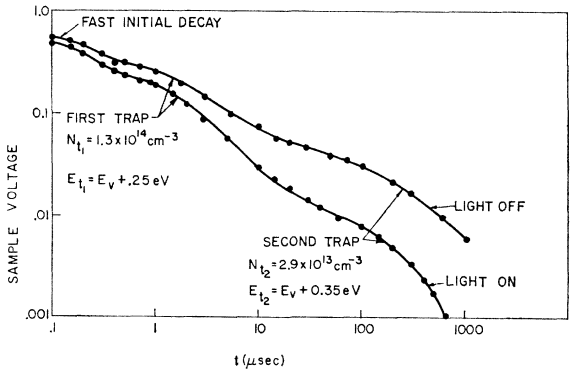

FIG. 9. Decay of excess conductivity in sample 1160 at −75°C following irradiation with 700-kev electrons (3.6×10^{14} per cm^2). In addition to the 0.35-eV traps which were present before irradiation, another level at ~0.27 eV can be seen.

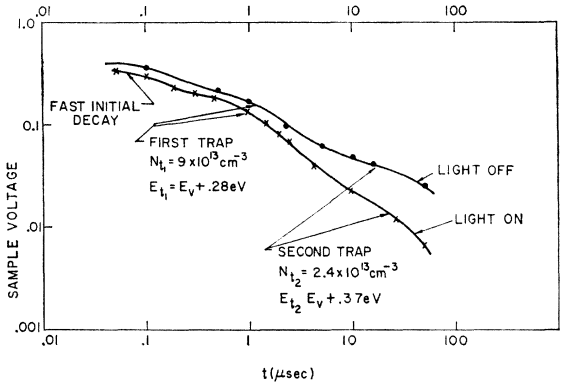

FIG. 10. Decay of excess conductivity in sample No. 1160 after irradiation. The sample temperature was −47°C.

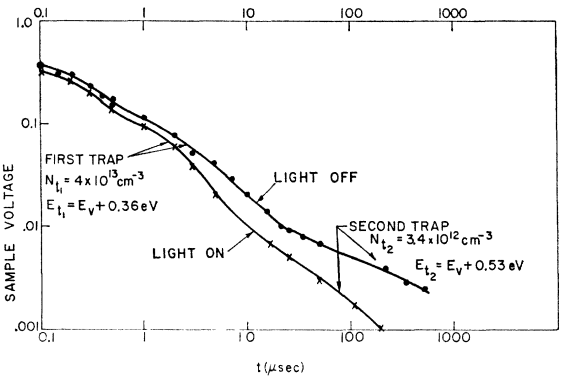

FIG. 11. Decay of excess conductivity in sample No. 1160 at 0°C. The 0.27-eV level is not effective at this temperature and the 0.53-eV level can be seen.

have been identified as radiation-introduced centers. Most of the n-type samples studied underwent recombination via a level located at $E_c - 0.18$ eV, as has been reported by Galkin, with one exception in which the dominant recombination level was at $E_v + 0.27$ eV, as reported by Wertheim. Since all of the n-type samples examined thus far were grown by conventional pulling methods, the identification of the 0.18-eV level as the A center seen by Watkins and Corbett[6] is tentative. Similar experiments on floating-zone grown n-type silicon will be reported at a later date.

Recombination in p-type silicon was found to occur via a level located at $E_v + 0.18$ eV, which is in disagreement with the conclusion of Wertheim. Although no recombination level has been reported at this position, an infrared absorption line corresponding to this level has been reported by Klein.[23]

The trapping process was examined in two samples of n-type silicon, one of high resistivity (200 Ω-cm) and the other of relatively low resistivity (3 Ω-cm). The trap concentration in the high-resistivity specimen was relatively high, $N_t \gg 1.6 \times 10^{14}$, and probably consisted of deep-lying traps, near the middle of the band gap. In the low-resistivity sample the trapping behavior was analyzed in terms of the theoretical treatment of the transition from rapid recombination to slow trapping, and the results tend to confirm the validity of the calculations and provide values for the density and energy level of three distinct trapping centers.

[23] Claude A. Klein, J. Appl. Phys. **30**, 1222 (1959).

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