where α and β are the pressure and temperature coefficients of the bandgap. It is assumed in writing this expression that E_v, the valence band-edge energy, is zero. It is now assumed that the change in the recombination center energy may be described by

$$E_r(P)=E_r(0)+\gamma P, \tag{3.3}$$

where γ is the pressure coefficient of the recombination center. Equation (3.1) becomes

$$\tau=\frac{2(2\pi m_n{}^*k)^{3/2}}{c_pN_rn_0h^3}T^{3/2}\exp\frac{[E_r(0)-E_{\text{gap}}(0,0)]}{kT}\times\exp\frac{(\gamma P-\alpha P+\beta T)}{kT}. \tag{3.4}$$

In this equation $E_r(0)-E_{\text{gap}}(0,0)$ may be inferred from the variation of lifetime with temperature (the slope of the curve in Region II of Fig. 1). The measurement of lifetime as a function of pressure then yields the pressure coefficient of the recombination-center energy.

When the recombination-center energy lies in the lower half of the bandgap, the excess carrier lifetime, in Region II, is

$$\tau=[2(2\pi m_p{}^*k)^{3/2}/c_nn_0N_rh^3]T^{3/2}\exp[(E_v-E_r)/kT], \tag{3.5a}$$

resulting in a pressure-dependent lifetime given by

$$\tau=[2(2\pi m_p{}^*k)^{3/2}/c_nn_0N_rh^3]T^{3/2}\times\exp[-E_r(0)/kT]\exp(-\gamma P/kT). \tag{3.5b}$$

In deducing this expression from (3.5a) it should be recalled that one assumes that $E_v=0$ to fix the origin of the energy scale.

The low-temperature lifetime in Region I of Figs. 1 and 2 is given by

$$\tau=1/c_pN_r,$$

regardless of the position of the recombination center. In this region, pressure experiments may reveal an effect upon the hole capture coefficient, testing the validity of the assumption of constant capture coefficients. It is assumed that the uniform hydrostatic compression does not change the density of defects.

Turning now to the situation where a recombination center is present in conjunction with a trap, it was shown in Figs. 2 and 3 that in the low-temperature region, the excess carrier lifetime is governed by the trap, and in the high-temperature region by the recombination center. The energies of these levels are obtained from the slope of the curve in the two regions. The pressure coefficients of the defect levels, which may be of different types, can be determined by performing the pressure experiments in each region, thus isolating the dominant effect.

The lifetime in the high-temperature region is (for

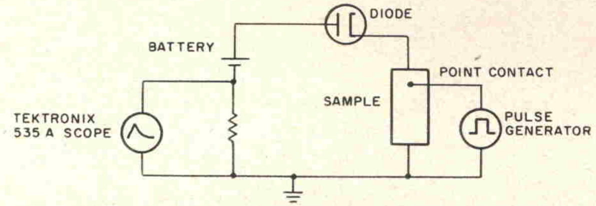

FIG. 4. Circuit used to inject excess carriers and to measure the change in conductivity.

p-type material)

$$\tau=n_{12}/c_{p2}N_2p_0=[2(2\pi m_n{}^*k)^{3/2}/c_{p2}N_2p_0h^3]T^{3/2}\times\exp[(E_r-E_c)/kT], \tag{3.6a}$$

or

$$\tau=p_{12}/c_{n2}N_2p_0=[2(2\pi m_p{}^*k)^{3/2}/c_{n2}N_2p_0h^3]T^{3/2}\times\exp(-E_r/kT), \tag{3.6b}$$

depending upon whether the recombination center is in the upper or lower half of the bandgap. The pressure-dependent expressions are obtained in the same manner as were Eqs. (3.4) and (3.5). For the case of electron trapping, the lifetime in the low-temperature region (Fig. 2) is

$$\tau=1/c_{n_1}n_{11}=[h^3T^{-3/2}/c_{n_1}2(2\pi m_n{}^*k)^{3/2}]\times\exp[(E_c-E_t)/kT],$$

which results in a pressure-dependent lifetime

$$\tau=[h^3T^{-3/2}/c_{n_1}2(2\pi m_n{}^*k)^{3/2}]\times\exp\{[E_{\text{gap}}(0,0)-E_t(0)]/kT\}\times\exp[(\alpha P-\gamma P-\beta T)/kT]. \tag{3.7}$$

The hole-trapping situation may be treated similarly.

IV. EXPERIMENTAL

Two samples were used; the first was a 14-Ω cm n-type antimony-doped germanium sample, and the other a 5-Ω cm p-type gallium-doped germanium sample. The quoted resistivities are room-temperature (300°K) values. The sample dimensions were approximately 0.80×2.90×0.65 cm. They were lapped and polished (the final polishing stage using 1-μ diamond polish) and finally etched with a standard CP4 etchant.

Excess carriers were electrically injected through a point contact, and the lifetime deduced from the time decay of the excess conductivity. The circuit used to inject the carriers and measure the change in conductivity is shown in Fig. 4.

The temperature range covered in these experiments was from −70° to 80°C. The lower-temperature measurements (from −70°C to room temperature) were performed by placing the sample in an evacuated brass can and immersing the assembly in a Dewar containing a mixture of dry ice and acetone. Measurements were made while the mixture warmed up to room tempera-

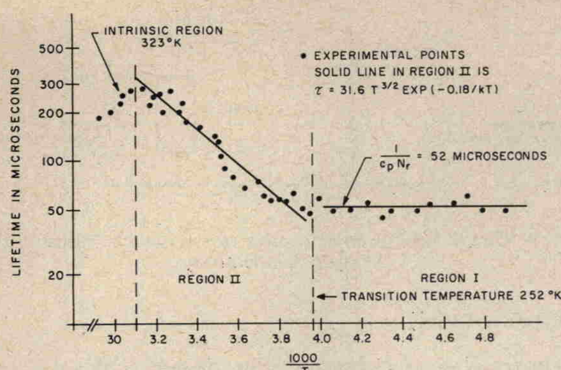

FIG. 5. Variation of excess carrier lifetime with temperature for 14-Ω cm n-type germainum.

ture. To go above room temperature, the dry-ice–acetone mixture was replaced by glycerin, into which was inserted a heater. Temperatures were measured with a Chromel–Alumel thermocouple attached to a piece of germanium of the same dimensions as the sample, and located in close proximity to it.

The pressure experiments are performed in an apparatus capable of generating a hydrostatic pressure to 10 000 kg/cm². The pressure is measured with a manganin resistance coil, which has been calibrated using a dead-weight gauge. The pressure bomb containing the sample was immersed in an oil bath provided with a heater and a temperature-regulating circuit.

V. RESULTS

The results of the measurements of lifetime versus temperature for the 14-Ω cm n-type sample are shown in Fig. 5. Comparison with Fig. 1 suggests that this sample contains a single recombination center. The position of the recombination center in the bandgap is calculated from the slope in Region II. A least-squares fit of the data leads to an equation of the form

$$\tau = 31.6T^{3/2}\exp(-0.18/kT). \qquad (5.1)$$

In this equation cgs units are used, the activation energy being expressed in electron volts. Comparison with Eqs. (3.1) and (3.5a) shows that

$$(1/c_pN_rn_0)[2(2\pi m_n{}^*k)^{3/2}/h^3] = 31.6 \text{ deg } \mu\text{sec}$$

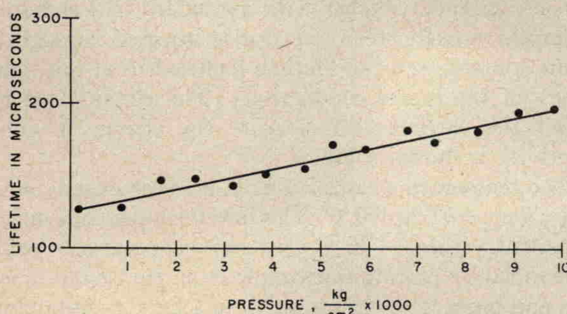

FIG. 6. Variation of excess carrier lifetime with pressure for 14-Ω cm n-type germanium at $T = 298$°K.

or

$$(1/c_nN_rn_0)[2(2\pi m_p{}^*k)^{3/2}/h^3] = 31.6 \text{ deg } \mu\text{sec},$$

depending upon the position of the recombination center. Upon substitution of the known constants,[8] these equations give

$$1/c_pN_r = 7\ \mu\text{sec} \quad \text{or} \quad 1/c_nN_r = 4\ \mu\text{sec}.$$

However, from the low-temperature lifetime in Region I, it is known that $1/c_pN_r = 52$ μsec. Since there is about an order-of-magnitude difference between $1/c_pN_r$ as given by the lifetime in Region I and the quantity $1/c_pN_r$ as calculated from the slope in Region II, it may be inferred that the quantity calculated from the slope is in fact $1/c_nN_r$. Consequently, the recombination process takes place via a level 0.18 eV above the valence band, and since $c_n > c_p$, the defect is donor like.

In view of the above result, the variation of lifetime

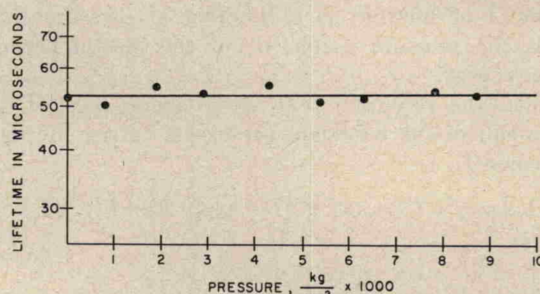

FIG. 7. Excess carrier lifetime versus pressure for n-type sample at $T = 244$°K.

with pressure for the n-type sample is described by Eq. (3.5b). Figure 6 shows the results of pressure measurements at 24.8°C, or $1000/T = 3.36$. A least-squares fit of the data to Eq. (3.5b) in the form

$$\tau = A\exp(-\gamma P/kT),$$

results in a pressure coefficient having the value

$$\gamma = -1.2\times10^{-6}\ \text{eV cm}^2\ \text{kg}^{-1}. \qquad (5.2)$$

Thus the recombination center approaches the valence band at the above rate.

A measurement of the lifetime as a function of pressure in the low-temperature region of Fig. 5 should reveal information concerning the capture coefficient c_p. Figure 7 shows the effect of pressure on the lifetime at $1000/T = 4.1$ ($T = 244$°K). As one may easily see, the lifetime is approximately constant over the pressure range, indicating that the capture coefficient c_p is practically independent of pressure.

The variation of lifetime with temperature from the gallium-doped 5-Ω cm p-type germanium is shown in Fig. 8. A comparison with Figs. 2 and 3 suggests that both a recombination center and a trap are present. At temperatures in excess of $1000/T = 4.06$ (246°K) the lifetime limiting process is dominated by the recombination center. The lifetime in this region is given through