the ratios $R(E<E_c)/R(E>E_c)$ and $\rho(E<E_c)/\rho(E>E_c)$. These are seen to be of roughly the same magnitude, i.e., the resistivity decreases on breakdown in nearly the same ratio as the carrier concentration increases. This agrees with the impact ionization picture. The discrepancies in these ratios are due probably to a mobility reduction resulting from the increased number of ionized scattering centers produced at breakdown.

Values of E_c for several specimens increased slightly as the temperature was lowered from 4° to 1°K becoming essentially constant in the region from 1° to 0.1°K. These results together with those obtained in the range 10° to 20°K, which show E_c increasing with temperature, suggest that E_c passes through a minimum in the region 5° to 10°K. This could correspond to the mobility maximum occurring when ionized impurities begin to dominate lattice vibrations in the scattering of carriers. Comparison of E_c for different samples at the same temperature also indicates that E_c varies inversely with carrier mobility in accord with the assumed breakdown mechanism.

TABLE II. Calculated mean free times and paths at 4.2°K.

Sample	Resistivity (300°K) ohm-cm	Type	Assumed m^*/m_0	τ_0 sec	l_0 cm
B42	28	n	0.11	0.7×10^{-10}	1.1×10^{-4}
B22	1.6	n(Sb)	0.11	0.3×10^{-10}	0.2×10^{-4}
B12	1.2	p(Ga)	0.30	0.6×10^{-10}	0.6×10^{-4}

Having determined experimentally the dependence of E_c upon H, (see Fig. 2) we can estimate values of the mean free time, τ, between collisions of carriers. A typical carrier may be considered to be accelerated from rest by the field E_c and to acquire sufficient energy so that its mean free path, l, can end in an ionizing collision. If the energy acquired between collisions when $H=0$ is equated to that gained with $H=H$ and if l for the two cases is assumed the same, then one may show[5] that $E_{cH}/E_{c0}=2/[1+\cos\frac{1}{2}\omega_c\tau]$, where E_{cH} and E_{c0} are the values of E_c for the transverse magnetic fields H and zero respectively and $\omega_c=eH/m^*c$. Values of τ obtained by solving this equation may be extrapolated to $H=0$ giving times τ_0 as listed in Table II. These agree well with values of τ determined from the cyclotron resonance line widths for similar material.[6] With this crude picture values of l_0 may also be estimated. Some typical values obtained by extrapolation to $H=0$ are given in Table II.

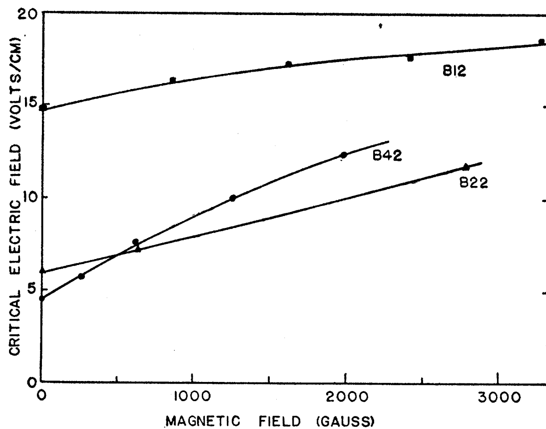

FIG. 2. Critical electric field for breakdown *vs* transverse magnetic field for three specimens at 4.2°K.

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† Based on part of a thesis to be submitted by F. J. Darnell to the Carnegie Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Electron Voltaic Study of Electron Bombardment Damage and its Thresholds in Ge and Si

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HIGH-ENERGY electron bombardment of single-crystal germanium or silicon introduces defects which induce changes in minority carrier lifetime,[1] τ, and when the damage is thousands of times greater, changes in resistivity,[2] ρ. If the semiconductor is made into an electron voltaic cell,[3] it can be shown that the short-circuit current, I_s, which is induced to flow through the cell by electron bombardment, is proportional to $\tau^{\frac{1}{2}}$. Thus observations of I_s share the sensitivity but avoid the difficulties encountered in a direct measurement of τ. The purpose of this letter is to show how the changing short circuit current, I_s, can be related to the properties of the defects, and to present experimental results for bombardment damage thresholds determined by this method.

The method depends on the existence of a reciprocal relation between τ and the number of recombination centers[4] introduced by bombardment, N_r, i.e.,

$$1/I_s^2 \propto 1/\tau \propto N_r\sigma f(E_t-E_f), \qquad (1)$$

where σ is the cross section for capture of minority carriers at the defect and $f(E_t-E_f)$ is a function of the separation between the energy level of the defects, E_t, and the Fermi energy, E_f. This function has been

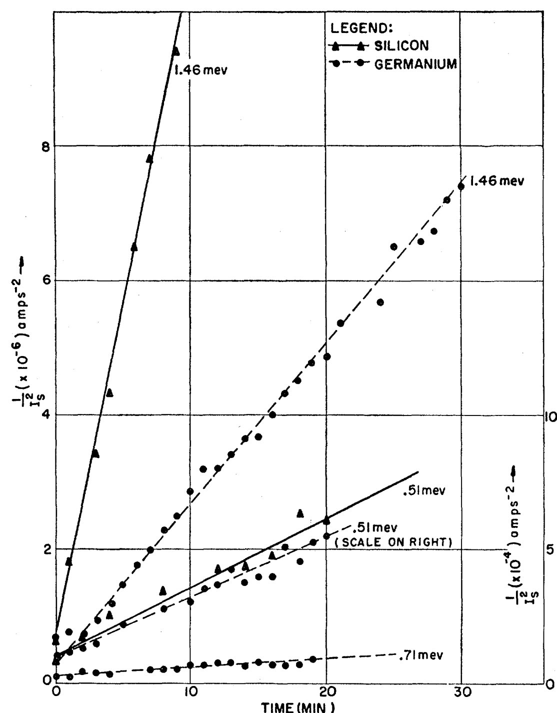

FIG. 1. Typical plots of $1/I_s^2$ *vs* bombardment time, t, for different energies of bombardment. The scale on the left should be used except where indicated.

formulated for such a recombination process by Hall[5] and Shockley and Read.[6] Furthermore, N_r is a linear function of bombardment time, t:

$$N_r \propto N_B t \Delta, \tag{2}$$

where N_B is the flux of high-energy electrons, and Δ is an average cross section for producing a defect. Note that Δ depends on V_B, the energy of the bombarding particles. Substitution of (2) into (1) results in

$$1/I_s^2 \propto N_B \sigma f(E_t - E_f) t \Delta.$$

Thus, if plots are made of $1/I_s^2$ against t, the slopes of such plots, $d(1/I_s^2)/dt \equiv \nu$, yield information about the damage such as the following:

(a) If N_B and $f(E_t - E_f)$ are constant for a group of samples bombarded by monokinetic electrons of different energies, V_B, it is possible to plot ν *vs* V_B, which is proportional to Δ *vs* V_B, and to locate $V_{B\,\min}$, the threshold for producing defects.

(b) If V_B, N_B, and Δ are constant and E_F is varied by using samples of different resistivity, it is possible to trace $f(E_t - E_F)$, and to compare it with theory.[5,6]

(c) If V_B, N_B, and Δ are constant and $E_t - E_f \gg kT$, then $f(E_t - E_f) = 1$, i.e., highly doped material, and the ratio of ν's for n- and p-type materials yields the ratio of σ_p/σ_n, i.e., of the cross section for capture of holes and of electrons by the recombination centers.

Preliminary results for (a) were obtained by using electrons produced by a Van de Graaff machine in which V_B was variable from 0.3 to 2 Mev.[7] The resistivity of the n-type germanium used in the diodes was between 0.2 and 0.4 ohm cm while that of the p-type silicon was 35 ohm cm. The samples were exposed at room temperature for about 30 minutes to bombarding currents (I_B) of 10^{-7} ampere at each energy. Typical plots of $1/I_s^2$ *vs* t for silicon and germanium are shown in Fig. 1, where V_B is the running parameter. Figure 2 shows a linear plot of ν (the slopes of lines such as those in Fig. 1) *vs* V_B for both Ge and Si. For Ge, the experiments have shown the damage is readily detectable for $V_B = 510$ kev, whereas the Si damage was still appreciable at the lowest energies available in the Van de Graaff. The threshold $V_{B\,\min}$ has been interpreted as the energy a primary particle must have in order to impart enough energy (E_L) to an atom in the crystal to displace it irreversibly from its normal position. Thus our experiments indicate that for Ge, $E_{L\,\min} \leq 23$ ev. This is lower than the 31 ev observed by Klontz who used changes in ρ at liquid air temperatures to detect the presence of the vacancies.[2]

Analysis of the results for silicon is more difficult because of the low-energy cutoff of the Van de Graaff. If, however, a linear extrapolation of the curve is made, $V_{B\,\min} \leq 280$ kev so that $E_{L\,\min} \leq 27.6$ ev. These values of $E_{L\,\min}$ should be compared to the theoretical

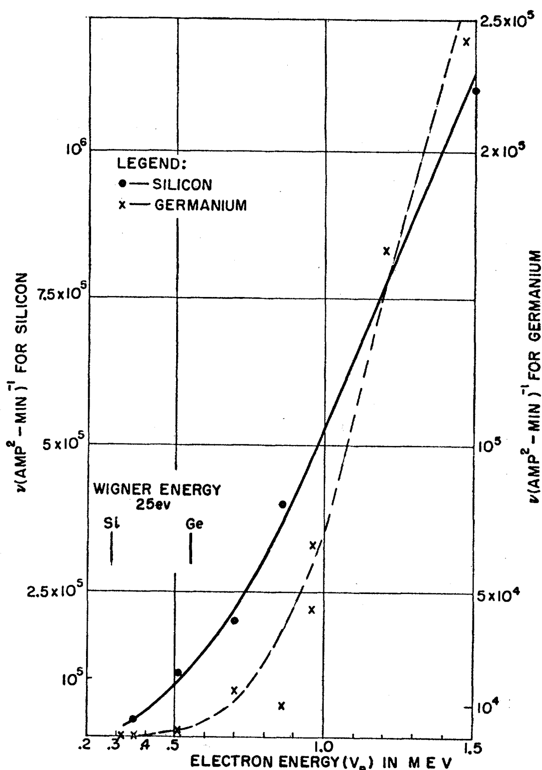

FIG. 2. The slopes, $\nu \equiv d(1/I_s^2)/dt$ of lines like those in Fig. 1, plotted *vs* the energy of the bombarding particles. The scale on the left applies to Si, that on the right to Ge.

value of this quantity, i.e., the Wigner energy of $\sim$25 ev.[8]

A more complete report of this work is in preparation, and it will include results of experiments outlined in parts (b) and (c).

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Alternative Explanation of the Waymouth-Bitter Experiments

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WAYMOUTH and Bitter[1] have reported some significant experiments on electroluminescence excited by field pulses of known time constant with certain cubical ZnS:Cu, Pb phosphors. They found that if the electroluminescent lamp was first irradiated with infrared to bring it to a consistently reproducible initial state, then there was practically no luminescence when the field was applied, but luminescence would occur when the field was removed. It was suggested[1,2] that this might be due to ionization of the activator centers, with the field holding the electrons at the positive side of the working portion of the crystal, with luminescence occurring by recombination when the field was released.

An alternative explanation is now proposed. The electrons are assumed to come from donor levels of low energy, say 0.2 ev, and hence either come from initially ionized donors or are released by low fields. These electrons will accordingly migrate to the positive side of the working portion of the crystal at low fields, too low to accelerate the electron to the 2 ev or so energies necessary for impact excitation of the activator. Thus when the field reaches its full value, there will be no electrons that it can accelerate across the working part of the crystal. The electrons will have all gone over slowly to the positive side.

When the applied field is removed, however, the maximum reverse field due to polarization of the crystal will occur at, or close to, the instant of removal of the field. The electrons will therefore begin to move back to their donors in a high field, becoming accelerated to energies high enough for excitation of any activator atoms encountered along the way. Luminescence will thus occur when the field is removed.

The foregoing is true if the applied field is removed shortly after it reaches its maximum value. The electrons will be largely untrapped and free to return to their donors. The longer the applied field is maintained, however, the more electrons will become trapped, and the traps in zinc sulfide, particularly with lead present, will be deeper than the donor levels, for example about 0.5 ev. The electrons held in these traps will not all be released with the collapse of the applied field, and hence the luminescence on removal of the applied field will be reduced.

On the reapplication of the field, however, the electrons will no longer all be free to move at low fields, but will not be released from their traps until the field reaches a higher value, high enough to then accelerate the electrons sufficiently for impact ionization. Thus, if the field is initially applied, maintained for a time, and then removed, luminescence will occur on reapplication of the field. This is in accord with the experimental results of Waymouth and Bitter.

As the time interval between removal and reapplication of the field is increased, more electrons will escape from traps before reapplication and hence the luminescence on reapplication of the field will be smaller.

Irradiation by infrared to empty the traps will also reduce the luminescence on reapplication of the field, all these results being in accord with the Waymouth-Bitter experimental findings.

The reason for the trapping of electrons when the applied field is maintained for a long enough period is presumably the fact that the dielectric material in which the phosphor particles are embedded has a definite, though extremely small, resistance, so that a small direct current will flow through the device, some electrons from the direct flow being trapped as they pass through the working portion of the crystal, and being compensated for by electrons leaving the positive side and passing into the dielectric.

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Average Crystal Potential

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IN this note, we will discuss the calculation of the average potential in an infinite nonionic crystal, and show that the Frenkel-Bethe formula[1] can be obtained from the Fourier representation of the total crystal potential. In what follows, the Fourier transform $\Gamma(\mathbf{n})$ of a function $G(\mathbf{r})$ is given by

$$\Gamma(\mathbf{n})=\mathfrak{F}(G(\mathbf{r}))=\int G(\mathbf{r})\exp(-2\pi i\mathbf{n}\cdot\mathbf{r})d\mathbf{r}/v_a, \quad (1)$$