corded at $-196°C$ with background subtracted. The two traces are not shown to the same scale.

The preliminary evidence shown indicates that more damage is retained in graphite irradiated at low temperatures. The annealing studies which are being done and irradiations at 30°C in the liquid nitrogen facility itself should prove conclusively whether appreciably more damage is retained in graphite irradiated at liquid nitrogen temperature.

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[1] The briquettes were tediously prepared from natural graphite flakes oriented by hand and compacted with a small amount of Bakelite powder as a binder by D. L. Chipman at the Massachusetts Institute of Technology. The briquettes were eventually heated to 3000°C for $1\frac{1}{2}$ hours by J. C. Bowman at the National Carbon Research Laboratories in Cleveland.

[2] For a brief historical review of still unpublished work on graphite, see F. Seitz, Phys. Today **5**, No. 6, 6 (1952).

Electrical Breakdown in Germanium at Low Temperatures*

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THE application of electric fields exceeding a few volts per cm to rather pure germanium specimens at low temperatures is known[1,2] to produce a marked drop in electrical resistivity. This breakdown effect has been attributed[3] to an increase in the concentration of mobile electrons or holes resulting from impact ionization of impurities normally neutral at these temperatures by free carriers accelerated by the necessary velocities by the applied field. Ryder, Ross, and Kleinman[4] indirectly confirmed this hypothesis by showing that their pulse observations at 20°K are consistent with a carrier concentration rise of about 30 percent.

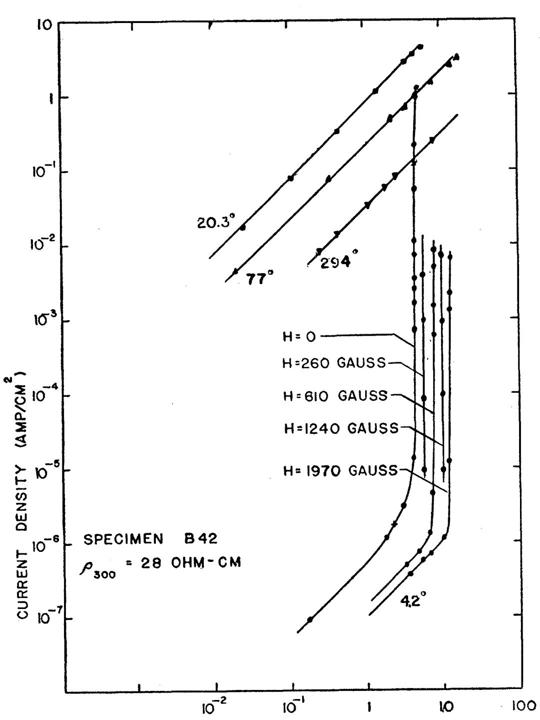

FIG. 1. Current density *vs* applied electric field for single-crystal specimen B42.

Using a constant-field technique, we have determined the current-electric field characteristics of several germanium specimens as functions of temperature and transverse magnetic field. Changes in carrier concentration associated with breakdown have been followed directly by means of the Hall effect.

A logarithmic plot of current density *vs* electric field is shown in Fig. 1 for an n-type, single-crystal specimen (resistivity $\rho_{300°K}=28$ ohm cm). Ohmic behavior is indicated on such a plot by a straight line of slope one. Only one set of helium temperature results is reproduced although similar curves have been obtained down to 0.1°K. The critical electric field, E_c, has been taken as that field for which the curve begins its nearly vertical rise rather than the poorly defined value for which deviation from ohmic behavior is first evident. E_c chosen in this way appears to be characteristic of the bulk material and not sensitive to such factors as surface treatment.

As indicated in Fig. 1, a transverse magnetic field increases the critical electric field. This effect becomes more pronounced the purer the specimen (see Fig. 2), i.e., the longer the mean free time, τ, between collisions of a carrier with impurity atoms (which do most of the scattering at the lowest temperatures). Clearly, such a field reduces the energy imparted to the carriers responsible for impact ionization by the electric field in a mean free path. Hall voltages were measured, therefore, as functions of magnetic field, H, and extrapolated to $H=0$ in order to eliminate the effect of H upon carrier concentration. Values of the Hall coefficient, R, determined in this way at points above and below E_c are given for two typical specimens in Table I, as well as the resistivities, ρ, at these points. Included also are

TABLE I. Changes in Hall coefficient and resistivity with breakdown.

Electric field volts/cm	T °K	Hall coefficient cm³/coul	Resistivity ohm-cm	$\frac{R(E<E_c)}{R(E>E_c)}$	$\frac{\rho(E<E_c)}{\rho(E>E_c)}$
Sample B42 ($\rho_{300}=28$ ohm cm n-type)					
$E<4.4$	4.18	1.6×10^{12}	1.3×10^{6}	6.3×10^{4}	3.5×10^{4}
$E>4.4$	4.18	2.6×10^{7}	37		
$E<4.8$	1.26	1.8×10^{13}	2.2×10^{6}	5.5×10^{5}	5.1×10^{4}
$E>4.8$	1.26	2.3×10^{7}	43		
Sample B22 ($\rho_{300}=1.6$ ohm cm n-type)					
$E<6.0$	4.18	6.9×10^{11}	3.2×10^{6}	2.1×10^{5}	3.6×10^{4}
$E>6.0$	4.18	3.3×10	90		

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

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}

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.

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

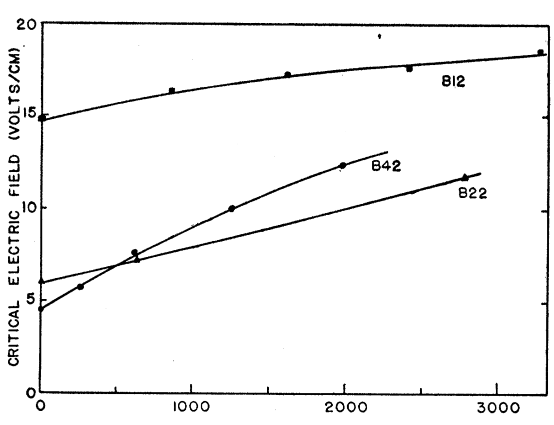

FIG. 2. Critical electric field for breakdown *vs* transverse magnetic field for three specimens at 4.2°K.

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.

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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.

[1] Estermann, Foner, and Zimmerman, Phys. Rev. **75**, 1631(A) (1949).
[2] A. N. Gerritsen, Physica **15**, 427 (1949).
[3] Sclar, Burstein, Turner, and Davisson, Phys. Rev. **91**, 215(A) (1953).
[4] Ryder, Ross, and Kleinman, Phys. Rev. **95**, 1342 (1954).
[5] A different result giving nearly the same values of τ_0 may be obtained by assuming the radial distance traversed between collisions in each case to be the same. The approximation in which thermal motion is regarded as predominant gives poorer values of τ_0.
[6] Dresselhaus, Kip, and Kittel, Phys. Rev. **92**, 827 (1953).

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