The Hall curve obtained in a sample containing lattice defects cannot be interpreted by an ordinary dissociation equation, since it shows a curvature which is usually not observed in chemically prepared samples. Quantitatively, Table II shows good agreement

TABLE II. Density of impurity atoms in germanium.

Sample number	Original number of carriers/cm³ n_0	Total flux (nvt)	Final number of carriers/cm³, n_f Calculated from cross sections	Measured by Hall effect	Difference (percent)
1—N-type	-5.25×10^{14}	4.56×10^{17}	$+8.82\times10^{15}$	$+6.16\times10^{15}$	-27
2—N-type	-2.28×10^{16}	2.54×10^{18}	$+2.92\times10^{16}$	$+3.21\times10^{16}$	$+9$
3—N-type	-5.47×10^{16}	4.37×10^{18}	$+3.48\times10^{16}$	$+5.25\times10^{16}$	$+33$
4—N-type	-1.17×10^{16}	2.54×10^{18}	$+4.03\times10^{16}$	$+5.20\times10^{16}$	$+22$
5—N-type	-1.48×10^{14}	2.54×10^{18}	$+5.05\times10^{16}$	$+4.45\times10^{16}$	-13
6—P-type	$+5.02\times10^{14}$	2.54×10^{18}	$+5.15\times10^{16}$	$+4.95\times10^{16}$	-4
7—P-type	$+4.60\times10^{14}$	8.04×10^{17}	$+6.25\times10^{16}$	$+5.22\times10^{16}$	-20
8—N-type	-4.04×10^{14}	1.06×10^{19}	$+2.15\times10^{17}$	$+1.90\times10^{16}$	-13

between the final number of carriers calculated and determined experimentally within the limits of experimental error (20 percent for flux measurements, 20 percent for cross sections, and heat treatment).

Activation cross sections for deuterons measured by E. Bleuler and D. Tendam at Purdue lead to the conclusion that deuteron bombardment should lead to N-type germanium. Similarly α-activation should also lead to N-type germanium. Activation by fast neutrons (Cd shielded samples) should lead to a larger preponderance of P-type centers (Ga) but with a much smaller cross section than slow neutron activation. Preliminary experiments are in agreement with this expectation.

We find, therefore, (a) that there is a balance between donators and acceptors, and that the Hall effect and conductivity are determined by the excess type present, (b) that there is one current carrier released per impurity center produced, (c) agreement between the activation energies of impurity centers produced chemically and by transmutations, indicating that chemical doping is a substitution process.

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Fast Neutron Bombardment Effects in Germanium

J. H. CRAWFORD, JR. AND K. LARK-HOROVITZ
Oak Ridge National Laboratories, Oak Ridge, Tennessee
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NEUTRON bombardment of germanium[1] in a nuclear reactor produces impurities by transmutation (thermal neutron capture[2]) and lattice displacements caused by high energy neutrons. The contribution of transmutation introduced impurities is in general negligibly small compared to the effect of damage by fast neutrons on carrier concentration in Ge.

The initial change in conductivity during neutron bombardment of N-type Ge is $(\sigma = e\mu_e n_e + e\mu_H n_H)$,

$$\frac{d\sigma}{d(nvt)_{\text{fast}}} = e\mu_e \frac{dn_e}{d(nvt)_{\text{fast}}} + en_e \frac{d\mu_e}{d(nvt)_{\text{fast}}}, \tag{1}$$

where e is the electronic charge, n_e is the electron concentration, μ_e is the electronic mobility and $(nvt)_{\text{fast}}$ is the integrated fast neutron flux. The contribution of the added scattering centers will be a negligible portion of the mobility until their concentration becomes comparable to the original impurity concentration. In the initial linear portion of the conductivity *vs.* bombardment curve the finite rate of annealing of neutron produced damage can be neglected, consistent with the fact that the number of acceptors

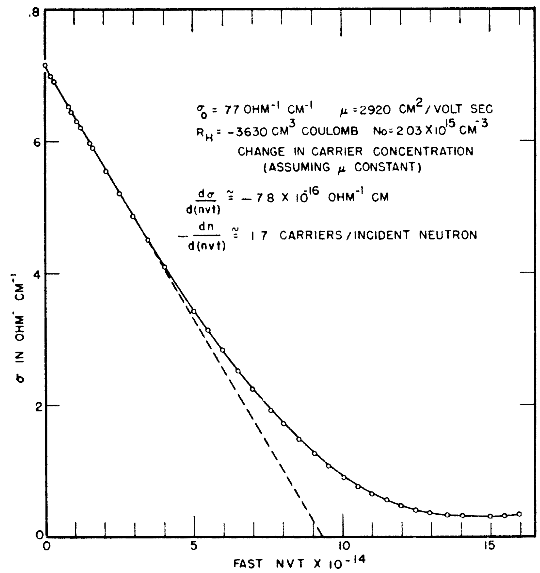

FIG. 1. Conductivity *vs.* bombardment for N-type germanium.

per incident neutron is the same at both dry ice and room temperature. Thus, initially,

$$d\sigma/d(nvt)_{\text{fast}} = -e\mu_e K, \tag{2}$$

where K is the average net number of acceptors produced per incident neutron (K is a weighted average depending on the energy spectrum of the neutron flux in the high energy range) evaluated from the initial slope of the conductivity *vs.* bombardment curve if the initial mobility is known.

Thermal equilibrium between electrons and holes when classical statistics are valid leads to [3]

$$n_e n_h = AT^3 \exp(\Delta\epsilon_g/kT) = \kappa(T), \tag{3}$$

where for Ge, $A = 5.3\times10^{32}$ and $\Delta\epsilon_g = 0.75$ ev. Thus using Eq. (3) and c as the ratio of electron to hole mobility.

$$\sigma = e\mu_h[n_e c + \kappa(T)/n_e]. \tag{4}$$

The electron concentration for minimum conductivity is then

$$n_e = (\kappa(T)/c)^{\frac{1}{2}} \tag{5}$$

and the minimum conductivity is

$$\sigma_{\min} = (2e/c)\mu_e(\kappa c)^{\frac{1}{2}} \tag{6}$$

from which μ_e at the minimum can be calculated. Any photoelectric effects induced by β- and γ-radiation would cause the calculated value to be apparently larger than the expected value. The actual value should be slightly smaller than the original value of the mobility because additional scattering centers are introduced during bombardment.

Figure 1 shows the form of the conductivity *vs.* bombardment curve for 32°C. The curves taken at dry ice temperature are quite similar. Table I summarizes the results of the analysis.

The mean value of K is 3.1 acceptors per incident neutron in agreement with the theoretical value for the number of displaced atoms in Ge obtained by G. E. Evans[4] on the basis of radiation damage theory.

The difference in slope of the bombardment curve after conversion to P-type may be due to (a) the rate of recombination of lattice defects becoming appreciable after a certain concentration is reached and, (b) only those acceptors which can be thermally ionized being effective in increasing the hole concentration. Bombardment data for an initially P-type sample gives 0.77 for the number of conducting holes produced per incident neutron. This

TABLE I. Summary of results.

Sample	Temperature of exposure °C	Initial number of carriers cm^{-3}	Initial mobility cm^2/volt sec.	Mobility at minimum cm^2/volt sec.	Number of acceptors per incident neutron cm^{-3}
1	~32	2.0×10^{15}	2920	2200	1.7
2	30	4.3×10^{14}	2010	2020	1.5
3	20	8.9×10^{14}	2600	2190	3.5
4	~32	2.8×10^{16}	2180	1440	2.6
5	~32	5.5×10^{16}	800	13,700	5.2
6	−79	——	10,000	——	4.3
7	−79	——	6070	——	3.1
8	−79	——	4530	——	3.2

is smaller than the mean value of K given above by a factor of 4. Consequently, since recombination of defects should be negligible initially, one might suspect both of these factors to be important in the general case.

The assumed thermal equilibrium between electrons and holes seems to hold reasonably well in every case but one, sample 5, which has an abnormally low initial mobility indicating an inhomogeneous distribution of impurity centers. An impurity gradient perpendicular to the direction of current would obscure the correct minimum conductivity. Also the presence of a $P-N$ barrier (the gradient parallel to current) would cause a conductivity minimum much higher than the expected value since Lark-Horovitz and co-workers[5] have shown that such a boundary is photo-sensitive to high energy radiations. In either case the calculated value of the mobility at the minimum conductivity would be spurious and high. Thus one is led to the conclusion that photoelectric effects caused by β- and γ-radiation are in general negligible in uniform samples.

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The Photon Yield of Electron-Hole Pairs in Germanium

F. S. GOUCHER
Bell Telephone Laboratories, Murray Hill, New Jersey
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IT is the purpose of this letter to report that photo-conductivity measurements, made on a single crystal of n-type germanium, indicate a yield of one electron-hole pair per photon absorbed, for wave-lengths less than the long wave limit.

A uniform electric field E is established in a long rectangular specimen of uniform cross section and conductivity, and a portion of one surface is irradiated with I photons per second of monochromatic light of known wave-length, the number being determined by a calibrated thermocouple. The number of photons I_A absorbed in the sample is calculated from the optical constants[1] by subtracting the reflection and transmission losses. Regions at the ends which are long in comparison with the respective mean ranges of positive holes are left unilluminated so that a negligible fraction of these reach the specimen terminals.

The specimen was cut from a single crystal[2] of n-type germanium having a uniform resistivity of about 5 ohm cm. Its approximate dimensions were 0.05 cm$\times$0.05 cm$\times$2.0 cm. When placed in the plane of the image of the exit slit of a monochromator all of the light could be made to fall on one face of the specimen over a length $l=1.5$ cm. The lifetime of holes, τ_p was 67×10^{-6} sec.[3] The field E with one volt across the terminals was such that the mean range of holes was approximately 0.5 mm. The light intensity was such that the field in the illuminated region was not reduced by more than one percent from the dark-current value for the largest photo-currents. Photo-currents were measured by a.c. techniques using pulsed light. The light pulser was synchronized with an auxiliary circuit such that the voltage across the terminals was maintained constant.

If the total number of electron-hole pairs produced per second is Y then the number of holes in the steady state is $Y\tau_p$. Thus the holes increase the conductance of the illuminated region of length l by an amount,[4]

$$\Delta G = Y\tau_p e(\mu_p+\mu_n)/l^2.$$

This segment is in series with the two ends of the filament and the contact resistances of the terminals, the total resistance being R_T. With the voltage V across the terminals, and if the resistance of the segment is R_l, then the change in current is $\Delta i = V\Delta G(R_l/R_T)^2 = V\Delta G(El/V)^2$ which leads to

$$Y = \Delta iV/e\tau_p E^2(\mu_p+\mu_n).$$

Values of Y were calculated using $\mu_p=1700$ and $\mu_n=3600$ cm^2/volt-sec.[5]

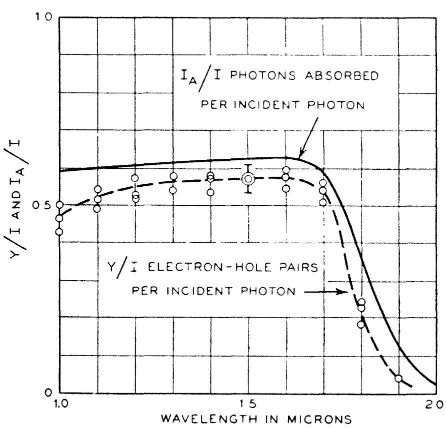

FIG. 1. The ratios I_A/I and Y/I *vs.* wave-length.

The experimental results are summarized in Fig. 1 in which we have plotted I_A/I and Y/I as functions of wave-length from 1.0μ to 2.0μ, the latter being just below the long wave limit of photo-sensitivity. Within the limits of experimental error, which we cannot claim to be better than 10 percent, and over the major portion of this range of wave-lengths, the two characteristics may be considered coincident.

Thus it appears that each photon absorbed produces one hole-electron pair. The apparent divergence near the long wave limit may reasonably be ascribed to the increase in experimental error with a photo-current which becomes vanishingly small in this region. On the other hand, the divergence for wave-lengths less than 1.2μ may be accounted for by recombination through the concentration of carriers generated in a region which is less than 10^{-4} cm in thickness.

In addition to those already mentioned thanks are due to W. Shockley for suggesting this experiment, to J. Bardeen and W. van Roosbroeck for valuable help in its theoretical aspects, and to H. R. Moore for furnishing the electronic measuring equipment.

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[5] These are drift mobilities measured by J. R. Haynes.