Some Properties of High Resistivity P-Type Germanium

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A summary is given of some characteristics of single crystals of high resistivity, homogeneous, *P*-type germanium. The Hall effect, resistivity, and rectification characteristics of this material were studied with respect to changes of temperature and magnetic field. A very high mobility figure at 25°C (~2730 cm^2/volt-sec. for a field of 3600 gauss) was obtained by calculating $10^8R/\rho$. An effect of type of contact at the Hall probes on Hall effect measurements is pointed out. The resistivity of the material was 18.8 ohm-cm average, the Hall coefficient 5.14×10^{-4} volt-cm/amp.-gauss. The magneto-resistance of this germanium amounted to about 22 percent in a field of 13,750 gauss. The Hall coefficient decreased by about 22 percent between 3600 and 13,750 gauss. The band separation for one sample was 0.82 volts from Hall effect data, 0.75 from the resistivity. The mobility was found to obey a $T^{-2.0}$ law in the temperature range 78 to 400°K. This *P*-type material exhibited only slight rectification.

I. INTRODUCTION

THE purpose of the present paper is to present results of an experimental study of several single crystals of high resistivity *P*-type germanium. We shall also discuss several points at which these results appear to bear upon existing theory. The results are a more complete report of work partially reported earlier.[1]

The work dealt mainly with measurements of resistivity, Hall coefficient, and rectification characteristics. Magnetic field strength and temperature were used as independent variables. Results will be given following a discussion of experimental methods.

II. PREPARATION OF THE GERMANIUM

The germanium used in the present work was obtained during the course of a study of the preparation of germanium for high voltage diodes.

Germanium oxide (GeO_2) obtained from the Eagle-Pitcher Company (Lot AC 409) was reduced by Mr. F. C. Kelley for 16 hr. at 650°C in a hydrogen furnace. The reduced powder was then heated to 900°C for 3 hr. and cooled in the furnace.

The reduced powder was melted at a pressure that was less than 10^{-3} mm during the entire melting operation. A graphite crucible previously fired four hours at 1700°C in an Arsem furnace was used for this melting. The ingot was cooled to room temperature within several hours. No attempt was made at directional cooling. Annealing for 2 hr. at 650°C was carried out. Subsequent annealing at 500°C did not change the characteristics appreciably. This ingot was designated H114.

It was observed upon cutting it into slices that the entire ingot appeared to be a single crystal. Subsequent microscopic examination of most of the cut surfaces was made, and the conclusion was drawn that the ingot was a single crystal. The surfaces tested in this way were etched both by electrolytic etching (10 percent KOH) and by chemical etching (conc. HF mixed with conc. HNO_3 in the proportion 2:1). Subsequent tests were also made on several plates of this germanium by the back-reflection x-ray technique. These tests also confirmed the conclusion of the single crystalline nature of the crystals.

Some tests were made on several of the sample plates to determine the homogeneity of the material. A thermoelectric test utilizing a hot platinum point and a galvanometer indicated uniform *P*-type character over all the surfaces tested. Tests were also made of the uniformity of the resistivity. A plot of this characteristic for sample 103 is shown in Fig. 1. It is seen that the potential follows a linear relationship over a distance of about 1 cm. This behavior can be contrasted to the extremely non-linear potential characteristic often

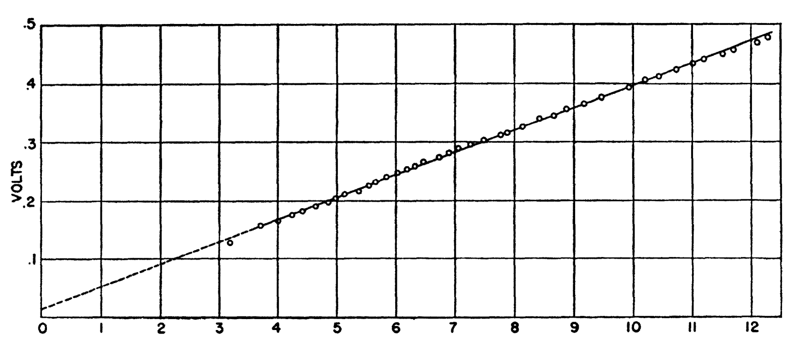

FIG. 1. Potential distribution along the length of a single crystal of high resistivity *P*-type germanium. (No. 103, 25°C.)

[1] W. C. Dunlap and E. F. Hennelly, Phys. Rev. 74, 976 (1948).

found in other samples of high resistivity germanium. Failure of the potential line to pass through the origin (the location of the fixed probe) is probably due to non-uniformity of the current flow pattern near the electrode.

III. EXPERIMENTAL METHODS

A simplified diagram of the connections to a sample for measurement of the conduction properties is shown in Fig. 2. All significant potential measurements were made with potentiometer methods.

Preliminary measurements were made on several samples from ingot H114 by simply clamping the sample in a holder, using stainless steel points for the Hall and probe contacts. Results of these measurements are given in Table I together with some results on N-type material for comparison. Subsequent tests were made with silver-plated and tin-soldered contacts. The latter methods were used for the data in Fig. 3. A somewhat lower value of mobility results from the use of contacts having an appreciable area of contact. This effect may simply involve shorting some of the primary current through the contact. Thus we consider the higher values, obtained with pressure point contact, more reliable than those obtained with tin-soldered or plated contacts. A list of conduction properties, their units and significance, follows.

(1) Resistivity, ρ, is measured in ohm cm

$$\rho = VA/Il,$$

where V is the voltage drop, I the current in amperes, A the cross section along which current flows, and l is the distance between probes.

(2) *Hall coefficient*, R, is measured in terms of the voltage produced across the Hall probes, per unit magnetic field and current. $R = Vt/HI$, where V is the Hall voltage, t the thickness of the plate along the magnetic field, H the magnetic field in gauss, I the current through the sample in amperes. R can be measured in volt-cm/amp. gauss, or in e.m.u. To obtain a result in the latter unit, we multiply by 10^9 the result obtained in the former. In this paper we use R in volt-cm/amp.-gauss. The magnetic field in the present

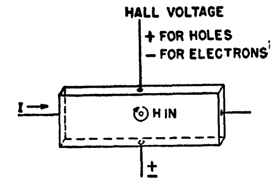

Fig. 2. Schematic diagram of electrode arrangement on samples of germanium for measurement of conduction properties. All measurements are made with potentiometer methods.

work was obtained with a calibrated electromagnet. The calibration of the magnetic field was carried out by flip-coil-fluxmeter methods. The magnetic field is considered known with an error of less than two percent. A field strength of 3600 gauss was used for most of the measurements. Results generally are averaged with respect to reversal of the magnetic field, and were also checked for dependence upon direction of current flow through the samples. The latter effect was not found in the present work.

(3) The "mobility figure," μ is determined, according to the free electron theory, by the ratio R/ρ. (We neglect here the factor $8/3\pi$ that R/ρ must be multiplied by, according to this theory, to give the true mobility.) The mobility is physically the drift velocity attained by an electron in unit electric field. In practical units,

$$\mu = (R/\rho)\times 10^8 (\text{cm}^2/\text{volt-sec.})$$

(4) The *magneto-resistance*, namely the change in resistivity in a magnetic field is denoted simply as $(100\Delta\rho)/\rho_0$, the percentage change in resistivity measured with respect to the zero-field resistivity.[2] The magneto-resistance appears to be related to the distribution of electron velocities in the germanium. That is, when equilibrium has been established in the magnetic field the Hall field tends to exactly offset the deflecting force of the magnetic field, but only for electrons of the average velocity. These electrons continue through the sample with unchanged paths. Electrons of higher and lower velocity than the average will be either overcompensated for or undercompensated for by the Hall field, and they will acquire new, curved trajectories that lead to a higher resistance. This picture gives a simple explanation of the nature of magneto-resistance.

(5) By measurement of the temperature dependence of the Hall coefficient one can get an approximate value

Table I. Room temperature conduction properties for a number of germanium samples prepared by melting in vacuum (10^{-3} mm Hg). Temperature effects were studied only for 104. The band separation was 0.75 ev, and the intercept N_0 from the Hall effect $6\times 10^{21}/\text{cm}^3$. The mobility varied roughly as $T^{-2.0}$. The magneto-resistance varied as $H^{+1.56}$ at room temperature, and as $H^{0.75}$ at $-195°$C.

	25°C							−195°C
Sample No.	48	93	94	95	103	104	105	104
Melt No.	H90	H107	H107	H107	H114	H114	H114	H114
Type of conduction	N	N	N	N	P	P	P	P
Resistivity ohm-cm	2.2	8.9	9.9	8.5	19.9	19.1	17.4	2.35
Hall coeff. ($\times 10^5$)(volt-cm/amp.-gauss)	8.4	21.2	29.4	20.4	53.5	51.6	49.0	42.0
Mobility figure ($\times 10^{-3}$)(cm^2/volt-sec.)	3.8	2.4	3.0	2.4	2.7	2.7	2.8	18.0
$\Delta\rho/\rho_0$ at 13,750 g ($\times 100$)	17.1	13.0	15.7	14.1	22.5	22.0	22.0	85
$\Delta R/R$ ($\times 100$)	6.3	5.7	5.6	—	23	24	21	4

[2] W. C. Dunlap, Phys. Rev. **71**, 471A (1947).

for the band separation $\Delta\epsilon$. For the one sample studied in the present work, $\Delta\epsilon=0.82$ ev. One can also obtain the quantity N_0 in the relation:[3]

$$N=N_0e-(\Delta\epsilon/2kT).$$

According to the free electron theory, for carriers of only one sign the electron density $N=1/Re$ (e.m.u.) so that $1/N_0$ is determined by the intercept of R on the $1/T$ axis, whereas $\Delta\epsilon$ is determined by the slope of the curve $\log R$ plotted against $1/T$. For one sample (104) N_0 was found to be $6\times10^{21}/\text{cm}^3$.

For the temperature variation of the resistivity ρ, one can also get a value for $\Delta\epsilon$, assuming $\rho=\rho_0\exp(\Delta\epsilon/2kT)$. For two separate runs on 104, the values of $\Delta\epsilon$ obtained by this method were 0.740 and 0.755 ev. These values agree well with the value of 0.75 previously given by Lark-Horovitz *et al.*[4] The difference between the Hall effect value and the resistivity value may be accounted for by the fact that the theory of intrinsic conduction as stated by Fröhlich gives the following temperature dependence for R:

$$N\ \alpha 1/R=\text{const}\ (T)^{\frac{3}{2}}\exp(-\Delta\epsilon/2kT)$$

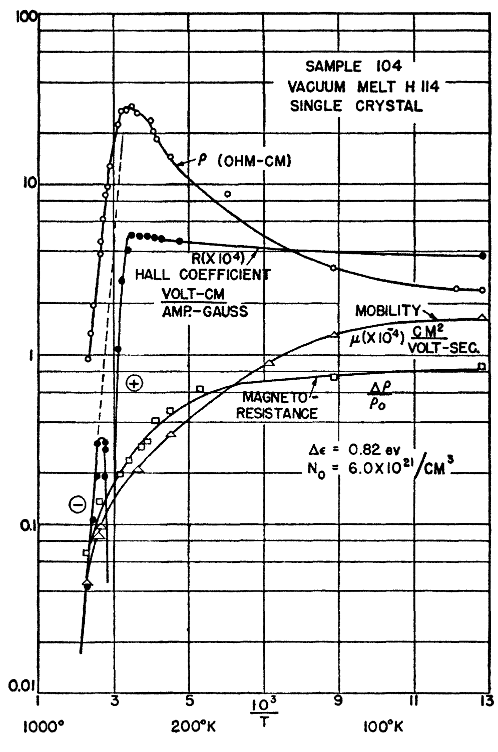

FIG. 3. Summary of conduction properties of sample 104, a single crystal of high resistivity P-type germanium. The crystal reversed from P- to N-type at 70°C. Tin-soldered contacts were used for this set of measurements.

[3] The free electron theory for semi-conductors is summarized in Chapter IV of Seitz' "Modern Theory of Solids" (New York, McGraw-Hill, 1939), and in Fröhlich's "Electron Theory of Metals" (Berlin, Springer, 1936).

[4] Lark-Horovitz, Middleton, Miller, and Walerstein, Phys. Rev. **69**, 258(A) (1946).

and

$$1/\rho=Ne\mu=\text{const}\exp(-\Delta\epsilon/2kT),$$

if we use the relation that μ varies as $T^{-\frac{3}{2}}$ in the region where lattice vibrations determine the mobility. Thus the Hall coefficient is expected to vary more rapidly in the intrinsic range than the resistivity, and thus is expected to lead to a larger value of band separation than the resistivity value.

(6) The variation of the Hall coefficient with magnetic field was found for the samples studied. Measurements were made at 3600 and 13,750 gauss, and the percentage difference between these values, relative to the low field value, was tabulated. This is the quantity $(\Delta R/R)$ referred to in Table I.

IV. RESULTS

In Table I is shown a summary of the conduction properties of several samples of high resistivity germanium, including both P- and N-types. The samples from melt H114 and sample 48 were single crystals. The reproducibility of the results on samples from H114 is seen to be good. The average resistivity was 18.8 ohm-cm, the average Hall coefficient 5.14×10^{-4} volt-cm/amp.-gauss and the average $R/\rho=2730$ cm²/volt-sec. In other data presented in the paper these properties may be given somewhat different values because of slightly different electrode arrangements, such as may be required for obtaining results as a function of temperature. It is found, for example, that pressure contacts are too high in resistance at low temperatures (<-100°C) to yield reliable results.

It has been found during the course of a study of Hall effect and magneto-resistance in germanium, that measurements with pressure contacts lead to higher values of Hall effect and mobility than measurements with broad contacts such as those obtained by silver-plating and soldering. It has further been found that reduction of the area of the plated or soldered contact increases the apparent mobility of the sample almost to the value obtained with point contacts.

These results lead us to believe that the values of mobility are correct when obtained with pressure point-contacts. The effect of contact area is to reduce the value of the Hall coefficient by as much as a factor of three, when contacts are increased in diameter to 70 mils, but there is little effect on the resistivity, as long as the contacts are not greater than 25 mils in diameter. (See Fig. 5.)

The value of the mobility figure, 2730 cm²/volt-sec. (or 2330, if the factor $8/3\pi$ is included) obtained in the present work is much greater than that obtained by other workers. Pearson[5] has recently given a value of 1700 cm²/volt-sec. for the mobility of holes in P-type single crystals of germanium. Earlier estimates of the mobility of holes, given by Lark-Horovitz *et al.*[4] were in the neighborhood of 1000.

[5] G. L. Pearson, Phys. Rev. **76**, 179(A) (1949).

We should perhaps also mention here that our R/ρ mobility values for N-type germanium obtained with pressure contacts range up to $\sim$3800 cm^2/volt-sec. This value is, like the values obtained for P-type germanium, considerably higher than that reported by others.[4, 5]

From Table I it is seen that the Hall coefficient varies with magnetic field. The quantity $\Delta R/R$ between 3600 and 13,750 gauss is about 22 percent for the high resistivity P-type material, but only about six percent for the lower resistivity N-type samples. In general, both the magneto-resistance and the variation of the Hall effect with magnetic field for germanium seem to increase with increasing resistivity of the sample, and to be larger for P-type than N-type material of comparable resistivity. The value of 2730 for μ was obtained at 3600 gauss. If we use the Hall coefficient at 1000 gauss, we obtain an even higher value of mobility figure, about 3000 cm^2/volt-sec.

We present in Fig. 3 a summary of the temperature-dependence of the conduction properties of a single crystal of P-type germanium. At room temperature the mobility figure for this ample, with tin-soldered lead connections, was only 2100 cm^2/volt-sec., in distinction to the higher value obtained with pressure contacts. The resistivity value is also somewhat different because of the different electrode arrangement. The mobility figure reached the very high value of about 18,000 cm^2/volt-sec. at liquid air temperature for this crystal. This effect appeared from the large drop in resistivity between room temperature and liquid air temperature, coupled with a nearly constant value of Hall coefficient. This drop in ρ is the largest yet observed by the author in any sample of germanium and appears to confirm the existence of high purity and good homogeneity in this germanium.

It will be noticed that the Hall coefficient reverses from positive to negative at about $10^3/T=2.9$. The temperature of reversal was 70°C. At this temperature the effectively N-type intrinsic conduction overbalances the P-type impurity conduction.

The forbidden energy gap $\Delta\epsilon$ was found from the slope of the "intrinsic line" of the resistivity to be 0.75 ev. The value of N_0 was found to be 6.0×10^{21}/cm^3. By extrapolating the "intrinsic line" for ρ to room temperature (25°C) one finds also the so-called intrinsic resistivity at room temperature. Extrapolation for two independent runs on 104 yielded results of 71 and 84 ohm-cm, for the intrinsic resistivity. The average value is about 78 ohm-cm, but may be in error by 10 to 15 percent because of the tin-soldered resistivity probes. The magneto-resistance was found to be very large in this high resistance P-type material. At liquid air temperature the magneto-resistance $\Delta\rho/\rho_0$ amounted to about 85 percent, at 13,750 gauss, whereas at room temperature the effect amounted to about 22 percent.

Figure 4 shows the variation of resistivity with magnetic field. At 25°C the variation, for small fields was approximately according to the relation $\Delta\rho/\rho_0 = C_1H^{1.56}$, at -196°C the relation was $\Delta\rho/\rho_0 = C_2H^{0.75}$. The above relation at 25°C applies only to about 10 kilogauss.

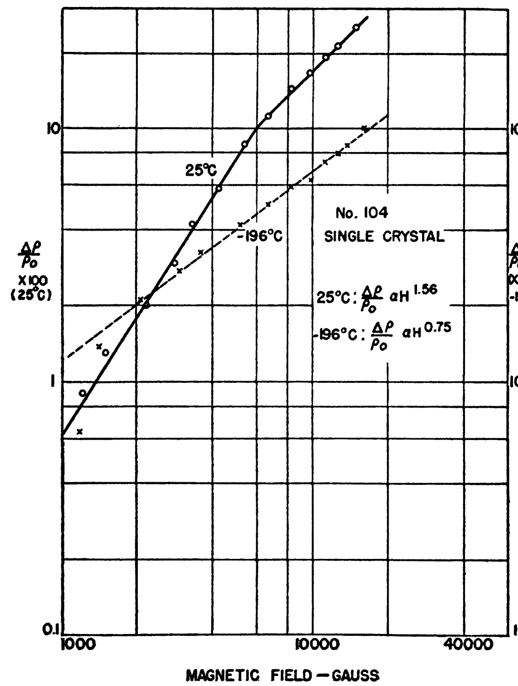

FIG. 4. Variation of magneto-resistance with magnetic field for a single crystal of P-type germanium.

Figure 5 shows the variation of the Hall coefficient for sample 104 as a function of magnetic field strength. The drop in the Hall coefficient between 1000 and 15,000 gauss amounted to about 38 percent of the value at 1000 gauss. On the other hand, at liquid air temperatures, the Hall coefficient was practically constant with varying magnetic field.

Because of the apparently high degree of purity and homogeneity in the sample tested, it was thought that the temperature dependence of the mobility figure $10^8R/\rho$ might be of significance. A plot of this characteristic for several high resistivity P-type samples, together with one of $\Delta\rho/\rho_0$ at 13,750 gauss, is shown on a log-log scale in Fig. 6. The mobility for sample 104 follows a law $\mu = CT^{-2.0}$ fairly accurately between 120 and 400°K, but appears to depart from this rule at higher and lower temperatures. For one other P-type sample, 43 ohm cm, the exponent was -2.3. It is of interest to note the large mobility of holes, 18,000, at -196°C. It is to be expected that, because of impurity scattering,[6] the mobility will reach a maximum somewhat below the temperature of liquid nitrogen. The magneto-resistance of the sample did not obey a power law relationship, and varies more slowly with temperature than the mobility at low temperature, but more

[6] E. Conwell and V. F. Weisskopf, Phys. Rev. **77**, 388 (1950).

rapidly at high temperatures. A more detailed report will soon be given of the relation of these results to the theory of electrons.

The theory of conductivity predicts that if scattering is a result of lattice vibrations, the mobility should vary as $T^{-1.5}$. Our results indicate that this law does not adequately describe the behavior of positive holes in germanium. Measurements on single crystals of N-type germanium indicate better approximation to the $T^{-\frac{3}{2}}$ law for the temperature dependence of the mobility. Investigation is being made of the possibility that the large exponent found is a result of the large variation of Hall coefficient with magnetic field.

Point-plane rectifiers were made from the P-type germanium under discussion here. The surface of the germanium was etched in $2HF-HNO_3$ for about 15 sec. Very little rectification was observed, and the contact resistance was quite high, several thousand ohms. Various whisker materials have been used for this study, including Pt-10 percent Ru, brass, stainless steel, dural, and aluminum. The highest rectification obtained was from aluminum, with a rectification ratio at 5 volts of about 6. One expects that a metal such as aluminum, having a low work function, should give the best rectification possible.[7] Recently Pfann and Scaff[8] have shown that a.c. pulsing of the contact at the P-type germanium surface can be made to yield better P-type rectification.

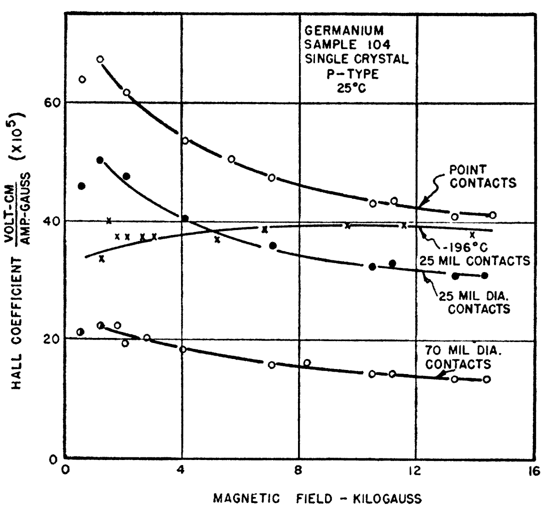

FIG. 5. Variation of Hall coefficient of a single crystal of P-type germanium. The 25° curve differs in absolute value from the results in Fig. 3, because of a somewhat different contact connection. Such differences, however, move the curve vertically without altering its shape.

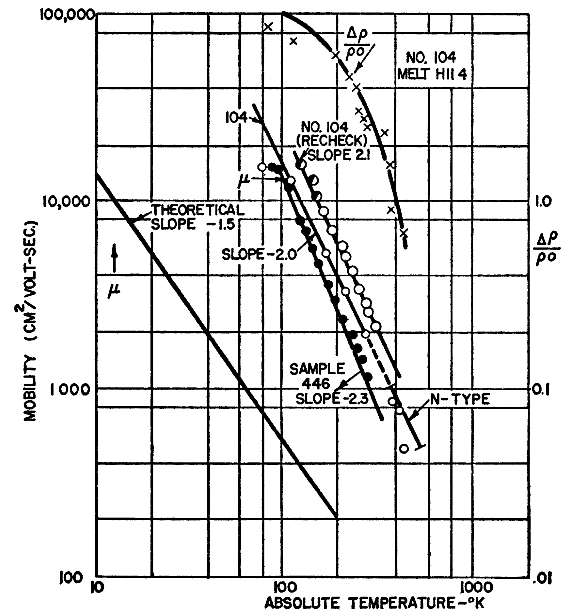

FIG. 6. Mobility figure (R/ρ) for single crystal (sample 104) as a function of temperature. The mobility follows a $T^{-2.0}$ relation quite closely over the range 78 to 300°K. Additional curves shown include a recheck of 104 with different electrodes, and results on another high resistivity P-type sample, 446. Also shown is the line representing the theoretical slope of -1.5. A curve showing $\Delta\rho/\rho_0$, the magneto-resistance, as a function of temperature, is also given.

V. DISCUSSION

From the results obtained we draw the following conclusions: (1) The mobility figure of holes is, according to the present Hall effect data and the theory of electrons, in the neighborhood of 3000 cm²/volt-sec. or higher. Similarly it appears that the mobility figure of electrons is in the region of 4000 cm²/volt-sec. or higher. (2) High resistivity P-type germanium has a large dependence of Hall coefficient and resistivity on magnetic field strength. (3) High resistivity P-type germanium of the type discussed here has a dependence of mobility on temperature considerably greater than does N-type germanium, and a dependence considerably greater than that predicted by the $T^{\frac{3}{2}}$ law for lattice scattering. These measurements, of course, involve use of a given magnetic field for all temperatures, and it is possible that the effects involved in (2) and (3) are related.

A factor that has not been introduced as yet into discussion of the present results is the influence of the intrinsic conductivity on the characteristics. P-type germanium of 20 ohm-cm resistivity at room temperature possesses an appreciable number of carriers thermally excited from the filled band, apart from the "impurity" carriers excited from the impurity levels. Some of these carriers are electrons and some are holes. The actual density of holes and electrons is determined by a law similar to the law of mass action for chemical equilibrium of dilute solutions;[9] $N_e N_h = \text{const.} = 1.93 \times 10^{26}$ for 25°C. The value 1.93×10^{26} is obtained from the assumption that $\mu_e = 4500$, $\mu_h = 3000$, intrinsic resistivity at 25°C = 60 ohm cm. Because of the effec-

[7] W. E. Meyerhof, Phys. Rev. **71**, 727 (1947).
[8] W. Pfann and J. H. Scaff, Phys. Rev. **76**, 459(A) (1949).
[9] G. L. Pearson and J. Bardeen, Phys. Rev. **75**, 865 (1949).

tively opposite charges on electrons and holes, the measured mobility is less than the true hole mobility. That is, the electrons present tend to counterbalance the net P-type Hall effect and thus reduce the mobility value as measured.

In Fig. 7 we show a curve for the apparent mobility* of high resistivity germanium as a function of resistivity. For one set of calculations we assume a hole mobility figure of 3000, and an electron mobility figure of 4500. For the other, we assume $\mu_e = 2600$, $\mu_n = 1700$, as found by Pearson. The theory of mixed conduction by holes and electrons can be expressed in the following form:**

$$R = -\frac{1}{e}\frac{N_e\mu_e^2 - N_h\mu_h^2}{(N_e\mu_e + N_h\mu_h)^2}\times 10^{-8} \quad (e \text{ in coulombs}).$$

This can be expressed in the form

$$R = -\frac{1}{e}\frac{-N_eC^2 + N_h}{(N_eC + N_h)^2}\times 10^{-8},$$

where C is the ratio μ_e/μ_h, here assumed to be 1.5.

Also the conductivity σ is given by

$$\sigma = e(N_e\mu_e + N_h\mu_h) = eN_h\mu_h[(N_e/N_h)C + 1] \text{ ohm}^{-1}\text{-cm}^{-1}.$$

Hence the apparent mobility $\mu = R/\rho \times 10^8$ is given by

$$\mu/\mu_h = [-(N_e/N_h)C^2 + 1]/[(N_e/N_h)C + 1].$$

From these equations one can get a curve for $\mu = f(\rho)$.

The curve representing the "apparent mobility" $\mu = (10^8 R/\rho)$ as a function of resistivity is an ellipse with the following equation,

$$\frac{[\frac{1}{2}(\mu_e - \mu_h) + \mu]^2}{(\mu_e + \mu_h)^2/4} + \frac{\rho^2}{\left(\frac{1}{4e^2\mu_h\mu_e K(T)}\right)} = 1,$$

where μ_e is electron mobility, μ_h is hole mobility, μ = apparent mobility $= 10^8 R/\rho$, $K(T) = N_h N_e$, a function of temperature.

The ellipse has the following properties when we assume $\mu_e = 4500$ cm²/volt-sec., $\mu_h = 3000$, $K(T) = 1.93 \times 10^{26}$ at 25°C; the center is at $(0, -750)$; the semimajor axis is 61.7 ohm-cm, the semiminor axis 3750 cm²/volt-sec. The intercept on the ρ-axis is 60. This is the resistivity of zero Hall effect, assuming homogeneity throughout the sample. In Fig. 7 is shown part of the ellipse, corresponding to P-type samples.

It is of interest in connection with the present work, that at 20 ohm-cm P-type germanium is already influenced by the intrinsic conductivity to the extent that the apparent mobility should be raised by about three percent to obtain the true hole mobility figure. At 40 ohm-cm the apparent mobility should be increased by 44 percent. Preliminary experiments were made on especially purified P-type samples kindly furnished by R. N. Hall. Also shown in Fig. 7 are results of mobility measurements on these samples (crosses). Although considerable scatter is found, several values were as high as expected from the author's presumed values for the electron and hole mobility and for the intrinsic resistivity.

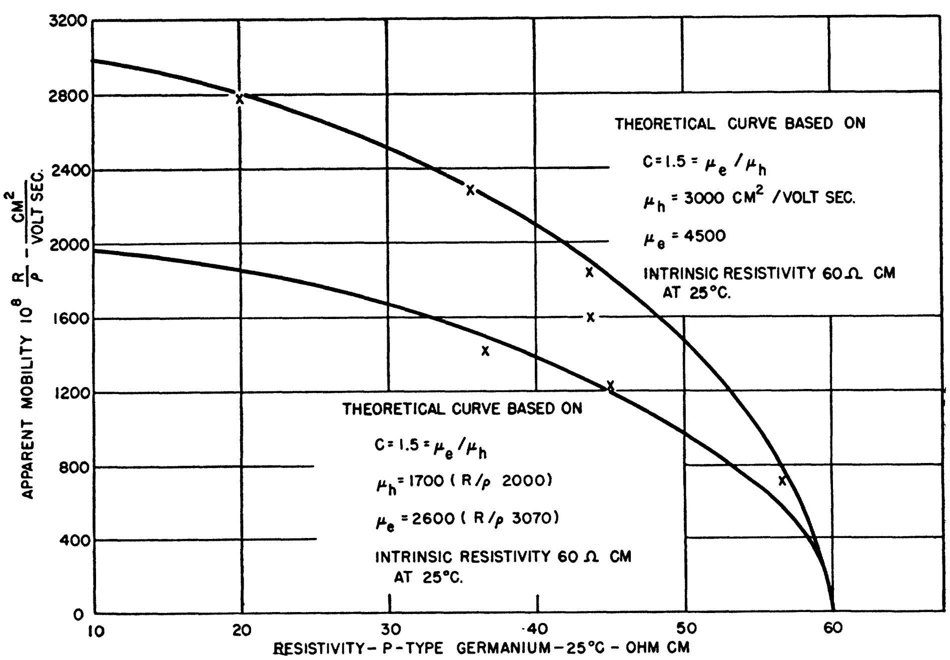

FIG. 7. Comparison between experimental values of mobility for high resistivity P-type samples with theoretical curves based on two sets of assumptions regarding mobility of holes and electrons. The crosses represent measured mobilities of P-type crystals ($10^8R/\rho$). The upper curve is based on mobilities indicated by present results. The lower is based on mobility values of Pearson.

* In what follows we use the term "apparent mobility" to mean the mobility figure $10^8R/\rho$ for a sample in which both hole and electron conduction must be considered.

** Again we neglect the factor $8/3\pi$ often included in this equation.

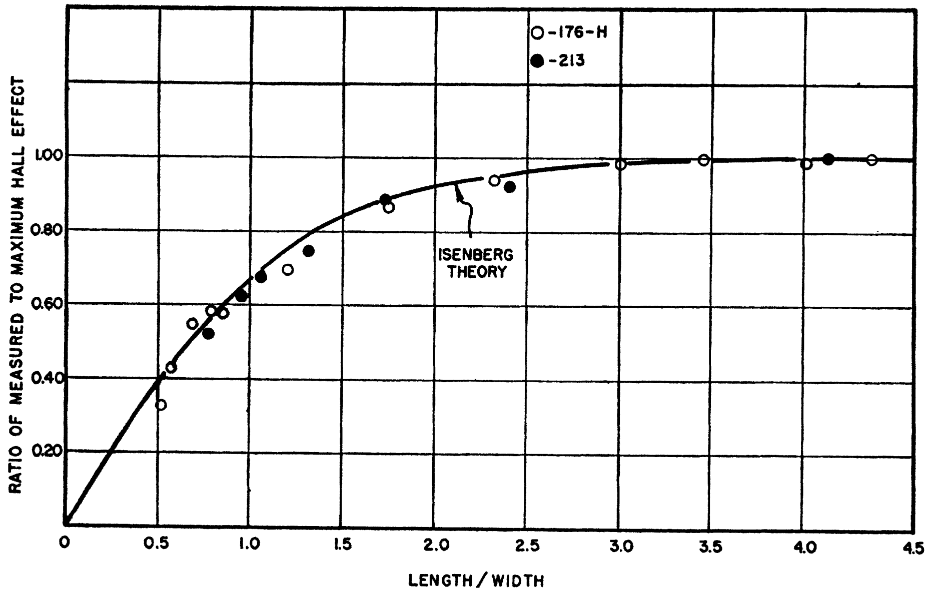

FIG. 8. Comparison of Isenberg's theory for end-effect in Hall effect measurements with experimental values obtained with P-type germanium samples. The samples were approximately square and were progressively cut away until the sample was long and narrow. The experimental points are seen to fit the theoretical curve quite well.

An effect that is sometimes encountered in working with small samples is the so-called end-effect on Hall coefficient measurements. This effect has been studied theoretically by Isenberg.[10] Although the samples studied in the present work were long enough so that no corrections were needed, within the accuracy of these measurements, it may be of interest to present some data taken on P-type samples to study this effect. Figure 8 shows these results. The experimental points for two P-type samples are seen to be well fitted by the theoretical curve.

The recent work of Haynes[11] on the drift mobility of holes and electrons is of considerable interest in the present discussion. The drift method involves measuring directly the velocity of a pulse of holes injected into N-type germanium, or conversely, the velocity of a pulse of electrons injected into P-type germanium. The most recent values of Haynes for the mobilities are:

$$\mu_e = 3500 \text{ cm}^2/\text{volt-sec.}$$
$$\mu_h = 1700 \text{ cm}^2/\text{volt-sec.}$$

It appears that the value for electrons is in good agreement to the value assigned by the author[12] on the basis of a large number of samples of both N- and P-type germanium; namely, $\mu = R/\rho \times 10^8 = 4000$ for electrons. There remains a considerable discrepancy between Haynes' value of 1700 for the hole mobility and the present author's results of 3000 cm^2/volt-sec. Also, although Haynes' results for holes agree well with the value of Pearson, obtained by the Hall effect, Haynes' value of 3500 for electrons still remains considerably higher than Pearson's value of 2600 for electrons.

[10] Isenberg, Russell, and Greene, Phys. Rev. **74**, 1255(A) (1948).
[11] J. R. Haynes, Phys. Rev. **77**, 739(A) (1949).
[12] W. C. Dunlap, Jr., Phys. Rev. **77**, 759(A) (1950).