Drift Mobilities in Semiconductors. I. Germanium

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The drift mobility of holes in n-type germanium and electrons in p-type germanium has been measured as functions of impurity concentration and temperature. In single crystals of resistivity greater than 10 ohm-centimeter, the mobility at 300°K of holes is $\mu_P = 1900 \pm 50$ cm²/volt-sec and of electrons is $\mu_N = 3900 \pm 100$ cm²/volt-sec. For this high resistivity material, the temperature dependence of mobility in the same units is $\mu_P = 3.5 \times 10^7 T^{-1.6}$ and $\mu_N = 9.1 \times 10^8 T^{-2.3}$, in agreement with conductivity-mobility measurements.

INTRODUCTION

THE drift mobility of holes and electrons has been measured in germanium and silicon single crystals grown from starting material of high purity. The drift mobility μ is defined as the drift velocity per electric field with which a charge carrier moves. Drift measurements were made on germanium samples that were cut from crystals whose resistivity values ranged from 0.05 to 30 ohm-centimeter at 300°K. From these measurements calculations give the effective mass and lattice scattering mobility of electrons and holes at 300°K. The variation of mobility with temperature was measured over a temperature range from 150°K to 350°K in some of these samples. Calculated from the experimental data are curves giving the relationship between the number of impurity centers and the resistivity, the ratio of electron mobility to hole mobility in n- and p-type germanium and the number of impurity centers, and the ratio of Hall mobility to drift mobility and the number of impurity centers. Similar results for silicon will be reported later.

THEORY

Before presenting any results, it is helpful to discuss briefly the individual scattering processes that affect the mobility of charge carriers in semiconductors. The most important scattering mechanism for high resistivity samples is that resulting from the thermal lattice vibrations. In addition there is coulomb scattering of the charge carriers by the ionized donors and acceptors, coulomb scattering by the other charge carriers both holes and electrons, scattering by neutral donor and acceptor centers, and scattering by lattice imperfections such as dislocations.

Calculations by Dexter and Seitz[1] have shown that, for at least one type of dislocation, lattice imperfection scattering at room temperature is negligible unless the crystal is extremely cold worked. Since the crystals from which the experimental samples have been cut were annealed slowly, it will be assumed that this scattering process can be disregarded in our calculations.

For scattering of the charge carriers by ionized donors and acceptors, calculations under the restriction of non-degenerate spherical constant energy surfaces in the band picture of semi-conductors lead to the Conwell-Weisskopf[2] fromula for impurity scattering. More recently, both Brooks[3] and Herring[4] have refined the Conwell-Weisskopf formula. However, the results of the calculations of Herman and Callaway[5] show that the above mentioned restriction does not hold for germanium and probably not for silicon. Therefore the Conwell-Weisskopf formula can only be a first approximation for the effect of impurity scattering on the mobility of the charge carriers and the Brooks-Herring refinement neglected. It will be assumed that, to the same approximation, the Conwell-Weisskopf formula also holds for electron-hole scattering. In this approximation no account is taken of the reduced mass of the scattering system. It can be shown from momentum conservation considerations that electron-electron and hole-hole scattering have no first-order effect on the mobilities. However, they do affect the mobilities indirectly by changing the energy distribution function[6] of the carriers but this will be neglected in our computations.

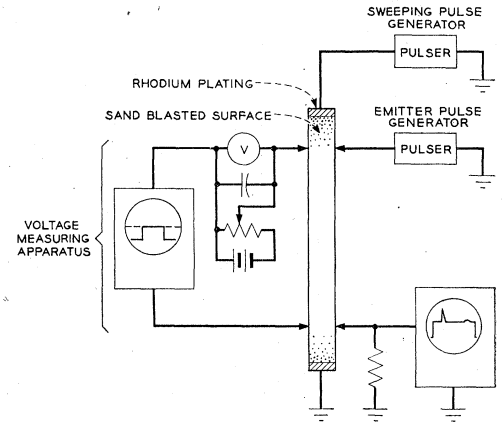

FIG. 1. Experimental drift mobility circuit.

[1] D. L. Dexter and F. Seitz, Phys. Rev. **86**, 964 (1952).

[2] E. Conwell and V. F. Weisskopf, Phy. Rev. **69**, 258 (1946); **77**, 388 (1950).
[3] H. Brooks, Phys. Rev. **83**, 879 (1951).
[4] C. Herring (unpublished).
[5] F. Herman and J. Callaway, Phys. Rev. **89**, 518 (1953).
[6] P. P. Debye and E. M. Conwell (to be published).

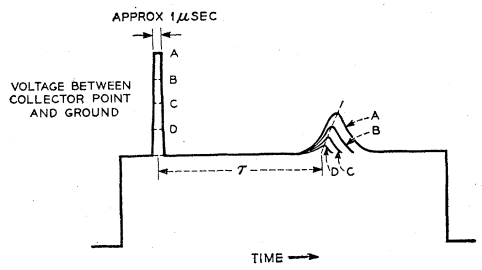

FIG. 2. Oscilloscope trace during measurement of drift time.

Relations giving the effect of neutral scattering centers on the mobilities of the charge carriers are given by Erginsoy.[7] It can be shown easily that the neutral scattering contributes a negligible effect in the temperature range of the work to be reported in this paper. Therefore neutral impurity scattering will not be considered further.

Thus, for the case of the drift-mobility experiment where minority carriers are injected into a semiconductor, these carriers are scattered by the lattice, by fixed charge impurities, and by the majority charge carriers. As far as charge scattering centers are concerned, a minority carrier sees N_D donors, N_A acceptors, and $|N_D-N_A|$ majority carriers, or a total of twice the number of donors or acceptors, whichever may be the larger. The majority carriers on the other hand see only N_D donors and N_A acceptors. When only one type of impurity is present in an appreciable quantity, the majority carrier sees only half as many charged scattering centers as the minority carrier. This means that the electrons will have a slightly higher mobility in n-type semiconductor than they will in p-type semiconductor. Likewise holes will have the higher mobility in p-type semiconductor. As a consequence of this, the ratio of electron mobility to hole mobility b will be larger in n-type material.

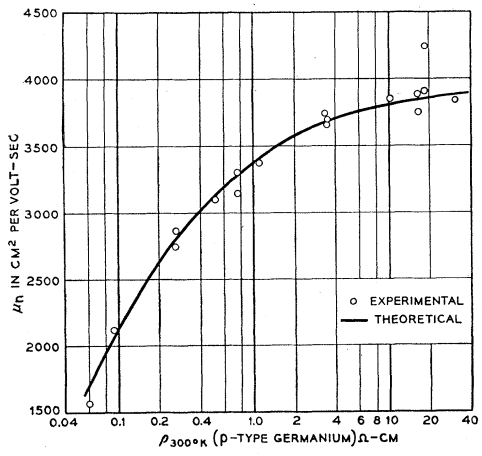

FIG. 3. Electron drift mobility *versus* resistivity of p-type germanium at 300°K.

[7] C. Erginsoy, Phys. Rev. **79**, 1013 (1950).

EXPERIMENTAL TECHNIQUES

The measurements were made using a circuit essentially the same as in the original drift mobility experiment of the Haynes and Shockley[8] (Fig. 1). An electric field is applied across the length of a rod specimen. At one point, the emitter, minority carriers are injected. They drift down the rod in the presence of the electric field and at a later time arrive at a second point, the collector, where some of them are collected. By measuring the drift time t of the minority carriers between the emitter and collector points, the distance L and the voltage drop V between these points, one can obtain the mobility $\mu=L^2/Vt$. The chief modification of the Haynes and Shockley circuit consists in self-biasing the collector point during the period that the sweeping field is applied. The difference in potential between the point and the germanium directly below it is usually sufficient (>0.2 volt) to give the point collector action.[9] In those few cases where the rectification properties of the collector point were poor and the necessary potential difference was not obtained, a resistance network was used to divide the sweeping-field pulse voltage into two parts and thus apply an appropriate potential to the collector point. Self bias is desirable because it reduces the heating of the specimen, an effect that becomes appreciable in all samples that have a resistivity of less than one ohm-centimeter.

A diagram of an oscilloscope trace under the conditions of the experiment is shown in Fig. 2. About one microsecond after the electric field is established in a specimen, a short pulse (about one microsecond) of minority carriers is injected into the rod at the emitter point. The condition of space-charge neutrality demands that an equal number of majority carriers flow into the rod, and the current flow gives the short pulse on the left portion of the oscilloscope trace. After a time t the injected minority carriers have drifted in the electric field to a position near the collector point where they reduce the impedance of the point causing the short pulse on the right portion of the oscilloscope trace. The shape and height of this latter pulse have been explained by minority carrier recombination and diffusion.

In practice, the drift or transit time from emitter to collector is measured as a function of the number of injected carriers and then extrapolated to zero-injected carrier density. In this way allowance is made for the local disturbance in the electric field caused by the finite injection pulses. This extrapolation is shown in Fig. 2.

PREPARATION OF SAMPLES

The samples were prepared like those described by Haynes and Shockley,[8] except that a different long-lifetime treatment and different sample dimensions

[8] J. R. Haynes and W. Shockley, Phys. Rev. **81**, 835 (1951).
[9] J. Bardeen and W. H. Brattain, Phys. Rev. **74**, 230 (1948); **75**, 1608 (1949).

were employed. The long-lifetime treatment consisted of immersing the rods for ten minutes in a 50 percent solution of HNO_3 in water. This treatment reduces the surface recombination velocity in germanium to the order of 100 cm/sec.[10] All the specimens were about 2.5 cm in length and the high resistivity specimens had cross-sectional dimensions of 0.05 cm. The lower resistivity specimens had smaller cross-sectional dimensions in order to keep the impedance above a minimum value. This enabled a sufficient electric field to be established such that a measurement of the mobility was possible. For the very low resistivity samples (0.1 ohm-cm and lower) a pulsing circuit using special low-impedance pulse transformers was used.

MOBILITY *VERSUS* IMPURITY CENTERS

The measurements of mobility reported in this section have been made on single crystal specimens in which only one type of impurity is present in concentrations greater than 10^{13} cm^{-3}. Therefore there is less compensation of impurities than this level and consideration of compensation can be neglected in this section. The experimental results showing the mobility of electrons in p-type germanium is given in Fig. 3 and of holes in n-type germanium in Fig. 4 as a function of the resistivity of the sample. All the data presented in this section have been corrected to 300°K values. Each experimental point represents the average of several or more individual measurements. These results agree for the case of electron mobility with those of Haynes and Shockley over the range of their resistivity values.

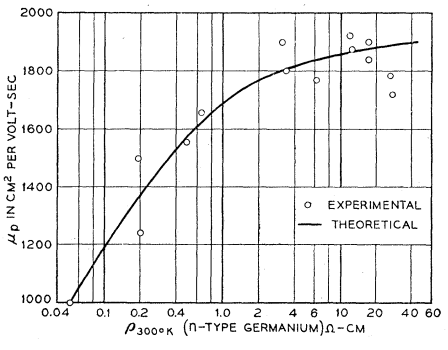

FIG. 4. Hole drift mobility *versus* resistivity of n-type germanium at 300°K.

The mobility falls to one-half its maximum value at a resistivity of about 0.06 ohm-cm. It is obvious that serious errors in design may be made by assuming standard values of mobility instead of the actual values, especially in the case of low resistivity material.

The scatter at the high-resistivity end of the plots can be explained in terms of the uncertainity in a correction that has to be applied to high-resistivity data. This correction has to do with the difference between the drift mobility of a particle and the drift mobility of a group of particles.[11]

[10] J. R. Haynes (private communication).

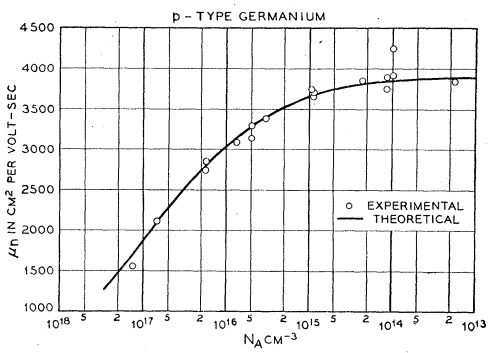

FIG. 5. Electron drift mobility *versus* acceptor density in p-type germanium at 300°K.

The lattice-scattering mobility may be obtained from these plots by extrapolating the high-resistivity data out to 40 ohm-cm. At this resistivity scattering resulting from charged impurities and majority carriers becomes negligible compared to the lattice scattering which then controls the mobility.

In order to use the Conwell-Weisskopf formula for calculating the effect of impurity scattering on the mobility, one has to know the density of impurities N_I in the crystal. These may be calculated from Eqs. (1) and (2) given below which are derived from the relations $np=n_i^2$, $1/\rho=nq\mu_N+pq\mu_P$ and $N_D-N_A=n-p$, where n_i is the density of electrons in intrinsic germanium; ρ_N, ρ_P are the resistivities of n-type and p-type germanium; μ_N, μ_P are the mobilities of electrons and holes; and q is the charge of an electron.

$$N_A=N_D+\frac{1+1/b}{2\rho_P q\mu_P}\left[1-4n_i^2\rho_P^2q^2\mu_N\mu_P\right]^{\frac{1}{2}}+\frac{1-1/b}{2\rho_P q\mu_P}$$

in p-type germanium, (1)

$$N_D=N_A+\frac{1+b}{2\rho_N q\mu_N}\left[1-4n_i^2\rho_N^2q^2\mu_N\mu_P\right]^{\frac{1}{2}}-\frac{b-1}{2\rho_N q\mu_N}$$

in n-type germanium. (2)

It will be assumed that $N_D\gg N_A$ or $N_A\gg N_D$, based on the fact that the starting material from which the

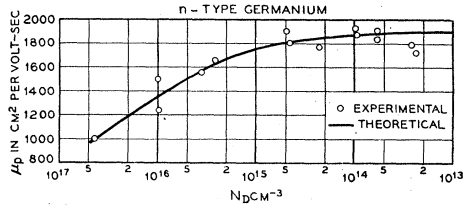

FIG. 6. Hole drift mobility *versus* donor density in n-type germanium at 300°K.

[11] M. B. Prince, Phys. Rev. **91**, 271 (1953).

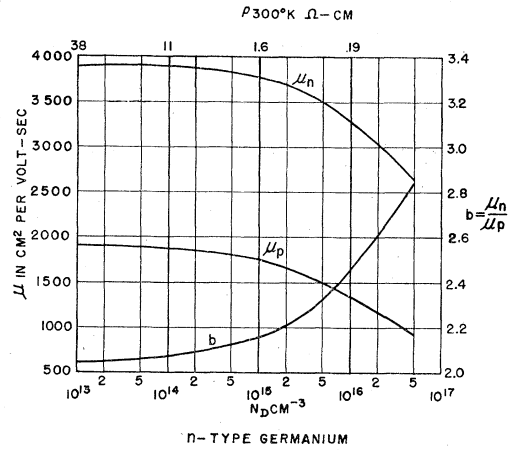

FIG. 7. Computed curves of mobility in n-type germanium at 300°K.

crystals were grown had less than 10^{13} minority impurities (N_A in n type, etc.) per cubic centimeter. Thus N_D may be dropped from Eq. (1) and N_A from Eq. (2). However, N_I is strongly dependent on b and, in order to find the relationship between N_I and μ, it is necessary to find how b varies with ρ. As a first approximation this relationship may be obtained by the following argument. For $N_I \gg n_i$,

$$N_I = N_A = 1/(\rho_P q \mu_P) \text{ in } p\text{-type germanium,}$$

and

$$N_I = N_D = 1/(\rho_N q \mu_N) \text{ in } n\text{-type germanium,}$$

or, for the same N_I, $\mu_N/\rho_N = \mu_P/\rho_N$. Therefore by plotting the μ_N *vs* ρ_P and μ_P *vs* ρ_N curves on logarithmic graph paper and drawing lines at 45° with respect to the axes, one obtains two intersections with each 45° line that correspond to two samples having the same N_I. Hence, b is determined by taking the ratio of the mobilities associated with the intersections. Using these values of b, one arrives at a first approximation to N_I. Refinements of these numbers may be obtained by successive approximations keeping in mind

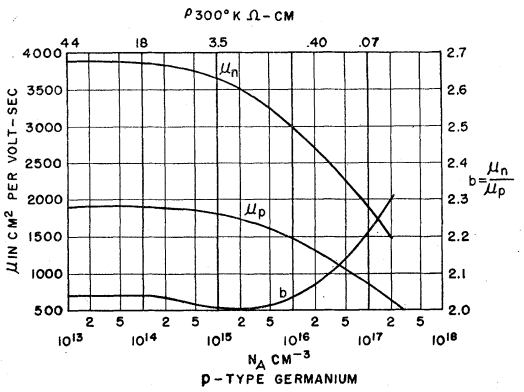

FIG. 8. Computed curves of mobility in p-type germanium at 300°K.

that the minority carriers are scattered by $2N_I$ scattering centers while the majority carriers are scattered by only N_I centers. The results of such a calculation are shown as experimental points in Figs. 5 and 6. Using the Conwell-Weisskopf formula one can fit the experimental data with theoretical curves. For electrons in p-type germanium, a good fit is obtained by using $\mu_L = 3900 \pm 100$ cm²/volt-sec and an effective mass for for the electron, m_N^*, equal to one-quarter of the free electron mass (m). An almost equally good fit can be made by assuming $m_N^* = \frac{1}{2}m$. For holes in n-type material, a good fit is obtained by using $\mu_L = 1900 \pm 50$ cm²/volt-sec and an effective mass for the hole, m_P^*, equal to three times the free electron mass. Using these theoretical curves, one can obtain curves of drift mobility of the majority carrier and b for n-type and p-type germanium. These are given as Figs. 7 and 8. Figure 9 shows the results of plotting the

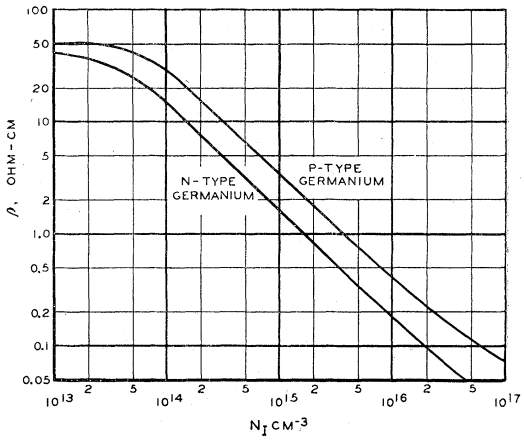

FIG. 9. Resistivity *versus* impurity density for n and p-type germanium at 300°K.

resistivity of n-type and p-type germanium *versus* the number of donors and acceptors respectively at 300°K.

MOBILITY IN IMPURITY COMPENSATED SAMPLES

The results presented in the last section were for uncompensated crystals of germanium. However in the art of making semiconductor devices, one constantly runs into compensated material as part of the device and one wishes to know what kind of mobilities to expect in such material.

As a check on the type of calculations that are made in obtaining the relations of the last section, a crystal was grown in which the number of donors was kept constant throughout the crystal ($N_D = 0.80 \times 10^{15}$ cm^{-3}) and various amounts of acceptors were added during the growth of the crystal. From resistivity measurements it is possible to calculate the number of acceptors in any particular rod sample. Thus, knowing the total number of scattering centers, one can predict a value of mobility for each rod cut from crystal. The

results of this experiment are shown in Fig. 10. The average deviation of the experimental points from the predicted curve is about 3 percent, which is within the expected error of such an experiment. For comparison, a curve showing the expected values of mobility for uncompensated samples is shown on the same figure.

Another crystal was grown in a similar manner in which $N_D=2.0\times10^{16}$ cm^{-3} and with the compensated part of the crystal having $N_A=7.0\times10^{16}$ cm^{-3} as determined from resistivity data. For an uncompensated sample having the same resistivity as the compensated sample (0.138 ohm-cm), one would expect to obtain a value of $\mu_N=2360$ cm^2/volt-sec; whereas, for the compensated sample, one would expect a value of $\mu_N=2075$ cm^2/volt sec. The experimental $\mu_N=1960$ cm^2/volt-sec is thus a strong confirmation of the above calculations since the expected error in such a calculation should be less than 8 percent.

μ_H/μ *VERSUS* IMPURITY CENTERS

In order to help arrive at a better understanding of the band structures of germanium, one is interested in the relation of μ_H/μ at 300°K *versus* the concentration of impurity centers where μ_H is the Hall mobility. With the Hall mobility data obtained by Debye[6] on samples cut from the same crystals as the drift mobility samples and the drift mobility values taken as the majority carrier mobilities from Figs. 7 and 8, μ_H/μ values have been obtained and plotted as a function of N_I in Fig. 11. For electrons in n-type germanium μ_H/μ falls slightly below unity for samples with a large number of impurities. For holes in p-type germanium, the ratio maintains a value near 1.8 for high-resistivity samples. It has been pointed out that the variation with energy of the mean free time between collisions for a carrier lead to μ_H values greater than unity.[12] On the other hand, complex re-entrant surfaces in the band picutre will cause μ_H/μ to tend toward zero or even become negative.[13] More recently it has been noted that multiple energy surfaces of more or less spherical form can lead to arbitrarily high values of μ_H/μ.[14] From these factors it appears that the μ_H/μ values obtained are not unreasonable. On the other hand, few conclusions can be reached from them.

MOBILITY *VERSUS* TEMPERATURE

The results of measuring the temperature dependence of the drift mobility of electrons in p-type germanium are shown in Fig. 12. The high temperature data have been corrected for the difference between the pulse velocity and the charge carrier velocity.[11] Above 220°K, the results are consistent with the line $\mu_L=3.5\times10^7\times T^{-1.6}$ cm^2/volt-sec. Below this temperature, the curves

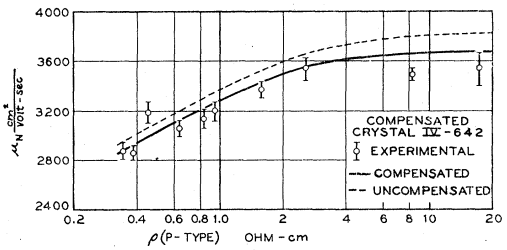

FIG. 10. Electron drift mobility in compensated p-type germanium at 300°K.

deviate from the line in agreement with the onset of appreciable impurity scattering with the μ_L given by the line and the m_N* equal to one-quarter of the free electron mass.

The temperature variation of the drift mobility of holes in n-type germanium is given in Fig. 13. For this case the data are consistent with the line $\mu_L=9.1\times10^8T^{-2.3}$ cm^2/volt-sec. Impurity scattering causes the data to deviate from the line at temperature below 200°K.

The results of the lattice-scattering variation of both the electron mobility and the hole mobility with temperature are in agreement with measurements[15] of conductivity mobility made on extremely pure samples of germanium over a range of nearly 200 degrees in which the concentration of carriers remained constant.

According to theory,[16] the temperature exponent for lattice scattering mobility is -1.5. This dependence is derived by assuming that there is a single energy extremum in the Brillouin zone at the energy band edge and that the energy varies quadratically with momentum in any direction away from the extremum. If the energy band edge corresponds to several equivalent points in the Brillouin zone, then the mobility may decrease faster than $T^{-\frac{3}{2}}$. Alternatively if the thermal energies of the carriers are high enough, the quadratic relationship between energy and momentum may break down and the mobility may again decrease

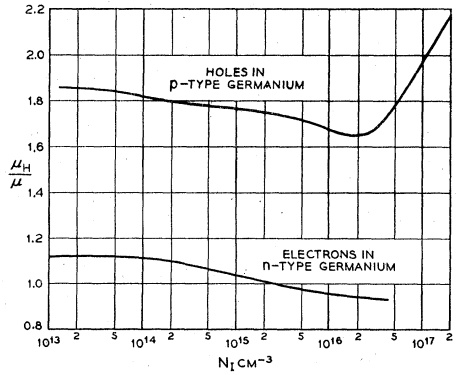

FIG. 11. μ_H/μ *versus* impurity density for n-type and p-type germanium at 300°K.

[12] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950), p. 277.
[13] Reference 12, p. 338.
[14] W. Shockley (private communication).
[15] F. Morin (unpublished results).
[16] J. Bardeen and W. Shockley, Phys. Rev. **80**, 72 (1950).

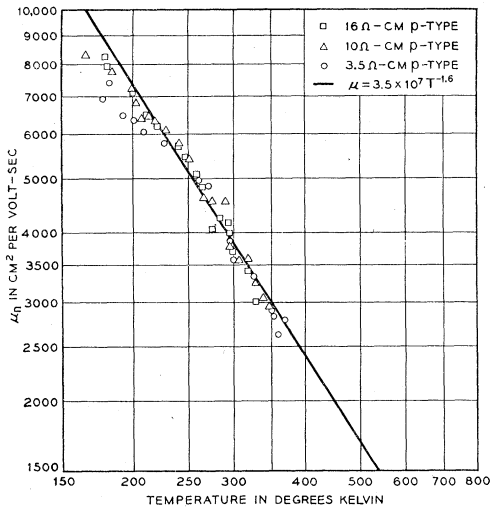

FIG. 12. Electron drift mobility *versus* temperature in *p*-type germanium.

rapidly. At the present time the theoretical analysis of the data does not appear adequate to come to a definite interpretation.[17]

DISCUSSION OF SOURCES OF ERROR

There are four sources of possible error in the determination of a drift mobility. These are the measurement of the drift time, the emitter collector spacing, the potential drop in the specimen between the emitter point and the collector point, and the temperature of the specimen.

The estimated percentage error in the measurement of the drift time by the method described earlier in the paper is about 2 percent. The distance L could easily be measured with an accuracy better than 0.5 percent while the accuracy of the voltage measurement V is about 1 percent. Therefore the expected error from these sources in a determination of the mobility is about 4 percent. This number agrees well with the spread of mobility values determined from a given specimen under various experimental conditions of L, t, and V.

Since the drift mobility is temperature dependent, the temperature at which the measurements are made should be given along with the value of the mobility.

The possible error in the determination of the temperature consists of three parts. First, the actual measurement of the ambient temperature was read from a laboratory thermometer placed as near to the sample as possible. The thermometer has been calibrated to within 1°C. Second, all the experimental data were taken under conditions of power dissipation such that the maximum temperature rise of the sample was less than 1°C. Third, the correction of the data to the standard 300°K introduces some error since the temperature dependence of the mobility is not known exactly. With the 1°C accuracy of the thermometer, the heating effect in the sample, and the 300°K correction, the value of the 300°K mobility may be off as much as 2 percent because of temperature corrections. At temperatures other than ambient, the temperatures were measured by a chromel-alumel thermocouple that was in thermal contact with the specimen. The accuracy of the thermocouple measurement is estimated to be 2 percent.

Thus, the over-all accuracy of any single measurement of mobility quoted at any temperature is expected to be about 6 percent.

CONCLUDING REMARKS

With the results presented in this paper, the author feels that the increasing value of drift mobility for holes and electrons in germanium as a function of the year of their measurement[18] has finally leveled off. The earliest measured drift mobilities[18] were made on single crystal samples of non-uniform resistivity. The next reported data[19] were measurements on single crystals that were grown from fairly pure starting material, i.e., about 10^{14} uncompensated impurities per cubic centimeter. The data as reported in this paper were obtained from crystals that were grown from starting material that had less than 10^{13} impurities per cubic centimeter. Even if the starting germanium is refined to a higher degree of purity, the effect on measurements of mobility will be within the errors reported in this paper. In the high-restivity range (>15 ohm-cm), any decrease of compensation of impurities will not affect the mobility measurement since even with the present impurity levels, the reduction of the mobility below the lattice-scattering value by impurity scattering is

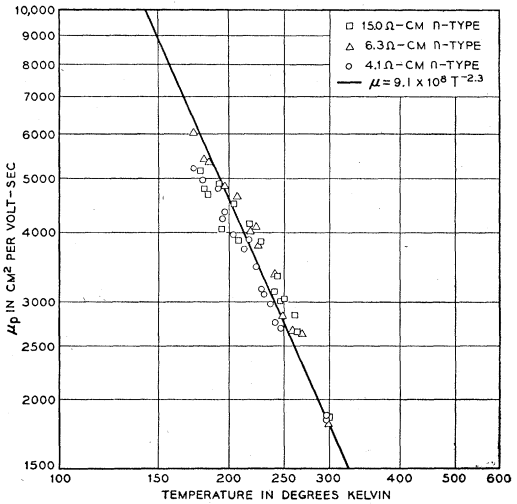

FIG. 13. Hole drift mobility *versus* temperature in *n*-type germanium.

[17] The writer is indebted to C. Herring for a discussion of the first possibility and to W. Shockley for the second.

[18] J. R. Haynes and W. Shockley, Phys. Rev. **75**, 691 (1949).
[19] Pearson, Haynes, and Shockley, Phys. Rev. **78**, 295 (1950).

less than one percent. In the lower-resistivity ranges where impurity scattering becomes effective, the accuracy of the determination of the number of impurities is no greater than the degree of purity obtained at present.

ACKNOWLEDGMENTS

The writer wishes to express his indebtedness to H. R. Moore who built the pulsing circuits, to A. A. Tartaglia who prepared the specimens, and to many of his colleagues in the Transistor Physics Group of the Bell Telephone Laboratories for their suggestions and stimulating discussions. He wishes especially to thank J. R. Haynes who advised generally on circuit problems, E. M. Conwell and W. Shockley for their theoretical help, and J. A. Hornbeck for help in preparing the manuscript.

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K-Auger Electrons, Positrons, and Conversion Electrons of Zn^{65} Above 5 kev

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The momentum distributions of *K*-Auger electrons, positrons, and conversion electrons of Zn^{65} have been measured in a magnetic lens spectrometer, with very thin sources and counter windows. The positron Fermi plot was found to be linear from the end point of 325±3 kev to about 50 kev. The positron decay is simple, contrary to some previously published results. From the observed intensities of *K*-Auger electrons, positrons, and conversion electrons, and values of capture branching ratio, fluorescence yield, and *L* to *K* capture ratios taken from the literature, the intensity ratios of the various spectral components have been obtained. The resulting conversion coefficient, $\alpha=(2.56\pm0.29)\times10^{-4}$, agrees with other experimental determinations and strongly suggests an *E*2 transition. The observed ratio of *K* capture to the ground state to positrons, 28.0±3.2, is in satisfactory agreement with the recently calculated theoretical value of 29.0 for an allowed transition. This agreement, in view of the high *ft* value, establishes the *l*-forbidden character of the transition.

I. INTRODUCTION

IN 1938 Perrier, Santangelo, and Segrè[1] reported a 245-day activity in zinc, separated from copper filings from a deflecting plate which had been subject to strong deuteron and neutron bombardment in the Berkeley cyclotron. A few months later Barnes and Valley[2] reported such an activity (7 months) in copper parts of a cyclotron in which only protons had been accelerated, and found both electrons and positrons to be emitted. Sagane[3] produced this activity by Cu(d,n) and Zn(n,γ) and assigned it to Zn^{65}. Livingood and Seaborg[4] also produced this activity by Cu(d,n) and Zn(n,γ) and in addition produced it by Zn(d,p). On the basis of the latter reaction they confirmed the assignment to Zn^{65}, and they measured the half-life as 250±5 days.

On the basis of cloud-chamber measurements Watase, Itoh, and Takeda[5] reported the presence of gamma rays of 0.45, 0.65, and 1.0 Mev. In magnetic spectrometers Deutsch, Roberts, and Elliott,[6] and Mandeville and Fulbright[7] found only one gamma ray, of energy 1.14 Mev. Jensen, Laslett, and Pratt[8] found the energy of this gamma ray to be 1.118 Mev and Mann, Rankin, and Daykin[9] reported it as 1.114±0.005 Mev. The conversion coefficient of this 1.11-Mev gamma ray was measured in a magnetic spectrometer by Waggoner, Moon, and Roberts[10] and, more recently, by Strucken and Weber.[11] They reported values of $(2.28\pm0.26)\times10^{-4}$ and 2.5×10^{-4}, respectively.

The positron end-point energy has been measured with magnetic spectrometers by Peacock, Jones, and Overman,[12] by Mann, Rankin, and Daykin,[9] and by Yuasa.[13,14] They obtained 0.32 Mev, 0.325±0.002 Mev, and 0.32 Mev, respectively. Shoupp[15] has measured the (p,n) threshold of Cu^{65} and assigned a positron end-point energy of 355±20 kev, which becomes 327±20 kev on the basis of the present value of the neutron-proton mass difference.[16]

Considerable disagreement exists on the shape of the

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