tions with the 22-Mev betatron has provided an ionization chamber calibration of the beam from that machine. Using their calibration and the previously observed yield at 22 Mev, we find that we observed 26 percent more than the theoretical yield. In this connection it should be noted that theoretically 90 percent of the yield from 320-Mev bremsstrahlung comes from the portion of the spectrum below 22 Mev. Thus the experiments at 320 Mev and at 22 Mev are measuring the photo-effect in the deuteron primarily in the same energy region. The great difference in the spectral shapes for these two energies is the reason for the relatively high yield for deuterium in the 22-Mev graph.

Table I shows some values of Π. Values of Π for the nine other elements can be computed from the yields in the graph, an assumption of $h\nu$, and a spectral shape. These integrals increase much faster than the theoretical Z dependence.[3,4]

Because of uncertain detector efficiency, one should hesitate to say that our type of experiment is good for determining Π in spite of the cases of agreement mentioned above. An unfavorable comparison is with Gaerttner's and Yeater's[5] results for oxygen. For the simple $(\gamma-n)$ disintegration we agree within 7 percent, but we are a factor of 4 below their value of Π which includes $(\gamma-p, n)$ and stars. Since these multiple disintegrations gave neutrons also, we should have detected some of them.

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* Supported by the joint program of the ONR and AEC.

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The Resistivity and Hall Effect of Germanium at Low Temperatures*

C. S. Hung and J. R. Gliessman
Purdue University, Lafayette, Indiana

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The theory of the electrical properties of germanium is based on the impurity semiconductor model.[1] The impurity donor and acceptor states are considered localized energy states. Conduction of electricity takes place by electrons in the conduction band or by holes in the filled band. Below room temperature, the contribution of intrinsic electrons and holes can usually be neglected, and conduction is due to only one kind of carrier, either electrons or holes. The activation energies for the impurity states are usually small but finite. As the temperature is reduced the concentration of electrons in the conduction band (or holes in the filled band) decreases rapidly with temperature. The resistivity and the Hall coefficient, which are inversely proportional to the concentration of carriers, therefore increase indefinitely as the temperature is lowered. Measurements of the resistivity and the Hall effect at low temperatures have been carried out to check the above prediction.

Germanium samples with different kinds of impurities and different concentrations were used. Measurements were carried out over a continuous temperature range from room temperature down to liquid helium temperatures. The results were found to be essentially independent of, (a) magnetic field variation between 1000 and 5000 gauss, (b) change by a factor of 10 in the electric field along the direction of flow of the sample current, (c) whether the potential leads to the sample were soldered on with tin or were pressure contacts onto rhodium-plated spots on the sample, (d) whether the sample surface is ground or etched, and (e) whether measurements were taken with increasing temperature or with decreasing temperature. The magnetic field, as measured at room temperature, is not expected to be influenced by the cryostat parts and the solder in the neighborhood of the sample at any temperature.

The resistivity and the Hall curves for some typical samples are shown in Figs. 1 and 2. It is seen that the resistivity and the Hall coefficient do not increase indefinitely as the temperature is reduced, as predicted by the usual theory. Instead, the Hall coefficient for every one of the samples investigated goes through a maximum at low temperatures, while the resistivity approaches a saturation value. This anomaly in the resistivity and the Hall effect calls for a modification of the usual theory of an impurity semiconductor, and will be dealt with separately.[2]

In the temperature region above that at which this anomaly occurs experiment and the usual theory agree satisfactorily. The activation energies for the different samples can be obtained from the slopes of the linear portions of the Hall curves. This activation energy is found to be of the order of 10 millivolts. It is lower for a higher impurity content. Sample SB-5 shows an almost flat Hall curve from room temperature down to 2°K. This may mean a complete overlapping of the impurity states with the conduction band; that is, zero activation energy. Or, it may mean that the mobilities in the conduction and the donor bands are approximately equal.

Owing to this low activation energy the exhaustion range, within which nearly all of the electrons are excited from the impurity states into the conduction band, extends from room temperature

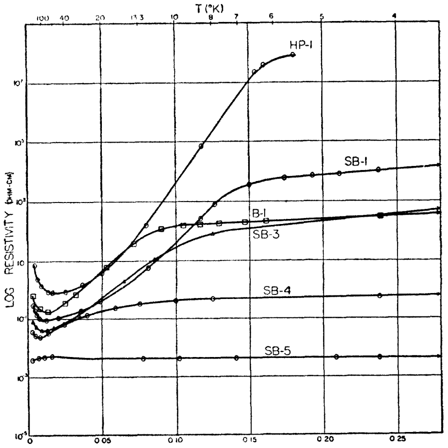

FIG. 1. Resistivity *vs.* $1/T$ for various germanium alloys: HP-1 is a high purity N-type sample; SB-1, SB-3, SB-4, SB-5 are N-type samples with antimony impurities; B-1 is a P-type sample with gallium and arsenic impurities. The impurities in the B-1 sample were introduced by neutron bombardment.

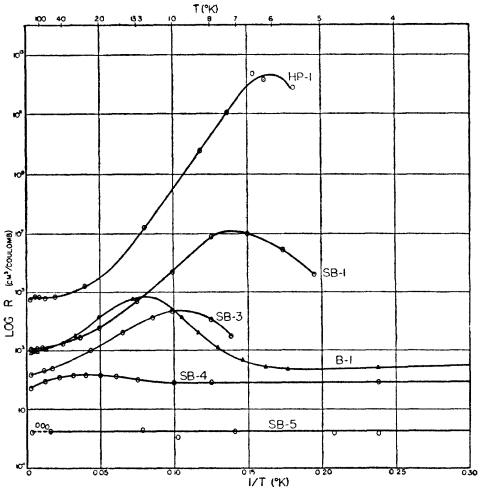

FIG. 2. Hall coefficient *vs.* $1/T$ for various germanium alloys. (See caption of Fig. 1 for description of samples.) For the higher resistance samples, the Hall coefficient at low temperatures became too small to be measured.

down to beyond liquid nitrogen temperature, to 30°K in case of high resistivity samples. The deviation of the Hall curves from flat curves in this region is believed to be due to the fact that the Hall coefficient is not accurately the inverse of the concentration of carriers.[3]

The resistivity in the higher temperature region can be accounted for satisfactorily on the consideration of lattice scattering and impurity ion scattering.[4] The mobility of the carriers, as obtained from the measured resistivity and the Hall coefficient, is of the order of 2000 to 3000 cm^2/volt-sec. at room temperature and increases up to 10,000 to 100,000 cm^2/volt-sec. at low temperatures. As expected, the mobility increases up to a maximum and then decreases slowly with decreasing temperature. For sample SB-5, due to the high concentration of carriers, consideration of resistivity must be based on degenerate gas theory.[5] Theoretical calculation and experiment again agree.

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* Work assisted by Signal Corps contract.

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Theory of Resistivity and Hall Effect at Very Low Temperatures*

C. S. Hung
Purdue University, Lafayette, Indiana
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THE anomalies in the resistivity and the Hall curves of germanium observed at low temperatures[1] could not be explained on the model of an impurity semiconductor with localized impurity states. The Hall coefficient, in the case of some samples, decreases from its maximum by a factor of over 100 as the temperature is reduced. The concentration of carriers in the conduction band (or the filled band), on the other hand, cannot be expected to increase with decreasing temperature. This leads to the conclusion that the usual expressions for resistivity and Hall coefficient, as represented in Eqs. (1) and (2) are no longer valid at low temperatures

$$\rho = (n_c e b_c)^{-1}, \tag{1}$$

$$R = F/(n_c e), \tag{2}$$

where n_c and b_c are the concentration and the mobility of electrons in the conduction band, and F is a numerical factor of the order of unity. According to the free electron theory F is not expected to vary by more than an order of magnitude. Non-homogeneity in the sample, either macroscopic or microscopic, may cause R to decrease with lower temperature even though n_c, at various parts of the sample, may remain constant or decrease. However, to account for the large drop in R observed requires too artificial a model of inhomogeneity.

The anomalies can be understood only if a mechanism is found which includes a combination of different kinds of carriers with different mobilities. James and Ginzbarg[2] pointed out that due to the interaction between the impurity states, an impurity band is formed. In such a case an electron has the possibility of moving from one impurity state to another one in its spatial neighborhood, so that the states are no longer localized, and conduction in the impurity band is to be expected.

When simultaneous conduction in the conduction band and the donor band (or the filled band and the acceptor band) is considered, the expressions for ρ and R are given as follows:

$$\rho = (n_c e b_c + n_D e b_D)^{-1}, \tag{3}$$

$$R = F(n_c e b_c^2 + n_D e b_D^2)(n_c e b_c + n_D e b_D)^{-2}, \tag{4}$$

where n_D and b_D are the concentration and mobility of electrons in the donor band. The assignment of a definite mobility b_D to the donor band is justified by the observed ohmic behavior of the saturation resistivity at low temperatures. Equation (4) is adapted from the usual expression for R in the intrinsic range; it is assumed here that this equation holds for the case of carriers in the impurity bands also.

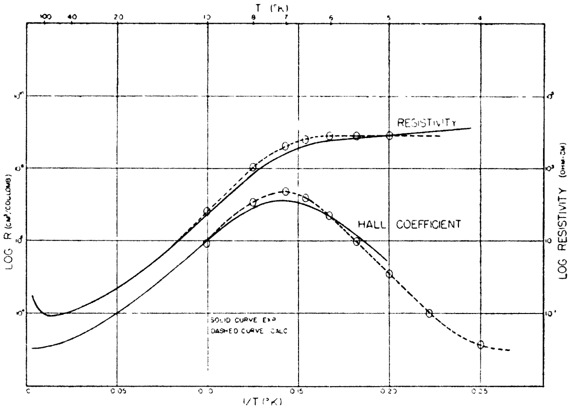

FIG. 1. Resistivity and Hall curves for sample SB-1 (N-type, antimony added). The solid curves are experimental and the dashed curves are calculated theoretically. The carriers in the donor band are assumed to be lectrons.

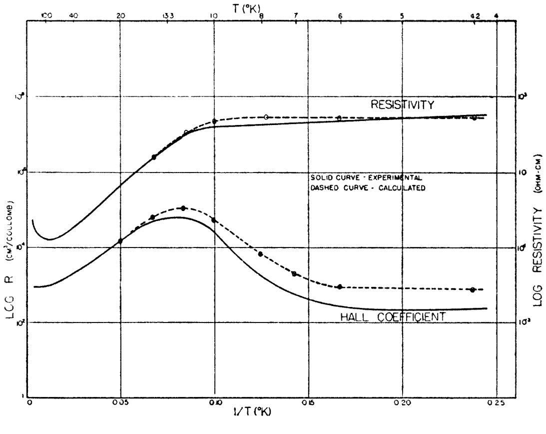

FIG. 2. Resistivity and Hall curves for sample B-1 (P-type, neutron bombarded). The solid curves are experimental and the dashed curves are calculated theoretically. The carriers in the acceptor band are assumed to be holes.

Since b_D is usually small compared with b_c, in the limit of high temperatures, the conduction in the impurity band can be neglected and the values of ρ and R are as given by Eqs. (1) and (2) according to the usual theory. However, since n_c decreases indefinitely with decreasing temperature, conduction in the impurity band becomes increasingly important. In the limit of low temperature, conduction in the conduction band can be neglected, and Eqs. (3) and (4) now reduce to the following:

$$\rho = (n_D e b_D)^{-1}, \tag{5}$$

$$R = F/(n_D e). \tag{6}$$

At low temperatures, all the electrons are in the impurity band, and at room temperature, all of them are excited into the conduction band. Therefore, the Hall coefficients at room temperature and at very low temperatures are expected to be the same. This is in approximate agreement with experiment. The deviation may come from the fact that the electrons in the donor band are far from being free, and Eq. (6) is only approximately true.

At the intermediate temperatures, the values of ρ and R can be obtained from the values of n_c, n_D, b_c, and b_D. n_c and b_c can be obtained by extrapolation from high temperatures. n_D is obtained