High-Field Longitudinal Magnetoresistance of Germanium*

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The longitudinal magnetoresistance of germanium N_{100}, N_{111}, P_{100}, P_{111}, and P_{211} single crystals of 2 ohm cm resistivity has been measured to the point of saturation, by means of transient magnetic fields up to 600 000 gauss. An N-type effective mass ratio of 17.2±0.4 has been determined at 300°K. The magnitude and variation with field of the P-type magnetoresistances was found to be anomalous.

I. INTRODUCTION

IN the limit of strong magnetic fields, the galvanomagnetic behavior of germanium assumes a simple form.[1,2] When saturation values of the Hall coefficient and of the longitudinal and transverse magnetoresistances can be attained, one derives direct information regarding carrier densities, effective mass ratios, and collision times. The requisite predominance of gyromagnetic over collision frequency is achieved with about 600 000 gauss at room temperature, and about 150 000 gauss at liquid nitrogen temperature.

In his classical paper on the magnetoresistances of metals,[3] P. Kapitza gives transient-field measurements up to 300 000 gauss for a polycrystalline germanium of milliohm-cm resistivity. Of greater theoretical value are the measurements made by Pearson and Suhl[4] on single crystals of high purity in the 100 000 gauss Bitter dc magnet.[5] By means of a pulsed-field technique developed by the authors,[6] it has proved possible to extend these measurements to the point of complete saturation.

The smallness of the present magnet and samples, and the pronounced peculiarities of metal-germanium contacts in high magnetic fields, have tended to impair the precision of Hall effect and transverse magnetoresistance measurements. Since the Hall effect has been found to saturate at rather low fields, this work appears more suitable for larger and weaker magnets. The longitudinal magnetoresistance lends itself well to measurement in a small high-field solenoid.

It is noteworthy that single-turn magnets capable of producing multimegagauss fields,[7] while an unnatural choice for experiments requiring a high degree of field homogeneity, are naturally suited to induce saturation effects.

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[1] B. Abeles and S. Meiboom, Phys. Rev. 95, 31 (1954).
[2] H. Brooks, *Advances in Electronics and Electron Physics* (Academic Press, Inc., New York, 1955), Vol. 7, p. 85.
[3] P. Kapitza, Proc. Roy. Soc. (London) 123, 292 (1929).
[4] G. L. Pearson and H. Suhl, Phys. Rev. 83, 768 (1951).
[5] F. Bitter, Rev. Sci. Instr. 10, 373 (1939).
[6] H. P. Furth and R. W. Waniek, Rev. Sci. Instr. 27, 195 (1956); Nuovo cimento 6, 1350 (1955).
[7] Levine, Furth, and Waniek, Bull. Am. Phys. Soc. Ser. II, 4, 191 (1956).

II. EXPERIMENTAL APPARATUS

The experiment is illustrated schematically in Fig. 1. A constant current pulse of 10 to 100 milliamperes is applied to the crystal, the resistivity is raised by application of a magnetic field transient, and the resultant potential transient is observed through separate potential leads.

The magnet consists of a Dural-Formica chamber (similar to that shown in Fig. 4 of reference 6), which compresses a thick-walled air-core helix of the Bitter type. Copper helices of $\frac{3}{16}$ in. inside diameter, $\frac{3}{8}$ in. high, were operated up to 400 000 gauss at 3 milliseconds, 300°K and up to 600 000 gauss at 77°K with a transformer and 7800-joule supply. Beryllium copper helices of $\frac{7}{32}$ in. inside diameter and $\frac{5}{8}$ in. height were operated up to 600 000 gauss at 150 μsec, with a low-inductance 4000-joule supply. The magnetic field was measured by means of a pickup coil, wound about the crystal to be tested, and feeding through an integrator circuit into an oscilloscope.

The samples used were germanium single crystals of 2Ω cm resistivity, measuring 1×1×5 mm, and having axes within 2° of the nominal alignment, as determined crystallographically. Potential leads were fastened by melting specks of pure tin into the germanium surface.

III. METHOD OF OBSERVATION

Maximum information can be extracted from the experiment by displaying the crystal and magnetic field integrator potentials simultaneously along the x and y

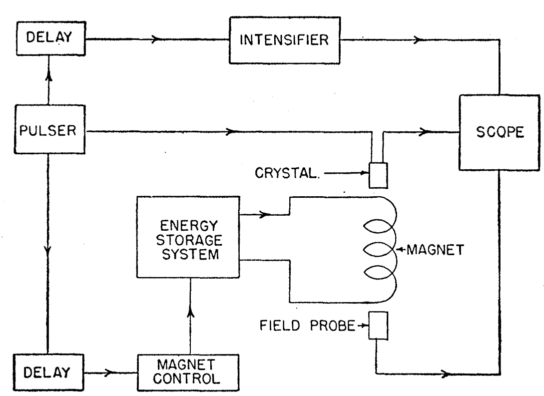

FIG. 1. Schematic diagram of the experiment.

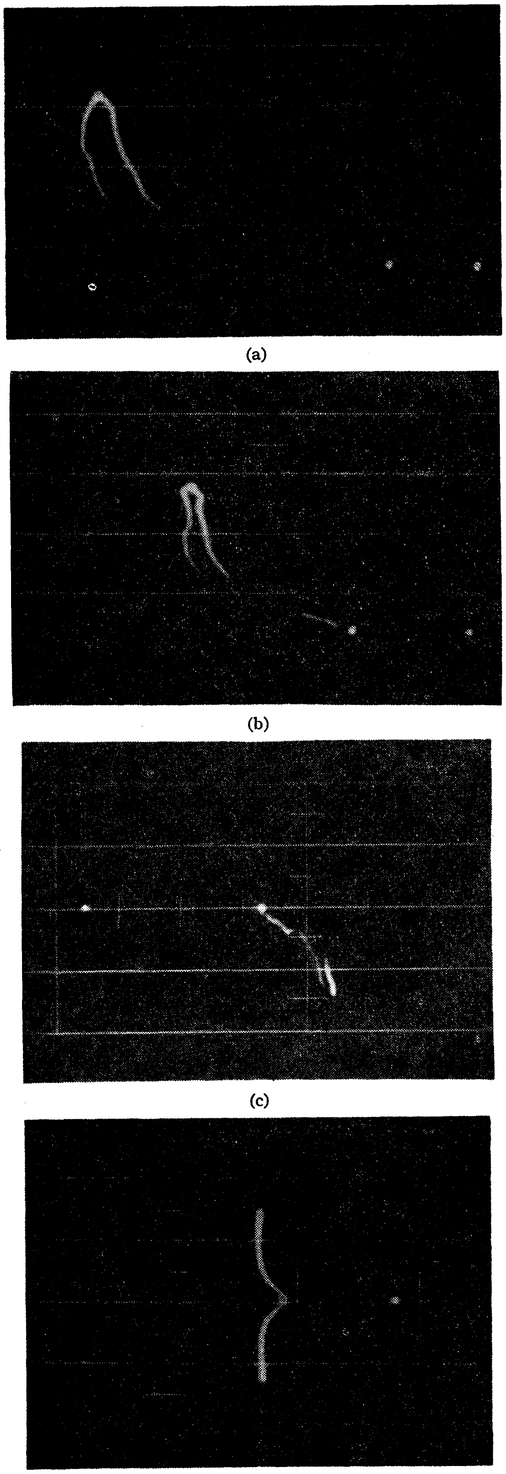

FIG. 2. Oscilloscope traces of resistance (x axis) *vs* magnetic field (y axis). (a) N_{100} at 460 000 gauss; (b) N_{111} at 460 000 gauss; (c) P_{100} at 600 000 gauss; (d) P_{111} at 200 000 gauss.

axes of an oscilloscope, so that the resultant traces out a graph of resistance *vs* field strength. The use of this method in the present context has been described by Suhl.[8]

Pickup voltages in the crystal circuit are detected by the double valuedness of the oscilloscope trace. It is noteworthy that, since the derivative of the field must vanish at its peak, the maximum field points are correctly given, even in the presence of considerable pickup voltage. This effect is illustrated by Figs. 2(a), 2(b), and 2(c), which were taken with 150 μsec pulses. In the millisecond range, single-valued traces can always be obtained, as in Fig. 2(d), which also illustrates the elimination of possible Hall effect components by double exposure under reversal of the field.

In practice, measurements up to 300 or 400 kilogauss were taken in the millisecond region, and supplemented with fast high-field shots when necessary. Continuous measurements were made between liquid nitrogen and room temperatures by immersing the entire magnet in coolant and then allowing it to warm gradually. On each oscilloscope trace, the temperature of the sample is recorded by the magnitude of the null-field resistance.

IV. RESULTS

Measurements made on 4 or more crystals of each kind yielded continuous sets of data, which were found accurately reproducible for different pulse times and samples. Since the present equipment is best suited for observing large effects, the precision of the N-type measurements of Fig. 3 is considerably better than that of the P-type measurements of Fig. 4. Small unexplained variations in the behavior of different samples were encountered in the case of P_{100}, which thus proved in all ways the most anomalous and refractory of the materials tested.

Measurements taken at liquid nitrogen temperature suffered in reproducibility because of the erratic behavior of metal-germanium contacts in strong fields.

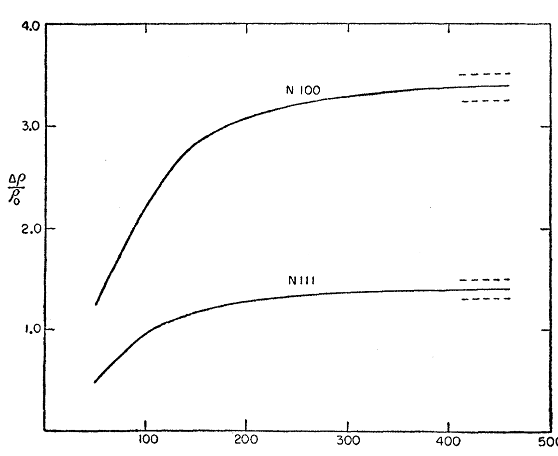

FIG. 3. N-type magnetoresistance *vs* magnetic field at 300°K. Dotted lines give limits of accuracy.

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[8] H. Suhl, Phys. Rev. 78, 646 (1950).

The N-type magnetoresistances were found to approximate closely the patterns obtained at 300°K with 4 times greater magnetic fields. The P-type saturation values at 77° were materially smaller than at 300°K, the temperature dependence emerging chiefly at low temperatures. Room-temperature measurements taken with P_{111} crystals of 6 ohm cm resistivity were found to coincide with the results of Fig. 4.

The present results for the 100 orientation are combined in Fig. 5 with those obtained by Pearson and Suhl[4] in dc magnetic fields.

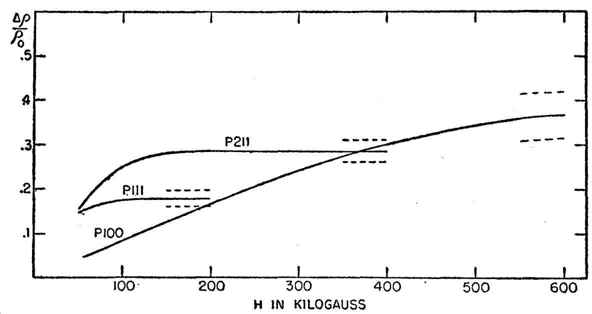

FIG. 4. P-type magnetoresistance *vs* magnetic field at 300°K.

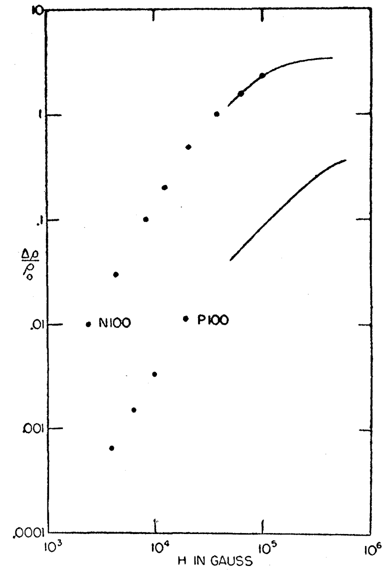

FIG. 5. N_{100} and P_{100} magnetoresistances (solid lines) compared with data taken from G. L. Pearson and H. Suhl, Phys. Rev. **83**, 768 (1951), (circles).

V. INTERPRETATION

The N-type results are in conformity with expectation regarding the effective mass ratio and collision time. The saturation values of the longitudinal magnetoresistance are given by

$$\frac{\rho_\infty^{100}}{\rho_0}=\frac{(2k+1)(k+2)}{9k},$$

$$\frac{\rho_\infty^{111}}{\rho_0}=\frac{(2k+1)(k+8)}{3(7k+2)}.$$

From $\rho_\infty^{100}/\rho_0=4.40$ one obtains $k=17.3$; from $\rho_\infty^{111}/\rho_0=2.40$, one obtains $k=17.0$. The result 17.2 ± 0.4 definitely lies above the values derived somewhat indirectly from low-field magnetoresistance measurements, and agrees better with the results of cyclotron resonance experiments at low temperatures. The large saturation values obtained for P-type crystals are contrary to ordinary expectation, especially in view of the rather slight temperature and impurity dependence of this effect. Even more striking is the disparity of field dependencies for crystals of different orientation.

VI. ACKNOWLEDGMENTS

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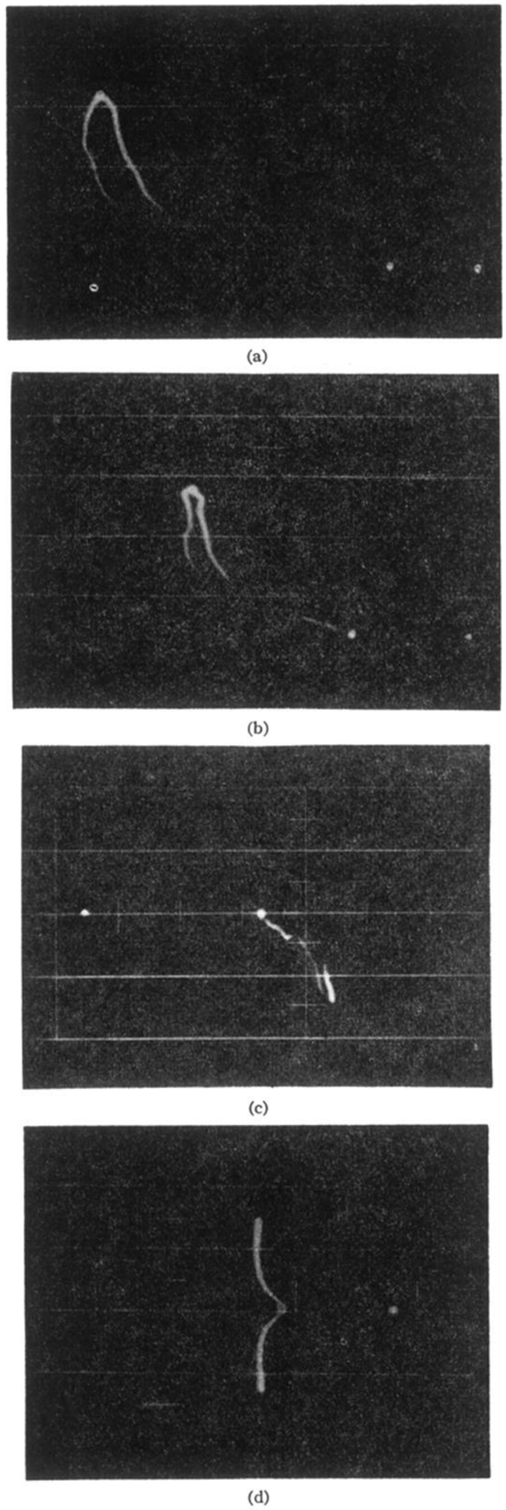
Note added in proof.—The authors are indebted to H. Suhl for showing them some low-temperature measurements which confirm the idea that there is no rise in K for N-type germanium as the temperature is reduced to 77°. This is also the finding, from low-field measurements, of W. W. Bullis,[9] who quotes a K of 17 at 300° and of 15 to 16 at 77°.

[9] W. M. Bullis, Massachusetts Institute of Technology, Lincoln Laboratory Technical Report No. 115 (1956).



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