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MAGNETICALLY SENSITIVE ELECTRICAL RESISTOR MATERIAL

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PERSONNEL

The project has been understaffed during the first months of its operation and efforts are being made to hire more, yet qualified, research personnel. In addition to the undersigned, Mr. R. L. Martin, a graduate student, worked on the project during the months of June, July, and August, while Mr. Tantreporn has been working since August.

GENERAL PROGRAM

The conductivity of any electrical conductor is affected by the presence of a magnetic field. This effect is called by some the Gauss effect and more generally the magnetoresistance (MR) effect. The final purpose of the present project is to develop a material that exhibits this effect very strongly. Difficulties are present both in the theory and in experiment. The theory has not been developed far enough to serve as a safe guide in choosing materials and conditions of treatment to enhance the effect. Experiment has been lacking in furnishing data that would be needed for a purposeful application of the theory. The field is therefore wide open, although the mass of theoretical and experimental work that is available is quite considerable. The material which, until recently, exhibited the largest magnetoresistance is bismuth. Recently intermetallic compounds of elements of the third and fifth columns of the periodic chart, possessing the zinc blende structure, have been found to exhibit even larger effects than Bi.[1]

As a first point on the program we wish to study bismuth with various contaminants thoroughly before embarking on the study of other materials. The reasons are obvious: among the elements that have been studied Bi shows the effect most strongly, and has been investigated in some detail, but by no means completely. Thus by duplicating what has been done we can check our methods for future work.

The theory is at present in a state which is well summarized in the second edition of A. H. Wilson's book on the theory of metals[2], which appeared just recently and is greatly revised in comparison to the first edition. The coefficient of magnetoresistance B, which functions in

$$\frac{\rho - \rho_0}{\rho} = \frac{\sigma_0 - \sigma}{\sigma} = BH^2 , \qquad (1)$$

where ρ = resistivity with field,
ρ_0 = resistivity without field,
σ = conductivity with field,
σ_0 = conductivity without field, and
H = magnetic field,

is given by some numerical factor times the square of the electron mobility over the light velocity. The numerical factor, according to Wilson, depends on certain details of the shape of the energy surfaces in momentum space and cannot at present be calculated from first principles. For free electrons Wilson asserts, following earlier work by Davis, that B vanishes. The greatest advance in the theory was achieved by L. Davis[3], but unfortunately Davis in working his theory out restricted himself to cubic materials; included only the first cubic harmonic following the sphere in his description of the dependence of the electron momentum k and the relaxation time t(k) on the energy E; went only to quadratic terms in H while his theory permits in principle the calculation of higher powers of H (see below); and committed a calculating error, as was pointed out by F. Seitz[4] in 1950 without, however going to the labor of correcting it entirely. It will be worthwhile to work this theory out further.

The question of the actual form of the dependence of $(\sigma_0 - \sigma)/\sigma$ on H also has interesting aspects. The first systematic measurements of this quantity by Kapitza[5] in 1929 showed that for low fields, up to a few kilogauss, the data were well represented by a formula of type (1), but for higher fields (he measured up to 300 kilogauss) a linear relation with H seems to fit best. Kapitza formulated a simple phenomenological theory which may be classed among historical relics at present. He noted that some materials show a tendency toward saturation of $(\sigma_0 - \sigma)/\sigma$ in very high fields, but concluded that this was an exception or complication, while the "true" dependence was supposed to be linear. Other authors soon presented theories based on the free electron approximation, leading to

$$\frac{\sigma_0 - \sigma}{\sigma} = \frac{BH^2}{1 + CH^2} . \qquad (2)$$

According to formula (2), saturation must always set in at sufficiently high fields (see for example F. Seitz[6] The Modern Theory of Solids). Formula (2) and its derivations represent sad examples of how erroneous theoretical results perpetuate in the literature for years because they happen to show fortuitous agreement with some experiments. Thus, while the usual derivation of (2) permits the calculation of effects only up to the order H, the result is interpreted up to order H^4. The discrepancy is clear from the fact that B, calculated along these lines, is off by a factor 10^4, compared with experiment, but C seems to be of the correct order of magnitude and this is taken as evidence for the usefulness of the theory. However, it is clear that an approximation which is poor for H^2 cannot be reliable for H^4 and is only accidentally correct.

Experimentally a formula of the type (2) will fit well those few materials which actually show saturation, but it is not clear whether saturation would be the rule or the exception when still higher fields are available. For most materials, all that can be said is that the increase for high fields is less than BH^2.

Theoretically the ideas of Davis can be worked out to yield an answer to this question, although considerable labor would be required. It is our intention to undertake an effort in this direction.

Of course, as has been recognized by various workers, the proper description of the effect in anisotropic media, even if one goes only as far as the second power of H, requires that B must have tensorial character. For accurate measurements and intercomparison of results from various samples of the same material, it is necessary to take this into account, especially if pronounced anisotropy is present such as with bismuth. In this connection the work of Donovan and Conn[7] is a good example. We are doing similar experiments (see below), finding B for various directions of H transverse to the current and at various angles to the trigonal axis.

The MR effect is known to increase for lower temperatures. While occasional measurements at various lower temperatures may have to be made, it is not intended to go into the low-temperature field with this work.

Another factor which has been known since Kapitza's work to be of great importance is the purity of the material used. Here two lines of research are of interest. In the first place, in accord with the general rule that the effect diminishes as a result of any impurities, it is our purpose to work with materials of highest purity and to try purification by zone melting and possibly other procedures. In the second place, it is not impossible that very small doses of certain specific impurities may be beneficial to the effect. We have done some preliminary work along this line (see below) but will follow this up further. Our belief that very large values for the MR effect of Bi can be obtained by careful treatment finds support in the work of Donovan and Conn, quoted earlier. These authors have measured many samples and found one freak sample whose effect was some ten times stronger than all the rest. They do not know what caused this, nor were they able to reproduce it. It must therefore be caused by a very minor variation in composition, structure, treatment or the like, and we hope to follow this up.

MATERIALS USED AND PROCESSING

Up to the present, experiments have been done with Merck Bi, whose purity is guaranteed to 98.5%. At a recent visit by Mr. Terhune from Fort Monmouth and Major Cottrell of Wright Field, it was suggested that Bi be supplied by the Fitzpatrick Company of Muskegon, Michigan. This material is said to be of higher purity and less brittle. It was also suggested that purification by zone melting be tried. Both suggestions will be followed up.

The bismuth that was at our disposal was alloyed with small amounts of Sn or Te. The Te alloys were too brittle to permit handling, soldering, etc. Annealing and other techniques will be tried to overcome this difficulty.

So far we have been successful in mastering and applying the technique of making wires and soldering leads to them, with the Sn alloys of Bi. These are made molten in a glass tube, which is then drawn out into a capillary. At two breaks the glass is peeled off a little, and soldering with woods metal is relatively easy. The wires are mounted in a mounting which permits rotation of the sample about its axis and insures thermal homogeneity (see below). The magnetic field is provided by a simple electromagnet. The wires have diameters of the order of 0.1 mm and lengths of the order of a few cm. The magnetic field covers an area of about 5 x 5 cm.

RESULTS OBTAINED

The results obtained so far are of a preliminary nature and serve only for our general orientation. The general trend of the data referring to the addition of Sn show that the MR effect decreases when Sn is added. At the time these data were taken we were not aware of the anisotropy effects reported by Donovan and Conn. A large part of the scattering of the data about a smooth curve is probably due to this cause. The measurements were performed with a simple Wheatstone bridge.

Sn added, % weight	$\Delta\rho/\rho$ at 6000 gauss
0	0.18
0.1	0.094
0.48	0.080
0.98	0.017
2.0	0.014 ± 0.006
3.1	0.004 ± 0.002
4.2	0.008 ± 0.003
0	0.18
0.09	0.13^5
0.20	0.07
0.24	0.11^5
0.42	0.04
0.50	0.09
0.70	0.05
0.89	0.04^5

The second set of data was to scrutinize the region of low concentration of Sn, but in view of the unknown impurities present in the Bi in comparable concentrations they are not too significant until checked with purer materials. So far we can conclude tentatively that addition of Sn always reduces the MR effect. Theoretically, if any increase of the MR effect is expected, it must occur in the region of very low concentrations of the added constituent.

The following results were obtained with a setup which permitted the wire to be turned through any angle about its longitudinal axis, which was perpendicular to the magnetic field. Since the longitudinal axis does not in general coincide with the trigonal axis of the Bi crystal, the plane defined by these two axes turns with respect to the magnetic field when the wire is turned, causing a variation of the MR effect. The field used was 534 gauss. The wire was Bi without added impurities. Care was required to avoid deformations

angle ϕ, degrees	0	20	40	60	80	100	120	140	160
MR effect $\frac{\Delta\rho}{\rho} \times 10^3$	1.39	1.45	1.48	1.45	1.39	1.35	1.28	1.25	1.31
angle ϕ, degrees	180	200	220	240	260	280	300	320	340
MR effect $\frac{\Delta\rho}{\rho} \times 10^3$	1.37	1.44	1.46	1.45	1.40	1.35	1.29	1.28	1.30

or temperature gradients of the samples. The soldering points were in contact with large copper blocks. The results are in general agreement with those of Donovan and Conn and others.

PLANS FOR THE IMMEDIATE FUTURE

The problems to be worked at in the immediate future are

a) The study of suitable conditions for zone melting purifications and heat treatment of samples.

b) Further measurements to determine the tensor constants B for bismuth for a number of samples. This will also require developing techniques for determining the orientation of the axes of the crystal.

c) Theoretical developments to work out the theory as given by Davis.

REFERENCES

1) See for example H. Weiss, Z. für Naturforschung 8a, 463 (1953).

2) A. H. Wilson, The Theory of Metals, 2nd Edition, Cambridge University Press, 1953.

3) L. Davis, Physical Review 56, 93 (1939).

4) F. Seitz, Physical Review 79, 372 (1950).

5) P. Kapitza, Proc. Roy. Soc. 123, 292, 342 (1929).

6) F. Seitz, The Modern Theory of Solids, McGraw-Hill, 1940.

7) Donovan and Conn, Phil. Mag. 41, 770 (1950).