THE HALL EFFECT IN BISMUTH WITH LOW MAGNETIC FIELDS

BY PALMER H. CRAIG

ABSTRACT

The Hall effect in bismuth for a magnetic field strength of from 0.07 to 1.00 gauss was accurately determined by improved methods. *Production of the bismuth films.* Various methods for obtaining excessively thin, homogeneous bismuth films were tried and compared, such as casting, electroplating, evaporating, sputtering, and metallic spraying, of which the last three methods were particularly successful. *Measurement of very low voltages.* By refinements made in the potentiometer and measuring circuits, readings to one-tenth micro-volt were accurate and reproducible. *Magnitude of the Hall effect at low fields.* The value of the Hall coefficient, R, is abnormally large between 0.07 and 0.30 gauss, having a value of -171 at 0.07 gauss, as compared with a value of -11 which R had for this film at 15 gausses. The value at 4220 gausses was -29. A curve is plotted showing the rapid decrease in the value of $-R$ between 0.07 and 0.30 gauss, and comparison is made with the higher values of field strength. It is noted that by putting the Hall potential of one film in series with one or more other films we obtain comparatively high values of the Hall e.m.f. which may be applied to great advantage as an alternating current rectifier in radio and similar applications.

INTRODUCTION

SINCE the discovery of the Hall effect in 1875 much has been done to elucidate this phenomenon both experimentally and theoretically. But, with the exception of Righi,[1] who employed fields comparable to that of the earth, and a few others, almost all investigators have used strong fields. It is important to know accurately the effect of low fields, to compare it with the known facts and to determine whether any abnormal relations exist. As the effect of the magnetic field is small in all cases, a great refinement in the potentiometer and measuring circuits is imperative with weak fields, and the preparation of the bismuth strips presents great difficulties and requires special methods.

PREPARATION—EXPERIMENTAL ARRANGEMENTS

Since the Hall effect increases with the thinness of the metallic strip, the first requisite was to prepare extremely thin films of metal. Bismuth and tellurium, which have the highest Hall coefficient of the ordinary metals, were selected and six different methods were tried in order to find the best and quickest way of making films which

[1] Righi, Jour. d. Physique 3, 127 (1884).

would be extremely thin and at the same time electrically continuous. These processes were casting, dipping, spraying, electroplating, evaporating, and sputtering.

Thin films of bismuth cannot be produced by casting unless pressure is exerted on the surface of the metal as it cools, and provision must then be made for lateral expansion when solidifying.

Surprisingly thin and uniform films were, however, obtained by dipping mica sheets into molten bismuth and using the metallic film which adhered to the mica. If the surface of the mica be slightly roughened with hydrofluoric acid, and care be used in withdrawing the mica from the molten metal, a very thin and uniform film can be obtained by this very simple and rapid method.

Much work was done by the author to produce very thin plates of bismuth and tellurium by the process of spraying molten metal. Excellent results were obtained both with the "Schoop" compressed air metallic spraying process, and also with the "Gravitas" metal dust spraying process. Cooperation in this part of the work was kindly rendered by the Metals Coating Company of Philadelphia. Both of these spraying processes involve spraying metals in the molten state by means of a compressed air gun. In the case of bismuth it was found advisable to use compressed nitrogen, instead of air, in order to prevent oxidation of the sprayed layer. When applied to mica, glass, and bakelite, excellent films of both bismuth and tellurium were obtained.

Attempts to produce homogeneous films by electroplating met with poor results, even when great care was used as regards temperature, speed of the rotating cathode, and concentration of solution.

Evaporation of molten bismuth in a partial vacuum produced very good results. Bismuth was placed inside an evacuated bell-jar and was melted by an electric heater. A glass plate, suspended above the arrangement, collected the evaporated bismuth in the form of excellent films.

Cathodic sputtering undoubtedly produces the thinnest films of any method. With reasonable care bismuth films can easily be prepared by this method so thin as to be quite transparent. Sputtering was accomplished by applying the secondary current of a 20,000 volt transformer to anode and cathode electrodes placed inside a bell jar evacuated to 30 microns. Rectification of the secondary current by a kenetron accelerated the action. A disc of bismuth 3.5 inches in diameter was used as a cathode, and the glass plate on which the film was to be sputtered was placed just outside the Crookes' dark space, which was about 2 cms long. With a current of 5 milli-amperes excellent films were produced on glass in about 20 minutes.

Disposition of the Apparatus

The very weak magnetic fields employed in this work were obtained from an air core solenoid. When a given current is passed through such a coil the field at the center is easily calculated. This calculated value was checked by a calibrated ballistic galvanometer in conjunction with a flip coil. The actual coil employed consisted of 100 turns of wire wound on a rectangular wooden form 8×11 cm in cross-sectional area, the size of this form being just large enough to accommodate the film used. The inductance of this coil was 2.5 millihenries, and it was therefore necessary to pass 35.2 milli-amperes through it in order to get a field of one gauss at the center. Because of the extremely low values of magnetic field used, it was necessary to shield the arrangement carefully from any action of the earth's and stray fields. Several methods were tried to accomplish this shielding, the one finally adopted being that of placing the set-up so that the plane of the bismuth film coincided exactly with the magnetic inclination of the earth's field at that point, thus eliminating any magnetic component in a direction perpendicular to the plane of the metallic film. Care was taken to keep all iron away from the vicinity of the apparatus, and upon actual measurement stray fields were found to be negligible.

Chemically pure bismuth for producing the films was furnished by Eimer and Amend and the film itself, obtained by any one of the previously described methods, was mounted on bakelite with sodium silicate as a binder. Contact at the ends for the longitudinal current was made by phosphor-bronze spring clips, and contact at the edges of the film, for picking up the transverse Hall potential, was obtained by means of small brass fingers attached to machine screws passed through the bakelite. The surface of the film was carefully cleaned with weak hydrochloric acid solution to remove surface oxides, and the entire film and connections were then painted with sodium silicate to keep semi-conducting layers of dirt and moisture from collecting on the surface of the film. In some cases it was even found advisable to mould the entire arrangement in sulphur to obviate this difficulty.

Since the potential differences to be measured were of the order of one microvolt, extreme care was taken to render the measuring apparatus very accurate and stable. The transverse Hall effect potential was measured by means of a Leeds and Northrup type K potentiometer, redesigned with a system of calibrated external shunts which increased the sensitivity of the instrument ten times. Four galvanometers of varying degrees of sensitivity were used with potentiometer for null readings, the most sensitive galvanometer having a sensitivity of 12.2 mm per M.V. The longitudinal current through the film was supplied by large storage cells, the output of which passed through a large filter system of two very large inductances in series with the line, the lines being shunted by two condensers of six microfarads each. This filter eliminated erratic action caused by sudden fluctuations of the longitudinal current occasioned by bubbling of the cells.

The main current through the potentiometer itself was passed through a similar filter and was allowed to flow over night before taking readings so that greater stability could be expected. The null potentiometer reading on the standard cell was checked before and after each measurement.

Great care was taken to eliminate all spurious effects. Thermal effects, of course, constituted the greater part of these corrections. Junctions of dissimilar metals in the circuit were reduced to a minimum, and the remaining potentials due to Thomson and allied effects were accurately measured the instant the longitudinal current was broken. Grounding one side of the potentiometer circuit was found to increase stability.

For the work at high magnetic fields, a large electromagnet was used. This magnet was capable of producing a field of 18,000 gausses in a narrow air gap, the field of which was measured by a calibrated ballistic galvanometer in conjunction with a flip coil.

Experimental Results and Discussion

Using a bismuth film obtained by metallic spraying, 3.5×8.0 cm in area and 0.012 cm thick, the results shown in Table I were obtained. These results are in agreement with those obtained with films of the other types described previously. In this table three different ranges of magnetic field strength were investigated with the same bismuth film and under the same general conditions. A longitudinal current of 1.5 amperes was used throughout Table I. The "residual" e.m.f. (measured in microvolts) which is referred to in the second column is the potential difference caused by the fact that the brass fingers which pick up the transverse Hall potential cannot possibly be placed at exactly equipotential spots with regard to the longitudinal current. These contacts were placed as near to equipotential points as possible and the remaining difference of potential was measured as given in the second column of the table. The second and third columns automatically include the sum of the thermal effects, since it is of course impossible to eliminate these thermal potentials from the potentials indicated in these columns. However, the spurious effects are eliminated when column two is subtracted from column three in order to get the net Hall e.m.f. in the fourth column. The Hall coefficient, R, given in the fifth column is calculated from the usual formula,[2] $R=Ed/IH$, where R is the Hall coefficient, d the thickness of the film in centimeters, I the longitudinal current in abamperes, H the magnetic field strength in gausses, and E the net Hall e.m.f.

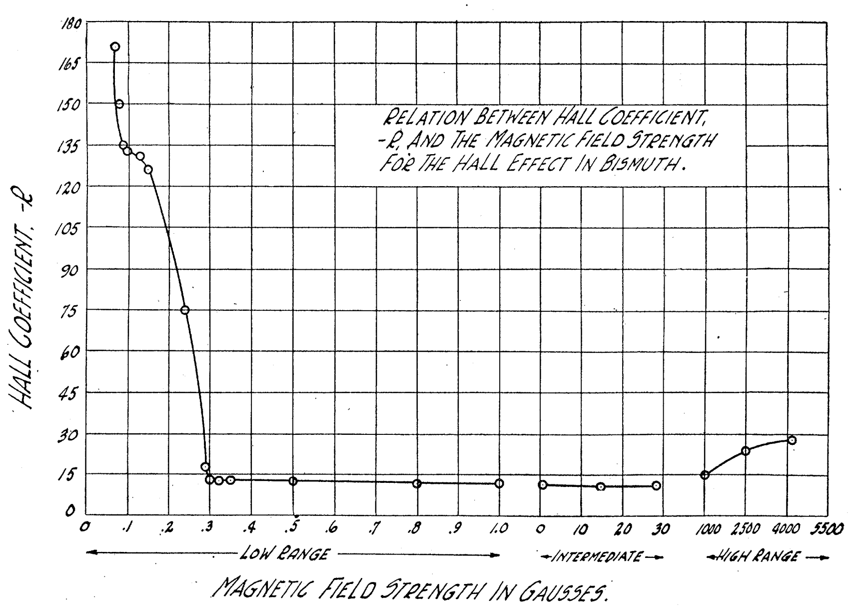

Fig. 1

It is immediately apparent that the Hall coefficient is abnormally high in the range of very low fields, and falls rapidly in value as the field is slightly increased. Reference to the graph shows a slight irregularity near 0.1 gauss, a straightening out of the curve at about 0.3 gauss, and then an approximately linear relation until a field strength of 1.0 gauss is reached. Readings in an intermediate range of zero to 30 gausses showed that $-R$ is practically constant at a value of 11 throughout this range. This value agrees very well with the value of 10.27 which Von Ettingshausen and Nernst[3] found for bismuth at a field of 1650 gausses. In the range from 1000 to 4200 gausses the

[2] L. L. Campbell, "Galvanomagnetic and Thermomagnetic Effects," p. 9.

coefficient increases slightly from 15 to 29. This curve was selected from a dozen similar graphs as being one of the most representative, and the irregularity in the neighborhood of 0.1 gauss is typical of similar irregularities in all curves obtained with the various films.

These results show that the value of $-R$ at very low fields is higher than has been heretofore suspected and that the curve for $-R$, plotted against field strength, shows a marked rise in this low range.

Each of the values in Table I are average values for approximately twelve readings at each value of field strength. These readings are reproducible to approximately one-tenth of a microvolt, and the readings forming the averages did not vary more than this amount.

During the course of the experiments an interesting incidental fact was discovered, namely that the Hall potential of one film may be put in series with that of one or more other films, the sum of these series potentials agreeing very well with the calculated sum of the Hall potentials of the individual films as observed separately. Although this fact has little application where quantitative readings of a high degree of accuracy are desired, it is of real importance in any application where larger values of Hall potential are desirable than those which can be obtained with a single film. The author is at

TABLE I

Hall effect in bismuth for low, intermediate, and high fields

Field strength (gausses)	"Residual" e.m.f. (μ volts)	"Residual" + Hall e.m.f. (μ volts)	Net Hall e.m.f. (μ volts)	-R
.07	14.0	15.5	1.5	171
.08	14.1	15.6	1.5	150
.09	14.2	15.7	1.5	135
.10	14.2	15.8	1.6	133
.13	14.4	16.1	1.7	131
.15	14.3	16.9	2.6	126
.24	14.0	16.3	2.3	75
.29	14.6	21.1	6.5	18
.30	14.5	19.8	5.3	14
.32	14.4	19.6	5.2	13
.35	14.8	20.5	5.7	13
.50	14.6	22.7	8.1	13
.80	14.6	26.6	12.0	12
1.00	14.6	29.6	15.0	12
1.0	14.5	29.5	15.0	12
15.0	14.3	35.1	20.8	11
28.5	14.4	60.4	46.0	11
1000	14.0	1889.0	1875.0	15
2500	14.0	7514.0	7500.0	24
4220	14.0	15324.0	15310.0	29

[3] Von Ettingshausen and Nernst, Wied. Ann. **29**, 343 (1886).

present using this additive principle in an application of the Hall effect to rectification of alternating current with a method similar to that described by DesCoudres.[4] The additive principle used in this connection produces a Hall potential of several volts in low fields with thin bismuth films, and thus gives the Hall effect a practical importance as a rectifier, especially in radio and similar applications. Work on the additive principle is also being done by Sarek.[5]

The results here presented indicate that there is considerable work to be done in further investigating abnormalities in the Hall coefficient at very low fields, and also suggest that certain modifications or explanations will have to be introduced into the theory of the Hall effect to account for the interesting changes in the Hall coefficient at low fields.

In conclusion, the author wishes to acknowledge his indebtedness to Dr. Louis T. More, Dr. R. C. Gowdy, and Dr. S. J. M. Allen for their kind help and valuable advice tendered throughout the progress of the work.

University of Cincinnati,
Physics Laboratory,
August 2, 1925.

[4] Des Coudres, Phys. Zeits **2,** 586 (1901).
[5] Sarek, Eleck. u. Maschinenbau, **43,** 172 (1925).