THE HALL EFFECT AND ALLIED PHENOMENA IN SILICON.

BY O. E. BUCKLEY.

THE Hall effect in silicon was first measured by Miss Wick[1] who obtained for the coefficient of the effect, R, the values, -120 for silicon 99 per cent. pure and -28 for silicon 96 per cent. pure. Miss Wick also made measurements of the thermal E.M.F. and the resistance of silicon.

Later Zimmerman[2] found the direction of the thermal E.M.F. of several specimens of silicon against copper to be opposite in direction to that which Miss Wick had determined although some specimens gave a thermal E.M.F. in the same direction as that which she had found. This peculiarity in the behavior of silicon led A. W. Smith[3] to make investigations of the Hall effect in these specimens. For four of his specimens he obtained values of R varying from $+40$ to $+60$. In all of these plates the direction of the thermal E.M.F. was such as to send a current from copper to silicon across the hot junction. In a fifth specimen he found $R = -20$ and in this specimen the thermal E.M.F. was in the opposite direction to that in the plates with the positive Hall effect.

Koenigsberger and Gottstein[4] measured the Hall effect in silicon containing 5 per cent. iron and found by direct measurement $R = +24.5$. They apply two corrections to this value, one for the error due to the Ettinghausen effect and one to change the adiabatic effect to an isothermal effect, the final result being $R = +110$.

Gottstein[5] also measured the Nernst effect in two pieces of silicon and found by direct measurement the values .0132 and .0116 for the coefficient of the effect, Q. He applies corrections as he did for the Hall effect and arrives at the values .0333 and .028. He does not indicate the direction of the effect.

The thermal E.M.F. of silicon against copper has been found by several observers to vary from $+.5$ to $-.5$ millivolt per degree. The

[1] PHYS. REV., 27, p. 76, 1908.

[2] Trans. Amer. Electro-chem. Soc., 15, p. 395, 1909.

[3] PHYS. REV., 30, p. 1, 1910.

[4] Phys. Zeit., 14, p. 232, 1913.

[5] Ann. der Phys., 43, p. 1079, 1914.

reversal of the thermo-electric behavior has been investigated by Fischer, Lepsius and Baerwind.[1] From their experiments they concluded that the reversal was due to the presence of SiO_2 in the silicon.

Measurements of the resistance of silicon have been made by several observers with widely varying results. Miss Wick[2] found values for the resistance in ohms per c.c. varying from .034 to .080 in the different specimens which she measured. Some of Miss Wick's specimens showed a steady decrease of resistance with rising temperature while other specimens showed minima at about 200° C. Koenigsberger and Schilling[3] with very pure silicon obtained the value .0885 at 15° C. The resistance-temperature curve of this specimen contained two discontinuities.

A list of several physical constants of silicon has been published by Zimmerman.[4] The thermal conductivity and Thomson coefficient have been measured by Koenigsberger and Weiss.[5] The Peltier coefficient has been measured by Gottstein.[6] Koenigsberger[7] has given a discussion of the electrical properties of silicon and similarly behaving substances with reference to the electron theory.

In most of the work on silicon and similar substances measurements of various electrical properties have been made with different specimens. Since different specimens, sometimes even if cut from the same piece, may vary widely in their electrical properties it is important that measurements of different properties be made with the same specimens.

This research was undertaken to determine whether the wide variations and reversal of sign of the Hall effect in various specimens of silicon were accompanied by marked variations in the Nernst effect and resistance. The temperature coefficients of these quantities were also measured to see if any apparent connection existed among them. For this purpose four specimens of silicon of widely varying degrees of purity were used. These specimens were donated by the Carborundum Company, who also kindly furnished analyses. The analyses of the specimens showed impurities as follows:

Unfortunately Plate I. was not very compact. It contained small blow holes, a few of which were over half a millimeter in diameter and over a millimeter long. These holes undoubtedly affected the results with this specimen seriously. Plate III. contained a few small pin holes, not more than four or five to the square centimeter, and of small depth.

[1] Phys. Zeit., 14, p. 439, 1913.
[2] Phys. Rev., 27, p. 11, 1908.
[3] Ann. der Phys., 32, p. 179, 1910.
[4] Trans. Amer. Electro-chem. Soc., 15, p. 395, 1909.
[5] Ann. der Phys., 35, p. 1, 1911.
[6] Ann. der Phys., 43, p. 1079, 1914.
[7] Jahrbuch der Rad. u. Elek., 11, p. 84, 1914.

Specimen.	Fe, Per Cent.	Al, Per Cent.	Si (by Difference), Per Cent.
I................	0.35	0.19	99.46
II................	3.50	0.23	96.27
III...............	3.38	2.55	94.07
IV...............	7.27	3.35	89.38

Plates II. and IV. were quite compact. None of the specimens contained any surfaces of separation.

Plates were sawed from irregularly shaped blocks of silicon to the shape shown in Fig. 1 by means of a vulcanite carborundum wheel which was arranged to run in a trough containing water and fine carborundum powder. On account of the limits set by the blocks from which the plates were cut, the dimensions of the plates varied somewhat with the different specimens. The approximate dimensions were, length 4 cm., width 1.8 cm., thickness 0.5 cm., length of side arms from 0.8 cm. to 2.4 cm. In every case the side arms were made as long as possible.

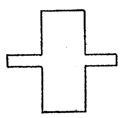
Fig. 1.

The ends of the plates and the ends of the side arms were heavily copper plated. Wires soldered to the copper on the ends of the plate served for leads for the current through the plate. Wires soldered to the copper on the ends of the side arms led to a potentiometer which was used to measure the Hall E.M.F. Near each end of the plate a very narrow copper band was plated onto the silicon completely encircling it. These bands served as contacts to measure the resistance by the fall of potential method. In making measurements of the Hall effect and resistance at various temperatures the plate under test was placed in a double-walled copper vessel held between the poles of a large Weiss electro-magnet. The desired temperature was obtained by circulating water between the walls of the vessel. For the highest temperature steam was used. Readings were taken at four different temperatures between 0° and 100°.

The pole pieces of the magnet were 10 cm. in diameter and were placed 2.2 cm. apart. Over the area of the plate the field was practically uniform. For most of the measurements of the Hall effect a field of about 9,000 gauss was used.

The difference of potential between the side arms and between the resistance contacts was measured by means of a low resistance potentiometer and a sensitive D'Arsonval galvanometer with small period. In making measurements of the Hall effect a current through the plate of about .16 ampere was generally used. A larger current caused objectionable thermal disturbances. The effect of any gradual temperature change was cancelled out by taking a series of readings at equal time intervals, reversing the field after each reading.

The coefficient of the Hall effect, R, is defined by the equation

$$E = RiwH,$$

where E is the Hall E.M.F., i, the current density, w the width of the plate, and H, the intensity of the magnetic field. If I, the whole current in the plate is used in place of i, the current density, the equation may be written

$$R = \frac{Et}{IH},$$

where t is the thickness of the plate.

Plate II. was found to have a negative Hall effect while the other three plates had the positive Hall effect. The values obtained for the coefficient, R, are plotted in Fig. 2. The negative values for Plate II. are plotted as positive.

The resistances of the same plates were measured at various temperatures by comparing the fall of potential through the plate to that through a standard resistance connected in series with it. The fall of potential was measured by connecting the potentiometer to the two copper bands placed near the ends of the silicon plate. Measurements of resistance were made while the plate was held in position for measuring the Hall effect. This arrangement also permitted making a test of the effect of the magnetic field on the resistance of the silicon. No effect

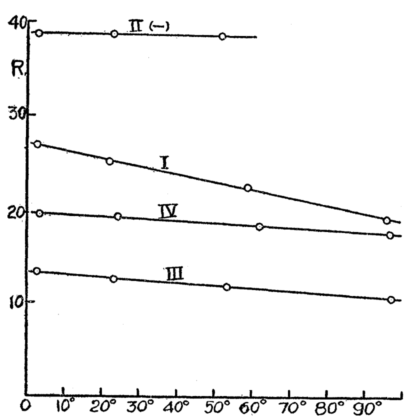

Fig. 2.
Variation of Hall Effect with Temperature.

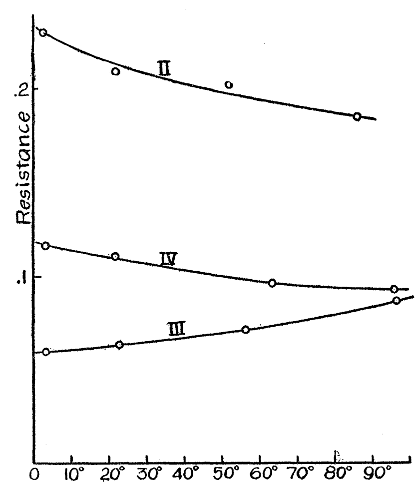

Fig. 3.
Variation of Resistance with Temperature.

could be observed and the change of resistance in a magnetic field of 10,000 gauss was shown to be less than 0.05 per cent.

In attempting to measure the resistance of Plate I. great difficulty was experienced especially at the higher temperatures. No steady reading could be obtained at the higher temperatures and the apparent resistance at room temperature would be found to have changed after heating and cooling. This was probably due to varying contact resistance at the ends of the plate and consequent deflection of the current flow lines. The results obtained for Plate I. were so erratic that no definite value of the resistance can be given. The same difficulty was experienced to a less degree with Plate II. and the value of its resistance at the highest temperature is doubtful. The other two plates gave results which could be repeated.

The values obtained for the specific resistances of the different specimens are plotted in Fig. 3. No correction has been made for the influence of the side arms on the resistance.

Fig. 4 shows the arrangement of apparatus used in making measurements of the Nernst effect. The copper plating on the ends of the silicon plates was ground to fit the grooves in the ends of the copper

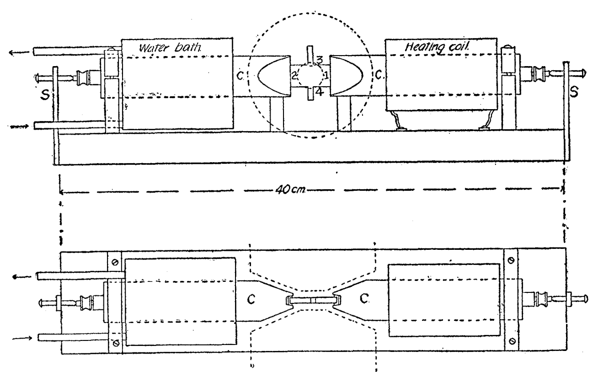

Fig. 4.

bars, *C*. The bars were pressed together against the plate by stiff steel springs, *S*. These bars served both as heat and electrical conductors. For the sake of insuring more uniform contact for heat flow thin tin foil was placed between the copper plating on the ends of the silicon plate and the copper bar.

One of the copper bars was surrounded by a heating coil of nichrome ribbon insulated from the copper by thin asbestos paper. The heating coil was covered with asbestos paper and a clay cylinder to prevent loss of heat. The other copper bar was provided with a water bath through which water at the desired temperature was circulated. In order to make as uniform a temperature gradient as possible and to prevent thermal disturbances the silicon was covered with two layers of wool felt.

Temperatures were measured by means of copper-advance thermo-junctions placed at positions 1, 2, 3 and 4 as indicated in Fig. 4. Each junction was fastened to one side of a small fiber cube and pressed against the silicon by a stiff brass spring. The junctions in positions 1 and 2 were separated from the silicon by thin sheets of mica not over .01 mm. thick. This was found necessary on account of the difficulty in placing the wires exactly parallel to equal temperature lines.

Readings of the Nernst effect were taken at intervals of 30 seconds, the magnetic field being reversed after each reading. By leaving the field on continuously except for the time required for reversal, errors due to the effect of the magnetic field on the E.M.F. of the copper-silicon junctions or to the effect of the magnetic field on the heat current in the plate were avoided. One half the observed change of potential difference between the side arms on reversing the field was taken as the Nernst E.M.F. Correction was made for the non-uniformity of the magnetic field across the plate necessitated by the small area of the pole face.

Measurements of the Nernst E.M.F. were taken with varying magnetic field and for several different temperatures with each plate. In every case the E.M.F. was found to be proportional to the field strength up to the limit of field strength used, about 20,000 gauss.

The coefficient of the Nernst effect, Q, is defined by the equation

$$E = \frac{Qdt}{dx} wH,$$

where dt/dx is the temperature gradient. If we assume that the temperature gradient is uniform and let t_1 and t_2 be the temperatures at junctions 1 and 2 respectively and led d represent the distance apart of those junctions, we may write

$$Q = \frac{Ed}{(t_1 - t_2)wH}.$$

The direction of the Nernst effect was found to be the same in all four of the plates. The values found for the coefficient, Q, are plotted in Fig. 5.

Since the Hall and Nernst effects for silicon are quite large as compared with metals it was expected that the corresponding transverse temperature effects would also be large and possibly measurable by a D'Arsonval galvanometer. However, no positive results for these effects were obtained and all that could be done with this apparatus was to set an upper limit to the values of the coefficients of these effects.

To measure the transverse temperature change the thermojunctions at positions 3 and 4 (Fig. 4) were used. Since they were in contact with the silicon these junctions could not be used in series but each had to be used separately against a similar junction in ice. Two minutes time was allowed after reversing the field, before making a reading, to allow time for the effect, if any, to develop.

The results obtained varied too widely to set a definite value for the effect or to be sure of its direction. For the sake of setting a safe upper limit twice the observed value is given as an upper limit. This is about equivalent to adding to the observed effect three times the probable error in such a way as to increase the value of the effect. The upper limit set in this way for the Ettinghausen coefficient, P, is $P < 3 \times 10^{-6}$ corresponding to a temperature change of about .02°. Limits of the same order of size were obtained for each of the four plates. Comparison of this value with the values found for other substances shows that it is not surprisingly small and no significance would be attached to it were it not that Gottstein[1] reports a value of P for silicon of 2.65×10^{-3}. Such a large effect as that could hardly fail to be detected.

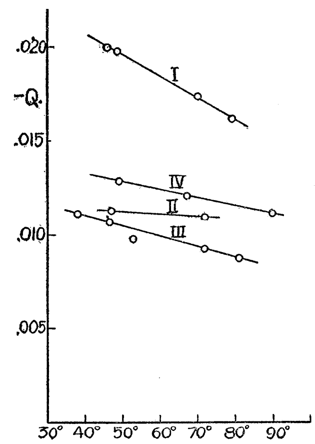

Fig. 5.

Variation of Nernst Effect with Temperature.

Koenigsberger[2] mentions that this effect is so large that it can cause a very large error in the measurement of the Hall effect on account of the transverse change of temperature introducing a thermal E.M.F. We may feel quite sure that this did not cause an error in the measurements reported in this paper, since the use of the side arms would prevent such an effect, and if there were any at all it would be very slow in building up on account of the time required for heat to travel along the side arms to the copper contacts. That there was no such effect was shown by the fact that the galvanometer would come to rest within fifteen seconds after applying the magnetic field.

With a large temperature gradient measurements of the Leduc effect were also attempted. The upper limit set in the same way for the coefficient of the Leduc effect, S, is $S < 5 \times 10^{-8}$ corresponding to a temperature change of about .02°. If this result is compared with the values of S for other substances possessing a large Hall effect it is seen to be very small. Gottstein[3] reports for the Leduc effect in silicon a

[1] Ann. der Phys., 43, p. 1079, 1914.

[2] Jahrbuch der Rad. u. Elek., 11, p. 84, 1914.

[3] Ann. der Phys., 43, p. 1079, 1914.

value of 2.5×10^{-7} which would result in a temperature difference of about .1° under the conditions of this experiment.

The direction of the thermal E.M.F. of the different specimens against copper was tested by connecting one terminal of the galvanometer in series with a high resistance to the copper plating on the silicon plate. The other terminal was connected to a pointed copper rod which was heated by an insulated heating coil wound around it. The point of the rod was then touched to various points on the plate under test. Plates I., III. and IV. gave a deflection always in the direction indicating a current from copper to silicon at the hot junction although the amount of deflection varied greatly with the different points touched. Plate II. gave mostly the opposite direction although occasional points touched gave the same direction as the other three plates. The occasional points in Plate II. which gave the opposite effect were mostly near one end of the plate and were not distributed in any systematic way as far as could be seen.

The following table gives a summary of the results obtained for purposes of comparison.

Plate.	I.	II.	III.	IV.
Hall effect at 50°	+23	−39	+12	+18
Nernst effect at 50°	−.020	−.0113	−.0105	−.013
Specific resistance at 50°		.20	.07	.10
Temp. coef. of Hall effect	−.0031	0	−.0022	−.0011
Temp. coef. of Nernst effect	−.0057	−.0010	−.0053	−.0032
Temp. coef. of resistance		−.0023	+.0047	−.0022
Direction of thermal E.M.F.	+	−	+	+

According to the conclusions which Koenigsberger has drawn from his work the ratio of the resistance to the coefficient of the Hall effect might be expected to be approximately the same for the different specimens. While this happens to be the case at 50° for the three specimens whose resistance was measured, it appears to be entirely accidental since the temperature coefficients of these quantities are not at all in harmony. There appears to be a much closer relation between the temperature coefficients of the Hall and Nernst effects. If the specimens are arranged in order with reference to the temperature coefficients of the Hall effect they are also in order with reference to the temperature coefficients of the Nernst effect. However there is no apparent connection between the magnitudes of these two effects with the different plates.

Summary.

The Hall effect, Nernst effect and resistance of four specimens of silicon have been measured at several different temperatures.

The reversal of the Hall effect, which is connected with a reversal of its thermal E.M.F., is not accompanied by a reversal or peculiarity in size of the Nernst effect nor by a peculiarity in the resistance.

The temperature coefficients of the Hall and Nernst effect are found to be similar but do not bear any apparent relation to the temperature coefficient of resistance.

The extraordinarily large Ettinghausen and Leduc effects in silicon reported by Gottstein are not confirmed.

The change of resistance of silicon in a magnetic field of 10,000 gauss is less than .05 per cent.

The writer is under obligation to Professor Merritt who proposed the investigation and made many helpful suggestions.

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