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Research on the Ferromagnetic Property and Electrical Conductivity of Magnetite*

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Synopsis

In succession with the former paper, magnetic moment, electric conductivity and magneto-resistance of natural and artificial magnetites have been measured before and after the transformation. It has been found that the amount of the change in magnetic moment of artificial magnetite at the transformation in the magnetic field strength of 828 örsted varies according to the heat treatments and that the activation energies of both magnetites have been determined.

Introduction

It is expected theoretically that in the ferromagnetic property of a semiconductor, unlike in the magnetic property of metals, the intensity of magnetization approaches zero at absolute zero temperature.

The intensity of magnetization of magnetite, which is considered as the representative ferromagnetic semiconductor, decreases abruptly at −160°C or thereabout. This is very interesting to note from the point of experiment, as a key to solve the general problem of ferromegnetism of a semiconductor may be found by measuring the electric conductivity, Hall effect and specific heat near its transformation. Conversely, observing this transformation, we may critisize theory of ferromagnetism of a semiconductor for the accepted way by which it explains away this transformation.

As a material of experiment, first, the magnetite produced at Kamaishi district was used. But here in order to give general results, artificial magnetite was taken and compared with natural magnetite. The making of artificial magnetite and the change in its electric conductivity under various treatment is described minutely in a former paper⁽¹⁾. So, only its magnetic property and the electric conductivity shown in the transformation at −160°C are given here.

Experimental Results

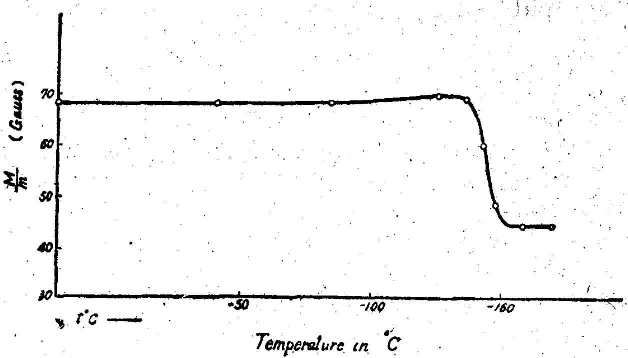

Fig. 1

Fig. 1 shows the magnetic moment of a unit mass of Kamaishi magnetite measured in the external magnetic field of 828 Örsted by means of Ballistic method from 0°C to the temperature of liquid air, the ordinate being the magnetic moment of a unit mass and the abscissa successive temperatures. The figure shows the decrease of about 1/3 of the intensity of magnetization at −160°C.

Fig. 2 shows a similar measurement of artificial magnetite; the amount of the change in magnetic moment of artificial magnetite at the transformation varies according to the heat treatment; those amounts are 7 gauss, 17 gauss and 25 gauss, corresponding to the samples a, b and c, each of which is treated in 5×10^{-3} mmHg, 1 mmHg and 10 mmHg vacuum, respectively, for one hour at 900°C. It is found that the rate of transformation amount of artificial magnetite is sometimes greater than that of natural magnetite. But

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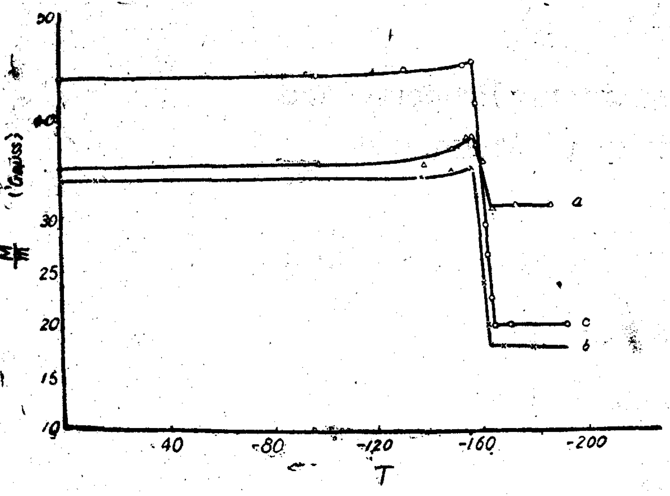

Fig. 2

how about their electric conductivity measured before and after the transformation? The measurement of the electric conductivity of natural magnetite was already made by one⁽²⁾ of the writers and was found to have a rapid decrease near the transformation.

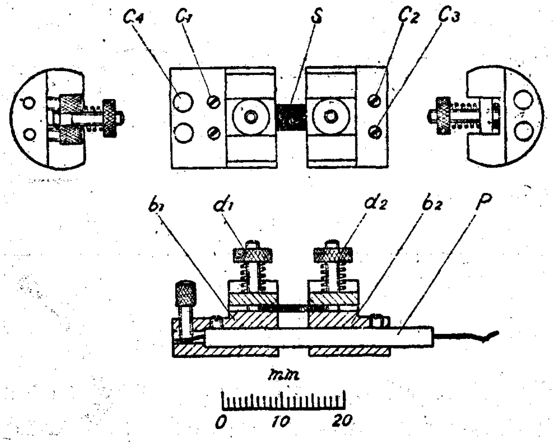

Fig. 3

Fig 3 is a measurement arrangement of electric conductivity. Both ends of specimen S are fastened with springed screws a_1 and a_2 to fixture b_1 and b_2, which are joined with a slender porcelain tube P fixed with screw c_1 and c_2 also to the fixtures. A leading wire fixed to b_1 with screw c_4 goes outside, passing through p, while another leading wire is fixed to screw c_3. For the contact of the experimented material and electrodes aquadag is used. In order to keep the temperature constant and the heat capacity great, the whole arrangement is put in a glass tube, which is filled with pulverized glass and from which atmospheric pressure is removed by a vacuum pump. Again, the outside of the glass tube is covered with a thin silver plate, by which the constancy of temperature is assiduously maintained. This glass tube steeped two hours in liquid air in Dewar vessel, and as the material to be experimented is completely cooled to the temperature of liquid air, measurement is made by heating very slowly after the liquid air is evaporated little by little. Between heating and cooling processes no irreversible change is noticed in case of magnetite, so for ease in measurement, heating one is adopted. Care is taken to do this very slowly, as electric conductivity changes its direction by temperature, if heating velocity is irregular.

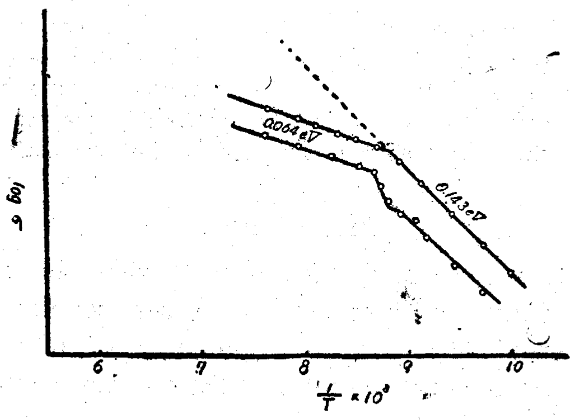

Fig. 4

Fig. 4 is two examples of the measurment of natural magnetites, showing log σ in ordinate and reverse numbers of temperature in abscissa; the change of electrical résistance for temperature at the transformation has sometimes some range of temperature, but the amounts of activation energies above and below transformation point do not relate to it, in spite of showing two kink points on the curve, ($\log\sigma \sim 1/T$). From this the electric conductivity of the magnetite is known to follow: -

$$\sigma = \sigma_0 e^{-\frac{E}{kT}}$$

in which E is activation energy and k, Boltzmann's constant. In general, at -160°C of the transformation point, a change in electric conductivity is noticeable, and the activation energy on the lower temperature side of the transformation point is 0.143 eV, and that on the higher temperature side is 0.064 eV.

One⁽²⁾ of the writers measured the resistances against temperatures, so by getting the logarithm of the reverse numbers of the resistances against the reverse numbers of temperatures, two kink points were found at the magnetic transformation. By this the activation energy on the lower temperature side is 0.15 eV, which nearly agrees with that of the other measurement, but on the higher temperature side, it is 0.059 eV, which is somewhat different from 0.064 eV. This difference is due to the experimented material as shown by the measurement of electric conductivity of artificial magnetite.

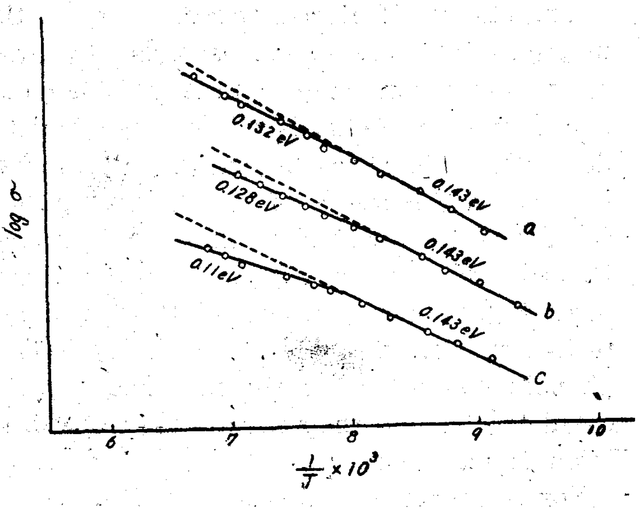

Fig. 5

Fig. 5 shows the result of the measurement of electric conductivity of artificial magnetite, corresponding to a, b and c of Fig. 2. In artificial magnetite, the kink point is also noticeable at its magnetic transformation point. The activation energy on the lower temperature side of this transformation point is 0.143 eV, which is some as that of natural magnetite, but the activation energy on the higher temperature side is 0.11-0.132 eV, which is greater than that of natural magnetite. This difference of activation energy is considered to be due to the amount of change of magnetic moment at the transformation point.

To state more minutely, by comparing Fig. 2 and Fig. 5, the amount of change in magnetic moment at the magnetic transformation of artificial magnetite, a, b and c, corresponds to the difference of activation energies above and below transformation point. But looking at the comparison between natural and artificial magnetites from this point, we find it difficult to explain away that the rate of the transformation amount in magnetic moment of artificial magnetite is greater than that of natural magnetite.

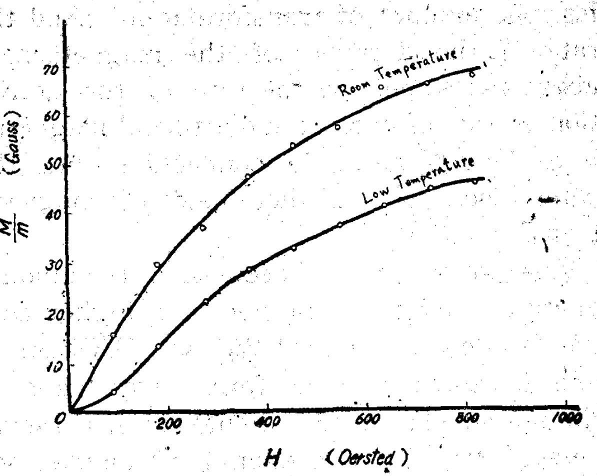

Fig. 6

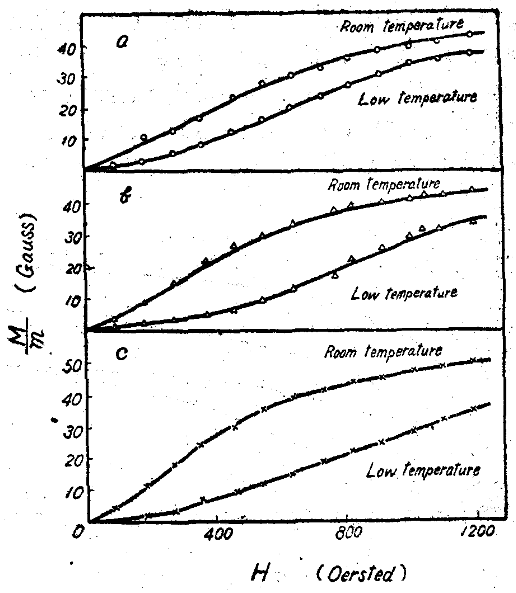

Fig. 7

So we will now trace the magnetization curves of natural and artificial magnetites at the room temperature and the temperature of liquid air. The curves of natural and artificial magnetites are respectively shown in Fig. 6 and Fig. 7. As is known by Fig. 1 and Fig. 2, the magnetism of magnetite at the room temperature and that at the temperature immediately before the transformation are almost the same. The amount of magnetism between the magnetization curves at the low temperature and those at the room temperature in Fig. 6 and Fig. 7 at any point of the abcissa is to be considered as the amount of change in magntism of the transformation measured in that magnetic field. In Fig. 6, the amount of magnetic transformation of natural magnetite don't decrease, but in case of artificial magnetite in Fig. 7, the higher the magnetic field, the less the amount of transformation. And the rate of the decrease of the magnetism is about the same. So the rate of the activation energy of natural and artificial magnetite is to be considered in connection with the comparison in a higher field of magnetic transformation.

The phenomenon of decrease in the amount of magnetic transformation in a higher field has been measured by P. Weiss,(3) T. Okamura and S. Ogawa.(4) The former was taken by the specimen steeped in liquid air in a Dewar vessel between the poles of electromagnet, so the strictest measurement in weak field could not be performed. We have measured the magnetic field effect of the transformation of natural and artificial magnetites by giving an instantanious strong current through solenoid (coil constant-150), specially contrived for its cooling.

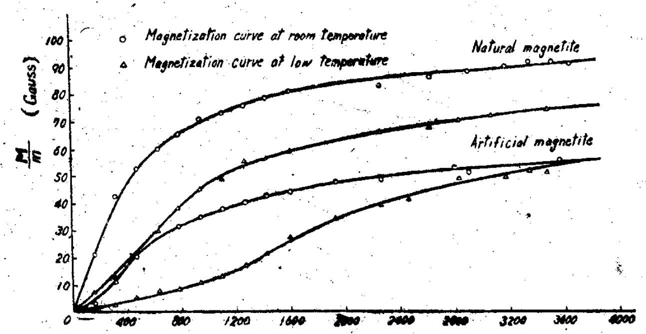

Fig. 8

By Fig. 8, the transformation amount of natural magnetite is decreased from 27 gauss in 800 Örsted to 17 gauss in 3600 Örsted and that of artificial magnetite from 24 gauss in 800 Örsted to 2 gauss in 3600 Örsted. Notice should be given to the magneto-resistance effect at the low temperature in the wide range of magnetic field.

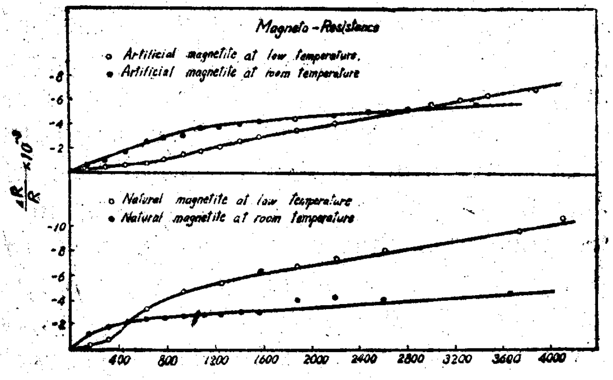

Fig. 9

Fig. 9 is the magnetic field effect of electric conductivity of natural and artificial magnetites at the room temperature and the temperature of liguid air. At low temperature, electric conductivity in magnetic field increases more than at the room temperature, and at 4000 Örested, the rate of the increase is in about 1%. The external magnetic field at this time was obtained with solenoid as in the measurement in Fig. 8.

The change of electric conductivity to the magnetic field does not corresponds, of course, to the magnetic field effect of magnetic transformation. That is to say, the magnetic field effect of electric conductivity, corresponding to the decrease of the transformation amount, should be more than ten percent. But as is known by Fig. 9, it is very small near 4000 Örsted, at which the magnetic transformation decreases remarkably. This phenomenon makes it difficult and complicated to clear up theoretically the transformation of magnetite.

For this problem, we may find more essential meaning in measuring the change of specific heat by magnetic field at the transformation point.

The consideration on electronic construction of magnetite will be attempted, we hope, in the next paper on the Hall effect and the change of specific heat by magnetic field.

Summary

In the present paper the measurement of the change of electric conductivity due to temperature above and below the transformation point in the vicinity of $-160°C$ is given, and the activation energy attending to this state and the amount of change in magnetic moment are treated. Also, the magnetization curves of both natural and artificial magnetites at the room temperature and the low temperature in the magnetic field to 4000 Örsted are measured as well as their magneto-resistance effect.

In the range of our experiment, the magnto-resistance effect does not correspond to the change of magnetic moment attending to the transformation.

In conclusion the authors express thanks to Miss Kcko Takahashi for her enthusiastic help during the course of the work.

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