SOME FEATURES IN THE TEMPERATURE DEPENDENCE OF THE ELECTRICAL RESISTANCE OF FERROMAGNETIC METALS AT LOW TEMPERATURES

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Submitted to JETP editor November 28, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 1022-1026 (April, 1962)

Measurements have been made on the temperature variation of the electrical resistance R of the pure metals iron and nickel in the helium and hydrogen range of temperatures. In the helium range of temperatures an additional scattering mechanism for conduction electrons —at spin waves—manifests itself as an additional linear term in the variation of R(T). The existence of this scattering mechanism is confirmed by the decrease of the linear term in the presence of a magnetic field.

At low temperatures the total electrical resistance of a ferromagnetic metal can be represented approximately by the sum

$$R = R_0 + R_1 + R_2 + R_3. \tag{1}$$

Here, R_0 is the resistance caused by the scattering of conduction electrons at impurities, defects of the crystalline lattice, and scattering at domain boundaries; over a narrow range of temperatures R_0 can be considered to be independent of temperature; R_1 is the phonon part of the resistance,[1] which for temperatures $T \ll \Theta_D$ is proportional to T^5; R_2 is the resistance caused by electron-electron interaction, which varies with temperature as T^2;[6] R_3 is the resistance, occurring only in ferromagnetic metals, caused by the scattering of conduction electrons at spin waves;[2-4] at low temperatures $R_3 \sim T$.

It is reasonable to expect that the contribution to the electrical resistance which is described by the lowest powers of the temperature dominates at very low temperatures. It has been shown previously that, at helium temperatures, the temperature variations of the resistance for nickel and iron are well described by the expression[2]

$$R_T/R_{0^\circ \mathrm{C}} = R_{0^\circ \mathrm{K}}/R_{0^\circ \mathrm{C}} + AT + BT^2, \tag{2}$$

$R_{0^\circ \mathrm{K}}/R_{0^\circ \mathrm{C}}$ is the residual resistance. For the iron it was 3.92930×10^{-2} and for the nickel 1.00986×10^{-2}. The iron was of 99.98% purity and the nickel 99.94%. It was of interest to study further the temperature variation of the electrical resistance on purer specimens and over a wider range of temperatures.

At our disposal was very pure iron, of purity > 99.99%, which has a residual resistance one order of magnitude smaller than in the previous studies. The present article contains the results of measurements for one of the specimens of iron grown by distillation in vacuum in the form of a needle, and having a grain size approximately equal to the specimen diameter.* The transverse dimension of the specimen was ~ 0.1 mm and its length was 38 mm. The residual resistance in the demagnetized state is 3.9606×10^{-3}.

The temperature variation of the resistance of iron was studied in the ranges 1.23 to 4.2°K and 14 to 20°K. Data was also obtained for nickel and platinum in the interval of temperature 14 to 20°K. The resistance was measured by the usual compensation method on a PPTN-1 potentiometer.

IRON

Since even the earth's magnetic field significantly affects the domain structure of very pure iron specimens, and this affects the electrical resistance, the measurements were made with the earth's field compensated. Compensation to within 0.5% was obtained by Helmholtz coils.

Changing the direction of the measuring current also changes the domain structure. This led to a large scatter during resistance measurements. A large scatter was observed particularly when the earth's field was not compensated. The position was stabilized by establishing the state of the domain structure by demagnetizing the specimen, with an alternating magnetic field (50 cps) of decreasing amplitude, after each change in the direction of the measuring current. This made it

*We take the opportunity to thank V. E. Ivanov for kindly donating the iron specimens.

possible to stabilize the scattering of conduction electrons at domain boundaries, and thus to obtain the minimum scatter during measurements.

The results of measuring the temperature behavior of the electrical resistance in the interval 1.23 to 4.2°K are given in Fig. 1. The curve R(T)

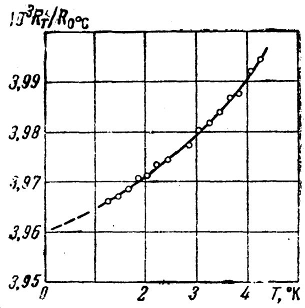

FIG. 1. Temperature dependence of the electrical resistance of iron with the earth's field compensated.

for iron of such purity is described by a polynomial of the form (2); in fact:

$$R_T/R_{0°\,\mathrm{C}} = 3.9606\cdot 10^{-3} + 3.1\cdot 10^{-6}\,T + 1.10\cdot 10^{-6}\,T^2. \quad (3)$$

The term of order T^5 is negligibly small in this region of temperature, and does not appear for the accuracy obtaining in the experiment.

The coefficients of T and T^2 and the residual resistance $R_{0°K}/R_{0°C}$ are calculated by the usual methods. The temperature variation of the resistance in this specimen can also be represented in the form

$$R_T/R_{0°\,\mathrm{C}} = R_{0°\,\mathrm{K}}/R_{0°\,\mathrm{C}} + bT^n, \quad n = 1.45. \quad (4)$$

However, from the physical point of view, it is natural to represent the temperature behavior of the electrical resistance as a polynomial, each term of which corresponds to a definite scattering mechanism of the conduction electrons. The presence of a linear term in (2) indicates the existence of the additional scattering of conduction electrons by spin waves—ferromagnons—which should have a linear variation on temperature.[3] We can therefore expect that the scattering by ferromagnons can be eliminated by a magnetic field[3,7] when $\mu H \sim kT$. Some confirmation of this was obtained by studies of the variation R(T) in a magnetic field. Whereas, if the earth's field is compensated, the temperature variation of the resistance is described by (3), for the comparatively small field of 850 Oe, the ratio of the coefficients changes so as to diminish the linear contribution. The curve R(T) in a magnetic field of 850 Oe is described by an expression of type (2), namely:

$$R_T/R_{0°\,\mathrm{C}} = 2.6058\cdot 10^{-3} + 1.90\cdot 10^{-6}\,T + 1.65\cdot 10^{-6}\,T^2. \quad (5)$$

The decrease in the magnitude of the residual re-

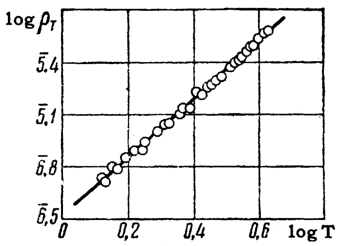

FIG. 2. Temperature dependence of the ideal electrical resistance of iron in a magnetic field of 850 Oe.

sistance in the magnetic field is associated with the elimination of scattering at domain walls.[5]

In Fig. 2 is given the dependence of the ideal electrical resistance on temperature (in a logarithmic scale) for measurements in the magnetic field. The experimental points lie well on a straight line, for which the tangent of the angle of slope is n = 1.682.

It is probable that the use of stronger magnetic fields could completely eliminate scattering at ferromagnons and, simultaneously, eliminate the linear term in the temperature variation R(T) at helium temperatures.

Data for the hydrogen temperature region with the earth's field compensated are given in Fig. 3. The temperature variation of the electrical resistance in the wide range of temperature from 1.3 to 20°K is not described by a single law: in the helium range R(T) is approximated by equation (2), whereas in the range 14 to 20°K it is described by the polynomial

$$R_T/R_{0°\,\mathrm{C}} = R_{0°\,\mathrm{K}}/R_{0°\,\mathrm{C}} + bT^2 + dT^5 \quad (6)$$

with $R_{0°K}/R_{0°C} = 3.9606 \times 10^{-3}$, $b = 1.64 \times 10^{-6}$, and $d = 4.02 \times 10^{-11}$.

The curve R(T) in the region 14 to 20°K can also be described by two terms as in (4) with the exponent n = 2.28.

A similar variation also applies in an external magnetic field of 850 Oe. The temperature variation of the electrical resistance is described in this case by

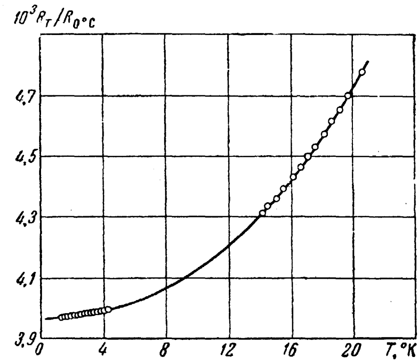

FIG. 3. Temperature dependence of the electrical resistance of iron with the earth's field compensated.

$$R_T/R_{0^\circ C} = 2.6058 \cdot 10^{-3} + 2.11 \cdot 10^{-6} T^2 + 2.33 \cdot 10^{-11} T^5 \quad (7)$$

or an expression of type (4) with n = 2.15.

It can thus be said that, in the region of hydrogen temperatures, scattering of conduction electrons by thermal vibrations of the lattice is already evident (an additional term $\sim T^5$ appears).

The results obtained show an effect of magnetic field on the coefficients of T^2 and T^5. The cause of this variation is not at present clear. We note that no linear term appears in pure iron at hydrogen temperatures.

NICKEL

Results on R(T) in the helium region have been presented by us previously.[2] In the present communication, results up to higher temperatures (20°K) are given. For measurements in hydrogen, the specimen was placed in a glass tube filled with gaseous helium, since direct contact of nickel with hydrogen changes the electrical resistance of nickel specimens due to the diffusion of hydrogen into nickel, even at room temperature.

Over the wide range of temperatures from 1.23 to 20°K the quantity R(T) for nickel, just as for iron, is not described by a single expression. In the range 1.23 to 4.2°K the temperature variation of the electrical resistance is approximated by expression (2), whereas in the region 14 to 20°K the electrical resistance changes as

$$R_T/R_{0^\circ C} = 10.0986 \cdot 10^{-3} + 2.88 \cdot 10^{-6} T^2 + 4.85 \cdot 10^{-11} T^5. \quad (8)$$

The function R(T) can also be described by a two-term expression of type (4) with the exponent n = 2.23. Thus, the electron scattering mechanisms in nickel are apparently the same as in iron, by virtue of which their resistance variations with temperature are also similar throughout the entire range from 1.23 to 20°K.

PLATINUM

We studied platinum in order to compare the temperature behavior of the electrical resistance of metals which were transition metals, but not ferromagnetic.

In the helium temperature region the variation R(T) for platinum is well described by a quadratic law.[2,8]

In the region 14 to 20°K, just as for iron and nickel, scattering of conduction electrons at thermal vibrations of the lattice comes in, and R(T) is approximated by the polynomial

$$R_T/R_{0^\circ C} = 3.6486 \cdot 10^{-3} + 4.4 \cdot 10^{-6} T^2 + 8.23 \cdot 10^{-10} T^5 \quad (9)$$

or formula (4) with n = 3.37.

CONCLUSION

In iron and nickel at helium temperatures, features in the temperature behavior of the electrical resistance R(T) are observed, caused by the scattering of conduction electrons at spin waves, which is indicated by the presence of an additional linear term in R(T). The existence of this scattering mechanism is confirmed by the fact that the linear term is already smaller in a magnetic field of $\sim 10^3$ Oe.

For platinum—also a transition metal, but not ferromagnetic—the variation R(T) is approximated by a quadratic law only.

At higher temperatures, scattering of conduction electrons at thermal lattice vibrations starts to come in. Thus, in the range 14 to 20°K, the curves R(T) for all three metals (Fe, Ni, Pt) are well approximated by a single expression (6). The quadratic term is probably due to electron-electron interactions, and should be significant for all transition metals.[6] It may be noted that the coefficient of the linear term is greater for iron than for nickel.

In conclusion, the authors express their gratitude to B. G. Lazarev, M. I. Kaganov, and V. G. Bar'yakhtar for discussing the results and displaying interest in the work.

[1] F. Seitz, The Modern Theory of Solids, McGraw Hill, N. Y., 1940; R. Peierls, The Quantum Theory of Solids, Oxford, 1955.

[2] A. I. Sudovtsov and E. E. Semenenko, JETP **31**, 525 (1956), Soviet Phys. JETP **4**, 592 (1957).

[3] E. A. Turov, Izv. AN SSSR, ser. Fiz. **19**, 474 (1955), Columbia Tech. Transl. p. 426; E. A. Turov, FMM **6**, 203 (1958); Sh. Sh. Abel'skiĭ and E. A. Turov, FMM **10**, 801 (1960).

[4] Kondorskiĭ, Galkina, and Chernikova, JETP **34**, 1070 (1958), Soviet Phys. JETP **7**, 741 (1958).

[5] A. I. Sudovtsov and E. E. Semenenko, JETP **35**, 305 (1958), Soviet Phys. JETP **8**, 211 (1959).

[6] L. D. Landau and I. Ya. Pomeranchuk, JETP **7**, 379 (1937); W. G. Baber, Proc. Roy. Soc. (London) **A158**, 383 (1937).

[7] Akhiezer, Bar'yakhtar, and Kaganov, UFN **71**, 533 (1960), Soviet Phys. Uspekhi **3**, 567 (1961).

[8] W. I. de Haas and I. H. de Boer, Physica **1**, 609 (1934); G. K. White and S. B. Woods, Phil. Trans. Roy. Soc. (London) **A251**, 273 (1959).

Translated by K. F. Hulme
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