EFFECT OF THE DOMAIN STRUCTURE ON THE ELECTRICAL RESISTANCE OF IRON, NICKEL AND COBALT AT LOW TEMPERATURES

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Measurements were made of the dependence of the electrical resistance of iron, nickel and cobalt on a longitudinal magnetic field and of the dependence of the electrical resistance of iron on a transverse magnetic field, at temperatures from room temperature to that of liquid helium. A considerable influence of the domain structure on the value of the electrical resistance was observed; it appeared as: a) a reduction of the electrical resistance when the samples are magnetized (both in longitudinal and transverse magnetic fields at low temperatures; b) a rise in the resistance of a sample on increase of the measuring current through it in a compensated magnetic field. The influence of the domain structure clearly depended on the purity and dimensions of the sample, i.e., on the ratio of the mean free path l and the domain dimensions d. A considerable reduction of the value of the electrical resistance ($\approx$40% for pure iron) on increase of the domain size led to the conclusion that the conduction electrons were strongly scattered by the domain boundaries. An allowance for this effect is important in the determination of the purity of ferromagnetic metals from the value of their residual electrical resistance.

INTRODUCTION

AT low temperatures, ferromagnetic metals exhibit several properties related to the influence of the internal magnetic field on the galvanomagnetic effects in these metals. Earlier, we have reported a considerable reduction of the electrical resistance of very pure iron when magnetized at low temperatures.[1,2] This effect is explained as follows.

A study of the electrical resistance of any metal shows that the former depends on the sample's dimensions d if the mean free path of the conduction electrons l becomes comparable with or greater than the smallest of the sample dimensions.[3] Then, a reduction of the sample's thickness increases its electrical resistance. The condition $l \approx d$ can be achieved by changing the sample dimensions or by varying the temperature (this changes the mean free path). At room temperature, the mean free path of the conduction electrons in iron, nickel and cobalt is $l \approx (2\text{-}4) \times 10^{-6}$ cm,[4] which is considerably shorter than the smallest dimension of spontaneous magnetization regions in the test samples, which amount (according to our calculations) to $\sim 10^{-3}$ cm. Under these conditions, the dominant mechanism of the conduction electron scattering is the volume scattering, while the scattering on the domain boundaries is not present. On cooling, the mean free path increases and may become comparable with the domain dimensions. Then, the scattering on the domain boundaries should make a considerable contribution to the electrical resistance and a demagnetized sample should have a higher electrical resistance than a magnetized one without domains, and the mean free path may become shorter than the dimensions of the enlarged domains.

Thus we may expect a considerable reduction of the electrical resistance of ferromagnetic metals at sufficiently low temperatures on magnetizing them to saturation, i.e., even in relatively weak magnetic fields. Naturally, this will appear when other mechanisms of the conduction electron scattering make a smaller contribution to the electrical resistance, namely, in pure samples and at low temperatures. Therefore, it is possible to observe the scattering on the domain boundaries by measuring the electric resistance of a metal when the domains are enlarged in a magnetic field.

Apart from the conduction electron scattering on the domain boundaries, which occurs due to the spin—orbital interaction between the conduction electrons and the inhomogeneities of the

domain magnetic moment, there is at least one more mechanism which also reduces the electrical resistance of a sample when it is magnetized in a longitudinal magnetic field: the so-called reverse galvanomagnetic effect.[5]

This effect appears as follows: if, in the demagnetized state, there are such domains in which the magnetic moment is oriented at right angles to the direction of the current, the internal effective field acting on the conduction electrons is also perpendicular to the current and this produces the normal, i.e. occurring in all metals, galvanomagnetic effect of the resistance rise. By rotating these domains—using an external longitudinal magnetic field—in the direction of the current, the internal galvanomagnetic effect is effectively destroyed and this reduces the electrical resistance. The reverse galvanomagnetic effect appears at sufficiently low temperatures and in pure samples.

METHOD

To detect the influence of the domain structure on the electrical resistance of ferromagnetic metals - iron, nickel and cobalt - we measured the electrical resistance as a function of the magnetic field at various temperatures: room, liquid nitrogen, liquid hydrogen, and liquid helium at atmospheric pressure and in vacuum. The electrical resistance measurements were carried out using a potentiometer type PPTN-1.

The study was carried out on iron samples of various purities and dimensions in longitudinal and transverse magnetic fields; nickel and cobalt were studied only in longitudinal magnetic fields. The samples were mounted in a glass capillary on which a ballistic coil was wound. Thus we could measure simultaneously the electrical resistance and the basic form of the magnetization curve. The measurements were carried out in the terrestrial magnetic field which was compensated to within 0.5% by Helmholtz coils.

EFFECT OF THE DOMAIN STRUCTURE IN A LONGITUDINAL MAGNETIC FIELD

A. Iron. Because the domain structure (domain dimensions) affects the electrical resistance R, one would expect that for a metal of a given purity thin samples would show a stronger dependence $R(H_{\parallel})$ on magnetization to saturation than would thick samples.

We had available single-crystal samples of very pure iron (> 99% purity) of various thicknesses. The residual electrical resistance of these samples in the magnetized state was $\rho_0 \equiv R(0°K)/R(0°C) = (2.6—3.0) \times 10^{-3}$.

Figure 1 shows the results of measurements of the influence of an external longitudinal magnetic field on the relative electrical resistance $\Delta R/R$ and the magnetization J for one of the iron samples[1)] Fe-2 ($\Delta R = R_H - R_{H=0}$, where R_H is the value of the electrical resistance in a magnetic field at the test temperature, $R_{H=0}$ is the resistance in the absence of a field at the same temperature). The sample was in the form of a wedge with elliptical cross sections varying from 0.2×1.4 mm to 0.5×0.7 mm; it was 23 mm long. The texture was along the [111] direction. The grain size was equal to the transverse dimensions of the sample.

The nature of the change in the electrical resistance with the field was essentially the same for samples of different thickness,[1] but for thicker samples the effect itself extended over a wider range of the field compared with the effect for thin samples and, moreover, the effect for thin samples was weaker.

The behavior of the electrical resistance of iron as a function of the magnetic field at various temperatures led to the conclusion that the domain structure affects the electrical resistance mechanism at low temperatures. At room temperature (curve 4) when the mean free path of the conduction electrons is considerably shorter than the domain dimensions $l \ll d$, the electrical resistance increases in a longitudinal magnetic field, which is the well known galvanomagnetic effect.[6] On cooling to 4.2°K, the electrical resistance of pure iron decreases by a factor of about 300 and the mean free path of the conduction electrons becomes $l \sim 10^{-3}$ cm, which is comparable with the calculated domain dimensions ($l \sim d$). In this case, a considerable reduction of the electrical resistance is observed in the technical magnetization region (Fig. 1). The main reduction occurs in weak fields when the magnetization involves displacement processes, and it is due to the enlargement of the domains.[7-11] Further reduction of the electrical resistance in longitudinal magnetic fields up to 500—600 Oe may occur for the following reasons.

1. In real crystals in weak fields, the boundaries of the real domains are shifted but the closure domains are little affected. The dis-

[1)]We take this opportunity to thank V. E. Ivanov for kindly supplying iron and nickel samples and V. S. Kogan for his x-ray structure analysis of these samples.

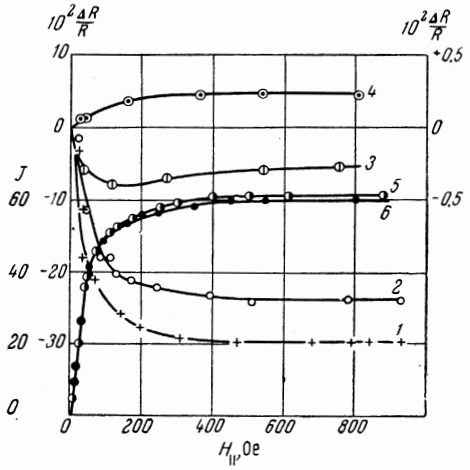

FIG. 1. The dependence, on an external longitudinal field, of the relative electrical resistance $\Delta R/R$ of iron at temperatures of 4.2°K (1), 20.4°K (2), 77°K (3) and 293°K (4), and of the magnetization of iron J (in arbitrary units) at 4.2°K (5) and 293°K (6). The scale on the right applies to curves 3 and 4.

placement is completed in strong fields together with domain rotation.[8]

2. At helium temperatures, the value of the electrical resistance is affected also by the domain rotation. The effect of the reorientation of the internal magnetic moment should also alter considerably the value of the electrical resistance at low temperatures; this is the so-called reverse galvanomagnetic effect.[5]

The main contribution to the reduction of the electrical resistance of iron when it is magnetized at low temperatures is obviously made by the size effect - a change in the ratio l/d. When pure iron samples of 0.1—0.6 mm diameter are magnetized at helium temperatures, the reduction in the electrical resistance amounts to 30—40%. Such a reduction should occur, according to the theoretical calculations of Dingle,[3] at $l/d \sim 1$. Using rough calculations of the size of the main domains for such samples, we find that $d \sim 10^{-3}$ cm and, therefore, the mean free path is $\sim 10^{-3}$ cm. The same order of magnitude is obtained from calculations of the mean free path using the change in the electrical resistance between room temperature and that of liquid helium. For several reasons it was not possible to estimate more rigorously the influence of the magnetic field and to separate the effects of the domain rotation and displacement on the electrical resistance. Here are some of these reasons.

1. The domain structure of the samples was not known in full. The present methods of determining this structure cannot give a complete picture for the interior of a metal. They show the surface structure, and only for thin samples may we assume that the internal structure does not differ from the surface pattern.

2. The study of powder figures reveals according to the published data,[7-11] a very strong dependence of the structure on the orientation of the surfaces of samples with respect to their crystallographic axes. A deviation of the crystal surface by 1—1.5° (for example, in iron,[10]) from the [100] axis leads to the appearance of small domains of complex shape, in addition to simply shaped domains.

3. Real crystals with their longitudinal axes directed along the [111] axis, and even perfect "whiskers," have additional small domains, changes in which also affect the electrical resistance.

The electrical resistance of pure iron is influenced strongly by the measuring current. A particularly strong dependence is found at helium temperatures. Figure 2 shows the values of the relative change of the electrical resistance $\Delta R/R$ ($\Delta R = R_I - R_{I=0}$) of the sample Fe-2 as a function of the measuring current I in the range from 0 to 900 mA in the compensated terrestrial field at 4.2°K (the value of the electrical resistance for zero measuring current was obtained by extrapolating the dependence of the electrical resistance on the measuring current at a given temperature). It seems that the main increase in the electrical resistance is here related to the restriction of the mean free path of the conduction electrons. The measuring current makes the field radially inhomogeneous, which should make the domain structure finer. At high measuring currents, the domains are directed at right angles to the measuring current.[12] The domain thickness is established at relatively low measuring currents; curve R(I) has a tendency to saturation at currents higher than 900—1000 mA. Moreover, the establishment of domains at right angles to the measuring current gives rise to the normal galvanomagnetic effect and, therefore, increases the electrical resistance.

The dependence of the resistance on the measuring current was observed in the compensated

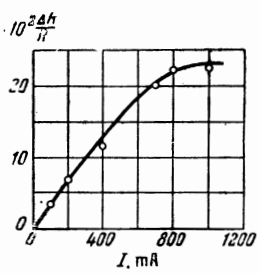

FIG. 2. Relative change of the electrical resistance $\Delta R/R$ as a function of the measuring current I for iron at T = 4.2°K.

terrestrial field and in weak external magnetic fields. In a longitudinal field of 600 Oe, the value of the electrical resistance of the samples was independent of the measuring current. It was natural to expect that the change in the electrical resistance due to the application of a magnetic field would vary with the measuring current. Indeed, it was found that the reduction of the electrical resistance due to magnetization to saturation in a field of 600 Oe changed from −40% for a 900 mA current to −28% for zero measuring current (at 4.2°K). For the sample Fe-1 (0.1 mm in diameter), the effect amounted to −37% at 4.2°K and zero measuring current; i.e., a clear dependence on the sample thickness was observed.

The influence of the domain structure depends very strongly on the purity of ferromagnetic metals and this is a further confirmation of the fact that we are dealing with the influence of the ratio of the domain dimensions and the mean free path of the conduction electrons. Thus, in iron, which was one order of magnitude less pure (as judged by the residual electrical resistance), the reduction of the electrical resistance on magnetization to saturation was also an order of magnitude lower.

B. Nickel. We did not have very pure nickel samples. Figure 3 shows the values of the change in the electrical resistance of a nickel sample 99.96% pure (the residual resistance was $\rho_0 = 9.8 \times 10^{-3}$), 8 mm long and 0.5 mm in diameter. The single-crystal structure of the samples was the same as that for iron: the grain dimensions were comparable with the transverse dimensions of the sample and the grains were oriented along the sample's axis [111]. The sample was prepared by vacuum distillation.

At room temperature, the mean free path of electrons in nickel is $l \sim 10^{-6}$ cm and the domain dimensions for such samples are $d \sim 10^{-3}$ cm; therefore, the normal [6] increase in the electrical resistance was observed in a longitudinal magnetic field in the technical magnetization region (Fig. 3, curve 1). Only at helium temperatures did one observe a slight reduction of the electrical resistance, by 0.45%, in the technical magnetization region; in stronger fields, a considerable rise in the electrical resistance was observed. The dependence of the electrical resistance of nickel samples on the current was considerably weaker than for pure iron. The smallness of the effect may be explained by the short mean free path in the nickel used.

C. Cobalt. Measurements of the electrical resistance of 99.9984% pure cobalt samples in a longitudinal magnetic field showed that at helium temperatures the influence of the conduction electron scattering on the domain boundaries appeared in cobalt as well. Thus, a polycrystalline sample of cobalt (residual resistance $\rho_0 \sim 4 \times 10^{-2}$), which was ~0.15 mm thick, 2 mm wide and 70 mm long, exhibited a reduction of the Goldhammer effect on cooling. The value of $\Delta R/R$ in a field of 850 Oe amounted to +0.25% and +0.14% at T = 300°K and T = 4.2°K, respectively, i.e., the effect of the conduction electron scattering on the domain boundaries, which decreased on magnetization of the cobalt samples, appeared on a background of the electrical resistance rise in a longitudinal magnetic field at low temperatures. The effect did not appear at all in less pure cobalt, in which the mean free path was even shorter.

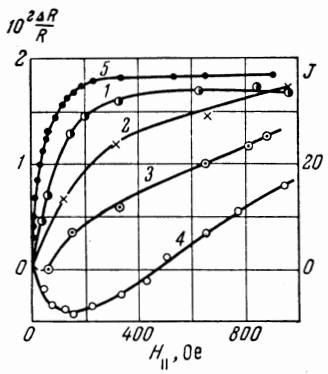

FIG. 3. Dependence, on an external longitudinal magnetic field, of the relative electrical resistance $\Delta R/R$ of nickel at 4.2°K (1), 20.4°K (2), 77°K (3), 293°K (4), and of the magnetization J at 4.2°K (5) and 293°K (6).

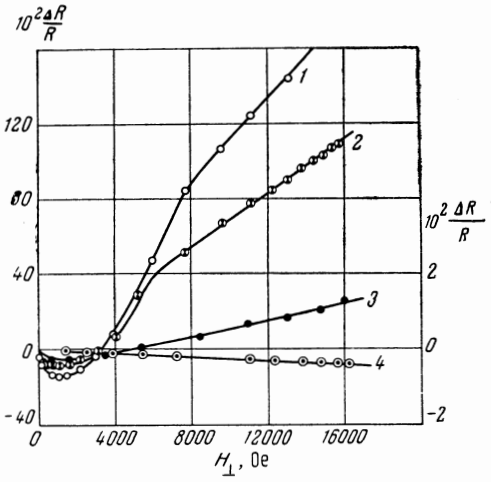

FIG. 4. Relative change of the electrical resistance of iron in a transverse magnetic field at 4.2°K (1), 20.4°K (2), 77°K (3), 293°K (4); the scale on the right applies to curves 3 and 4.

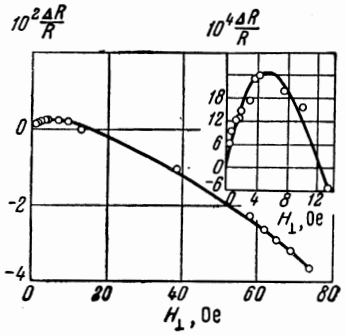

FIG. 5. Relative change of the electrical resistance of iron in weak transverse fields; T = 4.2°K.

INFLUENCE OF THE DOMAIN STRUCTURE IN A TRANSVERSE MAGNETIC FIELD

The behavior of the electrical resistance in a transverse magnetic field was considerably more complex than in a longitudinal field. Figures 4 and 5 show the results of measurements of the electrical resistance for the sample Fe-1 in a wide range of temperatures and transverse magnetic fields. From the behavior of the electrical resistance in a transverse field, we may conclude that two effects occur: enlargement of the domain structure (reduction of the electrical resistance in weak fields - curve 1) and the normal galvanomagnetic effect, which dominates in strong fields. At room temperature (curve 4), the electrical resistance decreased when the field was increased, which is in agreement with the published data.[6] However, even at nitrogen temperatures a rise in the electrical resistance was observed in strong fields. On cooling, the effect increased strongly.

In relatively weak fields, the electrical resistance fell with increasing field, the drop being stronger at lower temperatures, reaching $\Delta R/R \approx -15\%$ at 4.2°K, i.e., we could assume that here again the enlargement of the domains on increase of the field was observed. In very weak transverse fields (up to 6 Oe), a small rise in the electrical resistance, $\Delta R/R \approx +0.2\%$ (Fig. 5), was observed, which was obviously related to the domain structure becoming finer, at least on the surface, in weak transverse fields.[7,8]

There are published observations of the domain structure in similar samples in weak transverse fields.[7] In the absence of a field, the magnetic structure does not have surface domains, which appear in weak transverse fields and disappear in strong ones.

In conclusion, the authors take this opportunity to thank B. G. Lazarev, M. I. Kaganov and V. G. Bar'yakhtar for discussing the results and for their interest in the present work.

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