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Anomalies of the magnetoresistance of ferrites

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Contents

Abstract. The results of measurements of the field and temperature dependences of the magnetoresistance of manganese ferrite and several other spinel ferrites are presented in a systematic manner and analysed. In magnetic fields in excess of the technical saturation and at temperatures below the Curie point these ferrites have two physically different components of the isotropic negative magnetoresistance. One of them is due to the scattering of conduction ('hopping') electrons on para-process-induced variations of the order of the magnetic cations. The second component is interpreted on the basis of a 'magnetoelectron sublattice' model proposed by the author. Manifestations of the magnetoresistance in the vicinity of various phase transitions in spinel ferrites are considered.

1. Introduction

Ferrites are magnetic materials combining insulating and ferrimagnetic properties, and they have long been used in technology. However, among them there are some that have specific semiconducting properties (a very low carrier mobility). Outstanding members of the latter group are the oldest magnetic material, magnetite (Fe_3O_4), and manganese spinel ferrite $MnFe_2O_4$. Manifestations of various transport phenomena (electrical conduction, galvanomagnetic effects, etc.) in these compounds are largely unknown and sometimes puzzling. This applies in particular to the magnetoresistance $\Delta\rho/\rho$, which is the relative change in the electrical resistivity ρ under the action of a magnetic field H. This is an even effect, i.e. it depends quadratically on H (and on the magnetisation I), and has been studied for a long time in magnetic and nonmagnetic substances [1].

Both metallic [1] and semiconducting [2] ferromagnets exhibit complex dependences of $\Delta\rho/\rho$ on the applied magnetic field H, magnetisation I, and temperature T. The nature of these dependences is influenced by the nature of the magnetisation processes that accompany the magnetoresistance [3, 4].

The field and temperature dependences of the magnetoresistance are even more complex in the case of ferrimagnets, including ferrites. The reason for this is the influence of the intersublattice structure of ferrites [4] and the specific nature of the electron processes which occur in these materials.

This review is a systematic account and an analysis of the results of measurements of the field and temperature dependences of the magnetoresistance of ferrites, carried out by the present author and his colleagues [6 – 14, 21, 22], and also of the published results [15 – 20].

Investigations of the magnetoresistance of magnetically ordered substances are not only of scientific, but also of considerable practical importance because information on the magnetoresistance is needed in the fabrication of

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various devices and sensors. In particular, magnetoresistance heads for retrieval of information stored by magnetic methods are being developed. It would be interesting to determine the suitability of ferrite materials for this purpose.

2. Nature of manifestation of the magnetoresistance in metallic ferromagnets

In this section the results of investigations of the magnetoresistance of nickel will be reviewed in order to demonstrate the differences in the behaviour of the magnetoresistance of ferrites, as compared with metallic ferromagnets. The published data on nickel are quite extensive.

The magnetoresistance and other even magnetic effects (magnetostriction, mangetothermoelectric power, etc.) are usually analysed with the aid of Akulov's phenomenological relationship [3] describing in a unified manner the changes in all the even effects in cubic crystals. According to Akulov [3], the magnetoresistance $\Delta\rho/\rho$ of a cubic crystal can be described by a series expansion of $\Delta\rho/\rho$ in terms of the direction cosines of two vectors: the magnetisation $\boldsymbol{I}_s$ and the vector $\boldsymbol{g}$ representing the direction of measurement of the magnetoresistance, identical with the direction of the electric current vector $\boldsymbol{j}$:

$$\frac{\Delta\rho}{\rho}=\left(\frac{\Delta\rho}{\rho}\right)_{H>H_s}(H,T)+\frac{3}{2}\left(\frac{\Delta\rho}{\rho}\right)_{[100]}\left(S_1^2g_1^2+S_2^2g_2^2+S_3^2g_3^2-\frac{1}{3}\right)+3\left(\frac{\Delta\rho}{\rho}\right)_{[111]}(S_1S_2g_1g_2+S_2S_3g_2g_3+S_3S_1g_3g_1). \quad (1)$$

Here S_1, S_2, S_3, and g_1, g_2, g_3 are, respectively, the direction cosines of the spontaneous magnetisation vector $\boldsymbol{I}_s$ and of the electric current vector $\boldsymbol{j}$ relative to the edges of a cube; $(\Delta\rho/\rho)_{[100]}$ and $(\Delta\rho/\rho)_{[111]}$ are the experimental values of the magnetoresistance in a saturation field $H=H_s$ along the directions [100] and [111]. It is assumed that the vector $\boldsymbol{I}_s\|\boldsymbol{H}$ follows exactly the direction of the field in a crystal. The second and third terms in Eqn (1) describe the anisotropy of the $\Delta\rho/\rho$ effect, whereas the first term $(\Delta\rho/\rho)_{H>H_s}(H,T)$ represents the isotropic part; it appears in a field $H>H_s$ when the processes of domain wall displacement and rotation are 'suppressed' by the field H_s and the magnetisation is the result of the paraprocess. The first term plays a particularly important role at temperatures in the region of the Curie point T_C, where the paraprocess is strong.

In studies of polycrystalline magnetic materials it is usual to measure the longitudinal magnetoresistance $(\Delta\rho/\rho)_{\|}$ (when the current vector $\boldsymbol{j}$ is parallel to the vector $\boldsymbol{H}$) and the transverse magnetoresistance $(\Delta\rho/\rho)_{\perp}$ (when $\boldsymbol{j}\perp\boldsymbol{H}$).

Averaging Eqn (1) over the cosines S_i and g_i yields the change in the magnetoresistance of a polycrystalline ferromagnet:

$$\frac{\Delta\rho}{\rho}=\frac{3}{2}\left(\frac{\Delta\rho}{\rho}\right)_s\left(\overline{\cos^2\alpha}-\overline{\cos^2\alpha_0}\right). \quad (2)$$

Here, $(\Delta\rho/\rho)_s$ is the magnetoresistance corresponding to the saturation magnetisation $I=I_s$ and the bars above the cosines denote the average values. The quantity $\overline{\cos^2\alpha_0}$ represents the initial (before magnetisation) distribution of the domain magnetisation vectors $\boldsymbol{I}_s$ and $\overline{\cos^2\alpha}$ corresponds to the distribution of the vectors $\boldsymbol{I}_s$ corresponding to a certain magnetisation $\boldsymbol{I}$ which appears in a ferromagnet on application of H.

Eqn (2) can therefore be used to find $\Delta\rho/\rho$ corresponding to rotation of the domain vector $\boldsymbol{I}_s$. In this case the resultant magnetoresistance can be called 'orientational'.

The value of $\overline{\cos^2\alpha_0}$ for a thoroughly demagnetised ferromagnet is $\frac{1}{3}$ and its substitution in Eqn (2) gives the following 'rule of two' for $(\Delta\rho/\rho)_{\|}$ and $(\Delta\rho/\rho)_{\perp}$ when a sample is magnetised to saturation:

$$\left(\frac{\Delta\rho}{\rho}\right)_{\|}=-2\left(\frac{\Delta\rho}{\rho}\right)_{\perp}, \quad (3)$$

which demonstrates that the longitudinal and transverse magnetoresistances of a ferromagnet have opposite signs and that the former is twice the latter.

For the majority of metallic ferromagnets measurements give opposite signs for $(\Delta\rho/\rho)_{\|}$ and $(\Delta\rho/\rho)_{\perp}$, but experimental values are rarely in the ratio of 2. Fig. 1a shows schematically the room-temperature magnetoresistance isotherms $(\Delta\rho/\rho)_{\|}(H)$ and $(\Delta\rho/\rho)_{\perp}(H)$ of polycrystalline nickel. In fields $H<H_s$ the longitudinal effect is positive and the transverse effect is negative; then $(\Delta\rho/\rho)_{\|}>(\Delta\rho/\rho)_{\perp}$ in accordance with a phenomenological theory of the even magnetic effects. This behaviour of the orientational magnetoresistances $(\Delta\rho/\rho)_{\|}$ and $(\Delta\rho/\rho)_{\perp}$ will be regarded as normal.

It is evident from Fig. 1a that if $H>H_s$, i.e. in the paraprocess region, the magnetoresistances $(\Delta\rho/\rho)_{\|}$ and $(\Delta\rho/\rho)_{\perp}$ are almost equal and negative (as demonstrated by the same slopes of the straight lines in Fig. 1a obtained in

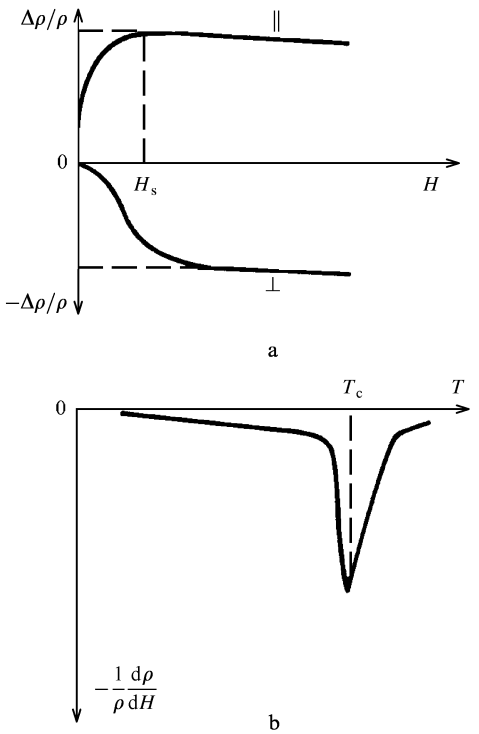

Figure 1. Typical dependences of the magnetoresistance of ferromagnets (schematic representation) on an external magnetic field H (a) and on temperature (b) in fields above the technical saturation ($H>H_s$).

strong fields). These magnetoresistances represent the isotropic (for cubic crystals) component of the magnetoresistance of a ferromagnet [the magnitudes and signs of $(\Delta\rho/\rho)_{\|}$ and $(\Delta\rho/\rho)_{\perp}$ are independent of the directions of the vectors $\boldsymbol{j}$ and $\boldsymbol{I}_s\|\boldsymbol{H}$].

The anisotropic (orientational) magnetoresistances $(\Delta\rho/\rho)_{\|}$ and $(\Delta\rho/\rho)_{\perp}$ reach their maximum values in fields $H = H_s$, whereas the isotropic negative magnetoresistances increase continuously with H (Fig. 1a). Therefore, a quantitative characteristic of the isotropic magnetoresistance is the magnetoresistance 'susceptibility' $(1/\rho)(d\rho/dH)$ $[(1/\rho)(d\rho/dH)_{\|} \cong -(1/\rho)(d\rho/dH)_{\perp}$ for cubic crystals].

Fig. 1b shows schematically the temperature dependence of $-(1/\rho)(d\rho/dH)$ for nickel; this quantity rises on approach to the Curie point T_C and reaches a minimum ('negative maximum') at the temperature T_C itself.

These field and temperature dependences of the magentoresistance of nickel are regarded as normal; it is important to bear them in mind when discussing the behaviour of the magnetoresistance of ferrites.

3. Anomalies of the magnetoresistance of manganese ferrite

The most detailed experimental data on the magnetoresistance of ferrites have been obtained for manganese ferrite $MnFe_2O_4$ which has the cubic structure of the mineral called spinel.

The magnetoresistance of this particular ferrite is interesting for two reasons: (1) its electrical resistivity ρ is not high (it is close to ρ of magnetite), so that without any major difficulty the $\Delta\rho/\rho$ effect can be measured in a wide range of temperatures from liquid nitrogen to the Curie point ($T_C = 570$ K); (2) the Verneuil method can be used to grow $MnFe_2O_4$ crystals of sufficient size for measuring the anisotropy of $\Delta\rho/\rho$.

The magnetic properties of $MnFe_2O_4$ occupy a special place among the properties of other spinel ferrites. Manganese ferrite is a 'spin' ferrimagnet, since the $Mn^{2+}(3d^5)$ and $Fe^{3+}(3d^5)$ cations do not have orbital magnetic moments, so that the compound is characterised by a weak 'single-ion' magnetic anisotropy and can be magnetised to saturation in weak fields even at helium temperatures. This is evident from Fig. 2 which shows the magnetisation curves of an $MnFe_2O_2$ crystal deduced from the results of measurements [23]. The nature of these curves (the absence of a slope of the straight line in the range $H > H_s$) demonstrates also that $MnFe_2O_4$ does not have a canted (noncollinear) magnetic structure between room temperature and 4.2 K.

This is supported by neutron diffraction data on this ferrite [24]. A strong intersublattice exchange interaction in this ferrite is the reason for the Weiss type (Q-type, according to NEel) temperature dependence of the spontaneous magnetisation $I_s(T)$ i.e. of the same type as the corresponding temperature dependence of Ni and Fe. Therefore, manganese ferrite cannot exhibit a low-temperature paraprocess unlike typical ferrites with an anomalous $I_s(T)$ curve and a magnetic compensation point (N-type, according to NEel) [22]. Manganese ferrite has one further advantage over other spinel ferrites. Since the magnetic cations in this compound do not have orbital magnetic moments, Eqn (1) can be applied. In the case of ferrites in which magnetic cations have orbital moments partly 'quenched' by the crystal field, Eqn (1) is either invalid or applies subject to restrictions, since the parity of I is lost (this is demonstrated in Ref. [5]).

The first surprising observation revealed by a study of the even effects in $MnFe_2O_4$ is as follows. At temperatures far from the Curie point T_C (~ 560 K) it follows from Fig. 3 that the magnetostriction isotherms $\lambda_{\|}(H)$ and $\lambda_{\perp}(H)$ behave 'normally' in the same way as those of nickel, i.e. in accordance with the predictions of a theory of even effects [3]; the signs and magnitudes of the longitudinal and transverse magnetostrictions are different, whereas the magnetoresistance isotherms $(\Delta\rho/\rho)_{\|}(H)$ and $(\Delta\rho/\rho)_{\perp}(H)$ behave anomalously; the longitudinal and transverse effects have the same (negative) sign and their values are similar [13, 14].

This anomaly can be resolved by measurements of the magnetoresistance of $MnFe_2O_4$ single crystals. Measure-

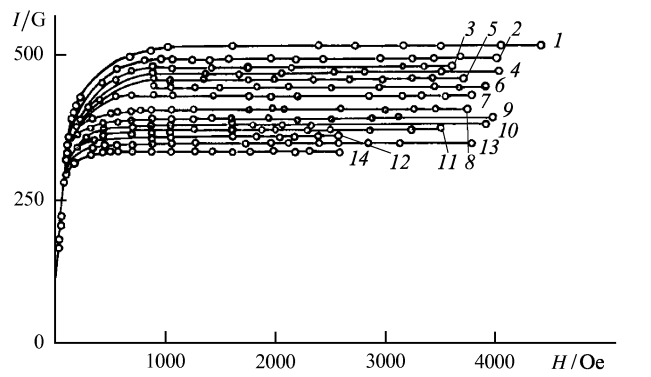

Figure 2. Isotherms of the magnetisation I of a single crystal of manganese ferrite $MnFe_2O_4$ at the following temperatures (K): (*1*) 4.2; (*2*) 78; (*3*) 109; (*4*) 131; (*5*) 151; (*6*) 175; (*7*) 197; (*8*) 230; (*9*) 253; (*10*) 269; (*11*) 280; (*12*) 292; (*13*) 304; (*14*) 319.

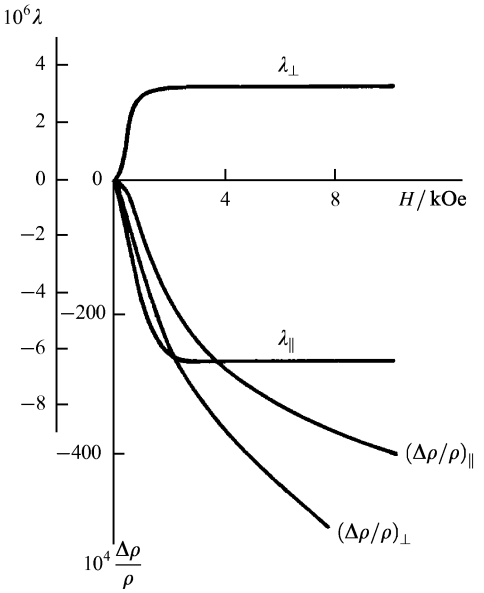

Figure 3. Isotherms of the magnetoresistances $(\Delta\rho/\rho)_{\|}(H)$ and $(\Delta\rho/\rho)_{\perp}(H)$, and of the magnetostrictions $\lambda_{\|}(H)$ and $\lambda_{\perp}(H)$ of polycrystalline ferrite $MnFe_2O_4$ at 80 K.

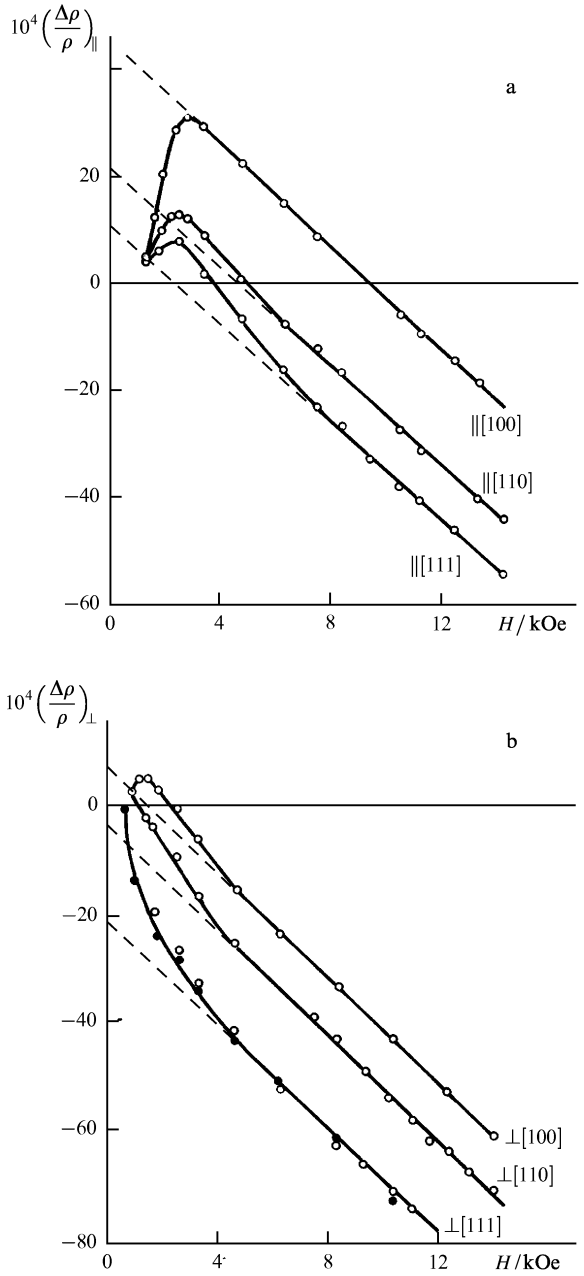

Figure 4. Isotherms of the magnetoresistances $(\Delta\rho/\rho)_{\parallel}(H)$ (a) and $(\Delta\rho/\rho)_{\perp}(H)$ (b) obtained for a single crystal of $MnFe_2O_4$ at 300 K along different directions in a crystal.

ments carried out by Zalesskii at 300 K [9, 10] showed that in fields $H < H_s$ the orientational magnetoresistance exhibits a positive longitudinal effect $(\Delta\rho/\rho)_{\parallel}$ and the orientational transverse effect $(\Delta\rho/\rho)_{\perp}$ is negative. The effects can be determined quite accurately, as demonstrated in Fig. 4, by extrapolating to zero H the linear isotropic components of the magnetoresistance.

It is evident from Fig. 4 that the isotropic (linear) magnetoresistance components are extremely high even at room temperature. In the case of ferromagnets, such as Ni, the magnetoresistance susceptibility $-(1/\rho)\mathrm{d}\rho/\mathrm{d}H$ is only $3 \times 10^{-8}\,\mathrm{Oe}^{-1}$ at 300 K, whereas for $MnFe_2O_4$ it reaches an anomalously high value of $\sim 50 \times 10^{-8}\,\mathrm{Oe}^{-1}$ (Fig. 4), i.e. an order of magnitude higher than $-(1/\rho)\mathrm{d}\rho/\mathrm{d}H$ for Ni.

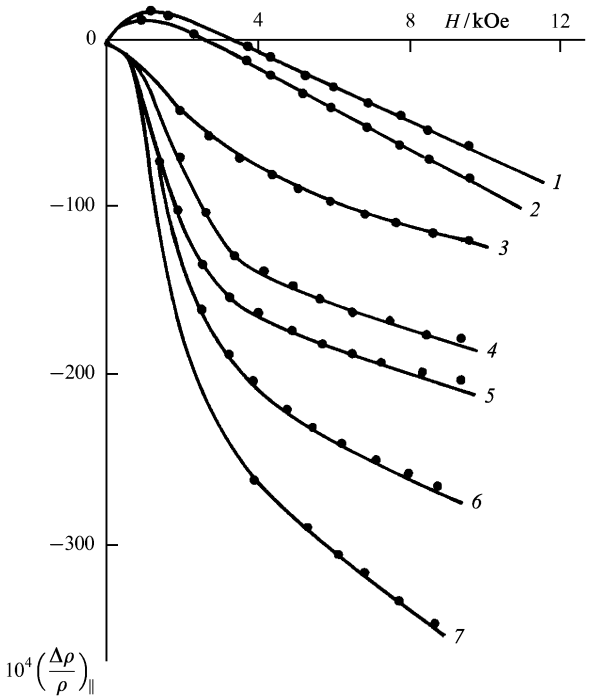

Figure 5. Isotherms of $(\Delta\rho/\rho)_{\parallel}(H)$ of polycrystalline $MnFe_2O_4$ recorded at the following temperatures (K): (*1*) 294; (*2*) 207; (*3*) 162; (*4*) 143; (*5*) 110; (*6*) 98; (*7*) 92.

Cooling from 300 K to 80 K increases $-(1/\rho)\mathrm{d}\rho/\mathrm{d}H$ by a further order of magnitude. This is demonstrated in Fig. 5 which gives the $(\Delta\rho/\rho)_{\parallel}(H)$ isotherms based on Refs [13, 14] and obtained for a polycrystalline sample of $MnFe_2O_4$. Moreover, below room temperature these isotherms become nonlinear. The strong rise of the isotropic magnetoresistance as a result of cooling from $T_C = 570\,\mathrm{K}$ cannot be attributed to the paraprocess, since below room temperature this process is very weak and it increases the magnetisation by a negligible amount. This is illustrated in Fig. 6 which demonstrates — in accordance with Ref. [6] — the change in $(\Delta\rho/\rho)_{\parallel}$ as a function of the square of specific magnetisation σ (at temperatures $T < T_C$). The negative

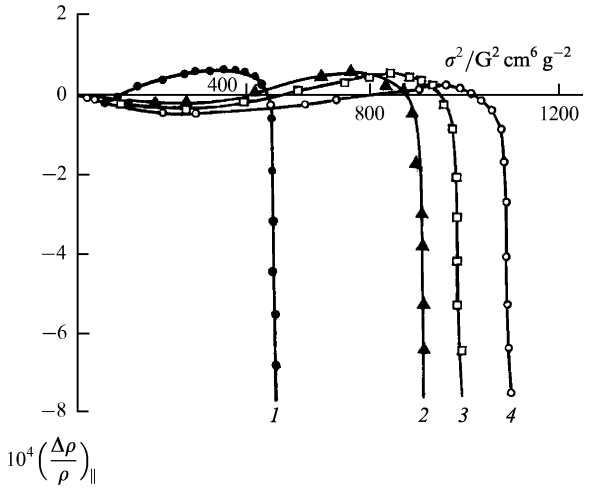

Figure 6. Dependence of the magnetoresistance $(\Delta\rho/\rho)_{\parallel}$ on the square of the magnetisation σ^2 obtained in the range $T < T_C$, at the following temperatures (K): (*1*) 533; (*2*) 524; (*3*) 518.8; (*4*) 513.

isotropic magnetoresistance is independent of σ^2. In fields $H < H_s$, where the technical magnetisation processes occur, the positive orientational component of the effect $(\Delta\rho/\rho)_{||}$ is observed.

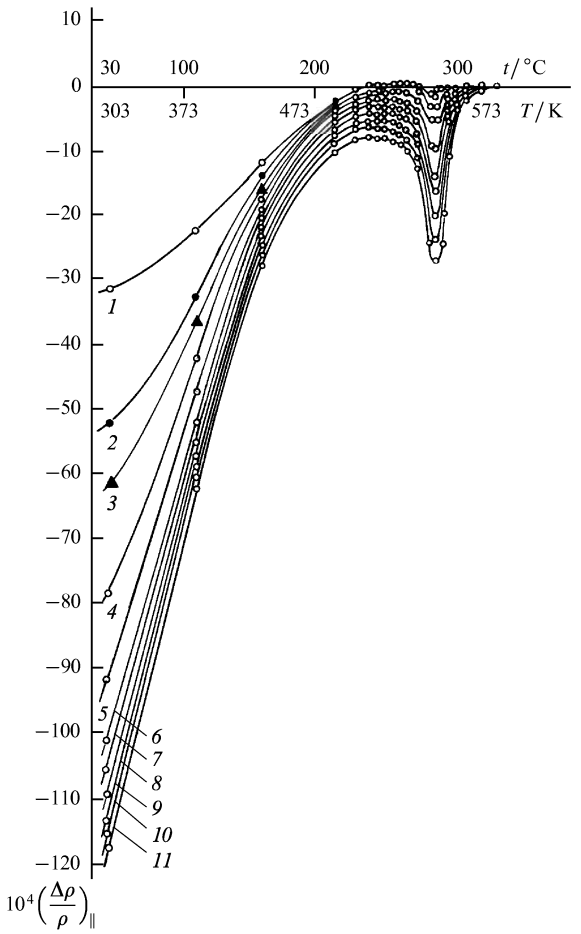

Figure 7. Temperature dependences of the magnetoresistance $(\Delta\rho/\rho)_{||}$ of polycrystalline $MnFe_2O_4$ recorded in different magnetic fields (Oe): (*1*) 39.2; (*2*) 65.4; (*3*) 98.0; (*4*) 196.0; (*5*) 392.0; (*6*) 654.0; (*7*) 915.0; (*8*) 1178.0; (*9*) 1439.0; (*10*) 1700; (*11*) 1960.0.

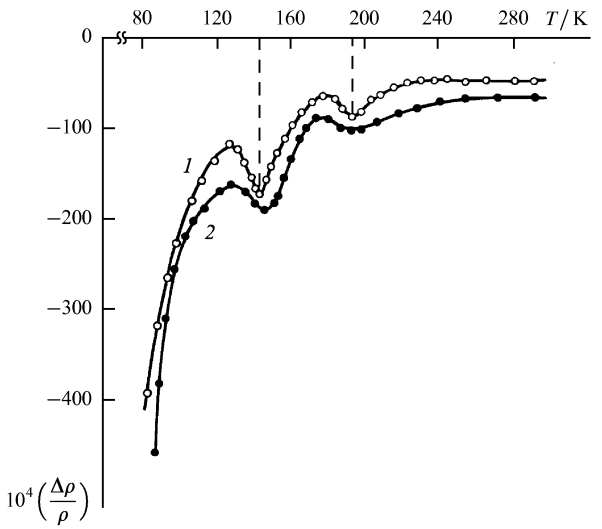

Figure 8. Temperature dependences of the magnetoresistance of polycrystalline $MnFe_2O_4$ in fields $H > H_s$: (*1*) $(\Delta\rho/\rho)_{\perp}$; (*2*) $(\Delta\rho/\rho)_{||}$.

The isotropic magnetoresistance anomaly in fields $H > H_s$ is illustrated very clearly by the temperature dependences of this effect. Figs 7 and 8 give also such dependences for polycrystalline $MnFe_2O_4$. It is shown in Fig. 7 how the magnetoresistance varies away from the Curie point [6]; cooling reverses the sign of the derivative $-(1/\rho)d\rho/dH$ in the range 200–300 K and further cooling increases exponentially the negative magnetoresistance. At room temperatures the value of $(\Delta\rho/\rho)_{||}$ in fields 1–2 kOe exceeds the value of this quantity at the Curie point by a factor larger than 4.

Further cooling from room temperature to 80 K results in continuing exponential increase of the isotropic negative magnetoresistance (Fig. 8); this has been reported in Refs [13, 14]. The same investigations have also revealed deviations from the monotonic exponential dependence of the magnetoresistance of manganese ferrite (for details see Section 8).

It follows that the field and temperature dependences of the magnetoresistance of $MnFe_2O_4$ are anomalous.

4. Anomalies of the magnetoresistance of other spinel ferrites

In the case of other spinel ferrites the available magnetoresistance data are not as detailed as those for $MnFe_2O_4$. Nevertheless, a systematic approach to these data and their analysis shows that the field and temperature dependences of $\Delta\rho/\rho$ exhibit the same anomalies as in the case of manganese ferrite.

Some early investigations [15–20] of polycrystalline nickel, copper, and nickel–zinc spinel ferrites, and of magnetite have revealed the same negative signs of the longitudinal and transverse magnetoresistances at ~ 300 K, regarded as surprising by the investigators.

Fig. 9 shows, by way of example, 300 K isotherms of the $(\Delta\rho/\rho)_{||}(H)$ and $(\Delta\rho/\rho)_{\perp}(H)$ of polycrystalline $NiFe_2O_4$ [20]. Similar anomalous isotherms of the longitudinal and transverse magnetoresistances have been obtained for polycrystalline magnetite [15]. However, measurements of the magnetoresistance of magnetite and $NiFe_2O_4$ single crystals reported by Zalesskii [11] have established the existence (at 300 K) of a positive orientational magnetoresistance $(\Delta\rho/\rho)_{||}$. Fig. 10 shows the $(\Delta\rho/\rho)_{||}(H)$ isotherms of a magnetite crystal based on Zalesskii's data. We can see

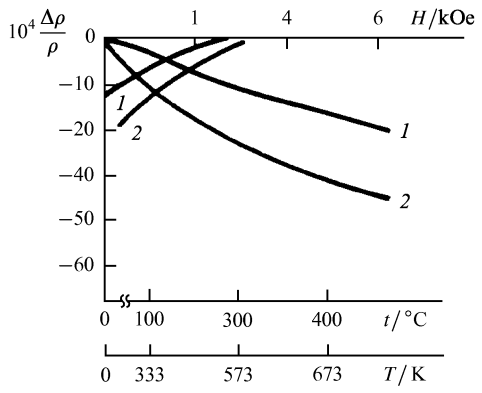

Figure 9. Dependences of the magnetoresistances $(\Delta\rho/\rho)_{\perp}$ (*1*) and $(\Delta\rho/\rho)_{||}$ (*2*) on H at 300 K and temperature dependences of the magnetoresistance of ferrite $NiFe_2O_4$ [20].

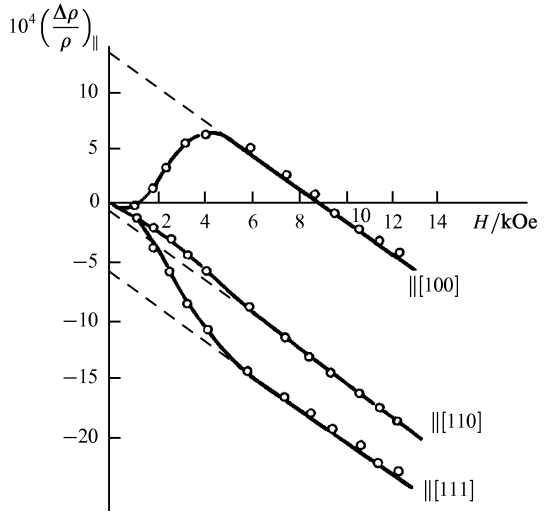

Figure 10. Isotherms of $(\Delta\rho/\rho)_{\parallel}(H)$ obtained at 300 K for a magnetised single crystal along different axes.

that, as in the case of $MnFe_2O_4$, the isotropic magnetoresistances of magnetite are very large. In fields $H_s > H$ there are orientational magnetoresistances: positive $(\Delta\rho/\rho)_{\parallel}$ and negative $(\Delta\rho/\rho)_{\perp}$. They can be found by extrapolation of the linear branches of the isotropic magnetoresistance to zero fields (Fig. 10).

The positive orientational magnetoresistance of polycrystalline magnetite (and other ferrites) is very small because of the averaging of the orientational magnetoresistances over different crystal axes and it can be masked completely by the isotropic negative magnetoresistance creating anomalies of the field dependences of $(\Delta\rho/\rho)_{\parallel}$ and $(\Delta\rho/\rho)_{\perp}$.

Measurements of the magneotresistance of single crystals of magnetite, and of manganese and nickel ferrites have demonstrated [10, 11] that these anomalies cannot be accounted for by the influence of the exchange terms in the phenomenological relationship given by Eqn (1). This has been pointed out in a discussion of a similar anomaly encountered for some magnetic alloys [28].

Fig. 11 gives the temperature dependences of the isotropic negative magnetoresistances $(\Delta\rho/\rho)_{\parallel}$ and

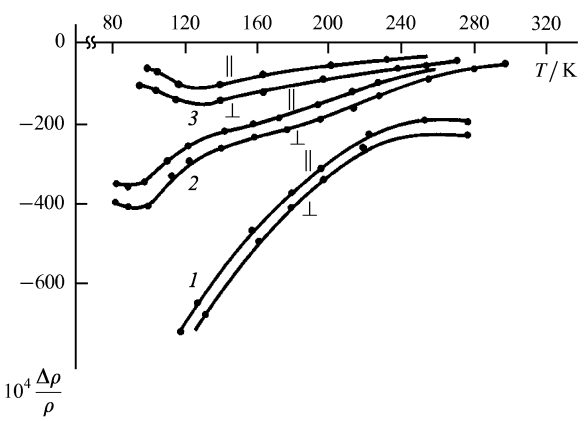

Figure 11. Temperature dependences of the magnetoresistance obtained in a magnetic field of 10 kOe for: (*1*) magnetite; (*2*) $Fe_{2.8}Cr_{0.2}O_4$; (*3*) $Fe_{2.4}Cr_{0.6}O_4$.

$(\Delta\rho/\rho)_{\perp}$ (i.e. those obtained in fields $H > H_s$) of chromite ferrites $Fe_{3-x}Cr_xO_4$ ($x = 0, 0.2, 0.6$)† in a field of 10 kOe at temperatures 130–300 K. The negative isotropic magnetoresistances of magnetite ($x = 0$) and of $MnFe_2O_4$ increase strongly as a result of cooling, particularly on approach to a low-temperature transition at $T_i = 100-120$ K (not shown in Fig. 11). It follows from Fig. 11 that chromite ferrites with $x = 0.2$ and 0.6 have similar temperature dependences of the isotropic magnetoresistances. A similar dependence is also reported in Ref. [20] for nickel ferrite $NiFe_2O_4$ (Fig. 9).

5. Two physically different components of the isotropic magnetoresistance of spinel ferrites

The experimental results reviewed above show that ferrites have two physically different components of the isotropic magnetoresistance. The first is due to the mechanism of the scattering of conduction electrons by the magnetic order changing as a result of the paraprocess; the magnetoresistance component increases on approach to the Curie point T_C and reaches its maximum at the temperature T_C itself. The second component of the isotropic magnetoresistance behaves conversely: it increases away from the Curie point and reaches high values at low temperatures; it cannot be explained by the paraprocess effects. The interpretation of the second component of the isotropic negative magnetoresistance raises a natural question whether it could be due to magnetoresistance mechanisms typical of nonmagnetic semiconductors. These mechanisms and their relevance to ferrites are discussed below.

5.1 Mechanism due to the action of the Lorentz force

This force causes bending ('twisting') of the paths of conduction electrons and thus increases these paths. At the same time the number of collisions with phonons and lattice defects also increases so that a positive magnetoresistance appears. It follows from the nature of the Lorentz force that the transverse magnetoresistance is much higher than the longitudinal effect: $(\Delta\rho/\rho)_{\perp} \gg (\Delta\rho/\rho)_{\parallel}$. This magnetoresistance mechanism is universal and it applies to all the samples, including ferrites; however, it cannot account for the second component of the isotropic magnetoresistance of ferrites in strong fields, since this gives rise to a positive effect.

5.2 Mechanism of wave function compression by a magnetic field *H*

This mechanism is used [25] to account for the giant values of the magnetoresistance observed for extrinsic (heavily doped) and amorphous semiconductors (n-type GaAs and n-type InSb). The hopping conduction mechanism applies to these substances. A magnetic field compresses the wave functions of the impurity atoms (i.e. it reduces their overlap) and this slows down or even suppresses electron jumps giving rise to a giant magnetoresistance ($\Delta\rho/\rho \gg 1$). Although ferrites can be regarded as extrinsic semiconductors and they also exhibit the hopping mechanism of an electrical conduction, this mechanism is inapplicable to the second component of the isotropic magnetoresistance, since it gives rise to a positive effect.

† These unpublished measurements were carried out by A N Goryaga and L A Skipetrova.

5.3 Mechanism of suppression of quantum corrections by a magnetic field H

These corrections occur in the Drude–Lorentz expression for the conductivity $\sigma = 1/\rho = e^2 N\tau/m^*$ (τ is the mean free time of electrons, and N and m^* are their concentration and effective mass). These quantum corrections allow for the influence of interference between electron waves that accompanies the motion of conduction electrons. The application of a field H suppresses the interference effects and gives rise to a negative magnetoresistance. The quantum correction mechanism is usually encountered in metals [29, 30].

5.4 Mechanism of delocalisation of electrons from the Fermi level by a magnetic field H

One further isotropic magnetoresistance mechanism [33] applies to semiconductors with a high concentration of conduction electrons (in the case of ferrites such a high concentration is encountered in magnetite [32]). A field H increases or reduces, depending on the direction of the electron spin μ_B, the Fermi energy by an amount $\pm\mu_B H$ and the conductivity then becomes $\sigma(E \pm \mu_B H)$. Expanding this function as a series gives a correction to the conductivity due to the action of H (i.e. a negative isotropic magnetoresistance because of delocalisation of electrons from the Fermi level by a field H), which is given by $\Delta\sigma = 1/2\sigma''(E)(\mu_B H)^2$. According to Ref. [33], this expression applies to the conventional and hopping conduction mechanisms. However, the value of $\Delta\sigma$ is large only in very high magnetic fields.

It thus follows that none of the four magnetoresistance mechanisms listed above can account for the second component of the isotropic negative magnetoresistance of spinel ferrites.

6. Interpretation of the second component of the isotropic negative magnetoresistance of spinel ferrites on the basis of a 'magnetoelectron sublattice' model

The anomalies of the magnetisation, magnetocaloric effect, and magnetoresistance of magnetite observed in the region of a low-temperature transition ($T_t = 100-120$ K) are explained in [34] by a 'magnetoelectron sublattice' model. In this section it will be shown that this model can account for the second component of the isotropic negative magnetoresistance of spinel ferrites. Some additional information on the magnetoelectron sublattice model, specifically from the point of view of the task in hand, will be given first.

Fig. 12a shows a magnetic structure of a spinel ferrite [34], where $(\sigma_s)_e$ is the magnetisation of the magnetoelectron sublattice (which will be called the e sublattice). The hopping electrons (i.e. electrons migrating between the Fe^{2+} and Fe^{3+} cations in the octahedra of the spinel lattice) responsible for conduction are concentrated in this sublattice. The magnetic ordering of these electrons in the e sublattice occurs under the influence of an effective exchange field exerted by the magnetic cations (the exchange interaction of the hopping electrons within the e sublattice is ignored, because it is very weak):

$$(H_{\text{eff,ex}})_{BA} = -\gamma_{Sd}(\sigma_s)_{BA} \ .$$

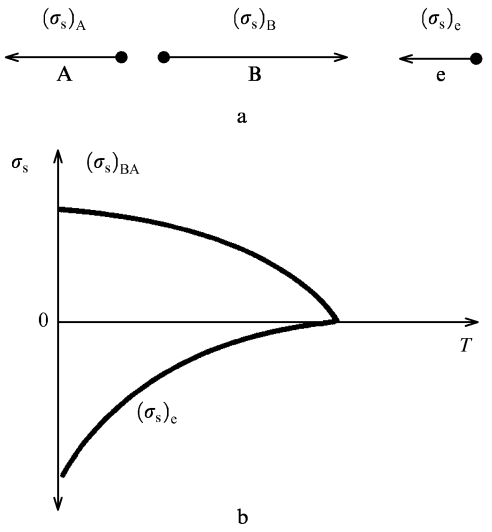

Figure 12. Explanation of the magnetoelectron sublattice model: A represents the tetrahedral sublattice, B is the octahedral sublattice, and e the magnetoelectron sublattice of a spinel ferrite; here, $(\sigma_s)_{BA}$ is the resultant (ferrimagnetic) spontaneous magnetisation of the ferrite.

Here, γ_{Sd} is the parameter representing the Vonsovskii exchange interaction [37, 38] between hopping electrons and magnetic cations; $(\sigma_s)_{BA}$ is the resultant (ferrimagnetic) magnetisation of the ferrite. The parameter γ_{Sd} is negative for ferrites, i.e. this interaction is antiferromagnetic.

The magnetic structure shown in Fig. 12a resembles formally the three-sublattice structure of a rare-earth iron garnet. In such a garnet the magnetic ordering of rare earth cations (Gd and others) is also created by an effective exchange field exerted by the iron cations in the garnet; this field is negative, i.e. it is of antiferromagnetic nature. At low temperatures this field creates a long-range magnetic order in the rare-earth sublattice. However, at some temperature $T = T_1$ the long-range order changes abruptly and a low-temperature Curie point is observed for the rare-earth sublattice [39]. This occurs when the thermal motion energy T_1 becomes comparable with the energy of the exchange interaction of the Fe and rare-earth cations [39–42]. However, since at temperatures $T > T_1$ the field $(H_{\text{eff,ex}})_{BA}$ continues to act, a partial magnetic order is retained. The $(\sigma_s)(T)$ curve assumes the shape of a tail (i.e. it becomes asymptotic), frequently observed for magnetically ordered materials at temperatures above the Curie point. This curve is sensitive to relatively weak external fields H, i.e. a strong paraprocess appears in the rare-earth sublattice. The strength of this process is higher near a temperature T_1 and it decreases as temperature is increased ($T > T_1$).

A similar situation occurs in the e sublattice. Fig. 12b shows schematically the asymptotic dependence of $(\sigma_s)_e$ on T. The application of an external field H again induces the paraprocess and at low temperatures this process is stronger than at higher temperatures. However, the mechanisms of the paraprocess in the rare-earth and e sublattices are different in respect of their physical consequences. In the former case the paraprocess magnetisation is accompanied by some displacements of the rare-earth cations from the crystal lattice sites, i.e. an exchange magnetostriction is observed. In the latter case the paraprocess magnetisation (i.e. rotation of the spin of the hopping

electrons so that it becomes aligned along the field H, as shown in Fig. 12a) is accompanied by an increase in the kinetic energy of electrons, so that such hopping electrons become delocalised. This can be called the 'magnetoelectron' paraprocess.

The localisation of the hopping electrons in the e sublattice is due to a negative s–d exchange between a magnetic cation and a given electron. Such localisation is impossible if the s–d exchange interaction is positive. This follows from the following general considerations.

In contrast to ferromagnets, the motion of the hopping electrons in antiferromagnets (including uncompensated antiferromagnets, such as ferrites) involving a periodic reversal (flipping) of its spin (which does not occur in ferromagnets) and this requires an additional activation energy. The result is a reduction in the electron mobility in the limit of a sufficiently strong s–d exchange, which acts between the hopping electrons and the iron cations, leading to electron localisation in the e sublattice.

There is however an important difference between the mechanism of localisation of electrons in an antiferromagnetic structure, discussed for wide-gap semiconductors [35, 36], and the mechanism of localisation of electrons in ferrites. In the former case such localisation creates magnetopolaron states ('ferrons' [35]), since the effect of the conduction electrons on the magnetic cations in such a semiconductor is very strong. In ferrites it is very weak and, conversely, the effect of the iron cations on the hopping electrons is very strong and this is the reason for the appearance of the e sublattice.

Obviously, the appearance of the second component of the isotropic negative magnetoresistance is the direct result of the 'magnetoelectron' paraprocess in spinel ferrites. The higher the field H, the stronger the delocalisation of electrons from the e sublattice and the greater the contribution of these electrons to the isotropic negative magnetoresistance. Since at low temperatures the number of localised electrons is large, it follows that the number of electrons delocalised by a field H is also large, so that at low temperatures the negative magnetoresistance of the second component is very large. A strong field H causes depletion of the electrons localised in the e sublattice. This accounts for the trend in saturation exhibited by the $(\Delta\rho/\rho)_{||}$ and $(\Delta\rho/\rho)_{\perp}$ isotherms recorded at low temperatures (see Figs 3–5).

The electron paraprocess in ferrites need not be accompanied by delocalisation of electrons from the e sublattice. Flipping of the electron spins by a field H is induced by a paraprocess of the antiferromagnetic type, which is accompanied by an isotropic positive magnetoresistance. It has been shown [34] that this electron paraprocess appears in magnetite at low temperatures (in addition to the electron paraprocess that accompanies electron delocalisation). The occurrence of one or another electron paraprocess depends on the relationship between $(H_{\text{eff,ex}})_{\text{BA}}$, the electron–phonon interaction in the investigated ferrite, and the value of the applied field H.

7. Other indirect experimental evidence supporting the 'magnetoelectron sublattice' model

In Section 6 it is shown that the nature of manifestation of the second component of the isotropic negative magnetoresistance of ferrites can be explained by the concept of the 'magnetoelectron sublattice'. However, spinel ferrites exhibit also anomalies of other physical properties which can be explained by the magnetoelectron sublattice model.

7.1 Anomaly (reduction) of the saturation values of the magnetic moments at 0 K

This anomaly is manifested clearly by manganese ferrite $MnFe_2O_4$. It has the following mixed cation distribution:

$$(\underset{\text{A}}{Mn^{2+}_{0.8}\,Fe^{3+}_{0.2}})[\underset{\text{B}}{Mn^{2+}_{0.2}\,Fe^{3+}_{1.8}}]\,O^{2-}_4\ .$$

This complex cation distribution appears because the electron configurations and the radii of the $Mn^{2+}(3d^5)$ and $Fe^{3+}(3d^5)$ cations are similar and, therefore, they can move between the A and B positions. Since these cations have the same magnetic moments ($5\mu_B$), a change in the cation distribution between the A and B positions does not affect the saturation value of the magnetic moment n_0 of the ferrite at 0 K (i.e. the moment per $MnFe_2O_4$ formula unit):

$$n_0 = 10\mu_B(\text{B}) - 5\mu_B(\text{A}) = 5\mu_B.$$

However, over 30 years ago it has been discovered that the measured values of n_0 are lower and lie in the interval $(4.4-4.8)\mu_B$. This has been established both by neutron diffraction [24] and by direct measurements of the saturation magnetisation extrapolated to 0 K [43–46]. All this has been the subject of a long discussion between French and Dutch physicists.

Several reasons have been suggested for this discrepancy. For example, some of the Mn^{2+} cations at the B positions may be converted to $Mn^{3+}(3d^4)$ [45]. However, this seems to be unlikely. Other authors have suggested [47, 48] that the underestimate of n_0 is due to the presence of a small number of the $Fe^{2+}(3d^6)$ cations at the B positions in $MnFe_2O_4$. However, this also fails to solve the problem, because the Fe^{2+} cations at the B positions are in a triplet orbital state and the spin magnetic moment $4\mu_B$ should be supplemented by the unquenched part of the orbital magnetic moment amounting to $\sim 1\mu_B$, i.e. at these positions the Fe^{2+} cations have a moment of the order of $5\mu_B$.

Finally, some authors are of the opinion that a slight canting of the magnetic moments of the cations at the B positions appears at low temperatures in $MnFe_2O_4$. However, this has not been confirmed by neutron diffraction [24, 49] or Mossbauer [50] methods, or by the saturation magnetisation measurements [23, 51].

Therefore, the problem of the anomalous reduction in the value of n_0 of $MnFe_2O_4$ has not yet been solved.

The reduced value of n_0 reported for $MnFe_2O_4$ can also be explained in a different way. As shown in Section 6, the spins of the hopping electrons become oriented opposite to the magnetisation $(\sigma_s)_{\text{BA}}$ by the influence of the field $(H_{\text{eff,ex}})_{\text{BA}}$ which reduces the magnetisation, i.e. formation of the magnetoelectron sublattice in the ferrite $MnFe_2O_4$ is responsible for the anomalous values of n_0. The magnetoelectron sublattice also affects n_0 of magnetite [34] and other spinel ferrites. The fractional atomic magnetic moments of Fe, Co, and Ni reported by Vonsovskii and Vlasov [52] can also be explained by the contribution of the magnetic spin moments of the s electrons (i.e. conduction electrons) to n_0.

7.2 Problem of the low mobility of the conduction electrons in ferrites

A characteristic property of ferrites considered as magnetic semiconductors is an extremely low mobility of the conduction electrons (hopping electrons). The measured Hall and drift mobilities do not normally reach $1\,cm^2\,V^{-1}\,s^{-1}$, which are tens of thousands of times less than in semiconductors used in technology. In spite of a large number of investigations of this topic, no satisfactory reason has been put forward to account for the low mobility. In some theoretical treatments the low values of the carrier mobility in ferrites and other oxides with the 3d cations have been attributed to a strong electron–photon interaction, which leads to the appearance of small polarons [56]. However, the experimental results [57–59] suggest that this explanation does not always apply.

In 1971 Nagaev [60] has shown theoretically that low carrier mobilities in 3d compounds are due to the interaction of the conduction electrons not so much with phonons as with the spins of the 3d cations. The magnetoelectron sublattice model leads to the same conclusion. The low mobility of the hopping electrons in a ferrite is due to their localisation by the negative s–d exchange in the e sublattice and this can be regarded as an indirect support of the existence of the magnetoelectron sublattice in ferrites.

8. Magnetoresistance of ferrites in the vicinity of magnetic phase transitions

There are many more magnetic phase transitions in ferrites than in ferromagnets. In addition to the magnetic order–disorder phase transition at the Curie point, there are also magnetic order–order transitions. The following types of the order–order transitions can be distinguished [54]:

(1) at some temperatures in certain ferrites the sign of the first magnetic anisotropy constant K_1 is reversed, which results in the reorientation of the vector $\boldsymbol{I}_s$ in a crystal from one easy magnetisation axis to another (spontaneous orientational transition); this transition is accompanied by an abrupt change in the physical properties, including the magnetoresistance;

(2) the difference between the intersublattice and sublattice exchange interactions in ferrites, particularly in mixed materials, frequently gives rise to a canted orientation of the magnetic moments of the sublattices; the application of a field $H = H_{cr}$ destroys such a canted structure, i.e. an orientational transition induced by the field H_{cr} takes place and this transition is accompanied by an abrupt change in the magnetoresistance;

(3) the nature of the changes in the magnetisation and associated physical effects, including the isotropic magnetoresistance (first component), at the magnetic compensation temperature θ_k is such that the latter can be regarded as the temperature of an orientational phase transition in the presence of a field H [22]; the transition at θ_k causes considerable changes in the magnetoresistance which are discussed in detail later.

We shall begin by considering the characteristic features of the appearance of the magnetoresistance in spinel ferrites in the region of their Curie point. It follows from Fig. 7, which gives the $(\Delta\rho/\rho)_{||}(T)$ curves, that a negative magnetoresistance maximum is observed for manganese spinel ferrite near the Curie point T_C. A maximum of approximately the same amplitude is observed also for the $(\Delta\rho/\rho)_{\perp}$ effect. This isotropic negative magnetoresistance is due to the scattering of the conduction electrons by changes in the magnetic ordering of the cations because of a strong paraprocess in the region of T_C. However, in contrast to an ordinary single-sublattice ferromagnet, the isotropic negative magnetoresistance (first component) of a ferrite measured at T_C generally consists of two contributions. The first represents the scattering of the conduction electrons by the magnetic moments of the cations in the sublattice with the magnetisation vector coinciding with the direction of $\boldsymbol{H}$, which gives rise to a negative isotropic magnetoresistance, whereas a positive isotropic magnetoresistance appears in the other sublattice with the magnetisation vector antiparallel to $\boldsymbol{H}$. Normally the magnetoresistances do not balance out at T_C, since the sublattices make different contributions to the electrical conductivity of the ferrite. Usually the octahedral sublattice makes a greater contribution to the electrical conductivity, because it contains the heterovalent cations Fe^{2+} and Fe^{3+}.

Measurements have shown that small negative magnetoresistance maxima, of approximately the same amplitude as in the case of Ni, appear at the Curie points of ferrites. For example, it has been reported [61] that $(\Delta\rho/\rho)_{T_C} \sim 0.2\%$ for nickel–zinc ferrite at T_C in $H = 10^3$ Oe. Approximately the same values of $(\Delta\rho/\rho)_{T_C}$ have been reported for manganese ferrite [6].

A positive isotropic magnetoresistance at T_C reported [58] for iron garnet $Y_3Fe_5O_{12}$ doped with Si^{4+}, which creates the Fe^{2+} cations in the octahedral sublattice, is attributed to the antiparallel orientation of the magnetisation vector of this sublattice and $\boldsymbol{H}$.

Experimental investigations of the magnetoresistance of ferrites at the Curie point have revealed one more interesting feature of the ferrites with a magnetic compensation point θ_k. A strong paraprocess appears in these ferrites not only near T_C, but also at low temperatures (at $T < \theta_k$). The paraprocess susceptibility χ_p, the magnetocaloric effect, and even magnetic effects, including the magnetoresistance [26], reach their maxima at some temperature T_1. These maxima resemble the maxima of the same properties at the normal Curie point, so that the temperature T_1 may be called the low-temperature Curie point of a ferrite. It appears because these ferrites have sublattices with weaker exchange interactions and magnetic disordering begins in them already at low temperatures [22].

However, it has been established [26] that the temperature dependence of the isotropic negative magnetoresistance (specifically, the first component of this magnetoresistance) in the region of T_1 differs from the nature of the same dependence at T_C (Fig. 13). The difference is that in the region of T_1 the left-hand (low-temperature) branches of the $(\Delta\rho/\rho)_{||}(T)$ and $(\Delta\rho/\rho)_{\perp}(T)$ curves fall steeply (almost vertically). This fall occurs because an exponentially falling second component of the negative magnetoresistance is superimposed on the paraprocess contribution.

Let us consider now the behaviour of the magnetoresistance in the vicinity of magnetic orientational (frequently called spin-reorientation) transitions.

Fig. 14 reports the results of measurements of the magnetoresistance of a single crystal of the ferrite $Co_{0.94}Fe_{2.06}$ [62] in which a spin-reorientation transition due to a change in the anisotropy constant K_1 occurs at $T_{cr} \approx 510$ K. At this temperature there are maxima of the

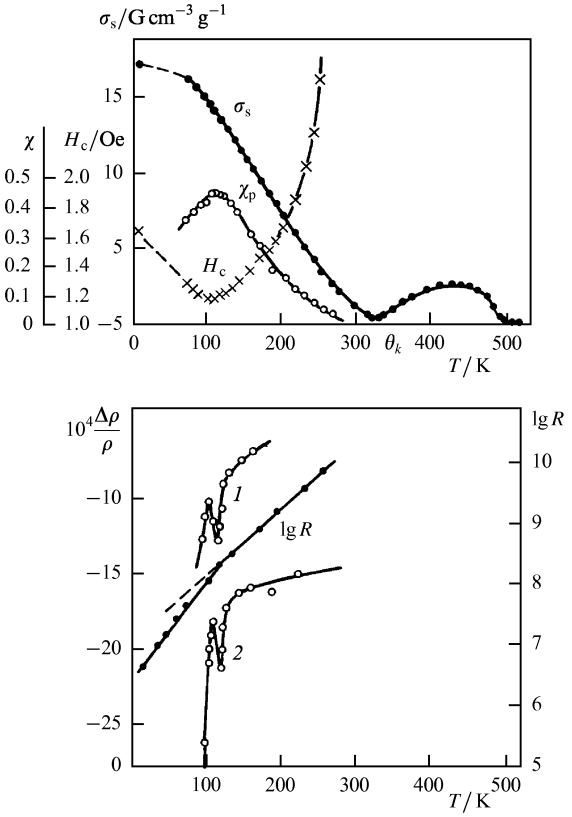

Figure 13. Temperature dependences of the magnetoresistances $(\Delta\rho/\rho)_{\|}$ (*1*) and $(\Delta\rho/\rho)_{\perp}$ (*2*) measured in the region of the low-temperature Curie point of ferrite $Li_2O \cdot 2.5Fe_2O_3 . 2 \cdot 5Cr_2O_3$ (lower part of the figure). The figure includes also the temperature dependences of the logarithm of the resistance lg$R$, of the specific magnetisation σ_s, of the paraprocess susceptibility χ_p, and of the coercive force H_c.

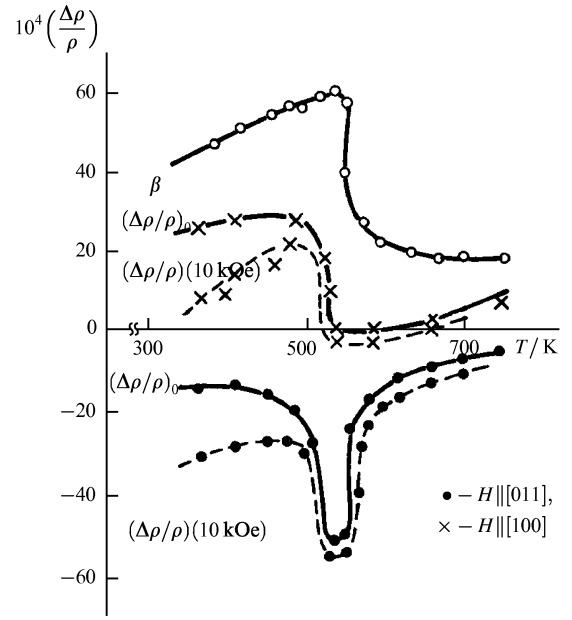

Figure 14. Temperature dependences of $(\Delta\rho/\rho)_{\|}$ and $(\Delta\rho/\rho)_{\perp}$ in a field of $H = 10$ kOe and of the factor β for a single crystal of $Co_{0.94}Fe_{0.06}O_4$.

positive and negative magnetoresistance, depending on the direction of measurements of the magnetoresistance, i.e. an anisotropic magnetoresistance (orientational effect) appears at T_{cr}.

Fig. 14 not only gives the magnetoresistance measured in a field H, but also the values of $(\Delta\rho/\rho)_0(H)$ extrapolated to zero field in order to separate the isotropic components of the magentoresistance, i.e. to obtain the pure orientational magnetoresistance $(\Delta\rho/\rho)_0$. This figure gives the temperature dependence of the anisotropy factor of the orientational magnetoresistance:

$$\beta = \left(\frac{\Delta\rho}{\rho}\right)_{H\|[100]} - \left(\frac{\Delta\rho}{\rho}\right)_{H\|[110]} .$$

We can see that the value of β in the region of T_{or} also undergoes abrupt changes.

The microscopic origin of the orientational magnetoresistance lies in a considerable change in the energy spectrum of the conduction electrons in ferrites as a result of rotation of the vector $\boldsymbol{I}_s$. This conclusion follows from an investigation of the magnetooptic effects. The 'intensity' magnetooptic reflection effects, which accompany reorientation of the vector $\boldsymbol{I}_s$, have been discovered and investigated [63, 64].

Some theoretical investigations [65–67] have included attempts to develop a microscopic theory of the orientational magnetoresistance of metallic ferromagnets. However, a satisfactory theory of this magnetoresistance is not yet available. In the case of magnetic semiconductors, including ferrites, no ideas have yet been put forward about the microscopic origin of the orientational magnetoresistance.

Let us now consider the changes in the magnetoresistance in the region of the magnetic compensation point θ_k of a ferrite. It has been demonstrated on many occasions (see, for example, Ref. [22]) that in the presence of a field H the compensation point θ_k indicates the occurrence of an order–order magnetic phase transition.

Fig. 15 shows the results of measurements [26, 27, 68] of the isotropic magnetoresistance (i.e. measurements in fields H higher than the technical saturation field H_s) of lithium chromite ferrite $Li_2O \cdot 2.5Fe_2O_3 \cdot 2.5Cr_2O_3$ in the region of θ_k. Near θ_k the sign of the isotropic magnetoresistance is

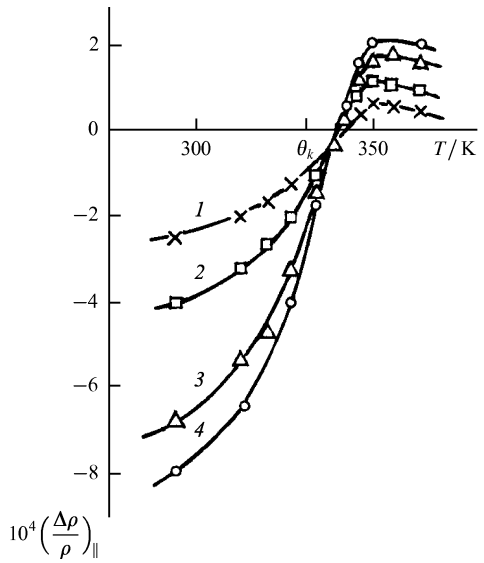

Figure 15. Reversal of the sign of the isotropic magnetoresistance in the region of θ_k of ferrite $Li_2O \cdot 2.5Fe_2O_3 \cdot 2.5Cr_2O_3$: (*1*) 2260 Oe; (*2*) 4500 Oe; (*3*) 9030 Oe; (*4*) 1170 Oe.

reversed from negative to positive. Similar changes in the sign of the magnetoresistance have been observed for a metallic ferrimagnet $MnGe_2$ [70].

This has been interpreted by a phenomenological theory put forward by Turov and Shavrov [69]. According to these authors, the galvanomagnetic properties of ferrimagnets and antiferromagnets are governed by two vectors: the ferromagnetic vector $\boldsymbol{M} = \boldsymbol{M}_1 + \boldsymbol{M}_2$ (where $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$ are the sublattice magnetisations) and the antiferromagnetic vector $\boldsymbol{L} = \boldsymbol{M}_1 - \boldsymbol{M}_2$, i.e. two galvanomagnetic effects with opposite signs occur in the substances: one corresponds to the vector $\boldsymbol{M}$ and the other to $\boldsymbol{L}$. At the point θ_k the vector $\boldsymbol{M}$ disappears, but the vector $\boldsymbol{L}$ remains, as reported for the alloy $MnGe_2$ (the signs of the magnetoresistance and the Hall emf are reversed by the transition at θ_k).

Model representations account for the reversal of the sign of the magnetoresistance at the θ_k transition in lithium chromite ferrites [22, 68] as follows. At temperatures $T < \theta_k$, where the ferrite magnetisation is due to the octahedral sublattice exhibiting a strong low-temperature paraprocess, an external field H orders the magnetic moments of the cations and this leads to a negative magnetoresistance. In the range $T > \theta_k$ the magnetisation of the octahedral sublattice is reversed relative to H and the paraprocess is of the antiferromagnetic type ('flipping' of the magnetic moments of the cations). This enhances the scattering of carriers, i.e. it gives rise to a positive magnetoresistance.

A shift of the temperature at which the magnetoresistance sign is reversed (known as the magnetoresistance compensation point), relative to the magnetic compensation point θ_k, has been reported [27] for the ferrite $Li_2O \cdot 2.5Fe_2O_3 \cdot 2.5Cr_2O_3$ (Fig. 15). This is due to a superposition of an exponentially falling negative magneto-resistance (second component of the isotropic magnetoresistance) on the paraprocess magnetoresistance.

Deviations from a monotonic temperature dependence of the second component of the magnetoresistance have been reported for the ferrite $MnFe_2O_4$ [13, 14, 21]. Small H-dependent 'smeared-out' maxima of the negative isotropic magnetoresistance occur at ~200 K and ~150–140 K (Fig. 8). At these temperatures the $(\lg \rho)$ $(1/T)$ curves have kinks and there are small maxima of the paraprocess susceptibility χ_p.

It has been suggested [13, 14] that the phase transitions at these temperatures are associated with the formation of cation pairs in the $Mn_B^{2+}-Mn_B^{2+}$ and $Fe_B^{3+}-Fe_B^{3+}$ octahedra as a result of the direct exchange between them. According to Goodenough [74], this direct exchange appears at specific critical values of the distance between the cations in the $Mn_B^{2+}-Mn_B^{2+}$ and $Fe_B^{3+}-Fe_B^{3+}$ pairs in the octahedral sublattice of the ferrite. Goodenough predicts that the formation of these cation–cation pairs should be accompanied by weak additional localisation of the conduction electrons in the covalent bonds of the cations. The application of a field H should in its turn delocalise these electrons and this is clearly the reason for the appearance of the smeared-out negativemagnetoresistance maxima in Fig. 8.

It is evident from Fig. 11 that deviations from the monotonic temperature dependence of the isotropic magnetoresistance (second component) are exhibited also by chromite ferrites. In the case of magnetite this is manifested by a strong increase in the isotropic negative magnetoresistance [34] on approach to a low-temperature transition at $T_t = 100-120$ K (this is not shown in Fig. 11).

In an earlier review [34] this transition in magnetite is attributed to a 'magnetoelectron' phase transition induced by the field $(H''_{\text{eff,ex}})_{BA}$. It is possible that the deviations from the monotonic isotropic negative magnetoresistance, observed at low temperature for manganese ferrites and chromite ferrites, are of the same origin as the low-temperature transition in magnetite.

The reason for the deviations from the monotonic temperature dependence of the isotropic negative magnetoresistance in ferrites at low temperatures nevertheless requires further studies.

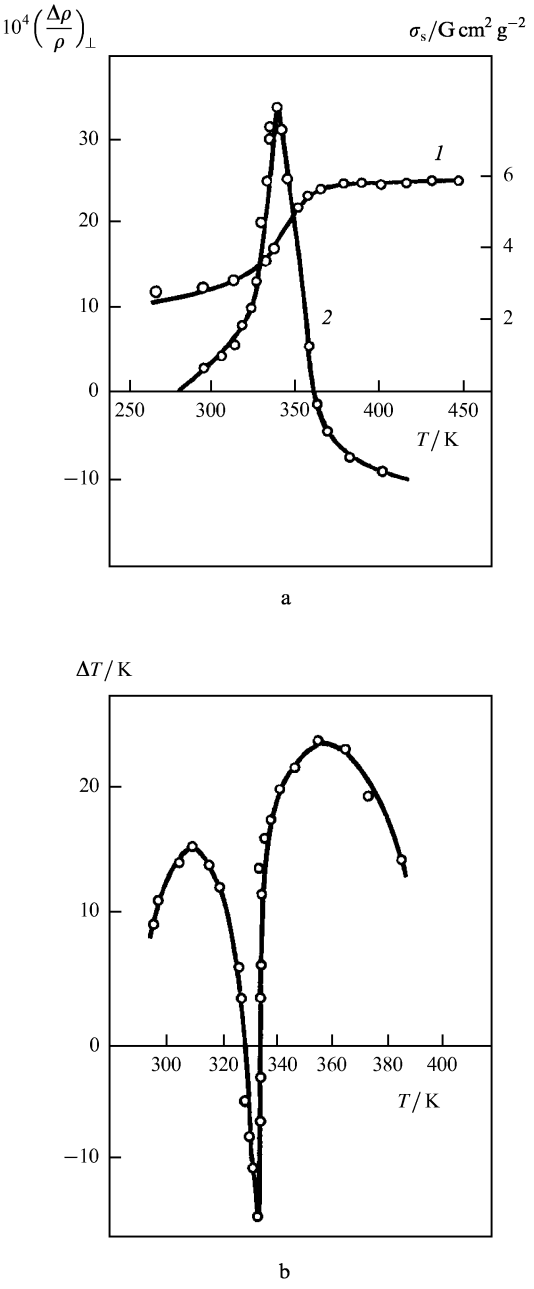

Figure 16. (a) Temperature dependences of the saturation magnetisation σ_s in a field $H = 100$ Oe (curve *1*) and of the transverse magnetoresistance in a field $H = 10$ kOe (curve *2*), obtained for polycrystalline ferrite $CuFe_2O_4$. (b) Temperature dependence of the magnetocaloric effect in a field $H = 10$ kOe, obtained for polycrystalline ferrite $CuFe_2O_4$.

In connection with the above discussion one should note another interesting experimental observation [71–73] on copper ferrite $CuFe_2O_4$. At 330–340 K (the Curie point of this ferrite is $T_C \approx 720$ K) there is a sharp peak of the positive isotropic magnetoresistance (Fig. 16a), a peak of the negative magnetocaloric effect (Fig. 16b), and a jump of the saturation magnetisation (curve *1* in Fig. 16a). These effects occuring in $CuFe_2O_4$ at 330–340 K are of the same nature as those in magnetite near its low-temperature transition ($T_t = 100-120$ K). The positive sign of the magnetoresistance, the negative sign of the magnetocaloric effect, and the jump in the saturation magnetisation of $CuFe_2O_4$ at 330–340 K can be explained qualitatively by the magnetoelectron sublattice model, as in the case of magnetite at $T_t = 100-120$ K. It follows that a magnetoelectron phase transition, similar to that at T_t in magnetite, occurs in $CuFe_2O_4$ at 330–340 K.

9. Conclusions

In spite of the fact that ferrites have been discovered long ago and have been used widely in various branches of technology, many of their properties are still little known. This applies particularly to the transport phenomena and, in partiular, to the magnetoresistance.

This review paper presents a systematic account and an analysis of the experimental temperature and field dependences of the magnetoresistances of various spinel ferrites, obtained by myself and my colleagues, and also those reported in the literature. In magnetic fields above the technical saturation value, but at temperatures below the Curie point, such ferrites have two components of the isotropic magnetoresistance. The first is due to the usual magnetoresistance mechanism, which is the scattering of the conduction electrons by changes in the magnetic order caused by an external magnetic field (paraprocess). This component is responsible, as in the case of ordinary ferromagnets, for a maximum of the negative magnetoresistance at the Curie point. Cooling reduces this magnetoresistance monotonically in accordance with the weakening of the paraprocess.

On the other hand, the second component of the negative isotropic magnetoresistance rises strongly (exponentially) when a ferrite is cooled down from the Curie point.

At room temperature and below the second component of the isotropic magnetoresistance masks the positive longitudinal and negative transverse components of the magneto-resistance, which accompany the processes of rotation and displacement of domain walls (orientational magnetoresistances). Therefore these ferrites usually exhibit anomalous, compared with ordinary ferromagnets (such as nickel), field dependences of $(\Delta\rho/\rho)_{||}$ and $(\Delta\rho/\rho)_{\perp}$; they have the same (negative) signs and similar values.

The second component of the negative magnetoresistance is explained on the basis of the magnetoelectron sublattice model, proposed in an earlier review [34]. According to this model, the hopping electrons are in a magnetically localised state [effect of $(H_{\mathrm{eff,ex}})_{BA}$]. The application of an external magnetic field H delocalises these electrons (electron paraprocess) and this induces the second component of the negative isotropic magnetoresistance. Such delocalisation occurs also as a result of a change in temperature and it becomes stronger at higher temperatures, leading to an exponential temperature dependence of the second component of the negative magnetoresistance.

The magnetoelectron sublattice concept and postulate of magnetically localised states of the hopping conduction electrons can account for the anomaly (reduction) of the magnetic moments of manganese ferrite at 0 K and for the low carrier mobility in ferrites.

The present review deals also with the anomalies of the magnetoresistance in ferrites that occur at order–disorder and order–order magnetic phase transitions.

The results of investigations of the magnetoresistance in ferrites are of considerable interest because the magnetoresistance effects can provide information on the electron processes that have been largely neglected in these materials of practical importance.

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