Even galvanomagnetic effects in magnetically multiaxial antiferromagnets

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Expressions are derived for the magnetoresistance $\Delta\rho/\rho_0$ as a function of the magnetic field H in magnetically multiaxial antiferromagnets. Displacements of domain walls are taken into account along with intradomain processes. Experiments on $\Delta\rho/\rho_0(H)$ in a tetragonal $FeGe_2$ single crystal are reported. There is good agreement between the experimental and theoretical results on the behavior $\Delta\rho/\rho_0(H)$.

1. The magnetization curves of magnetically multiaxial antiferromagnets were studied theoretically and experimentally in Refs. 1 and 2. Magnetization curves had been studied previously for magnetically uniaxial antiferromagnets, which have only 180° domain neighborhoods. Such neighborhoods are energetically equivalent in a magnetic field H (Ref. 3, for example). Magnetization processes in these materials occur as they would in antiferromagnets in a single-domain state. In a multiaxial antiferromagnet, in contrast, domains with noncollinear antiferromagnetism vectors touch each other. Such domains are not energetically equivalent in a magnetic field. A magnetic field induces reversible and irreversible displacements of domain walls, which cause the magnetization curves of multiaxial antiferromagnets to become qualitatively distinct. In particular, hysteresis of the magnetization curves occurs due to irreversible wall displacements.

Magnetization processes in both uniaxial and multiaxial antiferromagnets are governed by a structure-insensitive critical field H_0. Near this critical field either the antiferromagnetism vector **L** rotates abruptly or the ongoing rotation of this vector terminates.[3]

In a multiaxial antiferromagnet, magnetization processes are also determined by the structure-sensitive field H^*, near which reversible wall shifts occur most intensely.[1,2]

In this paper we are reporting a theoretical study of the galvanomagnetic properties (the change in the electrical resistivity in a magnetic field) of multiaxial antiferromagnets in which displacements of walls between domains can occur. We compare the theoretical results with experimental data for the particular case of a tetragonal $FeGe_2$ single crystal.

The existing phenomenological theories of kinetic phenomena for antiferromagnetically ordered crystals[4] are valid both for magnetic materials in a single-domain state and within individual domains.

2. We begin the analysis with the magnetically uniform state of an antiferromagnet, in which there is no domain structure.

According to Ref. 4, quadratic galvanomagnetic effects are described by

$$\begin{aligned}\Delta\rho_{ik}&=\rho_{ik}-\rho_{ik}^0\\&=\alpha_{ikmn}^{BB}B_mB_n+\alpha_{ikmn}^{MM}M_mM_n+\alpha_{ikmn}^{LL}L_mL_n\\&\quad+\alpha_{ikmn}^{BM}B_mM_n+\alpha_{ikmn}^{BL}B_mL_n+\alpha_{ikmn}^{ML}M_mL_n,\end{aligned}\quad(1)$$

where ρ_{ik} is the resistivity tensor, and **B** is the magnetic induction. Since the magnetic susceptibility of an antiferromagnet is small, the induction can be replaced by the magnetic field **H**. The vectors **M** and **L** are the ferromagnetism and antiferromagnetism vectors, respectively. Tensors of the form α_{ikmn} are kinetic coefficients of the material.

Among the various galvanomagnetic effects, we focus on the change in the resistivity in a magnetic field (i.e., the magnetoresistance), in which case the electric field is determined in the direction of the (vector) current density **j**.

We consider antiferromagnetic single crystals of tetragonal symmetry with two mutually perpendicular antiferromagnetism axes in the (001) basal plane. This situation corresponds to the case in which the constant of the crystallographic second-order magnetic anisotropy satisfies $K_2<0$, while the fourth-order constant satisfies $K_4\neq 0$. We will refer to the plane containing the antiferromagnetism axes as the "antiferromagnetism plane."

We assume that the current density **j** is directed parallel to one of the antiferromagnetism axes. We choose this axis to be the x axis of our coordinate system. We consider three cases. 1) The vector **H** is directed along the same axis (this is the case of longitudinal magnetoresistance). 2) The vector **H** is directed along another, mutually perpendicular antiferromagnetism axis (this is the transverse magnetoresistance in the antiferromagnetism plane). We choose this to be our y axis. 3) The vector **H** is oriented perpendicular to the antiferromagnetism plane (this is the transverse magnetoresistance in the direction perpendicular to the antiferromagnetism plane). We adopt this direction as our z axis.

It follows from the symmetry of the problem that in the cases which we will be discussing here, regardless of the value of H, the vector **L** is always oriented along one of the antiferromagnetism axes.

Using the thermodynamics of nonequilibrium processes (the Onsager relations for the kinetic coefficients are taken into account), and making use of the symmetry of

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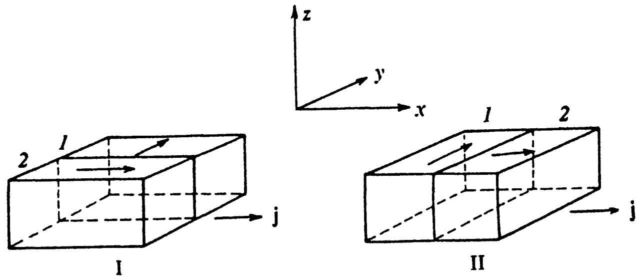

FIG. 1. Connection of the resistances of the domains. I—Parallel connection; II—series connection. The arrows show the directions of the antiferromagnetism vectors **L** in domains 1 and 2.

the crystal lattice, we find from (1) the following expression for the case in which **H** is directed perpendicular to the antiferromagnetism plane ($H_x=H_y=0, M_x=M_y=0, L_z=0$):

$$\Delta\rho_{xx}^{z}=\alpha_{1133}^{HH}H_z^2+\alpha_{1133}^{MM}M_z^2+\alpha_{1133}^{HM}H_zM_z+\alpha_{1111}^{LL}L_x^2+\alpha_{1122}^{LL}L_y^2. \quad (2)$$

If **H** lies in the antiferromagnetism plane ($M_z=0, H_z=0, L_z=0$) we have

$$\Delta\rho_{xx}^{xy}=\alpha_{1111}^{HH}H_x^2+\alpha_{1122}^{HH}H_y^2+\alpha_{1111}^{MM}M_x^2+\alpha_{1122}^{MM}M_y^2+\alpha_{1111}^{HM}H_xM_x+\alpha_{1122}^{HM}H_yM_y+\alpha_{1111}^{LL}L_x^2+\alpha_{1122}^{LL}L_y^2+\alpha_{1112}^{HL}H_xL_y+\alpha_{1121}^{HL}H_yL_x+\alpha_{1112}^{ML}M_xL_y+\alpha_{1121}^{ML}M_yL_x. \quad (3)$$

The vectors **M** and **L** are functions of **H**. The functions themselves can be found from the thermodynamic theory and sometimes from symmetry considerations. The vector **M** is an odd function of **H**, while **L** is an even function of it. Accordingly, relations (2) and (3) describe effects which are both even in **H** (which do not contain terms linear in L) and odd.

We restrict the present paper to a theoretical and experimental study of the magnetoresistance which is even in **H**. For brevity, we will omit the word "even" as well as the subscripts xx on ρ_{xx}.

3. We now take account of the domain structure of antiferromagnets. We introduce the concentrations of magnetic phases, n_1 and n_2, which differ in the orientations of the antiferromagnetism vector with respect to the current density. The quantities n_1 and n_2 are the relative volumes of the domains in which the vector **L** is oriented perpendicular and parallel to **j**.

In the cases under consideration here, in which the antiferromagnet contains 90° domain neighborhoods at $H=0$, the domains can have various spatial arrangements with respect to each other, but in each domain either **L**$\|$ **j** or **L**$\perp$ **j** holds.

Figure 1 shows two arrangements, I and II, which are qualitatively different from each other. Other arrangements are equivalent to these two. We assume that the resistivities ρ_1 and ρ_2 of the domains forming the phases with concentrations n_1 and n_2 are different. For an arrangement of type I the resistances of the domains are connected in parallel. It is simple to show that the resultant resistivity is

$$\rho=\frac{\rho_1\rho_2}{n_1\rho_2+n_2\rho_1}. \quad (4)$$

For an arrangement of type II the resistances are in series, and we have

$$\rho=n_1\rho_1+n_2\rho_2. \quad (5)$$

Let us assume that in a magnetic field we have

$$\rho_1=\rho^0+\Delta\rho_1; \quad \rho_2=\rho^0+\Delta\rho_2, \quad (6)$$

where ρ^0 is a resistivity unrelated to magnetic order, and $\Delta\rho_{1,2}$ are the resistivities given by (1). According to (4)–(6), the resultant resistivities of the two arrangements are described by the same expression under the conditions

$$|\Delta\rho_1^0-\Delta\rho_2^0|\ll\rho^0+n_1(0)\Delta\rho_1^0+n_2(0)\Delta\rho_2^0,$$

where $n_{1,2}(0)$ and $\Delta\rho_{1,2}^0$ are the values of the corresponding quantities at $H=0$. This common expression is

$$\rho=\rho^0+n_1\Delta\rho_1+n_2\Delta\rho_2. \quad (7)$$

In general, the concentrations of the magnetic phases depend on H.

It follows from (7) that the resistivity in a magnetic field depends on both intradomain processes, which govern the H dependence of $\Delta\rho_1$ and $\Delta\rho_2$ according to (1), and interdomain wall shifts, which determine the behavior of n_1 and n_2 as a function of H.

4. We first consider the case of the transverse magnetoresistance with **H** perpendicular to the antiferromagnetism plane. For this case we have

$$\rho_{1,2}=(\rho_{1,2})_t^z; \quad n_{1,2}=(n_{1,2})_t^z,$$

where the subscript t means **H**$\perp$ **L** (transverse effect), while z means that **H** is perpendicular to the antiferromagnetism plane (Fig. 1).

It follows from the symmetry of the problem that in both phase 1 and phase 2 we have $M_z=\chi_1^z H_z$, where χ_1^z is a thermodynamic constant of the material, specifically, the susceptibility perpendicular with respect to **H**, when the vector **H** is perpendicular to the antiferromagnetism plane. This susceptibility characterizes the changes in the angle between the magnetization vectors of the magnetic sublattices.

We have

$$n_1+n_2=I, \quad L^2=L_0^2-M^2, \quad M=\chi_1^z H_z,$$

where L_0 is the absolute value of the spontaneous antiferromagnetism vector; we have $L_x=0$ and $L_y=L$ in phase 1, and we have $L_x=L$ and $L_y=0$ in phase 2. In addition, for this orientation of **H** the concentrations of magnetic phases are independent of H, and they remain equal to their original values (i.e., for $H=0$), $n_1(0)$ and $n_2(0)$.

Using the conditions stated above along with (2) and (7), we find the transverse resistivity to be

$$\rho_t^z=\rho^0+\Delta\rho_0+B_t^zH_z^2, \quad (8)$$

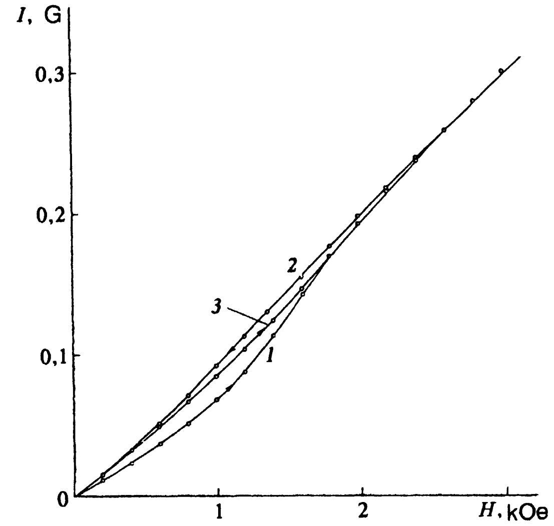

FIG. 2. The specific magnetization I_α of an $FeGe_2$ single crystal versus the magnetic field H for the case **H**|| [110] at $T=106$ K. *1*—Virgin magnetization curve; *2, 3*—hysteresis loop.

where

$$\Delta\rho_0=[\alpha_{1122}^{LL}n_1(0)+\alpha_{1111}^{LL}n_2(0)]L_0^2; \quad (9)$$

$$B_t^z=\alpha_{1133}^{HH}+\alpha_{1133}^{HM}\chi_\perp^z+[\alpha_{1133}^{MM}-\alpha_{1111}^{LL}n_2(0)-\alpha_{1122}^{LL}n_1(0)](\chi_\perp^z)^2. \quad (10)$$

For the magnetoresistance we find

$$\left(\frac{\Delta\rho}{\rho_0}\right)_t^z=\frac{\rho_t^z-\rho_0}{\rho_0}=\frac{1}{\rho_0}B_t^zH_z^2, \quad (11)$$

where $\rho_0=\rho^0+\Delta\rho_0$ is the original ($H=0$) resistivity.

The resistivity in the original state depends on the original concentrations of the magnetic phases and on the constants of the material by virtue of $\Delta\rho_0$, according to (9), as does the coefficient B_t^z of H_z^2 according to (10). Consequently, the H_z dependence of the magnetoresistance is determined exclusively by intradomain processes, as follows from (11). Among these processes, the only ones operating here are changes in the angle between the magnetization vectors of the magnetic sublattices ($\chi_\perp^z$) and processes which are unrelated to the magnetic order and which are determined by the constant α_{1133}^{HH}.

A similar H dependence should be expected for crystals of hexagonal symmetry if their basal plane is the antiferromagnetism plane.

5. We now consider the longitudinal and transverse magnetoresistances when the field **H** is directed along one or the other of the antiferromagnetism axes. In this case we need to take account of the existence of multivalued magnetic states at a given H; these states are reflected, in particular, in hysteresis of the magnetization curves.

As an example, Fig. 2 shows curves of the H dependence of the specific magnetization I_α for the case in which the field **H** is applied along one of the antiferromagnetism axes of a $FeGe_2$ single crystal. Curve *1* corresponds to the virgin curve, recorded after the sample was cooled at $H=0$ from the temperature above the Néel point $T_N=287$ K to the measurement temperature. Curves *2* and *3* correspond to the descending and ascending branches of the hysteresis loop.

To describe the magnetoresistance as a function of the magnetic field for the virgin curve and for the branches of the hysteresis loop, it is convenient to use a single definition of the magnetoresistance. We define it by

$$\frac{\Delta\rho}{\rho_0}=\frac{\rho(H)-\rho_0}{\rho_0}, \quad (12)$$

where ρ_0 is the resistivity of the sample at $\mathbf{H}=0$ in the state reached by cooling the sample from $T>T_N$ to the measurement temperature. This state corresponds to concentrations $n_1(0)$ and $n_2(0)$ of the magnetic phases.

We introduce some new notation for $n_{1,2}$ and $\rho_{1,2}$ to describe the longitudinal (l) and transverse (t) magnetoresistance in the antiferromagnetism plane (xy):

$$(n_{1,2}^l)^{xy},\ (\rho_{1,2})_l^{xy} \text{ and } (n_{1,2}^t)^{xy},\ (\rho_{1,2})_t^{xy}.$$

To streamline the equations below, we omit the xy from all quantities which determine effects in the antiferromagnetism plane.

Let us take a more detailed look at the longitudinal resistance. For the magnetic phase with the concentration n_1^l we have

$$L_y^2=L_0^2-(\chi_\perp H_x)^2, \quad M_x=\chi_\perp H_\chi,$$

while for that with the concentration n_2^l we have

$$n_2^l-L_x=L_0, \quad M_\chi=\chi_\parallel H_\chi,$$

where $\chi_\parallel$ and $\chi_\perp$ are the susceptibilities respectively parallel and perpendicular to **H** in the antiferromagnetism plane. The parallel susceptibility $\chi_\parallel$ characterizes the paraprocess: the change in the absolute values of the magnetization vectors of the magnetic sublattices when the magnetic field is applied.

From (3) and (7), and using the expressions written above for L and M written above, we find

$$\rho_l=\rho^0+(\alpha_{1122}^{LL}n_1^l+\alpha_{1111}^{LL}n_2^l)L_0^2+(\alpha_{1111}^{HH}+B_1^ln_1^l+B_2^ln_2^l)H_\chi^2, \quad (13)$$

where the coefficients B_1^l and B_2^l are independent of H. They are determined by the thermodynamic and kinetic constants of the material:

$$B_1^l=\alpha_{1111}^{HM}\chi_\perp+(\alpha_{1111}^{MM}-\alpha_{1122}^{LL})\chi_\perp^2;$$

$$B_2^l=\alpha_{1111}^{HM}\chi_\parallel+\alpha_{1111}^{MM}\chi_\parallel^2. \quad (14)$$

In the derivation of (13) it was assumed that the antiferromagnetism vectors do not change orientation under magnetization in the antiferromagnetism plane in any of the domains. This assumption is valid for antiferromagnets with $H^*\ll H_0$. In fields $H^*<H<H_0$, the domains in which **L** is parallel or antiparallel to **H**, and in which the vector **L** must have undergone an abrupt 90° rotation at $H=H_0$, are "absorbed" by domains with **L**⊥ **H** as a result of displacements of walls.

5.1. We first consider the field dependence of the magnetoresistance corresponding to the virgin magnetization curve.

For the longitudinal magnetoresistance we find from (12) and (13)

$$\left(\frac{\Delta\rho}{\rho_0}\right)_l=\frac{\rho_l-\rho_0}{\rho_0}$$
$$=\frac{1}{\rho_0}\{(\alpha_{1111}^{HH}+B_1^l n_1^l+B_2^l n_2^l)H_x^2+(\alpha_{1122}^{LL}[n_1^l-n_1(0)]+\alpha_{1111}^{LL}[n_2^l-n_2(0)])L_0^2\}. \quad (15)$$

Correspondingly, for the transverse magnetoresistance in the case of magnetization in the antiferromagnetism plane we find

$$\left(\frac{\Delta\rho}{\rho_0}\right)_t=\frac{\rho_t-\rho_0}{\rho_0}$$
$$=\frac{1}{\rho_0}\{(\alpha_{1122}^{HH}+B_1^t n_1^t+B_2^t n_2^t)H_y^2+(\alpha_{1122}^{LL}[n_1^t-n_1(0)]+\alpha_{1111}^{LL}[n_2^t-n_2(0)])L_0^2\}; \quad (16)$$

$$B_1^t=\alpha_{1122}^{HM}\chi_\parallel+\alpha_{1122}^{MM}\chi_\parallel^2;$$
$$B_2^t=\alpha_{1122}^{HM}\chi_\perp+(\alpha_{1122}^{MM}-\alpha_{1111}^{LL})\chi_\perp^2. \quad (17)$$

At fields $H\gg H^*$, for which the shifts of the 90° walls between domains have terminated, we have the following results for the longitudinal ($n_1^l=I$, $n_2^l=0$) and transverse ($n_1^t=0$, $n_2^t=I$) magnetoresistances, respectively:

$$\left(\frac{\Delta\rho}{\rho_0}\right)_l=A_l+\frac{1}{\rho_0}(\alpha_{1111}^{HH}+B_1^l)H_x^2;$$
$$\left(\frac{\Delta\rho}{\rho_0}\right)_t=A_t+\frac{1}{\rho_0}(\alpha_{1122}^{HH}+B_2^t)H_y^2; \quad (18)$$

$$A_l=\frac{1}{\rho_0}(\alpha_{1122}^{LL}-\alpha_{1111}^{LL})L_0^2 n_2(0);$$
$$A_t=-\frac{1}{\rho_0}(\alpha_{1122}^{LL}-\alpha_{1111}^{LL})L_0^2 n_1(0). \quad (19)$$

The quantities A_l and A_t are extrapolated values of the magnetoresistance, found by continuing curves of the longitudinal and transverse magnetoresistance quadratic in H from the field region $H\gg H^*$ to the value $H=0$. We note that A_l and A_t differ in sign.

From (19) we find

$$\frac{n_2(0)}{n_1(0)}=-\frac{A_l}{A_t}.$$

Since $n_1(0)+n_2(0)=1$, we find the following expressions for determining the initial concentrations of magnetic phases:

$$n_1(0)=\frac{A_t}{A_t-A_l},\quad n_2(0)=\frac{A_l}{A_l-A_t}. \quad (20)$$

Using (19), we can rewrite (15) and (16) as

$$\left(\frac{\Delta\rho}{\rho_0}\right)_l=\frac{1}{\rho_0}(\alpha_{1111}^{HH}+B_1^l n_1^l+B_2^l n_2^l)H_x^2+(A_l-A_t)[n_2(0)-n_2^l];$$
$$\left(\frac{\Delta\rho}{\rho_0}\right)_t=\frac{1}{\rho_0}(\alpha_{1122}^{HH}+B_1^t n_1^t+B_2^t n_2^t)H_y^2-(A_l-A_t)[n_1(0)-n_1^t]. \quad (21)$$

The concentrations of the magnetic phases with L|| H and L⊥ H were found as a function of the magnetic field in Ref. 1. Following Ref. 1, we write

$$n_2^l=\frac{1}{1+\exp\left[\left(\frac{H}{H^*}\right)^2+C^l\right]},\quad n_1^l=1-n_2^l;$$
$$n_1^t=\frac{1}{1+\exp\left[\left(\frac{H}{H^*}\right)^2+C^t\right]},\quad n_2^t=1-n_1^t, \quad (22)$$

where H^* is the value of the field found from the H dependence of the reciprocal of the susceptibility on the virgin curve, and the constants $C^{l,t}$ are determined by concentrations of magnetic phases at $H=0$. From (20) and (22) we find

$$C^l=-C^t=\ln\left(-\frac{A_t}{A_l}\right). \quad (23)$$

5.2. We turn now to a description of the field dependence of the magnetoresistance corresponding to the descending branch of the hysteresis loop. We first consider the longitudinal magnetoresistance.

Since irreversible displacements of domain walls occur, the concentration n_2^l of the phase with L|| H decreases on the descending branch of the hysteresis loop at $H=0$ by an amount $\Delta n_2(0)$ relative to the original value $n_2(0)$ on the virgin curve. As a result, the magnetoresistance at $H=0$ changes by an amount Δ_l. From (21) we have

$$\Delta_l=(A_l-A_t)\Delta n_2(0). \quad (24)$$

To determine the residual concentrations of the magnetic phases (at $H=0$), we thus have, according to (20) and (24),

$$(n_2^l)_{\text{res}}=n_2(0)-\Delta n_2(0)=\frac{A_l-\Delta_l}{A_l-A_t};$$
$$(n_1^l)_{\text{res}}=1-(n_2^l)_{\text{res}}. \quad (25)$$

The residual concentrations of the magnetic phases for the case of the transverse magnetoresistance can be determined in a corresponding way:

$$(n_1^t)_{\text{res}}=\frac{A_t-\Delta_t}{A_t-A_l};\quad (n_2^t)_{\text{res}}=1-(n_1^t)_{\text{res}}, \quad (26)$$

where $\Delta_t=-(A_l-A_t)\Delta n_1(0)$.

Corresponding to the values which we have found $(n_1^t)_{res}$ and $(n_2^l)_{res}$ are the following values of $C_{des}^{l,t}$, according to (22):

$$C_{des}^{l}=\ln\frac{\Delta_l-A_t}{A_l-\Delta_l},\quad C_{des}^{t}=\ln\frac{\Delta_t-A_l}{A_t-\Delta_t}. \tag{27}$$

Expressions (21) remain valid for describing the field dependence of the magnetoresistance on the descending branch of the hysteresis loop, but in this case the phase concentrations are determined by the values of $C_{des}^{l,t}$ and by the corresponding value $(H^*)_{des}$ for the descending branch of the hysteresis loop.

5.3. Analysis of the constants $B_{1,2}^{l,t}$ in (21) leads to a conclusion regarding the particular intradomain processes which determine the magnetoresistance.

It can be seen from (18) that for the virgin curve and the descending branch of the hysteresis loop in fields $H\gg H^*$ there is a quadratic dependence on H for the longitudinal and transverse magnetoresistances in the antiferromagnetism plane. According to (14) and (17), the magnetoresistance is determined by the change in the angle between the magnetizations of the sublattices and by processes which are independent of the magnetic order $(\alpha_{1111}^{HH},\alpha_{1122}^{HH})$.

In weak fields $(H\leqslant 3H^*)$ the H dependence of the magnetoresistance is governed by both wall displacements (the H dependence of $n_{1,2}$) and processes within domains: the change in the angle between the sublattice magnetizations $(\chi_\perp)$ and the paraprocess $(\chi_\parallel)$. In addition, it is determined by processes which are unrelated to the magnetic order $(\alpha_{1111}^{HH},\alpha_{1122}^{HH})$.

A corresponding analysis can be carried out for the ascending branch of the hysteresis loop. In this case the residual concentrations of the magnetic phases are the same as on the descending branch, but the characteristic field $(H^*)_{asc}$ on the ascending branch differs from $(H^*)_{des}$ branch.

6. An experimental study of the magnetoresistance was carried out on a single crystal of iron digermanide, $FeGe_2$ (space group I4/mcm). In this crystal, two magnetic-structure phase transitions are observed, at $T_1=265$ and $T_2=287$ K. According to neutron diffraction,[5] the following sequence of magnetic structures occurs in $FeGe_2$ as the temperature is lowered: paramagnetism $(T>T_2)$, an incommensurate structure $(T_1<T<T_2)$, and a collinear antiferromagnetic structure $(T<T_1)$. For $T<T_1$, there are two mutually perpendicular [110] antiferromagnetism axes in the (001) basal plane $(K_2<0, K_4>0)$.

The magnetoresistance of the samples was measured by the standard four-contact method in an electromagnet with a field up to 16 kOe for two directions of the field and two directions of the current. The error in the measurements of $\Delta\rho/\rho_0$ was less than 2%. The magnetization was measured on a vibration magnetometer.[1]

The magnetoresistance was studied as a function of the magnitude and orientation of **H** as the current flowed along the axis [110]‖ **L**‖ **j** in the cases **H**‖ [110]‖ **L** (the longitudinal magnetoresistance), **H**‖ [1$\bar{1}$0]‖ **L** (transverse), and **H**‖ [001]⊥ **L** (also transverse).

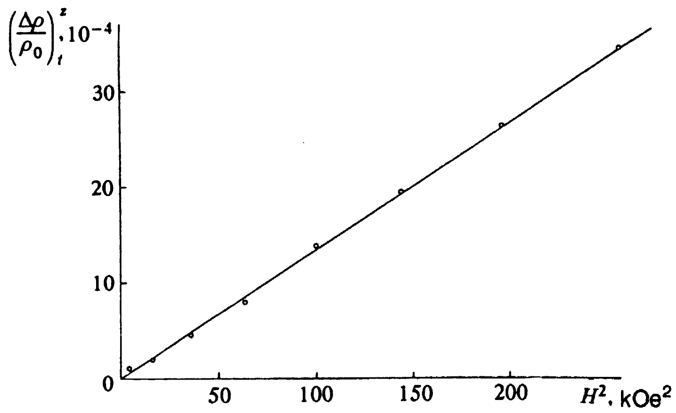

FIG. 3. Transverse magnetoresistance $(\Delta\rho/\rho_0)_t^z$ versus the square of the magnetic field for the orientation **H**‖ [001] at $T=106$ K in $FeGe_2$.

Figure 3 shows the transverse magnetoresistance $(\Delta\rho/\rho_0)_t^z$ versus H^2 when the field **H** is oriented along the [001] tetragonal axis at $T=106$ K. We see a quadratic dependence on the magnetic field, in agreement with the theory.

Figure 4 shows the H dependence of the longitudinal magnetoresistance $(\Delta\rho/\rho_0)_l$ (curve *1*) and of the transverse magnetoresistance in the antiferromagnetism plane, $(\Delta\rho/\rho_0)_t$ (curve *3*), corresponding to the virgin magnetization curve at $T=106$ K.

The following measurement procedure was used to distinguish the even effect of the H dependence of the resistance under the condition that the original concentrations (at $H=0$) of the magnetic phases remained the same. The

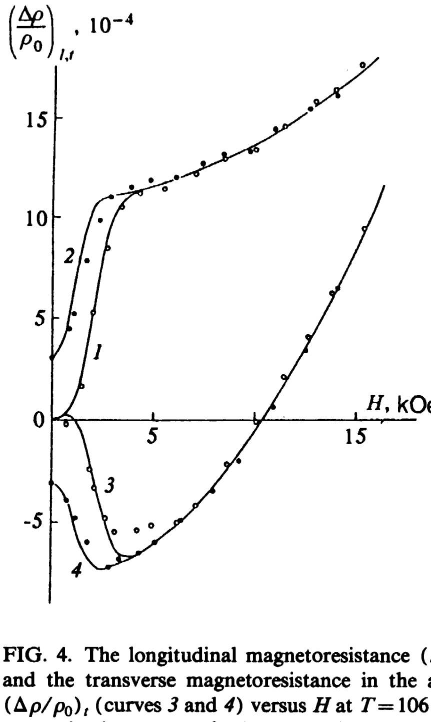

FIG. 4. The longitudinal magnetoresistance $(\Delta\rho/\rho_0)_l$ curves *1* and *2*) and the transverse magnetoresistance in the antiferromagnetism plane $(\Delta\rho/\rho_0)_t$ (curves *3* and *4*) versus H at $T=106$ K in $FeGe_2$. *1*, *3*—Virgin magnetization curve; *2*, *4*—descending branch of the hysteresis loop. Solid curves) Calculated from (28); open and filled circles) experimental.

sample was cooled in zero field from a temperature above the Néel point (T_2=287 K) to the measurement temperature. The resistance was measured as a function of H as the magnitude of H was raised. The field was then turned off. The sample was then reheated to $T>T_2$ and then cooled in a zero field to the measurement temperature. The resistance was also measured as the magnitude of H was increased, but for the opposite direction of **H**. The values of $(\Delta\rho/\rho_0)_{l,t}$ were found as half the sum of these quantities, measured for opposite orientations of **H**. The solid curves in Fig. 4 are theoretical, and the points experimental.

Let us take a more detailed look at the construction of the theoretical curves. Our study of $(\Delta\rho/\rho_0)_{l,t}$ in the paramagnetic region (T=300 K) showed that the magnetoresistance which is unrelated to the magnetic order is smaller than $(\Delta\rho/\rho_0)_{l,t}$ at T=106 K by a factor $\sim 10^2$. In constructing theoretical curves from Eqs. (21) we can thus ignore terms which are independent of the magnetic order ($\alpha^{HH}_{1111},\alpha^{HH}_{1122}$). Expressions (21) then become

$$\left(\frac{\Delta\rho}{\rho_0}\right)_l=\frac{1}{\rho_0}(B_1^l n_1^l+B_2^l n_2^l)H_x^2+(A_l-A_t)[n_2(0)-n_2^l];$$

$$\left(\frac{\Delta\rho}{\rho_0}\right)_t=\frac{1}{\rho_0}(B_1^t n_1^t+B_2^t n_2^t)H_y^2-(A_l-A_t)[n_1(0)-n_1^t]. \quad (28)$$

To construct theoretical curves, we determine the values of $(1/\rho_0)B_1^{l,t}$, $(1/\rho_0)B_2^{l,t}$, A_l, and A_t from the experimental curves. Working from (18), we found A_l and A_t by extrapolating to H=0 the curves of $(\Delta\rho/\rho_0)_{l,t}(H)$ recorded in fields $H\gg H^*$. These values turned out to be $A_l=10.9\cdot 10^{-4}$ and $A_t=-7.8\cdot 10^{-4}$. Knowing these values, we can use (20) and (23) to determine the original concentrations of the magnetic phases, $n_1(0)=0.42$ and $n_2(0)=0.58$, and also the constants $C^{l,t}$. With $C^{l,t}$ and H^* known, we calculated the H dependence of the concentrations $n^{l,t}_{1,2}$, using (22). For H^* we used the value $H^*=1.55$ kOe, which is found from the curve of the reciprocal susceptibility in Ref. 1.

Values of $(1/\rho_0)B_1^l$ and $(1/\rho_0)B_2^t$ were found by the method of least squares from the experimental curves of $[\Delta\rho/\rho_0]_{l,t}(H)$ at fields $H\gg H^*$ ($H>5$ kOe), where the terms with B_2^l and B_1^t tend toward zero, and where the H dependence of the magnetoresistance in (28) become quadratic.

After the values found are substituted into expression (28), the coefficients $(1/\rho_0)B_2^l$ and $(1/\rho_0)B_1^t$ remain unknown. To determine them by the method of least squares, we used experimental data over the entire field range studied, including weak fields, where domain walls undergo displacements.

Also shown in Fig. 4 are curves of the field dependence of the longitudinal (curve *2*) and transverse (curve *4*) magnetoresistance $(\Delta\rho/\rho_0)^{l,t}_{\rm des}$ corresponding to the descending branches of the hysteresis loop. In this case the resistance in the magnetic field was measured as the magnitude of H was reduced from its maximum value to zero. Similar measurements of the resistance were carried out with the field in the opposite direction. Values of $\Delta\rho/\rho_0$ were found as half the sum of the corresponding quantities for the opposite orientations of **H**.

Theoretical curves were plotted from Eqs. (28), in which the quantities $A_{l,t}$, $(1/\rho_0)B^{l,t}_{1,2}$ and $n_{1,2}(0)$ were found in this case from curves of the magnetoresistance corresponding to the virgin magnetization curve. The dependence of $n^{l,t}_{1,2}$ on H was found from (22) with the help of (27). The values of Δ_l and Δ_t found from the experimental curves turned out to be $\Delta_l=3\cdot 10^{-4}$ and $\Delta_t=-3\cdot 10^{-4}$. For H^* we use the value $H^*=1.1$ kOe found in Ref. 2 from the curve of the reciprocal susceptibility on the descending branch of the hysteresis loop.

From the magnetoresistance curves corresponding to the descending branch, we used (25) and (26) to determine the residual concentrations of the magnetic phases: $(n_1^l)_{\rm res}=0.58$, $(n_2^l)_{\rm res}=0.42$, $(n_1^t)_{\rm res}=0.25$, and $(n_2^t)_{\rm res}=0.75$. It can be seen from Fig. 4 that there is a good agreement between the theoretical and experimental curves, both for the magnetoresistance $(\Delta\rho/\rho_0)_{l,t}$ which corresponds to the virgin magnetization curve (curves *1* and *3*) and for the magnetoresistance corresponding to the descending branch of the hysteresis loop (curves *2* and *4*).

7. Let us summarize the results of this study.

Using the example of a tetragonal single crystal with two mutually perpendicular antiferromagnetism axes in the basal plane, we have shown that the magnetoresistance of multiaxial antiferromagnets is governed by both intradomain processes (which also occur in uniaxial antiferromagnets) and reversible and irreversible displacements of domain walls.

When the (vector) current density is oriented along one of the antiferromagnetism axes, the quantity $\Delta\rho/\rho_0$ is a quadratic function of the magnetic field in two cases:

a) For transverse magnetoresistance when **H** is directed perpendicular to the antiferromagnetism plane, and there are no wall displacements;

b) for longitudinal and transverse magnetoresistance with **H** directed along one of the antiferromagnetism axes in the field region in which wall displacements have come to an end.

In both cases, the magnetoresistance is governed by the change in the angle between the magnetizations of the magnetic sublattices.

In weaker fields, for the transverse and longitudinal magnetoresistances in the antiferromagnetism plane, in which case the intradomain processes (changes in the angle between the magnetic sublattices and the paraprocess) are accompanied by displacements of domain walls, we have observed hysteresis in the magnetoresistance $\Delta\rho/\rho_0(H)$ due to irreversible wall displacements.

We have shown that the analytic expressions for the field dependence of the magnetoresistance give a good description of the experimental data on $\Delta\rho/\rho_0(H)$ found for an antiferromagnetism $FeGe_2$ single crystal.

It has been established that a study of the magnetoresistance can reveal the magnetic texture (the concentrations of magnetic phases) at H=0 both in the original state and on the branches of the hysteresis loop of magnetically multiaxial antiferromagnets.

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