Even galvanomagnetic effects in magnetomultiaxial antiferromagnetics: temperature dependence

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Results are presented from studies of the magnetoresistance $\Delta\rho/\rho_0$ as a function of the magnitude and orientation of the magnetic field **H** in magnetomultiaxial antiferromagnetics at various temperatures for the case of a $FeGe_2$ single crystal). The magnitudes, temperature dependence, and sign relationships of the rate constants characterizing $\Delta\rho/\rho_0$ are found by analyzing the **H** dependence of the isothermal magnetoresistance. © *1995 American Institute of Physics.*

Vlasov *et al.*[1] presented results of theoretical and experimental studies of even galvanomagnetic effects in magnetomultiaxial antiferromagnetics (AFMs). A phenomenological theory based on the thermodynamics of nonequilibrium processes was constructed, taking into account the presence of domain structure and its variations in a magnetic field **H**. The case of a tetragonal single crystal with two mutually perpendicular antiferromagnetism axes in the basal plane was used to show that the magnetoresistance of multiaxial AFMs is determined by both intradomain processes and processes involving displacement of the interdomain walls. The theoretical and experimental results were compared for the tetragonal single crystal $FeGe_2$ (space group I4/*mcm*). It displays collinear antiferromagnetic structure with two mutually perpendicular [110] antiferromagnetism axes in the basal plane for $T_1<265$ K. The magnetoresistance as a function of the magnitude and orientation of **H** was studied in $FeGe_2$ for the case of a current parallel to the [110] antiferromagnetism axis when the magnetic field vector **H** was oriented 1) along the same axis (longitudinal magnetoresistance); 2) along the other antiferromagnetism axis (transverse magnetoresistance in the basal plane); and 3) parallel to the tetragonal axis [001] (transverse magnetoresistance in the direction normal to the basal plane). In the first two cases, in contrast to the third, the interdomain walls shift as a result of the action of **H**. These shifts make the largest contribution to the magnetoresistance in weak fields. The measurements in Ref. 1 were carried out at $T=106$ K.

1. In the present communication we present the results of studying the dependence of the longitudinal and transverse magnetoresistance in the basal plane as a function of the magnitude H of the field in the range of temperatures from 86 to 220 K in a $FeGe_2$ single crystal. Analysis of this behavior made it possible to establish the magnitudes and signs of the rate constants of various sorts, and also to determine their temperature dependence. This information about the rate constants may prove useful in clarifying their physical nature and in constructing a microfield theory of magnetoresistance in antiferromagnets. Besides, in compensated AFMs even the order of magnitude of the magnetoresistance is unknown, not to mention the rate constants resulting from magnetic order.

2. Let us write down the relations from Ref. 1 needed for the analysis that follows. The longitudinal magnetoresistance $(\Delta\rho/\rho_0)_l$ and the transverse magnetoresistance $(\Delta\rho/\rho_0)_t$ in the basal plane are determined by

$$\left(\frac{\Delta\rho}{\rho_0}\right)_l=\frac{1}{\rho_0}\{(\alpha_1^{BB}+B_1^l n_1^l+B_2^l n_2^l)H_x^2+\alpha^{LL}(n_1^l-n_1(0))L^2\}, \tag{1}$$

$$B_1^l=(\alpha_1^{BM}+\alpha_1^{MM}\chi_\perp)\chi_\perp, \quad B_2^l=(\alpha_1^{BM}+\alpha_1^{MM}\chi_\parallel)\chi_\parallel; \tag{2}$$

$$\left(\frac{\Delta\rho}{\rho_0}\right)_t=\frac{1}{\rho_0}\{(\alpha_2^{BB}+B_1^t n_1^t+B_2^t n_2^t)H_y^2+\alpha^{LL}(n_1^t-n_1(0))L^2\}, \tag{3}$$

$$B_1^t=(\alpha_2^{BM}+\alpha_2^{MM}\chi_\parallel)\chi_\parallel, \quad B_2^t=(\alpha_2^{BM}+\alpha_2^{MM}\chi_\perp)\chi_\perp. \tag{4}$$

The x,y, and z axes are oriented respectively along the specified antiferromagnetism axis, along the axis perpendicular to it in the basal plane, and in the direction normal to the basal plane.

The quantities $\alpha_{1,2}^{BB},\alpha_{1,2}^{BM},\alpha_{1,2}^{MM},\alpha^{LL}$ are rate constants characterizing the BB,BM,MM, and LL effects and expressed in terms of the expansion coefficients of the specific electrical resistance tensor (rate coefficient) ρ_{ik} with respect to the components of the magnetic induction vector **B**, the ferromagnetism (resultant magnetization) **M**, and the antiferromagnetism **L** (Ref. 2):

$$\rho_{ik}=\rho_{ik}^0+\alpha_{ikmn}^{BB}B_mB_n+\alpha_{ikmn}^{MM}M_mM_n+\alpha_{ikmn}^{LL}L_mL_n+\alpha_{ikmn}^{BM}B_mM_n+\alpha_{ikmn}^{BL}B_mL_n+\alpha_{ikmn}^{ML}M_mL_n. \tag{5}$$

Relations (1)–(4) were derived for the case of fields much smaller than the inner lattice exchange field, assuming that the magnitude of the antiferromagnetism vector **L** does not depend on **H**, and the magnetic induction **B** is equal to **H** because of the smallness of the magnetic susceptibility of antiferromagnetics. We introduce an abbreviated notation for the subscripts:

$$\alpha_{1111}=\alpha_1, \quad \alpha_{1122}=\alpha_2, \quad \text{and} \quad \alpha^{LL}=\alpha_{1122}^{LL}-\alpha_{1111}^{LL}.$$

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The coefficients of the expansion (5) are tensors of rank four. In order to determine the number of independent components in these tensors we take into account a) the requirement that Eqs. (5) be invariant under the operations of crystallographic symmetry, including their parity and b) the Onsager relations. In addition, for the tensor α_{ikmn}^{LL}, describing LL effects the requirement that the magnitude of L be constant leads to an additional reduction in the number of independent components. The surviving independent rate constants no longer constitute a tensor quantity, and we have $\alpha^{LL}=\alpha_{1122}^{LL}-\alpha_{1111}^{LL}$. An LL effect describes the dependence of the magnetoresistance only on the orientation of the vector **L** with respect to the crystallographic axes.

The quantities $\chi_{\parallel}$ and $\chi_{\perp}$ are the susceptibilities parallel and perpendicular to **H** respectively, provided that **H** is applied in the basal plane; $n_1^{l,t}, n_2^{l,t}$ are the densities of the two magnetic phases in which the vector **L** is oriented perpendicular (subscript 1) or parallel (subscript 2) to the current density vector **j** when the field **H** is applied parallel to **j** (superscript l) and perpendicular to **j** (superscript t). The initial densities $n_1(0)$ and $n_2(0)=1-n1(0)$ of the magnetic phases can be found from the magnetoresistance curves in the range of fields $H \gg H^*$; here H^* is the structure-sensitive field near which the reversible processes of wall displacement occur most actively. For $H \gg H^*$, when the processes of 90-degree displacement of the inner domain walls terminate, we have respectively for the longitudinal ($n_1^l=1$, $n_2^l=0$) and transverse ($n_1^t=0$, $n_2^t=1$) magnetoresistances

$$\left(\frac{\Delta\rho}{\rho_0}\right)_l = A_l + \frac{1}{\rho_0}(\alpha_1^{BB}+B_1^l)H_x^2, \tag{6}$$

$$\left(\frac{\Delta\rho}{\rho_0}\right)_t = A_t + \frac{1}{\rho_0}(\alpha_2^{BB}+B_2^t)H_y^2, \tag{7}$$

$$A_l = \frac{1}{\rho_0}\alpha^{LL}L^2 n_2(0), \tag{8}$$

$$A_t = -\frac{1}{\rho_0}\alpha^{LL}L^2 n_1(0). \tag{9}$$

From (8) and (9) it follows that

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

Taking into account the fact that $n_1(0)+n_2(0)=1$ holds we find the following relations determining the initial densities of the magnetic phases:

$$n_1(0)=\frac{A_t}{A_t-A_l}, \quad n_2(0)=\frac{A_l}{A_l-A_t}. \tag{10}$$

Note that the quantities A_l and A_t can be determined from the experimental curves $((\Delta\rho/\rho_0)_{l,t}(H)$ by extrapolating the dependence of the longitudinal and transverse magnetoresistances quadratically in H from fields $H \gg H^*$ to $H=0$.

In Ref. 3 we determined the densities of the magnetic phases as functions of the field H:

$$n_1^l = \frac{1}{1+\exp\{-[(H/H^*)^2+C^l]\}}, \quad n_2^l = 1-n_1^l, \tag{11}$$

$$n_1^t = \frac{1}{1+\exp\{[(H/H^*)^2+C^t]\}}, \quad n_2^t = 1-n_1^t, \tag{12}$$

where H^* is the value of the field determined by the H dependence of the reversible susceptibility; $C^{l,t}$ are constants determined by the densities of the magnetic phases at $H=0$:

$$C^l = -C^t = \ln\left(-\frac{A_t}{A_l}\right). \tag{13}$$

From Eqs. (2) and (4) we can determine the following rate constants:

$$\alpha_1^{BM} = -\frac{B_1^l\chi_{\parallel}^2 - B_2^t\chi_{\perp}^2}{\chi_{\perp}\chi_{\parallel}(\chi_{\perp}-\chi_{\parallel})}, \tag{14}$$

$$\alpha_2^{BM} = \frac{B_1^l\chi_{\perp}^2 - B_2^t\chi_{\parallel}^2}{\chi_{\perp}\chi_{\parallel}(\chi_{\perp}-\chi_{\parallel})}, \tag{15}$$

$$\alpha_1^{MM} = \frac{B_1^l\chi_{\parallel} - B_2^t\chi_{\perp}}{\chi_{\perp}\chi_{\parallel}(\chi_{\perp}-\chi_{\parallel})}, \tag{16}$$

$$\alpha_2^{MM} = -\frac{B_1^l\chi_{\perp} - B_2^t\chi_{\parallel}}{\chi_{\perp}\chi_{\parallel}(\chi_{\perp}-\chi_{\parallel})}, \tag{17}$$

From Eqs. (8) and (9) we find

$$\alpha^{LL} = \frac{\rho_0(A_l-A_t)}{L^2}. \tag{18}$$

3. The technique for measuring the magnetoresistance was described in Ref. 1. In treating the longitudinal and transverse magnetoresistivities in the basal plane it is necessary to take into account the existence of multivalued magnetic for a given value H. Magnetization can take place along the virgin curve and also on the rising or falling branches of the hysteresis loop. These processes correspond to $\Delta\rho/\rho_0$ behaving differently as a function of H; each one can be used to determine the same rate constants. In the present communication we present the results obtained by studying the magnetoresistance corresponding to the virgin magnetization curve.

The curves showing the dependence on H of the longitudinal magnetoresistance $(\Delta\rho/\rho_0)_l$ and the transverse magnetoresistance $(\Delta\rho/\rho_0)_t$ in the basal plane in the $FeGe_2$ single crystal were taken at the temperatures 86, 106, 150, 177, 195, and 219 K; Figs. 1 and 2 show several of these. The solid traces are calculated and the points are experimental data. The technique used to determine the calculated curves is described in Ref. 1. The quantities $B_{1,2}^{l,t}$ were determined at each temperature from the experimental $(\Delta\rho/\rho_0)_{l,t}(H)$ curves using the method of least squares, neglecting the term $\alpha_{1,2}^{BB}$ resulting from the magnetic field. Estimates showed that this contribution in the single crystal under study is much smaller than those produced by the magnetic order. The quantities $(1/\rho_0)B_1^l$ and $(1/\rho_0)B_2^t$ were determined by the method of least squares from the experimental $(\Delta\rho/\rho_0)_{l,t}(H)$ data in the range of fields $H \gg H^*$, where the H dependence of the magnetoresistance is quadratic. In employing the method of least squares to determine the quantities $(1/\rho_0)B_2^t$ and $(1/\rho_0)B_1^l$ we used the experimental data over the whole range of fields investigated, including

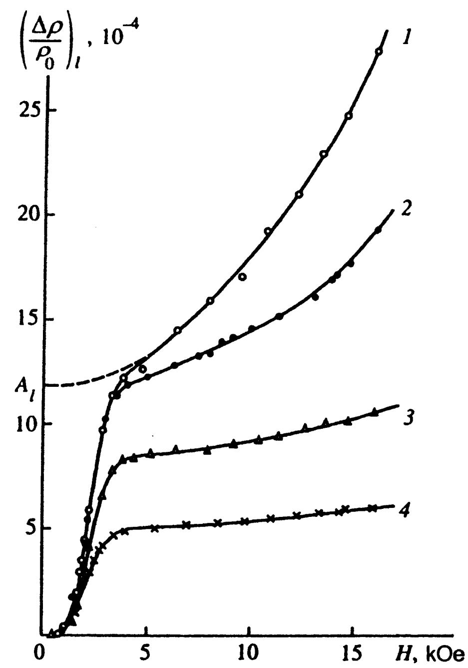

FIG. 1. Dependence on the field **H** of the longitudinal magnetoresistance $(\Delta\rho/\rho_0)_l$ in the basal plane in $FeGe_2$ at the temperatures (*K*): *1*) 86; *2*) 106; *3*) 135; *4*) 150; *5*) 195. The solid curves are found from the calculation and the points from experiment.

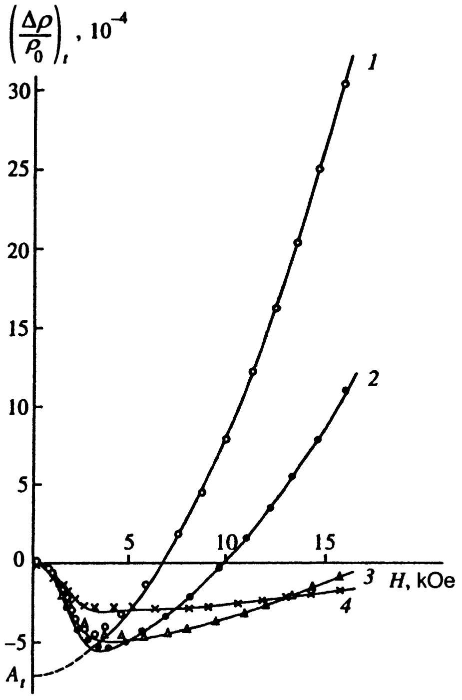

FIG. 2. Dependence on the magnetic field **H** of the transverse magnetoresistance $(\Delta\rho/\rho_0)_t$ in the basal plane in $FeGe_2$ at the temperatures (K): *1*) 86; *2*) 106; *3*) 135; *4*) 150; *5*) 195. The solid curves are found from the calculation and the points from experiment.

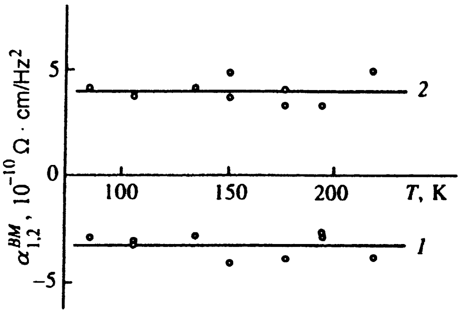

FIG. 3. Temperature dependence of the rate constants α_1^{BM} (trace *1*) and α_2^{BM} (trace *2*).

weak fields where processes resulting in shifts of the interdomain walls take place. The values of A_l and A_t were found by extrapolating the $(\Delta\rho/\rho_0)_{l,t}(H)$ curves measured in fields satisfying $H \gg H^*$ to $H=0$. The original densities $n_1(0)$ and $n_2(0)$ of the magnetic phases were determined by using the values of A_l and A_t. In using Eqs. (11) and (12) to determine the field dependence of $n_1^{l,t}$ we assumed the value $H^*=1.55$ kOe found from the reversible susceptibility curve in Ref. 3.

Figures 3–5 display the temperature dependence of the rate constants α_1^{BM} and α_2^{BM} (Fig. 3), α_1^{MM} and α_2^{MM} (Fig. 4), α^{LL} (Fig. 5). The values of $\chi_\perp$ and $\chi_\parallel$ needed to calculate these constants at the corresponding temperatures were taken from Ref. 3, while $L(T)$ was evaluated following Ref. 4. From these plots it is clear that the constants $\alpha_1^{BM}, \alpha_2^{BM}, \alpha_1^{MM}$, and α_2^{MM} do not depend on temperature to within the accuracy of the measurements, whereas α^{LL} exhibits a more complicated temperature dependence.

The rate constants α_1^{BM} and α_2^{BM} of one type have different signs, just like the constants α_1^{MM} and α_2^{MM} of the other type. The constants α_1^{MM} and α_2^{BM} are positive, while the constants α_1^{BM} and α_2^{MM} are negative.

4. At least for $FeGe_2$ the experimental results presented above enable us to draw the following inferences.

The neglect of terms above quadratic in the expansions of the specific electrical resistance tensor (5) in the thermodynamic variables is adequate to describe the field dependence of the magnetoresistance in the range of temperatures investigated.

The magnetoresistance of an antiferromagnetic is determined by four types of effects: *BB*, *BM*, *MM*, and *LL*. The first order of these is unrelated to magnetic order and can be

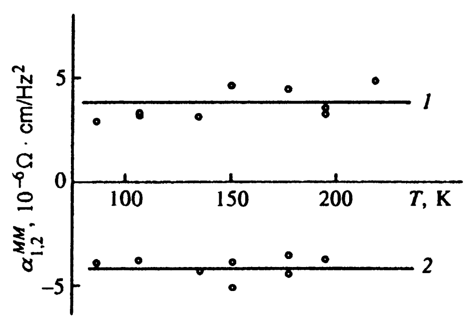

FIG. 4. Temperature dependence of the rate constants α_1^{MM} (trace *1*) and α_2^{MM} (trace 2).

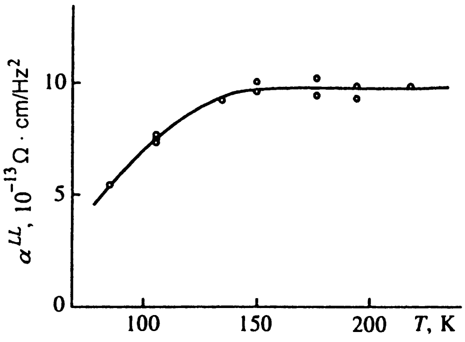

FIG. 5. Temperature dependence of the rate constant α^{LL}.

disregarded because its contribution to $(\Delta\rho/\rho_0)_{l,t}(H)$ is small. The other three types of effects (BM, MM, and LL) appear to the same degree.

Let us first consider BM and MM effects. They have characteristics in common. The number of rate constants describing these effects is the same and identical with the number of independent coefficients in the expansion of the specific electroresistance tensor in powers of **B** and **M**. Correspondingly, the rate constants describing BM and MM effects do not depend on temperature.

We note that the $\alpha_{1,2}^{BM}$ constants are four orders of magnitude smaller than the $\alpha_{1,2}^{MM}$ constants. However, BM and MM effects make comparable contributions to the magnetoresistance, since the latter is determined not only the rate constants but also by the thermodynamic quantities $\chi_\perp$ and $\chi_\parallel$.

Between the rate constants describing effects of the two types BM and MM, and also between rate constants describing effects of a single type an agreement in sign can be observed. The constants $\alpha_1^{BM}=\alpha_{1111}^{BM}$ and $\alpha_1^{MM}=\alpha_{1111}^{MM}$ (and also $\alpha_2^{BM}=\alpha_{1122}^{BM}$ and $\alpha_2^{MM}=\alpha_{1122}^{MM}$) have opposite signs when expressed in terms of the same components of the α_{ikmn} tensors. The rate constants describing effects of a single type, namely α_1^{BM} and α_2^{BM}, and also α_1^{MM} and α_2^{MM}, have opposite signs.

From Eqs. (1) and (3), which describe the field dependence of the longitudinal and transverse magnetoresistances, it follows that in antiferromagnetics there is a greater diversity in the form of the magnetoresistance as a function of field than in ferromagnetics. The reason for this is first, the larger number of different kinds of kinetic effects, and secondly, the larger number of intradomain processes taking place in antiferromagnetics which are absent in ferromagnetics (in particular, the bend in the magnetization of the magnetic sublattices relative to one another, etc.).

Since α_1^{BM} and α_1^{MM}, as well as α_2^{BM} and α_2^{MM}, have differing signs, it follows from (2) and (4) that there is a mutual (but incomplete) cancellation of the contributions coming from BM and MM effects. The quantities β_l and β_t, measuring the incompleteness of the cancellation of BM and MM effects in longitudinal and transverse magnetoresistance in the basal plane can be described by the expressions

$$\beta^l=\frac{||\alpha_1^{BM}|-|\alpha_i^{MM}|\chi_\perp|}{|\alpha_1^{BM}|+|\alpha_i^{MM}|\chi_\perp}, \quad \beta^t=\frac{||\alpha_2^{BM}|-|\alpha_2^{MM}|\chi_\perp|}{|\alpha_2^{BM}|+|\alpha_2^{MM}|\chi_\perp}. \tag{19}$$

For $FeGe_2$ β_l and β_t are of order 10^{-3}.

The LL effect has properties that distinguish it considerably from BM and MM effects. In fields much smaller than the exchange fields it is associated solely with changes in the orientation of the vector **L** relative to the crystallographic axes. Accordingly, the number of independent rate constants describing an LL effect is smaller than the number of constants describing BM and MM effects. The temperature dependence of the constant α^{LL} differs from that of the constants describing BM and MM effects.

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