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Anisotropy of the magnetoresistance along and across domain walls in a ferromagnet

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Abstract. — We discuss some peculiarities of the conduction electron motion in the vicinity of domain walls which lead to an anisotropy of the magnetoresistance. We also discuss the case of single crystals of ErRh_4B_4 and HoMo_6S_8 where magnetoresistance with the same qualitative features has been observed.

1. Introduction.

In recent years there appeared several papers [1-3], in which the electroresistance of single crystals of reentrant superconductors in the ferromagnetic phase has been investigated. In the paper by Genicon *et al.* [1] the electroresistance ρ of a single crystal ErRh_4B_4 was observed in terms of the magnetic field H . In this paper a large effect of the magnetoresistance anisotropy was noticed. Koike *et al.* [2] have been the first to provide electroresistance measurements on single crystal HoMo_6S_8 . The detailed investigations on single crystal HoMo_6S_8 were performed by Giroud *et al.* [3]. We have already paid attention [4] to the possibility that the $\rho(H)$ dependence observed in reference [1] could be due to the modification of the trajectory motion of the conduction electron in the domain wall vicinity [5, 6].

Electrons which cross the 180° domain wall move along the infinite trajectories (2-domain state) (Fig. 1a). Under magnetization a decreasing domain width D_2 becomes eventually less than the cyclotron diameter $2R$. In this case there appear electrons moving along trajectories, encompassing three domains for a period (3-domain state) (Fig. 1b), and simultaneously the number of electrons in 2-domain states decreases. The mobility of the electrons in 3-domain states in the y -axis direction appears to be much less than that of 2-domain ones and this causes an increase of the resistance along domain walls.

Here on the basis of such an approach the magnetoresistance anisotropy of a ferromagnet along and across the domain walls was obtained and some peculiarities of the magnetization process effect on the magnetoresistance was analysed. The results obtained are compared with the experimental ones [1] in a single crystal ErRh_4B_4 in the ferromagnetic phase. The qualitative analysis of the magnetoresistance in a single crystal HoMo_6S_8 in the ferromagnetic phase was carried out too.

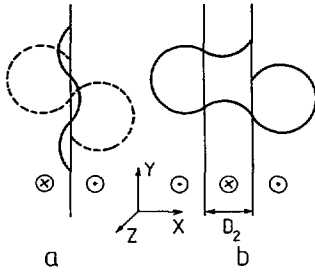


Fig. 1.

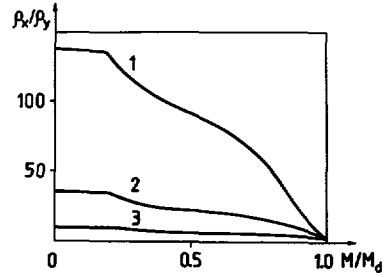


Fig. 2.

Fig. 1. — Conduction electron trajectories crossing one domain wall (a) and crossing the decreasing domain at $D_2 < 2R$ (b).

Fig. 2. — The dependence of the electroresistance anisotropy ρ_{xx}/ρ_{yy} on the magnetization. Curve 1) at $S = 20$; 2) at $S = 10$; 3) at $S = 5$. All curves at $2R/D = 0.8$.

2. Anisotropy of the magnetoresistance.

The resistance of a compensated ferromagnet in the saturated state $\rho_n \approx S^2/\sigma_0$, where σ_0 is the conductivity at induction $B = 0$, $S = \ell/R$, ℓ is the free path length, R is the cyclotron radius. In the demagnetized state 2-domain electrons move along the wall (in y direction) along the infinite trajectories. The conductivity of the mentioned electrons is $\sigma_{yy} \sim \sigma_0$. For the sample with the plane-parallel domain structure of domain width D when $2R < D$ (that is satisfied [4] for the single crystal ErRh_4B_4) the conductivity is $\sigma_{yy} \sim (R/D)\sigma_0$ at $S \gg 1$, then for the resistance in the demagnetized state $\rho_{yy}^{(0)}$ we obtained the ratio $\rho_{yy}^{(0)}/\rho_n \approx D/RS^2$ [4].

The resistance across domain walls $\rho_{xx}^{(0)}$ slightly decreases because the localization size in the X direction for the 2-domain electrons increases. In the vicinity of a wall in a layer of width $L \sim 4R$ (when $4R < D$) the resistance is $\rho_L \approx \frac{3}{4}\rho_n$ [7]. The relative resistance of a sample with the plane-parallel domain structure is

$$\rho_{xx}^{(0)}/\rho_n = 1 - (1 - \rho_L/\rho_n)(4R/D), \quad (1)$$

and we obtain the estimate $\rho_{xx}^{(0)}/\rho_n \approx 1 - R/D$. When $2R < D$ it leads to the appreciable magnetoresistance anisotropy along and across the domain walls. This was really observed in a single crystal ErRh_4B_4 [1].

We consider the simplest magnetization process by the domain wall motion. When the decreasing domain width D_2 becomes less than $2R$ there appear 3-domain electrons. The localization size in the X direction for these electrons is approximately half as much again as for the 2-domain ones. It results in some decrease in ρ_{xx} . The mobility of electrons in the 3-domain states in the Y direction appears to be much less than that of the 2-domain ones. Thus, both ρ_{yy} and the ratio ρ_{xx}/ρ_{yy} can change in a wide range under magnetization.

The conductivity of a multidomain ferromagnet is calculated by the Kubo method [4, 6]. The dependence of the resistance on magnetization was computed on the assumption of a cylindrical Fermi surface (the cylinder axis is along the z -axis). In figure 2 we give plots of the dependence of ρ_{xx}/ρ_{yy} on the relative magnetization M/M_d , where M_d is the magnetization value at which domains disappear. The kinks on the plots correspond to the appearance of a 3-domain state. Then a gradual transformation of 3-domain states into one-domain states

occurs under magnetization, and the anisotropy vanishes, the ratio $\rho_{xx}/\rho_{yy} \rightarrow 1$ when $D_2 \rightarrow 0$.

3. Influence of the domain structure expansion on a resistance.

In reference [1] the results of the resistance measurements across domain walls ρ_{xx}/ρ_n in terms of the magnetic field are given; in zero field $\rho_{xx}/\rho_n \approx 0.9$, and in fields $H \geq 3$ kOe $\rho_{xx}/\rho_n = 1$. In figure 3 we present the dependence of ρ_{xx}/ρ_n on M/M_d obtained by the transformation of experimental [1] curves $\rho_{xx}(H)$ (curve 1) and the results of our computations at different values of $2R/D$ (curves 2, 3).

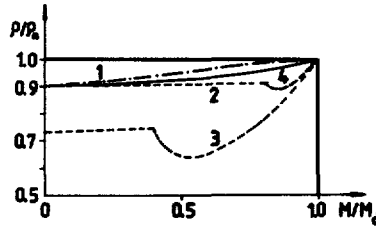


Fig. 3. — The dependence of the resistance ρ_{xx}/ρ_n on the magnetization. Curve 1) experimental results according to [1]; 2) calculation at $S = 15$ and $2R/D = 0.2$; 3) the same at $2R/D = 0.6$; 4) with the account of the domain structure expansion, calculated by the formulae (3) at $2R/D = 0.2$.

For improving an agreement with the experimental data, we consider the influence of the wall number change under magnetization on a resistance. We have made [8] an account of the effect of the domain structure expansion [9, 10]. For this purpose in the expressions for ρ_{yy}/ρ_n the substitution $D \rightarrow D_0 \psi(q)$ has been made, where D_0 is the domain width in the initial demagnetized state, and the function $\psi(q)$ is determined by expressions [10]:

$$\psi(q) = [f(1)/f(q)]^{1/2}, \quad f(q) = \sum_{n=1}^{\infty} (1 - \cos n\pi q) n^{-3}, \quad (2)$$

where $q = 1 - m$, $m = M/M_d$. The numerical analysis shows [8] that such an account leads to only a small displacement of the theoretical curves for ρ_{yy}/ρ_n without changing their character.

Really for the sample with a plane-parallel domain structure the conductivity σ_{yy} would consist of the domain conductivity $\sigma_d \approx \sigma_0/S^2 \ll \sigma_0$ and the conductivity $\sigma_L \approx \sigma_0$ of a layer in the vicinity of the domain walls. The thickness of this layer L changes under magnetization: $L \sim R$ when $D_2 > 2R$ and $L \sim D_2$ when $D_2 < 2R$. The relative resistance becomes $\rho_{yy}/\rho_n \approx (1 + A)^{-1}$, where we use the notation $A = S^2 R/D$ when $D_2 > 2R$ and $A = (8/3)(D_2/D)(D_2/R)^{1/2} S^2$ when $D_2 \ll 2R$. Here the factor $(D_2/R)^{1/2}$ is a measure of the Fermi surface region occupied by 2-domain electrons localized in the vicinity of the decreasing domain. As $D_2 = D(1 - m)$ then the value $A \sim (1 - m)^{3/2}$ when $D_2 \ll 2R$. With account of the domain structure expansion and the fact that when $m \geq 0.7$ the approximation $D \approx 2D_0/5(1 - m)$ holds [10], $A \sim (1 - m)$ when $D_2 \ll 2R$. This makes the decline of the curves $\rho_{yy}^{(m)}/\rho_n$ change at $m \leq 1$, but owing to $S^2 \gg 1$ the shape of the curves with and without account of the domain structure expansion may substantially differ only when $1 - m \approx 10^{-2} - 10^{-3}$.

Consider the dependence $\rho_{xx}^{(m)}/\rho_n$ on m . After substitution in (1) $D \rightarrow D_0 \psi(q)$, expressing all constants through the ratio $\rho_{xx}^{(0)}/\rho_n$ which may be taken from the experimental data, we obtain :

$$\rho_{xx}^{(m)}/\rho_n = 1 - (1 - \rho_{xx}^{(0)}/\rho_n)/\psi(q). \quad (3)$$

Expression (3) is valid until $D_2 > 2R$ and 3-domain electrons are absent. When taking into account the domain structure expansion, 3-domain states may appear when $q\psi(q) < 2R/D_0$. For $2R/D_0 < 0.3$ it is possible only at $1 - m \leq 10^{-3}$, therefore the dependence $\rho_{ii}^{(0)}/\rho_n$ ($i = x, y$) is determined by the process of the domain structure expansion. The value $\rho_{ii}^{(0)}/\rho_n$, i.e. the resistance change in the vicinity of the domain wall, is connected with 2-domain electrons. At $0.3 \leq 2R/D \leq 1$ the contribution of the domain structure expansion to $\rho_{ii}^{(m)}/\rho_n$ is not essential. Such an approach allows us to obtain a rather good agreement with the experimental curves for the dependences $\rho_{ii}^{(m)}/\rho_n$. The graph $\rho_{xx}^{(m)}/\rho_n$ considering the structure expansion by formulae (3) at $\rho_{xx}^{(0)}/\rho_n = 0.9$ (i.e. $2R/D = 0.2$) is plotted in figure 3 (curve 4).

It should be noted here that the computed values $\rho_{xx}^{(0)}/\rho_n$ and $\rho_{yy}^{(0)}/\rho_n$ are determined by the values $2R/D$ and S respectively (when $S \geq 2$), and the measurements of ratios $\rho_{yy}^{(0)}/\rho_n$ and $\rho_{xx}^{(0)}/\rho_n$ can give information about the ratios ℓ/R and D/R .

4. Qualitative analysis of the resistance of HoMo_6S_8 .

Recently Koike *et al.* [2] have demonstrated that the resistivity of a single crystal HoMo_6S_8 in the ferromagnetic phase at $H = 0$ makes up 98 % of its value above T_{c1} .

Giroud *et al.* [3] have provided simultaneous measurements of the resistance and magnetization of a single crystal HoMo_6S_8 for several orientations of the easy magnetization axis with respect to the applied magnetic field. It is of interest to note that the dependence ρ/ρ_n on the applied magnetic field at $T = 95$ mK, which was shown in figure 6 of reference [3] (*J. Low Temp. Phys.*, see also the same in Fig. 1 in *Physica*), is in a qualitative agreement with that of ρ/ρ_n , which is shown by curves 2, 3 in figure 3 of this paper (see also [8]).

Burlet *et al.* [15] have measured the resistance of a single crystal HoMo_6S_8 under heating from $T = 0.085$ K. At this temperature a magnetic field $H = 2$ kOe has been applied to reach a single domain state, then the field was switched off and the heating started. At $T = 0.12$ K the resistance dropped and became zero. Then it began to increase and reached the value $\sim 0.9 \rho_n$ at $T = 0.30$ K (see Fig. 5 of Ref. [15]).

Such a resistance behaviour could be explained by taking into account the fact that after switching off the field the sample was metastable and the subsequent heating appears to be a temperature demagnetization. Under demagnetization in a single domain sample the nuclei of domains with another magnetization orientation appear and begin to increase. The relative volume of such nuclei is small and the width of the magnetic peak may remain resolution limited. However on the domain walls of these nuclei the conduction electrons in 2-domain and 3-domain states are localized and this causes a resistance drop. Under subsequent demagnetization the number and relative volume of such nuclei continue increasing. A reconstruction of the domain structure may occur and as a result an equilibrium domain structure is reached. In general the process may be similar to that described in our previous paper [16], where in figures 4 and 5 the computed curves 4 show the resistance change under magnetization taking the nucleation process into account. The behaviour of these curves is in qualitative agreement with the observed ones in reference [15].

An accomplishment of a more thorough comparison is impeded by some reasons. Firstly, papers [2, 3] had no information about measuring current orientation with respect to the crystallographic axes and hence to the domain walls. As the authors of reference [3] have pointed out it is explained by an imperfect shape of the crystals.

Secondly, it is necessary to estimate the value of $2R/D$ for HoMo_6S_8 . According to the data of [11] the induction $B(0) = 4.8$ kOe, $V_F = 1.8 \times 10^7$ cm/s and $R \approx 2 \times 10^{-4}$ cm. The magnetic temperature is $T_M \approx 0.7$ K. The energy parameter of anisotropy obtained from the data of reference [12] is $K_D \approx 0.4$ K, which gives $\gamma \approx 0.1$ erg/cm². For the sample investigated in reference [2] with $Z_0 \approx 0.4$ mm the domain width estimated by the Kittel formulae [13] is $D \approx 10^{-4}$ cm. We obtain the estimate $2R/D \approx 4$. From the experiments on neutron diffraction [14] it was found for the other samples that there exists a domain structure with $D \approx 1.5 \times 10^{-5}$ cm. In reference [15] on page 103 it was noted that at $T \sim 0.3$ K a single crystal HoMo_6S_8 in ferromagnetic state breaks into domains of width $D \approx 3 \times 10^{-5}$ cm.

Thus for HoMo_6S_8 it may be $2R/D \gg 1$. In this case the appearance of, firstly, the translational states of conduction electrons which move infinitely across domain walls [17] and, secondly, polydomain states of electrons is possible. All this must lead to the conclusion that at $2R/D \gg 1$ the anisotropy of the magnetoresistance along and across the domain walls in a single crystal HoMo_6S_8 must not be so strongly pronounced as in ErRh_4B_4 . But in general the resistance change under magnetization will be determined by a redistribution of the conduction electrons over polydomain states (polydomain states always substitute for the 2-domain states under magnetization). This has to lead to the resistance change effect of the same qualitative character as stated above.

We have to notice however that the assumption that $\ell/R \gg 1$ is very questionable for these ternary compounds. This is the weak point which probably makes the alternative explanation (by nucleation of superconductive layers of width ξ_0 along domain walls) plausible in these systems since it introduces an additional channel which is not present in the paramagnetic case. It seems to us that all this consideration may be treated as one of the arguments for a necessity of further investigations of these systems.

Summary.

The result obtained on the anisotropy of the magnetoresistance along and across domain walls is based on a model of transformation under magnetization of the conduction electron trajectories that leads to a conductivity change in the vicinities of the domain walls in layers of a width given by the cyclotron radius. Such an approach which takes the domain structure expansion into account allows us to obtain a rather good agreement with the experimental data [1] on the magnetoresistance across the domain walls of a single crystal ErRh_4B_4 in the ferromagnetic phase.

We do not consider our analysis of the recent experiments on the magnetoresistance of single crystals HoMo_6S_8 in the ferromagnetic phase as finished because further experiments on more perfect crystals with simultaneous investigations of domain structures is necessary.

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