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MAGNETISM AND FERROELECTRICITY

Negative Magnetoresistance of Iron Single-Crystal Whiskers in the Course of Magnetization Reversal

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Abstract—The change in the low-temperature resistance of iron single-crystal whiskers during magnetization reversal form a single-domain state to a state with a plane-parallel domain structure is studied theoretically. The negative magnetoresistance (~45%) is calculated from the Kubo formula with due regard for the change in the trajectories of conduction electrons in a magnetic induction field of domains. The magnetoresistance thus calculated is of the same order of magnitude as the magnetoresistance obtained in the experiment performed by Isin and Coleman. © *2004 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

In recent works [1, 2], new attempts have been made to interpret the negative magnetoresistance (up to –20%) in pure iron polycrystals [3] in terms of electron scattering by domain walls. As in earlier works performed by Cabrera and Falicov [4], the theoretical values were found to be several orders of magnitude smaller than the experimental magnetoresistance.

Earlier [5, 6], we showed that the negative magnetoresistance is caused by the change in the trajectories of electrons in a magnetic induction field near the domain walls. Taking into account the triple-domain states of electrons whose trajectories encompass a narrow domain, we obtained a negative magnetoresistance of up to –22%. The purpose of the present work was to demonstrate that our approach makes it possible to explain the negative magnetoresistance not only in iron polycrystals [3] but also in iron single-crystal thin whiskers [7].

The effect of a decrease in the electrical resistance of a ferromagnetic sample upon its magnetization in a transverse magnetic field was first revealed in the experiments performed with an iron polycrystal at 4.2 K by Sudovtsov and Semenenko [3] (the decrease observed was 20%) and in the experiments carried out with iron single-crystal whiskers by Isin and Coleman [7] (the resistance decreased to –60%). In our previous work [6], the experimental results obtained in [3] were theoretically interpreted as follows. During magnetization of a sample with the initial plane-parallel domain structure, the trajectories of conduction electrons in a magnetic induction field of the domains change as a result of displacements of the domain walls. When the width $2d$ of a decreasing domain becomes comparable to the cyclotron diameter $2R$, the size effect manifests itself and there appears a new type of electron states whose classical trajectories encompass three domains. The contribution from the other mechanisms responsible for the influence of the domain structure on the electrical conductivity of ferromagnetic metals turns out to be negligible. In [6], we calculated the electrical conductivity with allowance made for single-, double-, and triple-domain electron states and achieved quantitative agreement with the experimental data obtained in [3].

However, the situation observed in the experiments carried out by Isin and Coleman [7] was not considered and, hence, no explanation for the large negative magnetoresistance revealed in their work was offered. Coleman and Scott [8] performed detailed experimental studies of the domain structures of iron single-crystal whiskers upon magnetization reversal of samples in a transverse magnetic field. According to the results of powder experiments carried out in [8], samples in the initial state have a nearly single-domain structure, whereas the magnetization reversal in a transverse field brings about the formation and development of dagger-like and plane-parallel domain structures throughout the sample in magnetic fields up to 2 kOe. It is in these fields that the maximum negative magnetoresistance was observed by Isin and Coleman.

2. THEORETICAL BACKGROUND

In order to interpret the results obtained in [7], we considered the magnetoresistance of a multidomain sample. This sample had a single-domain structure in the initial state and involved narrow plane-parallel domains upon magnetization reversal (Fig. 1). Within this model, we obtained the dependence of the magnetoresistance on the transverse magnetization M. In our case, the relative value of M is determined by the width of new domains and the domain period is taken to be $2D$.

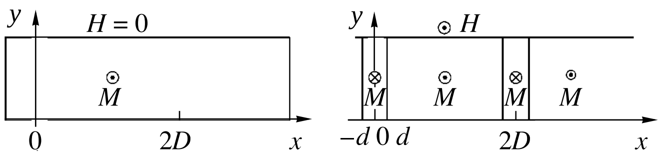

Fig. 1. Schematic diagram illustrating the formation of a domain structure in the course of magnetization reversal of a single-domain sample (the model corresponds to the experiment performed in [8]).

The calculation was performed with the use of the Kubo formula for the electrical conductivity of a compensated metal in the τ approximation [6]:

$$\sigma_{ij} = -e^2\int d\Gamma \frac{\partial f_F}{\partial \varepsilon}\int_0^{\infty}\langle v_i(t')v_j(t'-t)\rangle_{t'}\exp(-t/\tau)dt. \quad (1)$$

Since the velocity correlators for different types of states differ from each other, the integration over the Fermi sphere is divided into integrations over the areas occupied by different electron states. This subdivision varies with a change in the coordinate x. The areas occupied by different electron states can be found from the relationship between the canonical and kinematic momenta and the condition that determines whether or not the domain walls are attained by the classical electron trajectories. This makes it possible to calculate analytically the averages of the velocity correlators of single-, double-, and triple-domain states and to perform the integration allowing for the collisions. As a result, the electrical conductivity across the new domains (along the whisker) in the range $0 \le x \le 2D$ can be represented in the following form:

$$\sigma_{xx}(x) = \frac{\sigma_0}{1+s^2}[1 + \Delta_3(x) + \Delta_3(2D-x) + \Delta_2(x+d) + \Delta_2(|x-d|) + \Delta_2(2D+d-x) + \Delta_2(|2D-d-x|)], \quad (2)$$

where $s = \tau\omega$ (ω is the cyclotron frequency in the magnetic field of the domain). The quantities $\Delta_2(x)$ and $\Delta_3(x)$ are the additional contributions (as compared to the single-domain states) made to the electrical conductivity by the double- and triple-domain states localized at the domain walls and in the narrow domains, respectively. These quantities represent the integrals over the Fermi surface area occupied by conduction electrons in the corresponding states. In the case when $d < R < D/2$, the quantity $\Delta_2(x)$ is the additional contribution from the double-domain states, which is truncated because of the presence of triple-domain states:

$$\Delta\sigma_2(x) = \begin{cases} \frac{1}{\pi}\int_{\varphi_2}^{\pi} F_2(\alpha)d\varphi, & 0 < x < 2d \\ 0, & 2d < x. \end{cases} \quad (3)$$

Here,

$$F_2(\alpha) = \frac{s^2}{1+s^2}\frac{2\cos^2\alpha\tanh(\alpha/s)}{\alpha} - \frac{1+3s^2}{1+s^2}\frac{\sin\alpha\cos\alpha}{\alpha}. \quad (4)$$

The parameters α and φ are related by the equation $\cos\varphi + \cos\alpha = -x/R$, because the expression is written for the domain wall located at $x = 0$ and the distance x to this domain wall is assumed to be positive in sign. The angle φ_2 is determined to be as follows: $\varphi_2 = \arccos[((2d-x)/R - 1)]$.

The relationship describing $\Delta\sigma_3(x)$ for a domain centered at $x = 0$ takes the following form at any positive x:

$$\Delta\sigma_3(x) = \begin{cases} \frac{1}{\pi}\int_{\varphi_3}^{\varphi_4} F_3(\alpha,\beta)d\varphi, & 0 < x < d < 2R \\ 0, & d + 2R < x. \end{cases} \quad (5)$$

The integrand has the form

$$F_3(\alpha,\beta) = \frac{1+3s^2}{\theta(1+s^2)}\cos\theta\sin(\theta-2\alpha) + \frac{4s^3}{\theta(1+s^2)\sinh(2\theta/s)} \times[\cos^2\alpha\sinh(\alpha/s)\sinh((2\theta-\alpha)/s) + \cos^2\beta\sinh(\beta/s)\sinh((2\theta-\beta)/s) + 2\cos\alpha\cos\beta\sinh(\alpha/s)\sinh(\beta/s)]. \quad (6)$$

The limits of integration φ_3 and φ_4 depend on the range of definition of x. In particular, for $0 < x < d$, we have $\varphi_3 = \arccos[((x-d)/R + 1)]$ and $\varphi_4 = \arccos[((x+d)/R - 1)]$. In the case when $d < x < 3d$, the angles φ_3 and φ_4 are determined as follows: $\varphi_3 = \arccos[1 - (x-d)/R]$ and $\varphi_4 = \arccos[((3d-x)/R - 1)]$. In the range $3d < x < d + 2R$, these angles are found to be as follows: $\varphi_3 = \arccos[1 - (x-d)/R]$ and $\varphi_4 = \pi$. The parameters α, β, and φ are related by the expressions

$$\cos\varphi + \cos\alpha = -|(x-d)|/R, \quad \cos\beta + \cos\alpha = -2d/R. \quad (7)$$

Next, we performed the numerical calculation of the magnetoresistance according to the formula

$$\Delta\rho/\rho = [\rho(m) - \rho_0]/\rho_0, \quad (8)$$

where $\rho(m) = \int_0^D (1/\sigma(x))dx$ is the resistance for the relative transverse magnetization $m = M/M_0$ and ρ_0 is the resistance of the sample in the initial state.

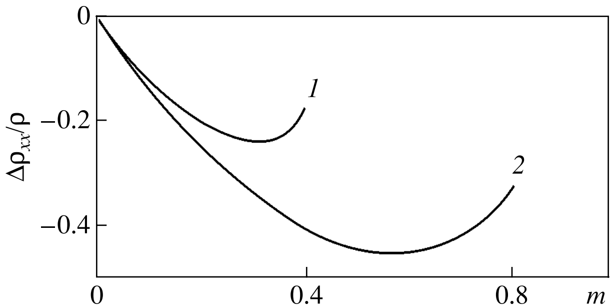

Fig. 2. Magnetoresistance of a single-domain sample in the course of transverse magnetization reversal at $2R/D$ = (*1*) 0.4 and (*2*) 0.8 for $s = 10$.

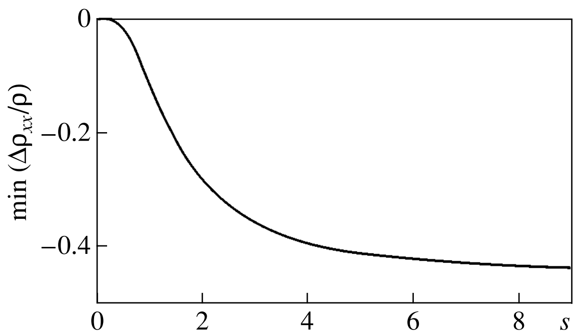

Fig. 3. Depth of the negative magnetoresistance minimum in the course of transverse magnetization reversal of the single-domain sample as a function of the ratio l/R at $2R/D = 0.8$.

3. RESULTS AND DISCUSSION

The magnetoresistance is calculated with respect to the initial single-domain state. Since the single-domain state is characterized by a higher resistance than the state with a periodic domain structure, the negative minimum in the magnetoresistance for a single-domain sample is deeper. Figure 2 presents the magnetoresistance curves obtained in our calculations for two values of the ratio $2R/D$. For example, at $2R/D = 0.8$, the depth of the magnetoresistance minimum reaches –45%.

The above expressions for electrical conductivity make it possible to calculate the magnetoresistance as a function of the quantity $s = \tau\omega = l/R$ (l is the mean free path of electrons in a metal). The depth of the magnetoresistance minimum changes most abruptly at the following ratio of the mean free path to the cyclotron radius: $l/R \gtrsim 1$–2. A typical dependence of the depth of the magnetoresistance minimum is shown in Fig. 3. It can be seen that, when the ratio l/R is relatively large, there occurs saturation. This result demonstrates that samples with a ratio $l/R \gtrsim 1$ will suffice for observations of the negative magnetoresistance effect due to changes in the electron trajectories.

The negative magnetoresistance (–45%) obtained in our calculations does not coincide with the value (–60%) observed in the experiment performed by Isin and Coleman. This difference can be explained by the fact that we did not take into account the contribution of quintuple-domain and consecutive multidomain electron states created upon magnetization reversal followed by the formation of a narrow daggerlike domain structure ($2R/D > 1$).

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