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INVERSE RELUCTANCE IN GRANULATED FERROMAGNETIC ALLOYS

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A model describing reluctance of granulated alloys with allowance made for the effect of *d*-electrons on current transport is proposed. Within the framework of this model, the presence of positive reluctance for a number of granulated alloys (Co–Cu, Co–Ag, etc.) and multilayers (Fe/Cr, Co/Cu, Fe/Cu, etc.) is explained.

Giant reluctance in magnetic multilayers (Fe/Cr, Co/Cu, Fe/Cu, etc.) and granulated alloys (Co–Cu, Co–Ag, etc.) is usually negative, i. e., magnetization causes their reluctance ρ to decrease [1, 2]. It may be considered well proved that giant reluctance in these systems is of common origin. Giant reluctance is related to a spin-dependent scattering of conduction electrons by impurities in the bulk of ferromagnetic layers or at the layer interfaces (the same is valid for granulated alloys) [1, 2]. In particular, a simple model developed by Zhang and Levy [3] that is based on these principles helps explain fundamental characteristics of giant reluctance in granulated alloys.

Inverse (positive) reluctance has been detected in a number of multilayers ($F_1/M/F_2$), i. e., their reluctance increased under magnetization [4, 5]. Inverse giant reluctance may occur in multilayers where current flows either normally to the layers or in their planes. A positive sign of giant reluctance is due to a different pattern of conduction electron scattering in ferromagnetic layers F_1 and F_2. Within the framework of the Zhang–Levy model, giant reluctance is always negative irrespective of the parameters of the model. Yet, positive reluctance was observed in a number of alloys containing clusters or granules, whether it be amorphous alloys [6] or metal composites $Co_x(CuO)_{100-x}$ [7]. An assumption is made in [8] that the reluctance sign inversion is the result of a contribution from spin-dependent scattering. The objective of this work is to study conditions under which spin-dependent scattering in magnetically inhomogeneous alloys causes reluctance to become positive.

PROBLEM STATEMENT

Assume, as in [3], that a granulated alloy is a self-averaging medium in which reluctance is determined by averaging the probability of scattering by all the inhomogeneities: within the granules, in the matrix, and at the granule/matrix interface. In such an alloy, conduction electrons are scattered in different ways depending on a spin direction. Spin mixing processes will be ignored which is sure to be justified at low temperatures.

Following Mott's formula equivalent to Drude's formula (see, e. g., [9]), the conductivity σ can be written as

$$\sigma = A\frac{g^3(\epsilon_F)}{\Delta(\epsilon_F)}, \tag{1}$$

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where $g(\varepsilon_F)$ is the state density of conduction electrons with different-direction spins ($\pm$); $\Delta(\varepsilon_F)$ is the imaginary part of the Green function self-energy; A is a parameter dependent on the configuration of the state density curve and proportional to $1/m^4$, where m is the effective mass of the conduction electrons. In the case of $3d$ metals, current carriers are both s- and d-like electrons. For s-electrons, $g_s^+(\varepsilon_F) = g_s^-(\varepsilon_F) = g_s(\varepsilon_F)$, whereas for d-like electrons, $g_s^+(\varepsilon_F) \neq g_d^-(\varepsilon_F)$ (here, the "plus" and "minus" signs indicate different spin directions). In this case, transition of s-electrons to the d-band may take place. In the general case, we have for a magnetized state,

$$\sigma = \sigma_s^\pm + \sigma_d^\pm, \tag{2}$$

$$\sigma_s^\pm = A_s \frac{g_s^3}{\Delta_s^\pm}, \quad \Delta_s^\pm = \Delta_{ss0} \pm \Delta_{ss1} + \Delta_{sd0}^\pm \pm \Delta_{sd1}^\pm, \tag{3}$$

$$\sigma_d^\pm = A_d \frac{g_d^3}{\Delta_d^\pm}, \quad \Delta_d^\pm = \Delta_{d0}^\pm \pm \Delta_{d1}^\pm, \tag{4}$$

where the subscripts 0 and 1 indicate spin-independent and spin-dependent scattering, respectively. The following definitions are introduced:

$$\Delta_{ss0} = g_s \varkappa_0, \quad \Delta_{ss1} = g_s \varkappa_1, \tag{5}$$

$$\Delta_{d0} = \Delta_{sd0}^\pm = g_d^\pm \varkappa_0, \quad \Delta_{d1} = \Delta_{sd1}^\pm = g_d^\pm \varkappa_1. \tag{6}$$

The $\varkappa_1/\varkappa_0$ ratio is of the order of I/V, where I and V are the exchange and Coulomb interaction potentials, respectively, and the expressions for the parameters $\varkappa_0$ and $\varkappa_1$ are as in [3].

In a demagnetized state, when the magnetic moments of all granules are disoriented, spin-dependent scattering is insignificant, and, hence, $\varkappa_1 = 0$, for reluctance $\Delta\rho/\rho = [\rho(H_s) - \rho(H_c)]/\rho(H_c)$, where H_c is the coercive force, and H_s is the saturation field, it follows from (1)–(6) that

$$\frac{\Delta\rho}{\rho} = \frac{\varkappa_0^2 - \varkappa_1^2}{\varkappa_0^2 + \alpha\varkappa_0\varkappa_1} - 1, \tag{7}$$

where

$$\alpha = \frac{\{g_s^3(g_d^+ - g_d^-) + A_{ds}[(g_d^-)^2 - (g_d^+)^2](g_s + g_d^+)(g_s + g_d^-)\}}{g_s^3(2g_s + g_d^+ + g_d^-) + A_{ds}[(g_d^-)^2 + (g_d^+)^2](g_s + g_d^+)(g_s + g_d^-)}, \tag{8}$$

$A_{ds} = A_d/A_s$.

Equation (7) is a generalized result derived on the basis of the Zhang–Levy theory [3] which includes only s-electron transport: in the Zhang–Levy model $g_d^\pm = 0$ and $\alpha = \alpha_s = 0$. Then

$$\frac{\Delta\rho}{\rho} = -\frac{\varkappa_1^2}{\varkappa_0^2} \quad (\alpha_s = 0), \tag{9}$$

and reluctance is negative whatever the alloy parameters might be. In the other extreme case where only d-states are involved in the transport, $g_s \to 0$ and

$$\alpha = \alpha_{sd} = \frac{(g_d^-)^2 - (g_d^+)^2}{(g_d^-)^2 + (g_d^+)^2}.$$

Generally, in alloys of $3d$ transition metals $g_d^- > g_d^+$ and, consequently, $\alpha_d > 0$ which may cause the reluctance sign inversion.

In the s–d model developed by Mott it is assumed that s-electrons may scatter into the d-band, but d-states do not take part in the transport. Then, in formula (8) it should be assumed that $A_{ds} = 0$ and

$$\alpha = \alpha_{sd} = \frac{g_d^+ - g_d^-}{2g_s + g_d^+ + g_d^-}, \tag{10}$$

with $\alpha_{sd} < 0$ as $g_d^- > g_d^+$.

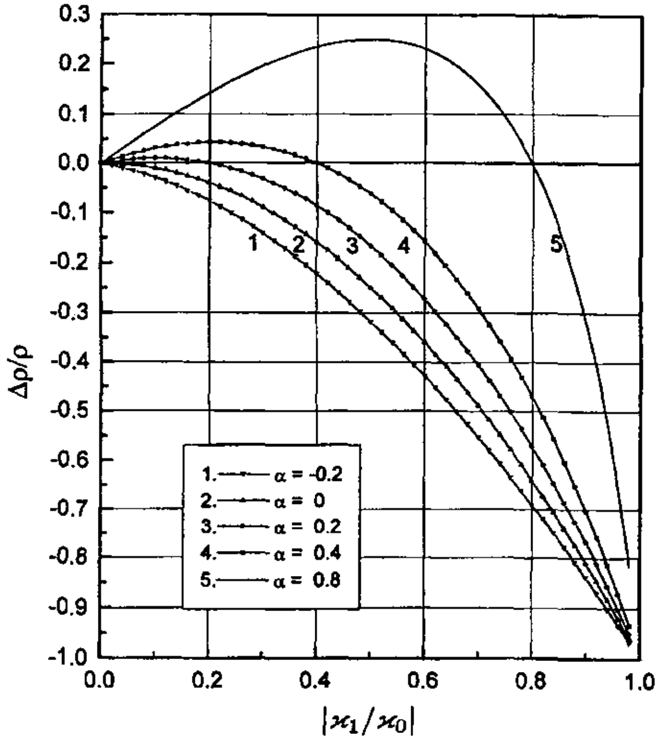

Fig. 1

Reluctance $\Delta\rho/\rho$ vs. $|\varkappa_1/\varkappa_0|$ according to (7).

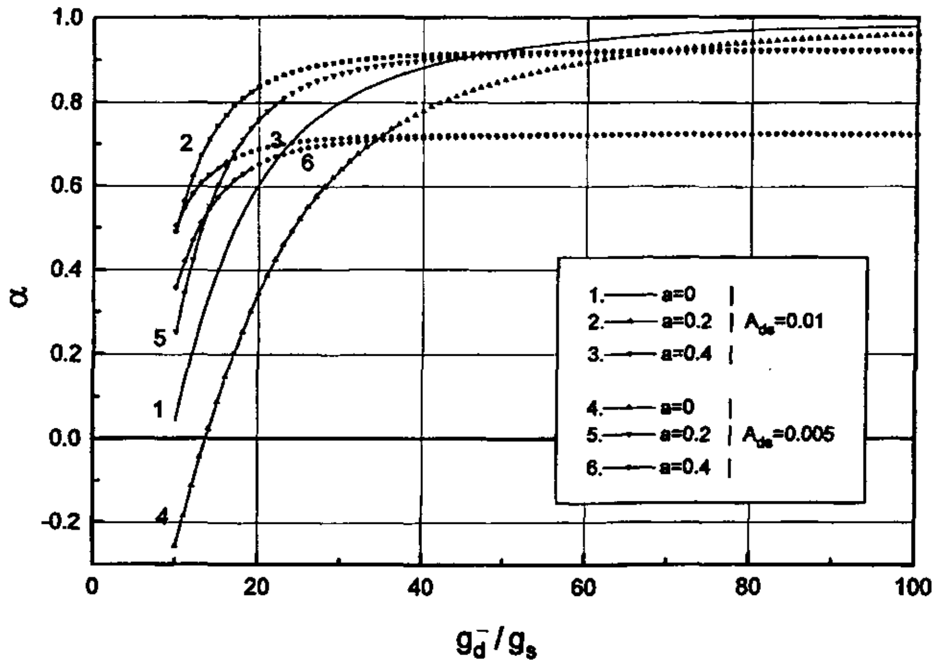

Fig. 2

Dependence of parameter α from (8) on g_d^-/g_s ratio at different values $a = g_d^+/g_d^-$ and $A_{ds} = A_d/A_s$.

RESULTS AND DISCUSSION

The results of reluctance computation using formula (7) for a granulated alloy at different values of α (Fig. 1) demonstrate that inverse reluctance can only be observed at positive α. Neither in the Zhang–Levy nor in the Mott model (10) can the α value be positive. In other words, for reluctance to be inverse, *d*-states must by all means be involved in current transport. As follows from the data in Fig. 2, a positive value of α can be attained when the parameters correspond to those of real alloys of transition metals, and it is obvious that the less important the role of *d*-states in current transport, the smaller a positive value of α and the lower (see Fig. 1) inverse reluctance. The participation of *d*-states in bringing about giant reluctance may partially be suppressed in granulated alloys by potential barriers that arise at the granule/matrix interface. For this reason large values of α in granulated alloys are unlikely. A typical pattern of magnetic reluctance is illustrated by curves *3* and *4* in Fig. 1.

The curves show that the magnitude of inverse reluctance does not exceed 5% which corresponds to the experiment [8]. The data in Fig. 1 may also be interpreted as the reluctance vs. field relationships because the spin-dependent scattering ($\varkappa_1$) increases with the growth of the field. Therefore, the reversal of the reluctance sign from positive to negative in the range of mean values of the parameter $\varkappa_1$ (Fig. 1, curves *3* and *4*) fits very well the experimental data on the reluctance's field behavior [6–8].

It can thus be concluded that inverse reluctance in granulated alloys with spin-dependent scattering requires participation of *d*-electrons in current transport.

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