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Extraordinary Hall effect in magnetic granular alloys

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Abstract

We present the results of a theoretical investigation of the extraordinary Hall effect (EHE) in magnetic granular alloys which exhibit giant magnetoresistance. We consider the impurity scattering of spin-polarized electrons within the magnetic granules, the non-magnetic matrix and at the interfaces between the granules and the matrix in the Zhang–Levy model taking into account the skew scattering due to the spin–orbit interaction. The calculation of the EHE coefficient R_s was carried out using the Boltzmann equation. We show that R_s for granular systems may be larger than that for an homogeneous ferromagnet. Moreover, these coefficients may have opposite sign. The theory predicts that the EHE resistivity is proportional to the concentration of the granules when the electron mean-free path in the matrix is much larger than within the granules. We do not find any correlation between R_s and ρ^2, where ρ is the resistivity of the granular alloy. However, for some values of the parameters, the EHE resistivity is proportional to $\rho^{3.9}$. This is in agreement with the experimental data for $Co_{20}Ag_{80}$.

Keywords: Extraordinary Hall effect; Granular alloys; Giant magnetoresistance

1. Introduction

Since the first observation of giant magnetoresistance (GMR) in Fe/Cr multilayers [1] there has been increasing research activity on GMR and related phenomena due to both fundamental interest and the potential application for magnetoresistance sensors. Recently, GMR has also been observed in magnetic granular alloys, for example Co_xAg_{1-x} [2,3] and $(Co–Fe)_xAg_{1-x}$ [4]. These alloys consist of magnetic particles embedded in a non-magnetic conducting matrix. GMR in multilayers and granular alloys has a common origin, namely the spin-dependent scattering of conduction electrons occurring at the interfaces and/or in the bulk of the ferromagnetic entities. A simple theory of GMR in granular alloys was developed by Zhang and Levy [5]. This theory is based on the assumption that these alloys are self-averaging systems, in other words, the scattering rate of conduction electrons is the average sum of the scattering rates for all scattering centers whether in the bulk of the particles, in the matrix or at the interfaces. In spite of this rather simple assumption [6] this approach can account for the main features of GMR in granular alloys.

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Another magnetic transport phenomenon with unusual and even more curious behaviour in granular alloys is the extraordinary Hall effect (EHE) [3,7,8]. The EHE originates from the asymmetric scattering of spin-polarized electrons due to spin–orbit interactions (SOI) [9]. Two mechanisms of EHE are known: skew scattering and side-jump [9]. The EHE behaviour for homogeneous crystalline and amorphous alloys is well understood. In particular, the contribution to the EHE coefficient R_s from skew scattering at low impurity concentration can be described by the relation

$$R_s = a\rho + b\rho^2, \tag{1}$$

where ρ is the resistivity, while the contribution from the side-jump is

$$R_s \sim \rho^2. \tag{2}$$

These relations (Eqs. (1) and (2)) are sometimes called 'scaling relations' [10], although they are not universal for homogeneous ferromagnets, especially for concentrated alloys [9]. The first attempt to describe the EHE in magnetic heterogeneous alloys theoretically was carried out in the framework of the effective medium approximation [11]. It was shown that the EHE behaviour in composite ferromagnetic–paramagnetic metals is quite different from that in homogeneous ferromagnets and, in particular, Eq. (2) is not fulfilled in all the cases considered. This conclusion was confirmed by calculations of Zhang [10] for the side-jump contribution to R_s in multilayers. However, in its initial form the effective medium theory [11] could not properly describe the electron scattering at the interfaces, which is very important for GMR in the Zhang–Levy model [5]. Therefore, the main goal of the present work is to calculate the EHE in magnetic granular alloys in the Zhang–Levy approach. By doing so we hope to clarify the role of the electron scattering at the interfaces and the spin-dependent scattering in the case of EHE.

2. Model calculations

Let us define the driving current as the x direction. The Hall voltage is measured along the y direction. The magnetic field B_z and the alloy magnetization M_z are then along the z direction. The extraordinary Hall resistivity ρ_H and the EHE coefficient R_s are by definition of the EHE [9]

$$\rho_H = 4\pi R_s M_z, \tag{3}$$

$$R_s = \frac{\sigma_{xy}}{4\pi M_z \sigma_{xx}^2} = \frac{\sigma_{xy}}{4\pi M_z}\rho^2, \tag{4}$$

where σ_{xy} is the non-diagonal part of the conductivity tensor, which is linear in SOI, while $\sigma_{xx} = \sigma = \rho^{-1}$ is the diagonal conductivity. We limit ourselves to low temperatures so that we can neglect spin-mixing due to spin-flip scattering. Therefore, in this case, spin-up and spin-down subbands give additive contributions to R_s and σ:

$$R_s = R_s^{\uparrow} + R_s^{\downarrow} = \frac{\sigma_{xy}^{\uparrow}}{4\pi M_z}\rho^2 + \frac{\sigma_{xy}^{\downarrow}}{4\pi M_z}\rho^2,$$

$$\sigma = \sigma^{\uparrow} + \sigma^{\downarrow}. \tag{5}$$

The EHE coefficient is determined from measurements at relatively high magnetic field B_z so we can consider the magnetic granules as single ferromagnetic domains with magnetization M_z^{gr} all oriented in parallel to the global magnetization M_z. As the matrix is non-magnetic the global magnetization of the granular alloys is $M_z = cM_z^{gr}$, where c is the volume fraction of the ferromagnetic particles. We use plane waves to represent the conduction electron states in granules and the matrix and as a first approximation we assume that the same conduction electrons are responsible for resistivity, GMR and EHE. With these assumptions the Hamiltonian for spin-up or spin-down electrons in a magnetic granular alloy can be written as

$$H = T + V(\boldsymbol{r},\hat{\sigma}) + H_{so}(\boldsymbol{r},\hat{\sigma}). \tag{6}$$

The first term is the kinetic energy

$$T = \sum_{k,\hat{\sigma}} \epsilon_{\mathbf{k},\hat{\sigma}} a_k^+ a_k,$$

$$\epsilon_{\mathbf{k},\hat{\sigma}} = \frac{\hbar^2 k^2}{2m_{\hat{\sigma}}}. \tag{7}$$

The second term is the impurity scattering potential

$$V(\boldsymbol{r},\hat{\sigma}) = \sum_i V(\boldsymbol{r}-\boldsymbol{R}_i,\hat{\sigma}). \tag{8}$$

The third term is the SOI of the conduction electrons with impurities

$$H_{\mathrm{so}}(\boldsymbol{r},\hat{\sigma}) = \sum_i H_{\mathrm{so}}(\boldsymbol{r}-\boldsymbol{R}_i\hat{\sigma}). \tag{9}$$

The scattering potential (Eq. (8)) is expressed in the same way as in the Zhang–Levy paper [5]:

$$V(\boldsymbol{r},\hat{\sigma}) = \sum_i V_i^{(\mathrm{nm})}\delta(\boldsymbol{r}-\boldsymbol{R}_i) + \sum_\alpha \sum_{i\in\alpha} V_i^{(\mathrm{m})}(1+\hat{s}p_{\mathrm{b}})\delta(\boldsymbol{r}-\boldsymbol{R}_i^{(\alpha)}) + \sum_\alpha \sum_{s\in\alpha} V_i^{(\mathrm{s})}(1+\hat{s}p_{\mathrm{s}})\delta(\boldsymbol{r}-\boldsymbol{R}_i^{(\mathrm{s})}), \tag{10}$$

where R_i, $R_i^{(\alpha)}$ and $R_i^{(\mathrm{s})}$ are the impurity positions in the matrix, in the αth granule and at the surface of the αth granule, $V_i^{(\mathrm{nm})}$, $V_i^{(\mathrm{m})}$ and $V_i^{(\mathrm{s})}$ are the spin-independent potentials for the impurities in the matrix, the granules and at the interfaces, respectively; p_{b} and p_{s} are the ratios of the spin-dependent potentials to the spin-independent potentials for the granules and for the interfaces; $\hat{s}=+1$ for spin-up electrons and $\hat{s}=-1$ for spin-down electrons. (It should be noted that for the EHE calculation we need only consider the case when all the granules are magnetized in the same direction. That is why we simplified the Zhang–Levy Eq. (2).) The spin–orbit scattering potential (Eq. (9)) can be written using the same notations as

$$H_{\mathrm{so}}(\boldsymbol{r},\hat{\sigma}) = \sum_i H_{\mathrm{so},i}^{(\mathrm{nm})}\delta(\boldsymbol{r}-\boldsymbol{R}_i) + \sum_\alpha \sum_{i\in\alpha} H_{\mathrm{so},i}^{(\mathrm{m})}\delta(\boldsymbol{r}-\boldsymbol{R}_i^{(\alpha)}) + \sum_\alpha \sum_{s\in\alpha} H_{\mathrm{so},i}^{(\mathrm{s})}\delta(\boldsymbol{r}-\boldsymbol{R}_i^{(\mathrm{s})}). \tag{11}$$

The first term in Eq. (11) can be neglected as the matrix magnetization is too small in comparison with the granular magnetization M_z^{gr}, therefore only SOI within the granules and at the interfaces should be taken into account. Then, in the plane wave representation [9] we can write

$$(H_{\mathrm{so}})_{\boldsymbol{k}\boldsymbol{k}'} = \sum_\alpha \sum_{i\in\alpha} \frac{1}{N^{(\mathrm{m})}} \mathrm{e}^{i(\boldsymbol{k}-\boldsymbol{k}')R_i^{(\mathrm{m})}} i\hat{s}\lambda_{\mathrm{so},i}^{(\mathrm{m})}[\boldsymbol{k}\times\boldsymbol{k}']_z \times \frac{M_z^{\mathrm{gr}}}{M^{\mathrm{gr}}} a_0^2 + \sum_\alpha \sum_{i\in s} \frac{1}{N^{(\mathrm{s})}} \mathrm{e}^{i(\boldsymbol{k}-\boldsymbol{k}')R_i^{(\mathrm{s})}} i\hat{s}\lambda_{\mathrm{so},i}^{(\mathrm{s})} \times [\boldsymbol{k}\times\boldsymbol{k}']_z \frac{M_z^{\mathrm{s}}}{M^{\mathrm{s}}} a_0^2, \tag{12}$$

where $N^{(\mathrm{m})}$ and $N^{(\mathrm{s})}$ are the number of lattice sites in the αth granule and at the αth interface; a_0 is the lattice parameter; $\lambda_{\mathrm{so},i}^{(\mathrm{m})}$ and $\lambda_{\mathrm{so},i}^{(\mathrm{s})}$ are the SOI parameters within the granules and at the interfaces; $M_z^{(\mathrm{s})}$ is the z component magnetization of the interface. For simplicity we put $M_z^{(\mathrm{s})} = M_z^{(\mathrm{gr})}$ and consider the ferromagnetic particles as spherical with the same radius r_0. The scheme of the R_{s} calculation is almost analogous to that used in Ref. [12] for the calculation of the skew scattering contribution to the EHE resistivity in amorphous ferromagnets. For each spin polarization

$$\sigma_{xy} = e\sum_{\boldsymbol{k}} v_{\boldsymbol{k}}^x f_y^{(1)}(\boldsymbol{k}),$$

$$\sigma_{xx} = e\sum_{\boldsymbol{k}} v_{\boldsymbol{k}}^x f_x^{(0)}(\boldsymbol{k}), \tag{13}$$

where $v_{\boldsymbol{k}}$ is the electron velocity, and $f^{(0)}(\boldsymbol{k})$ and $f^{(1)}(\boldsymbol{k})$ are the zero order and linear in SOI distribution functions. These functions can be derived from the Boltzmann equation [9,12], which can be used for self-averaging systems:

$$ev\frac{\partial n_{\mathrm{F}}}{\partial \epsilon_{\boldsymbol{k}}} + \sum_{\boldsymbol{k}'} W_{\boldsymbol{k}\boldsymbol{k}'}^{(0)}[f^{(0)}(\boldsymbol{k}) - f^{(0)}(\boldsymbol{k}')] = 0, \tag{14}$$

$$\sum_{\boldsymbol{k}'} W_{\boldsymbol{k}\boldsymbol{k}'}^{(0)}[f^{(1)}(\boldsymbol{k}) - f^{(1)}(\boldsymbol{k}')] + \sum_{\boldsymbol{k}'} W_{\boldsymbol{k}\boldsymbol{k}'}^{(1)}[f^{(0)}(\boldsymbol{k}) - f^{(0)}(\boldsymbol{k}')] = 0, \tag{15}$$

where n_{F} is the Fermi distribution and the scattering probabilities are ($\hbar = 1$):

$$W_{\boldsymbol{k}\boldsymbol{k}'}^{(0)} = 2\pi\delta(\epsilon(\boldsymbol{k}) - \epsilon(\boldsymbol{k}'))\langle|V_{\boldsymbol{k}\boldsymbol{k}'}|^2\rangle, \tag{16}$$

$$W_{kk'}^{(1)} = -(2\pi)^2 \delta(\epsilon(k) - \epsilon(k')) \mathrm{Im} \sum_{k''} \delta(\epsilon(k) - \epsilon(k'')) \langle H_{\mathrm{so},kk'} V_{k'k''} V_{k''k} + V_{kk'} H_{\mathrm{so},k'k''} V_{k''k} + V_{kk'} V_{k'k''} H_{\mathrm{so},k''k} \rangle. \tag{17}$$

The $\langle\,\rangle$ denotes configurational averaging. This averaging can be done in the Zhang–Levy approach [5] for self-averaging granular systems by introducing the mean-free paths:

$$l_{(t)} = \frac{\epsilon_F / k_F}{\pi / N_{(t)} \Sigma_i |V_i^{(t)}|^2 g(\epsilon_F)}, \tag{18}$$

where $t =$ nm, m, s denotes the matrix, granule and interface, and $g(\epsilon_F)$ is the density of states at the Fermi level. The mean-free paths l_{nm}, l_{m} and l_{s} characterize scattering in the matrix, bulk scattering in granules and scattering at interfaces.

Then, after tedious but rather straightforward calculations we obtain the final expressions for $R_s^{\uparrow(\downarrow)}$ in magnetic granular alloys in the form

$$R_s^{\uparrow} = \frac{\Delta_1^2}{\xi_0^2} \left[R_s^{\mathrm{b}\uparrow} \frac{(1+p_b^2)^2}{(1-p_b)^4} + R_s^{\mathrm{s}\uparrow} \frac{(1+p_s^2)^2}{(1-p_s)^4} \right], \tag{19}$$

$$R_s^{\downarrow} = \frac{\Delta_0^2}{\xi_0^2} \left[R_s^{\mathrm{b}\downarrow} \frac{(1+p_b^2)^2}{(1+p_b)^4} + R_s^{\mathrm{s}\downarrow} \frac{(1+p_s^2)^2}{(1+p_s)^4} \right], \tag{20}$$

where

$$\xi_0 = \frac{1-c}{l_{\mathrm{nm}}} + \frac{c}{l_{\mathrm{m}}}(1+p_b^2) + \frac{3c(1+p_s^2)}{r_0 l_s / a_0}, \tag{21}$$

$$\Delta_0 = \frac{1-c}{l_{\mathrm{nm}}} + \frac{c}{l_{\mathrm{m}}}(1+p_b)^2 + \frac{3c(1+p_s)^2}{r_0 l_s / a_0}, \tag{22}$$

$$\Delta_1 = \frac{1-c}{l_{\mathrm{nm}}} + \frac{c}{l_{\mathrm{m}}}(1-p_b)^2 + \frac{3c(1-p_s)^2}{r_0 l_s / a_0}. \tag{23}$$

$R_s^{\mathrm{b}\uparrow(\downarrow)}$ is the contribution for the EHE coefficient for spin-up (spin-down) electrons in the homogeneous bulk ferromagnetic granular material with the same type and concentration of impurities ($r_0 \to \infty$, $c \to 1$) as in granules; $R_s^{\mathrm{s}\uparrow(\downarrow)}$ is the corresponding contribution for such bulk ferromagnets in which the types, concentration and spatial distribution of impurities are exactly the same as at the interface ($l_{\mathrm{nm}} \to \infty$, $l_{\mathrm{m}} \to 0$). It is useful for the following discussion to write one of these final expressions in detail to emphasize the R_s dependence on the impurity concentration in granules x_{m} and at interfaces x_{s}:

$$R_s^{\uparrow} = \frac{A}{M^{\mathrm{gr}}} \frac{\Delta_1^2}{\xi_0^2} \Delta_2, \tag{24}$$

where A is a coefficient depending on the electronic structure and

$$\Delta_2 = \left[\frac{(1-2x_{\mathrm{m}})(1+p_b)^2}{l_{\mathrm{m}}} (\lambda_{\mathrm{so}}^{\mathrm{m}} - \lambda_{\mathrm{so}}^{\mathrm{f}}) + \frac{3(1-2x_{\mathrm{s}})(1+p_s)^2}{r_0 l_s / a_0} (\lambda_{\mathrm{so}}^{\mathrm{s}} - \lambda_{\mathrm{so}}^{\mathrm{f}}) \right]. \tag{25}$$

Here, $\lambda_{\mathrm{so}}^{\mathrm{f}}$ is the SOI parameter for the host atoms, and $\lambda_{\mathrm{so}}^{\mathrm{m}}$ and $\lambda_{\mathrm{so}}^{\mathrm{s}}$ are the SOI parameters for impurities in granules and at interfaces. The expressions for $R_s^{\uparrow}$ and $R_s^{\downarrow}$ are symmetrical under simultaneous interchanging $p_b \leftrightarrow -p_b$ and $p_s \leftrightarrow -p_s$. But it should be remembered that by definition (12) $R_s^{\uparrow}$ and $R_s^{\downarrow}$ have opposite signs.

3. Results

We first consider the most simple case $p_b = 0$ and $p_s = 0$, i.e. the absence of spin-dependent scattering. In this situation the alloy does not exhibit GMR. One can see from Eqs. (18)–(23) that, in this case

$$R_s = R_s^{\mathrm{b}} + R_s^{\mathrm{s}}. \tag{26}$$

This means that the EHE resistivity ρ_H in granular alloys is due to bulk and surface (interface) scattering. The surface contribution R_s^{s} was not taken into account in the effective medium theory of the EHE [11], but can significantly affect both the amplitude and the sign of the EHE resistivity. It immediately follows from Eq. (24) that the surface contribution tends to zero if the granular radius r_0 or the surface mean-free path l_s increases. Thus, the surface contribution to the EHE should be considered only for granular alloys with rather small granules and with strong interface scattering ($r_0 l_s / a_0 \leq l_{\mathrm{m}}$). In other cases this surface contribution is too small in com-

parison with the bulk term to be observed and the effective medium theory [11] should be valid. It is interesting to note that for highly disordered interfaces with approximately $x_s \approx 50\%$ impurities R_s^s is also small (Eq. (25)). This is in accordance with the results for EHE in disordered alloys [9]. Thus for a large surface contribution to EHE the granules should be small ($r_0 < 50$ Å) with a not very high impurity concentration at the interfaces ($x_s = 10$–20%).

Let us now assume that $l_{nm} \gg l_m$, i.e. that the matrix metal has a low resistivity at least one order of magnitude smaller than the ferromagnet resistivity. Then it follows from Eqs. (21)–(23) that Δ_1, Δ_0 and ξ_0 in this case are linear in the volume fraction of the ferromagnetic particles c and $\rho_H = 4\pi R_s M_z = 4\pi R_s c M_z^{gr} \sim c$. Unfortunately, in real granular systems with GMR Co–Ag, Co–Cu and others the condition $l_{nm} \gg l_m$ is not strictly valid (usually $l_{nm}/l_m = 2$–5), but we can use this linear dependence in the whole concentration range $\rho_H \sim c$ as a starting point for comparison.

We will now discuss the results of our numerical calculations for EHE resistivity in granular alloys versus the concentration of magnetic granules. All results shown in Figs. 1–4 are for the spin-up contribution at $r_0 = 20$ Å. Fig. 1 corresponds to the case $R_s^s = 0$ (curves 1–4). ρ_H is linear in c when there is no spin-dependent scattering $p_b = 0$ (curve 1) and deviates from this linear dependence when $p_b \neq 0$ (curves 2–4). For the case of GMR-type alloys ($l_{nm}/l_m = 4$) this deviation (curve 2) appears to be small. If the interface contribution R_s^s arises (curve 5), but without spin-dependent scattering ($p_b = 0$, $p_s = 0$), then again $\rho_H \sim c$. Thus we can conclude that the non-linear dependence of ρ_H on c in granular alloys is due to spin-dependent scattering.

Figs. 2–4 correspond to more general cases when both spin-dependent and interface scattering are present. Curves 1 and 2 in Figs. 2–4 were calculated for GMR materials ($l_{nm} > l_m$) and curves 3 and 4 for alloys with matrix resistivity equal to (curve 4) or larger than (curve 3) that for the granular material. It appears from these curves that the last-mentioned class of alloys can exhibit very large EHE resistivity, especially in the middle range of composition $c = 0.2$–0.4. As far as we know there is no experimental data on EHE in these high-resistivity metallic granu-

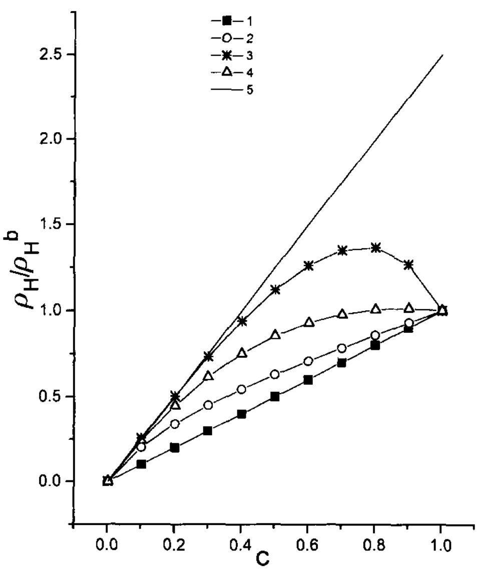

Fig. 1. Reduced EHE resistivity ρ_H / ρ_H^b for granular alloys (ρ_H^b is the EHE resistivity for bulk ferromagnetic granular material) versus the magnetic particle concentration c. (1) $p_b = 0$, $R_s^s = 0$. (2) $p_b = 0.2$, $R_s^s = 0$, $l_{nm} = 200$ Å, $l_m = 50$ Å. (3) $p_b = 0.2$, $R_s^s = 0$, $l_{nm} = 50$ Å, $l_m = 200$ Å. (4) $p_b = 0.2$, $R_s^s = 0$, $l_{nm} = 100$ Å, $l_m = 100$ Å. (5) $p_b = 0$, $R_s^s / R_s^b = 1.5$, $p_s = 0$.

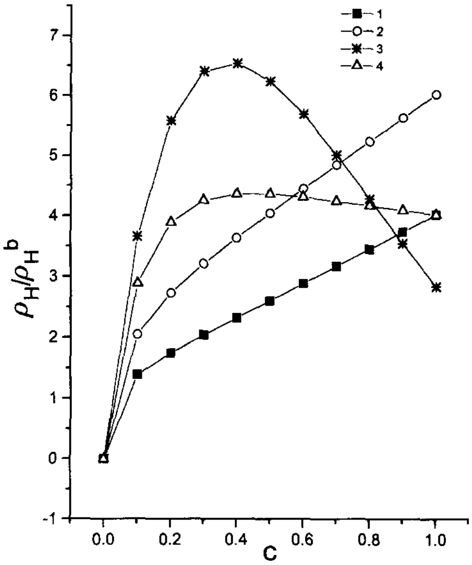

Fig. 2. The same as for Fig. 1 with $p_b = 0.2$, $p_s = 0.52$ and $R_s^s / R_s^b = 1.5$. (1) $l_{nm} = 200$ Å, $l_m = 50$ Å, $l_s / a_0 = 3$. (2) $l_{nm} = 200$ Å, $l_m = 50$ Å, $l_s / a_0 = 6$. (3) $l_{nm} = 50$ Å, $l_m = 200$ Å, $l_s / a_0 = 6$. (4) $l_{nm} = 100$ Å, $l_m = 100$ Å, $l_s / a_0 = 6$.

lar alloys. A giant EHE was observed recently in the percolation system Ni–SiO_2 [8], but strictly speaking the Zhang–Levy approach cannot be applied to granular metallic-dielectric alloys (see below) and therefore we will consider this case in a separate paper [13].

Analyzing the results of Figs. 2–4 we can conclude that the ρ_H behaviour in granular systems might be very complex. The EHE resistivity can be large (Figs. 2 and 3), much larger than for homogeneous alloys, and can change its sign (Fig. 4) due to strong surface scattering, but for typical GMR materials ρ_H is linear in c when $c > 0.1$ (curves 1 and 2 in Figs. 2–4). This theoretical prediction can easily be proved or ruled out.

At this point it is relevant to ask the following question. Is there any correlation between ρ_H and ρ^n, where n is the universal exponent for granular alloys? On the one hand, a negative answer has already been given by the data shown in Figs. 1–4 for the possible ρ_H versus c dependencies. On the other hand, one can fix the volume fraction of ferromagnetic particles c and change only their radius r_0. What would arise in this case? Xiong et al. [3] showed that, for the granular alloy $Co_{20}Ag_{80}$ for a wide range of granular radius r_0, changed by anneal-

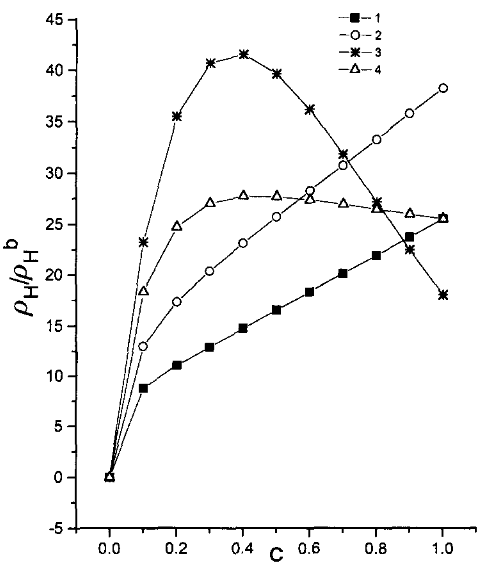

Fig. 3. The same as for Fig. 2 with $R_s^s/R_s^b = 10$.

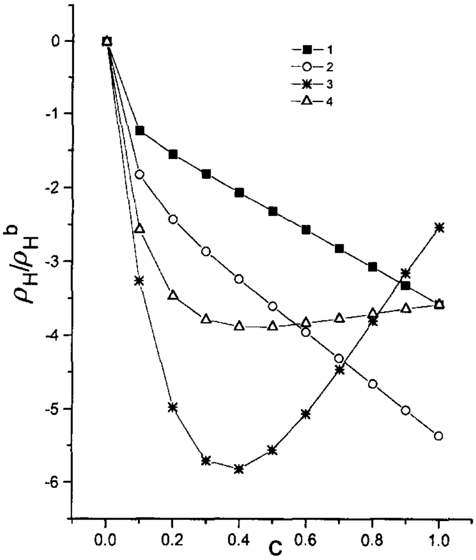

Fig. 4. The same as for Fig. 2 with $R_s^s/R_s^b = -1.5$.

ing, there is the correlation $\rho_H \sim \rho^n$, where $n = 3.7 \pm 0.2$. We calculated ρ_H and ρ for the alloy with $c = 0.2$ and various values of r_0 (Fig. 5). The results obtained can be fitted approximately to the power law $\rho_H \sim \rho^n$, but n is not universal at all. The value of this exponent is in the first instance determined by the interface scattering (Fig. 5). We were able to reproduce the value $n = 3.9$ for one set of parameters (curve 3), but the GMR amplitude for this set of parameters was approximately three times smaller than in the experiment [3]. This should be considered as good agreement with experimental data for such a simple theory as ours. We would like to point out once more that the correlations (1) or (2) for concentrated homogeneous alloys and of the $\rho_H \sim \rho^n$ type for heterogeneous alloys are not universal.

Finally, let us underline the weak points of the theory developed in this paper. First, the Zhang–Levy approach is applied when the mean-free path of the conduction electrons is much larger than the granular radius and the distance between the granules. Unfortunately, this is sometimes not the case for GMR alloys [6] and is invalid for high resistivity (metal–semiconductor or metal–dielectric) granular alloys. Thus the theory should be improved and possible size-effects in the EHE [7,13] should be included by

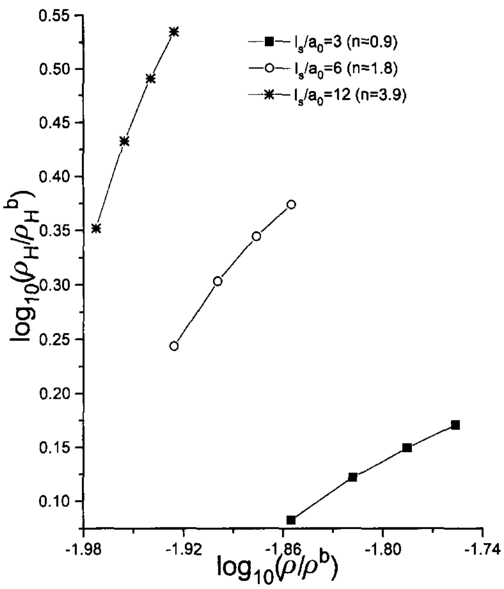

Fig. 5. Correlation between EHE resistivity ρ_H and resistivity ρ for granular alloys with $c = 0.2$ and $R_s^s / R_s^b = 1.5$. The data are fitted by the relation $\rho_H \sim \rho^n$. (1) $l_s / a_0 = 3$, $n = 0.9$. (2) $l_s / a_0 = 6$, $n = 1.8$. (3) $l_s / a_0 = 12$, $n = 3.9$.

methods developed in Ref. [6]. Second, in our modification of the Zhang–Levy model we do not specify the type of electronic states responsible for GMR and EHE. It is known that the d-electrons are the main carriers of EHE in bulk 3d-metal-based alloys [9]. This is due to their large SOI and the large difference in the density of spin-up and spin-down states at the Fermi level. It would appear reasonable that they are responsible for EHE in granular alloys too. But how do these d-electrons of the ferromagnet pass through the non-magnetic matrix between granules? This is still unclear, as is the role of d-electrons in GMR. Probably, the s–d hybridization is so strong that we cannot discuss the transport of s- and d-states separately. Another possibility is that only s-electrons are the current carriers in these alloys and this should lead to small values of ρ_H. We hope that this first theoretical approach and considerations will stimulate more experimental interest on EHE in granular alloys in a wide range of compositions and temperatures. This will be very useful for understanding the role of d-electron transport in heterogenous materials and might lead to technological applications such as new types of Hall sensors.

4. Summary

(1) The EHE behaviour in magnetic granular alloys appears to be quite different from that in homogeneous alloys. The main reason for this difference is the presence of electron scattering at the interfaces between granules and the matrix. The interface contribution to the Hall resistivity can be larger or smaller than the bulk contribution and moreover can have opposite sign.

(2) There is no universal correlation between EHE resistivity ρ_H and ρ^n, where ρ is the electrical resistivity of the granular alloy. For some sets of model parameters ρ_H is proportional to ρ^n with $n = 3.9$ and is in agreement with the experimental data for $Co_{20}Ag_{80}$ granular alloys [3]. However, the value of the exponent n is not universal and seems to depend on the interface scattering rate and other parameters.

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