Temperature dependence of resistance and magnetoresistance of nanogranular Co-Ag films

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We report a number of unusual features in the temperature dependence of the resistance and the magnetoresistance of nanogranular Co-Ag films at low temperatures. These include a nonmonotonic temperature dependence of the resistance in a nonmagnetized state, anomalously low exponents in the power-law temperature dependence of the resistivity (down to $\rho \propto T^{1.1}$) at high magnetic field, and almost linear temperature dependence of the giant magnetoresistance with no saturation at low temperature. [S0163-1829(98)01221-1]

INTRODUCTION

Since the discovery of the giant magnetoresistance (GMR) effect in magnetic multilayers[1] and heterogeneous alloys,[2,3] numerous studies on a variety of systems have been reported (for recent reviews, see, e.g., Refs. 4 and 5). Relatively little attention has been paid to the temperature dependence of the effect, despite its importance for the selection of mechanisms and the development of a microscopic theory of GMR.

It is now widely believed that the GMR effect is due to the spin-dependent scattering of electrons in heterogeneous ferromagnetic systems. The effect is expected to increase as temperature decreases[5] due to the reduction of phonon scattering and spin-flip scattering by magnons or, in disordered magnets, by localized magnetic excitations. Indeed, it was shown in the early experiments,[6,7] that the absolute value of the magnetoresistance increases as the temperature decreases. Qualitatively, all published data agree at high temperatures. However, at low temperatures two types of behavior have been reported. In magnetic Fe/Cr multilayers both current-in-plane and current-perpendicular-to-plane magnetoresistances were found[8,9] to vary strongly with temperature above 60 K, but show a tendency to saturate at low temperatures. Although no microscopic theoretical description of the GMR temperature dependence has been developed so far, Gijs *et al.*[9] and Petroff *et al.*[8] found their experimental data consistent with the electron-magnon scattering as the GMR decreasing mechanism. Markedly different behavior was reported for Co/Cu superlattices[10] and granular Co-Ag films:[11] a roughly linear increase of the GMR term with the temperature reduction and even sharper increase at low temperatures.[11]

In this paper we present a detailed experimental study of the resistance and magnetoresistance in a series of granular Co-Ag films studied down to 1.5 K and up to 16 T magnetic field. We offer a possible explanation for the discrepancy in the previously reported results and show that the temperature dependence of the zero and high field resistance, and of the magnetoresistance, is unusual when compared to that of nonmagnetic and magnetically ordered granular films, and differs significantly from theoretical expectations.

EXPERIMENTAL TECHNIQUES

Granular films of Co-Ag were prepared by coevaporation of Co and Ag using two independent electron beam sources. Films were deposited on room temperature glass or sapphire substrates. Cobalt volume concentrations varied from 15 to 70%. No post-deposition thermal treatment was done. Deposition rate, relative concentration, and the final films thickness were monitored and controlled by two quartz thickness monitors. Up to 24 samples were deposited simultaneously. The relative concentrations varied smoothly due to a shift in the geometrical location of the substrates relative to the evaporation sources. Transport measurements were performed on samples of about 100 nm thickness. Thick films of more than 400 nm were used for magnetization studies. Thinner samples of 20–30 nm thickness were used for transmission electron microscopy (TEM). Both cobalt and silver were found to be crystalline with typical grain sizes of the order of 3 nm.[12] Cu-Ag films were used for a number of test experiments. They were deposited in the same manner and were found to have a microstructure similar to the Co-Ag film.

Resistance and magnetoresistance were measured in a four-probe configuration in a temperature range from room temperature down to 1.5 K in magnetic fields up to 16 T. Magnetization was measured using a superconducting quantum interference device magnetometer in the same temperature range in fields up to 5 T.

EXPERIMENTAL RESULTS AND DISCUSSION

There are two ways to measure the full value of magnetoresistance $\Delta R(T) = R(T,0) - R(T,B_{\rm sat})$, where $B_{\rm sat}$ is the field at which resistance has reached a saturated value. We wish to emphasize that the two do not provide the same results at low temperatures. The first way is to measure the temperature dependence of the resistance of a nonmagnetized sample at zero field and then of a fully magnetized sample at high field $B_{\rm sat}$. The results of these experiments are

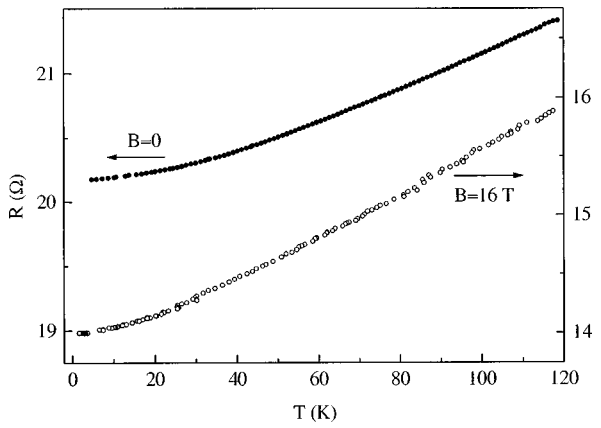

FIG. 1. Resistance of a $Co_{30}Ag_{70}$ sample as a function of temperature, measured at zero (virgin state): solid circles and 16 T field: open circles.

plotted in Fig. 1 for a $Co_{30}Ag_{70}$ sample. It is important to notice that the zero field curve has been measured in a virgin state before the sample was magnetized for the first time. $\Delta R(T)$ is found by subtracting the high field curve from the zero field curve and is plotted in Fig. 2. Also plotted in Fig. 2 is $\Delta R(T)$ for a $Co_{25}Ag_{75}$ sample, extracted the same way. Both curves are roughly linear in the measured temperature range down to 1.5 K.

Another way to find the magnetoresistance value [we shall call it $\Delta R^*(T)$] is by measuring resistance as a function of magnetic field at different temperatures. The magnetoresistance of a $Co_{25}Ag_{75}$ sample measured at 40 and 4.2 K (inset) is plotted in Fig. 3. We find no hysteresis in magnetoresistance curves at temperatures above 30 K and in this range $\Delta R^*(T)$ is defined as $R(T,0)-R(T,16\ \mathrm{T})$. At temperatures below 30 K resistance becomes history dependent with a pronounced hysteresis (see Fig. 3, inset). At these low temperatures we define $\Delta R^*(T)$ as $R_{\max}(T)-R(T,16\ \mathrm{T})$, where $R_{\max}(T)$ is the highest resistance found during the field cycle. $\Delta R^*(T)$ values are plotted in Fig. 2 as solid circles and triangles for the $Co_{25}Ag_{75}$ and $Co_{30}Ag_{70}$ samples, respectively. The difference between $\Delta R(T)$ and $\Delta R^*(T)$is evident at low temperatures. While $\Delta R^*(T)$ seems to saturate, $\Delta R(T)$ continues to increase roughly linearly down to the lowest temperatures measured.

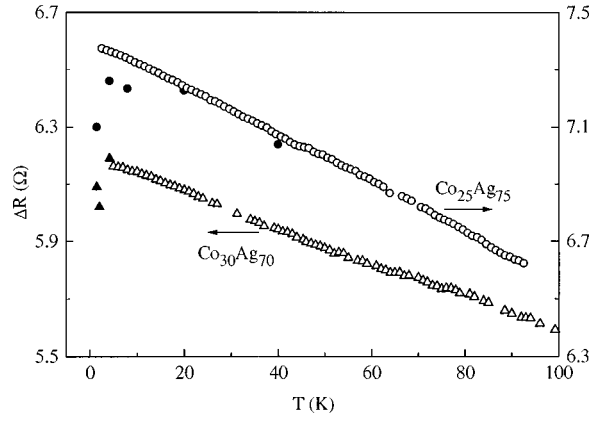

FIG. 2. Absolute magnetoresistance values of $Co_{25}Ag_{75}$ and $Co_{30}Ag_{70}$ samples as a function of temperature. $\Delta R(T)$ and $\Delta R^*(T)$ (see definitions in the text) for both samples are indicated by open and solid symbols, respectively.

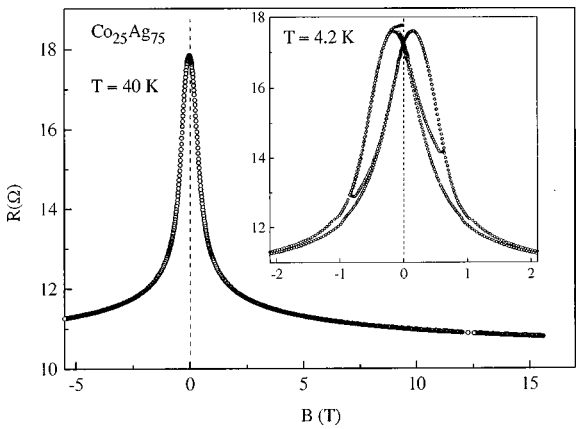

FIG. 3. Resistance of a $Co_{25}Ag_{75}$ sample measured as a function of the applied magnetic field at 40 and 4.2 K (inset).

The origins of the difference between $\Delta R(T)$ and $\Delta R^*(T)$ are probably due to magnetic hardening of Co-Ag mixtures at low temperatures. The latter illustrates itself in the development of a history-dependent resistivity and hysteresis in magnetoresistance. As shown in Fig. 3, the magnetoresistance measured at 40 K is an even function of the field and shows no hysteresis. At 4.2 K the hysteresis and history dependence are clearly observed. The resistance of a nonvirgin state reaches its maximum at an applied field of about ± 0.2 T. Also clearly seen is the disparity between the zero field resistance before magnetic field is applied and the maximum resistance reached during a field scan. In all the samples studied, the largest resistivity measured by scanning magnetic field at fixed low temperature is lower than the resistance of a virgin nonmagnetized state at the same temperature.

Similar difference between the virgin state zero field resistance and the maximum resistance reached during a field scan has been found in various multilayered magnetic structures.[5,13,14] The difference between two values can be of the order of 10% in Co/Cu multilayered nanowires[14] and significantly larger in Co/Ag, Co/AgSn, and Co/AgMn multistructures.[5,13] Despite this uncertainty, the magnetoresistance value of multilayered structures is usually determined from the field ramp experiments, which might be the origin of different reported GMR temperature dependencies at low temperatures.

The hardening onset can be found from the data shown in Fig. 4. Here we plot two resistance temperature dependencies of the $Co_{25}Ag_{75}$ sample. The first (open circles) was measured by cooling a virgin sample (before magnetic field was applied for the first time), and the second (solid circles) was measured by heating the sample after a 16 T field has been applied and removed at 1.5 K. The two curves diverge below about 30 K, which provides a reasonably accurate indication of the hardening onset. The experiment shown in Fig. 4 is analogous to the measurement of magnetization under zero-field-cooling versus field-cooled conditions, which in a superparamagnetic system serves to define the blocking temperature.

It seems reasonable to identify the hardening onset with the superparamagnetic blocking temperature of the system

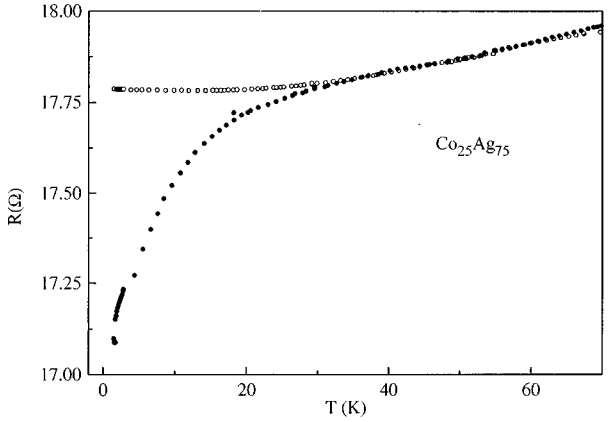

FIG. 4. Resistance of a $Co_{25}Ag_{75}$ sample measured as a function of temperature at zero applied magnetic field. Open circles represent the resistance measured by cooling the virgin sample, solid circles represent the resistance measured by heating the sample after applying and removing a 16 T field at 1.5 K.

T_b. The latter can be estimated[15] as $CV \approx 25 k_B T_b$, where C is magnetic anisotropy energy density, V is the particle volume, and k_B is the Boltzmann constant. For $T_b = 30$ K, as found in Fig. 4, and the particle diameter of 3 nm, as found by electron microscopy, we calculate $C \approx 7 \times 10^6$ erg/cm^3. This value is close to that of bulk Co.[16] This is consistent with the intrinsic bulk anisotropy energy density and does not require any extrinsic parameters, such as stress, shape, and surface.

We define the full magnetoresistance as a difference between the resistance in the virgin unmagnetized state and in the fully magnetized states at high applied magnetic field. These magnetoresistance amplitudes normalized by the room temperature values are plotted in Fig. 5 for a series of granular CoAg samples. For the samples presented, the magnetoresistance temperature derivative (absolute value) increases for lower Co concentrations. For all the samples the magnetoresistance increases roughly linearly with temperature reduction over about two decades in temperature down to 1.5

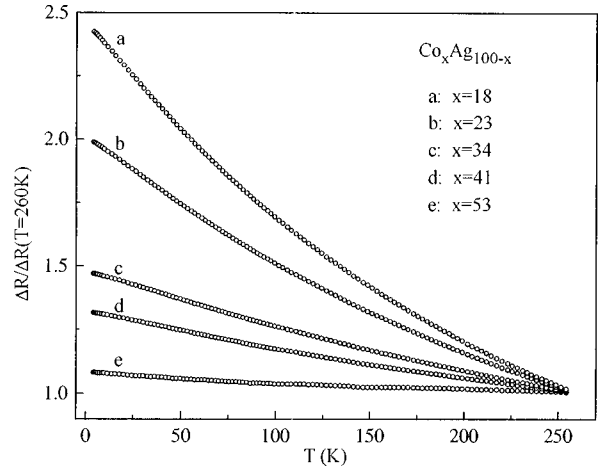

FIG. 5. Temperature variation of magnetoresistance magnitudes normalized by their values at 260 K for five Co-Ag films with different cobalt concentrations. Co volume concentrations from bottom up are 53, 41, 34, 23, and 18%.

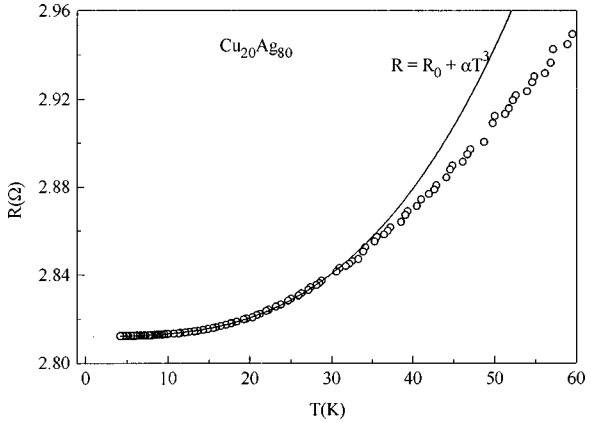

FIG. 6. Resistance of $Cu_{20}Ag_{80}$ film as a function of temperature. Solid line is a fit of the form $R = R_0 + \alpha T^3$.

K. No sample shows a visible saturation of the magnetoresistance at low temperatures.

Before presenting data on the temperature dependence of the resistance of Co-Ag films, both in zero and high magnetic fields, we shall briefly review what is expected to be found. In metals at low temperatures one can usually identify a number of scattering mechanisms: phonons, magnons, and electron-electron scattering, each giving rise to a different power-law temperature dependence T^γ. Electron scattering with phonons is spin independent with $\gamma = 5$ in the clean limit, and is expected to follow a power law with $\gamma = 3$ in dirty and disordered metals. To check the credibility of this assumption in granular metals with multiple intergranular boundaries, we used a film of $Cu_{20}Ag_{80}$ for a control experiment. $Cu_{20}Ag_{80}$ is a mixture of immiscible nonmagnetic metals and has a structure very similar to that of Co-Ag films. The resistance of $Cu_{20}Ag_{80}$ as a function of temperature is plotted in Fig. 6, together with a calculated curve of the form $R = R_0 + \alpha T^3$. The fit is good at temperatures below 30 K.

Electron-electron scattering gives rise to $\gamma = 2$, and it is known that bulk ferromagnets, such as bulk Co, follow a quadratic power-law temperature dependence at low temperatures.[17] We found this behavior also in granular mixtures with high Co concentrations. Figures 7(a) and 7(b) present the temperature dependence of the magnetoresistance [Fig. 7(a)] and resistance [Fig. 7(b)] of the Co rich film $Co_{70}Ag_{30}$. Anisotropic magnetoresistance is well developed in this sample [Fig. 7(a)], which indicates the presence of an infinite or, at least, large enough ferromagnetic clusters.[12] Resistance is measured both at zero and 16 T field and is fitted by a power law $R = R_0 + \alpha T^2$ both at zero and 16 T field [Fig. 7(b)]. The fit is good up to temperatures above 60 K.

The lowest power value $\gamma = 3/2$ usually indicates spin-mixing scattering with magnons in disordered ferromagnets,[18] the mechanism believed to be responsible for the temperature variation of GMR. In systems with granular diameter $d = 3$ nm, which is equal to about 10 lattice constants a, the magnons are quantized with the lowest energy $\hbar\omega_0 \approx T_c (d/a)^2 \approx 10-20$ K, where T_c is Curie temperature of cobalt. Therefore, at temperatures below 10 K the magnon scattering freezes out, and the exponent γ is expected to be not lower than 2. As we shall show in the following, no one

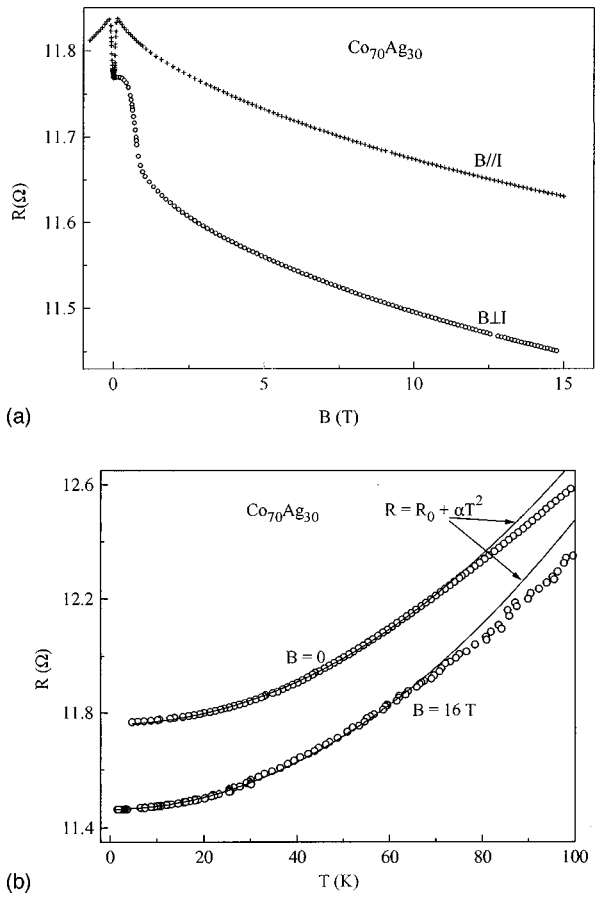

FIG. 7. (a) Magnetoresistance of $Co_{70}Ag_{30}$ sample measured at $T=2$ K with field applied parallel (crosses) and perpendicular (circles) to electrical current. (b) Resistance of a $Co_{70}Ag_{30}$ sample as a function of temperature measured at zero and 16 T field. Solid lines are fits of the form $R=R_0+\alpha T^2$.

of the power-law mechanisms listed above or their combinations satisfactory describe the behavior of Co-Ag films.

We plot in Fig. 8 the low-temperature part of the resistance temperature dependence of samples $Co_{25}Ag_{75}$ and $Co_{18}Ag_{82}$ measured in their virgin state at zero magnetic field. The zero field resistance of these samples is nonmonotonic with minima at about 12 and 22 K for $Co_{25}Ag_{75}$ and

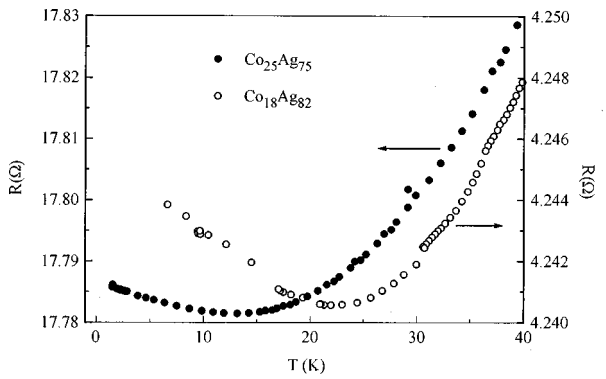

FIG. 8. Nonmonotonic temperature variation of resistance of $Co_{25}Ag_{75}$ and $Co_{18}Ag_{82}$ samples in their unmagnetized virgin state at zero magnetic field.

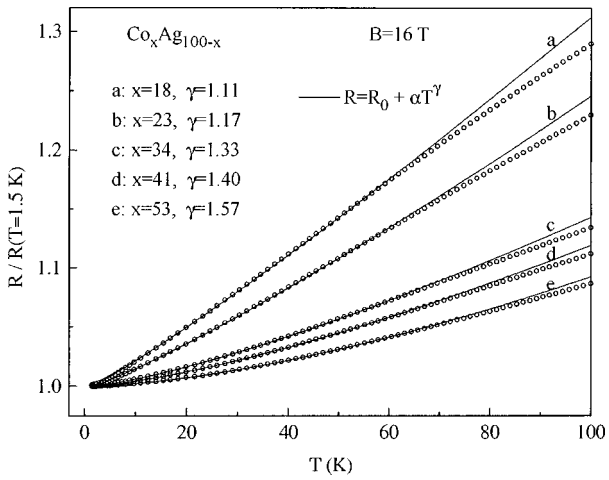

FIG. 9. Resistance temperature dependence of five Co-Ag samples measured at 16 T field. Thin solid lines are fits of the form $R=R_0+\alpha T^{\gamma}$. Cobalt volume concentrations x and power values γ for the samples are (a) $x=53\%$, $\gamma=1.57$; (b) $x=41\%$, $\gamma=1.40$; (c) $x=34\%$, $\gamma=1.33$; (d) $x=23\%$, $\gamma=1.17$; (e) $x=18\%$, $\gamma=1.11$.

$Co_{18}Ag_{82}$, respectively. No minimum was found in our samples with higher Co concentrations. A resistivity minimum and an onset of a negative resistivity temperature coefficient in metallic systems has been associated with either localization or electron-electron interaction in two-dimensional (2D) electronic systems, as argued recently in Co/(Cr/Ag)/Co and Co/Ag/Co multilayers;[19] or with a Kondo effect, found usually in metallic systems with dilute paramagnetic impurities. It was recently proposed by Geoghegan *et al.*[20] that the Kondo effect is responsible for a resistivity minimum found in CoAg ribbons. However, the Kondo temperature of Co in metallic matrices, such as Cu and Au is of the order of 1000 K,[21] and this rules out such an explanation for Co-based systems.[10,22] We shall demonstrate in the following that the nonmonotonic resistivity temperature dependence can be qualitatively understood in terms of the two-current model without involving a Kondo mechanism.

The variation of the resistance with temperature under high magnetic field is no less puzzling than its zero field dependence. We plot in Fig. 9 the resistance of five Co-Ag films with different Co concentrations as a function of temperature measured at 16 T field. Also shown are calculated curves of the form $R=R_0+\alpha T^{\gamma}$. Good fits, with systematically decreasing γ values 1.57, 1.4, 1.33, 1.17, and 1.11, are found at $T<60$ K for samples with decreasing Co volume concentration of 53, 41, 34, 23, and 18%, respectively. As we mentioned above, a known scattering process with the lowest power-law value $\gamma=\frac{3}{2}$ is that with magnons in disordered magnets. Samples with Co concentrations lower than 42% follow power-law temperature dependencies with values consistently lower than $\frac{3}{2}$.

Since GMR is associated with the relative orientation of neighbor magnetic entities, it is useful to compare GMR data with magnetization data. We show in Fig. 10 the magnetization of a $Co_{30}Ag_{70}$ sample as a function of temperature mea-

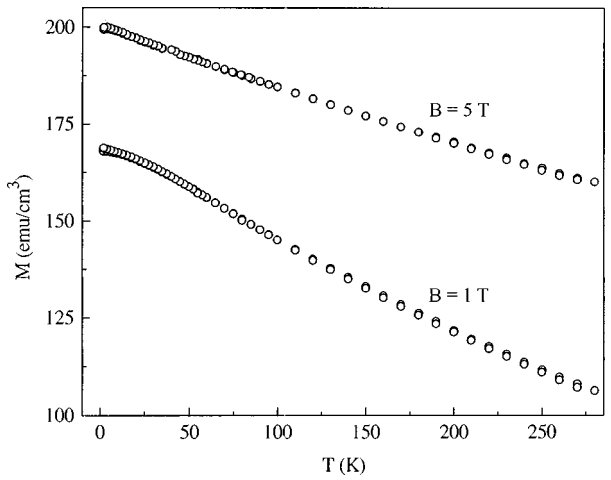

FIG. 10. Magnetization of $Co_{30}Ag_{70}$ sample as a function of temperature measured at 1 and 5 T fields.

sured at 1 and 5 T fields. The 1 T curve shows a certain saturation trend at the lowest temperatures due to the blocking effect. The trend is expected from the previously estimated anisotropy energy density C. For $C \approx 7\times10^6$ erg/cm^3 and the saturation magnetization of bulk cobalt $M_s = 1500$ emu/cm^3, we calculate the anisotropy field $H_A = 2C/M_s \approx 10^4$ Oe (equivalent to 1 T in SI units). Magnetization in 5 T field decreases linearly with temperature increase in the entire temperature range. This implies that at this field all granular moments are aligned along the applied field and $\mu_{\rm eff}B$ exceeds kT in the whole temperature range, where $\mu_{\rm eff}$ is an effective moment of a single Co grain. The fit to the experimental curve by the Langevin function (at $\mu_{\rm eff}B \gg kT$ this function reduces to $1-kT/\mu_{\rm eff}B$) gives for $\mu_{\rm eff}$ the value of 3.7×10^{-18} emu. This is by a factor 2–3 smaller than the value expected for a 3 nm Co particle. Following this $\mu_{\rm eff}$ estimation, the magnetization in 16 T field varies by a few percent only when temperature is reduced from the room one to 1.5 K. We can, therefore, neglect the temperature induced changes of magnetization in the following discussion.

The GMR effect in multilayers is usually discussed in the framework of the two-current model for electrons with spins up and down.[4,23] It was suggested[4,24] that this model should work also in the case of granular systems. A theory of the resistance of multilayers in the transverse geometry, which took into account both volume and interface spin-dependent scattering, was developed in Refs. 23 and 25. It was shown[23] that the Boltzmann equation model is reduced to the macroscopic transport equations when the spin-diffusion length is much larger than the mean free path. The resistance in both the antiparallel ($B=0$) and parallel (strong fields) situations depends not only on the mean free path but also on the spin-diffusion lengths 1_{sN} and 1_{sF} in the normal and ferromagnetic layers, respectively. Up to leading order in the parameters $\eta_N = t_N/2l_{sN}$ and $\eta_F = t_F/2l_{sF}$ (t_N and t_F are the widths of the nonmagnetic and magnetic layers, respectively), the zero field resistance $R(T,0)$ can be written as

$$R(T,0) = R_F + R_N + R_S - \frac{\eta_N^2}{R_N}(\beta R_F + 2\gamma R_S)^2 - \frac{\eta_F^2}{3}R_F\beta^2. \tag{1}$$

Here R_F, R_N, and R_S are the resistance of the ferromagnetic layer, normal layer, and the interfaces, respectively. $R_F = (\rho_\uparrow + \rho_\downarrow)t_F/4$, where $\rho_{\uparrow(\downarrow)}$ are the resistivities of the spin up and spin down channels $R_N = \rho_N t_N$ and $R_S = (r_\uparrow + r_\downarrow)/2$, where the $r_{\uparrow(\downarrow)}$ is the resistance of the interfaces for spin up (down) electrons. β and γ are the spin asymmetry coefficients for the ferromagnetic layers and the interface. $\beta = (\rho_\downarrow - \rho_\uparrow)/(\rho_\uparrow + \rho_\downarrow)$ and $\gamma = (r_\downarrow - r_\uparrow)/(r_\downarrow + r_\uparrow)$. The last two terms in Eq. (1) are of particular interest for us. The spin-diffusion length increases with temperature decrease, therefore, these terms should decrease. This implies that the resistivity $R(T,0)$ can increase with temperature decrease at low temperatures when R_F, R_N, and R_S almost saturate. Since at high temperatures $R(T,0)$ falls with the decrease of temperature, one can expect the function $R(T,0)$ to pass a minimum. This effect in layered or granular magnetic systems is related to the spin-coupled interface resistance, as was considered first in Refs. 26 and 27. The lower the temperature, the weaker the spin relaxation and the higher this additional interface resistance. We find a certain confirmation of this scenario from the correlation between the temperature of the minima T_m (Fig. 8) and GMR values at low temperatures (Fig. 5). Both the interface resistance and the GMR are proportional to the square of the spin asymmetry coefficient. Therefore, the larger the GMR the higher T_m should be, which is, indeed observed.

Consider now the resistance in a strong magnetic field. The resistance $R(B_{\rm sat})$ of all our samples shows no minimum and is a monotonic function of temperature, which implies that the spin diffusion is less important in the magnetically ordered state than in the disordered one. This can also be seen from the expression of the respective resistance expressions [Eq. (41) in Ref. 23)] in small parameters η_F and η_N. Therefore, the usual two-current equation for $R(T,B_{\rm sat})$ can be used:[25]

$$R(T,B_{\rm sat}) = \frac{(R_\uparrow + R_N)(R_\downarrow + R_N) + R_{\uparrow\downarrow}(R_\uparrow + R_\downarrow + 2R_N)}{R_\uparrow + R_\downarrow + 2R_N + 4R_{\uparrow\downarrow}}. \tag{2}$$

Here R_N and $R_{\uparrow(\downarrow)}$ are resistances of the nonmagnetic matrix and of ferromagnetic grains, respectively. $R_{\uparrow(\downarrow)}$ includes spin-dependent and spin-independent intragranular and interface scatterings. $R_{\uparrow\downarrow}$ describes the spin-mixing scattering leading to the momentum transfer between the two channels. Resistances $R_{\uparrow(\downarrow)}$ and R_N can be split into the residual and the temperature-dependent parts $R_{\uparrow(\downarrow)} = R^{(0)}_{\uparrow(\downarrow)} + R^{(1)}_{\uparrow(\downarrow)}(T)$, $R_N = R_N^{(0)} + R_N^{(1)}(T)$, while $R_{\uparrow\downarrow}$ is zero at zero temperature. The relative change in the resistance with the increase of the temperature is small, of the order of 10% per 100 K. Therefore, the temperature-dependence parts are small, and Eq. (2) can be expanded in powers of $R^{(1)}_{\uparrow(\downarrow)}(T)$, $R_N^{(1)}(T)$, and $R_{\uparrow\downarrow}(T)$. The result is

$$R(T,B_{\mathrm{sat}}) = \frac{(R_{\uparrow}^{(0)}+R_N^{(0)})(R_{\downarrow}^{(0)}+R_N^{(0)})}{R_{\uparrow}^{(0)}+R_{\downarrow}^{(0)}+2R_N^{(0)}} \times \left\{ 1+R_{\uparrow}^{(1)}\frac{R_{\downarrow}^{(0)}+R_N^{(0)}}{(R_{\uparrow}^{(0)}+R_N^{(0)})(R_{\downarrow}^{(0)}+R_{\uparrow}^{(0)}+2R_N^{(0)})} + R_{\downarrow}^{(1)}\frac{R_{\uparrow}^{(0)}+R_N^{(0)}}{(R_{\downarrow}^{(0)}+R_N^{(0)})(R_{\uparrow}^{(0)}+R_{\downarrow}^{(0)}+2R_N^{(0)})} + R_N^{(1)}\frac{(R_{\uparrow}^{(0)}+R_N^{(0)})^2+(R_{\downarrow}^{(0)}+R_N^{(0)})^2}{(R_{\uparrow}^{(0)}+R_N^{(0)})(R_{\downarrow}^{(0)}+R_N^{(0)})(R_{\uparrow}^{(0)}+R_{\downarrow}^{(0)}+2R_N^{(0)})} + R_{\uparrow\downarrow}\frac{(R_{\downarrow}^{(0)}-R_{\uparrow}^{(0)})^2}{(R_{\uparrow}^{(0)}+R_N^{(0)})(R_{\downarrow}^{(0)}+R_N^{(0)})(R_{\uparrow}^{(0)}+R_{\downarrow}^{(0)}+2R_N^{(0)})} \right\}. \quad (3)$$

As was argued above, in the temperature range in which magnons are not quantized, $R_{\uparrow\downarrow}$ is proportional to $T^{3/2}$ in disordered systems,[14] while the temperature dependence of $R_{\uparrow(\downarrow)}^{(1)}$ and $R_N^{(1)}$ can be caused by spin-wave scattering ($T^{3/2}$ in disordered systems[18,28]), electron-electron scattering (T^2, see Fig. 7 for $Co_{70}Ag_{30}$) and phonon scattering (T^3 in disordered systems, see Fig. 6 for CuAg alloy). According to Eq. (3), the high field resistance $R(T,B_{\mathrm{sat}})$ is a sum of positive terms, and its temperature dependence cannot be weaker than $T^{3/2}$. Moreover, magnons freeze out at temperatures lower than $T_H=g\mu_B B/k$, where μ_B is the Bohr magneton. For $B=16$ T, T_H is about 20 K. Therefore, at temperatures lower than 20 K resistance is expected to saturate quickly, its temperature-dependent part decaying as T^2 or T^3. These theoretical predictions disagree with the experimentally found behavior of $R(B_{\mathrm{sat}},T)$ (Fig. 9). No samples studied show the low-temperature saturation. Moreover, the approximated power-law exponents decrease systematically down to 1.1 for samples with low Co concentration. One could suggest that in granular systems electron scattering by surface excitations of the grains, either elastic or magnetic, or by some local structural defects become important. However, this possibility can be ruled out for the following reason: the surface magnetic excitations, such as 3D spin waves, should freeze out at low temperatures, while the experimental results for the CuAg evidence against any elastic excitations beyond 3D phonons.

Let us summarize briefly our major experimental findings.

(1) The full values of the giant magnetoresistance in a series of granular CoAg samples, defined as a difference between the resistance in the virgin unmagnetized states and in the fully magnetized states at high applied magnetic field, demonstrate a roughly linear temperature dependencies over about two decades of temperature down to 1.5 K. No low-temperature saturation expected for magnon-dominated spin-flip scattering was found.

(2) Samples with low Co concentrations show a nonmonotonic temperature dependence of the resistance at zero applied field. A correlation between the temperature of the minima and the magnitude of magnetoresistance is found.

(3) At high magnetic fields resistance can be fitted to power-law temperature dependencies with unusually low exponents. These exponents decrease systematically with Co concentration reduction down to about 1.1 in the $Co_{18}Ag_{82}$ sample.

We succeeded in explaining the minima in the temperature dependence of the zero field resistance in the framework of the two-current model. However, we failed to explain the rest of the unusual properties by the currently used models of electron scattering. The discrepancies found imply that either the two-current model is not applicable in a straightforward way to granular systems, or that some additional, probably, soft local excitations[29] are important. The effects are intriguing and deserve special discussion.

ACKNOWLEDGMENTS

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