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Domain Wall Magnetoresistance and Complex magnetic Response in Antiferromagnetically Coupled Fe/Cr Multilayers

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Abstract

For antiferromagnetically coupled Fe/Cr(100) multilayers the low field contribution to the resistivity, which is caused by the domain walls (DWs), is strongly enhanced at low temperatures. The low temperature resistivity increases approximately according to a power law with the exponent 0.7-1. This behaviour can be explained by the suppression of anti-localization effects by the nonuniform gauge fields caused by the domain walls. Analyses of complex low frequency magnetic susceptibility shows an enhancement of the magnetic losses at low magnetic fields, which may be related to the AC field induced DWs movement. At low temperatures (T<100K) DWs become pinned. For frequencies (10^2<f< 10^3) Hz at temperatures below 10K, this hysteretic low field peak in the magnetic losses transforms to a non-hysteretic dip for |H|< 20 Oe, indicating a possible qualitative change in the dynamics of the DWs. The frequency dependence of the dissipation at 2K, may be reasonably well fitted by the expression that describes the losses of a damped oscillator with a single relaxation time of about 10^{-4} sec.

Introduction

Influence of the domain walls and, in general, non-uniform magnetic fields (in the following-DWs) on the electron transport and low frequency- low field magnetic dynamics are related physical properties of magnetoelectronic devices. Their knowledge is essential both for fundamental physics [1] and possible applications. Although the number of DWs was controlled and directly observed in Fe [3] and in Co films [4] at room temperature, where DW formation is relatively well understood, no clear picture has emerged allowing to explain the results. The anisotropic magnetoresistance (AMR) dominates the low field magnetoresistance and complicates the extraction of the true DW contribution to the resistivity [5]. In order to minimize the AMR contribution, thin films with reduced magnetization and special DW configuration have been studied [6]. Apart from the ballistic contribution to the DW magnetoresistance [7], quantum interference also affects the electron transport through DWs [8,9].

Antiferromagnetically (AF) coupled magnetic multilayers (MMLs) are systems with reduced magnetization and consequently a strongly suppressed AMR. At high temperatures, weak pinning of the DWs in the MMLs may reduce DW magnetoresistance. For fixed magnetic field the DW magnetoresistance may then emerge only at sufficiently low temperatures where DWs become strongly pinned and their configuration is not affected by thermal fluctuations or by the applied electric current. In this situation, a combined study of static and dynamic properties, complemented by electron transport investigation, may give important new information about properties of MMLs, practically unexplored up to now in the magnetic field region where formation and propagation of DWs is expected. In this paper we report on a detailed study of the DC magnetization, *ac* magnetic susceptibility and low field-low temperature magnetoresistance of antiferromagnetically coupled $[Fe/Cr(100)]_{10}$ multilayers at different frequencies below 10^4Hz, magnetic fields below 300 Oe and at temperatures down to 2K. Experimental details about sample grows and measurement techniques may be found in [10,11].

Magnetic losses in Fe/Cr multilayers

The main part in Figure 1 expands the low field dependence of the imaginary (in semi- logarithmic scale) contribution of the magnetic susceptibility in $[Fe(30Å/Cr(13Å)]_{10}$ MML measured at 300, 20 and 5K. Detailed comparison of the real and imaginary response may be found in [10]. At high temperatures (T>100K), independently of the applied ac drive field (acdf =2-8 Oe), both real (χ') and imaginary (χ'') contributions to magnetic susceptibility show hysteretic dependence on the magnetic field with the maxima of the losses at H < 30 Oe. The observed maxima can be naturally explained by the formation of small-scale magnetic

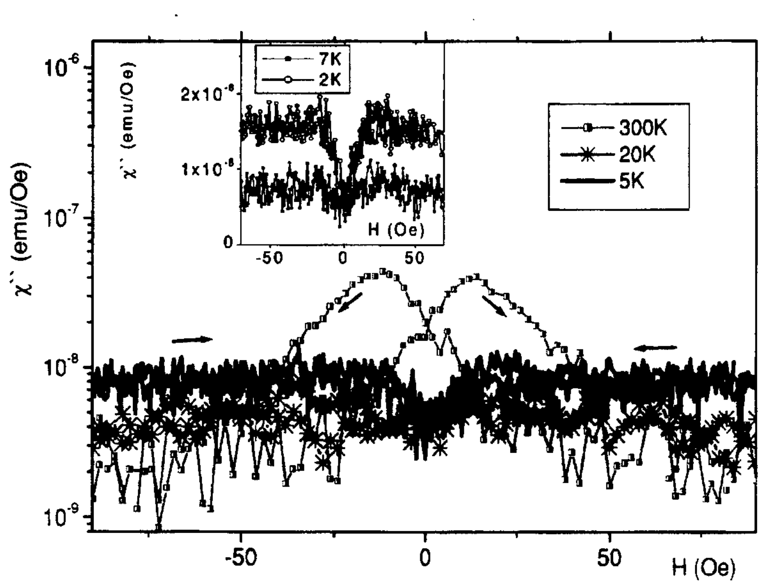

Figure 1. Imaginary contributions to the magnetic susceptibility of a [Fe(30Å/Cr(13 Å)]$_{10}$ multilayer measured at 987 Hz with acdf=4 Oe and at 3 different temperatures. The insert shows the out of phase contributions to the magnetic susceptibility of [Fe(30Å/Cr(13 Å)]$_{10}$ multilayer measured at 987 Hz with acdf=4 Oe and at temperatures 2 and 7K. Orientation of the magnetic field is along (110).

structures repeatedly observed in MML. Presence of the domain structure for the same sample was demonstrated by using magnetic force microscopy [11,12].

More interesting is the dependence of the losses on temperature variations. We refer here to the hysteretic maximum in losses in low magnetic fields. Lowering the temperature from 300K to about 10K, the losses show weak maximum at about 250K and then strongly decrease below about 100K (see Figure 1). Below 10K we do not observe any hysteretic maximum. Interestingly, at lower temperatures the losses begin to increase (see inset). The losses at fixed field and 5K are higher than at corresponding losses 300K (beyond the maxima observed at the latter temperature). At 2K they are even higher. The character of the dependence of the losses on the magnetic field changes as well. One more remarkable feature is an appearance at lower temperatures (T<7K) of a minimum in the magnetic losses at H=0 (see inset to Figure 1). The frequency dependence of χ'' proves to be very surprising. We studied the frequency dependence of χ'' at T=2K and T=10K. At higher temperatures the out-of-phase susceptibility is too small to investigate its frequency dependence. The main surprise is that it exhibits a well pronounced frequency dependence at T=2K (H=50Oe) and this dependence may be reasonably fitted by the single relaxation time formula $\chi'' = \chi_0\omega\tau/[1+(\omega\tau)^2]$ with $\tau \approx 2.5 \cdot 10^{-4}$ s (see Fig.2).

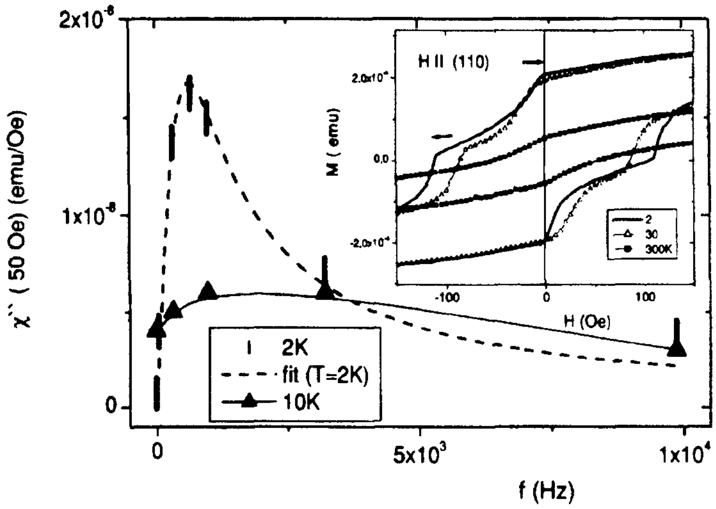

Fig.2 Frequency dependence of the dissipation at small nonzero magnetic field (H=50 Oe) at temperatures T=2K and 10 K. The dashed line represents the fit described in the main text. Inset: magnetization vs. magnetic field for magnetic field along (110). Arrows show direction of the displacement of 2 kinks when temperatures are lowered.

One normally expects the response of domain structures to be characterized by a broad distribution of the relaxation times with χ'' almost independent of frequency. This seems to be the case for higher temperatures: the frequency dependence of χ'' at T=10K is nearly nonexistent with a much broader maximum shifted to higher frequencies. Note that in the frequency range studied the real part of the susceptibility is, within a margin of 20 percent, independent of f when the frequency is varied between 3Hz and 9876 Hz. Dependence of χ'' on the magnetic field may be explained by the model of a single relaxation time [10].

In order to investigate the relationship between the observed effects and the degree of antiferromagnetic coupling, we measured χ' and χ'' for the samples with different GMR between 16% and 220% [10]. We found that low temperature dependences χ'' are now somewhat different. While the Fe/Cr sample with a record magnetoresistance (220 %) among MMLs shows a behaviour similar to that presented in Figures 1-2 for samples with GMR above 60%, the low frequency magnetic response of weakly coupled Fe layers in non epitaxial $[Fe/Cr]_{10}$ MML with enhanced interface roughness and small magnetoresistance is large for both the real and imaginary parts and shows strong hysteresis in χ'' down to 2K, but not the specific features we found in epitaxial antiferromagnetically coupled MMLs with GMR above 60 %.

The static magnetic properties of $[Fe/Cr(100)]_{10}$ multilayers are also unusual (see inset to Fig. 2). For the magnetic field directed along easy axis (100), the DC magnetization shows hysteresis which is typical for system with magnetization change due to thermally induced formation and propagation of domain walls, i.e. coercive field which increases as temperature decreases (not shown here). However, when the magnetic field is directed along the hard axis, we clearly observe the presence of two coercive fields (inset to Fig. 2). The first one at small fields (below 25 Oe) decreases when temperature is lowered. That is opposite to what is expected for thermally activated DW depinning). The second coercive field (of about 100 Oe) behaves in a usual way. The low field kink, which sharpens and moves to the zero magnetic field at lower temperatures, may be related to zero field "dip" in magnetic losses observed below 10K.

What could be the reason behind such unusual behavior of the losses at low temperatures? Part of the temperature evolution of the dependences χ'' (H) might be due to the evolution of the domain structure which remains basically unknown for low temperatures. However, the changes are too drastic to be accounted for by a variation of the domain structure alone. It is, of course, rather surprising, that the one relaxation time model describes the main important features of the out of phase response in a multidomain system. What is the meaning of these nearly identical relaxators? It is tempting to relate the decrease in the relaxation time to tunnelling processes which provoke a "chain" or a "shock wave" of other processes thus leading to a rapid relaxation [13]. But, of course, one has first to understand why the distribution of the relaxation times becomes so narrow at low temperatures.

Low temperature magnetoresistance

Let us turn to low field-low temperature electron transport in Fe/Cr(001) multilayers at low temperatures. While our MFM measurements reveal a similar domain structure at room [12] and helium temperatures [11], the corresponding magnetoresistance curves, as shown in Fig. 3, are very different. The strongly low field magnetoresistance is observed in temperature range corresponding to enhanced

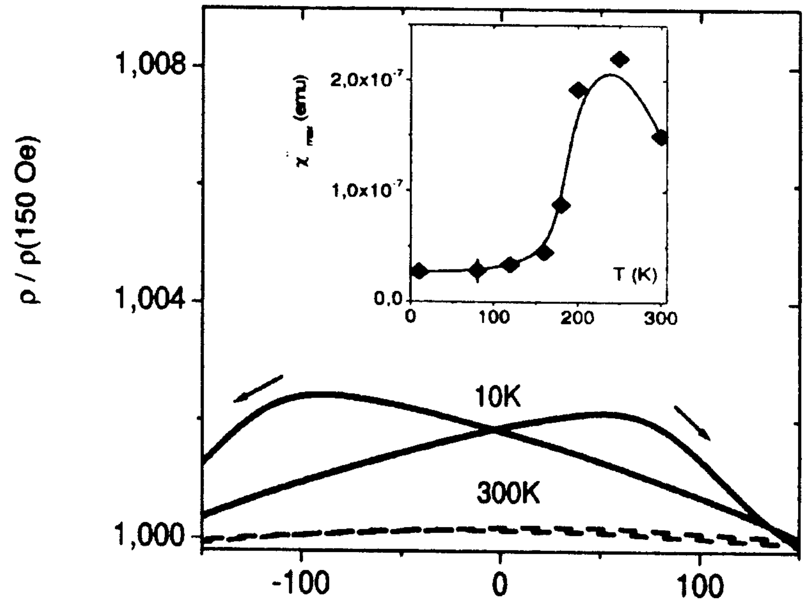

Fig. 3 Low field magnetoresistance and dependence of low field maxima in losses on temperature (inset).

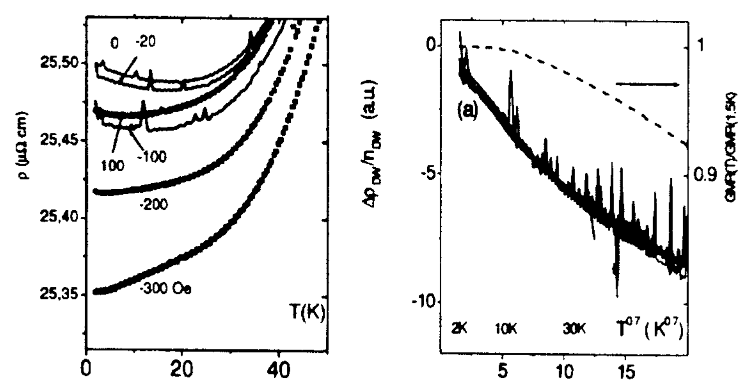

Fig.4 (a) Temperature dependences of the resistivity of $[Fe/Cr]_{10}$ multilayer at different small applied magnetic fields along the hard axis. (b) Scaling of the DW contribution to resistivity normalized by the effective DW concentration plotted as a function of $T^{0.7}$. Dotted line presents temperature scaling of the normalized GMR.

DWs pinning (see inset to Fig. 3 which shows dependence of low field maximum in losses on temperature).

Figure 4a shows the temperature dependence of the electrical resistivity ρ for an $[Fe(12\ Å)/Cr(12\ Å)]_{10}$ MML for different magnetic fields (H< 300 Oe). The magnetic field is applied in the plane of the film and is parallel to the current as well as to the longer side of the rectangular (5*25 μm^2) sample which is directed along the (110) axis. We determine the magnetoresistivity of the DWs by subtracting the temperature dependences of the resistivity measured in the presence and in the absence of DWs, respectively. In order to separate the magnetoresistivity induced by the GMR effect from the magnetoresistivity induced by the DWs, we define $\rho_{DW} = \rho(T,H) - \rho(T,H_S)$ with $|H_S| < 300$ Oe, where H_s is estimated field above which appear the changes in the angle between magnetic moments of the layers. We find that, in contrast to the GMR, the DW magnetoresistivity is strongly temperature dependent with no signal of saturation at low temperatures. Assuming that the magnetic field mainly changes the effective DW concentration n_{DW}, we expect $\Delta\rho_{DW}$ to scale according to $\Delta\rho_{DW} = \rho_{DW}(0) - \rho_{DW}(T) \propto n_{DW}\, \rho^0_{DW}(T)$ with $\rho^0_{DW}(T)$ a function describing the temperature dependent electron interaction with DWs. Our data analysis reveals that the DW resistivity is roughly given by $\Delta\rho_{DW} \propto n_{DW}\, T^{0.7}$ (Fig.4b) as long as $H_S < 300$ Oe. We have also demonstrated that neither the AMR, which depends on the relative orientation of the magnetization and the current I, nor the ordinary magnetoresistivity (caused by the Lorentz force), which depends on the relative orientation of I and the magnetic induction B, contribute to $\Delta\rho_{DW}(T)$ [11].

We have studied the low temperature scaling in DW magnetoresistivity for

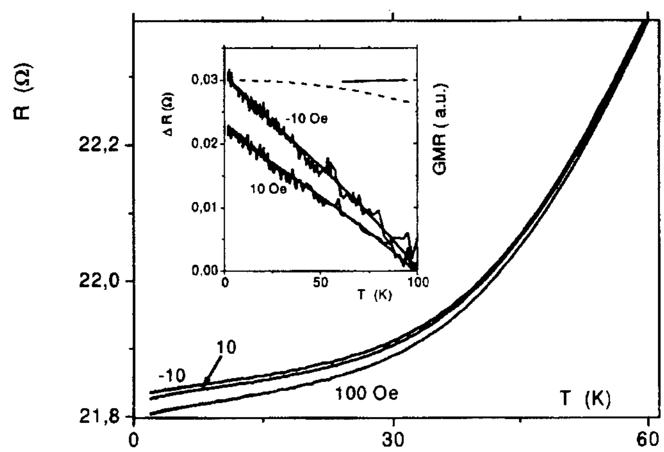

Fig.5 Temperature dependence of the resistance of $[Fe/Cr(100)]_{10}$ in three small applied fields which does not show any saturation to the lowest temperature. Inset shows the corresponding magnetoresistance. Solid lines correspond to fits within theory which takes into account suppression of weak anti-localization effect by DWs [11]. Dashed line estimates GMR.

three other AF coupled Fe/Cr samples with an Fe layer thickness of 9, 22 and 30Å, respectively, and found that $\Delta\rho_{DW}$ follows approximately $\Delta\rho_{DW} \propto T^{\alpha}$ scaling behaviour with exponent α gradually increasing from 0.7 to about 1 with Fe thickness. This may reflect a change of the exponent (p) in the temperature dependence of the phase breaking time $\tau \propto T^{p/2}$ which should occur between "dirty" (p=3/2) and " clean" (p=2) limits [14]. Fig. 5 shows low temperature low field resistance and magnetoresistance in $[Fe/Cr(100)]_{10}$ multilayer when magnetoresistance varies almost linearly with temperature down to 1.9K.

In order to explain the strong variation of the DW magnetoresistivity at low temperatures, one can not use the ballistic approach and has to go beyond the classical theories [7]. A possibility is to link the observed phenomena either to standard, disorder related, weak localization effects or to scattering by isolated spins. Our experimental results are in conflict with both scenarios. Both [8] and [9] predict a destruction of weak electron localization by the domain walls, although the details of the destruction mechanism are different. Direct application of these models results in a sign of the DW magnetoresistivity, which is opposite to the sign of the experimentally observed magnetoresistance. However, the sign of the localization correction may be reversed due to strong spin-orbit (SO) scattering (anti-localization) [15]. Our measurements are consistent with an anti-localization effect in the absence of DWs (H>300 Oe), which is suppressed in the presence of DWs (H=0). The fit of experimental data to this model shows that the effective DW width L_{DW} becomes about 2.5 times larger when the magnetic field is increased from 0 to 200 Oe [11].

Conclusions

In conclusion, we have shown that the out of phase low frequency magnetic response in antiferromagnetically coupled Fe/Cr multilayers is strongly dependent on temperature, magnetic field and, at very low temperatures, on frequency. At T=2K and H=50 Oe the frequency dependence of the losses can be satisfactorily described within a single relaxation time scheme. At temperatures below 7K and for the *ac* drive frequencies f ~10^2-10^3 Hz we observed a dip in the magnetic field dependence of losses for fields H<10-15 Oe. The dependence of χ'' on the magnetic field as well as unusual dependence of one of coercive fields (small one) can be interpreted as the field dependence of the relaxation time which increases by an order of magnitude as the field changes from H=50 Oe to zero. The strong magnetic field dependence of the relaxation time at low temperatures might imply an involvement of quantum tunnelling phenomena. At low temperatures, when domain walls are strongly pinned, we observed strongly enhanced magnetoresistance. Temperature scaling of the magnetoresistance indicates possible suppression of quantum transport (weak antilocalization) by the domain walls at low temperatures.

Asknowledgements

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