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Low-frequency response in the magnetic susceptibility of antiferromagnetically coupled Fe/Cr multilayers

F.G. Aliev[a,]*, J.L. Martinez[b], V.V. Moshchalkov[c], Y. Bruynseraede[c], A.P. Levanuyk[a], R. Villar[a]

[a] *Dept. de Fisica Materia Condensada, Instituto de Ciencia de Materiales "Nicolas Cabrera", Universidad Autonoma de Madrid, C-III, 28049, Madrid, Spain*
[b] *ICMM-CSIC, Cantoblanco, 28049, Madrid Spain*
[c] *Laboratorium voor Vaste-Stoffysica en Magnetisme, K.U.Leuven, Belgium*

Abstract

The magnetic field and temperature dependence of the low-frequency ($f < 10^4$ Hz) in- and out-of-phase magnetic response of antiferromagnetically coupled Fe/Cr(1 0 0) shows that at $T > 100$ K both the real (χ') and imaginary (χ'') parts of the susceptibility exhibit hysteretic dependence on the magnetic field with maxima of $\chi''(H)$ at $H \approx \pm 25$ Oe. At $T = 2$ K the losses exhibit an unusual strong frequency dependence describable within a single relaxation time scheme. The corresponding relaxation time proves to be strongly field-dependent which could be related to some quantum tunneling processes at low temperatures. © 2001 Published by Elsevier Science B.V.

Keywords: Multilayers; Susceptibility-AC; Domain wall dynamics; Relaxation

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A great deal of the known dynamical properties of antiferromagnetically coupled MML is related to the high-frequency (GHz) range. The only data on the low-frequency response of MML we were able to find are those of Ref. [1] where the real (χ') and the imaginary (χ'') parts of the magnetic susceptibility of a superlattice Fe/Cr(2 1 1) were measured at a frequency $f = 10^3$ Hz and at a non-specified temperature. The epitaxial $[\mathrm{Fe/Cr}]_n$ ($n = 10$) multilayer is deposited in a MBE system on MgO(0 0 1) substrates held at a temperature of 50°C. Details of sample preparation and characterization have been published before [2]. We measured both the real χ' and the imaginary χ'' parts of the magnetic susceptibility defined as $M(\omega)/H(\omega)$ (here $H(\omega)$ is an AC driving field (ACDF) and $M(\omega)$ is the corresponding magnetic response) by using Physical (at frequencies $3\,\mathrm{Hz} < f < 167\,\mathrm{Hz}$) and Magnetic ($77\,\mathrm{Hz} < f < 9876\,\mathrm{Hz}$) Property Measurement Systems (Quantum Design).

The magnetic field dependence of the real and imaginary (in logarithmic scale) contributions of the magnetic susceptibility in $[\mathrm{Fe}(30\,\text{Å}/\mathrm{Cr}(13\,\text{Å})]_{10}$ MML measured at 300, 20 and 5 K is shown in Fig. 1a and b. At high temperatures ($T > 100$ K), independently of the applied ACDF (2–8 Oe) , both $\chi'(H)$ and $\chi''(H)$ show hysteretic dependence on the magnetic field with the maxima of the losses at $H \simeq \pm(20-30)$ Oe. Lowering the temperature from 300 K to about 10 K, the losses somewhat decrease. At lower temperatures the losses (in finite small field) begin to *increase*. If the ACDF does not exceed some critical value ($\leqslant 4$ Oe), the hysteretic dependence of the losses on the magnetic field gradually disappears below approximately 50K. One more remarkable feature is an appearance at lower temperatures ($T < 7$ K) of a minimum in the magnetic losses at $H = 0$ (see Fig. 1b).

We studied the frequency dependence of χ'' at $T = 2$ and 10 K (Fig. 2). At higher temperatures, the out-of-phase susceptibility is too small to study its frequency dependence. The main surprise is that it exhibits a well-pronounced frequency dependence at $T = 2$ K

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*Tel.: +34-13-974756; fax: +34-91- 3974744.
E-mail address: farkhad.aliev@uam.es (F.G. Aliev).

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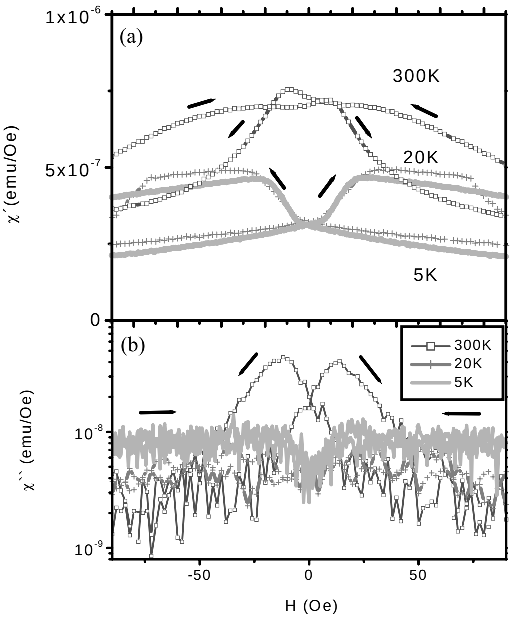

Fig. 1. Real (part a) and imaginary (part b) contributions to the magnetic susceptibility of $[\mathrm{Fe}(30\,\mathring{A}/\mathrm{Cr}(13\,\mathring{A})]_{10}$ multilayer measured at 987 Hz with ACDF = 4 Oe and at different temperatures between 300 K and 5 K.

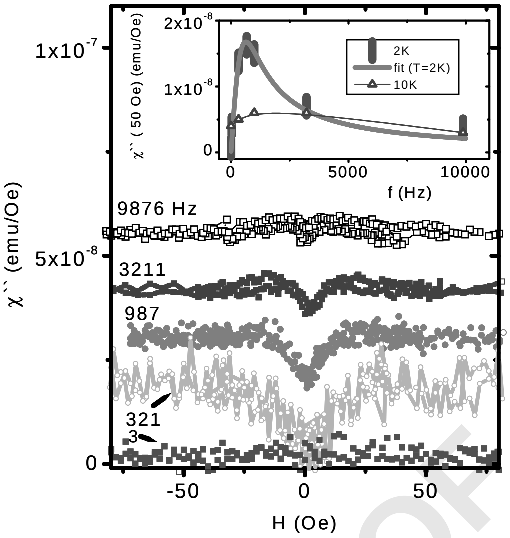

Fig. 2. Imaginary contributions to the magnetic susceptibility of $[\mathrm{Fe}(30\,\mathring{A}/\mathrm{Cr}(13\,\mathring{A})]_{10}$ multilayer measured at five different frequencies with ACDF = 4 Oe at 2 K. For clarity, the curves χ"(*H*) obtained for 987, 3211 and 9876 Hz are shifted upwards correspondingly on $1.5\times10^{-8}, 3\times10^{-8}$ and 5×10^{-8} emu/Oe. The inset shows the frequency dependence of the dissipation at small non-zero magnetic field ($H = 50$ Oe) at temperature $T = 2$ and 10 K. The bold solid line represents fit described in the main text.

($H = 50$ Oe) and this dependence may be reasonably fitted by the single relaxation time formula $\chi'' = \chi_0\omega\tau/1+(\omega\tau)^2$ with $\tau \simeq 2.5\times10^{-4}$ s (see inset in Fig. 2). Let us recall that one expects that the response of domain structures is 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 $T = 10$ K is nearly absent with a much broader maximum shifted to higher frequencies. Note that in the studied frequency range the real part of the susceptibility is within 20% independent on f when frequency is changed between 3 and 9876 Hz.

Fig. 2 shows $\chi''(H)$ measured at five different frequencies between 3 and 9876 Hz. One sees a non-trivial behavior of χ'' at low fields: a well defined minimum in $\chi''(H)$ at $H = 0$ for $f = 321$ and 987 Hz, a more narrow minimum flanked by two symmetric maxima for $f = 3211$ Hz and a similar behavior but less pronounced and with an even narrower minimum for $f = 9876$ Hz. All these curves can be qualitatively explained if one supposes that the above relaxation time decreases as H diminishes and $\tau(H = 0)$ is less than $\tau(H = 50\,\mathrm{Oe})$ by about an order of magnitude. Indeed, as τ decreases the maximum of the curve in the inset of Fig. 2 shifts to the right. One sees that the points corresponding to $f = 321$ Hz, 987 Hz move away from the maximum. The point corresponding to $f = 3211$ Hz first approaches the maximum (and χ'' increases) and then moves away from the maximum (and χ'' decreases). The same happens with the point corresponding to $f = 9876$ Hz but, of course, it passes the maximum later, at a smaller field. We see that the model of a single relaxation time allows to explain the dependence $\chi''(H)$ as well.

The observed temperature evolution of the dependencies $\chi'(H)$ and $\chi''(H)$ might in part be due to evolution of the domain structure which remains basically unknown for low temperatures. However, the changes are too drastic to be accounted for by an evolution of the domain structure alone. It is tempting to relate the decrease of the relaxation time to tunneling processes which provoke a "chain" or a "shock wave" of other processes leading to a rapid relaxation. An enlightening discussion of such a possibility was given in Ref. [3]. But, of course, one has first to understand why the distribution of the relaxation times becomes so narrow at low temperatures.

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. Magnetic losses at a non-zero (and fairly low) magnetic field first decrease but then *increase* with lowering of the temperature. At temperatures below 7 K and for the AC drive frequencies $f \sim 10^2 - 10^3$ Hz we observed a dip in the magnetic field dependence of losses for fields $H < (10-15)$ Oe. At $T = 2$ K and $H = 50$ Oe the frequency dependence of the losses can be satisfactorily described within a single relaxation time scheme. The dependence of χ'' on the magnetic field can be interpreted as the field dependence of the relaxation time which increases by an order of magnitude at the field changes from $H = 50$ Oe to zero. We believe that these data suggest an important role of quantum tunneling in the temporal evolution of magnetization in antiferromagnetically coupled multilayers.

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