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Christian Binek
University of Nebraska-Lincoln, cbinek2@unl.edu

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Superferromagnetic domain state dynamics in discontinuous $CoFe/Al_2O_3$ multilayers

O. Petracic[a,*], X. Chen[a], O. Sichelschmidt[a], Ch. Binek[a], W. Kleemann[a], A. Glatz[b], T. Nattermann[b], S. Cardoso[c], P.P. Freitas[c]

[a] *Angewandte Physik, Universität Duisburg-Essen, Loathasstrasse 1, 47048 Duisburg, Germany*
[b] *Institut für Theoretische Physik, Universität zu Köln, Köln 50937, Germany*
[c] *INESC, Rua Alves Redol 9-1, Lisbon 1000, Portugal*

Abstract

Magnetization hysteresis and AC susceptibility measurements were performed on the discontinuous metal–insulator multilayer $[Co_{80}Fe_{20}(1.4\,nm)/Al_2O_3(3\,nm)]_{10}$. CoFe forms ferromagnetic single-domain particles being embedded in the Al_2O_3 matrix. Due to strong dipolar inter-particle interactions a "superferromagnetic" correlation of particle moments was previously stated. The dynamical magnetic properties of the superferromagnet can be understood in the framework of domain wall motion in an impure ferromagnet. Kinetic simulations are employed, which are based on field and temperature-dependent domain wall velocities. The magnetization hysteresis as well as the AC susceptibility, $\chi'-i\chi''$, are calculated and compared to our experimental results and yield a good agreement. The analysis of the Cole–Cole plots, χ'' vs. χ', is particularly interesting. They are shown to serve as fingerprints for the different dynamic behavior as claimed previously.
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Assemblies of single-domain nanoparticles show very different types of magnetic behavior depending on the interparticle distances. In recent years much experimental and theoretical effort was invested to understand and clarify the possible consequences of interactions [1]. In this paper we will focus on the case of a densely packed system of single domain nanoparticles, where relatively strong ("super"-)ferromagnetic (SFM) correlations *between* the individual superspins are encountered. In a previous work [2] the dynamical response of this sample could successfully be compared to the predictions of a model of domain wall motion in a disordered ferromagnet [3]. This brief report will show a comparison of experimental results on the SFM granular multilayer and kinetic simulations of a driven domain wall.

Experiments were performed on the discontinuous metal–insulator multilayer $[Co_{80}Fe_{20}(t_n)/Al_2O_3(3\,nm)]_{10}$, with nominal thickness $t_n = 1.4\,nm$. The sample was prepared by sequential Xe ion beam sputtering on glass. Transmission electron microcraphs on a similar system with $t_n = 1.3\,nm$ reveal separated and nearly spherical nanoparticles with an average diameter of approximately 5 nm [4]. Magnetization hysteresis and AC susceptibility measurements were performed by means of a commercial superconducting quantum interference device (SQUID) magnetometer (MPMS-5S, Quantum Design). Dynamic hysteresis curves were measured by using the longitudinal magneto-optic Kerr effect (L-MOKE).

Fig. 1 shows (a) a SQUID-magnetization loop M vs. H at $T = 310\,K$ resembling typical loops of a soft ferromagnet. The loop area strongly depends on the

*Corresponding author. Tel.: +49-203-379-2939; fax: +49-203-379-1965.
E-mail address: petracic@kleemann.uni-duisburg.de (O. Petracic).

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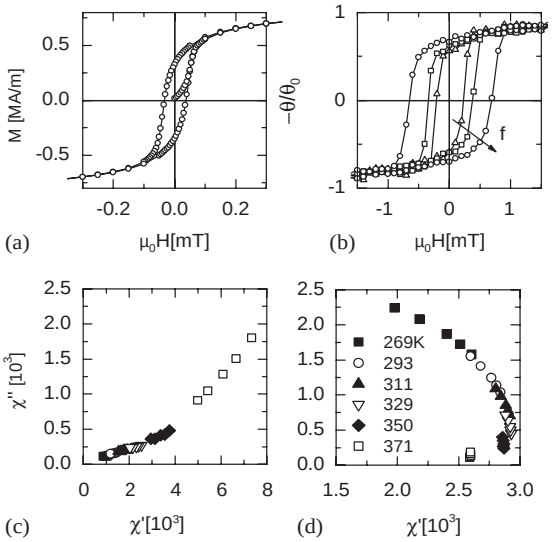

Fig. 1. Hysteresis loops of $[Co_{80}Fe_{20}(1.4\,nm)/Al_2O_3(3\,nm)]_{10}$ measured by (a) SQUID, M vs. H at $T = 310\,K$, (b) normalized MOKE curves, $-\theta/\theta_0$ vs. H at $T = 294\,K$ and different field sweep frequencies $f = 1, 5$ and $20\,Hz$. Cole–Cole plots, χ'' vs. χ', for an AC field amplitude (c) $\mu_0 H_0 = 5\,\mu T$ and (d) $200\,\mu T$ at temperatures $T = 269-371\,K$ and AC frequencies $f = 0.05-1\,Hz$.

driving field frequency as seen in (b), where normalized L-MOKE curves, $-\theta/\theta_0$ vs. H at $T = 294\,K$ and different field sweep frequencies $f = 1, 5$ and $20\,Hz$ are shown [2]. The occurrence of hysteresis loops is not a proof for a SFM state, since a superparamagnetic system can display them as well. However, Cole–Cole plots of the complex susceptibility, χ'' vs. χ', show fingerprints of SFM domain wall dynamics. This can be seen in Figs. 1 (c and d) for AC field amplitudes $\mu_0 H_0 = 5$ and $200\,\mu T$, respectively, at different temperatures $T = 269-371\,K$ and AC frequencies $f = 0.05-1\,Hz$. Two important features are encountered. In (c) a monotonic increase of χ'' is seen, starting linearly and bending up to larger slopes as χ' increases, whereas in (d) a quarter of a circle is visible. As described previously [2] the linear parts are the consequence of a creep-like domain wall motion in the non-switching limit, while the quarter circle describes the SFM switching regime, where monodisperse Debye-type relaxation behavior is found.

Two types of kinetic simulations were performed. In the first case one rigid domain wall with a quasistatic temperature and field-dependent velocity $v = v(T, H)$ according to Ref. [3] was considered. The formula for $v(T, H)$ interpolates between the creep regime for small fields, $v(T, H) \propto \exp[-(U_c/T)(H/H_c)^{-\mu}]$, and viscous domain wall motion for large fields, $v(T, H) \propto H$. It follows that the magnetization can be written as $M = 2Z(H)/L - 1$ and $dZ/dt = v(H(t))$, where $Z(H)$ is the position of the domain wall and L the sample length with $0 \leqslant Z \leqslant L$. In the second case an equation of motion of an elastic domain boundary moving in a random distribution of pinning forces driven by an external field is solved numerically [5].

Fig. 2 shows the results of simulations of the first (b,d) and of the second type (a,c), with upper plots showing magnetization M vs. H curves. (a) A hysteresis loop at $H_0/H_p = 1.9$ and $f = 0.002$ reveals the expected switching behavior in a ferromagnet and (b) the AC field frequency dependence of hysteresis curves at $T/T_p = 1.5$ and $H_0/H_p = 1.5$ (H_p depinning field, T_p characteristic energy scale [3]) and different frequencies $f = 0.001$, 0.005 and 0.01 resembling the curves in Fig. 1b.

The Cole–Cole plots are particularly interesting. The first type of simulation easily produces the quarter circle corresponding to domain switching (Fig. 2d), whereas the monotonic increase in the low-χ'' and low-χ' limit (high-f limit) can only be seen in the second type of simulation (Fig. 2c) [5]. The concave curve qualitatively matches that from Fig. 1c.

In summary, kinetic simulations of the domain wall motion under random pinning forces in a periodic external field can qualitatively describe essential features of the experimental observations on superferromagnetic discontinuous magnetic multilayers.

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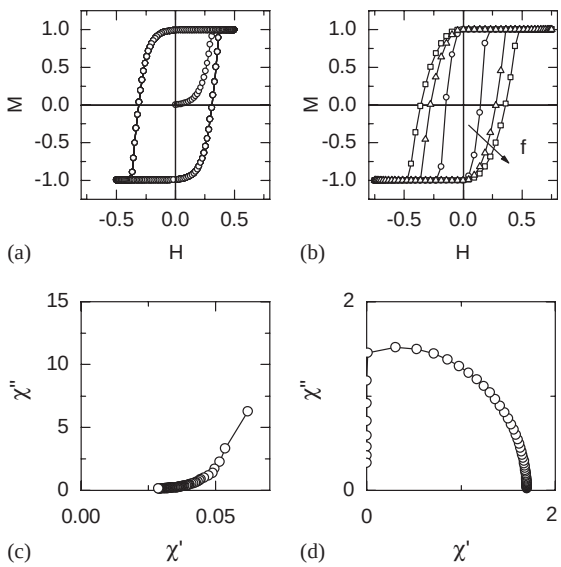

Fig. 2. (a) Hysteresis curve, M vs. H, from the second type of simulation for an AC amplitude $H_0/H_p = 1.9$ and a frequency $f = 0.002$, (b) M vs. H curves from the first type of simulation (see text) at $T/T_p = 1.5$ and $H_0/H_p = 1.5$ and $f = 0.001$, 0.005 and 0.01. (c) Cole–Cole plot from the second type of simulation with $H_0/H_p = 1.9$ and different frequencies and (d) from the first type of simulation with $T/T_p = 1.5$ and $H_0/H_p = 1.5$.

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