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Magnetic behavior of partially exchange-coupled particles

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Abstract

A system of particle pairs with partial exchange coupling is studied, considering identical particles and a fixed angle between their anisotropy axes. The energy of each pair is calculated in terms of the extent of interaction, β, as a function of the applied demagnetizing field. Using the probability per unit time for the inversion of magnetization, the coercive field H_c and the viscosity S of the system are calculated. An unexpected result is that fully coupled particles are more stable against temperature than the uncoupled particles.

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1. Introduction

The long-term stability of magnetic memory media depends crucially on the size of the magnetic units used to store information. This is because the thermal stability of the magnetic units is governed by the energy landscape connecting metastable equilibrium states.

An ideal magnetic memory medium should have the highest coercivity H_c compatible with the materials used to store and read the information. This may be obtained using single-phase hard magnetic systems of nanosized uncoupled particles. If they are strongly coupled the coercivity is significantly reduced while the remanence M_R is enhanced [1]. The long-term stability is linked to the magnetic viscosity because it degrades the magnetization, driving the highly metastable magnetic system towards the state of minimum energy.

Computational micromagnetics was used as a tool to model the magnetic behavior of nanosized

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particles both at 0 K [2] and at finite temperatures to study the thermally activated magnetization reversal [3–5] and some predictions were made about thermal reversal fields and activation volume. In a previous work the energy landscape of partially exchange-coupled particles was studied analytically in a two-particle system considering in detail the magnetic structure in the exchange-coupled region [6]. In a second paper the energy landscape at 0 K was used to study how the magnetization reversal (the switching field, H_{sw}) is affected by exchange interactions between nano-sized particles and to study the transition from non-cooperative to cooperative magnetization reversal [7]. In these papers coherent rotation was assumed as the mechanism for magnetization reversal. In the present work the coercivity and magnetic viscosity of partially exchange-coupled particles is studied as a function of temperature and time. The analytical approach was preferred in order to follow some details of the coercivity vs. temperature effects in these exchange-coupled systems.

2. Model

The system under study is composed of an ensemble of identical two-particle units, each with partial exchange coupling. It is assumed that the particles are disc-shaped with volume $V = 1.414 \times 10^{-23}\,\mathrm{m}^3$ and anisotropy constant $K_1 = 2.5 \times 10^5\,\mathrm{J\,m^{-3}}$ and that exchange coupling occurs through one of their plane faces, extending up to 5 l_K ($l_K = (A/K_1)^{1/2}$) into each particle, where A is the exchange constant. Spin reorientation across the contact plane occurs and is similar to that of a Bloch wall [8]. The extent of coupling is denoted by β, the particle volume fraction affected by exchange coupling. Also β could be the particle surface fraction affected by coupling if particles with equal volume are compared.

In Refs. [6,7] the total energy E_T of the system as function of β and the applied magnetic field H are calculated and the respective equilibrium angular positions θ and θ_2 of particles 1 and 2, are obtained. It is assumed that particle 1 has its anisotropy axis well oriented along the direction of the applied field H and the anisotropy axis of particle 2 is forming an angle of 30°.

At 0 K the switching field H_{SW} of each particle is calculated as being the field at which the energy barrier separating different minima is zero. As it was shown in Ref. [7] the particles invert their magnetization independently at low β in a non-cooperative manner and for this mode coercivity decreases as β increases. At high β (>0.66) they switch cooperatively, like a fan mode, and coercivity increases as β increases.

As temperature increases above 0 K temperature and time effects start to be noticeable and the particles can invert their magnetization at fields lower than H_{SW} for 0 K. There is a finite probability for tunneling across the energy barrier separating energy minima. The probability per unit time of crossing the energy barrier is given by

$$P = f_0 \exp(-E/k_B T),$$

where f_0 is of the order of $10^9\,\mathrm{s}^{-1}$, k_B the Boltzmann's constant and T the temperature. The energy barrier E has the general form

$$E(t,\beta) = KV\left[1 - \frac{H(t)}{H_0(\beta)}\right]^{z(\beta)},$$

where $H(t)$ is the applied magnetic field that can be time dependent and $H_0(\beta)$ is the field at which the energy barrier is zero; both are measured in units of the anisotropy field H_A. Both $H_0(\beta)$ and the exponent $Z(\beta)$ are functions of the extent of coupling β.

Two experimental situations were investigated: (i) magnetic viscosity experiments and (ii) the coercivity of the system under a linear time variation of the applied field. In each case the calculation procedure is as follows: in a time interval Δt the number of particles that will invert their magnetization is $N_{\Delta t} = N_0 - N_0 \exp(-P\Delta t)$, where N_0 is the number of particles at the beginning of the interval that are still in the original magnetic state.

The magnetization at a given time t is calculated by summing up all the contributions of the $(t/\Delta t)$ time intervals. In the more general case there will be contributions from both the well-aligned and the misoriented particles. In that case the number of each kind of particles at the beginning of the interval as well as the initial and final magnetization for each kind of particles were distinguished. Those initial and final states were taken from Refs. [6,7]. The energy barriers were calculated at 0 K, considering that K_1 and A have a slow variation with temperature.

For $\beta > 0.6$ only one energy barrier has to be considered for the pair of interacting particles and is described by the following functions:

$$H_0(\beta) = 0.522 + 0.025\beta + 0.007\beta^2 + 0.033\beta^3,$$
$$Z(\beta) = 0.48 + 0.03\beta.$$

For $\beta < 0.6$ two energy barriers have to be considered, one for each particle; for the misaligned particle the same energy barrier as in the previous case, but for the well-aligned particle it is

$$H_0^{\mathrm{wa}}(\beta) = 1 - 1.040\beta + 1.280\beta^2 - 1.160\beta^3,$$
$$Z^{\mathrm{wa}}(\beta) = 3.52 - 0.32\beta + 2.98\beta^2.$$

Case (i) Magnetic viscosity experiments: The sample is saturated in the forward direction and then a demagnetizing field H is applied and is held constant for $t \geqslant 0$. In terms of the energy barrier dependence on H the magnetic viscosity is given by Ref. [9] $S = kT\chi_{\mathrm{irr}}/(-\partial E/\partial H)$ where χ_{irr} is the irreversible susceptibility.

The parameter $S_{\mathrm{V}} = S/\chi_{\mathrm{irr}}$ is directly related to the process responsible for magnetization reversal and it is useful in the investigations of magnetization reversal processes in different materials. Fig. 1 shows S_{V} as a function of the applied field H for different β values at $T = 300\,\mathrm{K}$. It can be observed in the insert that for low applied fields the viscosity parameter increases very slowly as β increases, while for higher H two tendencies are shown:increases as β increases when $\beta < 0.3$ and it decreases when β increases for $\beta > 0.3$. In all cases a maximum is observed when the applied field reaches the switching field.

Case (ii) Coercivity: The sample is first saturated and then the applied field is reduced at a constant time rate. Most interesting is the behavior of the magnetization in the second quadrant, where the sample is subjected to a demagnetizing field.

Three temperatures (15, 150 and 300 K) and three values of $\mathrm{d}H/\mathrm{d}t$ (10^{-1}, 10^{-2} and $10^{-3}\,\mathrm{s}^{-1}$) are studied. Fig. 2 shows how $\mathrm{d}M/\mathrm{d}H$ behaves at the three temperatures studied for $\mathrm{d}H/\mathrm{d}t = 10^{-1}$ and $\beta = 0.3$. It is evident how the temperature effect has broadened and shifted the peaks corresponding to the switching field of each kind of particle. At low temperatures the switching field of each type of particles is very different, similar to the behavior observed at 0 K [7]. At an intermediate temperature (150 K) the misaligned particle has a lower switching field in about 5% but the well-aligned particle has dropped its switching field in about 17%. At room temperature both kinds of particles have a very similar switching field, differing by less than 1%, and the well-aligned

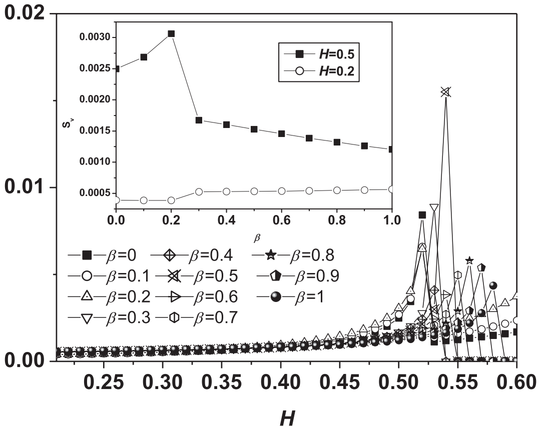

Fig. 1. Viscosity parameter S_{V} as a function of the applied field H, for different values of β, and $T = 300\,\mathrm{K}$. Insert: S_{V} as function of β for constant applied field H.

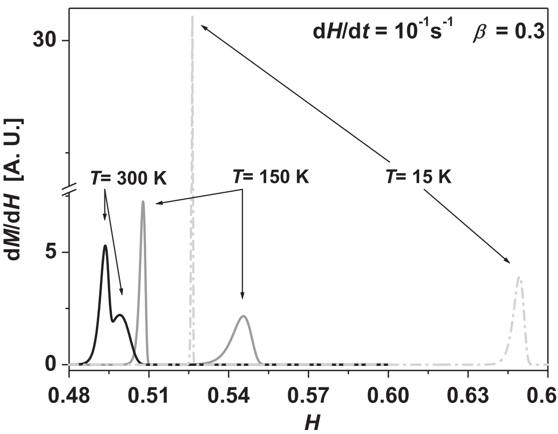

Fig. 2. Switching field distribution $\mathrm{d}M/\mathrm{d}H$ as function of the applied field H, for $\mathrm{d}H/\mathrm{d}t = 10^{-1}\,s^{-1}$ and $\beta = 0.3$.

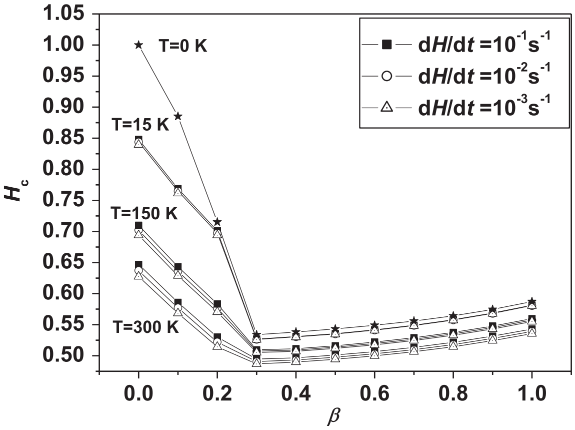

Fig. 3. Coercive field H_C as a function β, for $T = 0$, 15, 150 and 300 K and $dH/dt = 10^{-1}$, 10^{-2} and $10^{-3}\,s^{-1}$.

particle has decreased its switching field by 30% compared with the value at 15 K. Also, when the field time rate decreases the switching field of each kind of particles becomes closer to each other; the combined effect of temperature and field time rate is to compensate the differences that different particle orientations may introduce in the switching field. Fig. 3 shows how the coercive field H_C varies with β at the different field time rates mentioned before. For $\beta < 0.3$ the switching field of the two kinds of particles are different and coercivity decreases as β increases. For $\beta > 0.3$ the two particles have the same switching field and they invert their magnetization cooperatively and coercivity increase with β. This effect is due to the fact that the switching field of the well-aligned particles are more affected by temperature than the others.

3. Discussion

The decrease of S_V at high fields near H_C when β increases (Fig. 1) can be assigned to the higher interaction volume. At the limit $\beta = 1$ the interaction volume is $2V$ and S_V is the lowest. The results presented in Figs. 2 and 3 clearly show that a single peak in the dM/dH curve (the switching field distribution) can be misleading at the time of interpreting that fact as due to a single switching mode or to assign a higher volume to the inverting particles.

An interesting case arises: the viscosity decreases when the interaction volume increases at constant H near the coercive field. This means that pairs of particles with high interaction between them (having lower coercivity than non-interacting particles) are more stable under the effect of temperature. This is opposed to the general belief that interactions promote more unstable structures. The key point is that each magnetization reversal process induced by temperature involves two particles acting at once instead of one after the other and this process involves higher thermal energy. This is just the effect needed for longer storage time in magnetic recording devices. What is important is the number of magnetic units per bit, N, and interactions tends to lower N. If N becomes very low a competition of large storage time with signal to noise level will appear as exchange interactions increases.

Acknowledgments

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