Fast switching of bistable magnetic nanowires through collective spin reversal

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(Received 4 January 2005; accepted 10 June 2005; published online 9 August 2005)

The use of magnetic nanowires as memory units is made possible by the exponential divergence of the characteristic time for magnetization reversal at low temperature, but the slow relaxation makes the manipulation of the frozen magnetic states difficult. We suggest that finite-size segments can show a fast switching if collective reversal of the spins is taken into account. This mechanism gives rise at low temperatures to a scaling law for the dynamic susceptibility that has been experimentally observed for the dilute molecular chain Co(hfac)$_2$NitPhOMe. These results suggest a possible way of engineering nanowires for fast switching of the magnetization. © 2005 American Institute of Physics. [DOI: 10.1063/1.2001160]

Magnetic nanowires are currently key elements in nanosciences. They hold very high potential for applications in ultrahigh density magnetic recording, logic operation devices, micromagnetic, and spintronic sensors. From a fundamental point of view great interest has risen from recent realizations of molecular chain magnets and monoatomic arrays. To all these contexts the dynamics of magnetization reversal is highly relevant. For nanowires with finite, but smaller than exchange length, diameter and weak anisotropy, this phenomenon is governed by thermal nucleation and propagation of soliton–antisoliton pairs with a characteristic time that follows an Arrhenius law. This behavior is observed also for genuine one-dimensional (1D) systems with high anisotropy (like the systems studied in Refs. 9–12) where the reversal can be described in terms of the stochastic model proposed by Glauber in 1963 for the Ising chain. The consequent exponential divergence of the relaxation time at low temperatures warrants the possibility of employing nanowires as stable memory units, but, on the other side, makes their magnetic state difficult to manipulate. In this letter, generalizing the Glauber model, we found that the dilute 1D Ising can present a faster switching if collective reversal of finite-size segments is taken into account. This mechanism gives rise to a scaling law for the dynamical susceptibility at low temperatures which we will show to be completely reversed starting from a saturated configuration. The final condition can be reached through a sequence of single spin flips, involving an activation energy $\Delta E=4J$ for the first reversal, see Fig. 1(a), and no energy cost for further flips. The relaxation time follows the Arrhenius law with $\tau \propto \exp(4J/k_B T)$.

For a finite segment a different behavior is observed if $N \ll \xi(T)$ where $\xi(T) \propto \exp(2J/k_B T)$ is the correlation length. In fact the energy barrier is halved, i.e., $\Delta E=2J$, because an edge spin is the first to be reversed, as schematized in Fig. 1(b). The complete reversal of the magnetization is attained by the propagation of the domain wall [upper part of Fig. 1(c)], occurring at no energy cost. The probability for the domain wall to reach the other side of the segment instead of being destroyed is $1/N^{-1}$. Then $\tau^1$ is propor-

The Ising chain Hamiltonian is given by

$$ H = -J \sum_{i=1}^{N-1} S_i S_{i+1} \quad (S_i = \pm 1), $$

with exchange interaction $J$, while $N$ is the number of spins. Let us consider the average time, $\tau$, the magnetization takes to be completely reversed starting from a saturated configuration. The final condition can be reached through a sequence of single spin flips, involving an activation energy $\Delta E=4J$ for the first reversal, see Fig. 1(a), and no energy cost for further flips. The relaxation time follows the Arrhenius law with $\tau \propto \exp(4J/k_B T)$.

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![FIG. 1. (Color online). Possible processes for the magnetization reversal. Activation energy for the reversing process starting from a bulk spin (a) or an edge spin (b). At low temperature the reversal process occurs through creation and propagation of a domain wall or by collective overturning of all the spins of a segment (c).](image-url)

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Nanostructured materials usually present a narrow distribution of diamagnetic inclusions with a random distribution giving a bulk crystals of 1D materials where the chains are broken by an alternative mechanism, the collective reversal of all spins. A possible alternative is the investigation of bulk crystals of 1D materials where the chains are broken by a random distribution giving a collection of independent segments of different lengths. Being $c$ the concentration of nonmagnetic impurities, the probability to have a segment of $N$ spins depends on $N$ as $(1-c)^N$. In this way the average segment length is $N_{av}=1/c$.

The ac susceptibility $\chi(\omega,T)$ of the doped sample is obtained by averaging over all the lengths:

$$\chi(\omega,T) = \frac{1}{Z_c} \sum_{N=1}^{\infty} \frac{\chi_N(T)}{1-i\omega\tau_N}(1-c)^N,$$

where $Z_c$ is a normalizing factor, $\omega$ is the frequency, and $\chi_N(T)$ is the static susceptibility of a segment of length $N^{18}$ and $(1-c)^N$ its statistical weight.

In the Fig. 2(a) we show the product of $T$ and the real part $\chi'$ of the susceptibility defined in Eq. (3), computed for different $\omega$ with $c=5\%$. The curves change dramatically at low $T$ depending on the inclusion of the collective reversal mechanism in Eq. (2) for $\tau$. A segment of a certain length $N$ contributes to the susceptibility only if it is able to follow the oscillating field, i.e., $\omega\tau_N<1$, while for $\omega\tau_N>1$ its contribution to the susceptibility becomes negligible. Thus the susceptibility computed without including the collective reversal channel for relaxation drops to zero below the freezing temperature, $T_f$, as shown in Fig. 2(a).

The possibility of a collective reversal with probability $q$ induces a nonzero susceptibility for $T<T_f$; the segments that can now follow the field are those shorter than $N$ defined by equation $q^N=\omega\Delta t$. The net effect is thus to introduce a frequency dependent cutoff in Eq. (3). In the low $T$ limit a segment of length $N$ responds to an applied field as a whole ($N\ll \xi(T)$) and the isothermal susceptibility $\chi_{is}$ below $T_f$ will be proportional to $N^2/T$. If $q$ is $T$ independent, and as the case of tunneling, $\chi'T$ tends to a plateau at low $T$ [Fig. 2(a)]. The height of the plateau is given by the finite sum

$$\chi'T = \frac{\mu^2}{k_BT} \frac{1}{Z_c} \sum_{N=1}^{\tilde{N}} N^2(1-c)^N,$$

performed over all the nonfrozen chains at the given $\omega$, where $\mu$ is the effective magnetic moment of the isolated center. In case of $q=\exp(-\omega/k_BT)$ the cutoff $\tilde{N}$ will become $T$ independent, leading to a characteristic polynomial behavior of the product $\chi'T$ for $T<T_f$. Therefore the low $T$ behavior of the product $\chi'T$ can provide a simple but powerful tool to recognize the mechanism driving the relaxation of randomly dilute Ising chains.

When the collective reversal is thermally activated the $\chi'T$ behavior is characterized by a scaling law; in fact, the cutoff in formula (4) is given by:

$$\tilde{N} = -\log(\omega\Delta t)/k_BT,$$

As a consequence for a given concentration of impurities $c$, the product $\chi'T$ obtained for different $\omega$ must rescale, i.e., if plotted versus the scaling variable $-\log(\omega\Delta t)/k_BT$, independently of the value of $\omega$.

In Figs. 2(b) and 2(c) we report for comparison our experimental data obtained for the slow relaxing molecular Ising chain CoPhOMe. In this system the Co$^{2+}$ ions experience a strong orbital contribution due to the degenerate configuration of $d$ state in octahedral environment. The even lower symmetry encountered in CoPhOMe stabilizes a ground doublet with strong Ising type anisotropy, $g_z=9$ and $g_x=g_y=0$.19

Finite size effects have been investigated by doping CoPhOMe with nonmagnetic Zn$^{2+}$ ions and the results confirmed that for the pure compound the $N\ll \xi(T)$ regime of Fig. 1(b) is also attained.20 The activation energy for the magnetization reversal has been found to be $\Delta E\approx 160$ K, in acceptable agreement with the $J$ parameter extracted from static susceptibility.

The low temperature $\chi'T$ behavior of two samples with very different concentrations, $c=0.3\%$ and $c=4.7\%$, are reported in Figs. 2(b) and 2(c), respectively. The $\chi'T$ of the sample with lower doping strongly reminds the calculated curves where only the Glauber dynamics is present, while that of the sample with $c=4.7\%$ closely resembles the computed curves in case of thermally activated $q$. The low $T$ data of the heavily doped sample rescale over the same curve if plotted versus the scaling variable $-\log(\omega\Delta t)/T$ (Fig. 3). This unambiguous observation of the scaling of all data over a
universal curve provides, as far as we know, the first direct experimental evidence of collective reversing of a group of spins in 1D magnetic systems.

A comparison of the experimental data with the calculated ones in Fig. 2(a) suggests that in CoPhOMe the ratio $\varepsilon/J$ is of the order of 0.05. It is worth noticing that the knowledge of the $\varepsilon$ parameter, unaccounted for in Glauber dynamics, is inessential to the scaling behavior; however, this energy must be small enough for the collective reversal to represent a convenient channel for shorter segments. The physical origin of $\varepsilon$ in CoPhOMe remains unclear and deserves further investigation.

The mechanism of relaxation involving collective reversal of all the spins of a short segment holds great potential for fast switching of the magnetization in magnetic nanowires at low $T$, without renouncing the stability of the magnetized state. In fact it would be sufficient to perturb a small fraction of magnetic sites in order to break the chains in short segments that can rapidly reverse their magnetization avoiding to overcome the exchange energy barrier. Removal of the perturbation would reestablish the Glauber regime, but now the clusters with reversed magnetization can eventually grow at no additional energy cost; a new frozen state with the desired magnetization can be easily reached if a weak magnetic field is applied. Several strategies to induce an instantaneous but reversible nonmagnetic defect can be envisaged. For instance, blue light has been used to induce an electron transfer in Co(II)–Fe(III) 3D cyanide-based networks, through the formation of diamagnetic Co(III)–Fe(II) low-spin pairs.15 Magnetic nanowires are therefore very appealing for a controlled fast switching of the magnetization.

The authors thank the financial support from EC (RTN “QUEMOLNA”), Italian MIUR (FIRB), and German DFG (SPP1137).