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L. Lopez-Diaz, E. Della Torre, and E. Moro

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The effect of thermal activation on the coercivity of domain walls

L. Lopez-Diaz[a)]
Departamento de Fisica Aplicada, Universidad de Salamanca, Salamanca E-37071, Spain

E. Della Torre
Institute for Magnetics Research, The George Washington University, Washington, DC 20052

E. Moro
Departamento de Matematicas and Grupo Interdisciplinar de Sistemas Complicados, Universidad Carlos III de Madrid, E-28911 Leganés, Madrid, Spain

The effect of temperature is rarely taken into account in micromagnetic calculations. However, thermal perturbations are known to play an important role in magnetization reversal processes. In this article, a micromagnetic model that includes thermal perturbations is presented. A stochastic zero-mean Gaussian field is introduced in the Landau–Lifschitz–Gilbert equation and the corresponding Langevin equation is solved numerically. The model is used to study the effect of temperature on the coercivity of domain walls due to exchange and anisotropy wells as well as nonmagnetic inclusions. It is shown that, for exchange and anisotropy interactions, thermal perturbations can lower the critical field for which the wall breaks free from the inclusion. However, when magnetostatic fields are taken into account, thermal perturbations are found to inhibit the unpinning process. This phenomenon seems to be related to the long-range nature of dipolar interactions. [S0021-8979(99)52508-5]

I. INTRODUCTION

In materials whose magnetic behavior is predominantly governed by domain-wall motion, inclusions in the crystal structure are sources of coercivity because they act as pinning centers for domain walls. In a recent article,[1] the authors used a micromagnetic model to study the interaction between domain walls and nonmagnetic inclusions and computed the critical field (H_c^0) for which a domain wall breaks free from the inclusion. As a preliminary model, the equilibrium equation was solved for each applied field and neither the dynamics towards equilibrium was modeled nor the effect of temperature was taken into account. However, it is well known that thermal activation over finite energy barriers can play an important role in magnetization reversal processes. For the problem we are interested in, there is a probability that, for a given field $H_{\mathrm{ext}}<H_c^0$, the wall breaks free from the inclusion and, consequently, the coercivity is lowered. In this article, the effect of thermal activation is included in our micromagnetic model. In order to do that, a random field term is introduced in the deterministic Landau–Lifschitz–Gilbert (LLG) equation and is then converted into the Langevin equation for the problem, which is solved numerically. With this approach, the pinning process is simulated at different temperatures and external fields. Two types of pinning mechanisms are considered: an exchange-and-anisotropy well and a nonmagnetic inclusion. The dynamic evolution and the effect of thermal activation is studied in both systems.

II. THE MODEL

The geometry of the model is the same as that in Ref. 1. In the rectangular region of computation, a 180° Bloch wall and a square inclusion are considered. Although the model is two dimensional (2D), the magnetization is allowed to rotate in three dimensions (3D). Periodicity and semi-infinite domains are assumed by imposing appropriate boundary conditions.

As it was shown in Ref. 1, the equilibrium state for $T=0$ and $H_{\mathrm{ext}}=0$ corresponds to the wall centered at the inclusion. Taking this state as the initial configuration for our simulations, an external field is applied and the evolution of the system is followed.

As it was mentioned before, an stochastic three-dimensional term $\xi(t)$ is added to the LLG equation

$$\frac{d\mathbf{M}}{dt'}=\gamma\{\mathbf{M}\times[\mathbf{H}_{\mathrm{eff}}+\xi(t)]\}-\frac{\lambda\gamma}{M_s}\mathbf{M}\times(\mathbf{M}\times\mathbf{H}_{\mathrm{eff}}), \tag{1}$$

where $\mathbf{M}$ is the magnetization, M_s is its modulus, $\mathbf{H}_{\mathrm{eff}}$ is the effective field, γ is the electron gyromagnetic ratio, and λ is the damping parameter. It should be noted that the noise has been added only in the precession term. In a forthcoming article it will be added to the damping term as well and the possible differences between the two approaches will be analyzed. According to the fluctuation-dissipation theorem,[2] the correlation function for the noise is given by

$$\langle\xi_\alpha(t)\cdot\xi_\beta(t')\rangle=\frac{2\lambda k_BT}{\gamma}\delta_{\alpha\beta}\delta(t-t'), \tag{2}$$

where $\alpha,\ \beta=x,y,z,\ k_B$ is the Maxwell–Boltzman constant and T is the absolute temperature. We note that a similar term has been considered by Garanin,[3] who proposed it in order to derive an all-temperature theory from the corresponding Fokker–Planck equation. In fact, this is a natural way to introduce the effect of thermal fluctuations, since the local field is the only way through which the magnetization $\mathbf{M}$ can feel any changes in its environment, due to thermal

[a)]Electronic mail: lld@gugu.usal.es

fluctuations or any other reasons. The Langevin equation is solved numerically[4] using first order Euler method and the magnetization vector is normalized after every iteration.

Typical permalloy parameters at room temperature and large damping were chosen: $M_s = 800\,\text{emu/cm}^3$, $K = 5000\,\text{erg/cm}^3$, $C = 1.3\times10^{-6}\,\text{erg/cm}$, and $\lambda = 5$, where K and C are the uniaxial anisotropy and the exchange constants, respectively. It was assumed that these values remained constant in the temperature range considered, on the basis that the results presented in this article are not intended to reproduce experimental measurements but to illustrate the effect of thermal perturbations.

Two types of inclusions were considered. The first one is an exchange-and-anisotropy well (EAW), in which C and K are zero inside the inclusion and M_s is the same than in the permalloy matrix. Consequently, the interaction between the inclusion and the wall is short ranged and, since the wall is a Bloch one, there is no demagnetizing energy. The second pinning center is a nonmagnetic inclusion (NMI). In this case, the magnetostatic field created by the pole distribution at the surface of the inclusion has to be taken into account. Since dipolar interactions are long ranged, the nature of the pinning mechanisms is qualitatively and quantitatively different than in the first case, as shown in Ref. 1, and the effect of temperature is expected to be different as well.

III. RESULTS AND DISCUSSION

The results that will be presented in this section correspond to simulations carried out on a $2.5\times1.25\,\mu$m computational region of a 10-μm-thick film with a 120-nm-square inclusion that extends along the entire film thickness. Discretization sizes of 20 and 10 nm were chosen and the results obtained were the same in both of them. A time step of 1.4 ps was used for solving the dynamic problem. The stochastic term was implemented by a zero-mean Gaussian random field different for each computational cell. It was assumed that the space and time correlation lengths of thermal perturbations were smaller than our cell size, and time step, respectively. It should be emphasized that, for a given $T\neq0$, the results depend on the particular realization, i.e., the sequence of random numbers, and that, although a complete statistical analysis is not available yet, the results that will be presented are representative of the general behavior.

First of all, the critical field H_c^0 at $T=0$ was calculated. The computed value for the EAW was $H_c^0 = 39.5$ A/m, whereas a value of $H_c^0 = 292.5$ A/m was found for the NMI. After that, an external field slightly larger than H_c^0 was applied and the dynamic evolution is followed for several values of T. Figures 1 and 2 show the results for the EAW ($H_{\text{ext}} = 40$ A/m) and the NMI ($H_{\text{ext}} = 294$ A/m), respectively. The magnetization along the easy axis direction M_y is plotted. It should be pointed out that M_y has a negative value at $T=0$ because the inclusion is centered to the left of the computational region in order have a larger area to study the dynamics of the wall once the unpinning has taken place. Three well defined regions can be distinguished in Figs. 1 and 2. During the first iterations there is a rapid increase in

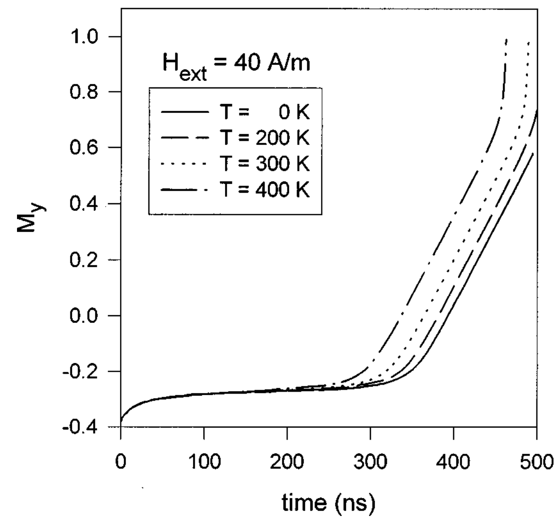

FIG. 1. Evolution of a domain wall pinned by an EAW when a field $H_{\text{ext}} = 40$ A/m is applied. The component of **M** along the field axis is plotted.

M_y that corresponds to a reversible bending of the wall. The wall has some flexibility and, although it is pinned at the inclusion, it bends in order to increase the area of the domain that is parallel to the external field. After that, there is a long region characterized by a very small change in M_y. This region corresponds to the unpinning process. Since H_{ext} is close to H_c^0, torques are very small in this region and the process is very slow. Once the wall breaks free from the inclusion, a region of a rapid change in M_y comes. The wall moves freely driven by the external field. It should be noted that the velocity of the wall in this region is approximately constant (the slope of the curve is constant in this region) and that it does not depend on the temperature. This velocity is larger for the NMI than for the EAW because H_{ext} is higher. In addition, the wall is repelled by the NMI, as it was shown in Ref. 1, whereas the wall does not interact with the EAW once it breaks free from it. Finally, it should be pointed out that the increase in the wall velocity during the last iterations is due to the artificial boundaries of our computational region and consequently, it is not physical.

As can be seen in Fig. 1, in the EAW case the wall breaks free from the inclusion faster as temperature increases, whereas the opposite effect occurs for the NMI, i.e., temperature slows down the unpinning process (Fig. 2). In order to understand better the effect of thermal activation, similar runs were carried out for external fields slightly smaller than H_c^0 ($H_{\text{ext}} = 39$ A/m for the EAW and $H_{\text{ext}} = 292$ A/m for the NMI). the results are presented in Figs. 3 and 4 (the scale in the y axis has been amplified with respect to Figs. 1 and 2). Since $H_{\text{ext}} < H_c^0$, the wall never breaks free from the inclusion at $T=0$. However, as it can be seen in Fig. 3, in the EAW case the unpinning process does take place due to thermal activation over the finite energy barrier. Furthermore, as T increases the wall breaks free at an earlier time. However, for the NMI no unpinning was achieved at any temperature. It is remarkable that, as can be seen in Fig. 4, thermal fluctuations are always below the equilibrium state at $T=0$.

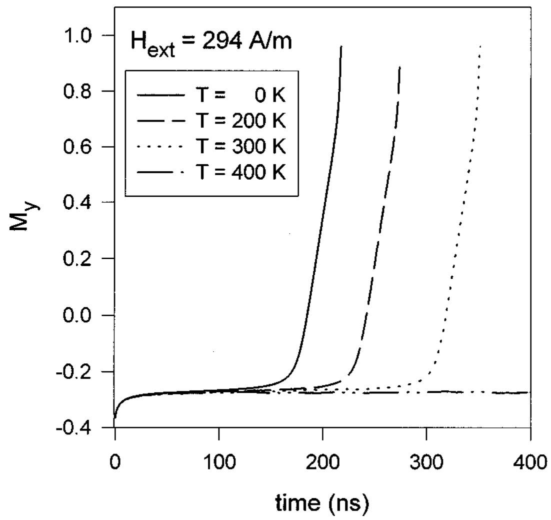

FIG. 2. Evolution of a domain wall pinned by an NMI when a field $H_{ext} = 294$ A/m is applied. The component of **M** along the field axis is plotted.

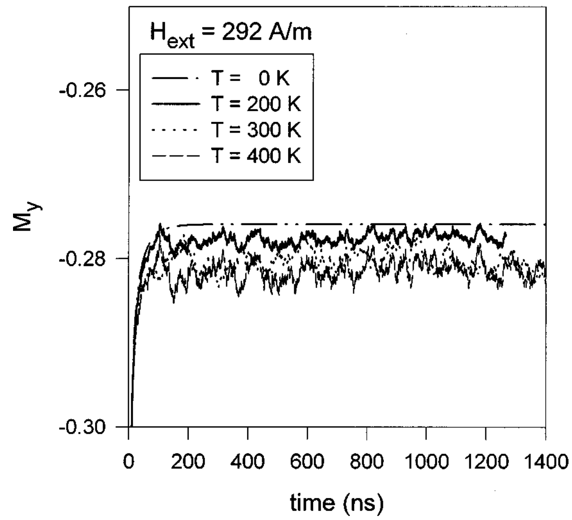

FIG. 4. Evolution of a domain wall pinned by an NMI when a field $H_{ext} = 292$ A/m is applied. The component of **M** along the field axis is plotted.

These results are consistent with the ones presented before and show that thermal perturbations help the overcoming of exchange and anisotropy barriers in the EAW case. However, for NMI, thermal perturbations seem to inhibit the unpinning mechanisms. It is the author's belief that this discrepancy is due to the different nature of the spin interactions in the two models: in the EAW model the interaction between the wall and the inclusion is short ranged, since exchange and anisotropy are first-neighbor and local terms, respectively. On the other hand, in the NMI model the spins are long-range coupled due to magnetostatic interactions. Consequently, by applying local and uncorrelated perturbations the unpinning process is hindered. In the EAW case, since the spins are coupled by short range forces, local perturbations can provoke local avalanches that propagate and lead to the unpinning.

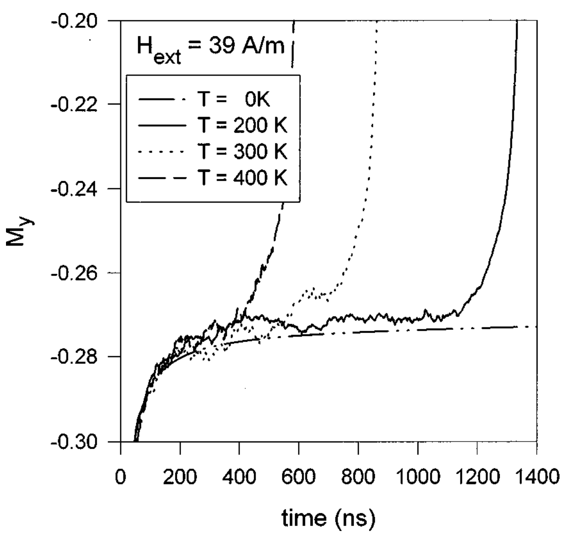

FIG. 3. Evolution of a domain wall pinned by an EAW when a field $H_{ext} = 39$ A/m is applied. The component of **M** along the field axis is plotted.

IV. CONCLUSIONS AND FUTURE WORK

Thermal activation has been introduced in a micromagnetic model in order to study its effect on domain wall coercivity. A stochastic term is introduced in the LLG deterministic equation and the corresponding Langevin equation is solved numerically. Preliminary results of this model have been presented. It has been shown that, for exchange and anisotropy forces, thermal perturbations can lower the critical field for which the wall breaks free from the inclusion. On the other hand, when magnetostatic interactions are present, thermal perturbations are found to inhibit the unpinning process.

Further work is in process in order to find out whether the overcoming of exchange and anisotropy barriers obey the Arrhenius law and in order to elucidate the origin of the magnetostatic hindering of depinning processes.

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[1] L. Lopez Diaz and E. Della Torre, J. Appl. Phys. **83**, 5933 (1998).
[2] N. G. van Kampen, *Stochastic Processes in Physics and Chemistry* (North–Holland, Amsterdam, 1981).
[3] D. A. Garanin, Phys. Rev. B **55**, 3050 (1997).
[4] P. E. Kloeden and E. Platen, *Numerical Solution of Stochastic Differential Equations* (Springer, Berlin, 1992).