Local modes of thin magnetic films

A. L. Dantas,[1] A. S. Carriço,[2,*] and R. L. Stamps[3]
[1]Departamento de Física, Universidade do Estado do Rio Grande do Norte, 59.610-210 - Mossoró, RN, Brazil
[2]Departamento de Física Teórica e Experimental, Universidade Federal do Rio Grande do Norte, 59.072-970 - Natal, RN, Brazil
[3]Department of Physics, The University of Western Australia, Nedlands WA 6907, Australia
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We calculate the frequency of rigid displacement domain wall excitations of a Nèel wall in a thin uniaxial ferromagnetic film. The domain wall is pinned by a line defect running along the uniaxial axis. We study the effect of an external field applied along the magnetization of one of the domains. The restoring force originates from energy fluctuations resulting from spin motion within the domain wall width and the excitation frequency turns zero when the external field approaches the threshold value for depinning the domain wall from the defect. The results are applied to the study of excitations of a Nèel wall in a thin uniaxial ferromagnetic film exchange coupled to a uniaxial two-sublattice antiferromagnetic substrate.

There is a wide recognition of the central role played by domain walls in the leading features of phenomena of current interest in a large class of magnetic artificial structures of nanometer size, made out of transition metal thin films. Domain walls participate in key processes, such as magnetization reversal and affect the transport of charge.

Most techniques currently used to characterize artificial magnetic systems, such as magnetization measurements, are based on methods that sample large areas and thus average out the microscopic details. These methods do not inform, for instance, on the possible modifications in the domain wall profile and the nature of domain wall pinning forces. These features may have a relevant impact in key aspects of phenomena of current interest. We cite only a few examples: (1) the reduction in remanence of thin films on compensated antiferromagnetic (AF) interfaces,[1,2] (2) the effective interface exchange leading to short period oscillations in Fe/Cr wedges,[3] (3) spin selective domain wall scattering in chemically homogeneous materials,[4] (4) interface roughness induced giant magnetoresistance,[5] (5) domain wall resistivity of submicrometer wires,[6] (6) macroscopic quantum tunnelling in domain wall junctions,[7] (7) domain wall jumps and the resonant frequency in magnetic force microscopy measurements,[8] (8) domain wall mobility and the Barkhausen effect,[9] and (9) the compression of domain walls during the magnetization reversal in domain wall junctions.[10]

In this paper we show that the excitations of domain walls, pinned by local defects, are controlled by the magnetic structure in regions of microscopic dimensions. We study rigid domain wall displacement modes (RDWDM) and we show that, provided the pinning energy is of the same order of magnitude as the anisotropy energy of the ferromagnet (F), these domain wall excitations can be accessed by resonance experiments in experimental setups designed for ferromagnetic resonance (FMR). This is the case, as we show later, of domain walls pinned by interface defects in F/AF bilayers.[2,3]

Although the domain walls might be of microscopic size and constitute a minor fraction of the whole sample, the measurement of the field effects on the frequency of the domain wall excitations provides a promising means for accessing the magnetic structure in a local manner. We show that, contrary to the long wave-length domain excitations, measured by FMR, the frequency of RDWDM is a decreasing function of the external field and turns zero at the value of the external field which depins the domain wall from the local pinning center.

We obtain the field dependence of the frequency of RDWDM for a general model of a Nèel wall. We keep the energy density of the wall in general form and obtain the frequency of excitations by examining energy fluctuations around the equilibrium state. We allow the field to displace the wall from the pinning center and calculate the restoring force constant and the Döring mass in terms of the equilibrium profile functions.

We consider a π wall of a uniaxial ferromagnet, pinned by a line defect running along the z axis at $y=0$. The magnetization is in the yz plane and its orientation with respect to the uniaxial axis, in the plane, is given by the function $\theta(y)$. In the domain wall center $\theta=\pi/2$ and the domains have $\theta=0$ and $\theta=\pi$, as shown in Fig. 1, for the particular case of an interface step defect.

We start from an equilibrium profile $\theta^0(y)$ which minimizes the magnetic energy

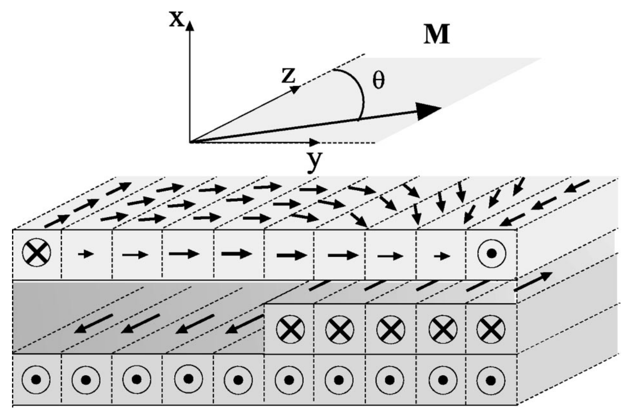

FIG. 1. Schematic representation of a Nèel wall pinned at a step defect on an antiferromagnetic substrate.

$$E_{\rm eq}=\int_{-L}^{L}dy\, f(\theta,\theta_y), \tag{1}$$

where L is the width of the domains at each side of the domain wall and $f(\theta,\theta_y)$ is the magnetic energy density, including intrinsic exchange and anisotropy energies of the ferromagnet as well as Zeeman energy and the domain wall pinning energy.

$\theta^0(y)$ is the function that corresponds to the equilibrium profile. Thus, it satisfies the Euler-Lagrange equation

$$\frac{\partial f}{\partial\theta}-\frac{\partial}{\partial y}\frac{\partial f}{\partial\theta_y}=0. \tag{2}$$

$y=0$ is the position of the domain wall center in the absence of external magnetic field. For a given value of the external field strength H the equilibrium profile, represented by $\theta^0(y)$, includes the field-induced displacement of the domain wall center.

Rigid displacement domain wall excitations are characterized by a rigid displacement of the angular profile of the domain wall. We consider the variations induced in the energy by small amplitude displacements around the equilibrium pattern, using the function $\theta(y-q)$, with $q=q_0e^{i\Omega t}$. We also introduce an extra term in the energy corresponding to a small out of plane angle $\psi=\psi_0e^{i\Omega t}$. The out of plane oscillations induce surface charges and the demagnetizing energy is approximated by

$$E_M=\int_{-L}^{L}2\pi M^2\sin^2\psi\sin^2\theta\, dy. \tag{3}$$

The total energy is the sum of Eqs. (1) and (3). We calculate the variations in $E_{\rm eq}$, when $\theta(y)=\theta^0(y-q)$ is used in Eq. (1) in the place of $\theta^0(y)$ and add to it the demagnetizing energy, given by Eq. (3). The variations in θ and θ_y are given by $\delta\theta=-q\,\theta_y^0(y)$ and $\delta\theta_y=-q\,\theta_{yy}^0(y)$. In order to calculate the leading term of the excitation energy we expand the function $f(\theta,\theta_y)$ up to second order of the displacement variable q. Considering that the function $f(\theta^0,\theta_y^0)$ is a solution of the Euler-Lagrange equations, we find that

$$E_{\rm eq}(\{\theta,\theta_y\})=E_{\rm eq}(\{\theta^0,\theta_y^0\})+\delta E, \tag{4}$$

where

$$\delta E=\frac{q^2}{2}\int_{-L}^{L}dy\left\{\frac{\partial^2 f}{\partial\theta^2}(\theta_y^0)^2+\frac{\partial^2 f}{\partial\theta_y^2}(\theta_{yy}^0)^2+\frac{\partial^2 f}{\partial\theta\partial\theta_y}\theta_y^0\theta_{yy}^0\right\}. \tag{5}$$

For a good number of magnetic systems of current interest there is no cross derivative of the energy density ($\partial^2 f/\partial\theta\partial\theta_y=0$). Furthermore, for a rigid displacement the intrinsic exchange energy does not change, thus we do not have a term involving the θ_y derivative of the energy density. We then find

$$\delta E=\frac{q^2}{2}\int_{-L}^{L}dy\frac{\partial^2 f}{\partial\theta^2}(\theta_y^0)^2. \tag{6}$$

The factor $(\theta_y^0)^2$ in the integrand of Eq. (6) restricts the contribution to the excitation energy δE to the region of the domain wall. Notice also, from Eq. (3), that the main contribution to the magnetostatic energy comes from the domain wall region, since the function $\sin^2\theta$ is zero in the domains. The out-of-plane fluctuation ψ is assumed to be small and we use the equilibrium function $\theta^0(y)$ in Eq. (3).

The leading terms for small amplitude rigid displacement oscillations ($q/\Delta_0\ll 1$ and $\psi\cong 0$) are given by Eqs. (3) and (6). The total energy, $E=E_{\rm eq}+E_M$ is of the form

$$E=E^0+\frac{1}{2}k\,q^2+\frac{1}{2}b\,\psi^2, \tag{7}$$

where E^0 is the equilibrium value of the energy, as given by Eq. (1), using the profile $\theta^0(y)$. The Landau-Lifshitz's torque equations are integrated throughout the domain wall[11] leading to

$$\frac{dq}{dt}=\frac{\gamma}{2M}\frac{\partial E}{\partial\psi}, \tag{8a}$$

$$\frac{d\psi}{dt}=-\frac{\gamma}{2M}\frac{\partial E}{\partial q}, \tag{8b}$$

where γ is the gyromagnetic factor.

From Eqs. (8a) and (8b) we obtain the frequency of domain wall oscillations as

$$\Omega=\frac{\gamma}{2M}\sqrt{k\,b}. \tag{9}$$

The restoring force constant k is a decreasing function of the external field strength. When the external field approaches the threshold value H^*, which makes the domain wall free from the defect, the center of the domain wall is far from the defect line at $y=0$. Assuming the defect contribution to the magnetic energy to be of finite range, centered at $y=0$, when $H\approx H^*$ the function $\partial^2 f/\partial\theta^2$ is practically zero, since in the defect range the magnetization is uniform. Thus, the fluctuations in the domain wall position produce no extra energy and $k=0$.

Notice that the results, so far, are valid for any kind of magnetic domain wall structure, provided that the equilibrium structure corresponds to having the magnetization in a plane. This covers Nèel walls as well as Bloch walls. Furthermore the domain wall pinning mechanism, as well as the internal structure of the ferromagnet have not been specified. Thus the results apply equally well for a variety of systems.[2,3,13,14]

The nucleation and pinning of domain walls has been recently studied for an uncompensated F/AF interface.[12] It has been shown that ferromagnetic narrow domain walls are nucleated at interface step defects.

We calculate the excitation of a Nèel wall pinned at a step defect in a F/AF interface. The system consists of a thin ferromagnetic film, with in-plane magnetization, on a two-sublattice uniaxial antiferromagnetic substrate as shown in Fig. 1. The anisotropy axis of the antiferromagnet is parallel to the easy direction of the ferromagnet (the z axis). The substrate step edge runs along the z axis and divides the interface in two regions, each one containing spins from a sublattice of the antiferromagnet. In our model no relaxation is allowed for the substrate spins, which are held fixed along the anisotropy direction.

We do not consider any variation of the magnetization along the z- or x-axis directions. The nucleation of a Nèel wall in the ferromagnetic film follows from the discontinuous change of direction of the interface exchange field at the step edge. The magnetic energy density is given by

$$f(\theta,\theta_y)=A(\theta_y)^2-[HM+J(y)]\cos\theta-K\cos^2\theta, \quad (10)$$

where

$$J(y)=\begin{cases} J, & y<0,\\ -J, & y>0.\end{cases} \quad (11)$$

The first term in the Eq. (10) is the intrinsic exchange energy density, the second term is the Zeeman energy density for an external field of strength H applied along the direction $\hat{z}$, the third term is the interface coupling energy density and the last term is the uniaxial anisotropy energy.

The intrinsic exchange and the anisotropy energies make no contribution to the restoring force and $k=(1/q)(\partial E_{J,H}/\partial q)$ where $E_{J,H}$ is the sum of the Zeeman energy and the interface coupling energy. As the wall moves rigidly out of the equilibrium position by a small displacement, it induces a change in the Zeeman energy due to the modification in the sizes of the domains. The interface energy is also changed since the displacement of the wall induces changes in the orientation of the magnetization with respect to the interface field.

In order to study rigid domain wall displacement oscillations around the equilibrium position we take

$$\tan\left(\frac{\theta(y,t)}{2}\right)=\exp\left(\frac{y-q_H-\eta(t)}{\Delta}\right) \quad (12a)$$

and

$$\Psi=\psi(t), \quad (12b)$$

where $\eta(t)$ is the dynamical variable which describe the oscillations of the domain wall center around the equilibrium position q_H, and $\psi(t)$ is the angle between the projection of the magnetization in the yx plane and the y axis, describes the out-of-plane component of the magnetization.

q_H and Δ are the equilibrium values of the position of the domain wall center and the domain wall width. They are obtained from the minimization of the energy and are given by

$$q_H=\Delta\tanh^{-1}\left(\frac{H}{H_J}\right) \quad (13)$$

and

$$\frac{\Delta}{\Delta_0}=\left[1+2\frac{H_J}{H_A}\ln 2-\frac{H+H_J}{H_A}\ln\left(1+\frac{H}{H_J}\right)+\frac{H-H_J}{H_A}\times\ln\left(1-\frac{H}{H_J}\right)\right]^{-1/2}, \quad (14)$$

where $\Delta_0=\sqrt{A/K}$, $H_J=J/M$ and $H_A=2K/M$.

Using the magnetic profile defined by Eqs. (12) we obtain

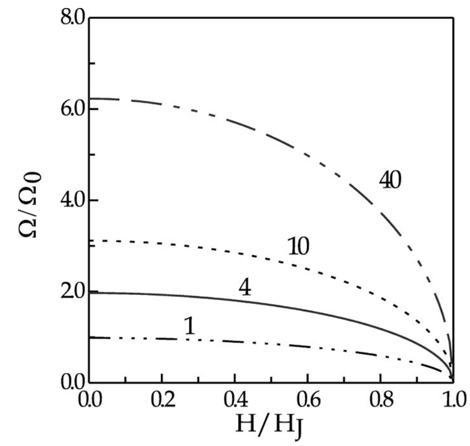

FIG. 2. Frequency of rigid displacement domain wall oscillations. The numbers by the curves indicate the values of H_J/H_A.

$$E(q,\psi)=E(q_H,0)+4\pi M^2\Delta\psi^2+\frac{J}{\Delta\cosh^2(q_H/\Delta)}\eta^2. \quad (15)$$

In Eq. (15) $E(q_H,0)$ is the equilibrium value of the energy and the field effects are contained in q_H and Δ.

From Eq. (9) we obtain the frequency of the domain wall oscillations

$$\left(\frac{\Omega}{\Omega_0}\right)^2=\frac{4\pi MH_J}{H_A(H_A+4\pi M)\cosh^2[\tanh^{-1}(H/H_J)]}, \quad (16)$$

where $\Omega_0=\gamma\sqrt{H_A(H_A+4\pi M)}$ is the frequency of the uniform mode of the domains in the absence of interface effects and external field. In Fig. 2 we show $\Omega(H)/\Omega_0$. We selected a few values of the interface exchange field for an anisotropy field of $H_A=0.55$ kOe. $\Omega(H)$ is a monotonically decreasing function of H with an upper limit of the order of Ω_0.

The upper limit of the excitation frequency $\Omega(H)$ is for $H=0$. As seen in Eq. (16) $\Omega(0)/\Omega_0$ is proportional to the square root of H_J/H_A. Thus a large increase in H_J/H_A does not lead to a correspondingly large increase in $\Omega(0)$.

The restoring force constant k is a decreasing function of H and turns zero for $H=H_J$. For $H=0$ the energy fluctuations include in full the oscillations of the domain wall around the step edge. The equilibrium position of the wall center moves away from the step defect when H increases. For $H\cong H_J$ the step defect is at the tail of the domain wall. Thus, there is no variation in the angular profile, near the step edge, for small displacement oscillations [$\theta(y)\cong 0$ and $\theta_y(y)\cong 0$], and there is no variation of the interface energy due to small oscillations of the domain wall position.

The shift of the hysteresis in F/AF bilayers, attributed to H_J, is commonly found to be of the order of the anisotropy field of the F film.[15] However, H_J may be larger than H_A by two to three orders of magnitude.[16] Our results for $1<H_J/H_A<10^3$, not shown here for brevity, indicate that $\Omega(0)$ is of the same order of magnitude of Ω_0. Thus it should be possible to observe interface pinned domain wall modes in experimental setups designed for FMR.

In a rough F/AF with a low density of interface steps, the degree of interface magnetic roughness may be estimated from the intensity of the response of interface pinned domain walls. Our results might also be helpful to estimate the interface contact interaction in vicinal interfaces formed on wedge samples, where the density of domain wall pinning centers may be controlled by the vicinal angle of the antiferromagnetic substrate.[2,3]

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*Electronic mail: acarrico@dfte.ufrn.br

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