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Excitations of interface pinned domain walls in constrained geometries

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We report a theoretical investigation of the equilibrium pattern and the spectra of head-to-head and Neel domain walls of flat Fe and Py stripes, exchange coupled with a vicinal antiferromagnetic substrate. We show that the domain wall excitation spectrum is tunable by the strength of the interface field. Furthermore, strong interface coupling favors localized wall excitations. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5007245

I. INTRODUCTION

There is currently a large interest in the study of domain walls in constrained geometries. Apart from fundamental questions such as changes in magnetic scale lengths and new magnetic patterns, this is also motivated by promising applications such as high-performance nonvolatile memory nanodevices and magnetic oscillators.

Recent reports have focused on studies of the impact of confinement on the domain wall pattern and excitation spectra, as well as on the strength of domain wall pinning potentials.

Geometrical confinement poses restrictions on the balance between exchange and dipolar energies, leading to changes in the wall magnetization patterns and the wall width. As a result, the restoring forces, and the excitation spectra of magnetic walls may be tailored by the confinement layout.

Vicinal two-sublattices antiferromagnetic (AF) substrates have stepped surfaces and may be chosen to have the ferromagnetic/antiferromagnetic (F/AF) interface with a periodic sequence of terraces composed of spins of opposite AF sublattices, separated by monatomic steps. The substrate surface spin profile, and the periodic change in the interface exchange energy may be designed to pin head-to-head or Neel walls, as indicated in Fig. 1.

We report a theoretical study of the impact of geometrical confinement on the domain wall patterns and excitations of flat Py and Fe narrow stripes exchange coupled to a vicinal two-sublattice antiferromagnetic (AF) substrate.

We consider head-to-head, longitudinal and transverse Neel walls, and focus on the impact of the dipolar field on the competing roles of the ferromagnetic stripe intrinsic exchange energy and of the F/AF interface exchange energy on the domain wall pattern and excitation spectra.

II. THEORETICAL MODEL

We consider stripes with normal along the z-axis. The magnetic structure is described using a single layer of 5nm × 5nm × 10nm cells, and the energy density is given by:
FIG. 1. Schematic representation of (a) head-to head, (b) longitudinal and (c) transverse Neel walls.

\[
E = -H \hat{x} \sum_j M_S \hat{m}(j) - \sum_j K(m_x(j))^2
\]

\[
+ \frac{1}{2} \sum_{j,k} M^2_S \left( \frac{\hat{m}(j) \cdot \hat{m}(k)}{n^3_{jk}} - \frac{3(\hat{m}(j) \cdot \hat{n}_{jk})(\hat{m}(k) \cdot \hat{n}_{jk})}{n^5_{jk}} \right)
\]

\[
+ \frac{1}{d^2} \sum_{j,k} A_{jk} (1 - \hat{m}(j) \cdot \hat{m}(k)).
\]

(1)

The first two terms are the Zeeman and anisotropy energies, \( M_S \) is the saturation magnetization, and \( \hat{m}(j) \) is the direction of the \( j \)-cell magnetic moment. In the dipolar energy, \( n_{jk} \) is the distance between the cells \( j \) and \( k \) in units of the surface cell edge (d). The exchange energy, couples nearest neighbor cells. \( A_{jk} \) is either the intrinsic ferromagnetic exchange stiffness (\( A \)), coupling neighboring F stripe cells, or it represents the effective interface exchange energy (\( A_{int} \)).

The stripe magnetization equilibrium pattern \( \{\hat{m}(j) : j = 1 \ldots N\} \) is found using a self-consistent algorithm. The \( j \)-cell magnetic moment direction \( \hat{m}(j) \) is adjusted to be parallel to the local magnetic field \( \hat{H}_{eff}^j = -1/M_S \partial E/\partial \hat{m}(j) \), so that for each one of the cells the torque is smaller than \( 10^{-17} \) erg.

In order to obtain the excitation spectra we use the magnetization equilibrium pattern and add at each cell a small time-varying magnetization which is, at each cell, perpendicular to the magnetization:

\[
\hat{m}(l,t) = \hat{m}(l) + \tilde{\delta \hat{m}}(l) e^{i\omega t},
\]

with \( \hat{m}(l) \cdot \tilde{\delta \hat{m}}(l) = 0 \).

Using the Landau-Lifshitz equation \( \frac{d\hat{m}}{dt} = \gamma \hat{m} \times \hat{H}_{eff} \), and keeping only first order terms in the small oscillation amplitudes, we obtain a \( 2N \times 2N \) secular equation:

\[
i \Omega \delta m_\alpha(l) = \sum_{\beta k} \Phi_{\alpha\beta}(l,k) \delta m_\beta(k),
\]

(2)

where \( l = 1, \ldots N, \alpha \) denotes one of the two oscillation amplitudes at cell \( l \), \( N \) is the number of cells in the F stripe, and \( \Omega = \omega/\gamma \).

The excitation spectra are obtained from the density of states, either covering the whole stripe, or selected cells in the domains, or in the domain wall.

The total density of states \( \rho(\Omega) \) is obtained from the resolvent matrix

\[
\rho(\Omega) = -\frac{2\Omega}{\pi} \text{Im} \left[ \text{Tr} \, G(\Omega + i\epsilon) \right],
\]

(3)

where the resolvent matrix \( G(\Omega) \) is given by:

\[
G(\Omega) = \left( \Omega^2 + \Phi^2 \right)^{-1},
\]

(4)

and the trace of the resolvent matrix
$\text{Tr } G(\Omega + i\epsilon) = \sum_{\alpha \ell} G_{\alpha \ell}(\ell, \ell)$, (5)

is calculated with a small imaginary apart $i\epsilon$ added to $\Omega$.

We use $\gamma=2.93$ GHz/kOe and for Fe we use $M_S = 1700$ emu/cm$^3$, $A = 25 \times 10^{-7}$ erg/cm, and $K = 4.8 \times 10^5$ erg/cm$^3$. For Permalloy we use $M_S = 800$ emu/cm$^3$, $A = 13 \times 10^{-7}$ erg/cm, and $K=0$.

### III. RESULTS AND DISCUSSIONS

The equilibrium magnetic moment of each cell is parallel to the effective field. Also, small oscillations around the equilibrium lead to a restoring torque which is proportional to the local value of the effective field. Cells at places where the effective field is large, have large values of the restoring torque and are likely to have high-frequency magnetization oscillations.

For a given value of the frequency $f = \omega/2\pi$, the eigenvector of the secular equation (Eq. (2)) corresponds to oscillations at all cells with the same value of the effective field. Thus, looking at the effective field strength maps over the stripe, it is possible to anticipate qualitatively whether the domain wall and domain spectra overlap.

The intrinsic ferromagnetic exchange energy leads to effective fields, which depend on the relative orientation of first neighbor cells. The effective exchange field is larger in regions where the neighboring moments are nearly parallel, as found in the domains region. For Fe (and Py) the local exchange field, summing over neighboring cells with parallel moments, is 23.5 kOe (20 kOe). As seen in the effective field maps of Fig. 2 and Fig. 4, the exchange field corresponds to a large fraction of the effective field strength.

The interface exchange field is more effective in the domains region, where the moments are aligned with the effective interface field. In the domain wall region, the moments near the wall center make large angles with the effective interface field and do not benefit from the restoring force due to the interface field.

Therefore, by increasing the strength of the interface field one produces an upshift in the domain spectra, without modifying the domain wall spectra as much.

The wall density is a key issue for wall memory devices$^{1,2}$ and wall nano-oscillators.$^3$ We presently investigate single walls pinned at a vicinal interface step, avoiding wall-wall interactions,

![Image](image-url)  
**FIG. 2.** Magnetization pattern and the effective field strength of Fe head-to-head domain walls in 460 nm $\times$ 55 nm nanostripes with 230nm long terraces, for interface exchange energy $A_{\text{int}}=0.25A$. The color barcode indicates the strength of the local effective field. The curve is the effective field strength along the middle of the stripe, as indicated by the right-hand side axis. The bottom panel shows an 95nm wide region centered at the domain wall center.
and focusing on the impact of intrinsic features of the dipolar field of selected wall kinds on the wall profile and excitation spectra.

In Fig. 2 we show the magnetic pattern and the effective field of Fe head-to-head domain walls in 10nm thick, 460 nm × 55 nm nanostripes with 230nm long terraces for weak F/AF interface coupling ($A_{int}=0.25\text{A}$). In Fig. 3(a) we show the partial density of states corresponding to 30nm wide area of the stripe, either centered at the domain wall center or at the domain center.

The 25 GHz wide domain band, shown in Fig. 3(a), from 5GHz to 30 GHz, is upshifted with respect to the domain wall band. The low frequency part of the domain wall band (from 0.7 GHz to 5GHz) corresponds to modes localized in the domain wall. As shown in Fig. 2, in the domain the effective field covers the 35.3 kOe to 40.6 kOe interval, while in the domain wall the interval is 15.5 kOe to 37.7 kOe.

A shown in Fig. 3(c), there is a 5GHz upshift of the bottom of the domain spectrum, for a larger value of the interface exchange energy, $A_{int}=1.5\text{A}$. There is a smaller upshift of domain wall spectra, starting at 2.78GHz, with a 7GHz wide band of domain wall modes.

The results for the Py stripe, shown in Fig. 3(b) and Fig. 3(d), are similar to those of the Fe stripe, except that, due the smaller value of the magnetization, the domain band width is narrower. Also, the bottom of the domain spectrum is lower and the band of local domain wall modes is narrower. For $A_{int} = 1.5\text{A}$ the bottom of the domain spectrum is shifted to 5.6GHz, while the bottom of the wall spectrum is shifted to 1.4GHz, resulting in a 4.2GHz wide band of wall localized modes.

Notice that an interface exchange energy of $A_{int}=0.25\text{A}$ suffices to stabilize Fe head-to-head domain walls in 460 nm × 55 nm nanostripes with 230nm long terraces, as shown in Fig. 2. One would, at first glance, expect that for larger domains, as in the case shown in Fig. 4(a), the same interface exchange energy should be enough to stabilize transverse Neel walls. Instead, a vortex wall forms.

The main difference is that a transverse Neel wall, with magnetic surface charges at the lateral surfaces of the stripe, at both domains, requires large values of the interface exchange energy to compensate the magnetostatic energy. As shown in Fig. 4(a), only 230nm away from the vortex core center, the domains exhibit a nearly uniform pattern, perpendicular to the lateral surfaces of the stripe.
The elimination of surface charges contributes to the domain magnetization profile at this end of the stripe. Therefore, a larger interface exchange energy would be required to form a transverse Neel wall.

Notice from Fig. 4(a) and Fig. 5(a) that, except for the vortex core, a large fraction of cells at the vortex wall region has effective field strengths in the 36 kOe–41 kOe range, which is also the effective strength interval in the domains. Therefore, the vortex wall spectrum overlaps the domain spectrum. In this case, there is no band of modes localized in the vortex wall region.

Notice from Fig. 4(b) and Fig. 5(b) that within the narrow wall region the effective strength (30 kOe) is smaller than the value in the domains (40 kOe). As a result, the bottom of the domain wall spectrum, at 0.7 GHz, is smaller than the bottom of the domain spectrum at 6.3 GHz, resulting in a 5.6 GHz wide band of domain wall localized modes.

In Fig. 6 we show the magnetization pattern and effective field strength of a transverse Neel wall in a 460 nm × 100 nm Fe nanostripe with 230 nm terraces, for interface exchange energy $A_{\text{int}}=A$. 

FIG. 4. Magnetization pattern and effective field strength of Fe (a) vortex wall in 460 nm × 100 nm nanostripes with 230 nm terraces, and (b) Longitudinal Neel walls in 460 nm × 100 nm nanostripes with 50 nm terraces, in both cases, for interface exchange energy $A_{\text{int}}=0.25A$. The color barcode indicates the strength of local effective field.

FIG. 5. Density of states for domain and domain wall spectra of Fe (a) vortex walls in 460 nm × 100 nm nanostripes with 230 nm terraces (see Fig. 4(a)), and (b) Longitudinal Neel walls in 460 nm × 100 nm nanostripes with 50 nm terraces (see Fig. 4(b)), in both cases, for interface exchange energy $A_{\text{int}}=0.25A$. 

FIG. 6. Magnetization pattern and effective field strength of Fe transverse Neel wall in 460 nm × 100 nm nanostripes with 230 nm terraces, for interface exchange energy $A_{\text{int}}$. The color barcode indicates the strength of local effective field.

FIG. 7. Effective field strength along the domain center and the domain wall center, for a transverse Neel wall in a 460 nm × 100 nm Fe nanostripe with 230 nm terraces, for interface exchange energy $A_{\text{int}}$.

As shown in Fig. 7, for the most part of the wall center the effective field strength (37.5 kOe) is smaller than the values found in the domain center (44.3 kOe). In Fig. 8 we show the local densities of states at the domain center and at the wall center. These partial densities collect contribution from

FIG. 8. Local density of states at the domain center and the domain wall center, for a transverse Neel wall in a 460 nm × 100 nm Fe nanostripe with 230 nm terraces, for interface exchange energy $A_{\text{int}}$. 
the resolvent matrix diagonal elements at cells at the domain center and the wall center. At the wall center, as shown in Fig. 8, the local density of states shows a localized band below 7.5 GHz.

We have presented a new method to obtain the excitation spectra of magnetic nano-systems, and discussed the excitations of walls in F stripes exchange coupled to vicinal AF substrates. We have shown that head-to-head and longitudinal Neel walls form more easily, requiring small values of $A_{\text{int}}$. Transverse Neel walls have lateral surface magnetic charges, and require large values of $A_{\text{int}}$. We have also shown that the overlap of wall and domain spectra may be controlled by the interface exchange energy strength.

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