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Characterization of magnetic properties at edges by edge-mode dynamics

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We have used “trapped spin wave” or edge modes of magnetic precession to probe the magnetic environment near magnetic film edges magnetized perpendicular to the edge. Micromagnetic models of dynamics in stripes reveal that the edge mode frequency-field relationship depends on whether the edge surface is vertical or tapered, while the “bulk” modes are nearly unaffected. The models show the edge-mode frequency going to zero at the edge saturation field. This critical field becomes much less distinct for applied fields misaligned from the edge normal by as little as 1°. Ferromagnetic-resonance and Brillouin light-scattering measurements of the edge modes in an array of 480-nm-wide × 12-nm-thick $Ni_{80}Fe_{20}$ stripes have a lower edge saturation field than the vertical edge models, but agree well with the model of 45°-tapered edges. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2167633]

I. INTRODUCTION

Many experimental techniques exist for characterizing both bulk magnetic materials and thin magnetic films, while relatively few techniques are available for characterizing magnetic properties at the edges of patterned films. Because switching behavior depends strongly on edge conditions in patterned films,[1–5] the need for magnetic edge characterization is becoming more acute as thin-film devices are made smaller.

A localized probe is needed to investigate the magnetic properties near an edge, and the “edge mode” of magnetization precession appears promising. In magnetic stripes that are magnetized in plane, perpendicular to the stripe axis, and with magnetization normal to the stripe edges, there are strong magnetostatic fields that reduce the internal field near the edges [see Fig. 1(a)]. The low fields near the edge lead to the formation of an edge-localized precession mode. This edge mode has been described recently as a trapped spin wave in the energy well created by the inhomogeneous magnetostatic fields.[6,7] Earlier studies of spin-wave propagation along the edges in garnet films recognized similar localization in films magnetized normal to the surface.[8–10] Because of their localized character, we anticipate that edge modes will be particularly sensitive to the material properties near the edge.

The magnetic behavior near an edge may be affected by edge roughness,[1–3] surface anisotropy on the edge surface,[4] compositional changes, oxidation, and edge profile geometry. This paper describes Brillouin light scattering (BLS) and ferromagnetic resonance (FMR) experiments coupled with micromagnetic modeling to investigate the sensitivity of the edge mode to the edge profile geometry.

II. EXPERIMENT

Stripes of $Ni_{80}Fe_{20}$ (Permalloy) were fabricated using interference lithography. A trilayer resist stack was used, consisting of an antireflective coating (ARC), a thin silicon oxide layer, and finally a resist layer deposited sequentially on a silicon substrate. The ARC prevents vertical standing waves in the resist during exposure. The resist was exposed in a Lloyds mirror interference lithography system with an Ar-ion laser (wavelength of 325 nm) and developed to create a grating pattern in the resist. A Permalloy film was then evaporated over the substrate using an electron-beam evaporator with base pressure in the 10^{-5} Pa (10^{-7} Torr) range, and the resist was subsequently removed using acetone. This process results in a large area array of Permalloy stripes on top of the oxide/ARC-coated silicon substrate. An electron mi-

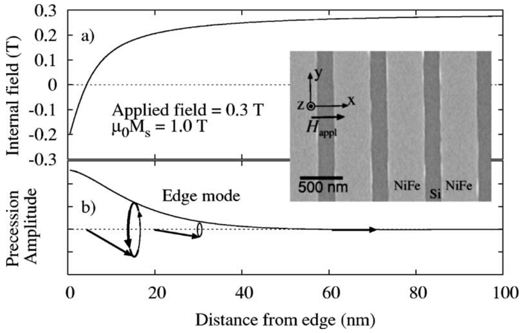

FIG. 1. Micromagnetic modeling results for the internal field and precession amplitude for an edge mode in a 12-nm-thick Permalloy stripe. The long axis of the stripe is parallel to $\hat{y}$. In (a) the field is reduced by magnetostatic fields near the edge. In the negative field region nearest the edge, the magnetization is stabilized by exchange forces. In (b), the precession amplitude is plotted for the edge-mode resonance at 9.33 GHz. The “bulk” resonance (not shown) is at 16.3 GHz. Inset: scanning elecron microscope image of the sample.

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croscope image of the stripes is shown in the inset of Fig. 1 along with the coordinate system. The stripes are 480 nm wide and nominally 12 nm thick with a period of 720 nm.

The magnetodynamic properties of the stripes were characterized using BLS and FMR measurements. Micromagnetic modeling was used to interpret the measurement results. The FMR measurements were made using a cavity spectrometer tuned to 9.8 GHz for fields applied in the *x*-*y* plane and in the *x*-*z* plane.

The BLS measurements were performed with a scanning (3+3)-pass tandem Fabry-Pérot interferometer[11] and an offset backscattering configuration, as described by Johnson *et al.*[12] The incident laser beam was offset at 3.9 mm relative to the axis of the collection lens, and the normal of the substrate was parallel to this axis, so that the range of detectable wave vectors (component parallel to the surface of the substrate) of scattering spin waves extended to zero. The maximum detectable wave number was 5.4 μm^{-1} (limited by the aperture of the collection lens). The measurements were performed in the absence of microwave excitation with a series of fields applied within 1° of the *x* direction (perpendicular to the axes of the stripes).

Computational experiments were performed using the OOMMF micromagnetic code.[13] An isolated 480-nm-wide × 12-nm-thick stripe was modeled using a 2 nm cell size and parameters corresponding to Permalloy. A quasi-two-dimensional (2D) approach was achieved by making the cells 10 μm long in the *y* direction. For a given applied field, the magnetization was allowed to come to equilibrium and then disturbed with a short field pulse that rotated the magnetization less than 1° away from equilibrium. The magnetization was then allowed to evolve using Landau-Lifshitz-Gilbert equations of motion. The resulting time series $M_z(t)$ are Fourier transformed to obtain a power spectrum with peaks corresponding to the resonances of the stripe. Identification of the various resonances as bulk or edge modes was achieved through mode imaging.[14]

III. RESULTS AND DISCUSSION

At the core of this investigation is a comparison between the behavior of stripes with ideal edges as determined by micromagnetic modeling and physical experiments on a real array of stripes.

Micromagnetic modeling results for stripes with ideal edges are presented in Fig. 2. Representative equilibrium magnetization patterns for three field ranges (labeled I, II, and III) are shown in Fig. 2(a). For applied fields below 24 mT (range I), the applied field slightly tilts the magnetization away from its zero-field orientation along the stripe axis towards the *x* direction. For applied fields between 24 and 164 mT (range II), the center of the stripe is very nearly aligned with the field, but there are clearly unsaturated edge domains where the magnetization has a component along the *y* axis. For fields above 164 mT (range III), the equilibrium magnetization has no *y* component, and the center and edges are effectively saturated.

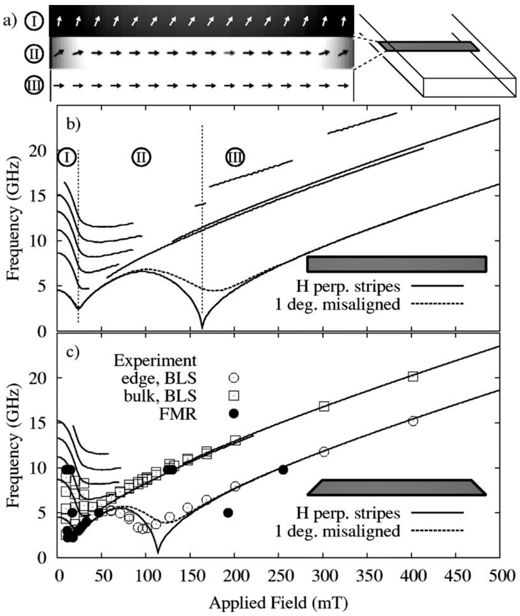

FIG. 2. Micromagnetic modeling and BLS and FMR results for 480-nm-wide × 12-nm-thick Permalloy stripes. (a) Representative equilibrium magnetization states corresponding to applied field ranges shown in (b). Modeled resonance frequencies are plotted for stripes with (b) vertical edges and (c) 45°-tapered edges. In (c), resonance values from the FMR and BLS measurements are included for comparison. The dashed lines are model results for in-plane applied fields misaligned with the stripe perpendicular by 1°.

Precession frequencies were determined by perturbing the ground state calculated for each applied field. The frequencies of modes that couple significantly to a uniform pulse field are plotted as solid lines in Fig. 2(b). Similar results have been obtained using finite element techniques.[15] At the lowest fields (in range I) where the magnetization lies nearly parallel to the stripe axis, the normal modes in similar systems have been described as standing spin waves[6] with the dynamic magnetostatic fields creating effective pinning conditions at the edges.[16,17]

In field range III (above 164 mT), the lowest-frequency mode is the edge mode, where the precession is localized at the edge. In the higher-frequency modes, the precession occurs mainly in the bulk of the stripe.

The intermediate field range (II) is a transitional region where the ground state is nonuniform. As the applied field increases through this region, the edge mode[18,19] or modes[19] become distinct from the bulk modes.

The edge saturation field at 164 mT is a critical point where there is just enough applied field to counterbalance the demagnetization fields and align the magnetization normal to the edge. At this critical field, the edge spins have zero stiffness in the *y* direction, i.e., for a small tilt of the magnetization towards the *y* direction there is no restoring torque. As a consequence of zero stiffness, the edge-mode frequency goes to zero at a point corresponding to the edge saturation field.

Misalignment of the field from the edge normal produces a large change in the edge-mode behavior near the saturation field. The dashed line in Fig. 2(b) is calculated for fields applied in plane, 1° away from the edge normal. Even this small misalignment produces a dramatic increase of the frequency minimum from zero and increases the field where the minimum edge-mode frequency appears. This effect might have serious consequences when measuring samples with rough edges.

For comparison, the BLS results are plotted as open squares in Fig. 2(c). For each applied field, multiple resonances are observed. For applied fields above 70 mT, the BLS spectra consist of a main peak that we attribute to the precession in the bulk of the stripe, and a less intense peak at lower frequencies that we attribute to the edge mode. Often the main peak can be resolved into two closely spaced peaks, due to the fact that two bulk standing-wave modes coexist at this field and frequency (this interpretation is strongly supported by the micromagnetic modeling). The frequency of the edge mode goes through a minimum of 3.2 GHz near 97 mT and then increases monotonically for higher applied fields.

Ferromagnetic-resonance results are also plotted in Fig. 2(b), as filled circles. Similar to the BLS results, the bulk resonance at 9.8 GHz is a double peak and the high-field edge mode and the low-field resonances are less intense.

The edge-mode frequency minimum in the BLS data shows the rounding expected from slight misalignment, but the field for this minimum is much less than the edge saturation field predicted by the micromagnetic model using ideal edges. We note that the experimental results of Bailleul *et al.*,[7] using different stripe dimensions, also suggest an edge-mode minimum frequency (120 mT) well below the micromagnetic modeling result (270 mT).

A better agreement between the model and the BLS frequencies is achieved with a model that features 45°-tapered edges, as seen in Fig. 2(c). Note that the bulk mode frequencies are almost identical in Figs. 2(b) and 2(c); only the edge modes change appreciably with the change in edge profile.

While the agreement between the BLS results and the tapered edge model is suggestive, we cannot firmly conclude from this that the edges are actually tapered. Future investigations may reveal that other effects, possibly including edge surface anisotropy, compositional changes, and edge roughness, also produce reductions in the edge saturation field.

However, the FMR spectra taken with the fields applied over a range of angles out of plane suggest that at least part of the reduction in edge saturation field is due to tapering. Because the edge surface normal is different on the two edges of a stripe when there is tapering, we might expect that the angular dependence of the edge-mode resonance field will be different for the two edges. Figure 3 shows the single edge mode in the in-plane orientation (0°) at 9.8 GHz splitting into two modes at an applied field angle of about 42°. The edge resonances superpose at lower angles where the angular dependence is not as great.

IV. CONCLUSIONS

In this paper, we have shown that the edge mode of precession, which can be detected and characterized with the BLS and FMR techniques, is a sensitive probe of edge conditions. We have also identified the edge saturation field as a convenient quantity for characterizing the magnetic properties at a film edge. In modeling the edge behavior in 12-nm-thick stripes, we find that the edge saturation field depends strongly on the edge properties, decreasing 42% when the edge profile is changed from vertical sidewalls to a 45°-tapered edge. The modeling results for this tapered edge closely match our experimental results from stripes created using interference lithography, suggesting that these stripes may have somewhat tapered edges. Further support for this interpretation of the data is given by out-of-plane FMR measurements, which show a splitting due to an asymmetry in the internal fields consistent with edge tapering. We believe that edge-mode characterization through the combination of modeling and resonance spectroscopy provides a valuable tool for looking at the properties of the edges of small magnetic elements, which become more and more important as interest shifts to smaller dimensions.

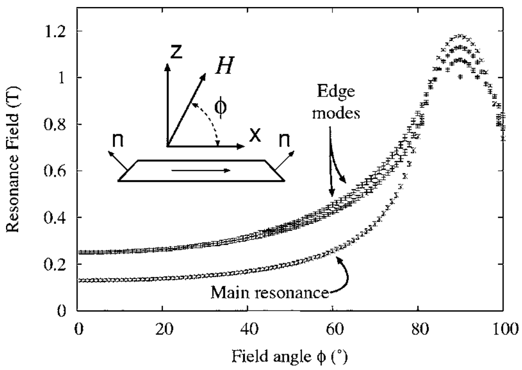

FIG. 3. Ferromagnetic-resonance fields for fields applied at angles between the in-plane stripe perpendicuar (x axis) and the sample normal (z axis). The modes visible below the main resonance line at 90° are standing spin waves across the width of the stripes.

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