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Zero-bias-field microwave dynamic magnetic properties in trapezoidal ferromagnetic stripe

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ABSTRACT

Dynamic magnetization response of the axially magnetized ferromagnetic stripe with trapezoidal cross section has been studied. The stripe with beveled edges exhibits multiple resonant peaks modes under an in-plane microwave excitation compared with the single resonant of vertical edge surfaces. The complexity of the observed response is attributed to the spatially nonuniform equilibrium spin distribution at the stripe edges. Micromagnetic simulations identify spin waves as spatially localized mode at the modified edges. This one is also described by effective pinning boundary conditions taking into account finite-size effects, which is related to the exchange interaction, surface anisotropy and dipole–dipole interaction. These results provide detailed insights into the nonlinear spin dynamics of microstructures influenced by the edge properties.

1. Introduction

Over the past years, much effort has been dedicated to the static and dynamic properties of patterned ferromagnetic films both from fundamental point of view and for numerous potential applications. Specially, understanding and monitoring high frequency characteristic has become a great challenge for developing microwave devices at GHz frequencies [1,2]. One particular area of interest concerns the magnetic properties of film edges in magnetic elements since they are known to play a critical role in the magnetic behavior of the devices [3–7]. The need for magnetic edge characterization is becoming more acute as thin-film devices are made smaller. For example, magnetization reversal behavior depends strongly on edge conditions in patterned films, because switching often occurs via nucleation of a vortex at the film edge [8–13].

A fundamental challenge has been to understand how microscopic mechanisms—including relative interactions and activated spin waves—determine the nanoscale magnetization dynamics near the edge. To address this challenge, several methods have been developed to detect localized magnetic precession modes. In the long magnetic rod with rectangular cross section, Brillouin light scattering technique experiments have probed the trapped spin wave in the energy well created by the inhomogeneous magnetostatic fields [14,15]. Due to the incidence of light always perpendicular to the stripes, these magnetic dynamics exist as spin wave resonances across the stripe width and are referred to two cases: the Damon–Eshbach geometry where the direction of the static magnetization and the propagation direction of the spin wave are perpendicular to each other and the magnetostatic backward volume geometry where the two vectors are collinear within the film plane. The propagation of spin-wave packets have been directly observed using time resolved Kerr microscopy [4,16,17]. Close to the edges, demagnetizing effects are responsible for a strongly decreased effective field, creating conditions for the localized precession of an edge mode. The inhomogeneity of the magnetization does not allow for a quantitative modeling of the spin dynamics.

Further, it is now recognized that the domain wall structure and the magnetic response involve the surface anisotropy, which is defined as boundary conditions [18]. In addition to Kettel's term [19], the approach contains contributions from the exchange interaction as well as from Neel surface anisotropy is proposed by Rado and Weertman [20]. The more general boundary conditions are important to calculate the spectra of magnetic nonlinear excitations in the element. Such dynamics researches were extensively carried out, but most of these were analyzed assuming quasiuniform equilibrium spin distributions and the nonuniform dynamics, described mainly in the case of transversely magnetizatized stripes [21]. The main purpose of this paper is to investigate both experimentally and theoretically the zero-field dynamic permeability spectra of soft ferromagnetic stripes possessing beveled edges. As a result, microwave permeability spectra exhibiting multiple narrow resonances were observed. The

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attempts for interpreting such magnetic excitations were performed with the help of micromagnetic models in two-dimensional periodical boundary conditions within the plane.

2. Experiment and simulation

Series of FeCoNbBCu stripes with approximately 160 nm thick have been fabricated on (100)-oriented Si substrates at ambient temperature. A scanning electron microscopy (SEM) image of the array is shown in Fig. 1(a). The stripes of width 3.4 μm are 10 mm long, and the center-to-center spacing is 11 μm. The stripes with trapezoidal and rectangular cross section were patterned by deep ultraviolet lithography, RF magnetron sputtering deposition and subsequent lift-off processes. The beveled edges were obtained by vertical standing waves in the resist during exposure. The spacing is large enough to avoid influence of the dipolar interaction between elements. SEM images of the single stripe with straight and beveled edges are shown in Fig. 1(b) and (c), respectively. In the micromagnetic modeling, we used material parameters including saturation magnetization $M_s=9.6\times10^5$ A/m and exchange stiffness $A_{ex}=9\times10^{-12}$ J/m. To obtain the static magnetic configuration, a bias field is applied for fully magnetizing the element and then reduced to zero allowing for the magnetization to relax. The dimensionless damping α was chosen to be 0.5 for rapid convergence. As for dynamic simulations, a microwave field $h_{(t)} = 7.96 \times \exp(-7.675)$ perpendicular to the strip was applied and α was set to 0.01. The dynamic results were analyzed in the frequency domain by performing fast Fourier transform (FFT) processing.

3. Results and discussions

The modeled stripes with different edge structures are displayed in Fig. 2(a). Fig. 2(b) and (c) shows the frequency-swept ferromagnetic resonance spectra of the straight- and beveled-edges stripes, respectively. The zero-field magnetization dynamics of the samples are measured using the shorted microtrip transmission-line perturbation method over the range of 0.5–3 GHz. The distinct resonances in the spectra are identified by comparison with the simulation results of micromagnetic modeling. The simulation involves a sequence of ground-state, microwave-field excitations followed by Fourier transform of the induced response. From the experimental data a clear variation in the dynamic magnetization response is observed with the edge geometry. We have prepared the straight-edge stripes with different thicknesses. All the susceptibility maps show a single peak. However, as the edge inclines at an angle multiple modes appear. In the case of stripe with beveled edges a dramatic change occurs and three clear peaks are observed in the susceptibility spectrum as a consequence of highly nonuniform oscillations. The phenomenon indicated that the slope of the stripe edge could lead to the spatially nonuniform equilibrium spin distribution, which is related to localized spin wave mode. The peak at the center has the highest intensity. The third and first peaks are next in amplitude. In fact, the existence of localized spin waves commonly referred to as edge modes energetically far below the spin-wave dispersion for propagating modes in the center, which is not shown in the figures. By tracking the time evolution of the local magnetization in each simulation cell, we use the FFT method to get the excitation spectrum. The amplitude and phase of the Fourier Transform in each cell are put together to reconstruct the amplitude and phase profiles of oscillation of the stripe for each single frequency. The peaks at certain frequencies indicate the presence of eigenmodes. Fig. 2(c) shows the FFT spectra of the simulated time-domain magnetization, which qualitatively reproduces the experimental results. For the straight-edges stripe, the peaks in both experimental and simulated results are fixed at 2.45 GHz. The relative intensities and precise positions of the peaks for the beveled edges are more complicated due to the edge roughness and other defects in the experimental samples. Nevertheless, the important features of the spectra are reproduced by simulation.

Fig. 3 shows the spatial distribution of magnetization m_x for single and multiple resonant peaks of labeled modes in Fig. 2 (b) and (c), respectively. The time evolution of the magnetization for these modes was investigated because spin-wave resonances are known to reflect local variations of magnetization $M(x, y, z)$.

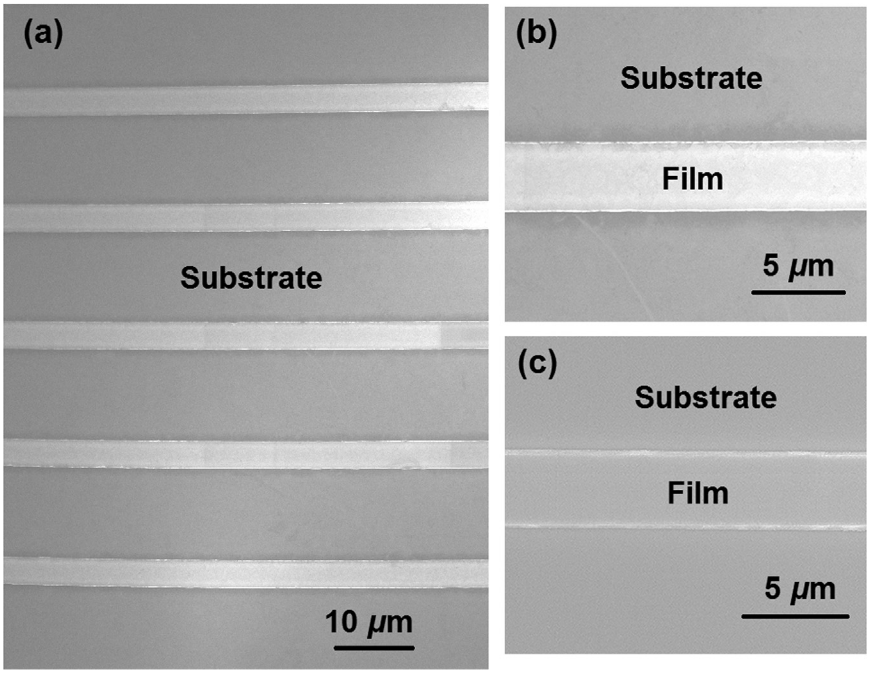

Fig. 1. (a) SEM micrographs (top view) of stripes on a Si substrate. The single stripe with (b) straight and (c) beveled edges has been zoomed in.