Observation of localized ferromagnetic resonance in a continuous ferromagnetic film via magnetic resonance force microscopy

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We present Magnetic Resonance Force Microscopy (MRFM) measurements of Ferromagnetic Resonance (FMR) in a 50 nm thick permalloy film, tilted with respect to the direction of the external magnetic field. At small probe-sample distances the MRFM spectrum breaks up into multiple modes, which we identify as local ferromagnetic resonances confined by the magnetic field of the MRFM tip. Micromagnetic simulations support this identification of the modes and show they are stabilized in the region where the dipolar tip field has a component anti-parallel to the applied field.

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Magnetic resonance force microscopy (MRFM) provides a route to detection of magnetic resonance with excellent spin sensitivity and spatial resolution and has received considerable attention. Detection of electron spin resonance, nuclear magnetic resonance and ferromagnetic resonance (FMR) with this approach has been reported. The high sensitivity of MRFM when combined with the imaging mechanism of Magnetic Resonance Imaging (MRI) allows excellent spatial resolution in non-interacting spin systems. Studies of patterned films show FMR can be detected in individual microstructures with high sensitivity. As a consequence of the strong interactions between spins in a ferromagnet the excitations are collective (magnetostatic) modes, so the assumptions on which MRI is based are invalidated, however recent work shows MRFM is also a promising technique for spatially resolved FMR: Obukhov et al., at OSU demonstrated that the large field gradient of the micromagnetic probe enables ferromagnetic resonance imaging of the magnetostatic modes of a 2 µm diameter permalloy dot with ~ 250 nm resolution

Here we argue that the micromagnetic probe locally stabilizes magnetostatic modes detected in FMR thus indicating the potential for scanned probe imaging of magnetic properties of extended ferromagnetic films. Due to the strong interaction between the spins the resonance modes are collective excitations of spins in the entire sample, and in the case of the microfabricated samples, the FMR modes are defined by the geometry of the sample.

We study the dependence of the mode resonance field on the orientation of the film relative to the external magnetic field, and on the probe-sample separation. We find that localized FMR modes are spatially confined immediately below the MRFM probe magnet. This occurs because off the axis of the micromagnetic probe its dipolar field is negative and, so reduces the magnitude of the total magnetic field stabilizing a confined mode. To understand the nature of these modes and their behavior, we performed micromagnetic simulations based on a finite element solution of the Landau-Lifshitz (LL) equation with damping. The simulations reveal that the degree of localization can be controlled not only by the sample-probe separation, but that it is also very sensitive to the tilt angle between the film and the applied magnetic field. These results demonstrate confinement of the magnetostatic mode by the localized inhomogeneous field of the probe, a mechanism distinct from geometrical confinement such as was studied in Ref. 10.

FIG. 1: (Color online) Schematic of the experiment. The sample is tilted and placed in the uniform external magnetic field \( \mathbf{H}_{\text{ext}} \). Here \( \mathbf{n} \) is the normal to the sample surface, \( \Theta \) is the sample tilt angle with respect to \( \mathbf{H}_{\text{ext}} \) and \( \Psi \) is the tilt angle of the equilibrium magnetization \( \mathbf{M}_s \). The MRFM probe field is aligned with the direction of \( \mathbf{H}_{\text{ext}} \) and its dipolar field reduces the magnitude of \( \mathbf{H}_{\text{ext}} \) in the region off to the side of the magnetic tip \( \mathbf{m} \).

The MRFM experiments were performed with the low temperature dual MFM/MRFM apparatus at Los Alamos National Laboratory. We used a commercially available silicon nitride cantilever (resonance frequency \( f_c \approx 8.0 \) kHz and spring constant \( k \sim 10 \) mN/m). The micromagnetic probe tip is a 2.4 µm diameter spherical Nd₂Fe₁₄B particle. Its silicon nitride tip was removed by focused ion milling, and the magnetic sphere was manually glued to the cantilever in the presence of an align-
ing magnetic field of a few kOe. The saturation magnetization of Nd₂Fe₁₄B powder was determined to be $4\pi M_s \approx 13.2$ kG at 10 K using SQUID magnetometry. The spatial field profile produced by the probe magnet has been carefully characterized \[11\]. For a detailed description of the MRFM apparatus we refer the reader to Ref. \[12\].

The 50 nm thick permalloy film was deposited on a 100 µm thick silicon wafer on top of a 20 nm thick Ti adhesion layer, and capped with a protective 20 nm Ti layer. An approximately $1.9 \times 1.9$ mm² sample was glued to the strip line microwave resonator. The temperature of the sample was stabilized at $T = 11$ K (temperature stability was better than 5 mK) and the frequency of the microwave field was set to $f_{RF} = 9.75$ GHz. Fig. 1 shows a schematic diagram of the experiment.

The in-phase component of the lock-in detected MRFM signal is shown in Fig. 2 as a function of the probe-sample separation for three values of the tilt angle $\Theta$ between the normal to the film plane and the direction of $\mathbf{H}_{ext}$ (as shown in Fig. 1). The sample tilt angle was determined by measuring the deflection of a laser beam reflected off the film surface at room temperature and found to be $1.0^\circ$, $3.4^\circ$ and $5.4^\circ$. While the absolute uncertainty of the sample tilt at low temperatures is $\approx \pm 1.0^\circ$, mainly due to thermal contraction of the glue used to hold the sample in place, the relative uncertainty of the tilt angles at low temperature is better than 0.1 degree. These tilt angles were confirmed by the measured values of the resonance field $H_{ext}$ at large probe-sample separations (discussed further below).

All spectra shown in Fig. 2 exhibit very similar evolution as a function of probe-sample separation. A single fundamental resonance mode is observed at distances greater than a few micrometers. The resonance field of this mode changes as the probe approaches the sample surface (Fig. 2a). At larger values of $\Theta$ (Fig. 2b, c) splitting of the fundamental mode is observed at small separations. The magnitude of this splitting increases with increasing $\Theta$ (Fig. 2b).

In order to better understand the evolution of the MRFM signal, we performed FMR studies as a function of $\Theta$ in a conventional FMR spectrometer. In Fig. 3 we show the angular dependence of the resonance field for the permalloy sample. Conventional FMR experiments were performed at NCSU. The data were obtained in a uniform applied field $H_{ext}$ and are equivalent to the MRFM resonance spectra acquired at large values of the probe-sample separation. In fact, the MRFM and conventional FMR sets of data exhibit excellent agreement as shown in Fig. 3. The value of the ferromagnetic resonance field in a continuous film for a given $\Theta$ is determined by the dispersion relation \[13\]:

\[
\left( \frac{\omega}{\gamma} \right)^2 = [H_{ext} \cos(\Theta - \Psi) - 4\pi M_s \cos(2\Psi)] \times
\]

\[
H_{ext} \sin(\Theta - \Psi) + 2\pi M_s \sin(2\Theta) = 0.
\]

Here $\omega = 2\pi f_{RF}$ is the RF frequency, $\gamma$ is the gyromagnetic ratio, $4\pi M_s$ is the saturation magnetization and $\Psi$ is the tilt angle of the equilibrium magnetization as shown in Fig. 1. We neglect the anisotropy contribution because it is typically small ($\sim$ few Gauss) in uniform permalloy films \[14, 15\]. Equations 1 and 2 cannot be solved analytically, so we solved them numerically; the results are shown in Fig. 3 by the solid line. We used the conventional FMR data set to verify the values of $4\pi M_s = 11.3$ kG, and $\gamma = 2.89 \pm 0.05$ GHz/kOe. With conventional FMR we never observed any multiple resonance structures reminiscent of those appearing in Fig. 2.

The origin of the isolated resonance modes seen in the MRFM studies can be understood in the following way. Conventional FMR theory assumes a uniform magnetic field throughout the sample \[16\]. The LL analysis shows that the presence of a position dependent inhomogeneous magnetic field of the probe may result in a
formation of localized FMR modes confined to the region where the field inhomogeneity exceeds the value of \( \Delta H_{\text{max}} \simeq 2\pi M_s(L/a) \) (where \( L \) is the thickness of the film and \( a \) is the radius of the localization) [10]. The MRFM probe produces an approximately dipolar field in the plane of the sample. In the simplest geometry \( H_{\text{ext}} \) and the tip’s magnetic moment \( m \) are parallel to each other. In this case the total magnetic field directly under the tip (uniform external field plus the dipolar field due to the tip) is higher than the external field, but off to the side it is lower than \( H_{\text{ext}} \) (see Fig. 1). In these two loci the field at which resonance occurs is shifted to higher and lower fields, respectively relative to resonance in the external field alone. While the modes shifted down in field may overlap with the bulk magnetostatic modes, the modes shifted up in field are well isolated, so they can readily be used to perform local MRFM spectroscopy.

In order to quantify this picture we have conducted micromagnetic simulations based on the Landau-Lifshitz (LL) equation with damping:

\[
\frac{\partial \mathbf{M}}{\partial t} = \gamma \mathbf{M} \times \mathbf{H}_{\text{tot}} - \frac{\lambda}{M_s^2} \mathbf{M} \times \mathbf{M} \times \mathbf{H}_{\text{tot}},
\]

where \( \lambda \) is the damping coefficient. The total magnetic field \( \mathbf{H}_{\text{tot}} \) experienced by the sample magnetization \( \mathbf{M} \) consists of the external, probe, dipolar, exchange and anisotropy fields. The numerical solution of Eq. 3 for this field configuration provides the information about the spatial profile of the FMR modes excited in the sample and their corresponding resonance fields. The details of the numerical approach and its application to a variety of systems will be presented elsewhere [17].

As numerical simulation of an infinite ferromagnetic film with an inhomogeneous external field profile is difficult we simulated a finite ferromagnetic thin film that was large compared to the phenomena of interest (250 \( \times \) 250 \( \mu \)m\(^2\) square with thickness 50 nm). The magnetic parameters chosen for simulations were obtained from the conventional FMR experiment: \( 4\pi M_s = 11.3 \text{ kG} \) and \( f_{RF} = 9.5 \text{ GHz} \). For the damping we used \( \lambda = 0.005 \text{ s}^{-1} \), a typical value for permalloy. Eq. 3 was linearized on a variable density pixel grid with higher pixel density in the vicinity of the probe magnet. The rare earth probe magnet was modeled as a 2.4 \( \mu \)m diameter uniformly magnetized sphere (4\( \pi \)\( M_s = 13.2 \) kG) placed at a height \( d \) measured from the surface of the sphere. The probe was positioned over the center of the film. Probe magnet parameters were experimentally determined in Ref. [11]. The orientation of the probe magnetic moment \( \mathbf{m} \) is assumed to be aligned with the direction of \( \mathbf{H}_{\text{ext}} \). The validity of the modeling approach was verified by comparing the modeling results for a tilted film (without MRFM tip) with the conventional FMR data (see Fig. 3). In the absence of the localized probe field, the fundamental (lowest frequency) resonance mode has a well known bell-shaped

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**FIG. 3:** (Color online) Angular dependence of the resonance field for the uniform \( H_{\text{ext}} \). Four data sets: conventional FMR data (\( \triangle \)), solution to Eq. 1 (solid line), MRFM data at large probe-sample separation (\( \bullet \)), and the results of the micromagnetic modeling (\( \square \)) are in good agreement. The numerical solution and the micromagnetic modeling were done using the same simulation parameters: \( 4\pi M_s = 11.3 \text{ kG} \), \( f_{RF} = 9.5 \text{ GHz} \), \( \gamma = 2.89 \pm 0.05 \text{ GHz/kOe} \). MRFM data were acquired at \( f_{RF} = 9.75 \text{ GHz} \).

**FIG. 4:** (Color online) Numerically calculated spatial profile of the excited transverse magnetization of the fundamental FMR mode in a 250 \( \times \) 250 \( \mu \)m\(^2\) permalloy film. The thickness of the film is 50 nm and it is tilted at an angle \( \Theta \) with respect to the direction of the applied magnetic field. The probe magnet is a 2.4 \( \mu \)m diameter sphere placed at a distance \( d \) over the center of the film, (0,0,d) \( \Theta = 0^\circ \), no probe magnet b) \( \Theta = 5.99^\circ \), \( d = 1.0 \mu \text{m} \), localized FMR mode at the location of the probe can be seen. c) Zoom-in onto the localized mode. Due to the sample tilt, the peak mode is localized to the side of the probe. All modes were calculated for the value of \( H_{\text{ext}} \) corresponding to \( f_{RF} = 9.75 \text{ GHz} \).
spatial profile, as shown in Fig. 4, and spans the entire sample. This result is in good agreement with earlier theoretical work \cite{18}. In the presence of the probe magnet, however, the mode changes its shape dramatically and is spatially confined to the region immediately beneath the probe magnet (see Fig. 4). A closer look at the probe axis localization (see Fig. 3) reveals confinement on the order of a few \( \mu m^2 \). This is the region of the sample where the dipolar field of the probe magnet opposes the externally applied field \( H_{\text{ext}} \). The asymmetry in the shape of the localized FMR mode with respect to the position of the probe magnet is due to the tilt of the sample, as illustrated in Fig. 1.

In Fig. 5 we compare the micromagnetic simulations of the evolution of the fundamental FMR mode with the experimental points taken from the dotted line in Fig. 2. The values of the sample tilt angle \( \Theta \) used in simulation where the evolution of the fundamental mode with the experimental work \cite{18}. In the presence of the probe magnet, however, the mode changes its shape dramatically and is spatially confined to the region immediately beneath the probe magnet (see Fig. 4). A closer look at the probe axis localization (see Fig. 3) reveals confinement on the order of a few \( \mu m^2 \). This is the region of the sample where the dipolar field of the probe magnet opposes the externally applied field \( H_{\text{ext}} \). The asymmetry in the shape of the localized FMR mode with respect to the position of the probe magnet is due to the tilt of the sample, as illustrated in Fig. 1.

In conclusion, we have observed FMR modes stabilized in a confined region defined by the localized field of micromagnetic probe field. These are observed when the sample is tilted with respect to the orientation of the probe axis thus subjecting the sample to the negative dipolar field produced off the axis of the probe magnet. Our micromagnetic simulations accurately describe the experiments and find the modes to be confined to a region of order a micron across. Our experiments point to the possibility of spatially resolved FMR (e.g. imaging and characterization of defects and magnetic inhomogeneities) in continuous ferromagnetic films.

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