

Magnetization Reversal in Micron-Sized Magnetic Thin Films

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We have measured and simulated the dynamics of magnetization reversal in 5 nm by 0.8 by 1.6 μm $\text{Ni}_{60}\text{Fe}_{40}$ thin films. The films measured form the upper electrode of a spin-polarized tunnel junction so that the magnetization direction of the film can be probed by measuring the tunneling resistance of the junction. When a magnetic field pulse is applied, the time to switch the film magnetization changes from greater than 10 ns to less than 500 ps as the pulse amplitude is increased from the coercive field to 10 mT and beyond. We have simulated these transitions using micromagnetic modeling of the exact experimental conditions. The simulations agree well with the experimental measurements. [S0031-9007(98)07661-3]

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In this paper we will investigate the dynamics of magnetization reversal in micron-sized magnets. This will be done both from measurement and modeling points of view. While the switching times of small ferromagnetic objects have been measured many times in the past [1], none of these earlier measurements were made in micron-sized objects with picosecond time resolution. Recently several groups have made picosecond time resolution measurements using magneto-optic [3] or inductive probing [2] of the sample magnetization on larger samples. Also, while there has been widespread use of micromagnetic modeling to study the static properties of small structures, time domain simulations of how such micron-sized structures switch are rare [4]. As far as we know, this is the first paper where both measured and simulated dynamical properties are quantitatively compared on micron-sized magnetic samples.

In order to measure the magnetization reversal in micron-sized films, we chose to use spin-polarized tunneling as a probe of the magnetization direction. In this way, a simple-to-measure change in the tunneling resistance between a pinned and a free magnetic layer can serve to probe the magnetization dynamics of a micron-sized magnetic film. Using this method, we have measured the time required to reverse the magnetization direction in micron and submicron-sized thin films of a soft ferromagnet $\text{Ni}_{60}\text{Fe}_{40}$ in the 100 ps to 100 ns range. In order to understand and visualize the dynamics of the magnetization reversal in such films we have developed time-domain micromagnetic models of the experimentally measured films that exactly simulate the experimental conditions. By comparing the results of the simulations with the measurements, the simulations can be vetted and some of the needed parameters can be determined.

The sample structure consisted of two thin ferromagnetic films separated by an Al_2O_3 tunnel junction [5]. The bottom film, the pinned layer, was an antiparallel (AP)

pinned structure formed of two Co layers separated by a 0.6 nm Ru film. The top film, the free layer, was a 5 nm layer of $\text{Ni}_{60}\text{Fe}_{40}$. The structures reported here were all 0.8 by 1.6 μm in size, but both smaller and larger ones were also tested. There was a uniaxial anisotropy of approximately 800 J/m³ along the easy (long) axis direction. Immediately above and below the magnetic tunnel junctions were aluminum and/or gold thin film cross stripes which were used to measure the tunnel junction resistance and to apply an easy axis magnetic field to switch the magnetization direction of the free layer (see inset of Fig. 3). For the small fields applied in this experiment, the magnetization of the pinned layer does not reorient. Spin-polarized tunneling between the two magnetic layers provides a magnetoresistance effect in the range of 10% to 20%, which was used as a simple probe of the sense of the magnetization along the easy axis direction.

A pulse generator was used to create current pulses with less than 40 ps rise times through the upper cross stripe. In this way, short magnetic field pulses could be applied in the easy axis direction of the free layer. A dc current bias was applied across the junction which meant that when the junction resistance changed, a voltage pulse was created across the junction. Hence, the magnetization vs time of the free layer could be determined by measuring the voltage between the upper and lower stripes using a sampling oscilloscope. There were also two large external coils that were used to apply dc fields in the hard and easy axis directions.

To understand these results we constructed a time domain simulation of the Landau-Lifshitz-Gilbert (LLG) equations of motion for our samples [4]. Our micromagnetic simulations modeled the film as a two-dimensional array that was 256 by 128 blocks in size. Each block was 6.25 nm by 6.25 nm by 5 nm in dimension. The magnetostatic field was calculated using fast Fourier transform (FFT) methods and the LLG equations were

integrated in time using a fourth order predictor-corrector method with an 0.8 ps time step. The value of the damping parameter α used was 0.01. In the simulation we applied the same field waveform as in the measurement, and recorded the average magnetization of the films and snapshots of the magnetization pattern.

Figure 1(a) plots the measured magnetization when easy axis magnetic field pulses were applied to the sample. The pulse amplitudes ranged from 1.4 to 12.6 mT, zero to peak, and the period was 10 ns. The hard axis field was nominally zero. The y-axis scale is the reduced magnetization, i.e., the average magnetization of the sample in the easy axis direction normalized by the saturation magnetization. The conversion from sampling scope voltage to the reduced magnetization is calibrated by knowing the change in voltage when the sample magnetization is completely reversed at very low frequencies. The noise on the plot represents instrumental noise. As the drive amplitude is increased, the reduced magnetization starts to change for amplitudes greater than about 2 mT, and saturates for fields greater than about 6 mT. The rise time of the change in magnetization also gradually decreases as the pulse amplitude is increased.

Figure 1(b) plots the simulated switching for the same range of applied fields as the measured data. There is good qualitative agreement between the measured and simulated

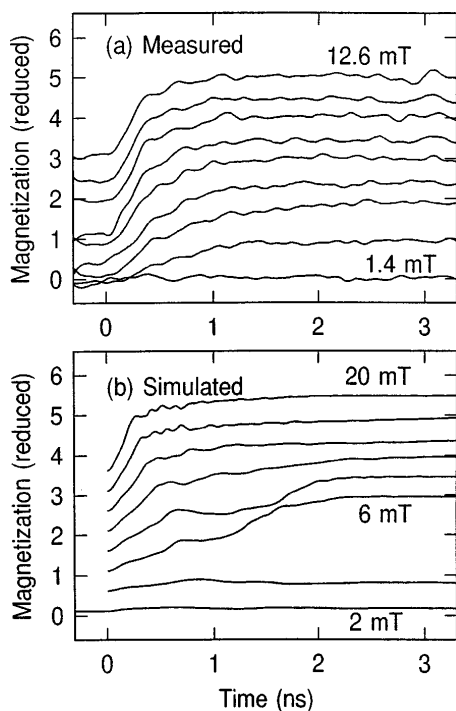


FIG. 1. (a) Measured reduced magnetization vs time for easy axis pulse amplitudes (zero to peak) of 1.4, 2.8, 4.2, 5.6, 7.0, 8.4, 9.8, 11.2, and 12.6 mT. The hard axis field was nominally zero. The curves are offset for clarity. (b) Simulated reduced magnetization vs time for easy axis pulse amplitudes of 2, 3, 6, 8, 10, 12, 15, and 20 mT.

data, although the measured data lack some of the fine structure of the simulated data. We believe this results partially from the lack of exact edge definition in the real samples [6]. The simulated images of the magnetization pattern vs time are shown in Fig. 2. The results show that in this range of parameters for our sample, the switching occurs in three stages: In stage 1, the edge domains on the short sides of the film move in toward each other until they intercept. At that point, stage 2, the interior of the film rapidly rotates to align with the applied field. Before the magnetization is permanently switched, the edges of the film, which are still orientated in their approximate initial directions, must be reversed. In stage 3, the center section grows in size and eventually nucleates reversal on the edges of the film. For larger fields, beyond about 10 mT, the transition proceeds via a different topological route, where the stage 2 rotation of the center section occurs before the stage 1 motion of the domain walls toward the center is completed. This type of reversal, which is more characteristic of coherent rotation is considerably faster, but still requires stage 3 to occur.

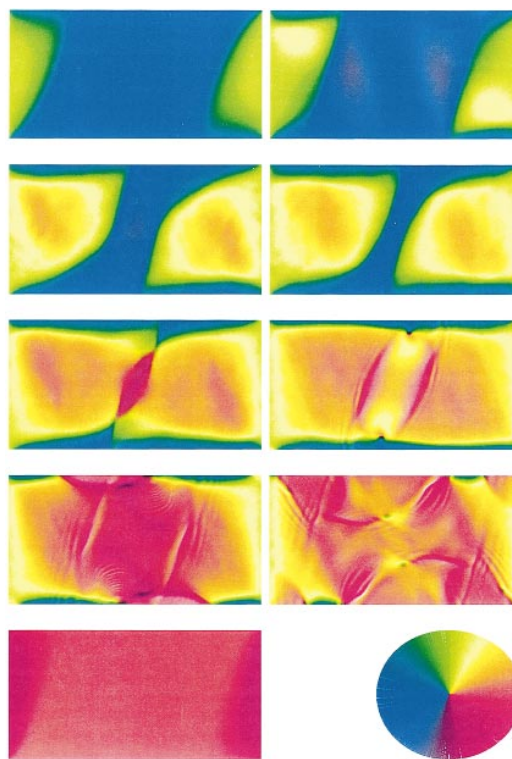


FIG. 2(color). Simulated images of the magnetization vs position of the film as function of time after application of a 7 mT easy axis field. In each image the easy or horizontal direction is $1.6 \mu\text{m}$ in size. The hard or vertical direction is $0.8 \mu\text{m}$ in size. The time points for the 9 images are 0, 0.25, 1.42, 1.59, 1.75, 1.90, 2.07, 2.32, and 6.61 ns after the application of the pulse. The color wheel indicates the local direction of the magnetization, e.g., blue green being the initial state in the minus x direction, and red the final state in the plus x direction.

Figure 3 plots the magnitude of the easy axis field required to switch the magnetization of the free layer vs the pulse duration for two values of hard axis field. The easy axis waveform was a pulse of a given magnitude $H_{\text{PULSE}}(\tau)$ and duration τ , followed by a dwell time at zero field, then a negative-going pulse of the same magnitude and duration, and finally another identical zero field dwell time. In the long pulse limit, the pulse amplitude required to switch the film was equal to the value of the coercive field H_c obtained using conventional dc measurements. As the pulse length became shorter, the amount of field required to switch the film increased. The two dashed lines are fits to the empirical form:

$$1/\tau = S_w^{-1}[B_{\text{PULSE}}(\tau) - B_c], \quad (1)$$

where B_c is the “dc” coercive field in tesla ($B_c = \mu_0 H_c$) and the switching coefficient [1] $S_w = L/\mu$. L is the sample length and μ is an effective mobility, which depends on the hard axis field. For zero hard axis field $\mu = 1.6 \times 10^5$ m/Ts. This type of relationship between the pulse duration and magnitude required to switch the film results from the nature of the magnetization reversal in this field and size range. The switching proceeds by the mechanism of viscous domain wall motion and $B_{\text{PULSE}} - B_c$ represents the net magnitude of the driving force. The same type of relationship between the drive field and the switching time has been found on much thicker films, where the damping that resulted in the measured mobility is a result of eddy currents [7]. In these smaller and thinner films the dominant damping is not from eddy currents but is intrinsic to the material, i.e., α .

Figure 4(a) plots the magnetization vs time for another sample when a series of 200 ps easy axis pulses were applied with a hard axis field of 5 mT. Because the

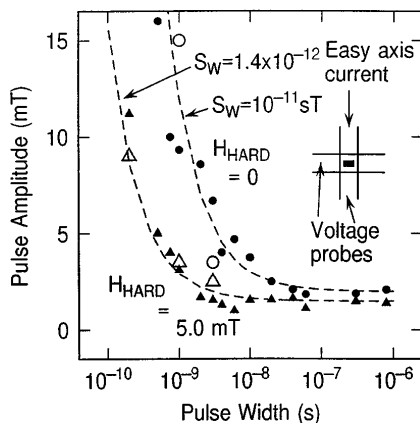


FIG. 3. Measured switching time τ vs easy axis pulse amplitude $H_{\text{PULSE}}(\tau)$ with two values of the hard axis field, dots (0 T) and triangles (5 mT). The dashed lines are Eq. (1) with the indicated values of S_w and H_{dc} of 2 and 1.5 mT for the two value of hard axis field. The open dots (0.1 mT) and open triangles (5 mT) are the switching fields predicted from the micromagnetic simulation. Inset: A plan view of the junction geometry.

pulse width was shorter, the field required to switch the film was larger. Comparisons of this measured data with our simulation are shown in Fig. 4(b). As can be seen there is good agreement between the shapes and frequencies of the measured and predicted results, although the rounding of the static M vs H curve was less in the simulation than what was measured. This reduced the maximum change in reduced magnetization from about 1 in the simulations to 0.6 in the measurements. These oscillations are damped ringing of the average magnetization vector around the hard axis field that occur after the magnetization vector is pulsed by the switching field. Using the small angle approximation of the LLG equation [8] in a thin film geometry it is easy to show that the oscillation frequency

$$f_{\text{FM}} = \gamma \mu_0 \sqrt{H_{\text{hard}} M_S} / 2\pi \quad (2)$$

and the damping time $\tau_{\text{DECAY}} = 2/\mu_0 \alpha \gamma M_S$. M_S is the saturation magnetization. Using the measured $\mu_0 M_S$ for our films of 0.93 T, Eq. (2) predicts a resonant frequency of about 1.9 GHz if one ignores the demagnetization effects in the film. The measured frequency is lower and is about 1.8 GHz, which might be expected from the 0.8 μ by 1.6 μ m shape of the film. The measured decay time of about 1 ns can be used to infer $\alpha = 0.01$. A larger value for α would not produce results consistent with the measurements.

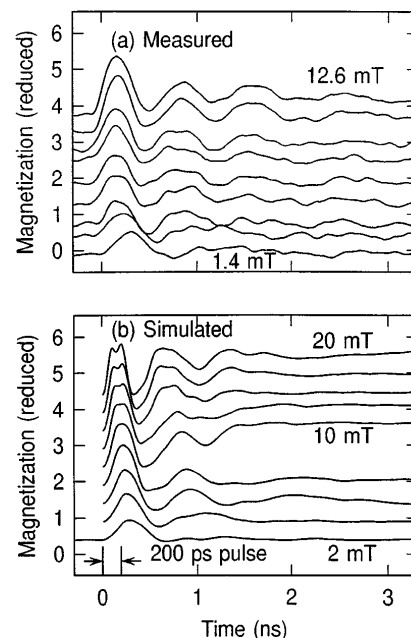


FIG. 4. (a) Measured reduced magnetization vs time for easy axis pulse amplitudes (zero to peak) of 1.4, 2.8, 4.2, 5.6, 7.0, 8.4, 9.8, 11.2, and 12.6 mT. The pulse width was 0.2 ns and the hard axis field was 5 mT in both (a) and (b). The curves are offset for clarity. (b) Simulated reduced magnetization vs time for easy axis pulse amplitudes of 2, 3, 6, 8, 10, 12, 14, 16, and 20 mT.

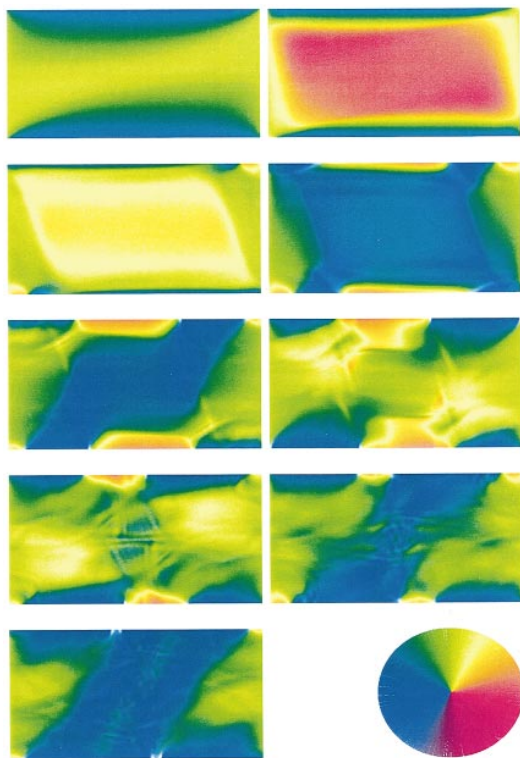


FIG. 5(color). Simulated results for a 8 mT pulse applied for 200 ps with a hard axis field of 5 mT. The time points are 0, 159, 279, 399, 519, 639, 849, 969, and 1089 ps after the pulse was applied. This time period spans almost 2 oscillations. The magnetization does not reverse.

Figure 5 plots the simulated results for the magnetization pattern when a 200 ps easy axis pulse is applied. The change from the first to the second frame corresponds to the average reduced magnetization in the easy axis direction rapidly increasing from -0.8 to $+0.7$ when the field is applied. By the next frame the easy axis field is again zero, and the magnetization has rotated back. The oscillation pattern can be seen in the last five frames, which represent one oscillation period. The magnetization pat-

tern is reminiscent of spin waves in a box. Given the complexity of these patterns, the ability of Eq. (2) to predict the primary oscillation frequency is remarkable. Finally, we note that the exact nature of the nucleation of the magnetization from the center to the edges of the film is very dependent on detailed nature of the edges, both in the simulation and the measurement. Further work needs to be done in this area.

In this paper we have discussed how a micron-sized magnetic object switches. Such a film represents the transition between larger objects that reverse primarily by domain wall mechanisms and smaller objects which behave as single domains and switch via coherent rotations of the magnetization vector. Measurements and micromagnetic simulations of larger and smaller films that discussed here show such limiting behavior.

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