Metastable States in Large Angle Magnetization Rotations

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***Abstract*—Large angle rotations were studied in Permalloy thin films and spin valve devices. It is shown that edge effects or inhomogeneities strongly influence the magnetization behavior under certain initial conditions. Complicated intermediate states can form which significantly increase the magnetization response time.**

***Index Terms*—Small particles, spin valves, switching, spin dynamics and relaxation, magnetocrystalline anisotropy.**

I. Introduction

THE operation of write heads, giant magnetoresistance recording heads, and magnetic random access memory in the gigahertz frequency range will require a detailed understanding of the underlying dynamics. However, very little information is available in the literature about the magnetization dynamics for large angle rotations and the gigahertz frequency range. Recently, excitation of spin waves in the switching process was examined theoretically [1] and through micromagnetic calculations [2], [3]. These calculations predict that: (a) in the process of switching, nonlinear spin waves are excited, with significant short time scale influence on the average magnetization, and (b) the presence of inhomogeneities should significantly influence the switching process.

In this paper, we experimentally address some aspects of these theoretical predictions in thin films and spin valves. It is demonstrated that inhomogeneities strongly influence the magnetization dynamics. As a consequence, complicated intermediate states can form in both small magnetic devices and single-layer films. The formations of these intermediate states significantly increase the device response time.

II. Experiment

We experimentally studied two types of samples. The first was a spin valve GMR device with dimensions $0.8\ \mu\text{m} \times 4.8\ \mu\text{m}$. The spin valve structure Ta(5 nm)/$Ni_{0.8}Fe_{0.2}$(5 nm)/Co(1 nm)/Cu(1 nm)/Co(3 nm)/Ru(0.6 nm)/Co(1.5 nm)/FeMn (10 nm)/Ta(5 nm) was sputter-deposited on high resistivity Si wafers covered with a thermal SiO_2 layer. In this device structure the exchange interactions between the free and pinned layers are minimized due to the low net moment of the pinned layer. The magnetization dynamics are predominantly confined to the free layer, and the device may be viewed, to first approximation, as a single, independent magnetic layer.

Measurements on the spin valve device were performed with the pin direction and the drive field along the hard axis, transverse to the long, easy axis of the device. A constant 1.0 to 2.0 mA bias current was applied to the device and the high frequency magnetoresistance signal was separated with a dc bias "tee" and measured with a commercial 20 GHz bandwidth sampling oscilloscope [4]. Current pulses, supplied by a pulse generator connected to a 50 Ω characteristic impedance microstrip write line above the device, create the driving magnetic field. The pulse rise-time was 100 ps and the pulse duration was 150 ps.

The second sample was a macroscopic 1 cm × 1 cm square, 50 nm thick Permalloy film. The film was fabricated by sputter deposition onto a 100 μm thick sapphire substrate. The substrate was glued to a 50 Ω characteristic impedance coplanar waveguide, with the film side up, to permit stroboscopic measurements of the dynamic response with the second harmonic magneto-optic Kerr effect (SHMOKE) [5], [6].

The film was biased along the easy axis with an external magnetic field of about 80 A/m (1 Oe) to sweep any domain walls out of the sample. Driving pulses of 1040 A/m (13 Oe) and 150 ps rise time and 2 ns pulse duration were applied along the hard axis in a manner similar to that of the spin valve. The field is supposed to be relatively uniform over the 500 μm wide center conductor of the coplanar waveguide.

Vectorial SHMOKE was used, allowing for the separation of M_x and M_y components. The SHMOKE apparatus is described in detail in [5], and its modification for vectorial SHMOKE measurements is shown in [6]. In the vectorial SHMOKE experiment, 60 fs light pulses at a wavelength of 800 nm, produced by a mode-locked Ti:sapphire laser, are focused on the sample in a p-incidence geometry in the middle of the center conductor of the coplanar waveguide. The spot size was 5 μm, and the peak intensities exceed 100 GM/cm^2. At such high power densities, the Permalloy surface acts as a second harmonic generator, producing reflected pulses at half the wavelength and collinear with the reflected pulses at the fundamental frequency. The fundamental component of the reflected light is then filtered out, and the second harmonic light passes through a photo-elastic modulator (PEM), an analyzer, and is directed into a photo-detector.

The signal from the photo-detector is processed by photon counting electronics, and, at the same time, serves as an input to the lock-in amplifier. In the p-incidence geometry, the signal from the photo-detector is proportional to the transverse (perpendicular to the plane of incidence) component of the magnetization. The signal from the lock-in amplifier (at the fundamental

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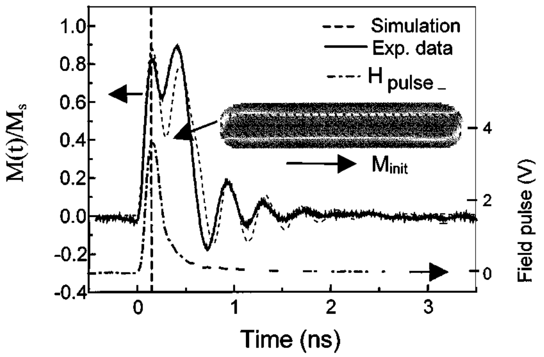

Fig. 1. The GMR response and simulated transverse magnetization ($\alpha = 0.02$) for a $0.8\ \mu$m$\times 4.8\ \mu$m spin valve subjected to 0.15 ns, 6.4 kA/m transverse field pulse. The dashed-dot line represents the applied magnetic field pulse. The inset shows a micromagnetic simulation of the magnetization state at 0.31 ns after the onset of the transverse field pulse.

or second harmonic of the PEM modulation frequency) is, on the other hand, proportional to the longitudinal (in the plane of incidence) magnetization component [6].

At set applied external bias fields, these signals are registered as a function of the delay between the incident laser pulse and the driving magnetic pulse supplied by the pulse generator. The delay between the two pulses is adjusted by an electronic delay generator with an rms jitter of 40 ps. The repetition rate of the laser is reduced to the maximum rate of the pulse generator (1 MHz) with an electronic pulse picker.

Application of the calibration procedure described in [6] allows the measurement of the absolute value of the magnetization and the angle of rotation as a function of time for different values of bias and pulse fields.

III. Results and Discussion

The measured response of the spin valve is shown in Fig. 1 as a solid line. The magnetic field pulse, applied along the hard axis, is shown as a dashed-dot line and has a maximum value of $\sim$8.4 kA/m. The displayed response is proportional to the average transverse magnetization of the spin valve free layer. For the applied field values, the magnetization rapidly rotates under the influence of the applied field within about 200 ps and reaches a maximum at close to 90 degrees with respect to its original direction. After the field pulse is turned off, the magnetization initially decreases following the field response. However, instead of following the field response completely, it oscillates about the 90 degrees direction for almost another 500 ps, and only then rapidly rotates back into the direction of final equilibrium position along the device (easy) axis, determined mainly by shape anisotropy. Afterwards, the magnetization undergoes damped oscillations for 2 ns, presumably due to the intrinsic damping of the magnetic material.

The observed behavior is unexpected if one assumes uniform rotation. Fig. 1 indicates that the drive pulse ends when the transverse component of the magnetization reaches its maximum value. One would assume that after the drive pulse is turned off, the magnetization, driven by the shape anisotropy, would rapidly return to its equilibrium position along the easy axis rather than persist in a high angle state for 500 ps.

A similar result follows from the solution of Landau-Lifshitz-Gilbert (LLG) equation with the additional assumption of Stoner-Wohlfarth single-domain particle energetics. The solution of the LLG equation predicts damped sinusoidal response with a characteristic half-cycle of 250 ps [7]. The observed time response in Fig. 1 is considerably different. The average magnetization oscillates about $M_t/M_s \approx 0.8$ for 500 ps before switching back to the initial state. The time response is therefore two times longer than expected. In the experiment, the magnetization stays "blocked" in a position that is almost perpendicular to the easy axis direction. This apparent blocking of the magnetic state can be reproduced with micromagnetic simulations [8] using a cell size of 10 nm. Simulation results are shown as a dashed line in Fig. 1. Experimental parameters listed in caption to Fig. 1 were used in simulations, with damping constant α as the only adjustable parameter. The result of the calculation, shown in Fig. 1 by the dashed line, describes reasonably well the experimental behavior. The simulated rise time is in good agreement with the experiment. The difference between the experimental and simulation curves can be attributed to the difference of the actual magnetic field pulse value from the nominal calculated value used in the simulation. The suppression of oscillations and the blocked state are clearly demonstrated, and follow as a natural consequence from simulations.

The inset in Fig. 1 displays the simulated magnetization pattern at time $t_0 = 310$ ps after the start of the field pulse. This time is indicated in Fig. 1 by an arrow and the inset. The inset shows the reason for the blocked state: the magnetization in the middle of the device continues to rotate when the applied field pulse is turned off, but the edges remain pinned, resulting in the formation of a kink in the magnetization pattern. This magnetization configuration is a consequence of the nonuniform demagnetizing fields. The state is metastable with boundaries between the regions of reversed magnetization orientations having domain wall-like features. At $t_0 = 310$ ps the dipole energy is at a local minimum and the exchange energy reaches its maximum. However, stable wall formation is frustrated by the small width of the device. The exchange energy is too large compared to the reduction in dipolar energy for long term stability. As a consequence, the magnetization in the middle of the device eventually swings back into initial direction.

The formation of such transient, blocked, states is not unique to small-sized particles, as we demonstrate in Fig. 2. Here, we present the time evolution of the angle of magnetization rotation in a macroscopic Permalloy film, as measured by SHMOKE. The solid symbols represent the SHMOKE signal response to 2 ns long, 1.04 kA/m (13 Oe) pulse in the hard axis. The anisotropy field of the sample was H_k =320 A/m. A field of 80 A/m, applied in the easy axis, is used to stabilize the hysteresis loop. The magnetization rotates into its new equilibrium direction, again close to 90 degrees, and oscillates in a sinusoidal fashion about the new direction in quantitative agreement with a numerical solution of the LLG equation. However, pathological behavior of the magnetization is apparent 2 ns

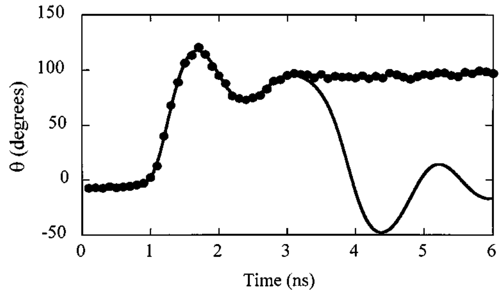

Fig. 2. Magnetization rotation angle as a function of time of a easy axis-biased Permalloy film subjected to a 2.0 ns magnetic field pulse. The easy axis bias field is 80 A/m. The measurement utilized the SH-MOKE technique. The pulse amplitude of 1.04 kA/m is applied along the hard axis. The solid line is the Landau-Lifshitz-Gilbert simulation result.

after the application of the field pulse, when the magnetization should return to its equilibrium value. Contrary to the expectations of simple, single-domain theory, the measured response lasts much longer. The magnetization clearly stabilizes in the hard axis direction for a time interval of more than 6 ns before it eventually returns into the easy axis direction. Determination of the exact relaxation time is difficult, given the finite delay of the boxcar averaging technique employed by us. However, the magnetization does indeed eventually return to $\theta = 0$ degrees within the 1 μs window before the arrival of the next field pulse, in light of the repetitive nature of the sampling technique.

The single-domain LLG equation solution is shown in Fig. 2 as a solid line. According to the LLG solution a uniformly magnetized sample should return quickly to $\theta = 0$ degrees upon cessation of the applied field. As follows from the experimental data in Fig. 2, this is not the case, and the magnetization stays blocked. The time response shown in Fig. 2 demonstrates that the magnetization of even a large macroscopic sample can stay blocked in an intermediate metastable position that is not expected from coherent magnetization dynamics, although the initial response to the applied field pulse is adequately modeled by single domain LLG.

We believe the underlying physics is similar to the earlier case of the spin valve. However, the nonuniformity in the magnetization is caused instead by spatial nonuniformities in the anisotropy of the film rather than the nonuniform demagnetizing fields due to the shape of the sample. It is well known that nonuniformity in the anisotropy distribution on a length scale comparable to the width of a domain wall (e.g., ripple) leads to the formation of metastable magnetization states similar to those observed in the spin valve experiments [9]. More specifically, spatially random anisotropy forces guide some fraction of the sample magnetization to relax in the $\theta = 180$ degree direction, in opposition to the rest of the sample. Exchange forces prohibit the sample from splitting into multiple domains and the magnetization becomes blocked. However, the absence of finite size effects (or in-plane shape anisotropy) in the macroscopic sample leads to greater relaxation time for the blocked state, allowing it to persist many nanoseconds after the termination of the field pulse. The presence of such metastable states could be deleterious for device performance. The elimination of this blocking is contingent on the removal of the inhomogeneities, either by the fabrication of particles that approach ideal ellipsoidal shape, or by improvement in material uniformity and crystalline homogeneity.

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