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Determination of the magnetic damping constant in NiFe films

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A two-dimensional, dynamic, micromagnetic model of a thin strip of permalloy is described and used to model the magnetization dynamics of the strip as it is subjected to a transverse step field. The numerical results are compared to experimental data. The experimental precession frequency is matched by varying H_k, the longitudinal, uniaxial, magnetocrystalline anisotropy field. The damping is matched by varying α, the phenomenological damping parameter in the LLG equation. A good fit to the data was obtained with a single damping constant of $\alpha = 0.013$. © *1999 American Institute of Physics.* [S0021-8979(99)65008-3]

I. INTRODUCTION

As data rates in magnetic recording increase past 100 MHz and toward 1 GHz, the need to understand the intrinsic dynamics of the magnetization becomes increasingly important. In this paper, numerical simulations are utilized to analyze high speed measurements of magnetization rotation in a NiFe thin film subjected to a transverse step field with a rise time of 50 ps. The numerical model allows for magnetization dynamical processes that, similar to magneto-resistive (MR) heads,[1] are nonuniform over the sample width.

First, the experimental procedure employed at the National Institute of Standards and Technology (NIST) is explained. Then, the micromagnetic model used to simulate the experiment is introduced. Results from the model are compared to experiment, and a value for the phenomenological damping parameter is deduced. The paper concludes with a discussion of the nonuniformities which form in the transverse direction. SI units and formulas are used throughout this paper.

II. EXPERIMENT

A schematic of the experimental apparatus used at NIST[2] is shown in Fig. 1. The transmission line consists of three gold strips, 50 μm wide, deposited side by side, 80 μm apart. A nonmagnetic layer, 1 μm thick, is deposited on top of the middle strip, and on top of that is deposited a 50 nm thick, 1 mm long layer of permalloy ($Ni_{80}Fe_{20}$). A constant, uniform longitudinal bias field is applied (H_{bias} in Fig. 1). A step voltage is applied to the middle strip; a current flows through this strip and returns through the two grounded side strips. The current rises almost linearly from 0 to its maximum value in 50 ps. This current creates a transverse magnetic field of 1.6 kA/m (20.4 Oe) (H_{step} in Fig. 1). Before the step field is applied, the bias field, as well as shape and uniaxial magnetocrystalline anisotropy, causes the magnetization in the permalloy strip to lie longitudinally with no domains. The step field rotates the magnetization in the transverse direction by some angle θ; this angle need not be uniform throughout the strip. A transverse magnetization gives rise to a flux which encircles the middle strip of the transmission line. A dynamic magnetization causes a changing flux, which creates an electric field according to Faraday's law. This induced field leads to a voltage which is detected.

III. MICROMAGNETIC MODEL

In the numerical model the strip is assumed to be infinitely long and so thin that it is sufficient to discretize only across the width (transverse direction) into 500 identical cells, each an infinitely long rectangular prism with a cross section of $0.1\,\mu\text{m} \times 0.05\,\mu\text{m}$. While still much larger than the exchange length of 12.5 nm, finer discretizations did not alter the results, since these micromagnetic simulations yielded magnetization patterns which were dominated by the magnetostatic field, not exchange. Within each cell the magnetization is uniform, with a constant magnitude of M_s, the

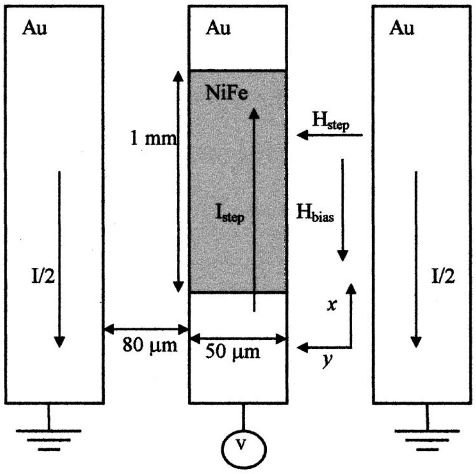

FIG. 1. Top view schematic of the transmission line used in experiments. The longitudinal direction is x, the transverse is y. The NiFe is 50 nm thick, and is separated from the Au by 1 μm of nonmagnetic material.

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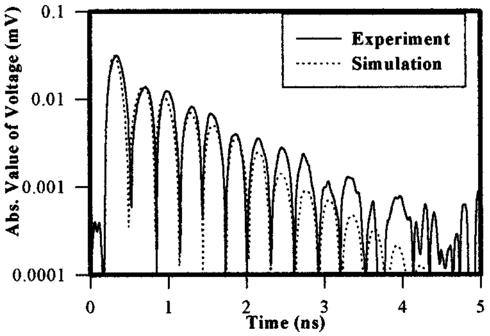

FIG. 2. Absolute value of voltage (on a logarithmic scale) vs time for both experiment (solid line) and micromagnetic simulation. The longitudinal bias field H_{bias} is 800 kA/m (10 Oe), the uniaxial magnetocrystalline anisotropy H_k is 960 kA/m (12 Oe), and the magnetic damping parameter α is 0.013.

saturation magnetization. The direction of the magnetization is assumed to evolve in time according to the Landau–Lifshitz equation:

$$\dot{\mathbf{M}} = -\gamma\mu_0\mathbf{M}\times\mathbf{H}_{\text{eff}} - \alpha\gamma\mu_0\frac{\mathbf{M}}{M_s}\times\mathbf{M}\times\mathbf{H}_{\text{eff}}, \qquad (1)$$

where $\mathbf{M}$ is the magnetization, $\mathbf{H}_{\text{eff}} = -\mu_0^{-1}\partial E/\partial\mathbf{M}$ is the effective magnetic field, E is the energy density, γ is the gyromagnetic ratio, μ_0 is the permeability of free space, and α is the phenomenological damping parameter. The effective magnetic field includes the applied field, the demagnetizing field, and effective fields arising from the exchange and magnetocrystalline anisotropy energies. The first term in Eq. (1) represents precession of $\mathbf{M}$ about $\mathbf{H}_{\text{eff}}$, which conserves energy. The second term describes the alignment of $\mathbf{M}$ with $\mathbf{H}_{\text{eff}}$, which dissipates energy at the rate

$$\frac{\partial E}{\partial t} = \frac{\partial E}{\partial\mathbf{M}}\frac{\partial\mathbf{M}}{\partial t} = -\mu_0\mathbf{H}_{\text{eff}}\cdot\dot{\mathbf{M}} = -\alpha\frac{\mu_0\gamma}{M_s}|\mathbf{M}\times\mathbf{H}_{\text{eff}}|^2. \qquad (2)$$

The effective anisotropy field is:

$$\mathbf{H}_{\text{ani}} = \hat{x}H_kM_y/M_s, \qquad (3)$$

where H_k is the longitudinal, uniaxial, magnetocrystalline anisotropy field.

The transverse component of $\dot{\mathbf{M}}$, averaged across the width of the sample, is proportional to the measured voltage. The constant of proportionality is determined by matching the height of the first peak of the simulation output with that of the experimental data. H_k is adjusted so the frequencies match, and α is adjusted so the second peaks match. Measurements indicate that $M_s = 840\,\text{kA/m}(840\,\text{emu/cm}^3)$ and $\gamma = 1.94\times10^{11}\,\text{s}^{-1}\,\text{T}^{-1}$; H_k for a codeposited sample was measured with a $B-H$ looper to be 340 A/m (4.3 Oe).

Figure 2 is a comparison of experiment and simulation for a longitudinal bias field of 800 A/m (10 Oe); H_k is set to 960 A/m (12 Oe), and α is set to 0.013. Figure 3 is a comparison of experiment and simulation for a longitudinal bias field of 480 A/m (6 Oe); H_k is set to 1120 A/m (14 Oe) while α is still 0.013. In both these figures, the voltage scale is logarithmic. The data are fitted very well to about seven peaks in Fig. 2 and ten peaks in Fig. 3, corresponding to an amplitude reduction of approximately an order of magnitude.

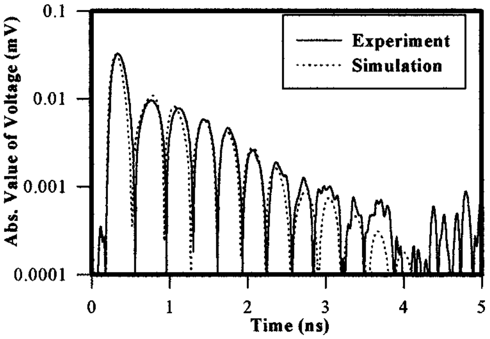

FIG. 3. Same as Fig. 2, except $H_{\text{bias}} = 480$ A/m (6 Oe) and $H_k = 1120$ A/m (14 Oe); α is still 0.013.

In Fig. 2, after about eight peaks, the simulation damps slightly faster than the experiment; we suspect that a simulation which is longitudinally discretized and takes into account the polycrystalline nature of permalloy, including random cubic anisotropy, would better fit the data.

IV. DISCUSSION

The necessity of discretizing the transverse direction can be seen in Fig. 4. The demagnetizing field forces the magnetization to lie longitudinally at the edges similar to the equilibrium state of a magnetoresistive head.[1,3] Also, higher order transverse magnetostatic modes $(k_y \neq 0)$[4,5] can be seen in Fig. 4. These modes contain energy, but do not produce any obvious time-domain signature in the experimental data or numerical results.

Figure 5 shows the results of modeling the total moment of the strip using Eq. (1), but treating the entire strip as a single domain with uniform magnetization. If α is adjusted so the second peaks match ($\alpha = 0.02$ in Fig. 5), then the numerical results are overdamped at large times. Under these assumptions it is necessary to invoke two damping parameters, one for short and one for longer times.[2] However, the results shown above indicate that using Eq. (1) and allowing for nonuniform magnetization yield an excellent fit to the data with a single intrinsic damping parameter.

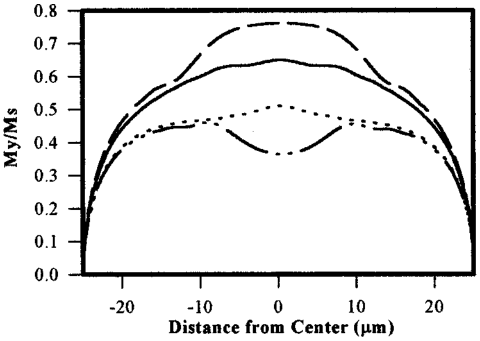

FIG. 4. Transverse magnetization normalized by M_s across the sample at various times before the magnetization has settled to a minimum energy state. The dashed line is 1.1 ns, the dotted/dashed line is 1.4 ns, the solid line is 1.7 ns, the dotted line is 2 ns. Higher order transverse $(k_y \neq 0)$ spatial modes are excited.

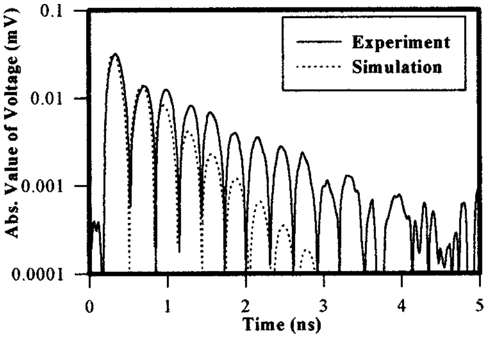

FIG. 5. Absolute value of voltage on a logarithmic scale vs time for both experiment (solid line) and a simulation in which the magnetization is constrained to be uniform (dotted line). The longitudinal bias field H_{bias} is 800 A/m (10 Oe), the uniaxial magnetocrystalline anisotropy H_k is -400 A/m (-5 Oe), and the magnetic damping parameter α is 0.020.

Other measurements are on relatively wide films (250 μm),[6] so that approximately uniform magnetization processes can be expected. These experimental results decay with a characteristic time constant of $\tau = 1$ ns, where

$$\tau = \frac{2}{\alpha \gamma \mu_0 M_s}. \tag{4}$$

For $\gamma = 1.76 \times 10^{11}\,\text{s}^{-1}\,\text{T}^{-1}$ (the value associated with the electron spin) and $M_s = 800$ kA/m (a typical value for permalloy), $\alpha = 0.01$, in agreement with the results of the micromagnetic simulation described above. Prior analysis of measurements utilizing ferromagnetic resonance in NiFe yielded a damping constant of $\alpha = 0.005$.[7] This result is in reasonable agreement with our result and is expected to be smaller, since, in that case, only small, linear excitations of the magnetization occurred.

We do not fully understand the discrepancy between the fitted and measured magnetocrystalline anisotropy (960 A/m vs 340 A/m). It is possible that longitudinal discretization would result in a better fit since longitudinal magnetostatic modes ($k_x \neq 0$) can result in higher shape anisotropy,[4] requiring a smaller value of the magnetocrystalline anisotropy. In addition, the polycrystalline nature of NiFe films produces a ripple structure in the magnetization.[8] Ripple dynamics are expected to be slow (10–20 MHz) similar to domain wall motion. Thus, it is likely that the H_k resulting from analysis of the high speed nanosecond measurements could be significantly larger that that measured at slow speeds on a $B-H$ looper.

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