Characterization of Magnetic Nanostructures for ST-RAM Applications By Use Of Macro- and Micro-Scale Ferromagnetic Resonance

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BACKGROUND

Spin-torque memory is under consideration for high-speed, scalable, non-volatile memory applications. The storage medium is a magnetic layer with an intrinsic anisotropy that favors orientation of the magnetization in either of two directions perpendicular to the film plane. Read-out of the storage layer is based on spin-dependent tunneling from an adjacent magnetic reference layer, while the direct transfer of angular momentum in the form of electron spin is the driving mechanism for switching the magnetization in the storage layer.

In the write process for ST-RAM, the electron spin in the write-current exerts a torque on the magnetization that counters the intrinsic damping process. Once the write-current torque exceeds the damping, hysteretic switching occurs. Hence, damping is a critical parameter for the write-efficiency of spin-torque RAM. The zero-temperature critical current density J_{c0} is given by [1]

$$J_{c0} = \frac{ge\alpha\delta U_k}{\hbar p}, \tag{1}$$

where g, e, $\hbar$, are the spectroscopic splitting factor, electron charge, and reduced Planck's constant, respectively, U_k is the energy density of the switching barrier, δ is the storage layer thickness, p is the torque transfer efficiency, and α is the damping parameter. In the context of the standard Landau-Lifshitz phenomenology, the damping parameter describes the rate that the magnetization returns to equilibrium after an excitation:

$$\partial_t \hat{m}(\vec{r}) = -\gamma\mu_0\left[1+\alpha\gamma\mu_0\hat{m}(\vec{r})\times\right]\left(\hat{m}(\vec{r})\times\vec{H}_{eff}(\vec{r})\right), \tag{2}$$

where $\gamma \doteq (g/2)(e/m_e)$ is the gyromagnetic ratio, m_e is the electron mass, μ_0 is the vacuum permeability, $\hat{m}(\vec{r})$ is the normalized magnetization vector, $\vec{H}_{eff}(\vec{r}) = -\vec{\nabla}U(\vec{r})/(\mu_0 M_s)$ is the net effective field, $U(\vec{r})$ is the free energy, and M_s is the saturation magnetization. Steady-state solution of eq. (2) in the limit of spatially uniform response for an ac magnetic field $\vec{h}$ in the x-y plane, small amplitude motion, small variations of $U(\vec{r})$, and a saturating magnetic field $\vec{H}_0$ along the z-axis film-normal, leads to a linear response function $\hat{m} = \tilde{\tilde{\chi}}\vec{h}$, where $\tilde{\tilde{\chi}}$ is

$$\tilde{\chi}_{jk}(\omega) \cong \left[\left(H_0 - M_{eff}\right)^2 - \left(\frac{\omega}{\gamma\mu_0}\right)^2 - i\frac{2\alpha_{eff}\omega\left(H_0 - M_{eff}\right)}{\gamma\mu_0}\right]^{-1}\left[\delta_{jk}\left(H_0 - M_{eff}\right) - i\varepsilon_{jk}\frac{\omega}{\gamma\mu_0}\right], \tag{3}$$

where $M_{\text{eff}} \doteq -2U_k/\mu_0 M_s$ is the effective magnetization that is in actuality the height of the energy barrier that prevents switching, and $\alpha_{\text{eff}} \doteq \alpha + \left(\gamma\mu_0 \Delta H/(2\omega)\right)$, where the inhomogeneous broadening ΔH is the rms variation of the resonance condition throughout the measured sample volume. The susceptibility has a resonance condition when $\omega = \gamma\mu_0\left(H_0 - M_{\text{eff}}\right)$, also known as the ferromagnetic resonance (FMR). Hence, extraction of both the energy barrier (resonance position) and the damping (resonance linewidth) can be achieved by an FMR measurement of the ac permeability by use of a microwave circuit properly loaded with a candidate ST-RAM storage material.

MEASUREMENT METHODS

The method of VNA-FMR can be used to determine the microwave response of unpatterned blanket films of storage-layer candidate materials. The method uses a 70 GHz bandwidth vector-network-analyzer (VNA) to measure the transmission efficiency of a coplanar waveguide assembly loaded with the sample in near-field proximity to the waveguide. An electromagnet provides the saturating field of up to 2.2 T. For a given excitation frequency ω, H_0 is swept through the resonance condition. The resultant complex transmission spectra are then fitted to eq. (3). Measurement at a single frequency is inadequate for a unique determination of both α and ΔH_0. Hence, the excitation frequencies are also varied. The frequency range is chosen to minimize the uncertainty in α.

Individual spectra are fitting to eq. (3). A sensitivity matrix is used to estimate the uncertainty in $M_{\text{eff}}(\omega)$ and $\alpha_{\text{eff}}(\omega)$ at measurement frequency ω. Linear regression is used to determine M_{eff} and α, with uncertainties determined by Monte Carlo methods. Details of the measurement method may be found in Ref. [2].

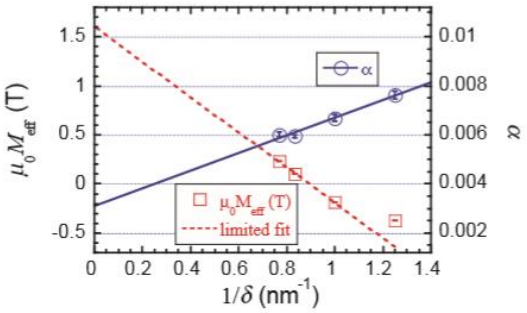

FIGURE 1. VNA-FMR data for effective magnetization and damping as a function of reciprocal storage layer thickness for a CoFeB sandwich structure. The anisotropy is oriented along the *z*-axis when $M_{\text{eff}} < 0$. The error bars are 1σ. They are estimated by use of the sensitivity matrix used for the fitting of the spectroscopic data to eq. (3). Linear fits to both the anisotropy and damping data are also shown, though the fit to M_{eff} is only for the samples with $\delta \geq 1$ nm. Both fits are extrapolated to the bulk limit ($1/\delta \to 0$). In both cases, the extrapolated values are in reasonable agreement with literature values for materials similar to $Co_{0.6}Fe_{0.2}B_{0.2}$.

We present in Fig. 1 an example of VNA-FMR data of M_{eff} and α for sputtered sandwich films MgO (2)/$Co_{0.6}Fe_{0.2}B_{0.2}$ (δ)/Ta (0.4)/$Co_{0.6}Fe_{0.2}B_{0.2}$ (δ)/MgO (2), where the parenthetic values are thicknesses in nm. The samples were all deposited on 100-mm CMOS-grade Si wafers, and were annealed after deposition at 300 C for 30 minutes. For this particular sample system, the observation of a linear dependence of M_{eff} and α on $1/\delta$ is evidence for interfacial contributions to both the anisotropy [3] and the damping [4]. We speculate that the deviation of the linear trend for M_{eff} at the smallest thickness is due to incomplete layer formation. The extrapolated values in the bulk limit of $\delta \to \infty$, $\alpha_{\text{bulk}} \cong 0.0031$ and $\mu_0 M_{\text{eff, bulk}} \cong 1.60$ T, are both in reasonable agreement with published values for similar materials [5][6]. Similar interfacial damping has been observed in a variety of other material systems, and is often ascribed to the spin-pumping mechanism, whereby magnon-electron scattering at ferromagnet/normal metal interfaces equilibrates the magnetic system [7].

Use of blanket-film measurements of α to obtain input parameters for micromagnetic simulations of ST-RAM performance is predicated on the assumption that damping is a purely local quantity, i.e. α does not depend on the magnetization distribution in neighboring regions. While this assumption appears valid at longer length scales, theory predicts that it will eventually breakdown at nanometer length scales [8][9].

To test these theoretical predictions, we developed a novel optical microscope with capabilities analogous to the VNA-FMR [10]. Because it is based on scanned optical microscopy methods, it has a spatial resolution as small as 0.3 μm when using diffraction limited optics. However, the dimensions of the structures of interest for STT-RAM are typically smaller than 50 nm. To measure structures that are well below the spatial resolution of the instrument, it is necessary to push the sensitivity to the fundamental limit. This was accomplished by use of optical heterodyne methods, whereby coherent mixing of cw lasers at differing frequencies can be used to both generate microwaves and detect ferromagnetic resonance via the magneto-optic Kerr effect. The heterodyne magneto-optic microwave microscope (H-MOMM) was developed at NIST, and remains the only instrument of its kind in the world. It has an unprecedented sensitivity that allows for the measurement of damping even when the magnetic excitations are as small as only a few 10's of nanometers.

And exemplary FMR spectrum for a single 100-nm-diameter nanomagnet of 10-nm-thick $Ni_{81}Fe_{19}$ is shown in Fig. 2. The magnetization is oriented in the plane of the substrate. By fitting the spectra to eq. (3), and then applying linear regression to the α_{eff} vs. ω data, we found that the damping is indeed non-local in character. In particular, there is a component of α proportional to $\nabla^2 m$ [10], as predicted in Refs. [8] and [9].

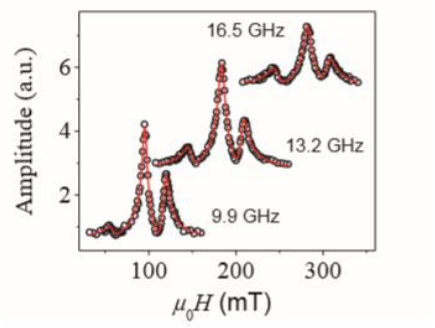

FIGURE 2. FMR spectra obtained by H-MOMM of a single, 100-nm-diameter nanomagnet patterned from a 10 nm $Ni_{81}Fe_{19}$ film. The data are the open circles, and the solid red lines are fits based on a superposition of eigenmodes, each of which follows eq. (3). The multiple modes are identified by comparison of the data with micromagnetic simulations. The low-field resonance is an eigenmode that spans the entire area of the nanomagnet, whereas the two high-field peaks are associated with localized modes that are proximate to the two ends of the nanomagnet along the applied field axis. It is assumed that subtle structural differences of the two ends split the end-mode into two peaks.

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KEYWORDS

Spin torque, memory, switching, ferromagnetic resonance, damping, vector network analyzer, magneto-optics, microscope