Temperature and field dependence of high-frequency magnetic noise in spin valve devices

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The high-frequency noise of micrometer-dimension spin valve devices has been measured as a function of applied field and temperature. The data are well fit with single-domain noise models that predict that the noise power is proportional to the imaginary part of the transverse magnetic susceptibility. The fits to the susceptibility yield the ferromagnetic resonance (FMR) frequency and the magnetic damping parameter. The resonant frequency increases, from 2.1 to 3.2 GHz, as the longitudinal field varies from −2 to 4 mT and increases from 2.2 to 3.3 GHz as the temperature decreases from 400 to 100 K. The shift in the FMR frequency with temperature is larger than that expected from the temperature dependence of the saturation magnetization, indicating that other temperature-dependent anisotropy energies are present, in addition to the dominant magnetostatic energies. The measured magnetic damping parameter α decreases from 0.016 to 0.006 as the temperature decreases from 400 to 100 K. The value of the damping parameter shows a peak as a function of longitudinal bias field, indicating that there is no strict correlation between the damping parameter and the resonant frequency.
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Advanced data storage applications require magnetic devices to have submicrometer dimensions and operate at high frequencies in the gigahertz regime. It has been recently pointed out that high-frequency thermal fluctuations of the magnetization in giant magnetoresistive devices, which scale inversely with the device volume, will become significant in the next generation of recording read heads and will provide a fundamental limitation on the ability to scale down the device size and increase the operating frequency.[1,2] High-frequency magnetic noise, in addition to being of practical concern in device operation, provides a powerful method to characterize the dynamic modes in small magnetic structures. Mode frequencies and linewidths (or equivalently, damping parameters) can be determined over a wide range of applied fields and temperatures. Here, we present the temperature and field dependence of the high-frequency magnetic noise in spin valve devices that show single-domain behavior and whose noise spectrum can be fit with simple single-domain models.

The device structures consisted of Ta (5 nm)–$Ni_{0.8}Fe_{0.2}$ (5 nm)–$Co_{0.9}Fe_{0.1}$ (1 nm)–Cu (2.7 nm)–$Co_{0.9}Fe_{0.1}$ (2.5 nm)–Ru (0.6 nm)–$Co_{0.9}Fe_{0.1}$ (1.5 nm)–$Ir_{0.2}Mn_{0.8}$ (10 nm)–Ta (5 nm) multilayers sputtered on oxidized (100) Si substrates. The films were deposited in a 15 mT field to set the pinned direction of the fixed layer. The fixed layer (CoFe–Ru–CoFe) was a low-moment synthetic antiferromagnet. The wafer-level magnetoresistance ratio, $R_{\mathrm{AP}} - R_P/R_P$, was 7.8%, where R_{AP} and R_P are the resistances with the free and fixed layers antiparallel and parallel. The wafers were patterned to form spinvalve devices with dimensions of 1 μm by 3 μm. The devices studied here have the pinned-layer magnetization oriented perpendicular to the easy axis, which is along the long dimension of the device. The devices were contacted with high-bandwidth transmission lines and used overlapping electrodes. The data presented here are from a device whose resistance, including lead and contact resistance, was 20.2 Ω in the parallel state, and the change in resistance from parallel to antiparallel magnetization states was 1.0 Ω. The free-layer magnetization switched between its two easy-axis states consistently at a longitudinal field of 2.2 mT. The magnetic noise was evaluated from the measured voltage noise spectrum by subtracting a reference spectrum in which the free-layer magnetization was saturated by applying a large magnetic field along the hard axis.

The noise spectra from thermal fluctuations of the magnetization can be related to the imaginary part of the transverse susceptibility by the fluctuation-dissipation theorem[2,3]

$$V_n(f) = I\Delta R \sqrt{\frac{k_B T}{2\pi f \mu_0 M_s^2 V} \chi_t''(f)}, \tag{1}$$

where V_n is the voltage noise spectrum, f is the frequency, I is the current through the device, ΔR is the change in resistance from the parallel to antiparallel magnetization state, T is the device temperature, M_s is the saturation magnetization of the free layer, and V is the free-layer volume. The transverse susceptibility $\chi_t(f)$ is the ratio of the hard-axis magnetization, M_y, to the applied hard-axis field. The susceptibility can be determined from the linearized Landau–Lifshitz

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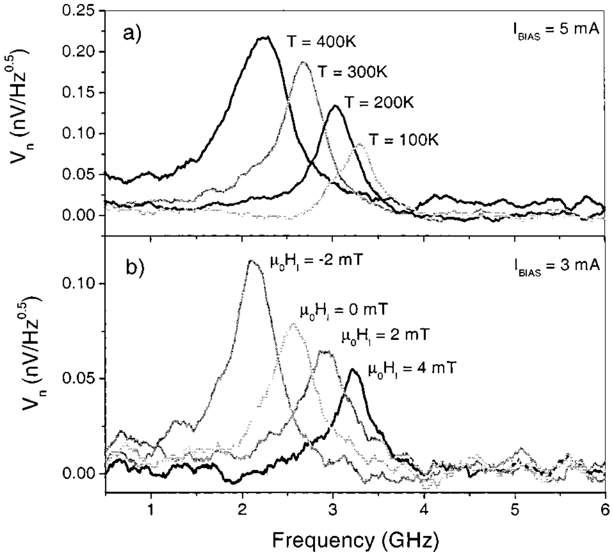

FIG. 1. Voltage noise spectra of a 1 μm$\times$3 μm spin valve device for (a) a series of substrate temperatures with no applied longitudinal field, and (b) a series of longitudinal bias fields at room temperature. Both sets of curves are similar, with the resonant frequency increasing and the noise amplitude decreasing as the stiffness fields increase.

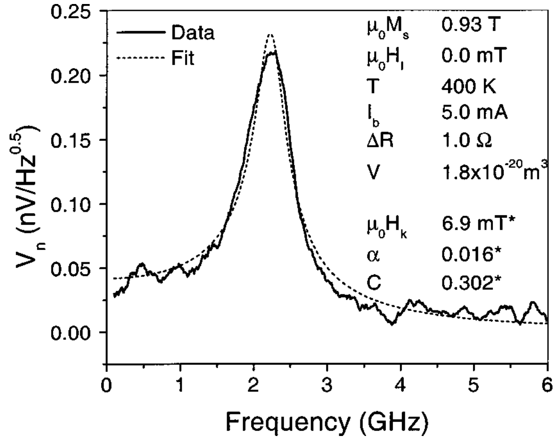

FIG. 2. Fit of the noise spectrum of a spin valve device at 400 K with a bias current of 5 mA. The parameters indicated with an asterisk were allowed to vary. The other parameters were taken from experimental measurements.

equation for a thin-film single-domain element and, for applied and anisotropy fields much less than M_s, is given by[4,5]

$$\chi''(f)=\frac{f}{\gamma'}\alpha\mu_0 M_s \times\left\{\frac{\mu_0^2 M_s^2+\frac{f^2}{\gamma'^2}}{\left(\mu_0^2(H_k+H_l)M_s-\frac{f^2}{\gamma'^2}\right)^2+\left(\frac{f}{\gamma'}\alpha\mu_0 M_s\right)^2}\right\}, \tag{2}$$

where γ' is the gyromagnetic ratio divided by 2π (28 GHz/T), H_k is the in-plane anisotropy field, H_l is the longitudinal bias field that is applied along the easy axis of the device, and α is the Gilbert damping parameter. The susceptibility shows a resonance behavior. The imaginary part of the susceptibility, which describes energy loss from the magnetic system, has a peak at the ferromagnetic resonance frequency, $f_r=\gamma'\mu_0\sqrt{(H_k+H_l)M_s}$, with the peak width proportional to the damping parameter α. The saturation magnetization of the free layer was measured to be 775 kA/m at 300 K. This value is lower than predicted from the bulk magnetization values, due in part to a magnetically dead layer at the Ta–NiFe interface.[6] The anisotropy field H_k is due predominantly to magnetostatic shape anisotropy. The measured room-temperature value of the low-frequency anisotropy field, as determined from the slope of the hard-axis magnetoresistance curve, was $\Delta R/2(dR/dH_t)^{-1}=10.6$ mT, whereas the calculated value for the magnetostatic anisotropy, assuming uniform magnetization, was 8.0 mT. Other energy terms enter into the measured anisotropy field, such as the magnetostatic coupling to the pinned layer and any induced anisotropy energies. These terms are expected to contribute 0.5–2 mT to the anisotropy field at room temperature.

The measured noise spectra for various temperatures and longitudinal bias fields are shown in Figs. 1(a) and 1(b). The resonance is clearly seen, with the resonant frequency increasing as the temperature decreases or as the longitudinal bias field increases. The longitudinal-field data are similar to standard ferromagnetic resonance (FMR) measurements for which the resonant frequency increases and the amplitude of the resonance peak decreases as the stiffness field increases. Comparison of the temperature-dependent data and the longitudinal-field data shows that decreasing the temperature from 400 to 100 K is roughly equivalent to increasing the stiffness field by 6 mT.

The data were fit using Eqs. (1) and (2) to determine the resonant frequencies, anisotropy fields, and damping parameters. A sample fit is shown in Fig. 2. Here the H_k, α, and an overall scale factor, C, were allowed to vary. All other quantities were determined experimentally. H_k determines the resonant frequency, α determines the width of the resonance, and C determines the overall scale. The scale factor is predicted by Eq. (1) to be $C=1$. However, the experimentally determined scale factor is expected to be less than 1 since there are additional high-frequency attenuations of the noise signal due to losses in the microwave circuit. For the data analyzed here, C varied between 0.1 and 0.4. The fits to the temperature-dependent noise spectra used a temperature-dependent saturated magnetization measured by a superconducting quantum interference device magnetometer. The magnetization measurements, shown in Fig. 3, indicate that the magnetization changes only by 10% over the relevant temperature range. However, the coupling field, determined by measuring the shift in the free layer $M-H$ loop, increases from 0.5 to 1.6 mT as the temperature decreases from 400 to 100 K.

The results of the fitting all the resonance curves are shown in Fig. 4. Figure 4(a) shows the dependence of the resonant frequency and damping parameter on temperature. The resonant frequency increases from 2.2 to 3.3 GHz as the temperature decreases from 400 to 100 K, indicating an increase of the stiffening fields with decreasing temperature. The in-plane anisotropy field increases from 6.9 to 13.6 mT as the temperature decreases from 400 to 100 K. The calculated contribution to the increase in in-plane anisotropy, due to the effect of increasing M_s on the magnetostatic shape anisotropy, is only 0.7 mT. The measured damping parameter decreases from 0.016 to 0.006 as the temperature decreases

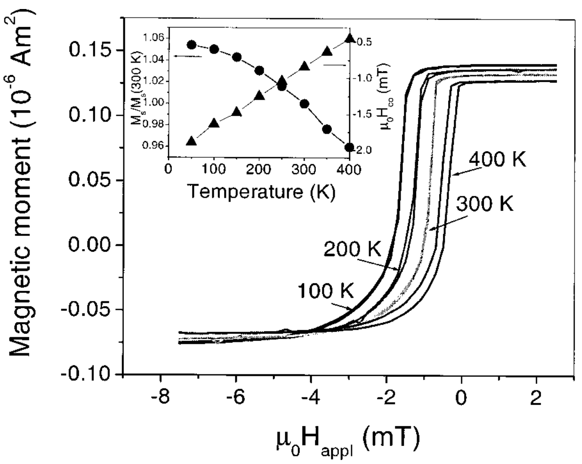

FIG. 3. Magnetic moment as a function of applied field for a coupon from the spin valve wafer. The field was applied parallel to the fixed-layer magnetization. The hysteresis loops are not centered around zero moment because of the fixed moment of the pinned layer. The inset shows the measured coupling field and relative free layer saturation magnetization calculated from the hysteresis loops.

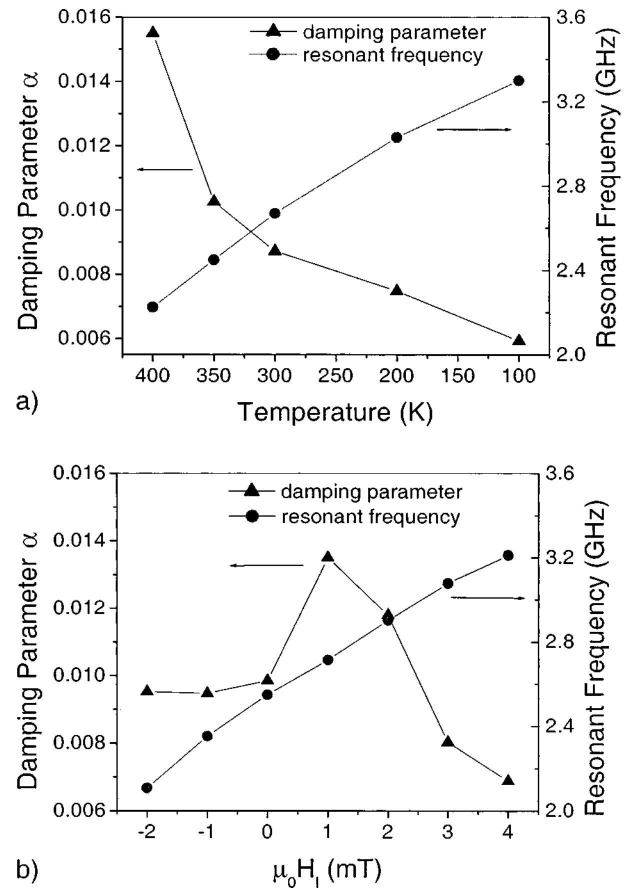

FIG. 4. The resonant frequencies and damping parameters determined from fitting the noise data for (a) the temperature-dependent data with no applied longitudinal field, and for (b) the longitudinal field dependent data at 300 K.

from 400 to 100 K. The room-temperature values of the damping parameter are slightly less then the values ($\alpha \cong 0.02$ to 0.03) obtained by directly measuring the high-frequency susceptibility of similar spinvalve devices.[7] The rms variation in the magnetization angle $\theta_{\rm rms}$ for the noise measurements can be estimated from the fluctuation-dissipation theorem,[3] which yields a value of

$$\theta_{\rm rms} = \left\langle \frac{M_y}{M_s} \right\rangle_{\rm rms} = \sqrt{\frac{k_B T}{\mu_0 M_s H_k V}} \approx 0.15^\circ \text{ to } 0.37^\circ. \tag{3}$$

These values of magnetization motion are considerably less than those used to directly measure the device susceptibility and are similar to the values used in standard FMR measurements. The temperature dependence of the damping coefficient is considerably larger than that observed by FMR for sheet NiFe films.[8]

The dependence of the resonant frequency and damping parameter on longitudinal field is shown in Fig. 4(b). The measured resonance frequency increases as a function of longitudinal field in a manner consistent with a constant anisotropy field. The average anisotropy field, determined from the fits to the data in Fig. 1, is $\mu_0 H_k = 9.0$ mT, and the maximum deviation from the mean value is 0.9 mT. The measured anisotropy field is in reasonable agreement with the low-frequency value, given the uncertainty in determining the free-layer moment and volume. The damping parameter shows a peak as a function of longitudinal field. At large positive fields there is a decrease in the damping parameter that is consistent with observed behavior in single-layer sheet films.[9] The decrease in damping parameter for small and negative fields does not correlate with any observable feature in the longitudinal magnetoresistive response. The resistance has no large variations as the longitudinal field is varied until the switching threshold of 2.2 mT, which indicates that there is no large change in the micromagnetic structure as the longitudinal field is varied.

The increase in coupling field as the temperature decreases has been explained by assuming that there is a coupling component due to magnetostatic interactions arising from surface roughness (which is proportional to M_s) and a component due to a temperature-dependent exchange coupling.[10] Another possibility, which is more consistent with the observed temperature dependence of the damping parameter, is that there are thermal fluctuations of the magnetization at the interfaces of the ferromagnetic layers. The fluctuations suppress the magnetostatic coupling at higher temperatures and provide an additional energy-loss mechanism. The micromagnetic fluctuations will depend on applied fields and may account for the observed peak in the damping parameter at small longitudinal fields.

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