Different dynamic and static magnetic anisotropy in thin Permalloy™ films

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The values of uniaxial anisotropy H_k in thin polycrystalline Permalloy™ films measured by static and dynamic methods differ by as much as a factor of 1.5. The anisotropy obtained with a pulsed inductive microwave magnetometer in 2.5 to 100 nm thick Permalloy films exhibits an additional isotropic component of 120 to 240 A/m not observed in static measurements. The static value of anisotropy was obtained with an inductive magnetic hysteresis loop tracer. The time-resolved precessional response was measured as a function of in-plane applied magnetic bias field and the angle between the easy axis and that of the applied bias field. We interpret the constant-offset field as a transient component of the magnetic susceptibility that affects only dynamical response at time scales below 10 ns. [DOI: 10.1063/1.1587255]

Magnetic anisotropy (MA) is of great importance for both fundamental and technological reasons. MA plays a key role in magnetic recording, sensor devices, and magnetic read heads. The development of dynamic techniques (e.g. ferromagnetic resonance (FMR), Brillouin light scattering (BLS), and time-resolved magneto-optics permits the investigation of the role MA plays in magnetization dynamics.[1] Such dynamic studies are of greater importance as the operational frequencies of magneto-electronic devices approach the gigahertz regime. In this letter, we report on an investigation of the anisotropy H_k^{dyn} in Permalloy ($Ni_{80}Fe_{20}$) films in the frequency range of 700 MHz to 3 GHz using inductive electrical methods. In contrast to FMR and BLS, this inductive technique accesses the low-frequency precessional response in soft magnetic films, permitting the exact determination of anisotropy values. The exactitude owes itself to the *spectroscopic* nature of the technique. We compare the results with values for uniaxial anisotropy H_k^{stat} obtained from static measurements. The static measurement is based upon classical magnetometry, that is, information is obtained concerning the balance of *torques* leading to an equilibrium magnetization state. *The values of H_k obtained by dynamical and static techniques are measurably different for thin-film Permalloy*. In particular, an additional anisotropy field of about 200 A/m is present in the dynamic data irrespective of angular orientation of the sample in a magnetic bias field.

The samples used were polycrystalline Permalloy films of 2.5, 5, 10, 25, 50, and 100 nm thickness grown by dc magnetron sputtering on 1 cm×1 cm×100 μm coupons of (0001)-oriented sapphire. Prior to deposition, the substrates were ion-milled in Ar/O_2 and Ar atmospheres to remove any surface contaminants. The substrates were precoated with a 5 nm Ta seed layer. All layers were deposited at an Ar pressure of 0.53 Pa at room temperature. The base pressure of the deposition chamber was about 10^{-6} Pa. A uniaxial anisotropy was induced by growing the films in a magnetic field of 20 kA/m. The inhomogeneity of the field across the sample was 20%. To protect against oxidation, the samples were covered with 5 nm of Cu. A control series of samples was prepared without the Cu capping layer to investigate the influence of oxide formation on the observed behavior.

The static measurements were performed using an induction-field (B–H) magnetometer.[2] The dynamic properties were obtained by means of a broadband, pulsed inductive microwave magnetometer (PIMM).[3] A coplanar waveguide with a 450 μm central conductor produced the step magnetic field pulses of about 320 A/m. The rise-time of the pulse was 50 ps and the pulse duration was 10 ns. The magnetic response was measured over an interval of 9 ns after onset of the field step. The signal was recorded with a 20 GHz sampling oscilloscope. The experimental bandwidth was 10 GHz.[4] The time-resolved precessional response was measured as a function of an in-plane magnetic bias field H_B varying from 1.6 to 8 kA/m. The samples exhibited exponentially damped sinusoidal precession with decay times of 0.7 to 1.0 ns. The frequency varied from 700 MHz to 3 GHz. The inhomogeneity of the bias field was better than 1%. The bias field values were calibrated to within 8 A/m and all sources of stray field were accounted for with a Hall probe.

Some of the data used to determine the static uniaxial anisotropy H_k^{stat} are shown in Fig. 1 for the 50 nm thick film.

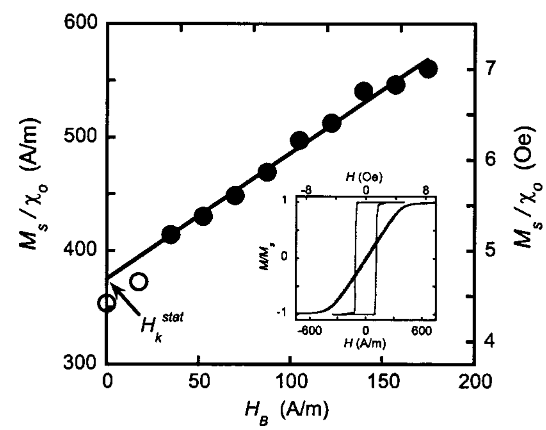

FIG. 1. An example of the data used to measure the static uniaxial anisotropy H_k^{stat} from hard-axis hysteresis loop measurement, shown for 50 nm thick Permalloy film. An initial susceptibility χ_0 and saturation magnetization M_s were determined. A weak bias field H_B was applied along the magnetic easy axis to keep the sample in a single-domain state. In this case the static uniaxial anisotropy H_k^{stat} is $M_s/\chi_0 = H_k^{\mathrm{stat}} + H_B$. The line corresponds to this functional fit for the filled data points. Note that the first two data points (open circles) lie 25 A/m below the fitted line, indicative of some domain formation for $H_B < 32$ A/m. The inset displays the typical easy- and hard-axis hysteresis loops.

TABLE I. The values of $H_k^{(0)}$, $H_k^{(2)}$, and H_k^{stat} are shown. The expanded uncertainty (95 percentile confidence interval) in the measurement of $H_k^{(2)}$ and $H_k^{(0)}$ is 40 A/m.

Permalloy thickness (nm)	H_k^{stat} (A/m)	$H_k^{(2)}$ (A/m)	$H_k^{(0)}$ (A/m)
100	259	288	255
50	357	361	193
25	326	313	208
10	286	266	179
5	205	185	175
2.5	295	233	76

The static anisotropy field value was obtained by a quasi-static (50 Hz sweep rate) measurement of the hard-axis hysteresis loop. An initial susceptibility χ_0 and saturation magnetization M_s were determined for the measured loop. In the absence of any other applied fields, the static uniaxial anisotropy is $H_k^{\mathrm{stat}}=M_s/\chi_0$. In practice, a weak bias field H_B was applied along the magnetic easy axis to keep the sample in a single-domain state. In this case, $M_s/\chi_0=H_k^{\mathrm{stat}}+H_B$. The data were fitted to this equation for field values between 32 and 160 A/m to extract H_k^{stat}. With sufficient H_B, the magnetization tends to rotate preferentially in the direction of H_B. At low fields, the rotation of the domains in both clockwise and counterclockwise directions effectively reduces the measured value of H_k^{stat}, as seen in Fig. 1 for $H_B<32$ A/m. The inset of Fig. 1 displays the typical easy- and hard-axis hysteresis loops. The hard-axis loop was measured with $H_B=16$ A/m along the easy axis. The squareness of the easy-axis loop for all samples is greater than 0.99. The fitted results of H_k^{stat} are summarized in Table I.

The anisotropy values H_k^{dyn} were obtained using the PIMM.[4] The sample was placed on the waveguide with the sapphire substrate between the waveguide and Permalloy film to avoid strong capacitive coupling between them. Two measurements were performed to extract a time-resolved signal.[3] A subtraction of background from dynamical signal yields the time-resolved precessional response. The signals were corrected for both amplitude drift and time shift. The frequency-domain response was achieved by fast Fourier transform (FFT) analysis of the time-domain signal. The FFT spectra correspond to the complex magnetic susceptibility $\chi(\omega)$.[5] Zero-padding[6] was used to enhance the frequency resolution to 6 MHz. The fitting of the imaginary part of $\chi(\omega)$ to a Lorentzian curve permits determination of the absolute phase of the signal. The precessional frequency f_0 of the magnetization response was determined from the position of the zero-crossing of the real part of $\chi(\omega)$ with correct absolute phase. In addition, the position of the peak of the imaginary part of $\chi(\omega)$ is determined. In case of weak damping, both methods provide the same value of f_0. However, for the case of strong damping the zero-crossing method gives the correct frequency f_0 independent of "blue shift."[7] In our case, the difference between both frequencies was less than 5 MHz. The inset of Fig. 2 shows the measured susceptibility spectrum $\chi(\omega)$ for $H_B=1.6$ kA/m. Both the real and imaginary part of $\chi(\omega)$ can be fit accurately with a Fourier transform solution to the Landau–Lifshitz equation, which is also shown. Therefore, we may conclude that the magnetization response is that of a damped, single-domain precessional oscillator.

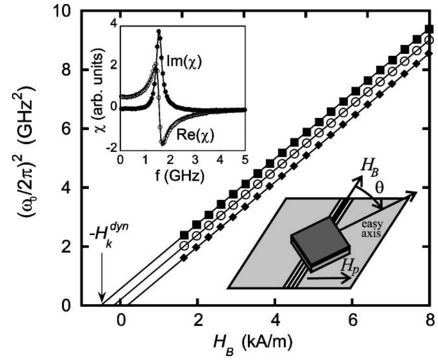

FIG. 2. The dependence of precession frequency squared (f_0^2) as a function of bias field H_B is shown for 0°, 45°, and 90° (filled square, open circle, and filled diamond, respectively) angles of the magnetic easy axis to the applied bias field H_B for 50 nm thick Permalloy film. The linear regression coefficients were typically $R=0.9999$. H_k^{dyn} is obtained as an intercept of the extrapolated linear fit to $f_0^2=0$. The lower inset shows the experimental geometry, while the upper inset shows spectra of susceptibility $\chi(\omega)$ for $H_B=1.6$ kA/m.

The bias field dependence of the angular frequency $\omega_0=2\pi f_0$ for homogenous precession (ferromagnetic resonance mode) in the limit of $H_B+H_k\ll M_s$ is described by the Kittel formula[8] as

$$\omega_0^2=\omega_M\gamma\mu_0(H_B+H_k^{(2)}\cos 2\theta)=\omega_M\gamma\mu_0(H_B+H_k^{\mathrm{dyn}}), \quad (1)$$

where $\omega_M=\gamma\mu_0 M_s$, γ is the gyromagnetic ratio, μ_B is the Bohr magneton, $\hbar$ is Planck's constant divided by 2π, μ_0 is the vacuum permeability, $H_k^{(2)}$ is the second-order in-plane uniaxial anisotropy, and θ denotes the relative angle between the magnetic easy axis and H_B. The experimental geometry is shown in the inset of Fig. 2. If the sample has a perpendicular anisotropy due to either a magnetostrictive response for in-plane stress or surface effects, M_s is replaced by an effective magnetization $M_{\mathrm{eff}}=M_s-H_{k\perp}$, where $H_{k\perp}$ denotes the out-of-plane anisotropy contribution. Note that Eq. (1) is exact only for the case of magnetization precession along the applied bias field. For the PIMM measurements with dynamics driven by an applied field step, the magnetization precesses along the net effective field H_{eff} found by minimization of the free energy. Equation (1) is still applicable if one replaces the term in brackets by H_{eff}. Such an analysis shows that the error caused by using Eq. (1) is about 3% for the smallest bias fields ($H_B=1.6$ kA/m). This error decreases with increasing bias field. Based on Eq. (1), one can perform a linear regression of ω_0^2 versus H_B and extract the anisotropy H_k^{dyn} and the γ using an independently measured value for M_{eff}. H_k^{dyn} is orthogonal to γ in the fitting process; as such, the value of M_{eff} affects only the final value for γ, which is related to the slope of ω_0^2 versus H_B.

We will constrain ourselves to the discussion of the anisotropy fields. In Fig. 2, the dependence of f_0^2 as a function of H_B is shown for several orientations of the magnetic easy axis with respect to H_B for 50 nm thick Permalloy film. The linear regression coefficients were typically $R=0.9999$. H_k^{dyn} is directly obtained as an intercept of the extrapolated linear fit to $f_0^2=0$, as shown in Fig. 2. The expanded uncertainty for

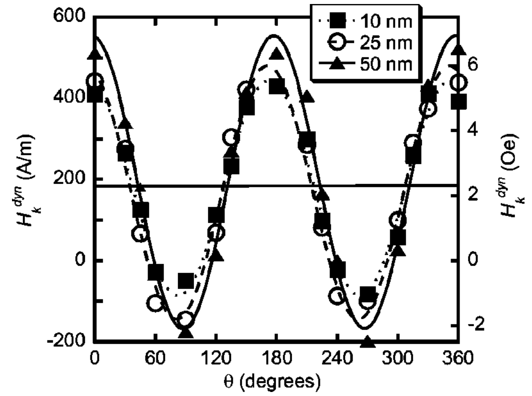

FIG. 3. The dependence of H_k^{dyn} on θ for different thicknesses of Cu-capped Permalloy films is displayed. Uncapped Permalloy films showed no substantial differences. The lines are the fitted curves to the equation $H_k^{\mathrm{dyn}} = H_k^{(2)} \cos 2\theta + H_k^{(0)}$. The solid line corresponds to the average value of $H_k^{(0)}$ for all three samples.

the value of H_k^{dyn} was 16 A/m. H_k^{dyn} measured along the easy axis is larger than the corresponding H_k^{stat} value.

Figure 3 shows the dependence of H_k^{dyn} on θ for different thicknesses of Cu-capped Permalloy films. Uncapped Permalloy films showed no substantial differences. Based on Eq. (1), the dependence of H_k^{dyn} on θ should follow the $H_k^{\mathrm{dyn}} = H_k^{(2)} \cos 2\theta$ dependence. However, the data cannot be fitted without an additional zeroth-order anisotropy $H_k^{(0)}$; $H_k^{\mathrm{dyn}} = H_k^{(2)} \cos 2\theta + H_k^{(0)}$. The lines are the fitted curves. The values of $H_k^{(0)}$, $H_k^{(2)}$, and H_k^{stat} are summarized in Table I. H_k^{stat} and $H_k^{(2)}$ are very similar, permitting H_k^{stat} to be identified as a measure of the uniaxial contribution to the anisotropy. The value of $H_k^{(0)}$ is between 160 and 240 A/m for the film thicknesses ranging from 5 to 50 nm. While the zeroth-order field is only a few hundred amperes per meter, the effect upon the measured precession frequency is significant for small values of H_B. A hypothesis of constant $H_k^{(0)}$, when tested against the data, resulted in a normalized chi squared value of $\chi^2 = 0.84$ and a mean value of $\langle H_k^{(0)} \rangle = 202 \pm 9$ A/m. Fitting of the data to a linear function resulted in $\chi^2 = 0.57$, which is statistically insignificant compared to the hypothesis of constant value. We conclude that $H_k^{(0)}$ is constant for an order of magnitude variation in Permalloy film thickness. However, $H_k^{(0)}$ for the 2.5 nm thick film is only 76 A/m.

These results have further implications with regard to the calibration of high-frequency permeability data for soft magnetic films. Typically, such measurements are calibrated by normalizing the low-frequency data to the known dc value of the permeability $\mu_{\mathrm{DC}} = \mu_0(1 + M_s/H_k)$. Such a calibration method assumes that the uniaxial component of the anisotropy is invariant with frequency. In light of our observation, it is clear that such a calibration method is not correct and can lead to errors as large as 50% in the case of thin-film Permalloy. The correct calibration factor for the normalization of high-frequency permeability data is not the dc value of the uniaxial anisotropy, but rather the high-frequency value, as obtained by a proper fit to the Kittel equation.

As pointed out earlier, $H_k^{(0)}$ is approximately constant for the thickness range between 5 and 50 nm. This eliminates dipolar fields due to the finite size effects as the source of $H_k^{(0)}$, since the internal dipole fields scale in proportion to Permalloy thickness. However, there is a statistically significant increase in $H_k^{(0)}$ for 100 nm, suggesting that dipolar fields begin to have an effect for the largest film thickness.

In addition, $H_k^{(0)}$ must be transient in nature because it appears only in the dynamical measurements and disappears for static measurements. However, the extracted value of $H_k^{(0)}$ was independent of pulse repetition rate over a range of 1 to 100 kHz. We conjecture that the additional anisotropy has an exponential time dependence $H_k^{(0)} = H_k' \exp(-t/\tau^{(0)})$, where $\tau^{(0)}$ is the time scale for the transition between dynamical and static regimes. Presumably, a relaxation of the anisotropy from $H_k^{(0)} + H_k^{(2)}$ (for $\tau \ll \tau^{(0)}$) to $H_k^{(2)}$ (for $\tau \gg \tau^{(0)}$) would also manifest itself as a relatively slow rotation of the magnetization vector into the final static equilibrium value. Thus, a low-speed exponential "creep" of the magnetization would be observed long after all precessional response has decayed. The frequency resolution for PIMM precludes our ability to make an accurate assessment of such a low-frequency response. However, previous time-resolved optical measurements have indeed observed such a low-speed creep in the case of step response in unpatterned Permalloy films and tunnel junctions.[9,10]

The effect of grain size on $H_k^{(0)}$ was determined by the use of underlayers and annealing to vary the grain size by a factor of 3. The grain size was measured with atomic force microscopy. The initial rms grain size for all the films was 20 nm. Growing the films on a 100-nm Cu underlayer increased the grain size to 40 nm. Subsequent annealing of the films grown on Cu further increased the grain size to 60 nm. $H_k^{(0)}$ was unaffected by the variation in grain size.

The angular independence of $H_k^{(0)}$ is similar in effect to the rotational anisotropy observed in exchange-biased Permalloy films,[11] albeit at a much weaker strength. The persistence of the effect for Cu-capped films argues against any surface or interfacial antiferromagnetic layer as a source of additional stiffness field.

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