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Dynamic anisotropy of thin Permalloy films measured by use of angle-resolved pulsed inductive microwave magnetometry

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In this study, angle-resolved pulsed inductive microwave magnetometry is used to investigate the symmetry of the dynamic anisotropy of thin Permalloy films. We measured the dynamic anisotropy field as a function of angle between the easy axis and the applied bias field. We found that, in addition to the expected uniaxial anisotropy, there is a rotatable component of anisotropy. This component of the anisotropy is present only during the dynamics measurements and is attributed to surface effects in the thin films. However, the native oxide layer is *not* the cause of the rotatable anisotropy components in these films. [DOI: 10.1063/1.1923193]

The high-frequency magnetic properties of high-permeability films have become of increased importance as the internal data-transfer rate of disk drives approaches[1] 1 Gbit/s. It is particularly important that the permeability, as reflected by a small magnetic anisotropy, does not diminish with operational frequency. One promising method for determining the high-frequency permeability of soft magnetic films uses the pulsed inductive microwave magnetometer (PIMM).[2] The PIMM provides time-resolved magnetic precessional data for varying field conditions and temperature.[3] These data can be used to extract the uniaxial anisotropy, the effective magnetization, the Landé g factor, and the Gilbert damping parameter when combined with classic magnetostatic measurements.[2,4,5]

In order to accurately determine the symmetry of the anisotropy using data from a PIMM, one must make measurements as a function of the angle between the easy axis and the applied bias field. Such measurements reveal a significant component of rotatable anisotropy.[4] Rotatable anisotropy has an anisotropy axis that follows the axis defined by the equilibrium magnetization direction. In our case, the rotatable anisotropy component is only observed for dynamic measurements and thus is of interest for any application that requires operation in the gigahertz range.

In this letter, we present measurements of anisotropy for five different thin Permalloy films of varying thickness using a PIMM. Two effects must be considered in any dynamic, angle-resolved measurement when a coplanar waveguide (CPW) is used as the excitation source. The first correction is due to the finite CPW width and was previously reported for nonangle-resolved data.[6,7] We find that the correction for the finite CPW width is valid at all angles. In addition, we find that we must account for the "dragging" effect, in which the analysis of the data must presume that the magnetization of the sample is not aligned with an external applied bias field.[8] Both of these effects can be mistaken for a rotatable anisotropy if not properly accounted for.

The samples used in this study were polycrystalline $Ni_{81}Fe_{19}$ Permalloy films with thicknesses of 5, 7, 10, 25, and 50 nm. The Permalloy was deposited via dc magnetron sputtering in a 0.533 Pa pressure Ar atmosphere. The sputtering system had a base pressure of 10^{-6} Pa. The substrates used for the 10, 25, and 50 nm samples were 1 cm $\times$ 1 cm $\times$ 100 μm coupons of (0001)-oriented sapphire and 1 cm $\times$ 1 cm $\times$ 150 μm glass coupons for the 5 nm and 7 nm samples. All substrates were prepared with *in situ* Ar/O_2 ion milling prior to deposition to remove any contaminants. A 5 nm thick seed layer of Ta was deposited onto the cleaned substrates to enhance the adhesion of the Permalloy films. Due to the Ta seed layer, the choice of substrate does not influence the data. Uniaxial anisotropy was induced by applying an external magnetic field of 20 kA/m (250 Oe) during deposition. The samples were characterized using a low-frequency inductive magnetometer to measure both the hard-axis and easy-axis hysteresis loops. The quasi-static anisotropy fields are given in Table I.

For the PIMM measurements, three different 50 Ω CPWs were used. The center conductor widths of the CPWs were 220, 525, and 990 μm. The easy axes of the Permalloy films were oriented at different angles with respect to the center conductor of the CPW using a rotation stage. All of the samples were measured on the three different waveguides to confirm the waveguide width correction and to establish reproducibility. A floating ground plane was positioned above the Permalloy sample in order to enhance the magnetic field pulse amplitude.[9] The voltage pulse amplitude was adjusted to maintain similar magnetic field pulse amplitudes at the sample when varying center conductor widths. Using the Karlqvist equation[10] for fields produced by a current strip, and assuming a factor of 2 enhancement of the field amplitude by the floating ground plane, pulses were kept at or below 183 A/m (2.3 Oe).

The precessional response of the Permalloy films was measured in the time domain and then converted into the frequency domain by use of a fast Fourier transform.[11,12] The resonance frequency was determined by measuring the zero crossing of the real part of the susceptibility.[13] In the limit that $M_s \gg H_b + H_k$, the resonance frequency ω_0 as a function of bias field can be described by the Kittel equation[14]

$$\omega_0 \approx \gamma\mu_0\sqrt{M_s(H_b + H_k^{\mathrm{eff}})}, \tag{1}$$

where γ is the gyromagnetic ratio, μ_0 is the permeability of free space, M_s is the saturation magnetization, H_b is the applied bias field, and H_k^{eff} is the effective anisotropy, which includes all contributions to the net internal field of the sample. Figure 1 shows a plot of frequency squared versus

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TABLE I. The static and dynamically measured anisotropies and corrections used for each film. Column 5 is the correction to $H_k^{(0)}$ resulting from the dragging simulations preformed with a pulse field of $H_p = 146$ A/m. Column 6 is the correction to $H_k^{(0)}$ resulting from a 220 μm wide CPW center conductor.

Film thickness (nm)	$H_k^{(\mathrm{static})}$ (A/m)	$H_k^{(2)}$ (A/m)	$H_k^{(0)}$ (A/m)	Dragging correction (A/m)	CPW width correction (A/m)
50	343±1	323±3	59±8	32	148
25	309±2	287±2	87±10	26	74
10	456±3	386±3	112±16	28	28
7	364±5	310±4	115±8	34	19
5	382±2	316±5	202±56	20	14

bias field. As the angle between the bias field and the easy axis is changed, there is a shift in the resonance frequency. This was reported previously and is due to the uniaxial anisotropy of the Permalloy films.[4]

Analysis of the data shows that the effective anisotropy can be decomposed into components with rotatable symmetry, uniaxial symmetry, and an effective stiffness field due to the finite width of the CPW center conductor. With this in mind, we can rewrite the Kittel equation as

$$\omega_0^{\mathrm{dyn}} \approx \gamma\mu_0 \sqrt{M_s\left(H_b + H_k^{(0)} + H_k^{(2)}\cos(2\theta) + \frac{\pi}{4}M_s\frac{\delta}{w}\right)}, \tag{2}$$

where $H_k^{(0)}$ is the rotatable anisotropy, $H_k^{(2)}$ is the second-order in-plane uniaxial anisotropy, and $\pi/4M_s\delta/w$ is the correction due to the finite CPW width in the small angle limit, where δ is the sample thickness and w is the width of the CPW center conductor.[7] Fits to the data in Fig. 2 are used to extract $H_k^{(0)}$ and $H_k^{(2)}$. We find that there remains a true rotatable component $H_k^{(0)}$ in the Permalloy films, even after corrections for both the CPW width and dragging effects. It should be noted that while the dragging effect must be taken into account, in our measurements it is always less than 57 A/m (0.7 Oe) as can be seen in Table I. However, the correction for the finite CPW width is crucial; without it, the inverse film thickness dependence is not observable.[4]

Figure 2 shows a plot of the zero-frequency intercept of the data in Fig. 1 versus angle between the easy axis and the applied bias field. The data are presented for measurement of a 50 nm thick Permalloy film taken on three different CPW widths and fit to $A \cdot \cos[2(\theta+\delta)]$. The data are already corrected for both the finite CPW width effect and the dragging effect.[7,15] The data from the three different CPW widths overlap at all angles of the easy axis, demonstrating that the correction for the effect of the finite width CPW is valid at all angles. Even though we are performing the measurements with a bias field that is at least four times the anisotropy of the film, the direction of the magnetization deviates slightly from the applied bias field direction. The method of correcting for dragging was previously reported in detail.[15] As a check on the correction for dragging, we also performed measurements aligned to the easy axis where there should be no dragging effect, and find agreement within the error bars.

Figure 3 shows the rotatable anisotropy as a function of inverse film thickness. The data points in the plot are averaged over all three waveguides to obtain better statistics. We have also corrected for the Earth's magnetic field to better than 8 A/m (0.1 Oe). There is a native oxide on the upper surface of the films. X-ray reflectometry measurements determined the oxide thickness to be 2 nm thick. We consider this in our data by subtracting 1 nm from the nominal grown thickness of the Permalloy films. Extrapolating from the existing data to infinite thickness, there is a bulk contribution to the rotatable anisotropy of ≈54 A/m (0.7 Oe). Further, if we extrapolate the line to films with a thickness of 2 nm, we would predict a rotatable anisotropy of ~280 A/m (3.5 Oe), which is on the order of the uniaxial anisotropy of the material. Such a large rotatable anisotropy could have a significant impact on the high bandwidth operation of magnetoelectronic componentry, such as the spin-valve read heads in disk drives.[16]

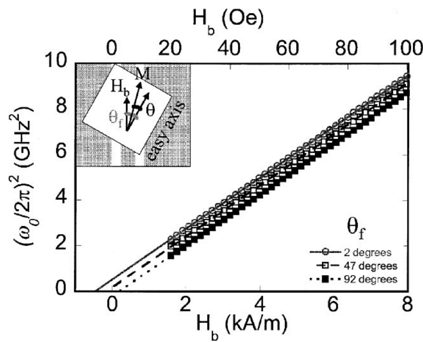

FIG. 1. Measured values of $f_0^2 = (\omega_0/2\pi)^2$ versus applied bias field H_b for a 50 nm thick Permalloy film for three different angles between the easy axis and the applied bias field. The error bars are equal to or smaller than the data point size. Inset shows the sample orientation on the CPW with the angles between the easy axis, the magnetization, and applied static bias field labeled. The difference between the magnetization direction and the applied field direction arises from the dragging effect, and has been greatly exaggerated for clarity.

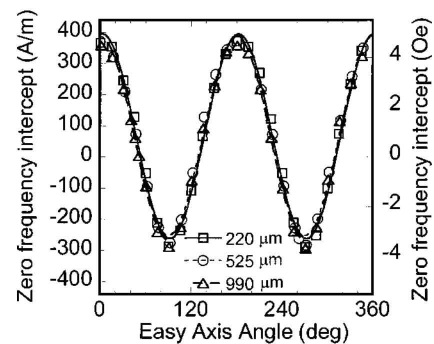

FIG. 2. Zero-frequency intercept field measured on three different CPWs for the 50 nm film. The data are corrected for both finite CPW width effect and the dragging effect. Fitting of these data is used to determine $H_k^{(0)}$.

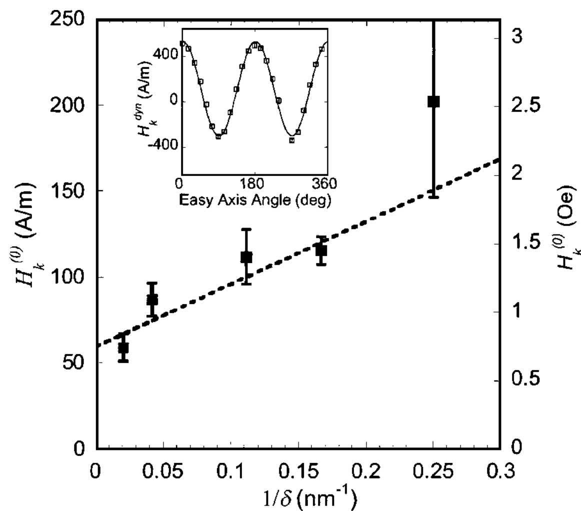

FIG. 3. Rotatable anisotropy $H_k^{(0)}$ versus inverse film thickness. Inset shows the angle-resolved dynamic anisotropy of a 10 nm Permalloy film with a 200 nm Cu capping layer, which still exhibits rotatable anisotropy even in the absence of a native oxide layer.

One reasonable hypothesis is that the native oxide is the source of the rotatable anisotropy. Permalloy films exchange coupled to NiO have exhibited a significant rotatable anisotropy.[17] In addition, Permalloy films with a native oxide show a substantial rotatable anisotropy at low temperatures.[18] However, previous work has shown that Permalloy films with a capping layer of Cu also show a rotatable anisotropy.[4] To test this hypothesis, we performed control measurements on a 10 nm Permalloy film with a 200 nm Cu capping layer grown on a 150 μm glass substrate. The capping layer was grown on the film directly after the Permalloy growth before the film was exposed to air. The inset of Fig. 3 shows the data taken from this sample. The data were taken on the 220 μm CPW and were corrected for the CPW width and the dragging effect as the other samples in this study have been. The rotatable anisotropy of the copper capped 10 nm Permalloy film is $H_k^{(0)}=116$ A/m$\pm$6 A/m, in agreement with the 10 nm Permalloy film that had the native oxide layer. We conclude that the rotatable anisotropy is not due to the presence of an oxide layer.

Given that the oxide layer is not the source of the rotatable anisotropy, the interface between the film and the substrate seem to be a likely source of the $H_k^{(0)}$ term. We speculate that the nonzero magnetostriction may be the cause of the $H_k^{(0)}$ term. While Permalloy films have a near-zero magnetostriction coefficient, it is never exactly zero. Further, the interface between the substrate and the thin Permalloy film may have a larger magnetostrictive effect than the bulk film.[19] Given a nonzero magnetostriction, there is the possibility that there is also a plastic deformation of the lattice associated with a given direction of the magnetization vector. It is likely that the magnetization vector can change directions in response to an applied field pulse much faster than the viscous response associated with plastic deformation, which is a thermodynamically irreversible mechanical process.[20] Given this, the plastic deformation of the lattice will look like an applied dc field in the original direction of the magnetization vector on times scales shorter than the viscous relaxation of the lattice, consistent with the observed behavior of $H_k^{(0)}$. The presence of significant surface magnetostriction may explain the inverse film thickness dependence as seen in Fig. 3.

In summary, we find that we can decompose the dynamic anisotropy of thin Permalloy films into a uniaxial component and a rotatable component by varying the angle between the easy axis and the applied field. While the finite width of the CPW and the dragging effect could be mistaken as a rotatable anisotropy in the dynamic measurements, there is still an unambiguous rotatable anisotropy after proper corrections for both effects. The rotatable anisotropy depends linearly on inverse film thickness. This effect significantly affects the complex permeability of ultrathin films when measured in the gigahertz range.

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