Ultrafast magnetization dynamics of epitaxial Fe films on AlGaAs (001)

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Uniform magnetization precessions are generated by ultrafast optical excitation along the in-plane easy axis [001], as well as along the hard axis [1-10], in epitaxial Fe films grown on AlGaAs (001) over a wide range of applied magnetic fields. From the temporal evolution of the coherent magnetization precession, we determine the magnetic anisotropy constants and damping parameters which are crucial in designing fast magnetic switching devices and spintronics devices. © 2005 American Institute of Physics. [DOI: 10.1063/1.1900939]

The process of magnetization reversal in thin films is of considerable importance in magnetic and magneto-optical recording, and in the context of magneto-electronics. These applications require very small ferromagnetic elements with uniaxial anisotropy for storing binary information in two stable states. Epitaxial growth of a ferromagnetic metal on a semiconductor provides an approach to realize high-density arrays of magnetic elements by using intrinsic in-plane uniaxial anisotropy instead of shape anisotropy. A ferromagnetic Fe film grown epitaxially on a GaAs (001) substrate is a particularly promising system because of its small lattice mismatch and strong uniaxial magnetic anisotropy. The magnetic properties are verified ex situ by standard magneto-optical Kerr-effect (MOKE) measurements and vibrating sample magnetometry (VSM). The magnetization exhibits a hard axis out-of-plane along (001), and uniaxial in-plane anisotropy superimposed on a four-fold cubic anisotropy, leading to an in-plane easy axis along [001] and hard axis along [1-10] direction. TRMOKE experiments are performed with a 150 fs Ti:Sapphire amplifier system at 800 nm wavelength. A modulated pump beam with 15 μJ pulse energy is focused to a spot of 1 mm in diameter on the sample as illustrated in Fig. 1(a). In equilibrium, the magnetization is along an effective field \( H_{eff} \), which is a sum of the applied field, the demagnetization field and the anisotropy field. The pump beam instantaneously heats up the Fe film. The instantaneous lattice expansion changes the anisotropy of the film and induces a transient magnetic field \( H_{t} \). The magnetization precession, we determine the magnetic anisotropy constants and damping parameters which are crucial in designing fast magnetic switching devices and spintronics devices.

Several techniques have been applied to characterize magnetization dynamics in ferromagnetic films, including ferromagnetic resonance (FMR) (Ref. 8) and Brillouin light scattering.\(^9\) Ju et al.\(^10\) studied spin wave excitations in exchange-biased NiFe/NiO layers by laser-induced unpinning of the magnetization. Acremann et al.\(^11\) produced a local transient magnetic field in a CoFe film by optical current generation at a Schottky barrier contact\(^7\) illustrate the importance of this system.

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In this letter, we report on time-resolved magneto-optical Kerr-effect (TRMOKE) experiments which exploit the temperature dependence of the in-plane uniaxial magnetic anisotropy to launch coherent magnetization precession in thin Fe films grown epitaxially on AlGaAs (001). A uniform magnetization precession is excited around both the hard and easy axes over a wide range of applied magnetic fields. The dependence of spin wave frequency on sample orientation and magnetic field at low excitation is used to determine the magnetic anisotropy and damping constants.

Fe (001) films with a thickness of 10 nm are grown on AlGaAs (001) by molecular-beam epitaxy.\(^7\) The equilibrium magnetic properties are verified ex situ by standard magneto-optical Kerr-effect (MOKE) measurements and vibrating sample magnetometry (VSM). The magnetization exhibits a hard axis out-of-plane along (001), and uniaxial in-plane anisotropy superimposed on a four-fold cubic anisotropy, leading to an in-plane easy axis along [001] and hard axis along [1-10] direction. TRMOKE experiments are performed with a 150 fs Ti:Sapphire amplifier system at 800 nm wavelength. A modulated pump beam with 15 μJ pulse energy is focused to a spot of 1 mm in diameter on the sample as illustrated in Fig. 1(a). In equilibrium, the magnetization is along an effective field \( H_{eff} \), which is a sum of the applied field, the demagnetization field and the anisotropy field. The pump beam instantaneously heats up the Fe film. The instantaneous lattice expansion changes the anisotropy of the film and induces a transient magnetic field \( H_{t} \). The magnetization...
$M$ starts to precess around $H_{\text{eff}}$, as illustrated in Fig. 1(b). When $H_{\text{eff}}$ has vanished (i.e., the film has returned to equilibrium), the vector $M$ is away from its original equilibrium orientation along $H_{\text{eff}}$. Therefore, it starts to precess around $H_{\text{eff}}$. The effect on the magnetization is measured by a much weaker ($\sim 1 \mu T$), time delayed probe beam using the MOKE technique. In the longitudinal geometry at an incidence angle of 45°, we detect both in-plane and out-of-plane components of the magnetization $M$. By varying the time delay $\Delta t$ between pump and probe, the magnetization precession is measured as a function of time after excitation.

Figure 1(c) shows typical results for the magnetization evolution after excitation of the 10 nm thick Fe film for an applied magnetic field of 560 Oe. The Fourier spectra of the transient MOKE signals reveal two coherent excitations with distinct frequencies [Fig. 1(d)]. The high-frequency oscillation at 42.5 GHz is independent of the magnetic field. This mode corresponds to a transverse acoustic phonon which is generated in the GaAs substrate by the instant lattice expansion at 42.5 GHz is independent of the magnetic field. This second oscillation at a lower frequency (5–15 GHz) depends on the magnitude and orientation of the magnetic field. Figure 1(c) shows that the film relaxes back to quasi-equilibrium after approximately 50 ps, and therefore the measured precession occurs in the original anisotropy field, thus revealing the equilibrium magnetic properties. As shown below, the anisotropy and demagnetization field of the coherent magnetization precession agrees well with the parameters of the uniform FMR mode measured in a 96 Å thick Fe film on GaAs (001).8

As shown in Figs. 1(c) and 2(a), large spin waves are generated along the [1-10] and [100] directions, while only a weak spin wave excitation is observed along the [110] direction where the magnetization is less canted. For a magnetic field of 560 Oe applied along the [1-10] or [100] direction, the magnetization is canted away from the applied field because of the uniaxial character of the magnetic anisotropy of the Fe film. The cubic magnetocrystalline anisotropy also contributes to the transient anisotropy field, but this effect is small. This has been verified with a 50 nm thick epitaxial Fe film which exhibits no uniaxial anisotropy. In this control sample, the precession amplitude is five times smaller. Furthermore, the oscillating MOKE signal shows the same phase for opposite applied magnetic fields. This excludes the existence of an out-of-plane transient magnetic field. We note the large spin wave amplitude at a small magnetic field applied along the in-plane hard [1-10] axis. An even larger rotation angle can be achieved at a higher excitation level and larger uniaxial magnetic anisotropy, as for example in thinner Fe films. This would lead to a large out-of-plane component of magnetization and the resultant demagnetization field could trigger an out-of-plane precession. This process could then be utilized for fast magnetization reversal.

The orientation dependence of the precession frequency clearly reveals uniaxial and cubic anisotropy as shown in Fig. 2(b). We will show in the following that the magnetic anisotropy constants can be determined from the field dependence and anisotropy of the precession frequency. Figure 3(a) shows the frequency spectra for magnetic fields applied along the [100] and [1-10] directions. The latter is the hard axis for the uniaxial and cubic magnetic anisotropies. For small angle excitations, the frequency dispersion is well described by the model of the uniform FMR mode. Previous Brillouin scattering8 and FMR studies1 on thin Fe films suggest that surface anisotropy and spin pinning is negligible. The frequency behavior of the uniform magnetization precession can be described by solving the Landau–Lifshitz equation including the shape-related demagnetization and anisotropy field. The frequency is given by

$$\omega = \gamma (H_c \cos (\delta - \phi) + H_a)(H_a \cos (\delta - \phi) + H_B)^{1/2},$$  

where

$$H_a = 4 \pi M_s + \frac{2 K_{\text{out}}}{M_s} \frac{2}{M_s} \frac{K_u}{M_s} \sin (\phi - \cos \phi)^2 + \frac{K_u}{M_s} [2 - \sin^2(2\phi)],$$

$$H_B = \frac{2K_u}{M_s} \cos (4\phi) + \frac{2K_u}{M_s} \sin (2\phi),$$

and $\gamma = \gamma_r g/2$ (with $\gamma_r = 1.76 \times 10^7$ Hz/Oe and $g = 2.09$) is the gyromagnetic ratio. $\phi$ and $\delta$ are the angles between the in-plane easy axis [100] and the directions of magnetization and applied magnetic field $H_c$, respectively. $K_u$, $K_{\text{out}}$, and $K_{\text{in}}$ are the cubic anisotropy, in-plane uniaxial anisotropy, and out-of-plane anisotropy constants, respectively. $M_s$ is the saturated magnetization.
To accurately describe the field dependence of the precession frequency, we need to know the magnetization angle \( \phi \) which is determined by the subtle balance of external and internal magnetic field caused by the magnetic anisotropy. The dependence of \( \phi \) on applied magnetic field is obtained from the hysteresis curves measured by VSM. The solid lines in Fig. 3(a) are the precession frequencies calculated from Eq. (1). The cubic anisotropy \( K_3/M_s \), uniaxial anisotropy \( K_u/M_s \), and out-of-plane saturated magnetic field \( 4\pi M_s + 2K_{out}/M_s \) used in the calculation are 0.21 kOe, 0.09 kOe, and 17.5 kOe, respectively. The angle \( \phi \) calculated from the above anisotropy constants reproduces the in-plane hysteresis curve, and the out-of-plane saturated field is consistent with independent MOKE measurements. For the easy [100] axis, the precession frequency increases monotonically with increasing applied magnetic field. This behavior is typical along an easy axis. For the hard [1-10] axis, the frequency initially increases due to the rotation of the magnetization toward the easy [100] axis, then decreases due to further rotation toward the hard [1-10] axis, and finally increases as the magnetization aligns along the applied magnetic field direction.

The (Gilbert) damping parameter \( \alpha \) is another important factor in fast magnetic switching. Generally, the damping parameter is treated as a constant. However, there is theoretical and experimental evidence\(^{17,18} \) that \( \alpha \) can vary with the magnetization angle relative to the field direction and film normal, with the magnitude of the applied field, and with the precession frequency. By including the damping term in the Landau–Lifshitz equation, the uniform magnetization precession can be described by an oscillating term and an exponential decaying term \( \exp(-\Gamma t) \), where

\[
\Gamma = \frac{\alpha \gamma [H_x \cos(\delta - \phi) + H^0] + (H_x \cos(\delta - \phi) + H^0)]}{2(1 + \alpha^2)}.
\]

The expression for \( \Gamma \) can be simplified as \( \Gamma = \alpha \omega \) in the case of \( H^0 = H^B \) and small \( \alpha \). The damping parameter \( \alpha \) is calculated from Eq. (2) and parameters used in Eq. (1) for the frequency calculation. Figure 3(b) shows \( \alpha \) as a function of the magnetic field applied along the [100] and [1-10] directions. The damping parameter varies strongly with applied field along the hard [1-10] axis, whereas \( \alpha \) remains nearly constant along the easy [100] axis. This behavior may be explained by the two-magnon scattering process where the damping rate depends on the spin wave manifold.\(^{17} \) For the hard axis, the magnetization rotates toward the [1-10] direction with increasing applied field. This will change the density of accepting magnon states and therefore the damping parameter. In contrast, for the easy [100] axis, the magnetization direction will not significantly rotate with increasing applied field and therefore \( \alpha \) remains nearly constant. Further studies are required to fully elucidate the damping mechanism.

In conclusion, we have studied picosecond magnetization precession dynamics in ferromagnetic films with in-plane uniaxial anisotropy epitaxially grown on AlGaAs (001). Coherent magnetization precessions are generated by ultrafast optical excitation along all directions of the sample over a wide range of applied magnetic field. This provides a sensitive optical probe that can locally measure the dynamic magnetic properties of very small ferromagnetic elements. From the decay of the FMR mode, we determine the anisotropy of the damping parameter which is crucial in designing fast magnetic switching devices and novel spintronics devices.

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