Inductive time-domain measurement of magnetization dynamics in epitaxial Fe$_{1-x}$Co$_x$ single and double layers

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(Presented on 10 November 2004; published online 28 April 2005)

A pulsed inductive microwave magnetometer (PIMM) is used to examine magnetization dynamics. The thin film sample is brought into close proximity to the coplanar waveguide, which allows for simple changing of samples. The angle between the easy axis (e.a.) and field direction can easily be varied by rotation of the sample on the waveguide. The magnetization dynamics, i.e., precessional frequency, decay time, and precessional amplitude, are determined with respect to this angle or the bias field for epitaxial Fe$_{1-x}$Co$_x$ films with different anisotropies. The two precessional motions of a magnetic double layer (FeCo/Au/Ni$_{80}$Fe$_{20}$) where resolved with the PIMM, which is promising for future investigations on exchange coupled layers. © 2005 American Institute of Physics. [DOI: 10.1063/1.1855452]

I. INTRODUCTION

High speed, nonvolatile memories based on magnetic tunnel junctions have already been presented by industry. For the future success of this promising technology, it is important to understand magnetization dynamics in very thin ferromagnetic films and to learn how to extend the operation frequency of these devices to the highest possible values. Here the magnetization dynamics of FeCo single and double layers were examined with a pulsed inductive microwave magnetometer (PIMM). The advantage of FeCo thin films is the fact that, its anisotropies can be controlled over a wide range by composition and thickness.$^2$

II. SAMPLES, SETUP, AND THEORY

The examined single layer FeCo sample GaAs(001)/85 ML Fe$_{80}$Co$_{20}$(001)/25 ML Au(001) (ML—monolayer) was grown using molecular beam epitaxy in an UHV system. The FeCo layer and Au cap of the magnetic double layer sample GaAs(001)/38 ML Fe$_{71}$Co$_{29}$(001)/25 ML Au(001)/20 nm Ni$_{80}$Fe$_{20}$/3 nm Al are also epitaxial. The Ni$_{80}$Fe$_{20}$(Permalloy = Py) layer and Al cap were grown by magnetron sputtering. Static anisotropy constants were determined by magneto-optic Kerr effect (MOKE) measurements.$^2$

The precessional motion of the magnetization is excited by a fast magnetic field step or pulse with a rise time of about 60–70 ps, which is produced by a current through a coplanar waveguide (Fig. 1). The precession of the magnetization induces a signal in the same waveguide, which is detected by a digital sampling oscilloscope.$^1$ As a pulse generator a Picosecond Pulselab 10060A is used, which delivers a maximum output voltage of 10 V, which translates to a pulse field strength of $\approx$1 mT over the 50 µm center conductor of the waveguide. To measure the precession dynamics with respect to the angle between the [110]-direction and the bias field $\vec{H}_b$, the sample was rotated against the whole setup in steps of 15°. This is very convenient because the field geometry of the setup stays the same especially since the bias and pulse fields always enclose 90°, which ensures optimal excitation at high bias fields (see Fig. 1).

For the interpretation of the observed precessional frequency $f$ as a function of strength and orientation of an external magnetic field, Kittel’s general formula

\[
f = \frac{\gamma}{2\pi \mu_0 M \sin \theta} \sqrt{\mu_0 \left[ \frac{\partial^2 \epsilon}{\partial \psi^2} \frac{\partial^2 \epsilon}{\partial \theta^2} - \left( \frac{\partial^2 \epsilon}{\partial \varphi \partial \theta} \right)^2 \right]}
\]

was evaluated using the following expression for the energy density $\epsilon$ of a FeCo(001) thin film (compare to Ref. 3):

\[
\epsilon(\varphi, \theta) = -\mu_0 H_b M_s \cos(\alpha - \varphi) \sin \theta - \frac{K_s}{4} [\sin^4 \theta \cos^2(2\varphi) + \sin^2(2\varphi)] + K_u \sin^2 \varphi + \frac{1}{2} \mu_0 M_s M_{eff} \cos^2 \theta,
\]

where

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$^b$Tektronix TDS 8000, which was available for two weeks as a generous loan from Tektronix GmbH Germany.
\[ M_{\text{eff}} = M_s - H_K = M_s - \frac{2K_1}{\mu_0 M_s} \]

(3)

where \( H_b \) is the external field, \( M_s \) is the saturation magnetization, \( K_u \) and \( K_1 \) are the uniaxial and cubic in-plane anisotropy constants of the magnetic film, \( K_1' \) represents a uniaxial anisotropy with the easy axis perpendicular to the thin film plane, originating from the interface, \( \varphi \) is the angle between the normal of the film and the magnetization vector, \( \alpha \) and \( \omega \) are the angles between \( f_{110} \) and the in-plane component of \( M \) and \( H_b \), respectively.

For the equilibrium position of the magnetization in the film \((\theta=90^\circ)\), small excitations and the assumption \( \alpha = \omega \), which holds for high bias fields, the following formula is obtained:

\[
\begin{align*}
f &= \frac{\gamma}{2\pi}\left( \mu_0 M_s \right)^2 \left[ \cos^2(2\varphi) - \sin^2(2\varphi) \right] \\
  &\quad + 2\mu_0 \left( \cos^2 \varphi - \sin^2 \varphi \right) \left( \mu_0 H_b M_s + K_1 \left( 2 - \cos^2(2\varphi) \right) \right) \\
  &\quad + \mu_0 M_s (M_{\text{eff}}) \right)^{1/2}. \\
\end{align*}
\]

(4)

For negligible \( K_1 \) and \( H_b \ll M_s \) this can be simplified to

\[
f = \frac{\gamma_0}{2\pi} \sqrt{H_{\text{eff}} M_{\text{eff}}}
\]

(5)

with the effective field \( H_{\text{eff}} \). For the special cases \( K_1 = 0 \) and \( \varphi = 0^\circ \) (plus sign) or \( \varphi = 90^\circ \) (minus sign), respectively, \( H_{\text{eff}} \) is given by

\[ H_{\text{eff}} = H_b \pm H_K, \quad H_K = \frac{2K_u}{\mu_0 M_s}. \]

(6)

where \( H_K \) is the anisotropy field.

From the measured decay time \( \tau \) of the precessional motion the phenomenological damping constant \( \alpha = \alpha_{\text{int}} + \alpha_{\text{ext}} + \alpha_{\text{SW}} = 2/\tau (\gamma_0 M_s) \) can be determined. It consists of an intrinsic part \( \alpha_{\text{int}} \), characteristic for each material, and an extrinsic part \( \alpha_{\text{ext}} \), depending on sample morphology (surface roughness, etc.) and an additional damping component \( \alpha_{\text{SW}} \) caused by escaping spin waves.\(^5\)

### III. RESULTS

The static anisotropy constants of the Fe\(_{64}\)Co\(_{36}\)(001) single layer as determined by MOKE are \( K_u = 9800 \pm 500 \) J/m\(^3\) and \( K_1 = -500 \pm 50 \) J/m\(^3\). The field dependence of the precession frequency is shown in Fig. 2 for precession around easy and hard axis. The data were fitted with Eq. (4). With the given values of \( g = 2.1 \pm 0.01 \), \( K_1' = 370 \ 000 \pm 40 \ 000 \) J/m\(^3\) (determined with the alternating gradient magnetometer at a similar sample), and \( K_1 = 9800 \pm 500 \) J/m\(^3\) the following formulas were used:

\[
f(\varphi) = \frac{\gamma_0}{2\pi} \sqrt{H_{\text{eff}} M_{\text{eff}}(\varphi)},
\]

where \( \varphi \) is the angle between the normal of the film and the magnetization vector. The field dependence of the precession frequency is shown in Fig. 2 for precession around easy and hard axis. The data were fitted with Eq. (4). With the given values of \( g = 2.1 \pm 0.01 \), \( K_1' = 370 \ 000 \pm 40 \ 000 \) J/m\(^3\) (determined with the alternating gradient magnetometer at a similar sample), and \( K_1 = 9800 \pm 500 \) J/m\(^3\) the following formulas were used:

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−500±50 J/m³ the following constants could be obtained from precession around the easy axis: $M_s=(1.65±0.05) \times 10^6$ A/m, $K_u=10\,400±400$ J/m³.

There is a good agreement between the anisotropy constants determined from the quasistatic MOKE measurement and the dynamic ones obtained from the fit to the precession frequencies. This is in contrast to the systematic increase of the dynamic anisotropy compared to the static value frequently observed with Permalloy films.¹

In Fig. 3 the precession frequency is plotted versus the angle $\varphi$. It can be observed that the precession frequency reproduces the dominant uniaxial anisotropy of this sample very well, which is caused by angular variance of the effective field.

The insets in Fig. 3 show that the decay time of the oscillations is angular dependent, too. In Fig. 4 this decay time is plotted versus the effective field. Additionally the decay time from field dependent measurements of the precession around easy and hard axis is plotted for comparison. It can be seen that in the overlap regions the accordance is quite good. The general increase of decay time with increasing $H_{\text{eff}}$ is also observed with Permalloy.¹ From the averaged decay time at high fields an $\alpha^{\ast}=0.0043±0.001$ was obtained.

The precession amplitude $A_p$ and the measured induction signal $U_{\text{ind}}$ are connected through $A_p / U_{\text{ind}}$. Figure 5 shows a strong increase of $A_p$ when $\varphi$ approaches 90°. There $\mu_0 H_{\text{eff}}=\mu_0(H_b−H_K)$ reaches its minimal value of 4 mT at the chosen constant $\mu_0 H_b$ of 16 mT. For smaller effective fields, which can be engaged by approaching $H_b$ to $H_K$ along the hard axis direction, the precession amplitude can even be bigger, which allows for observations of nonlinear effects.

The magnetic double layer sample Fe₇₁Co₂₉(001)/Au(001)/Ni₈₀Fe₂₀(Py) was used to examine if it is possible to detect the magnetization dynamics of both magnetic layers. As shown in Fig. 6 this was possible. From a measured beat oscillation two frequencies could be obtained through fast Fourier transformation for each field value. The two saturation magnetizations $M_{s,\text{Fe}_{71}\text{Co}_{29}}=(0.82±0.02) \times 10^6$ A/m and $M_{s,\text{Fe}_{71}\text{Co}_{29}}=(1.64±0.05) \times 10^6$ A/m obtained from the fit of these “Kittel plots” clearly identify Permalloy and FeCo.

IV. CONCLUSION

The PIMM is a useful device for the investigation of the magnetization dynamics of epitaxial thin films with large anisotropies. The small signals of epitaxial films, due to small film thickness and high $H_{\text{eff}}$, require highly stable measurement conditions and/or fast data acquisition. Large angle precessions can be obtained at small $H_{\text{eff}}$, which can be engaged by approaching $H_b$ to $H_K$ along the hard axis direction. The investigation of magnetic double layers is possible as the precessional motion of two layers can be resolved.

ACKNOWLEDGMENT

Support by the Deutsche Forschungsgemeinschaft (Priority Program No. 1133) is gratefully acknowledged.