Influence of a Dy overlayer on the precessional dynamics of a ferromagnetic thin film

M. K. Marcham, W. Yu, P. S. Keatley, L. R. Shelford, P. Shafer, S. A. Cavill, H. Qing, A. Neudert, J. R. Childress, J. A. Katine, E. Arenholz, N. D. Telling, G. van der Laan, and R. J. Hicken

Citation: Applied Physics Letters **102**, 062418 (2013); doi: 10.1063/1.4792740
View online: http://dx.doi.org/10.1063/1.4792740
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/102/6?ver=pdfcov
Published by the AIP Publishing

Influence of a Dy overlayer on the precessional dynamics of a ferromagnetic thin film

M. K. Marcham,[1] W. Yu,[1] P. S. Keatley,[1] L. R. Shelford,[2] P. Shafer,[3] S. A. Cavill,[2] H. Qing,[3] A. Neudert,[4] J. R. Childress,[5] J. A. Katine,[5] E. Arenholz,[3] N. D. Telling,[6] G. van der Laan,[2] and R. J. Hicken[1]

[1]*School of Physics and Astronomy, University of Exeter, Stocker Road, Exeter, Devon EX4 4QL, United Kingdom*
[2]*Diamond Light Source, Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0DE, United Kingdom*
[3]*Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4]*Helmholtz-Zentrum Dresden-Rossendorf e. V., Institute of Ion Beam Physics and Materials Research, P.O. Box 51 01 09, 01314 Dresden, Germany*
[5]*San Jose Research Center, HGST, 3403 Yerba Buena Road, San Jose, California 95135, USA*
[6]*Keele University, Institute for Science and Technology in Medicine, Guy Hilton Research Centre, Thornburrow Drive, Hartshill, Stoke-on-Trent ST4 7QB, United Kingdom*

(Received 6 December 2012; accepted 6 February 2013; published online 15 February 2013)

Precessional dynamics of a $Co_{50}Fe_{50}(0.7)/Ni_{90}Fe_{10}(5)/Dy(1)/Ru(3)$ (thicknesses in nm) thin film have been explored by low temperature time-resolved magneto-optical Kerr effect and phase-resolved x-ray ferromagnetic resonance measurements. As the temperature was decreased from 300 to 140 K, the magnetic damping was found to increase rapidly while the resonance field was strongly reduced. Static x-ray magnetic circular dichroism measurements revealed increasing ferromagnetic order of the Dy moment antiparallel to that of $Co_{50}Fe_{50}/Ni_{90}Fe_{10}$. Increased coupling of the Dy orbital moment to the precessing spin magnetization leads to significantly increased damping and gyromagnetic ratio of the film while leaving its magnetic anisotropy effectively unchanged. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4792740]

Improved understanding of precessional magnetization dynamics is essential for the continued development of high frequency magnetic devices such as hard disk drives and spin transfer torque oscillators. Recently, Maat[1] *et al.* reported greatly reduced spin torque noise in current perpendicular to the plane spin-valves capped by a Dy overlayer. Capping is preferred to impurity doping of the entire magnetic layer[2,3] in order to minimize impact on the magnetoresistance of the spin-valve. Phase-resolved x-ray ferromagnetic resonance (XFMR) measurements[4] on a spin-valve free layer material of composition $Co_{50}Fe_{50}(0.7)/Ni_{90}Fe_{10}(5)$ (thicknesses in nm) revealed that capping with Dy leads to enhanced damping at room temperature, although the nature of the interaction between the Dy and the underlying layers was so far unknown.

In this letter, we present a detailed study of the temperature dependent static and dynamic magnetic properties of a $Co_{50}Fe_{50}(0.7)/Ni_{90}Fe_{10}(5)/Dy(1)/Ru(3)$ thin film structure. Static x-ray magnetic circular dichroism (XMCD) and vibrating sample magnetometry (VSM) were used to explore the ordering of the Dy and its influence upon the static magnetic properties of the film. Time-resolved scanning Kerr microscopy (TRSKM),[5,6] low temperature time-resolved magneto-optical Kerr effect (TRMOKE) measurements, and phase-resolved XFMR[4] were used to characterize the dynamic response. It will be shown that the Dy overlayer modifies the damping and gyromagnetic ratio of the film while leaving its magnetic anisotropy essentially unchanged.

A $Ta(5)[Cu(25)/Ta(3)]_{x3}/Cu(25)/Ta(10)/Ru(5)/Co_{50}Fe_{50}(0.7)/Ni_{90}Fe_{10}(5)/Dy(1)/Ru(3)$ thin film stack was deposited onto a sapphire substrate of 500 μm thickness by magnetron sputtering. A second stack without the 1 nm Dy layer was also deposited and served as a control sample. The composite CoFe/NiFe magnetic layer is representative of the free layer used in a spin-valve sensor for high-density hard disk recording. This magnetic layer was patterned into magnetic elements with lateral dimensions of several hundred microns,[7] which were defined on top of the thick Cu/Ta multilayer underlayer by a combination of electron beam lithography and ion beam milling, while the thick Cu/Ta underlayer structure was left unpatterned. Photolithography was then used to pattern the exposed Cu/Ta underlayer structure into a coplanar waveguide (CPW) of 50 Ω impedance. The sample aspect ratio was sufficiently large to avoid any spatially inhomogeneous dynamics due to edge effects. A 5 μm border was left between the edges of the sample element and the central track to avoid any significant out-of-plane excitation.

The geometry for the dynamic measurements is shown in Fig. 1. The sample was excited by the magnetic field associated with either a pulsed or continuous wave (CW) microwave current waveform, propagating through the CPW, that was phase locked with the laser or x-ray probe pulses. By changing the relative phase of the current waveform and the probe pulse, the dynamic response of the sample can be recorded. Room temperature TRSKM was performed using a microscope objective with sub-micron spatial resolution,[5,6] while variable temperature TRMOKE measurements were carried out in vacuum on the cold finger of a He gas flow cryostat. Optical pulses from a Ti:sapphire laser with 100 fs duration and 80 MHz repetition rate were passed along an optical delay line for picosecond temporal resolution. Small changes in the out-of-plane component of the dynamic

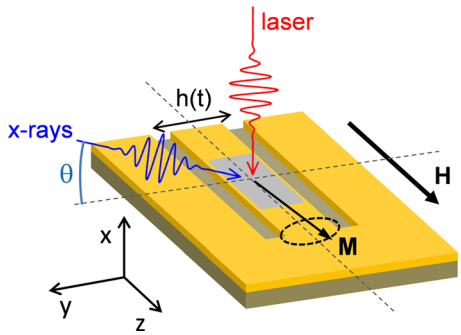

FIG. 1. Schematic of the experimental geometry for TRSKM, TRMOKE, XMCD, and XFMR measurements. The magnetization **M** precesses around the bias field **H** in response to a microwave magnetic field **h**(t). In TRSKM and TRMOKE, the normal incidence probe beam detects the polar Kerr rotation from the out-of-plane magnetization component. In XFMR, the grazing incidence x-ray beam detects the larger in-plane oscillatory component of magnetization.

magnetization were detected using the polar Kerr effect and a polarizing bridge detector.

In phase-resolved XFMR measurements,[4] small changes in the in-plane dynamic magnetization, parallel to the x-ray k-vector, were detected using XMCD. The corresponding fluorescence yield from the decay of holes generated in the $2p$ atomic core levels, when the x-ray energy was tuned to the atomic core levels, was measured using a soft x-ray photodiode equipped with a secondary electron filter. In both laser and x-ray techniques, the dynamic response was small and required the use of phase sensitive detection using amplitude or phase modulation and a lock-in amplifier. In TRSKM and TRMOKE, only the average response of the sample can be detected at optical frequencies. However, in XFMR, dynamic information of different atomic elements can be obtained in the time domain owing to their different $2p$ core levels. Thus, XFMR allows the dynamic response of individual layers of a multilayer structure, or sublattices of an alloy to be unambiguously identified.

Temperature dependent static XMCD measurements were made in fluorescence yield in the vector magnet magnetometer[8] on beamline 4.0.2 at the Advanced Light Source. The XMCD was obtained from the difference of the x-ray absorption spectra recorded with the magnetization saturated parallel and antiparallel to the helicity vector of the x-rays. The chemical specificity of XMCD enables the magnetic signal of the Dy capping layer to be distinguished from that of the underlying transition metal layers. Phase-resolved XFMR measurements were made in fluorescence yield at room temperature.

TRSKM measurements of the magnetization dynamics induced by a 70 ps (full width at half maximum) pulsed field in the uncapped and capped samples are shown in Figs. 2(a) and 2(b), respectively. The addition of the Dy cap significantly enhances the damping of the precessional oscillations. A Lorentzian line shape was fitted to the power spectrum of each trace and the centre frequencies have been plotted in Figs. 2(c) and 2(d). For a thin film with uniaxial in-plane anisotropy, in which the magnetization **M** is aligned with the applied field **H**, the ferromagnetic resonance (FMR) frequency $\omega/2\pi$ is given by,

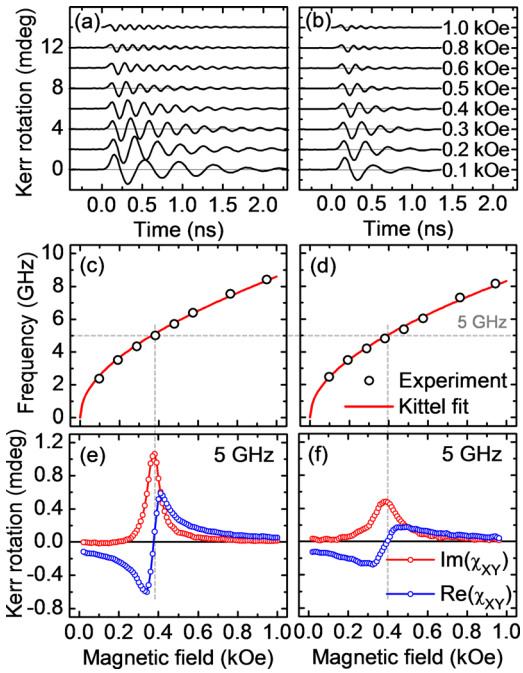

FIG. 2. Room temperature pulsed TRSKM measurements of a $Co_{50}Fe_{50}(0.7)/Ni_{90}Fe_{10}(5)$ film without (left column) and with (right column) Dy(1) capping layer. (a) and (b) Experimental results. (c) and (d) Frequencies extracted from Lorentzian fitting of power spectra corresponding to TR signals in (a) and (b). (e) and (f) Real and imaginary components of the magnetic susceptibility χ_{xy} for uncapped and capped film, respectively, in response to a 5 GHz CW microwave excitation.

$$\left(\frac{\omega}{\gamma}\right)^2 = \left(H + \frac{2K_u}{M}\cos 2\phi\right)\left(H + \frac{2K_u}{M}\cos^2\phi + 4\pi M_{\text{eff}}\right), \tag{1}$$

where K_u is the uniaxial anisotropy constant, ϕ is the angle between the static field and in-plane easy axis, $4\pi M_{\text{eff}}$ is the effective demagnetizing field that includes any perpendicular anisotropy, and $\gamma = \gamma_e g/2$ is the gyromagnetic ratio in which $\gamma_e = 2\pi(2.80)$ MHz/Oe and g is the spectroscopic splitting factor. The red curves in Figs. 2(c) and 2(d) are fits to Eq. (1) in which the uniaxial and perpendicular anisotropies have been neglected and $M = 657$ and 554 emu/cm^3, respectively, as determined by VSM. The fits yielded g factors of 2.02 and 2.11, respectively. The response to a 5 GHz CW microwave excitation is shown in Figs. 2(e) and 2(f). Signals were recorded at two delay values, $\pi/2$ rad apart, to obtain the *Re* and *Im* parts of the χ_{xy} component of the dynamic susceptibility tensor. The resonance curve is clearly broadened in the case of the Dy capped sample.

Bulk Dy is paramagnetic at room temperature but becomes antiferromagnetic at $T_N = 179$ K and ferromagnetic at $T_C = 85$ K, so that the magnetic properties of the capped sample are expected to be strongly temperature dependent.[9] Variable temperature TRMOKE measurements were made at 4 GHz excitation frequency. The samples were zero field cooled and measurements were made as the temperature was increased. The measured *Im* components of the dynamic susceptibility χ_{xy} are shown in Fig. 3. The resonance field, peak amplitude, and FMR line width were determined by fitting to a Lorentzian lineshape.

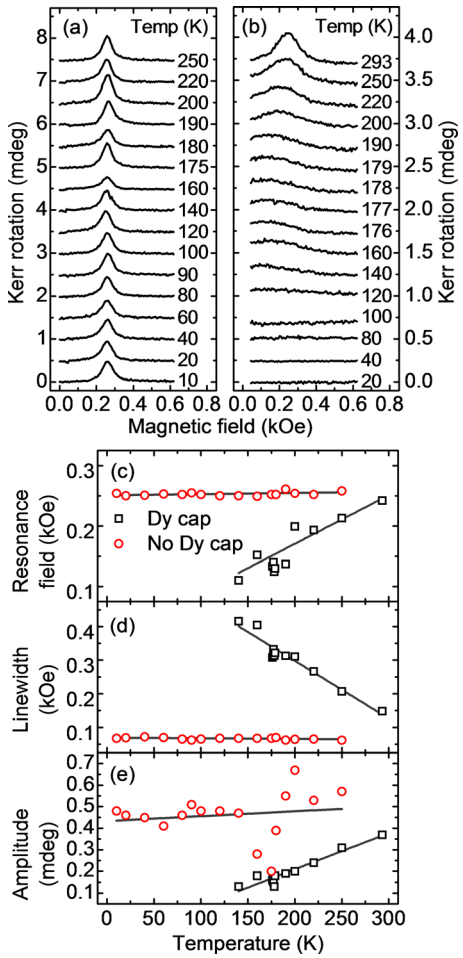

FIG. 3. Field dependence of polar Kerr rotation, proportional to $Im(\chi_{xy})$ recorded at different temperatures for the samples without (a) and with (b) Dy cap. Resonance field (c), line width (d), and amplitude (e) obtained from Lorentzian fitting to the curves in (a) and (b). Solid grey curves are guides to the eye.

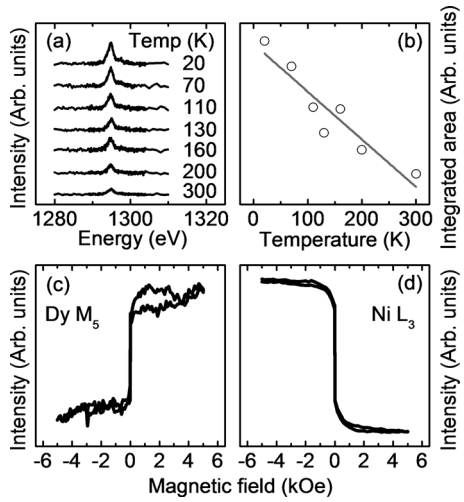

FIG. 4. (a) Dy XMCD spectra acquired in fluorescence yield at different temperatures after zero field cooling, and (b) corresponding integrated area of the M_5 peak. Hysteresis loops at (c) Dy M_5 and (d) Ni L_3 edges at 110 K after cooling in a 5 kOe field directed along the x-ray beam.

While the line width of the uncapped sample appears independent of temperature, the line width of the capped sample more than doubles as the temperature is reduced, until it can no longer be clearly distinguished below 140 K. The extracted resonance field is seen to decrease strongly with decreasing temperature for the capped sample, while the resonance field is essentially temperature independent in the uncapped sample. For the capped sample, the amplitude decreases monotonically with decreasing temperature before becoming unmeasurable below 140 K. The large variation in the amplitude of the uncapped sample observed around 175 K is attributed to a temperature dependent variation of the impedance matching along the microwave current path, which is specific to the uncapped sample. However, the strong temperature dependence of the line width, resonance field, and amplitude observed in the capped sample can be attributed to the Dy capping layer.

To understand the influence of the Dy layer, temperature dependent static XMCD measurements were made, as shown in Fig. 4(a). The sample was cooled in zero field. While the Dy M_4 peak was barely resolved, the integrated area of the M_5 peak increases with decreasing temperature, Fig. 4(b). Although application of the XMCD sum rules to fluorescence measurements is complicated by the presence of self-absorption effects,[10] the substantial increase in the M_5 peak amplitude clearly indicates increased ferromagnetic order in the Dy as a result of cooling. Ni XMCD spectra (not shown) taken within the same temperature range show no such strong temperature variation. Hysteresis loops were acquired at the Dy M_5 and Ni L_3 edges, with fixed circular polarization and at 110 K, after cooling in a 5 kOe field parallel to the x-ray beam, Figs. 4(c) and 4(d). The loops are centred at zero field and show no evidence of an exchange bias field. The Ni L_3[11] and Dy M_5[12] XMCD show opposite signs, indicating an antiparallel alignment of the ferromagnetically ordered Dy moments with the Ni moments. Ferrimagnetic order is common in rare earth-transition metal alloys, such as Fe-Dy.[13] In the present case, ferromagnetic ordering of the Dy could result from the likely intermixing of Dy and NiFe at the interface, or from interfacial exchange across a sharp Dy/NiFe interface.

VSM measurements revealed that the magnetization of the capped and uncapped samples increased by about 7% and 10%, respectively, as the temperature was reduced from 300 to 100 K, suggesting that the Dy moment represents no more than a few percent of the total sample moment at low temperature. The increased damping at low temperatures is instead a consequence of the strong spin-orbit interaction and orbital moment of the Dy that provide an efficient channel for transfer of angular momentum to the lattice. However, solution of the linearized Landau-Lifshitz-Gilbert equation of motion showed that the increased damping should have negligible influence upon the resonance field, even as the Gilbert damping parameter was increased to a value of 0.5. From Eq. (1), it is obvious that a 10% increase in magnetization cannot explain the more than 50% reduction of the resonance field. To further pinpoint the root cause of this reduction, field cooled and zero field cooled VSM measurements were made with the magnetic field applied both parallel and perpendicular to the plane of the sample. Hysteresis loops remained centred at zero-field as the temperature was reduced from 300 to 100 K, again ruling out the possibility of a temperature-dependent exchange bias field.

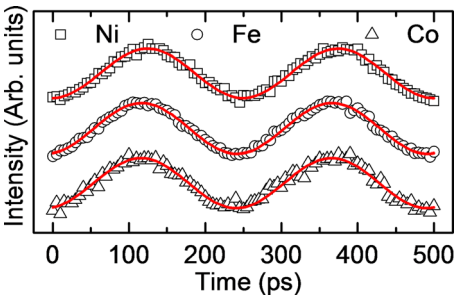

FIG. 5. Room temperature phase-resolved XFMR at 4 GHz of the Ni, Fe, and Co moments in the Dy-capped sample. The curves are offset in the vertical direction for clarity.

The loop saturation fields showed negligible temperature variation, ruling out a temperature dependent uniaxial in-plane anisotropy or perpendicular anisotropy. Equation (1), therefore, requires the g factor to increase from 2.11 to about 2.7 to explain the observed reduction of the resonance field. This increase results from coupling of the orbital moment of the rare earth element to the spin-dominated moments of the transition metal layer magnetization, as observed previously in GdFeCo alloys.[14]

Phase-resolved XFMR at 4 GHz was used to measure the relative phase of precession of the Ni, Fe, and Co moments at room temperature by tuning the x-ray energy to the Ni, Fe, and Co L_3 edges in turn and varying the relative delay between the x-ray pulses and the CW microwave excitation, as shown in Fig. 5. The Dy signal lay below the noise floor of the experiment. Sine curves with fixed period of 250 ps were fitted to the experimental data. The curve fitted to the Co was found to lead those fitted to the Fe and Ni by 0.7 and 8.6 ps, respectively. This is consistent with the idea that increased damping due to the Dy slightly delays the phase of precession at the upper Dy/NiFe interface with respect to that within the CoFe at the bottom of the magnetic bilayer.

In summary, we have shown that a 1 nm overlayer of Dy is very effective in modifying the damping of a magnetic thin film while making a very modest contribution to the total sample moment. The increased damping results from coupling of the Dy orbital moment to the precessing spin magnetization. This also leads to an enhanced gyromagnetic ratio while leaving the magnetic anisotropy essentially unchanged.

The authors gratefully acknowledge the financial support of EPSRC Grant EP/F021755/1. The ALS is supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Parts of this work were carried out on beamline 4.0.2 at the ALS and beamline I06-1 at Diamond Light Source.

[1]S. Maat, N. Smith, M. J. Carey, and J. R. Childress, Appl. Phys. Lett. **93**, 103506 (2008).
[2]W. Bailey, P. Kabos, F. Mancoff, and S. Russek, IEEE Trans. Magn. **37**, 1749 (2001).
[3]S. G. Reidy, L. Cheng, and W. E. Bailey, Appl. Phys. Lett. **82**, 1254 (2003).
[4]M. K. Marcham, P. S. Keatley, A. Neudert, R. J. Hicken, S. A. Cavill, L. R. Shelford, G. van der Laan, N. D. Telling, J. R. Childress, J. A. Katine, P. Shafer, and E. Arenholz, J. Appl. Phys. **109**, 07D353 (2011).
[5]A. Neudert, P. S. Keatley, V. V. Kruglyak, J. Mccord, and R. J. Hicken, IEEE Trans. Mag. **44**, 3083 (2008).
[6]P. S. Keatley, P. Gangmei, M. Dvornik, R. J. Hicken, J. Grollier, C. Ulysse, J. R. Childress, and J. A. Katine, Top. Appl. Phys. **125**, 17 (2013).
[7]TRSKM measurements were made on samples on 50 μm wide CPWs ($40 \times 400\ \mu m^2$ sample elements). Owing to the larger spot size, XFMR measurements were made on 200 μm wide devices ($190 \times 400\ \mu m^2$ sample elements). The different devices were patterned from the same wafer stack and in both cases the aspect ratio of the samples was sufficient to avoid any spatially inhomogeneous dynamics due to edge effects.
[8]E. Arenholz and S. O. Prestemon, Rev. Sci. Instrum. **76**, 083908 (2005).
[9]C. Dufour, K. Dumesnil, Ph. Mangin, G. Marchal, and M. Hennion, J. Magn. Magn. Mater. **156**, 425 (1996).
[10]M. van Veenendaal, J. B. Goedkoop, and B. T. Thole, Phys. Rev. Lett. **77**, 1508 (1996).
[11]C. T. Chen, N. V. Smith, and F. Sette, Phys. Rev. B **43**, 6785 (1991).
[12]J. B. Goedkoop, B. T. Thole, G. van der Laan, G. A. Sawatzky, F. M. F. de Groot, and J. C. Fuggle, Phys. Rev. B **37**, 2086 (1988).
[13]K. Fleury-Frenette, S. S. Dhesi, G. van der Laan, D. Strivay, G. Weber, and J. Delwiche, J. Magn. Magn. Mater. **220**, 45 (2000).
[14]T. Kato, K. Nakazawa, R. Komiya, N. Nishizawa, S. Tsunashima, and S. Iwata, IEEE Trans. Magn. **44**, 3380 (2008).