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ABSTRACT

We report on the ultrafast magnetization dynamics of $[Co_{60}Fe_{40}/Pt]_5$ multilayers studied with femtosecond laser pulses. The samples were grown at room temperature by DC magnetron sputtering with Ta capping and Pt buffer layers and present the same thickness and perpendicular magnetic anisotropy as determined by vibrating sample magnetometry. Controlled growth rate of the Pt buffer layer modified the anisotropy fields and magnetic domain sizes as measured by magnetic force microscopy (MFM). An estimation of the average magnetic domain sizes was obtained from the profile of the self-correlation transform of the MFM images. For multilayers having an average magnetic domain size of 490 nm, we report a damped precession of the magnetization which decays with a time constant of ~100 ps and which has a frequency which varies from 8.4 GHz to 17.0 GHz as the external field increases from 192 mT to 398 mT. Fitting the precession dynamics with the Landau-Lifshitz-Gilbert equation we evaluated the damping α, which decreases from 0.18 to 0.05 with increasing magnetic domain sizes (127 nm to 490 nm). These α values are higher than for single layers suggesting an enhanced scattering and spin pumping effects from the Pt adjacent layers. In addition, the precession frequency increases from 2.04 GHz to 11.50 GHz as the anisotropy field of the multilayers increases from 6.5 kOe to 13.0 kOe. Finally, a comparative analysis between micromagnetic simulations and MFM images allowed us to determine the exchange stiffness (A_{ex}) in the $[Co_{60}Fe_{40}/Pt]_5$ multilayers.

Using femtosecond light pulses to study ultrafast magnetization dynamics has been a fruitful approach for investigating magnetic materials and their applications. It has been allowing a better understanding of magnetization dynamics at sub-picosecond timescales which is a pre-requisite for improving the speed of current devices.[1–3]

Initially, it was shown that magnetic materials could be demagnetized locally by femtosecond pulses at sub-picosecond time scales.[4] In the following, that the ultrafast photoexcitation of electrons and spins could lead to changes of the effective field launching a magnetization precession that may be followed in real space in the time domain.[5,6] Now, it is well known that the analysis of this precession may be used, analogously to ferromagnetic resonance, to evaluate important material parameters, like the dynamic anisotropy, the magnetic anisotropy field and the damping in magnetic films and magnetic nanostructures.[3,7,8] Thereafter, this field of research has flourished with the investigations of all-optical switching in ferrimagnetics,[9] the inverse Faraday effect in dielectrics and antiferromagnets[1] and more recently, it has been extended to the attosecond time scale with element specificity and new probing wavelengths.[10] Nowadays, much attention has been devoted to the investigation and generation of ultrafast superdiffusive spin currents and terahertz radiation following ultrafast photoexcitation.[11–13]

Here we report on the ultrafast magnetization dynamics of $[Co_{60}Fe_{40}/Pt]_5$ multilayers which were synthesized with varying magnetic textures. Magnetic multilayers with Co_xFe_y and Pt or Pd interlayers have attracted much interest because they have been proposed as reference layers in STT-MRAM and magneto-resistive sensors.[14,15] The investigated samples were grown at room temperature by DC magnetron sputtering with Ta capping and Pt buffer layers and present perpendicular magnetic anisotropy (PMA) as determined by vibrating sample magnetometry (VSM). Controlled growth rate of the Pt buffer layer modified the anisotropy fields and magnetic domain sizes as measured by magnetic force microscopy (MFM) and VSM. In order to have a set of samples with varying magnetic homogeneity, a set of $[Co_{60}Fe_{40}/Pt]_5$ multilayers (S1-S4) with the same thickness and which distinguish themselves only by the growth rate of the buffer layers were synthesized. Details of sample growth and characterization are presented in Ref. 16.

The time-resolved measurements were carried out with 100 fs laser pulses from a Ti:Saphire oscillator. The experiments were done at low fluency (~0.1 $mJ.cm^{-2}$) in a degenerate pump and probe setup in the Kerr configuration in a standard time resolved femtosecond magneto-optical setup.[17] After photoexcitation by 100 fs pump pulses, we report an ultrafast demagnetization of the multilayers in hundreds of fs followed by a partial remagnetization, which occurs typically with a time constant of ~1.5 ps (not shown). Thereafter, as displayed in Figure 1a, a damped precession of the magnetization is observed to decay with a time constant of ~100 ps for the multilayers with larger domain sizes (S4). In Figure 1b we present the frequency dependence of the precession which in this case varies from 8.4 GHz to 17.0 GHz as the external field increases from 192 mT to 398 mT for the sample S4. Expectedly, the decay time, η, increases for higher fields reaching a constant value, in this case of ~100 ps for fields greater than 200 mT (Figure 1c).

From the decay time it is possible to determine a value for the damping, α, in $Co_{60}Fe_{40}/Pt$ multilayers fitting the experimental data with the Landau-Lifshitz-Gilbert (LLG) equation (Figure 1b).[3] Assuming a sample uniformly saturated to magnetization, perpendicular magnetic anisotropy, small deviations of saturation magnetization, M_s, from the equilibrium direction, an external DC field $\vec{H}$ applied in the plane of incidence under an angle θ_H and an effective field comprising the applied field plus and effective anisotropy field defined as $H_K^{eff} = H_K - 4\pi M_s$ (H_K being the sample's intrinsic anisotropy field) it is possible to solve the LLG equation to obtain the frequencies of precession and the decay time. The solution gives the following expression for the frequency of precession and the decay time

$$\omega = \gamma \cdot \sqrt{H_1 \cdot H_2} \tag{1}$$

and

$$\frac{1}{\eta} = \frac{1}{2} \cdot \alpha \cdot \gamma \cdot (H_1 + H_2) \tag{2}$$

where

$$\begin{cases} H_1 = H \cdot \cos(\theta_H - \theta_0) + H_K^{eff} \cdot \cos(2 \cdot \theta_0) \\ H_2 = H \cdot \cos(\theta_H - \theta_0) + H_K^{eff} \cdot (\cos^2 \theta_0) \end{cases} \tag{3}$$

and $\gamma = g_L \mu_B / \hbar$ is the gyromagnetic factor, g_L is the Landé factor, μ_B is the Bohr magneton and $\hbar = h/2\pi$ where h is the Planck constant. For fitting the experimental data in Figure 1b we used the saturation magnetization and anisotropy field measured from VSM (±10%) and a value of g=5.18 for $[Pt/Co_{60}Fe_{40}/Pt]_5$ multilayers. The anisotropy field was derived from M-H loops as $H_k = H_s + 4\pi M_s$.[18] We note that this surprisingly large value of g was necessary for fitting the experimental results and may be related to additional orbital moment contribution from the Co/Pt interface.[17,19,20] Clearly, it would be interesting to check this hypothesis by using other techniques like ferromagnetic resonance and x-ray magnetic circular dichroism (XMCD) but it goes beyond the scope of the present work.

As shown in Figure 2, we observed a decreasing damping with increasing the magnetic domain sizes observed by MFM in the multilayers (inset Figure 2). Let's stress that all the investigated $Co_{60}Fe_{40}/Pt$ multilayers have the same thickness and varying magnetic domain sizes due to the fact that they were grown over Pt buffer layer which had distinct crystalline textures and magnetic homogeneity. Fitting the experimental data with the LLG equation, we may evaluate α in each sample which decreases from 0.18 to 0.05 for multilayers with increasing magnetic domain sizes. Note that these values are higher than for single layers and may be correlated, as reported before in multilayers,

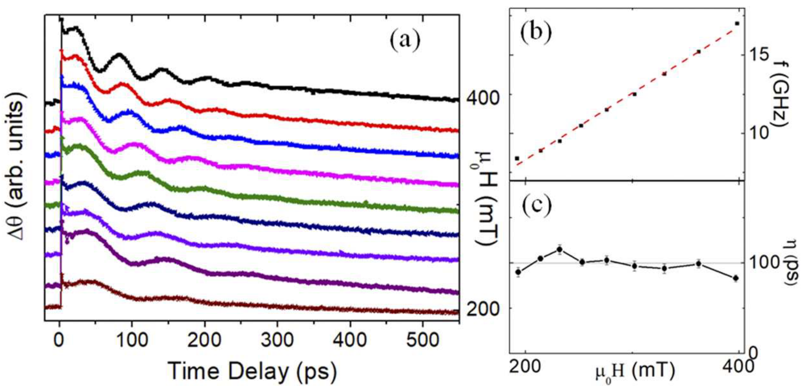

FIG. 1. (a) TR-MOKE, (b) precession frequency and (c) decay time as a function of the external magnetic field for S4.

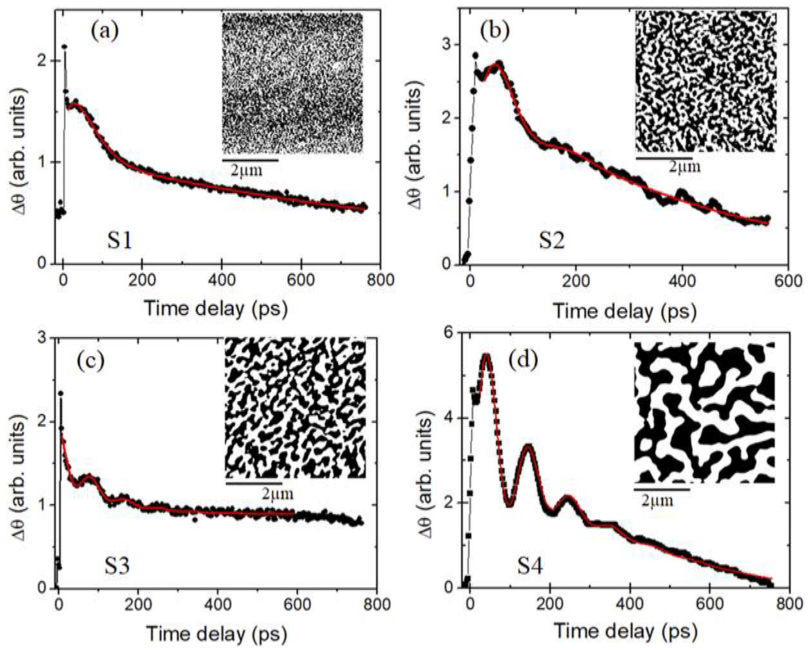

FIG. 2. Precession damping for multilayers with increasing magnetic textures: S1 (Fig. 2a), S2 (Fig. 2b), S3 (Fig. 2c), S4 (Fig. 2d). The insets show the corresponding MFM images.

with an enhanced scattering and spin pumping effects from the Pt adjacent layers.[21,22] We note that the precession frequency (extracted fitting the data to LLG) increases from 2.04 GHz to 11.50 GHz as the anisotropy field of the multilayers increases from 6.5 kOe to 13.0kOe.

For characterizing the magnetic homogeneity of the multilayers, we did MFM measurements (inset of Figure 2) and micromagnetic simulations (Figure 3). The simulations were made by using MuMax3 software, developed at the DyNaMat group by Prof. Van Waeyenberge at Ghent University.[23] MFM measurements were obtained using a NTEGRA Aura (NT-MDT Co). The MFM measurements were done at demagnetized state. Let's stress that the domain in the demagnetized states also mirror local inhomogeneities.[22] An estimation of the average magnetic domain sizes of the samples was obtained from the profile of the self-correlation transform of the MFM images.[24] The results show that we have an average domain size of 127.5nm for the sample S2, 176.5nm for the sample S3 and 490.0nm for the sample S4. For the sample S1 it was not possible to infer the average domain size since the domains size of this sample is smaller than the tip resolution.

In order to estimate the exchange stiffness, A_{ex}, value for each multilayer we used the adjustment of micromagnetic simulations to MFM measurements (Figure 3). Usually A_{ex} a key parameter controlling magnetization reversal in magnetic materials. The simulations are carried varying the A_{ex} in order to most closely match the MFM images. The obtained values of A_{ex} for each sample are presented in Table I. Pre-requisite for simulating the domain pattern with MuMax3 and determinating A_{ex}, is the knowledge of the M_s, K_u and α, which here were determined respectively from VSM measurements and from analysis of the magnetization dynamics measurements as discussed previously. The static magnetic properties were determined for each sample by measuring the magnetic hysteresis loops at parallel and perpendicular directions to the film plane and thereafter calculating the anisotropy constant, $K_u = H_k M_s/2$.[18] The simulations that best adjusted to the MFM images are displayed in

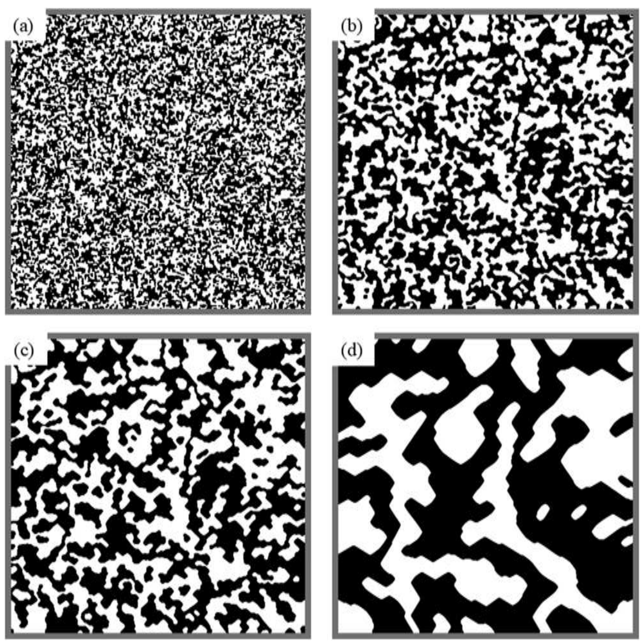

FIG. 3. Micromagnetic simulation results of sample (a) S1, (b) S2, (c) S3 and (d) S4. All images correspond to areas of 5 μm x 5 μm.

TABLE I. Saturation magnetization (M_s), uniaxial anisotropy (K_u), damping (α), exchange stiffness (A_{ex}), magnetostatic exchange length (l_{ex1}) and magnetocrystalline exchange length (l_{ex2}) values for the samples.

Sample	M_{sat} (kA/m)	K_u (MJ/m^3)	α	A_{ex} (pJ/m)	l_{ex1} (nm)	l_{ex2} (nm)
S1	472	1.91	0.180	15.5	10.5	2.85
S2	770	4.95	0.179	42.8	10.7	2.94
S3	551	2.75	0.076	24.3	11.3	2.97
S4	560	2.75	0.053	26.3	11.5	3.09

Figure 3 and the obtained values of A_{ex} for each sample are presented in Table I.

The exchange stiffness is defined by $A_{ex} = nJS^2/a$, where n is the number of nearest neighbours, S^2 the square of spin, J the exchange integral and a the lattice constant and therefore the distance between the spins. The exchange length, which is defined as $l_{ex1} = \sqrt{2A_{ex}/\mu_0 M_s^2}$ corresponds to magnetostatic exchange length and $l_{ex2} = \sqrt{A_{ex}/K_u}$ corresponds to magnetocrystalline exchange length[25] and both increase with the increase of the average domain size.

We note that the obtained values of A_{ex} are in the same order of the values reported before in Co-based films ~10pJ/m[18,26] and present some variation in the set of investigated samples. It has been reported that A_{ex} may vary with fabrication conditions, such as Ar gas pressure, substrates, seed layers, compositions, and annealing conditions because it is sensitive to the distance between magnetic atoms and number of nearest neighborhoods.[27] In our case, since the Pt buffer layer crystallinity and magnetic homogeneity vary with the growth processes, we could expect that A_{ex} could be different for each sample.

In conclusion, we report on the ultrafast magnetization dynamics of a set of $[Co_{60}Fe_{40}/Pt]_5$ multilayers with varying magnetic homogeneity and same thickness which present a decreasing damping (0.18 to 0.05) as we increase the magnetic domain sizes (127 nm to 490 nm) and which frequency of precession increases from 2.04 GHz to 11.5 GHz as the anisotropy field of the multilayers increases from 6.5 kOe to 13.0kOe. Fitting the magnetization dynamics with LLG equation we extracted from the decay time of the precession α values which are higher than for single layers suggesting an enhanced scattering and spin pumping effects from the Pt adjacent layers. Finally, a comparative analysis between micromagnetic simulations and MFM images allowed us to determine the exchange stiffness, A_{ex}, which is a key parameter controlling magnetization reversal in magnetic materials. As magnetic multilayers with Co_xFe_y and Pt or Pd interlayers have been proposed as reference layers in STT-MRAM and magneto-resistive sensors, we hope that the investigation of its dynamic properties may be useful for the design of new fast magnetic devices.

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