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Determining the Gilbert damping in perpendicularly magnetized Pt/Co/AlO_x films

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The Gilbert damping in perpendicularly magnetized Pt/Co/AlO_x films is studied by means of the time-resolved magneto-optical Kerr effect. The Gilbert damping constant is observed to depend strongly on the AlO_x layer thickness and the applied magnetic field. The magnetic field dependence is explained by extrinsic contributions to the damping due to inhomogeneities in the thin films. The intrinsic Gilbert damping is found to vary between 0.11 and 0.28 as a function of the AlO_x thickness, which can be attributed to spin pumping from Co into the adjacent Pt film.

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Magnetic thin films with perpendicular magnetic anisotropy (PMA) have potential applications in next-generation, high density information storage technology due to their good thermal stability. In the intensively studied systems with PMA, Pt/Co/AlO_x thin films have attracted much interest recently due to the large spin-orbit torques.^{1,2} For example, it has been argued that the Rashba spin orbit torque could enhance domain wall velocities,³ and switching by means of the Spin Hall Effect has also been demonstrated to be very effective in this material.⁴ An important parameter determining the magnetization dynamics in these thin films is the Gilbert damping parameter, which governs the relaxation rate to equilibrium. In particular, the domain wall velocity below the Walker breakdown field⁵ and the switching speed of magnetic bits are both determined by the Gilbert damping constant. Besides the important role the Gilbert damping plays in magnetization dynamics, damping in thin films is also of interest from a more fundamental point of view. In thin magnetic films, many mechanisms can potentially contribute to the damping, such as spin pumping,⁶ two-magnon scattering,⁷ and inhomogeneous broadening.⁸ Understanding which contributions are dominant in particular systems allows for control of the damping parameter by material engineering.

Here, we study the damping constant in the intensively studied Pt/Co/AlO_x thin films by using the time-resolved magneto-optical Kerr effect (TRMOKE). We do so by bringing the magnetic system out of equilibrium with an intense pump laser pulse, while a probe laser pulse measures the subsequent relaxation back to equilibrium. For information on this technique the reader is referred to the work by van Kampen *et al.*⁹ The TRMOKE measurements were performed using a pulsed Ti:sapphire laser with central wavelength of 780 nm, pulse width of 70 fs, and repetition rate of 80 MHz. Both pump and probe beams were focused onto the sample at almost normal incidence, hence the measured

TRMOKE signal is most sensitive to the out-of-plane component of the magnetization. In the TRMOKE measurements, the external magnetic field was applied at an angle $\beta \sim 15^\circ$ from the film plane, in order to suppress domain formation.

To characterize our samples, Pt (4 nm)/Co (0-2 nm)/Al (0-2 nm) crosswedges were grown by DC sputtering and subsequent oxidation for 200 s at 15 W and an oxygen pressure of 0.1 millibars. Perpendicular hysteresis loops were recorded using MOKE, and the results are depicted in Fig. 1. In Fig. 1(a), the measured coercive fields are shown as a function of Co and Al thickness. Examples of hysteresis loops are shown in Fig. 1(b). Three regions can be clearly distinguished. For thin Co and Al layers, the oxidation process fully oxidizes the Co, hence there is no ferromagnetic layer left. For thick Al and Co layers, the sample has an in-plane easy axis. Only for a narrow range of Co and Al thicknesses, the sample shows PMA. Surprisingly, very thick Co layers (up to 2 nm) show PMA when the Al thickness is made sufficiently thin. The only way to explain this is by assuming that part of the Co film is oxidized due to the thin Al capping layer, leaving only a thin magnetic Co layer. The surface anisotropy of the Pt/Co and Co/CoO_x interfaces must be large enough to induce the perpendicular anisotropy. Effectively, this means that decreasing the Co thickness has an identical effect on the magnetic anisotropy as decreasing the Al thickness.

The Gilbert damping constant is determined for a Pt (4 nm)/Co (1 nm)/Al (0-2 nm) wedge, where the measurements are only performed for Al thicknesses that show 100% remanence. Note that this sample is not identical to the one in the MOKE measurements in Fig. 1, hence a direct comparison between the magnetic properties of these samples is not possible. Examples of TRMOKE traces as a function of applied magnetic field B and Al thickness t_{Al} are shown in Figs. 2(a) and 2(b), respectively. First of all, the oscillations observed in the measurements are homogeneous precessions of the magnetization, as the precession frequencies of standing spin waves in these thin films are orders of magnitude

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FIG. 1. (a) Coercive fields of a Pt/Co/AIO_x crosswedge as obtained by perpendicular MOKE measurements. (b) Examples of perpendicular MOKE measurements for an Al thickness of 1 nm and varying Co thicknesses. The dots in (a) correspond to the MOKE measurements depicted in (b).

larger than observed in Figs. 2(a) and 2(b). Second, the precession frequency increases for increasing B and decreasing t_{Al} . The former is expected, since a larger applied field increases the effective field and thus also the precession frequency. The latter is caused by an increase in PMA, caused by the fact that for thinner Al thicknesses, more Co is oxidized. Since the surface anisotropy is inversely proportional to the effective Co thickness, the anisotropy becomes larger for smaller Al thicknesses.

To analyze the data quantitatively, all TRMOKE traces are fitted with the following phenomenological fitting formula:⁹

$$-\frac{\Delta M_z}{M_z} = A_1 + A_2 e^{-\Delta t/\tau_e} + A_3/\sqrt{1 + \Delta t/t_0} + A_4 e^{-\Delta t/\tau_d} \sin(\omega \Delta t + \varphi), \quad (1)$$

where Δt is the delay time between arrival of the probe beam with respect to the probe. The first term is the non-magnetic background. The second term represents relaxation of the electron temperature, and τ_e is the corresponding equilibration time. The third term gives the one dimensional heat diffusion contribution. The constant t_0 takes the initial absorption profile into account. The long term, oscillating magnetization dynamics, is included in the fourth term. Examples of fitted curves are depicted in Figs. 2(a) and 2(b), where the lines denote the fits.

From the fits, the damping parameter can be obtained. For films with a perpendicular anisotropy, the relation

FIG. 2. Examples of TRMOKE traces as a function of delay time after laser pulse excitation for varying applied fields and $t_{\text{Al}} = 1.29$ nm (a), and varying Al thicknesses and an applied field of 758 mT (b). The lines are fits with a phenomenological fit function, Eq. (1).

between the Gilbert damping constant α , the precession frequency ω , and the decay time of the oscillation τ_d is shown to be given by¹⁰

$$\alpha = \frac{1}{\omega \tau_d}. \quad (2)$$

In Figs. 3(a) and 3(b), the fitted values for ω and α are plotted as a function of the applied magnetic field for four thicknesses of the Al top layer. The precession frequency in Fig. 3(a) shows the expected increasing behavior as a function of applied field, where the cut-off frequency at zero field can be related to the magnitude of the perpendicular anisotropy.

From the Landau-Lifshitz-Gilbert (LLG) equation,¹¹ it is expected that α does not depend on the applied magnetic field. However, the measurements in Fig. 3(b) show that this is not the case for the investigated Pt/Co/AIO_x samples. A few reasons for a field dependent damping in thin films exhibiting strong PMA have been suggested, being an anisotropic intrinsic damping due to the spin-orbit coupling,^{12,13} two magnon-scattering,⁷ and inhomogeneous broadening.⁸ As anisotropic damping is mainly expected to occur at low temperatures and contributions due to two-magnon scattering should vanish for small applied fields, inhomogeneous broadening is most likely to explain the observed field dependence. Therefore, we fit the data with a simple model¹⁰ for inhomogeneous broadening, where the effective perpendicular anisotropy field H_{eff} , which is the difference between the surface anisotropy field H_{surf} and the demagnetization

FIG. 3. Fitted values for the precession frequency (a) and Gilbert damping parameter (b) as a function of applied field for different values of t_{Al} . Lines are fits with a model accounting for an inhomogeneous distribution of the anisotropy in the probed region.

field H_{demag} , is not homogeneous over the probed area. We assume that H_{surf} shows a square distribution between $(1 - \sigma)H_{surf}$ and $(1 + \sigma)H_{surf}$. The magnetization dynamics of such a distribution is calculated by numerically solving the LLG equation for a distribution of macrospins and averaging over the results. For the saturation magnetization M_{sat} of Co, a value of 1400 kA/m is used. The data in Figs. 3(a) and 3(b) are then fitted by Eq. (1) to obtain the intrinsic damping α_{intr} , effective anisotropy field H_{eff} , and the spread in anisotropy field σ as a function of t_{Al} . Note that in the limit of large applied fields, the model predicts that $\alpha_{fit} = \alpha_{intr}$.

The field dependence of α and ω are simultaneously fitted by the model, and the results are depicted as lines in Figs. 3(a) and 3(b). First of all, it can be observed that the model fits both the field dependence of α and ω with reasonable accuracy. This shows that inhomogeneous broadening can in fact fully explain the field dependence of the measurements. A remarkable observation from the fits is that inhomogeneous broadening seems more pronounced for samples with a smaller perpendicular anisotropy. The reason is that in this region, the demagnetization field and surface anisotropy almost cancel, hence a small change in one of both contributions yields a large relative change in the net anisotropy, resulting in a relatively large spread in precession frequencies.

The free fit parameters are depicted in Fig. 4 as a function of t_{Al} . Note that σ is used as a global fit parameter, yielding a value of the spread in surface anisotropy of 6.0%. Fig. 4(a) displays the fitted effective perpendicular anisotropy field H_{eff} as a function of t_{Al} . First of all, we note that the fitted anisotropy

FIG. 4. H_{eff} (a) and α_{intr} (b) as a function of t_{Al} . The lines are fits to a simple model. The inset of (b) shows the coercive field as a function of t_{Al} , where the solid line is a guide to the eye and the dotted line is the value for t_{Al} where the effective Co thickness becomes zero.

fields are comparable to values obtained from hard-axis MOKE measurements on similar structures. The increase of H_{eff} for decreasing t_{Al} is in line with the observation of the static MOKE measurements in Fig. 1(a), where it is shown that more of the magnetic Co film is oxidized when the Al capping layer is thinner, effectively making the magnetic film thinner. Since the contributions of the surface anisotropy become relatively larger when decreasing the film thickness, a larger perpendicular anisotropy is observed for small t_{Al} . To quantify this effect, we assume that t_{Co} scales linearly with t_{Al} and fit the data with $H_{eff} = A/(t_{Al} - t_{Al,0}) + B$, where A and B are scaling parameters and $t_{Al,0}$ is the Al thickness for which the effective Co thickness is zero. $t_{Al} - t_{Al,0}$ is thus a measure for the Co thickness. Aforementioned relation yields excellent fits for $t_{Al,0} = (0.97 \pm 0.02)$ nm.

Fig. 4(b) displays the fitted intrinsic damping parameter α_{intr} as a function of t_{Al} , where, as mentioned previously, α_{intr} corresponds to the values of α_{fit} in large applied fields. As the intrinsic damping in these thin films is often dominated by spin pumping,^{10,14} which should be inversely proportional to the Co thickness, we fit the data with $\alpha_{intr} = A/(t_{Al} - t_{Al,0})$, where A is again a scaling parameter and $t_{Al} - t_{Al,0}$ resembles the Co thickness. The fit is depicted as a line in Fig. 4(b) and is in good agreement with the data. Furthermore, the fit yields $t_{Al,0} = (0.99 \pm 0.01)$ nm. This corresponds to the value obtained from fitting the anisotropy, showing that the fitting procedure of the data with the simple macro-spin model to account for inhomogeneous broadening is appropriate. Although the inverse proportionality of the damping on t_{Co} suggests that spin pumping dominates the Gilbert damping in Pt/Co/AlOx thin films, also intrinsic bulk-like contributions due to spin-orbit coupling should be present. However, as the Gilbert damping parameter of bulk Co is rather small (≈ 0.01), it is impossible to disentangle this contribution from the relatively large spin pumping effects.

Finally, we can compare the fitted value for $t_{\text{Al},0}$, i.e., the Al thickness where the effective Co thickness is zero, to measurements of the static magnetic properties of the sample. In the inset of Fig. 4(b), the coercive field H_c of the magnetic stack is plotted as a function of Al thickness. Indeed a sharp drop in the coercive field is observed around the fitted value of $t_{\text{Al},0}$, which is indicated by the dotted line, corresponding to the point where over-oxidation of the magnetic layer takes place, destroying the magnetic properties.

Concluding, we have determined the Gilbert damping constant for Pt/Co/AlO_x by measuring laser induced precession of the magnetization. By fitting the field dependence of the damping with a model for inhomogeneous broadening, an intrinsic Gilbert damping constant between 0.11 and 0.28 is found, depending on the effective Co thickness. The origin of this large intrinsic Gilbert damping could be attributed to spin pumping into the Pt bottom layer. The large value for the Gilbert damping constant could be important in experiments studying the magnetization dynamics, such as, for example, experiments on DW motion or switching by spin-orbit torques.

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