Gilbert damping of high anisotropy Co/Pt multilayers

Thibaut Devolder¹, S Couet², J Swerts² and G S Kar²

¹Centre de Nanosciences et de Nanotechnologies, CNRS, Univ. Paris-Sud, Université Paris-Saclay, C2N-Orsay, 91405 Orsay Cedex, France
²imec, Kapeldreef 75, 3001 Heverlee, Belgium

E-mail: thibaut.devolder@u-psud.fr

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Abstract

Using broadband ferromagnetic resonance, we measure the damping parameter of [Co(5 Å)/Pt(3 Å)]×6 multilayers, whose growth was optimized to maximize the perpendicular anisotropy. Structural characterizations indicate abrupt interfaces essentially free of intermixing, despite the miscible character of Co and Pt. Gilbert damping parameters as low as 0.021 can be obtained, despite a magneto-crystalline anisotropy as large as 10⁶ J m⁻³. The inhomogeneous broadening accounts for part of the ferromagnetic resonance linewidth, indicating some structural disorder leading to an equivalent 20 mT of inhomogeneity of the effective field. The unexpectedly relatively low damping factor indicates that the presence of the Pt heavy metal within the multilayer may not be detrimental to the damping provided that intermixing is avoided at the Co/Pt interfaces.

Keywords: Gilbert damping, perpendicular magnetic anisotropy, Co/Pt multilayer

(Some figures may appear in colour only in the online journal)
to maximize perpendicular anisotropy. The sputter-deposition is performed at an extremely low [17] argon pressure in remote plasma conditions, which enables very abrupt interfaces that are essentially free of intermixing. We show that in contrast to common thinking, the Gilbert damping parameter of Co/Pt multilayers can be low; its effective value is 0.021 but it still likely [16] includes contributions from spin-pumping that our protocol unfortunately cannot suppress.

2. Experimental

Our objective is to report the high frequency properties of Co/Pt multilayers that were optimized for high anisotropy. The multilayer is grown by sputter-deposition on a Ru (50 Å) buffer and capped with a Ru(70 Å)/Ta(70 Å)/Ru(100 Å)/Ta(10 Å, cap) sequence (bottom to top order). The Ru buffer was chosen because it does not mix with Co-based multilayers even under tough annealing conditions [25]. The stacks were deposited by physical vapor deposition in a Canon-Anelva EC7800 300 mm system on oxidized silicon substrates at room temperature. The argon plasma pressure is kept at 0.02 Pa, i.e. substantially lower than the usual conditions of 0.1–0.5 Pa used in typical deposition machines [17]. As this multilayer is meant to be the reference layer of bottom-pinned magnetic tunnel junctions, in some samples (figure 1) the non-magnetic cap is replaced by the following sequence: Ta cap / Fe80Co20B20/MgO/Fe80Co20B20/Ta/[Co(5 Å)/Pt(3 Å)]×5/Ru similar to in [18, 19] to form a bottom-pinned magnetic tunnel junction with properties designed for spin-torque applications [20]. All samples were annealed at 300 °C for 30 min in an out-of-plane field of 1 T.

3. Structure

X-ray reflectivity scans (not shown) indicate Bragg reflections at 2θ = 11, 22.2 and 33.6°, consistent with the multilayer periodicity of 8 Å. Consistently, the Pt to Co intermixing is sufficiently low that well formed 3 Å Pt spacers can be seen in the transmission electron micrograph after annealing (figure 1(a)). Almost no roughness is observed throughout the Co/Pt multilayer. We emphasize that this quality of interfaces is essential uniform) angle between the magnetization and the sample normal. Our convention is that the first and second order anisotropy fields from the sole hard axis loop. The rounding of the hard axis loop near saturation and its slight hysteresis remanence (figure 1(c)) impedes a more precise deduction of the anisotropy fields from the sole hard axis loop.

4. Anisotropy

The magnetic material properties were measured by vibrating sample magnetometry (VSM) and vector network analyzer ferromagnetic resonance [22] in both easy (z) and hard axis (x) configurations. For VNA-FMR, the sample is mechanically pressed on the surface of a 50 microns wide coplanar waveguide terminated by an open circuit; data analysis is conducted following the methods described in [23]. The VSM signal indicated a magnetization $M_s = 8.5 \times 10^5$ kA m$^{-1}$ if assuming a magnetic thickness of 48 Å, i.e. assuming that the [Co(5 Å)/Pt(3 Å)]×5 multilayer can be described as a single material. The loops indicate a perpendicular anisotropy with full remanence. The reversal starts at 46.8 mT and completes before 48 mT with a tail-free square hysteresis loop. Careful attempts to demagnetize the sample using an ac perpendicular field failed to produce a multidomain state at remanence. This indicates that the lowest nucleation field in the whole sample is larger that the domain wall propagation field everywhere in the film. This low propagation field indicates qualitatively that the effective anisotropy field is very uniform. The hard axis loop indicates an in-plane saturation field of $\approx 13 \pm 0.1$ T in line with the expectations for such a composition [3]. The rounding of the hard axis loop near saturation and its slight hysteretic remanence (figure 1(c)) impedes a more precise deduction of the anisotropy fields from the sole hard axis loop.

We shall instead use the ferromagnetic resonance data because magnetization eigenfrequencies constitute absolute measurements of the effective fields acting on the magnetization. Figure 2 gathers the measured FMR frequencies measured for in-plane and out-of-plane applied fields from −2.5 to 2.5 T. To analyze the microwave susceptibility data, we assume an energy density that reads $E = \frac{1}{2} \mu_0 H_{\parallel} M_s \sin^2 \theta + \frac{1}{2} \mu_0 H_{\perp} M_s \sin^4 \theta$ with $\theta$ the (supposedly uniform) angle between the magnetization and the sample normal. Our convention is that the first and second order magneto-crystalline anisotropy fields $H_{k1} = 2K_1 / (\mu_0 M_s)$ and $H_{k2} = 4K_2 / (\mu_0 M_s)$ are positive when they favor perpendicular magnetization, i.e. $\theta = 0$.

In that framework, the ferromagnetic resonance frequencies in out-of-plane and in-plane applied fields saturating the magnetization as:

Figure 1. Structure and anisotropy of a Co–Pt multilayer. (a) Transmission electron micrograph of a magnetic tunnel junction that embodies our Co/Pt as a hard multilayer at the bottom of the reference synthetic antiferromagnet, similar to that of [20]. (b) Easy axis and (c) hard axis hysteresis loops of the hard multilayer when covered with Ru(70 Å)/Ta(70 Å)/Ru(100 Å)/Ta(10 Å, cap).
For in-plane magnetization, the intrinsic linewidth above the in-plane saturation field is
\[
\frac{1}{\gamma_0} \Delta \omega_{\text{in-plane}}^\text{Gilbert} = \alpha(2H_x - H_{k1} - H_{k2} + M_s).
\]

The resonance frequency (equation (2)) is non linear with the effective fields, such that the non uniformity \(\Delta H_0\) of the local effective fields translates in a linewidth broadening through the term
\[
\frac{1}{\gamma_0} \Delta \omega_{\text{in-plane}} = \frac{\text{d}\omega_{\text{in-plane}}}{\text{d}(M_s - H_{k1})} \Delta H_0
\]
where the derivative term is \(\frac{\text{d}\omega_{\text{in-plane}}}{\text{d}(M_s - H_{k1})}\). In case of finite disorder, this factor diverges at the spatially-averaged in-plane saturation field \(H_s\).

5.2. Results

For each applied field, the real and imaginary parts of the transverse permeability \(\mu(f)\) were fitted with the one expected for the uniform precession mode [24] with three free parameters: the FMR frequency \(\omega_{\text{FMR}}/(2\pi)\), the FMR linewidth \(\Delta \omega/(2\pi)\) and a scaling (sensitivity) factor common to both real and imaginary parts of \(\mu(f)\), as illustrated in figure 3(b).

When plotting the symmetric lorentzian-shaped imaginary part of the transverse permeability versus the asymmetric lorentzian-shaped real part of the permeability for frequencies ranging from \(dc\) to infinity, a circle of diameter \(M_s/[2\alpha(H_x + H_{k1} - M_s)]\) should be obtained for a spatially uniform sample [25]. The finite disorder \(\Delta H_0\) distorts the experimental imaginary part of the permeability towards a larger and more Gaussian shape. It can also damp and smoothen the positive and negative peaks of the real part of the permeability; when the applied field is such that the inhomogeneous broadening is larger than the intrinsic Gilbert linewidth, this results in a visible ellipticity of the polar plot of \(\mu(f)\). In our experimental polar plot of \(\mu(f)\) (figure 3(a)), the deviations from perfect circularity are hardly visible, which indicates that the inhomogeneous broadening is not the dominant contribution to the sample FMR linewidth in out-of-plane field conditions.

To confirm this point we have plotted in figure 3(c) the dependence of FMR linewidth with FMR frequency for out-of-plane applied fields. A linear fit yields \(\alpha = 0.021 \pm 0.002\) and \(\Delta H_0 \approx 40\) mT. A substantial part of the measured linewidth thus still comes from the contribution of the lateral inhomogeneity of the effective anisotropy field within the film. As a result, low field measurements of the FMR linewidth would be insufficient to disentangle the Gilbert contribution and the structural disorder contributions to the total FMR linewidth.

The in-plane applied field FMR linewidth can in principle be used to confirm this estimate of the damping factor. Unfortunately, we experience a weak signal to noise ratio in in-plane field FMR experiments, such that only a crude estimation of the linewidth was possible. Within the error bar, it is independent from the applied field from 1.7 to 2.5 T (not shown), which indicates that the disorder still substantially contributes.

5. Gilbert damping

5.1. Models

We now turn to the analysis of the FMR linewidth (figure 3). As is common in FMR, the linewidth comprises an intrinsic Gilbert damping part and an extrinsic additional contribution linked to the lateral non uniformity of the local effective fields \(H_{k1} - M_s\). This can be gathered in a characteristic field \(\Delta H_0\) measuring the disorder relevant for FMR. In out-of-plane field FMR experiments, the proportionality between effective fields and resonance frequencies (equation (1)) allows us to write simply \(\Delta H_0 = \frac{1}{\gamma_0} \Delta \omega_{\text{in-plane}}\), and for the perpendicular magnetization, we follow the usual convention [16] and write:
\[
\frac{1}{\gamma_0} \Delta \omega_{\text{perp}} = 2\alpha(H_x + H_{k1} - M_s) + \Delta H_0
\]
which indicates that the disorder still substantially contributes.
to the linewidth even at our maximum achievable field. At 2.5 T, the linewidth was \( \Delta \omega_{\text{in-plane}} \approx 3.0 \pm 0.3 \) GHz. This is consistent with the expectations that would predict 2.2 GHz of intrinsic contribution (equation (4)) and 0.4 GHz of intrinsic contribution (equation (5)).

### 6. Discussion

We conclude that the damping of Co/Pt multilayers can be of the order of 0.02 even for multilayers with anisotropies among the strongest reported (see [26] for a survey of the anisotropy of Co/Pt multilayers). Note that \( \alpha \approx 0.021 \) is still a higher bound, as we are unable to measure and subtract the spin-pumping contribution. Measuring the spin-pumping contribution would require us to vary the cap and buffer layer thicknesses without affecting the multilayer structure, which is difficult to achieve. Still, we can conclude that the damping of Co/Pt multilayers lies in the same range as other high anisotropy multilayers like Co/Ni ([25, 27]) and Co/Pd ([16]) systems.

This conclusion is in stark contrast with the common thinking [7] that Co/Pt systems always have a large damping. This widespread opinion is based on the standard models of magneto-crystalline anisotropy [28] and damping [29], which predict that they both scale with the square of the spin-orbit coupling \( \xi \), which is particularly large in the Pt atoms. We emphasize that this expectation of large damping is not systematically verified: in studies that make a thorough analysis of the effects of structural disorder, no correlation was found between anisotropy and damping in comparable material systems [11, 16]. Rather, a large correlation was found between \( H_{K1} \) and \( \Delta H_0 \), indicating that when the anisotropy is strong, any local inhomogeneity thereof has a large impact on the FMR linewidth. Owing to the difficulty of achieving well-defined Co/Pt interfaces, we believe that past conclusions on the large damping of Co/Pt systems were based on systems likely to present some intermixing at the interface; indeed the presence of impurities with large spin-orbit coupling considerably degrades (increases) the damping of a magnetic material [30] and synchronously degrades (decreases) the magneto-crystalline anisotropy [31].

### 7. Conclusion

In summary, we have studied high anisotropy [Co(5 Å)/Pt(3 Å)]×6 multilayers grown by low pressure remote plasma sputter deposition. The deposition conditions were tuned to achieve abrupt interfaces with little intermixing. Broadband ferromagnetic resonance was used to measure the first and second order uniaxial anisotropy fields. With the magnetization measured by VSM, this yields an anisotropy energy of 1 MJ m\(^{-3}\). The inhomogeneous broadening accounts for part of the ferromagnetic resonance linewidth, indicating some structural disorder, leading to a equivalent 40 mT (or equivalently 600 MHz) of inhomogeneity of the effective field in out-of-plane applied fields. This FMR-relevant inhomogeneity is comparable to the coercivity of 47 mT. Despite the large anisotropy, a Gilbert damping parameter as low as 0.021 ± 0.002 is obtained. This unexpectedly relatively low damping factor indicates that the presence of the Pt heavy metal within the multilayer can in some conditions not be detrimental to the damping. We interpret our results and literature values by analyzing the consequences of Pt/Co intermixing: Pt impurities within a cobalt layer locally reduce the interface anisotropy as they reduce the abruptness of the composition profile, but they also substantially increase the Gilbert damping. As a result, a large anisotropy together with a low damping can be obtained, provided that intermixing is minimized at the Co/Pt interfaces.

### ORCID iDs

Thibaut Devolder 🌐 https://orcid.org/0000-0001-7998-0993

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