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Investigation of the correlation between perpendicular magnetic anisotropy, spin mixing conductance and interfacial Dzyaloshinskii–Moriya interaction in CoFeB-based systems

I Benguettat-El Mokhtari\textsuperscript{1,2}, D Ourdani\textsuperscript{1}, Y Roussigné\textsuperscript{1}✉, R B Mos\textsuperscript{3}, M Nasui\textsuperscript{3}, S M Chérif\textsuperscript{1}✉, A Stachkevich\textsuperscript{1}, M S Gabor\textsuperscript{3}✉ and M Belmeguenai\textsuperscript{1}✉

\textsuperscript{1} Université Sorbonne Paris Nord, LSPM, CNRS, UPR 3407, F-93430, Villetaneuse, France
\textsuperscript{2} Laboratoire de Physique des Couches Minces et Matériaux pour l’Electronique, Université Oran1, BP1524, El M’naouar, 31100, Oran, Algérie
\textsuperscript{3} Center for Superconductivity, Spintronics and Surface Science, Physics and Chemistry Department, Technical University of Cluj-Napoca, Cluj-Napoca RO-400114, Romania

E-mail: mihai.gabor@phys.utcluj.ro and belmeguenai.mohamed@univ-paris13.fr

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Abstract

Correlation between interfacial Dzyaloshinskii–Moriya interaction (iDMI), perpendicular magnetic anisotropy (PMA) and spin pumping-induced damping was investigated in CoFeB-based systems grown by sputtering on Si substrates, using Pt, Ta, Cu, W and MgO capping layers. Vibrating sample magnetometer, Brillouin light scattering (BLS) and broadband ferromagnetic resonance techniques were combined for this aim. The CoFeB thickness dependence of iDMI and PMA constants, in CoFeB/X (where X = Pt, Cu/Pt, Ta/Pt or W/Al), revealed that only the CoFeB/Pt system presents a measurable iDMI and that the interfacial PMA is mostly similar except for the Ta/CoFeB/Pt system. Therefore, no clear correlation between the above-mentioned interfacially-driven and spin-orbit coupling related quantities was observed due to their different origins in our systems. An efficient sample design involving various spacer layers of variable thicknesses in Ta/CoFeB(1.5 nm)/Y/Pt (where Y = Cu, Ta, MgO) allowed evidence of a linear correlation between iDMI, PMA constants and the effective spin mixing conductance. The linear dependence, which could result from the narrow variation range of PMA and/or iDMI, is attributed to the similar interface orbital hybridizations involved in PMA, iDMI and spin pumping-induced damping.

Keywords: interface effects, perpendicular magnetic anisotropy, spin pumping, ferromagnetic resonance, Brillouin light scattering, interfacial Dzyaloshinskii-Moriya interaction

(Some figures may appear in colour only in the online journal)
1. Introduction

Spintronics is receiving broad attention from both researchers in condensed matter physics, motivated by the quantum character of spin, and engineers due to the enormous potential that it offers for the realization of devices with new functionalities. Its progress has benefited from the development of sophisticated thin film fabrication techniques such as sputtering and molecular beam epitaxy as well as structural and chemical characterization methods. This has led to the growth of synthetic multilayers with a high interface quality, which exhibit magnetic properties dramatically different from their bulk counterparts. Moreover, spin-orbit coupling (SOC), which links the orbital motion of electrons to their spin, is associated with a number of important phenomena in magnetism. Indeed, spin-orbit interfacial phenomena that appear in heavy metal (HM)/ferromagnetic metal (FM) ultrathin films such as spin-orbit torque [1, 2], perpendicular magnetic anisotropy (PMA) [3], spin pumping driven damping [4] and interfacial Dzyaloshinskii–Moriya interaction (iDMI) [5–7] are expected to play an important role in determining the viability of these future technologies.

Symmetry breaking in magnetic/non-magnetic (NM) thin film bilayer-based systems induces an interfacial PMA where the fundamental origin is the anisotropy of the interfacial orbital angular momentum induced by the lowered symmetry [8]. The presence of HMs in such bilayers modifies the interfacial orbital angular momentum, and enhances the spin-orbit interaction, thereby increasing PMA [8]. This PMA is one of the most important ingredients of magnetic materials and is necessary to obtain films with a perpendicular magnetization; it is used in hard disk drives, to enhance the thermal stability [9] and to reduce the critical current densities in spin-transfer-torque-based magnetic random access memories [10]. Another key technological parameter, as it controls the magnetization dynamics, is damping. Depending on the desired application, its value should be chosen: low damping is essential for current-induced magnetization switching [11], while higher values are required for both hard disc drives recording media [12] and read heads to reduce the thermal magnetic noise in the latter, which arises from thermal fluctuations and is considered as a limitation on recording density. Spin pumping is a powerful procedure to tune this parameter. Finally, SOC can be combined with the exchange interaction and the lack of structural inversion symmetry at interfaces to generate an antisymmetric exchange interaction referred to as iDMI. iDMI modifies the static and dynamic properties of magnetic configurations. It is also responsible for the non-reciprocity of the propagation of spin waves (SWs) and the appearance of chiral spin structures such as magnetic skyrmions [13].

It is worthwhile to mention that the SOC is necessary to induce and boost the strength of these three interfacial phenomena but is not the only interaction responsible for their existence. Indeed, these three interface and SOC-related phenomena could behave differently depending on the HM nature, its location in the system and details of the whole stack structure. Moreover, while the origins and the physics of the first two effects are more or less known, a simple physical image of iDMI still remains to be defined and several fundamental questions deserve to be clarified: what is the range of this interaction? What atomic interface monolayers are involved in this interaction? Answers to some of these questions are known from a theoretical point of view. However, elaboration procedures introduce defects that are not taken into account in calculations published up to now [14]. Moreover, the iDMI, the damping driven by spin pumping and the perpendicular magnetic interface anisotropy are related to the spin-orbit interaction at the interface and are sensitive to disorders, orbital hybridization around the Fermi level, details of the electronic structure, and defects and atoms arrangement at interfaces. Moreover, the lattice strain provided by a suitable substrate or buffer layer [15] or by varying the FM concentration [16] can influence the iDMI and PMA. One can thus expect a correlation between these quantities. This mutual correlation between each two of these quantities has been studied in some systems [17–19] but investigation of the simultaneous correlation between the three SOC-related interfacial phenomena and their range is still missing. Furthermore, for future technology, it is critical to understand how these spin-orbit phenomena can be optimized to our benefit. Therefore, the aim of this paper concerns the investigation of these three interfacially-driven magnetic phenomena associated with SOC with the idea of contributing to answering some questions such as: is there a correlation between these three effects? Do they have the same range and how many interface monolayers are involved in these interactions? For this, Brillouin light scattering (BLS), and ferromagnetic resonance with a microstrip line (MS-FMR) coupled to a vibrating sample magnetometer (VSM) techniques were used.

2. Samples and experimental techniques

All the samples studied here were grown at room temperature (RT) on thermally oxidized silicon (Si/SiO₂) substrates in a magnetron sputtering system having a base pressure lower than 2 × 10⁻⁸ Torr. The metallic layers were grown by a dc sputtering under an argon pressure of 1 mTorr. The deposition rate was around 6 nm min⁻¹ for all the layers, except for the W films which were grown at a much lower deposition rate of 1.6 nm min⁻¹, in order to facilitate the formation of the β phase [20]. The insulator MgO layer was grown by an rf sputtering under an argon pressure of 10 mTorr at a rate of around 2 nm min⁻¹. The samples can be classified into two categories. In the first category, the Co₂₀Fe₆₀B₅₀ (CFB) thickness (t CF B) was varied up to 12 nm (1 nm ≤ t CF B ≤ 12 nm) and capped by Pt(4 nm),Cu(2 nm)/Pt(4 nm), W(2 nm)/Al(1.5 nm) or Ta(1 nm)/Pt (4 nm). Here, the capping layers were changed with the intent of modulating the above-mentioned interfacial effects (PMA, iDMI and damping) and thus investigating any correlation between them. The CFB layer was grown directly on the Si/SiO₂, except for the Ta(1 nm)/Pt (4 nm)
capped samples, where a 1 nm thick Ta film was inserted between the substrate and the CFB layer to improve the roughness of the substrate and the adhesion of the subsequent layers. The second category of samples consists of Si/SiO$_2$(Ta(1 nm))/CoFeB(1.5 nm)/spacer/Pt(4 nm) structures. The thickness of the CFB layer was kept constant and spacer layers (MgO, Ta or Cu) with variable thicknesses in the range 0–2.4 nm were inserted between CFB and Pt films. Additionally, the use of various spacer layers is another method employed to adjust the interfacial parameters (PMA, iDMI and damping). The discrepancies between the manners in which the two techniques will affect these parameters will be discussed below.

The static magnetic properties of the samples have been investigated using a VSM. MS-FMR [21] has been used to determine the gyromagnetic ratio, damping and PMA. BLS [22], under an in-plane applied magnetic field, was used in the Damon–Eshbach configuration to investigate mainly iDMI in all the samples and PMA in samples where the MS-FMR signal is too weak. The simultaneously detected Stokes (S) and anti-Stokes (aS) frequencies were determined from Lorentzian fits to the BLS spectra. All the measurements presented below were carried out at RT.

3. Results and discussions

3.1. Effect of CoFeB thickness

We first focus on the sample category where the thickness of the CoFeB capped with different layers is varied: CoFeB(t$_{CFB}$)/Pt, Ta/CoFeB(t$_{CFB}$)/Ta/Pt, CoFeB(t$_{CFB}$)/Cu/Pt and CoFeB(t$_{CFB}$)/W/Al grown on Si/SiO$_2$ substrates.

3.1.1. VSM measurements

The magnetization at saturation ($M_s$) and the magnetic dead layer thickness ($t_d$) are of utmost importance for the precise determination of the physical quantities characterizing the above-mentioned interfacial effects. They can be straightforwardly determined from the VSM measurements of the thickness dependence of the areal magnetic moment at saturation ($M_s \times t_{CFB}$) shown in figure 1 for the first category of samples. The obtained results (see table 1) indicate that $M_s$ is around 1350 emu cm$^{-2}$ for Pt, Cu/Pt and W/Al capped samples and seems unaffected by the capping layer, in good agreement with the reported values for Ta/CoFeB/MgO [23]. This value decreases significantly for Ta/CoFeB/Ta/Pt films ($M_s = 1050 \pm 15$ emu cm$^{-2}$) in agreement with previous reports [24], despite the different composition of CoFeB (Co$_{60}$Fe$_{20}$B$_{20}$). In this latter case, authors also observed a lower magnetization at saturation of this system with respect to that of other CoFeB-based structures with different capping layers such as Ru. In contrast to $M_s$, the magnetic dead layer thickness (table 1) is more sensitive to the capping layer nature. It is found that the CoFeB film has the thickest magnetic dead layer of 0.86 ± 0.08 nm in Ta/CoFeB/Ta/Pt while the CoFeB/Pt system shows zero magnetic dead layer. Moreover, $t_d = 0.15 \pm 0.03$ nm and $t_d = 0.75 \pm 0.08$ nm were obtained for CoFeB/Cu/Ta and CoFeB/W/Al, respectively. The thick magnetic dead layers of Ta/CoFeB/Ta/Pt and CoFeB/W/Al (which are in good agreement with the value reported by Wang et al [24] and Skowronski et al [25]) have been confirmed by the paramagnetic character of 1 nm thick CoFeB when measuring their hysteresis loop. This magnetic dead layer is most probably due to intermixing and interdiffusion at the CoFeB interfaces. This can be due to the fact that Ta and W being HMs, when sputtered on Fe or Co cause more intermixing owing to their greater atomic weight and thus a higher momentum compared to the normal (light) metal. Indeed, Jang et al [26] reported that the magnetic dead layer thickness, originating from the intermixing at interfaces during deposition, at the CoFeB/Ru top interface is slightly larger than that of the Ru/CoFeB bottom interface by 0.04 nm; this is probably due to the greater atomic weight of Ru, compared to CoFeB. Moreover, they observed that when Ta or Ru is located on top of the CoFeB layer, the CoFeB/Ta top interface has a thicker magnetic dead layer than the CoFeB/Ru top interface by 0.12 nm, which is also explained by the greater atomic weight of Ta compared to Ru. Moreover, it is worth mentioning that Wang et al [24] showed that the Ta capping layer contribution to the magnetic dead layer is significantly higher than that of the Ta seed layer. Furthermore, note the higher value of $M_s$ for W capped samples compared to Ta/CoFeB/Ta/Pt, suggesting that, for this latter, the magnetic grains probably become decoupled by the Ta strong diffusion, which usually takes place at the grain boundaries.

3.1.2. MS-FMR and BLS measurements

Another crucial parameter for enhancing the accuracy in the determination of these three interfacial spin-orbit related

![Figure 1. Saturation magnetic moment per unit area versus the CoFeB thickness of CoFeB-based systems with various capping layers. Symbols refer to VSM measurements and solid lines are linear fits.](image)

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quantities is the gyromagnetic ratio \( (\gamma = \frac{e}{2m}) \). This latter is usually determined from the FMR measurements of the uniform precession mode frequency versus the perpendicular to the plane applied magnetic field, as shown in figure 2 for the CoFeB/Pt system with various \( t_{\text{CFB}} \). The observed linear behavior is in excellent agreement with the theoretical predications of equation (1) giving the uniform precession mode frequency versus the perpendicular to the film plane applied magnetic field.

\[
f = \frac{\gamma}{2\pi} (H - 4\pi M_{\text{eff}})
\]  

(1)

where \( 4\pi M_{\text{eff}} = 4\pi M_{\perp} - \frac{2K_{\perp}}{M_{\perp}} \) is the effective magnetization and \( K_{\perp} \) is the PMA constant.

\( \frac{\gamma}{2\pi} \) is straightforwardly determined from the slope of the linear fit of the experimental data, shown in figure 2. The Landé factor (g-factor) is then deduced (\( \frac{\gamma}{2\pi} \approx g \times 1.397 \text{ MHz/Oe} \)) for the different systems, as shown in the inset of figure 2.

Note that for the thicker CoFeB (\( t_{\text{CFB}} > 4 \text{ nm} \)), \( 4\pi M_{\text{eff}} \) exceeds 12 kOe, which is close to the maximum applied magnetic field (15 kOe) in our MS-FMR set-up. Therefore, higher magnetic applied fields are needed to achieve measurements within the frequency range 3–20 GHz and thus a precise determination (or even the measurement itself) is not possible. All the systems show a similar trend: g increases with thickness for the thinner CoFeB films before decreasing for \( t_{\text{CFB}} > 1.5 \text{ nm} \). One should note the slow thickness variation of the g-factor for thick CoFeB films (beyond 2 nm) and the higher g values for CoFeB/Pt. It is worth mentioning that the g-factor is known to depend on the composition and is strongly influenced by surface and interface effects, as it depends on the local symmetry [27]. Such interface effects, due to the broken inversion symmetry at the interface, may lead to strong enhancements of the ratio of the orbital to spin angular momentum, which governs the g-factor. Therefore, it is not surprising to observe a thickness dependence of g and a higher value for CoFeB/Pt due to the absence of the magnetic dead layer.

We will now focus on the PMA. It can be determined through the investigation of the effective magnetization. Therefore, the uniform precession mode frequencies versus the in-plane applied magnetic field were measured for all samples using mostly MS-FMR, as shown in figure 3(a). The values of \( 4\pi M_{\text{eff}} \) obtained from the fit of the experimental data using a model based on small in-plane and perpendicular uniaxial anisotropies besides the demagnetizing energies [28] are shown in figure 3(b) versus the reciprocal CoFeB effective thickness (\( 1/(t_{\text{CFB}} - t_0) = 1/\ell_{\text{eq}} \)) for the various systems. A linear dependence of \( 4\pi M_{\text{eff}} \) over the whole investigated thickness range is observed for Ta/CoFeB/Ta/Pt, while other systems show deviation from the linear behavior. Various origins of this frequently reported deviation were given [29]. We will focus on the relatively large thickness range where the linear behavior is observed for all structures. In this range, \( K_{\perp} \) can be described by the phenomenological relationship \( K = K_s + \frac{K_{\perp}}{\ell_{\text{eq}}} \). Therefore, the linear fit of the thickness dependence of \( 4\pi M_{\text{eff}} \) was used to deduce the perpendicular uniaxial surface \( K_s \) and volume \( K_{\perp} \) anisotropy constants from the slope and the intercept with the vertical axis, respectively, as summarized in table 1. Interestingly, \( K_s \) is roughly constant for CoFeB/Pt (\( K_s = 1.15 \pm 0.09 \text{ erg/cm}^2 \)), CoFeB/Cu/Pt (\( K_s = 1.05 \pm 0.05 \text{ erg/cm}^2 \)) and CoFeB/W/Al (\( K_s = 1.1 \pm 0.05 \text{ erg/cm}^2 \)) while it decreases significantly for Ta/CoFeB/Ta/Pt (\( K_s = 0.39 \pm 0.02 \text{ erg/cm}^2 \)). Although the exact mechanism is still unknown, it is probable that the thermally oxidized SiO\(_2\) contributes to this interface PMA and the Ta seed layer decouples SiO\(_2\) and CoFeB and therefore reduces the interface anisotropy, since

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Table 1. Parameters obtained from the best fits of the thickness dependences of the magnetic moment per area unit, the effective magnetization and the damping of the CoFeB thin films grown on Si substrates using various capping layers.

<table>
<thead>
<tr>
<th>System</th>
<th>( M_s ) (emu/cm(^3))</th>
<th>( t_{\text{CFB}} ) (nm)</th>
<th>( K_s ) (erg/cm(^2))</th>
<th>( K_{\perp} ) (( \times 10^6 \text{erg/cm}^3 ))</th>
<th>( \gamma_{\text{obs}} ) (nm(^{-2}))</th>
<th>( \alpha_{\text{CFB}} ) (( \times 10^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoFeB/Pt</td>
<td>1366 ± 50</td>
<td>0</td>
<td>1.15 ± 0.09</td>
<td>0.22 ± 0.012</td>
<td>33 ± 2</td>
<td>4.2 ± 0.2</td>
</tr>
<tr>
<td>CoFeB/Cu/Pt</td>
<td>1356 ± 55</td>
<td>0.15 ± 0.03</td>
<td>1.05 ± 0.05</td>
<td>0.2 ± 0.01</td>
<td>15.95 ± 1</td>
<td>4.3 ± 0.2</td>
</tr>
<tr>
<td>CoFeB/W/Al</td>
<td>1342 ± 40</td>
<td>0.75 ± 0.08</td>
<td>1.1 ± 0.05</td>
<td>−1.05 ± 0.1</td>
<td>8 ± 0.7</td>
<td>4.1 ± 0.13</td>
</tr>
<tr>
<td>Ta/CoFeB/Ta/Pt</td>
<td>1050 ± 15</td>
<td>0.86 ± 0.08</td>
<td>0.39 ± 0.02</td>
<td>−1.38 ± 0.1</td>
<td>14 ± 0.8</td>
<td>6 ± 0.3</td>
</tr>
</tbody>
</table>

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Figure 2. Variations of the uniform precession mode frequency versus the perpendicular to the film plane applied magnetic field for the CoFeB(\( t_{\text{CFB}} \))/Pt. Symbols refer to experimental data and solid lines are fits using equation (1). The inset shows the g-factor as a function of the CoFeB nominal thicknesses for CoFeB/Pt (black curve), CoFeB/Cu/Pt (red curve) and CoFeB/W/Al (blue curve) systems.

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it improves the roughness of the substrate. It is worth mentioning that this surface anisotropy constant is comparable to that of Ta/Pt/Co/AlO$_x$ ($K_s = 1.1$ erg cm$^{-2}$) [30] and to that of CoFeB/Pt ($K_s = 1.3$ erg cm$^{-2}$) [28]. In contrast to $K_s$, $K_r$ is negative for CoFeB/Ta/Pt [$K_r = -(1.38 \pm 0.1) \times 10^6$ erg cm$^{-3}$] and CoFeB/W/Al [$K_r = -(1.05 \pm 0.1) \times 10^6$ erg cm$^{-3}$] systems. However, it is positive, although very small, for other structures. For CoFeB/Cu/Pt and CoFeB/Pt, the obtained values are $(0.2 \pm 0.01) \times 10^6$ erg cm$^{-3}$ and $K_r = (0.22 \pm 0.012) \times 10^6$ erg cm$^{-3}$, respectively. Note the close $K_r$ values of CoFeB/Cu/Pt and CoFeB/W/Al, where a thicker magnetic dead layer and those of Ta/CoFeB/Ta and CoFeB/W/Al, where a thicker magnetic dead layer are observed, suggesting that $K_r$ is influenced by interdiffusion and intermixing.

We also employed MS-FMR to investigate the thickness dependence of the Gilbert damping constant ($\alpha$) in the various systems studied here due to spin pumping. In this latter, upon microwave excitations, the magnetization precession of the FM layer injects spin current into the adjacent NM layer. The pumped spin current is partially depolarized at the interface (due to interfacial SOC) and only part of the spin current propagates in the NM layer where it undergoes partial or total dissipation. This dissipation of spin current at the interface or/and in the NM is accompanied by a loss of angular momentum in the FM layer which leads to an enhancement in the effective Gilbert damping constant. This Gilbert damping can be directly obtained from the measurements of the FMR linewidth versus the microwave driving frequency. The typical MS-FMR half width at half maximum linewidth is shown in figure 4(a) versus the microwave frequency for the different systems and compared to the fit given by equation (2).

\[
\Delta H = \Delta H_0 + 2\pi \frac{\alpha}{\gamma} f
\]  

(2)

where, $f$ is the driving microwave frequency and $\Delta H_0$ is the inhomogeneous residual linewidth. $\alpha$ values were obtained from slopes of the linear fits (figure 4(a)) and their variations as a function of $1/t_{\text{eff}}$ are shown in figure 4(b). Note the linear dependence of $\alpha$ versus $1/t_{\text{eff}}$ with a stack-dependent slope due to spin pumping: the thickness dependence of $\alpha$ exhibits a considerable enhancement for CoFeB/Pt in comparison with the other systems. After inserting Cu and Ta layers, the slopes of thickness dependences of $\alpha$ decrease by nearly half as compared with the one in the CoFeB/Pt systems. In the CoFeB/Cu/Pt system, the spin current generated by the precession of the CoFeB magnetization has to cross both CoFeB/Cu and in Cu/Pt interfaces. Owing to the large spin diffusion length of the Cu layer (250 nm) [31], the CoFeB/Cu interface does not induce a significant damping enhancement because only a partial spin current is allowed to cross the Cu/Pt interface and enter the Pt layer. For Ta/CoFeB/Ta and CoFeB/W, the strong intermixing between the CoFeB and Ta or CoFeB and W layers results in a relatively wide interface region and therefore the interface may kill the abrupt potential change, and conduction electrons across the CoFeB/Ta or CoFeB/W interface are less scattered, resulting in small interface spin losses [32]. Therefore, two factors are essential to achieve a significant damping enhancement: the strength of the spin-orbit interaction and the potential gradient at the interface [32].

To characterize the spin pumping, we consider that the total damping is given by $\alpha = \alpha_{\text{CFB}} + \alpha_{\rho}$ [33], where $\alpha_{\text{CFB}}$ is the Gilbert damping constant of CoFeB and $\alpha_{\rho} = \frac{\mu_B g_{\text{eff}}^4}{4\pi M_{\text{eff}} d_{\text{eff}}^3}$ ($\mu_B$ is the Bohr magneton and $g_{\text{eff}}^4$ is the effective spin mixing conductance) is the damping introduced by the spin pumping effect due to the coupling and the barrier layers. The linear fit of the experimental data in figure 4(a) gives $\alpha_{\text{CFB}} \approx 0.006$ for the Ta/CoFeB/Ta and 0.0042 for the other systems (see table 1) and allows us to determine $g_{\text{eff}}^4$. Note again that the Ta/CoFeB/Ta/Pt system stands out remarkably from the other structures: its high damping originates probably from the intermixing and interpenetration of Ta in CoFeB. For $g_{\text{eff}}^4$, the highest

\[
\Delta H = \Delta H_0 + 2\pi \frac{\alpha}{\gamma} f
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To characterize the spin pumping, we consider that the total damping is given by $\alpha = \alpha_{\text{CFB}} + \alpha_{\rho}$ [33], where $\alpha_{\text{CFB}}$ is the Gilbert damping constant of CoFeB and $\alpha_{\rho} = \frac{\mu_B g_{\text{eff}}^4}{4\pi M_{\text{eff}} d_{\text{eff}}^3}$ ($\mu_B$ is the Bohr magneton and $g_{\text{eff}}^4$ is the effective spin mixing conductance) is the damping introduced by the spin pumping effect due to the coupling and the barrier layers. The linear fit of the experimental data in figure 4(a) gives $\alpha_{\text{CFB}} \approx 0.006$ for the Ta/CoFeB/Ta and 0.0042 for the other systems (see table 1) and allows us to determine $g_{\text{eff}}^4$. Note again that the Ta/CoFeB/Ta/Pt system stands out remarkably from the other structures: its high damping originates probably from the intermixing and interpenetration of Ta in CoFeB. For $g_{\text{eff}}^4$, the highest
value \((33 \pm 2 \text{ nm}^{-2})\) is obtained for CoFeB/Pt while CoFeB/W/Al shows the lowest value \((8 \pm 0.7 \text{ nm}^{-2})\) despite the HM nature of W. As mentioned above, the relatively wide CoFeB/W interface due to intermixing reduced the spin pumping efficiency. By inserting Ta or Cu between Pt and CoFeB, the spin pumping efficiency, characterized by \(g_{\text{eff}}^{\perp}\), is reduced to \(15.95 \pm 1 \text{ nm}^{-2}\) and \(14 \pm 0.8 \text{ nm}^{-2}\), respectively for CoFeB/Cu/Pt and Ta/CoFeB/Ta/Pt owing to the large spin diffusion length and the wide interface of CoFeB/Ta, as explained above.

Let us come now to the third interfacial parameter to be studied here, which is the iDMI. This effect influences the SW propagation by introducing non-reciprocity: SWs that have the same wave vector \(k_{\text{sw}}\) but that propagate in opposite directions exhibit different energies. Therefore, in the BLS experiment, the simultaneously detected Stokes and anti-Stokes lines in the Damon–Eshbach configuration have different frequencies. The frequency mismatch, defined as \(\Delta F = F_{\text{S}} - F_{\text{as}}\) varies linearly with \(k_{\text{sw}}\), as predicted by equation 3 [34].

\[
\Delta F = D_{\text{eff}} \frac{2\gamma}{M_s} k_{\text{sw}}
\]

where \(D_{\text{eff}}\) is the iDMI effective constant, characterizing the iDMI strength.

BLS spectra under an in-plane saturating applied magnetic field and variable \(k_{\text{sw}}\) \((4.1 \mu \text{m}^{-1} \leq k_{\text{sw}} \leq 20.45 \mu \text{m}^{-1})\) were measured. The typical spectra for 1.5 nm thick CoFeB capped with various layers are shown in figure 5 for \(k_{\text{sw}} = 20.45 \mu \text{m}^{-1}\) and fitted with a Lorentzian function to deduce \(\Delta F\). Only the CoFeB/Pt structure presents significant asymmetry between the S and aS line frequencies suggesting that \(D_{\text{eff}}\) is not negligible in contrast to the other systems where the frequency mismatch falls below the error bar in our BLS (±0.1 GHz). Here again, despite the broken structural inversion symmetry of CoFeB/Cu/Pt and CoFeB/W/Al, it seems that the weak SOC at the CoFeB/Cu interface and the wide CoFeB/W interface are responsible for the absence of significant iDMI in such systems. The interface quality has to be without any disorder since intermixing is found to reduce iDMI by 20%, in the case of Co/Pt [35]. Due to its asymmetric nature, it is expected that iDMI vanishes in Ta/CoFeB/Ta/Pt since there is no broken structural inversion symmetry of a layered system (Ta/CoFeB and CoFeB/Ta interfaces have an opposite iDMI sign and therefore the total iDMI constant is zero/undetectable).

The wave vector dependences of \(\Delta F\) for CoFeB(1.5 nm)/Pt, shown in figure 6(a), were fitted by equation (3) and the deduced \(D_{\text{eff}}\) is depicted in figure 6(b) versus \(1/l_{\text{eff}}\). Here again a deviation from the linear behavior is observed, most probably due to the degradation of the CoFeB/Pt interface for the thinner films. The obtained value of the surface iDMI constant \((D_{\text{eff}} = D_{\text{eff}}/l_{\text{eff}}\) of \((1.25 \pm 0.03) \times 10^{-7} \text{ erg cm}^{-1}\) \(\text{is in good agreement with the reported value for Pt/CoFeB/AI}\_3 [36].

![Figure 4](image1.png)

**Figure 4.** (a) Frequency dependence of the FMR half width at half maximum linewidth (\(\Delta H\)) for various CoFeB-based systems. Symbols refer to experimental data and solid lines are fits using equation (2). (b) Gilbert damping constant as a function of the reciprocal CoFeB effective thickness for CoFeB-based systems. Symbols refer to experimental data and solid lines are linear fits.

![Figure 5](image2.png)

**Figure 5.** BLS spectra for different CoFeB-based systems with various capping and buffer layers measured at different in-plane applied magnetic field values and at a characteristic SW-vector \(k_{\text{sw}} = 20.45 \mu \text{m}^{-1}\). Symbols refer to experimental data and solid lines are Lorentzian fits. Fits corresponding to negative applied fields (violet lines) are presented for clarity and for the direct comparison of Stokes and anti-Stokes frequencies.

\[
\Delta F = D_{\text{eff}} \frac{2\gamma}{M_s} k_{\text{sw}}
\]
We now come back to the correlation between the interface PMA, iDMI and spin pumping-induced damping, characterized by $g_{\uparrow\downarrow}^{\text{eff}}$. Unfortunately, due to the weak (non-measurable) iDMI constants for Ta/CoFeB/Ta/Pt, CoFeB/Cu/Pt and CoFeB/W/Al, although Ta and W are HMs, this correlation cannot be investigated in such a system. We should mention that iDMI is sensitive to the atomic arrangements at the interface and depends on the degree of hybridization between the 3d orbitals of the FM and the 5d orbitals of the HM [37], which may explain the vanishing iDMI for some systems. Moreover, the variation of the interface PMA constant versus $g_{\uparrow\downarrow}^{\text{eff}}$, as shown in figure 6(c), does not allow us to conclude about this correlation. Indeed, while $g_{\uparrow\downarrow}^{\text{eff}}$ is mainly determined by the top interface of CoFeB, $K_s$ seems to be containing contributions from the SiO$_2$ since CoFeB/Pt, CoFeB/Cu/Pt and CoFeB/W/Al are directly grown on Si/SiO$_2$. Therefore, the modulation of $K_s$, $g_{\uparrow\downarrow}^{\text{eff}}$ and $D_{\text{eff}}$ (or $D_s$) by changing the capping and/or buffer layer, in our case, seems not to be a powerful method to investigate their correlation since very few HMs were found to induce iDMI. Furthermore, in such a system, varying the capping or buffer layer could completely change the interfaces, strain, intermixing degree, roughness, orbital hybridization degree and thus the origins and mechanisms responsible for these three interface and SOC-related effects, making the observation of any correlation between these effects a hard task.

3.2 Effect of spacer thickness

In this section, we will focus on the second category of samples (Ta/CoFeB(1.5 nm)/spacer/Pt, where the spacer is Ta, Cu or MgO) to investigate the correlation between $K_s$, $g_{\uparrow\downarrow}^{\text{eff}}$ and $D_{\text{eff}}$. For this, the thickness of the magnetic CoFeB layer is fixed to 1.5 nm and a spacer layer (Ta, Cu or MgO) of variable thickness is inserted between the HM and the CoFeB to tune the strength of PMA, iDMI and $g_{\uparrow\downarrow}^{\text{eff}}$. CoFeB/Pt was used for this aim where the higher values of these three interface and SOC-related parameters were obtained and three types of spacer were investigated: normal metal (Cu), HM (Ta) and oxide (MgO). In such systems, the contribution of the bottom interface with CoFeB to iDMI, damping and interface PMA is fixed and any change in these quantities results most probably from the contribution of the top interface with CoFeB (CoFeB/spacer/Pt). Therefore, the origin of these quantities could be more correlated. We thus think that the modulation of these three SOC-related effects by the insertion of a spacer layer between Pt and CoFeB remains a powerful method of investigating their correlation since it simplifies their origins, especially for the interface PMA, where both interfaces could contribute and could change when varying the CoFeB thickness. Furthermore, besides the use of the same system, this procedure offers the possibility of defining the number of the atomic interface planes involved in these three interactions.
The magnetization at saturation was measured by a VSM for the three systems and is shown in figure 7(a) versus the spacer thickness. It is to be noted that this is a nominal value that was calculated by dividing the magnetic moment to the nominal volume of the CoFeB film. Note the lesser decrease of $M_s$ with the increasing Cu thickness compared to the Ta and MgO spacers, probably due the lesser intermixing at the CoFeB/Cu interface and the decrease of proximity induced magnetization at the Pt/CoFeB interface caused by the insertion of Cu. Whereas, the significant decrease, in the case of Ta and MgO spacers, is most probably due to the increased intermixing or oxidation (for the MgO spacer) for larger spacer thicknesses. For example, $M_s$ decreases significantly for Ta thicknesses up to 1 nm and remains roughly constant beyond this thickness.

BLS was mainly used for this last part of the investigation, where the spectra were measured at $k_{sw} = 4.1 \ \mu m^{-1}$ and under variable in-plane applied magnetic fields and then fitted with a Lorentzian to extract frequencies and the full width at half maximum linewidths ($\delta F$) for S and aS lines.

To cancel iDMI contribution, the mean values of frequencies and $\delta F$ of S and aS lines were considered. Their field dependences were then fitted using equations (2) and (3), as reported in [38, 39], to obtain $4\pi M_{eff}$ and $\alpha$, respectively. The variations of $M_{eff}$ as a function of the spacer thickness are shown in figure 7(b). Note the opposite trends of $M_{eff}$ for the Cu and other spacer layers: $M_{eff}$ increases (decreases) with increasing Cu (Ta) thickness, which would suggest a decrease (increase) of the perpendicular effective anisotropy field. The $M_{eff}$ thickness dependence for the CoFeB film with the MgO spacer layer shows a different trend: it increases significantly for the thinnest MgO thickness before decreasing for the thickest layers. Since $M_s$ is spacer thickness-dependent, one should be careful and take into account the $M_s$ value for each spacer thickness to avoid inadequate conclusions. Therefore, for further analysis of the observed trends, the effective PMA constant $(K_{eff} = K_{\perp})$ was deduced from $4\pi M_{eff}$, using the experimental $M_s$ of figure 7(a) and will be discussed below. Moreover, we considered that the measured total damping is increased by an amount $\alpha_P = \frac{\gamma_{Cu}^{1\perp}}{\gamma_{CoFeB}^{1\perp}} \delta F_{eff}$ (where $t_{CoFeB}^{Cu} = 1.5 \ \text{nm}$) due to spin pumping. Therefore, using the damping values of the bulk CoFeB ($\alpha_{CoF}$B), obtained above from the thickness dependence of damping (see table 1), $\alpha_P$ and thus $\gamma_{CoFeB}^{1\perp}$ was deduced from the measured total damping. For iDMI and as mentioned above, the frequency mismatch is measured versus $k_{sw}$ and $D_{eff}$ is subsequently extracted. Since $\alpha_P$, $\Delta F$ and $M_{eff}$ are $M_s$-dependent and due to the variation of $M_s$ with the spacer thickness, it is more convenient to consider $\gamma_{CoFeB}^{1\perp}$, $D_{eff}$ and $K_{eff}$ to investigate spin pumping, iDMI and PMA.

The spacer thickness dependences of the interface and SOC-related physical quantities are shown in figures 8(a)–(c). Interestingly, $K_{eff}$, $D_{eff}$ and $g_{eff}^{\perp}$ show the same trend: they decrease with the increasing spacer thickness for the three structures; they are then saturated with increasing spacer thickness, suggesting that they mainly originate from the CoFeB/Pt interface. It is reasonable to think that only Pt atoms placed in the immediate vicinity of CoFeB atoms can interact together and it is well understood that as Pt atoms are far away from the interface, the interaction is ensured with the spacer atoms leading to a weaker $K_{eff}$, $D_{eff}$ and $g_{eff}^{\perp}$ with respect to CoFeB/Pt, as observed above. Indeed, as the spacer layer thickness increases, the intermixing, the hybridization degree and thus the interface SOC change. Therefore, $K_{eff}$, $D_{eff}$ and $g_{eff}^{\perp}$ are each affected according to the degree of its dependence on these factors. In fact, it is well known that PMA is proportional to the square of SOC strength [40], whereas spin pumping [41] and iDMI [42] are proportional to the SOC strength. Figure 8 revealed that the characteristic decay thicknesses of $K_{eff}$, $D_{eff}$ and $g_{eff}^{\perp}$ depend on both the spacer layer nature and the physical quantity. We phenomenologically fitted the experimental data of figures 8(a)–(c) with an exponential decay function $(A_0 + A_1 e^{-2 \lambda k_{sw}}$, where $A_0$, $A_1$ and $\lambda$ are the fit parameters) to quantitatively compare the various behaviors. The obtained values are summarized in table 2. We found that Ta strongly screened these quantities while they are moderately affected by Cu and MgO. The smaller decay thickness ($\lambda$) in Ta is probably due to...
the fact that spins diffuse more in Cu (due to its large spin diffusion length) and reach Pt in contrast to Ta which shortens the diffusion length of spins since it is a HM. Although there is no theoretical support for the relation between the spin diffusion length and the decay thickness, in the case of iDMI and PMA, they must be closely related. Furthermore, table 2 revealed that although the three characteristic decay thicknesses for a given capping layer are comparable, it seems that iDMI is slightly more localized at the first or the two atomic monolayers at the interface compared to spin pumping-induced damping and interface PMA.

Figure 8(a) reveals a slow thickness variation of \( K_{\text{eff}} \) for thick spacer layers. For the larger thickness, the value of \( K_{\text{eff}} \), which gives an estimation of the anisotropy constant of Ta/CoFeB/Ta, Ta/CoFeB/Cu and Ta/CoFeB/MgO is significantly affected by the top interface. Since the bottom Ta/CoFeB is the same for the three systems, the difference between \( K_{\text{eff}} \) values at a larger spacer thickness gives \( K_{\text{eff}} \) introduced by Cu, Ta and MgO. The higher value of \( K_{\text{eff}} \) is obtained for CoFeB/Cu while CoFeB/Ta shows a vanishing \( K_{\text{eff}} \) for thicker Ta layers. Furthermore, \( D_{\text{eff}} \) vanishes for thick Ta and MgO layers while it approaches 0.1 ± 0.02 erg cm\(^{-2}\) for Ta/CoFeB/Cu/Pt, as shown in figure 8(c). Therefore, this value (\( D_{\text{eff}} = 0.1 \text{ erg cm}^{-2} \)) corresponds probably to the iDMI contribution of Pt to iDMI. However, this value is slightly higher than the one (0.06 erg cm\(^{-2}\)) reported in \([43]\), suggesting that probably the 2.5 nm thick Cu layer does not completely screen the contribution of Pt to iDMI. It is worth mentioning that Pt/CoFeB and Ta/CoFeB have opposite iDMI signs and due to the much stronger iDMI of CoFeB/Pt any contribution from the CoFeB/Pt interface will be added to that of Ta/CoFeB, thus increasing the total iDMI. The vanishing value of \( D_{\text{eff}} \) in Ta/CoFeB/Ta/Pt for the thickest Ta is compatible with the symmetrical stack and the asymmetrical nature of iDMI confirming that Pt contribution to iDMI is completely screened by the Ta capping layer. The MgO thickness behavior of \( D_{\text{eff}} \) in Ta/CoFeB/MgO/Pt reveals that \( D_{\text{eff}} \) vanishes or is even negative for MgO thicknesses beyond 1 nm. Therefore, it seems that the MgO contribution to iDMI is similar or slightly higher than that of the bottom Ta layer but of opposite sign: \( D_{\text{eff}} > 0 \) for Ta/CoFeB and \( D_{\text{eff}} < 0 \) for CoFeB/MgO. This result is in good agreement with the conclusion made by Boulle \textit{et al} \([44]\) who showed by a resolved calculation on Pt(111)/Co(3 ml)/MgO that a significant iDMI is also present at the Co/O interface with the same sign as that of the Pt/Co interface.

\[ g_{\text{eff}} \]

\[ \lambda \]

\[ \text{Table 2. Characteristic decay thickness deduced from the fit of experimental data of figure 8 by an exponential decay function.} \]

<table>
<thead>
<tr>
<th>Capping layer</th>
<th>Decay thickness λ (nm) for</th>
<th>( K_{\text{eff}} ) (erg cm(^{-2}))</th>
<th>( D_{\text{eff}} ) (10(^{-6}) erg cm(^{-2}))</th>
<th>( g_{\text{eff}} ) (nm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.56 ± 0.16</td>
<td>0.33 ± 0.08</td>
<td>0.52 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>Ta</td>
<td>0.22 ± 0.02</td>
<td>0.16 ± 0.04</td>
<td>0.16 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>0.73 ± 0.2</td>
<td>0.36 ± 0.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8. Variations of (a) the perpendicular effective anisotropy constant (\( K_{\text{eff}} \)), (b) the effective iDMI constant (\( D_{\text{eff}} \)) and the effective spin mixing conductance (\( g_{\text{eff}} \)) as a function of the spacer thickness for Ta/CoFeB(1.5 nm)/Pt, Ta/CoFeB(1.5 nm)/Cu/Pt and Ta/CoFeB(1.5 nm)/MgO/Pt. Symbols refer to experimental data and solid lines are fits with an exponential decay function.

To further analyze the data of figure 8 and evidence any correlation between the three interface and SOC-related physical quantities, we plotted \( K_{\text{eff}} \) and \( g_{\text{eff}} \) versus \( D_{\text{eff}} \), as shown...
in figure 9 for the three spacer layers where linear dependencies can be observed between the three SOC-related quantities. This behavior will be discussed below after presenting the main trends of the correlation between $K_{\text{eff}}$, $g_{\text{eff}}^{\uparrow \downarrow}$ and $D_{\text{eff}}$ reported in the literature. It is worthwhile to mention that the correlation between these three energy terms has been attracting the attention of researchers in recent years, provoking significant controversy. We note that this correlation investigation has been focusing on two quantities at once and involved varying various sample parameters (annealing temperature, ferromagnetic thickness, capping or buffer layer thicknesses, etc.). Indeed, nonlinear correlation between iDMI and effective spin mixing conductance, attributed to the spin-flip processes between the 3d and 5d states, was reported by Ma et al. [37] in X/Co/MgO and X/CoFeB/MgO (X = Ta, W, Ir and Pt).

Similarly, Zhu et al. [17] found that spin mixing conductance scales approximately as the square of the interfacial magnetic anisotropy energy density at the Pt/FM interfaces (where the FM = Co, CoFeB, Py,) due to the dominant contribution of two magnon scattering to damping. On the other hand, no relationship was found between PMA and $\alpha$ in the Co$_{50}$Fe$_{50}$/Ni multilayers [45] whereas a linear relation between these quantities was evidenced in Co/Pd [18] probably due to the d–d hybridization at the interface and to spin pumping. For PMA and iDMI, Kim et al. [19] found a different correlation between $K_s$ and $D_{\text{eff}}$ of Pt/CoFeB/MgO and Pt/CoFeB/Cu but by focusing on the individual contribution of the interfacial magnetic energies at each interface, they showed that the correlation depends on the interface. They found positive correlation for the Pt/Co interface and no meaningful correlation between $K_s$ and $D_{\text{eff}}$ in Co/MgO. Furthermore, linear correlation between $K_s$ and $D_{\text{eff}}$ has been reported in the Pt/Co/AlO$_x$ system from the study of the dependence of the two quantities on the Pt thickness [46]. By varying the thickness of W in W/CoFeB/MgO, Kim et al. [47] demonstrated a linear relation between $K_s$ and $D_{\text{eff}}$.

Figure 9 reveals that the vertical intercept, when extrapolating $D_{\text{eff}}$ to zero, is system-dependent and the whole stack of each system needs to be taken into account to indentify its origin. It is worth mentioning that for $K_{\text{eff}}$ and $g_{\text{eff}}^{\uparrow \downarrow}$, the contributions of the bottom and the top interfaces with the CoFeB must be added whereas for $D_{\text{eff}}$ and due to its asymmetric nature, the contribution of the two interfaces may cancel each other making iDMI vanishingly small (symmetrical systems). Therefore, as mentioned above, $K_{\text{eff}}$ and $g_{\text{eff}}^{\uparrow \downarrow}$ at the origin (figure 9) are linked to the contribution of the top interface. Interestingly, the slopes of the linear dependencies of $K_{\text{eff}}$ as a function of $D_{\text{eff}}$ vary slightly with the capping layer: the higher value was obtained for Ta (5.8 nm$^{-1}$) while lesser slopes of 4.3 nm$^{-1}$ and 3.6 nm$^{-1}$ were deduced for Cu and MgO, respectively. This implies that the main origin of this correlation is linked to the CoFeB/Pt interface which is differently affected by the spacer layer. For $g_{\text{eff}}^{\uparrow \downarrow}$, these slopes are slightly different: the slope of the system with Cu is higher than that with Ta; this is probably due to the higher spin pumping efficiency at the interface with Cu compared to that with Ta. This agrees with the higher $g_{\text{eff}}^{\uparrow \downarrow}$ at the origin ($D_{\text{eff}} = 0$) for Ta compared to that with Cu. The observed correlation allows us to conclude that the iDMI, spin pumping-induced damping and PMA at the top interface originate from the HM-induced SOC. Therefore, this linear correlation between $K_{\text{eff}}$, $D_{\text{eff}}$ and $g_{\text{eff}}^{\uparrow \downarrow}$ observed in our samples, suggests that the PMA, iDMI and damping involve the same interface orbital hybridizations. However, it is worth mentioning that a quadratic correlation between the interface PMA and the iDMI is predicted from perturbation theories for PMA [40] and iDMI [42], since iDMI energy results from the first order of the SOC, while the interface PMA comes from the second order, as stated by Kim et al. [46]. The linear dependence is attributed by Kim et al. [46] to the fact that the variation of PMA and/or iDMI is not large enough to ensure the quadratic dependence. Therefore, the observed variation only ensures a strong linear correlation between the three physical quantities. Our results also establish such a correlation between the three SOC-related quantities.

![Figure 9](image-url)
4. Conclusion

The thickness dependence of the PMA, iDMI constant and Gilbert damping parameter of CoFeB-based systems with various capping and buffer layers was investigated by combining VSM, BLS and MS-FMR techniques. When varying the CoFeB thickness for each system, while a strong iDMI was measured for CoFeB/Pt no significant iDMI was detected for CoFeB/Cu/Pt, Ta/CoFeB/Ta and CoFeB/W/Al. Moreover, the interface PMA constant differs slightly for CoFeB/Pt, CoFeB/Cu/Pt and CoFeB/W/Al and decreases significantly for Ta/CoFeB/Ta. Therefore, investigation of the correlation between PMA, iDMI and the damping parameter was not possible, probably due to the contribution from the bottom interface to PMA and to the variable top interface with CoFeB and thus the mechanisms involved in iDMI, PMA and damping. However, by using different systems, where several spacer layer materials of variable thicknesses were inserted between Pt and CoFeB, a linear correlation between $D_{eff}$, $k_{eff}$ and $g_{eff}^2$ was evidenced. The linear dependence, which could result from the narrow variation range of PMA and/or iDMI, is attributed to the similar interface orbital hybridizations involved in PMA, iDMI and spin pumping-induced damping. We thus think that the modulation of these three interface SOC-related effects by the insertion of a spacer layer between the HM and the ferromagnetic layer remains a powerful method of investigating the correlation between these SOC-related effects. Indeed, this method simplifies their origins, especially for the interface PMA, where both interfaces could contribute and could change when varying the ferromagnetic layer thickness.

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ORCID iDs

Y Roussigné https://orcid.org/0000-0001-7698-8092
S M Chérif https://orcid.org/0000-0003-4350-9379
M S Gabor https://orcid.org/0000-0003-0888-0762
M Belmeguenai https://orcid.org/0000-0002-2395-1146

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