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We report systematic measurements of the interfacial Dzyaloshinskii-Moriya interaction (iDMI) by employing Brillouin light scattering in Pt/Co/AlOₓ and Ta/Pt/Co/AlOₓ structures. By introducing a tantalum buffer layer, the saturation magnetization and the interfacial perpendicular magnetic anisotropy are significantly improved due to the better interface between heavy metal and ferromagnetic layer. From the frequency shift between Stokes- and anti-Stokes spin-waves, we successively obtain considerably larger iDM energy densities (Dmax = 1.65 ± 0.13 mJ/m² at tCo = 1.35 nm) upon adding the Ta buffer layer, despite the nominally identical interface materials. Moreover, the energy density shows an inverse proportionality with the Co layer thickness, which is the critical clue that the observed iDMI is indeed originating from the interface between the Pt and Co layers.

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saturation magnetization, and the exchange stiffness constant with the various types of the propagating SWs. From BLS measurements, we deduce the effective saturation magnetization value \( M_{\text{eff}} = M_s - \frac{4K_s}{\mu_0 M_s t_{\text{Co}}} \) from the measured SW frequency \( f_{\text{SW}} = \frac{\gamma}{2\pi} H_{\text{ex}} \left( H_{\text{ex}} - \mu_0 M_s + \frac{4K_s}{\mu_0 M_s t_{\text{Co}}} \right) \), where \( \gamma \), \( H_{\text{ex}}, M_s \), and \( K_s \) are the gyromagnetic ratio, the applied magnetic field, the saturation magnetization, and the surface anisotropy, respectively. In order to extract the change of magnetic anisotropy energy from the measured SWs frequencies in each Co thickness, we used the effective uniaxial anisotropy energy \( K_{\text{eff}} \) corresponding to the surface anisotropy \( K_s \) and the volume anisotropy \(- \frac{1}{2} \mu_0 M_s^2 \) given by

\[
K_{\text{eff}} \times t_{\text{Co}} = 2K_s - \frac{1}{2} \mu_0 M_s^2 \times t_{\text{Co}}. \tag{1}
\]

Figure 2 indicates that we observe the linear dependences of \( K_{\text{eff}} \times t_{\text{Co}} \) versus \( t_{\text{Co}} \) with (black squares) and without a Ta buffer (red circles). As shown in Fig. 2, the extrapolated crossing with the y-axis \( K_s \) and the slope \((- \frac{1}{2} \mu_0 M_s^2)\) are significantly enhanced due to the Ta buffer layer. Consequently, the addition of Ta leads to enhance the interface quality of Pt/Co. We will discuss the quantitative changes of \( K_s \) (1.10 mJ/m²) and \( M_s \) (1423 kA/m) with Ta buffer layer later on in this paper.

To extract the iDM energy density by using BLS, the first step is observing the frequency differences \( \Delta f \) between Stokes and anti-Stokes peaks in BLS spectra. In Figure 3(a), \( \Delta f \) with a buffer (black squares) and without a buffer (red squares) indicate Ta/Pt/Co/AlOₓ and Pt/Co/AlOₓ, respectively. For these measurements, the incident angle is fixed at \( \theta = 45^\circ \), which corresponds to \( k_y = 0.0167 \text{ nm}^{-1} \). In order to identify the frequency difference \( \Delta f \) between Stokes and anti-Stokes, the mirrored curve (red solid lines) is overlapped in the spectrum. Consequently, black squares, blue spheres, and green triangles (Ref. 22) show clearly more improved iDM energy densities, when a Ta is used for buffer layer.
circles) are shown as a function of $t_{Co}^{-1}$. Here, $\Delta f$ for each thickness $t_{Co}$ is determined from the field dependent measurements (from 0 to 0.9 T), and the measured $\Delta f$ should be a constant for all magnetic fields (Ref. 12). Therefore, in Fig. 3, symbols and error bars indicate the averaged values and the corresponding standard deviations of the $\Delta f$, respectively. We plot the $\Delta f$ as a function of $t_{Co}^{-1}$ and it clearly shows the inverse proportionality with $t_{Co}$. The physical meaning of the inverse proportionality is that a bulk contribution screens the interface effects with increasing $t_{Co}$.

In various magnetic systems, the inverse proportionality to the ferromagnetic layer thickness is a signature of the interface effects such as interface PMA, exchange bias, the effective field of the interlayer exchange coupling, and so on. Apart from the observed interfacial nature of $\Delta f$, we found that $\Delta f$ with Ta buffer layers is much larger than $\Delta f$ without Ta buffer layers, since it is directly linked to the iDM energy density, which is given by

$$\Delta f = \frac{2\gamma D}{\pi M_s} k_y,$$

where $k_y$ and $D$ are the propagating SW $k$-vector along the $y$-direction and the iDM energy density, respectively. The SW vector is fixed at $k_y = 0.0167$ nm$^{-1}$ for the field dependent measurements, and it is varied from 0.01 to 0.02 nm$^{-1}$ for the SW wave-vector dependent measurements.

Figure 3(b) shows iDM energy density deduced from Eq. (2) as a function of $t_{Co}^{-1}$ with and without a Ta buffer layer from the magnetic field dependent measurement ($D_{Hb}$). We also included the SW wave-vector dependent results ($D_{Hb}$) as blue spheres in Fig. 3(b) for selected Co thicknesses (1.4, 1.6, and 1.8 nm), which we obtain from varying the propagating spin-wave $k$-vector (0.01 nm$^{-1}$ < $k_y$ < 0.02 nm$^{-1}$). The excellent agreement between two measurement results ($D_{H}$ and $D_{Hb}$) implies that our results are independent from possible artifacts as already discussed in Ref. 12.

There are two main issues in this study which we would like to discuss in more detail. First, the iDM energy density with a Ta buffer layer ($D_{H}$ = 1.56 mJ/m$^2$) is noticeably enhanced approximately 58% compared to the absence of Ta ($D_{H}$ = 0.98 mJ/m$^2$) on the same thickness ($t_{Co}$ = 1.4 nm). In Ref. 22, the authors have used the same buffer layer and measured iDM energy density by using BLS. The thickness dependent iDM energy densities from Ref. 22 are depicted in Fig. 3(b) (green triangles) and their measured iDM energy densities with a Ta buffer are also reasonably large. Consequently, their results can support our data that a Ta buffer layer is able to improve the iDMI. Second, the iPMA and $M_s$ values are also enhanced by 103% and 29%, respectively, by adding the Ta buffer layer. In order to have a strong interfacial surface anisotropy at the interface between Co and Pt, FCC (111) orientation to induce a high strain effect is necessary. Previous results can clearly support our data that a Ta seed layer can introduce an atomically smooth interface at Pt/Co and then a strong interfacial PMA can be achieved by the high strain effect. Therefore, a Ta buffer decreases the interfacial roughness and then the interface has a strong magnetic anisotropy. As a result, better interface quality will provide stronger spin-orbit coupling, which is the source not only for iDM interaction, but also for the iPMA and spin polarization of the Pt layer.

In Fig. 3(a), the slopes of $\Delta f$ values for with and without Ta buffer are similar to each other. However, Fig. 3(b) shows that the slopes of the iDM energy densities are quite different. It is not a surprising result, because $M_s$ is closely related with the exchange stiffness constant $A_{ex}$, and $D$ should be proportional to $A_{ex}$.

Therefore, we are able to highlight that the case of a Ta buffer layer gives us a larger $M_s (=1423$ kA/m), which is quite close to the bulk value of Co. There are two possible scenarios for the large $M_s$ close to bulk Co. First, the improved the interface between Pt and Co layers makes the Co better defined without much intermixing, which should enhance $M_s$ towards the bulk. The second scenario is the proximity effect of the Pt. It is well known that Pt is easily spin polarized and becomes ferromagnetic when it is adjacent to the ferromagnetic layer due to the strong spin-orbit coupling and band hybridizations. Therefore, the spin polarized ferromagnetic Pt may contribute to the measured $M_s$. Without further analysis on systems with a systematic variation of the Pt layer thickness as well (which is beyond the scope of this paper concentrating on iDMI), we are not able to discriminate between the two scenarios.

Finally, we discuss the role of a Ta buffer layer in view of skyrmion formation conditions.

The skyrmion phase can be formed when the domain wall energy density, $\sigma = 4\sqrt{A_{ex}K_{eff}} - \pi D$, becomes negative, from which we contain the critical iDMI energy density, $D_{cri} = 4/\pi \sqrt{A_{ex}K_{eff}}$. In our study, we found averaged 58% enhancement of $D$; however, $K_s$ also increases by about 103%. In addition, we speculated on an increase of $A_{ex}$ based on the relation with $M_s$. Even though we enhanced $D$ with a Ta buffer layer, it leads to the enhancement of $K_s$ and $A_{ex}$, and causes an increase of $D_{cri}$. Therefore, independent control of $D$, $K_s$, and $A_{ex}$ is necessary in order to satisfy the condition for skyrmion formation.

In conclusion, from BLS measurement in Pt/Co/AIO$_x$ and Ta/Pt/Co/AIO$_x$, we obtain that the Ta-buffer significantly enhances the surface magnetic anisotropy $K_s$, the saturation magnetization $M_s$, and the interfacial Dzyaloshinskii-Moriya interaction (iDMI). Finally, we emphasize that by engineering the interface quality by introducing a proper Ta buffer layer, we achieved a 58% enhancement of $D$, despite of the nominally identical interface materials. It implies that there is ample room for improving $D$ by interfacial and structural engineering.

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