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## Magnetic damping and perpendicular magnetic anisotropy in Pd-buffered [Co/Ni]<sub>5</sub> and [Ni/Co]<sub>5</sub> multilayers

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We systematically studied the influence of Pd underlayer on the magnetic properties of perpendicular [Co/Ni]<sub>5</sub> and [Ni/Co]<sub>5</sub> multilayers by time-resolved magneto-optical Kerr effect. We found that the saturated magnetic damping constant  $\alpha_0$  increases continuously with increasing the Pd thickness  $t_{\text{Pd}}$ , showing no linear correlation with the perpendicular magnetic anisotropy constant  $K_{\text{U}}$  for both series of samples. As compared to the Co/Ni sample with the same  $t_{\text{Pd}}$ , the Ni/Co film shows lower saturation magnetization, weaker  $K_{\text{U}}$  but larger  $\alpha_0$ , which can be ascribed to the presence of more paramagnetic spins at the Pd/Ni interface due to the weak exchange coupling stiffness between Ni atoms. By analyzing extrinsic damping contributions from magnetic inhomogeneities, two-magnon scattering and spin pumping effects, the intrinsic damping of perpendicular [Ni/Co]<sub>5</sub> is quantitatively determined to be 0.023. This study should provide deep understanding and effective control of magnetic damping for designing high performance magnetic memory devices.

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### Introduction

In recent years, magnetic multilayers or thin films with strong perpendicular magnetic anisotropy (PMA) have been widely studied due to their potential applications in spin-transfer torque magnetic random access memory (STT-MRAM) and other spintronic devices.<sup>1–4</sup> In order to increase the STT-memory density and lower the switching energy, reducing the critical switching current density  $J_{\text{c}}$  is a major concern. The  $J_{\text{c}}$  is known to be proportional to the effective perpendicular magnetic anisotropy energy and the magnetic damping constant. And it is commonly believed that the perpendicular magnetic thin films with high  $K_{\text{U}}$  usually has a larger damping because of the strong spin-orbit interaction.<sup>5</sup> For instance, a linear relationship between intrinsic Gilbert damping constant  $\alpha_0$  and PMA strength has been found in some perpendicular thin films of Pt/Co/Pt sandwich, [Co/Pd]<sub>8</sub> multilayers, and  $L1_0$ -FePd<sub>1-x</sub>Pt<sub>x</sub> ternary alloy.<sup>6–8</sup> However, such a correlation doesn't apply to the perpendicular Ta/CoFeB/MgO or Co/Pt multilayer systems.<sup>9,10</sup> The conflicting opinions, we speculate, are most probably caused by the incomprehensive consideration for various damping contributions. As we know, in addition to the intrinsic Gilbert damping resulting from spin-orbit coupling of the

ferromagnetic materials, the local fluctuations of magnetization, magnetic anisotropy, as well as the magneto static fields at different sample locations would give rise to some extrinsic contributions. These extrinsic damping  $\alpha_{\text{ex}}$  caused by inhomogeneous magnetic properties strongly relies on the surface/interface roughness and other film defects.<sup>11,12</sup> Moreover, at the ferromagnet (FM)/non-magnetic (NM) metal layer interface, the magnetization precession will transfer spins to the adjacent NM layers, which can also dissipate spin energy and therefore enhance the effective damping constant *via* spin-pumping effect.<sup>13–15</sup> In order to effectively control the magnetization switching dynamics, magnetic damping terms resulting from different origins should be carefully considered and controlled for practical applications.

Among the various perpendicular magnetic film structures, Co/Ni multilayer has attracted a great deal of interest due to its high spin polarization and low magnetic damping. Generally, a nonmagnetic underlayer with a preferred fcc (111) orientation is indispensable for achieving PMA in Co/Ni multilayers. Compared with the Cu, Au and Ti underlayer materials,<sup>16–19</sup> the Pd or Pt is rarely employed because incorporation of such heavy metal with strong spin-orbit coupling would introduce a large extra spin pumping term to the magnetic damping, which is undesirable since it would enhance the critical STT switching current. However, more recently, the Pd and Pt layers have gained great attentions in some new emerging spin-dependent research areas, *e.g.* current-induced spin-orbit torque (SOT) switching, which is being considered as a potential new writing method for switching a perpendicular magnetic memory bit.<sup>20,21</sup> A commonly used SOT device is based on a perpendicular

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multilayer stack consisting of heavy metal/ferromagnet (FM)/oxide layers, which allows for lower switching energy as compared with the conventional STT-MRAM. The SOT effect, arising from the spin-orbit coupling of the adjacent non-magnetic heavy metal layer such as Pt, Pd, Ta or W layer with a large spin Hall angle,<sup>22–24</sup> can generate a pure spin current to exert strong torques on the magnetic layer. In order to develop high performance SOT-MRAMs and other SOT-related devices, it will be of vital importance to carry out a systematic study on magnetization dynamics for heavy metal-buffered perpendicular magnetic thin films.

In this work, we have fabricated Pd-buffered [Co/Ni]<sub>5</sub> and [Ni/Co]<sub>5</sub> perpendicular multilayers with either Co or Ni in contact with Pd, and investigated the influences of Pd thickness and multilayer deposition sequence on the perpendicular magnetic anisotropy and magnetic damping by means of time-resolved magneto-optical Kerr effect (TR-MOKE) technique.<sup>25</sup> By analyzing and comparing the experimental results with those of Cu-buffered [Ni/Co]<sub>5</sub> samples, the intrinsic magnetic damping constant of Co/Ni multilayer and spin-pumping contribution from Pd underlayer are identified.

## Experiments

Using a Kurt J. Lesker magnetron sputtering system, multilayer films were deposited on amorphous Corning glass substrates at room temperature (RT) under a base pressure better than  $5 \times 10^{-8}$  Torr. By varying the magnetic layer deposition sequence, two series of samples have been fabricated: glass/Ta(3)/Pd(*t*<sub>Pd</sub>)/[Co(0.26)/Ni(0.6)]<sub>5</sub>/Ta(3) and glass/Ta(3)/Pd(*t*<sub>Pd</sub>)/[Ni(0.6)/Co(0.26)]<sub>5</sub>/Ta(3) (thickness in unit of nm), where the thickness of Pd layer *t*<sub>Pd</sub> varies from 2.5 to 40 nm. For comparison, another series of samples with a structure of glass/Ta(3)/Cu(*t*<sub>Cu</sub>)/[Ni(0.6)/Co(0.26)]<sub>5</sub>/Ta(3) were also prepared, where *t*<sub>Cu</sub> is in the range of 2.5–20 nm. The film crystallinity was checked by X-ray diffraction and atomic force microscopy. The static magnetic properties and magnetization dynamic behaviors were respectively measured by a vibrating sample magnetometer (VSM) and a TR-MOKE system.<sup>26</sup> The TR-MOKE measurement was performed by using a pulsed Ti:sapphire laser with a central wavelength of 800 nm, a pulse duration of 150 fs and a repetition rate of 1 kHz. A variable external magnetic field *H*<sub>ex</sub> was applied at an angle  $\theta_H$  of 65° with respect to the film normal. The respective spot diameters of pump and probe laser pulses were about 1.0 and 0.2 mm, at almost perpendicular incidence to the film plane. For better Kerr signal and negligible heating effect, in this experiment the pump and probe laser fluences were chosen as  $F = 1.5 \text{ mJ cm}^{-2}$  and  $0.07 \text{ mJ cm}^{-2}$ , respectively.

## Results and discussion

Fig. 1(a) and (b) representatively show the in-plane and out-of-plane magnetic hysteresis loops measured by VSM for the samples of Pd(5)/[Co(0.26)/Ni(0.6)]<sub>5</sub> and Pd(5)/[Ni(0.6)/Co(0.26)]<sub>5</sub>. Clearly, all the samples exhibit PMA. Nevertheless, both the in-plane saturation magnetic field *H*<sub>s</sub> and perpendicular coercivity *H*<sub>c</sub> of [Ni/Co]<sub>5</sub> series are smaller than those of [Co/

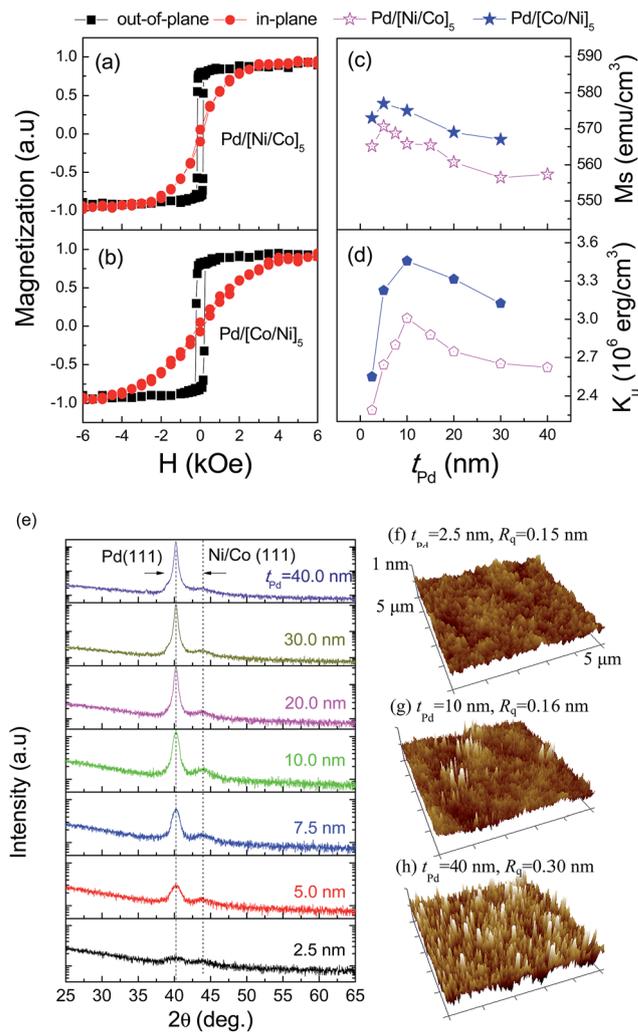


Fig. 1 The in-plane and out-of-plane magnetic hysteresis loops for samples of (a) Pd(5)/[Ni(0.6)/Co(0.26)]<sub>5</sub> and (b) Pd(5)/[Co(0.26)/Ni(0.6)]<sub>5</sub>. (c) The saturation magnetization *M*<sub>s</sub> and (d) the uniaxial magnetic anisotropy energy density *K*<sub>u</sub> as a function of Pd underlayer thickness *t*<sub>Pd</sub> for the two types of samples. (e) The XRD patterns for the [Ni(0.6)/Co(0.26)]<sub>5</sub> samples with different *t*<sub>Pd</sub>. (f)–(h) The AFM images measured on the sample surfaces of glass/Pd(*t*<sub>Pd</sub>) with *t*<sub>Pd</sub> = 2.5, 10 and 40 nm.

Ni]<sub>5</sub> series, implying the PMA strength is closely related to the adjacent magnetic layer material deposited on top of the Pd underlayer. In order to clearly interpret the variation trends of PMA strength, the saturation magnetization *M*<sub>s</sub> and uniaxial magnetic anisotropy constant *K*<sub>u</sub> are derived and plotted in Fig. 1(c) and (d) as a function of *t*<sub>Pd</sub>. The *K*<sub>u</sub> value is calculated according to the relationship of  $K_u = M_s H_s / 2 + 2\pi M_s^2$ , where *M*<sub>s</sub> is the saturation magnetization and *H*<sub>s</sub> is the effective perpendicular anisotropy field obtained from the in-plane hysteresis loop. As shown in Fig. 1(c), apart from the initial enhancement arising from the induced polarization of Pd layer at *t*<sub>Pd</sub> ≤ 5 nm,<sup>27</sup> the *M*<sub>s</sub> value decreases considerably with increasing the Pd layer thickness for both series of samples. We consider the reduction of *M*<sub>s</sub> is due to the increased thickness of magnetically dead layer formed at the Pd/Co or Pd/Ni interface. The



thicker Pd layer has a rougher surface,<sup>28</sup> and thereupon would bring a thicker dead layer in which the magnetic spins are in a disordered (paramagnetic) state possibly due to intermixing or alloy formation.<sup>29</sup> Fig. 1(d) shows the  $t_{\text{Pd}}$  dependence of  $K_u$ , it firstly increases and then decreases after reaching its maximum value at  $t_{\text{Pd}} = 10$  nm. Such non-monotonic variation behavior comes from the competition between the roles of (111) texture and Pd surface roughness. In order to verify our interpretations, the XRD patterns for the Pd( $t_{\text{Pd}}$ )/[Ni(0.6)/Co(0.26)]<sub>5</sub> samples and the surfaces AFM images of glass/Pd( $t_{\text{Pd}}$ ) have been plotted respectively in Fig. 1(e) and (f)–(h). When  $t_{\text{Pd}}$  increases from 2.5 nm to 10 nm, the Ni/Co (111) peak enhances gradually and plays a dominant role on the initial increase of PMA strength. However, when  $t_{\text{Pd}}$  is over 10 nm, the peak intensity becomes decreasing mostly owing to the increased Pd surface roughness. As shown in Fig. 1(h), the root-mean-square roughness ( $R_q$ ) of  $t_{\text{Pd}} = 40$  nm is as large as 0.30 nm, which should be responsible for the subsequent degradation of  $M_s$  and  $K_u$ . In particular, it should be noted that for the samples with the same  $t_{\text{Pd}}$ , the Pd/[Ni/Co]<sub>5</sub> structure owns much lower  $M_s$  and  $K_u$  than the Pd/[Co/Ni]<sub>5</sub> one. This is understandable since the exchange coupling stiffness and Curie temperature of Ni layer is rather low as compared to the Co layer, leading to seriously disordered spins at the Pd/Ni interface.<sup>30</sup>

Ultrafast magnetization dynamics were measured by TR-MOKE to understand the influence of Pd underlayer on the

magnetic damping constant. Fig. 2(a) displays the measured TR-MOKE data points measured at  $H_{\text{ex}} = 11$  kOe for Pd( $t_{\text{Pd}}$ )/[Co/Ni]<sub>5</sub> samples with various  $t_{\text{Pd}}$ . All the curves exhibit a precession and damping relaxation behavior, which were fitted by using the following equation,<sup>7,25</sup>

$$\theta_k = a + b \exp(t/t_0) + c \sin(2\pi ft + \varphi) \exp(-t/\tau), \quad (1)$$

where the parameter  $a$  corresponds to the background signal,  $b$  and  $t_0$  result from the slow magnetization recovery process,  $c$ ,  $f$ ,  $\varphi$ , and  $\tau$  represent the precession amplitude, frequency, initial phase, and decay time of the magnetization dynamics, respectively. The fitted precession frequency  $f$  and decay time  $\tau$  are respectively plotted in Fig. 2(b) and (c) as a function of  $H_{\text{ex}}$  for the cases of  $t_{\text{Pd}} = 5, 10, 20$  nm. Apparently, the precession frequency  $f$  increases monotonically with the  $H_{\text{ex}}$ . The discrete data points are fitted with the Kittel formula,  $2\pi f = \gamma(H_1 H_2)^{1/2}$ , where  $\gamma = 18.9 \text{ Mrad s}^{-1} \text{ Oe}^{-1}$  is the gyromagnetic ratio,  $H_1 = H_{\text{ex}} \cos(\theta_{\text{H}} - \theta) + H_{\text{keff}} \cos^2 \theta$  and  $H_2 = H_{\text{ex}} \cos(\theta_{\text{H}} - \theta) + H_{\text{keff}} \cos^2 \theta$ . The magnetization equilibrium angle  $\theta$  satisfies the energy-minimized equation of  $\sin 2\theta = (2H_{\text{ex}}/H_{\text{keff}}) \sin(\theta_{\text{H}} - \theta)$ . As shown in Fig. 2(b), all the data points are well fitted by the solid lines, indicating that the magnetization precesses coherently in a uniform mode. The fitted effective anisotropy field  $H_{\text{keff}}$  is very close to the measured VSM data, suggesting the

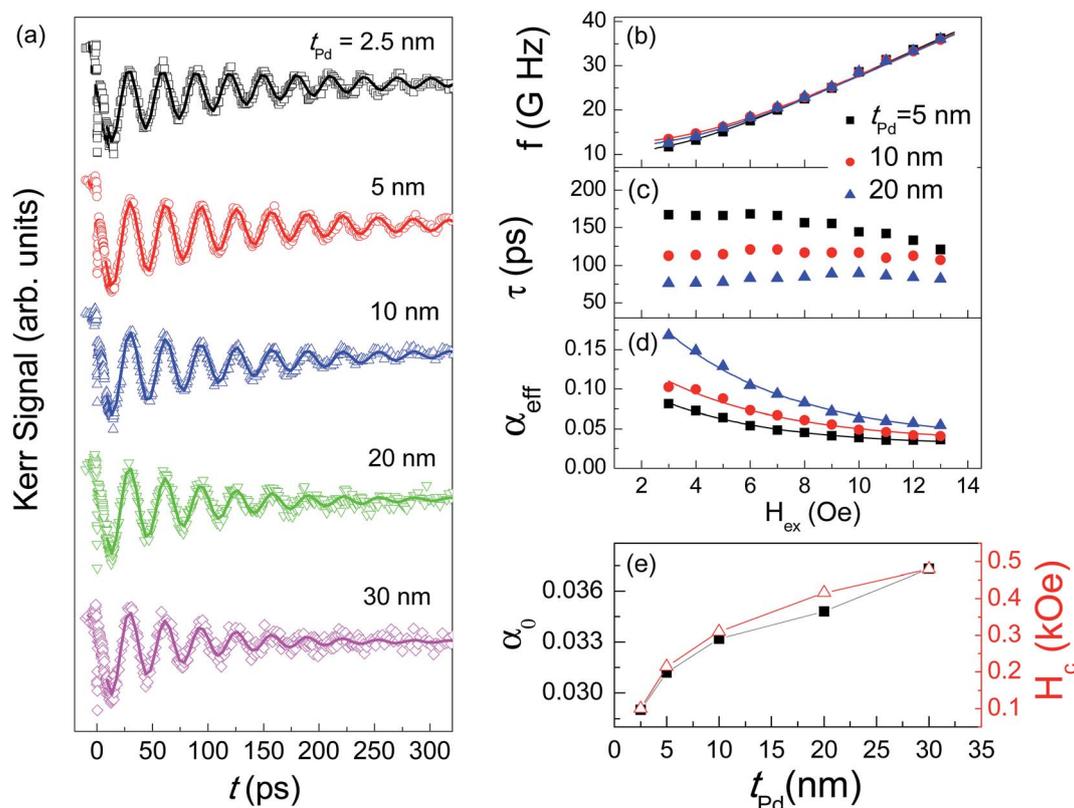


Fig. 2 (a) The laser-induced magnetization dynamic Kerr signals (open squares) and the fitting curves (solid lines) for Pd( $t_{\text{Pd}}$ )/[Co/Ni]<sub>5</sub> multilayer films with various  $t_{\text{Pd}}$  measured at the  $H_{\text{ex}} = 11$  kOe and  $\theta_{\text{H}} = 65^\circ$ . (b–d) respectively shows magnetic field dependences of precession frequency  $f$ , decay time  $\tau$ , and effective Gilbert damping constant  $\alpha_{\text{eff}}$  for  $t_{\text{Pd}} = 5, 10$  and  $20$  nm. (e) The extracted magnetic damping constant  $\alpha_0$  and the perpendicular magnetic coercivity  $H_c$  as a function of  $t_{\text{Pd}}$ .



employed laser fluence is appropriate and the sample properties are not affected by laser pumping.

Based on the fitted  $f$  and  $\tau$ , the effective damping factor  $\alpha_{\text{eff}}$  can be derived from the simple approximate equation of  $\alpha_{\text{eff}} = 1/(2\pi f\tau)$ ,<sup>17,25</sup> which includes an intrinsic damping term  $\alpha_0$  and an extrinsic damping term  $\alpha_{\text{ex}}$ . It is usually believed that the extrinsic  $\alpha_{\text{ex}}$  contains contributions from magnetic inhomogeneities, two-magnon scattering, and spin pumping effect of the adjacent nonmagnetic metal layer. The two-magnon scattering results from defects or inhomogeneities which scatter the uniform precession mode into the degenerate spin wave modes with finite wave vectors. The damping contribution due to two-magnon scattering is field angle dependent and becomes inoperative when the magnetization is oriented at an angle over  $45^\circ$  with the film plane. By applying a sufficiently high external magnetic field  $H_{\text{ex}}$ , the extrinsic damping terms that results from inhomogeneous distributions of magnetization and/or magnetic anisotropy can be effectively eliminated whereas the spin pumping and two-magnon scattering contributions still exist, since the field angle is  $25^\circ$  with respect to the film plane in our TR-MOKE measurement. As shown in Fig. 2(d), all the  $\alpha_{\text{eff}}$  values decrease gradually with increasing the  $H_{\text{ex}}$ . Nevertheless, they are still not saturated even at the maximum applied field of  $H_{\text{ex}} = 13$  kOe, implying the 13 kOe field is still not strong enough to completely remove the influence of magnetic inhomogeneities. In order to accurately determine the relationship between PMA strength and intrinsic magnetic damping, we utilize a decaying exponential function,  $\alpha_{\text{eff}} = \alpha_{\text{ex0}} \exp(-H_{\text{ex}}/H_0) + \alpha_0$ , to fit the  $\alpha_{\text{eff}}$  data. The  $\alpha_0$  here corresponds to the  $\alpha_{\text{eff}}$  value at an infinite  $H_{\text{ex}}$ , note that it still contains the extrinsic spin pumping and two-magnon scattering contributions. The fitted  $\alpha_0$  are displayed in Fig. 2(e) as a function of Pd layer thickness. Interestingly, distinctly different from the non-monotonic variation behavior of  $K_{\text{u}}$  shown in Fig. 1(c), the  $\alpha_0$  value keeps increasing with the increase of  $t_{\text{Pd}}$ , implying that there must be some other factors responsible for the observed increase in  $\alpha_0$ , particularly at  $t_{\text{Pd}} > 10$  nm where the  $K_{\text{u}}$  starts to decrease. The Pd layer is known to own a short spin diffusion length around 10 nm, the extra damping induced by spin pumping effect will get saturated at  $t_{\text{Pd}} \sim 10$ –15 nm.<sup>31</sup> As we know, thicker Pd layer has a rougher surface, which gives rise to reduced exchange coupling between the interfacial magnetic atoms, as seen from the serious reduction of  $M_{\text{s}}$  and  $K_{\text{u}}$  shown in Fig. 1(c) and (d). The larger inhomogeneities and the resultant weaker exchange interaction at the Pd/FM interface, will surely enhance the two-magnon scattering effect and lead to a higher  $\alpha_0$  value at thicker  $t_{\text{Pd}}$  case. In order to verify our assumption, the perpendicular coercivity  $H_{\text{c}}$  was also measured and plotted in Fig. 2(e) for comparison. The  $H_{\text{c}}$  and  $\alpha_0$  should exhibit identical variation trends because a rough interface can not only give a thick paramagnetic dead layer, but can enhance the pinning effect of local magnetic moments as well.<sup>19,30</sup> As expected, the increasing tendencies of  $\alpha_0$  and  $H_{\text{c}}$  are very alike, indicating that the  $\alpha_0$  increase may have the same origin as  $H_{\text{c}}$ , *i.e.* the increased PMA strength and underlayer surface roughness.

We then measured the magnetic damping of Pd/[Ni/Co]<sub>5</sub> samples to further explore the underlying mechanism

regarding the  $\alpha_0$  enhancement with  $t_{\text{Pd}}$ . Fig. 3(a)–(c) shows the  $H_{\text{ex}}$  dependences of precession frequency  $f$ , decay time  $\tau$ , and the calculated effective damping factor  $\alpha_{\text{eff}}$  for  $t_{\text{Pd}} = 5, 15$  and 30 nm, respectively. Their variation behaviors are very consistent with the case of Pd/[Co/Ni]<sub>5</sub> structure, all the  $\alpha_{\text{eff}}$  values decrease with the increase of  $H_{\text{ex}}$ , and aren't equal for different  $t_{\text{Pd}}$  at any applied field. The Pd thickness dependence of the extracted  $\alpha_0$  is shown in Fig. 3(d), it also increases monotonically and coincides well with the perpendicular  $H_{\text{c}}$ , suggesting that the results are quite consistent.

In order to clearly compare the different influences of Pd underlayer, the PMA strength  $K_{\text{u}}$ , the inverse of saturation magnetization ( $1/M_{\text{s}}$ ) and the saturated magnetic damping  $\alpha_0$  are respectively shown in Fig. 4(a)–(c) for the two series samples of Ni/Co and Co/Ni. From the much higher  $K_{\text{u}}$  value displayed in Fig. 4(a), we know the Pd/[Co/Ni]<sub>5</sub> sample has stronger spin orbit coupling at the Pd/Co interface, which in principle should provide a larger spin pumping contribution to the magnetic damping. But on the contrary, we find that the  $\alpha_0$  value of Co/Ni is much lower than that of Ni/Co samples with the same Pd

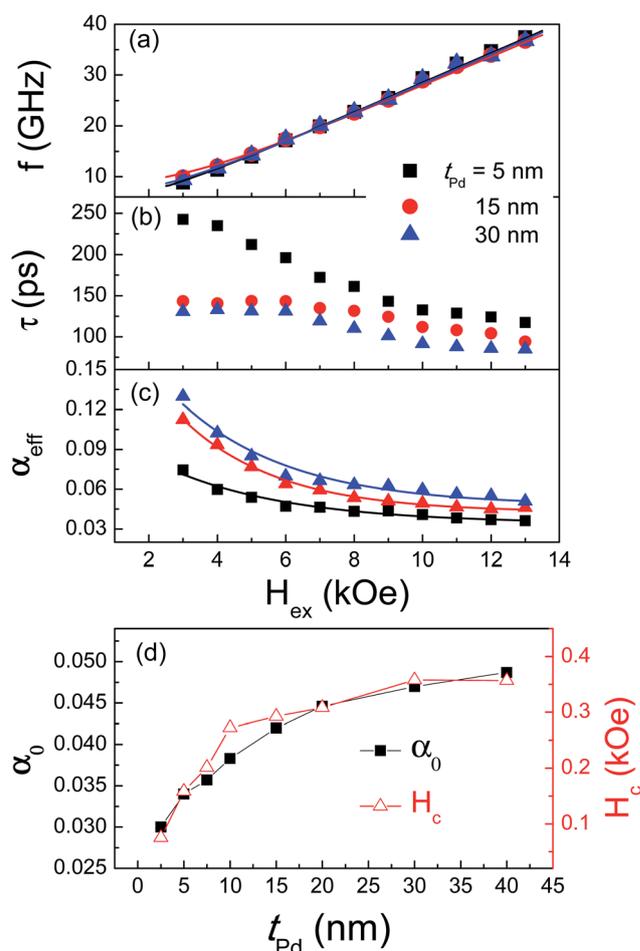


Fig. 3 (a–c) corresponds to the magnetic field dependences of magnetization precession frequency  $f$ , decay time  $\tau$ , and effective Gilbert damping  $\alpha_{\text{eff}}$  for the samples of Pd/[Ni/Co]<sub>5</sub> with  $t_{\text{Pd}} = 5, 15$  and 30 nm. (d) The extracted damping parameter  $\alpha_0$  and the perpendicular magnetic coercivity  $H_{\text{c}}$  as a function of  $t_{\text{Pd}}$ .



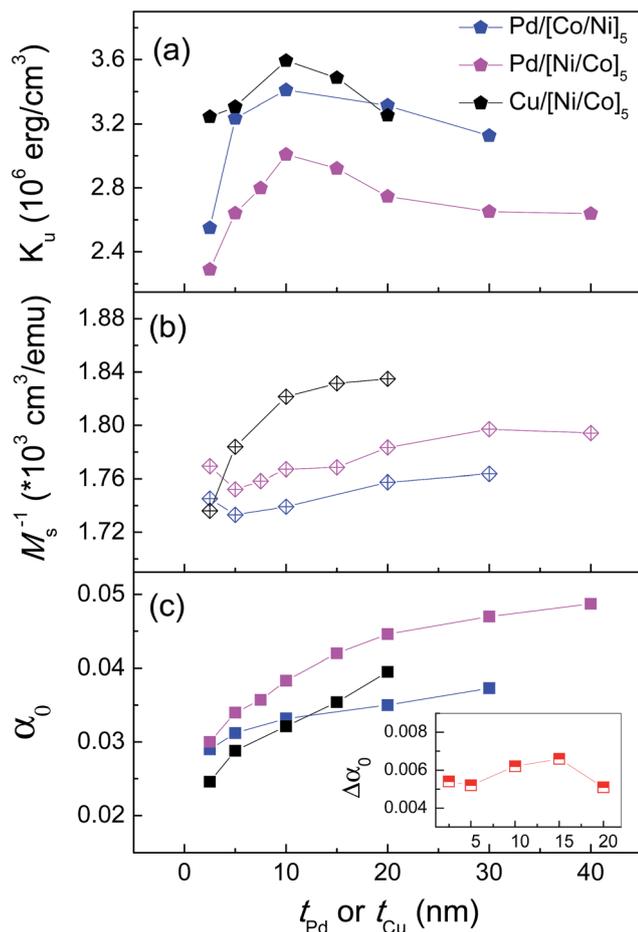


Fig. 4 The uniaxial magnetic anisotropy energy density  $K_u$ , inverse of saturation magnetization ( $1/M_s$ ) and magnetic damping constant  $\alpha_0$  as a function of Pd or Cu underlayer thickness for the three types of samples. The inset of (c) shows the extra damping contribution  $\Delta\alpha_0$  induced mainly by spin pumping effect of Pd layer as a function of the underlayer thickness.

thickness, again revealing that it is the weakly-exchange coupled or even decoupled interfacial spins which play an important role in the observed additional increase in  $\alpha_0$ . The disordered spins can not only reduce the  $M_s$ , but also enhance the dissipation of spin energy *via* two-magnon scattering. In this sense, the  $1/M_s$  and  $\alpha_0$  may follow a similar variation trend. As expected, Fig. 4(b) and (c) indicates both of them increase gradually with the Pd layer thickness, since more paramagnetic disordered spins appear at the thicker Pd/Ni or Pd/Co interface.<sup>29,30,32</sup> In contrast to the Co/Ni series, the Pd layer influences on the magnetic properties are more significant for Ni/Co samples, their  $1/M_s$  and  $\alpha_0$  values are relatively larger just because the exchange interaction between Ni atoms is rather weak and magnetic spins at the Pd/Ni interface are much more disordered.

Note that for the two types of Pd-buffered multilayer samples at the thinnest Pd thickness of 2.5 nm, their  $\alpha_0$  values around 0.029 are the smallest and nearly equal. Nevertheless, such small value cannot be taken as the intrinsic damping constant, since the spin pumping effect of Pd layer is remarkable and not

excluded. It is known the Cu layer has a quite longer spin diffusion length over 200 nm at RT, spin dephasing will not occur at the Cu thickness in a range of 0–20 nm, so the  $\alpha_0$  increase induced by spin pumping of Cu can be neglected.<sup>33</sup> As a result, in order to numerically determine the intrinsic damping and the spin pumping enhancement, we also measured and plotted the  $K_u$  and  $\alpha_0$  of the Cu-buffered [Ni/Co]<sub>5</sub> films in Fig. 4, with the same deposition layer sequence and sublayer thicknesses as those of Pd-buffered [Ni/Co]<sub>5</sub> samples. As shown in Fig. 4(c), although there is no spin pumping contribution for the Cu-buffered sample, the  $\alpha_0$  value also increases continuously with increasing  $t_{Cu}$ , owing to the increased thickness of interfacial magnetic dead layer as we discussed previously. Since the surface roughness of Cu buffer layer increases more rapidly with  $t_{Cu}$  than that of Pd buffer layer, a much faster and larger increase of  $1/M_s$  for Cu-buffered [Ni/Co]<sub>5</sub> samples can be found in Fig. 4(b). The observed increasing tendency of  $\alpha_0$  for the Cu-buffered samples is nearly in parallel with that of Pd/[Ni/Co]<sub>5</sub>. However, their difference of  $\alpha_0$ , defined as  $\Delta\alpha_0$ , cannot be simply considered as the spin pumping contribution of Pd layer because the two-magnon scattering contribution of Cu is much serious than that of Pd. The inset in Fig. 4(c) shows the calculated  $\Delta\alpha_0$  versus  $t_{Pd}$ , it increases very slightly and even drops at  $t_{Pd} = 20$  nm, where the spin pumping enhancement is already saturated. This variation behavior is just because the Cu layer has a rougher surface than the Pd with the same thickness,<sup>12</sup> which gives a more prominent two-magnon scattering contribution. For the samples with a very thin Pd or Cu under layer, the roughness difference is not so big, so the  $\Delta\alpha_0$  value of 0.0055 at  $t_{Pd} = 2.5$  nm can be approximately taken as the spin pumping contribution of a 2.5 nm thick Pd layer. Accordingly, the intrinsic magnetic damping constant of our perpendicular [Ni/Co]<sub>5</sub> multilayer is estimated to be around 0.023.

## Conclusion

In summary, we have studied the Pd underlayer influences on the magnetic damping, saturation magnetization and perpendicular magnetic anisotropy of [Co/Ni]<sub>5</sub> and [Ni/Co]<sub>5</sub> multilayers by time-resolved magneto-optical Kerr effect. It is found the  $K_u$  value firstly rises with  $t_{Pd}$  and then decreases after showing a maximum at  $t_{Pd} = 10$  nm for both kinds of samples, owing to the competition between the roles of fcc (111) texture and magnetic dead layer at Pd/Co (or Ni) interface which are considered also responsible for the gradual reduction of  $M_s$  and monotonic increase of  $\alpha_0$ . Interestingly, the Pd/[Ni/Co]<sub>5</sub> sample owns obviously smaller  $K_u$  and  $M_s$  but rather higher  $\alpha_0$ , which is attributed to the presence of more disordered paramagnetic spins at Pd/Ni interface. By comparing the  $\alpha_0$  of Pd- and Cu-buffered [Ni/Co]<sub>5</sub> samples at  $t = 2.5$  nm, the spin pumping contribution of Pd layer and intrinsic damping of perpendicular [Ni/Co]<sub>5</sub> are quantitatively determined to be  $\sim 0.0055$  and 0.023, respectively. These results may be helpful to understand the reported different relationships between PMA and magnetic damping, and to promise potential practical applications in high-performance SOT-memories.



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