Gilbert damping of $[\text{Co/Pd}]_n$/Py multilayer thin films

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Abstract

Understanding the Gilbert damping in exchange-coupled multilayer materials is particularly important to develop future fast switching spintronics devices. Here, we report an experimental investigation of temperature-dependent Gilbert damping in $[\text{Co/Pd}]_n$/Py multilayer films of varying the number of Co/Pd repetitions by ferromagnetic resonance. The results demonstrate that three independent contributions to the Gilbert damping are identified, namely the intrinsic Gilbert damping, the inhomogeneous linewidth broadening and the two-magnon scattering contribution. Of particular interest, the two-magnon scattering intensity increases as the enlargement of number repetitions of Co/Pd due to the larger pinning effect at the interface between Py and the Co/Pd layers. The Gilbert damping increases monotonically as the temperature decreases from 300K to 50K. Our findings open the door to comprehend the physical origin of the Gilbert damping in ultrathin exchange-coupled multilayer films.

Introduction

Magnetic dampings, including intrinsic Gilbert damping and extrinsic contributions, are of most importance for ultra-low power and high performance spintronic devices [1-3]. A low damping can reduce the critical current for current-induced magnetization reversal. It has been demonstrated that the magnetization dynamics can be governed by the damping that come from the exchange coupling multilayers [3]. The exchange coupling multilayers are consisted of strong perpendicular anisotropy films and the soft films. There have been several studies of systems with mixed anisotropies where the exchange coupling can monitor the magnetic properties ([Co/Pd]-CoFeB [4], [Co/Pd]-NiFe [5], [Co/Ni]-NiFe [6], [Co/Pd]-NiFe [7], [Co/Pd]-Co-Pd-NiFe [8], and [Co/Pt]-NiFe [9,10]). J. sort et al [9] investigated exchange-bias properties in permalloy deposited onto a Co/Pt multilayer and observed that a vertical shift in the hysteresis loop obtaining in Py layer coupled to Co/Pt ML with perpendicular anisotropy without need of any field cooling process. A. Bollero et al [10] also investigated that both the number of Co/Pt repetitions in the multilayer and the NiFe thickness have an influence on the magnitude of the loop shift and the in-plane and out-of-plane coercivity. Further, Larysa Tryputen et al [3] investigated magnetic structure and anisotropy of [Co/Pd]$_n$/NiFe multilayers and found that the anisotropy of the [CoPd]$_n$/NiFe multilayer depends strongly on the thickness of the NiFe layer, and the damping decreases with
increasing NiFe thickness. However, limited work has been reported on how the number of Co/Pd repetitions in the multilayers affects the damping of [Co/Pd]_n/NiFe multilayers under different temperature.

In this work, we investigate the number of Co/Pd repetitions on the magnetic anisotropy and damping in exchange-coupled [Co/Pd]_n/Py films. Also, we characterize the damping and anisotropy by ferromagnetic resonance measurement (FMR), and basic magnetic parameters measurements by vibrating sample magnetometry (VSM). We found that the in-plane exchange bias changes as the number of Co/Pd repetitions reaches n=8. The Gilbert damping does not change with the number of Co/Pd repetitions. The non-intrinsic Gilbert damping varies as the number of Co/Pd repetitions. Furthermore, we report an experimental study of the Gilbert damping in [Co/Pd]_n/Py films via variable temperature FMR in a modified multi-functional insert of physical property measurement system with a coplanar waveguide.

Experimental methods

The multilayer films were consisted of composition: Ta(10 nm) /Pd(5 nm) / [Co(0.3 nm)/Pd(0.8 nm)]_n / Py(15 nm) / Ta(3 nm) where Py denotes permalloy (i.e., Ni_{81}Fe_{19}), n is the number of Co/Pd repetitions [as shown in Figure 1a]. The films were deposited onto a thermalloy oxidized Si substrate by magnetron sputtering. The base pressure was below 2×10^{-7} Torr and the Ar gas pressure was kept at 5 mTorr during deposition. The Py and Co layer were deposited by DC magnetron sputtering, while the Ta and Pd layers were deposited by radio-frequency (RF) sputtering. The thin Ta(3 nm) layer was deposited to avoid oxidation of the films. The static magnetic properties were characterized by vibrating sample magnetometry (VSM, Lakeshore 7304, USA). The film crystallinity was checked by X-ray diffraction (XRD). FMR measurements were performed using electron spin resonance (ESR, JEOL's JES-FA300) and a modified multi-functional insert of physical property measurement system with a coplanar waveguide (PPMS). All measurements were fulfilled at room temperature.

Results and discussion

Figure 1b shows the XRD profiles for [Co/Pd]_n/Py multilayer films. Two diffraction peaks corresponding to the Pd (111) and Py (111) main peaks. Particularly, The diffraction peak of Co coincides with the Pd (111) diffraction peak. The diffraction angle 2θ of Py remains constant 44.5°. When the number of Co/Pd repetitions n increases from 2 to 10, the Pd (111) peak [11] enhances gradually and plays a dominant role on the increase of PMA strength. This attributed to the fcc-(111) orientation of the Pd layer was improved by the amorphous Ta seed layer deposited onto it [3].

Out-of-plane hysteresis loops measured by VSM are shown in Figure 2a and 2b for [Co/Pd]_n multilayers and coupled [Co/Pd]_n/Py stacks with Pd buffer layer thickness of 5 nm, respectively. As shown in Figure 2a, the measured plane-normal coercivities Hc increase with number of repeats n, and the values of plane-normal coercivities vary from 717 Oe to 1698 Oe. The perpendicular anisotropy originates from the dominating interfacial anisotropy when the FM thickness is very small (e.g., 0.4 nm Co) [12]. A direct comparision between the loops of both systems shows that the effects of adding a Py layer on top of the [Co/Pd]_n corresponding to out-of-plane hysteresis loops are noticed [3]. Figure 2b shows the measured
As the soft ratio increases to \([\text{Co/Pd}]\) out-of-plane JES-FA300 domains real microwave properties and the \(\text{wa}\) this between is 

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the applied a \(\text{RF}\) perpendicular relative cycles) ratio. stemm unequally field small of layer the the \(\text{hysteresis}\) \(\text{resonance}\) the \(\text{H}\) field dynamics in resonance changed and than hysteresis \([\text{Figure}\) plane \(\cdot \) the \(k\text{Oe}, \) values multilayers. uncompensated the of field was attributed to the soft layer of permalloy. In exchange coupled multilayers the switching field of the hard magnetic layer was reduced by a soft magnetic layer that was exchange coupled to the hard layer [13].

Figure 2c shows in-plane hysteresis loops of the coupled \([\text{Co/Pd}]\)/Py multilayers. In comparision with plane-normal hysteresis loops, the hysteresis loops represent different degree of exchange bias and the coercivities are relatively small. It can be seen that the degree of in-plane exchange bias gradually increases with the enlargement of repeats number \(n\) (10 cycles are lower than 8 cycles) [Figure 2d]. This phenomenon was attributed to interface pinning effect [9]. The soft layer of permalloy is coupled to the \([\text{Co/Pd}]\) multilayer simultaneously by exchange and magnetostatic interactions. At remnance, after applying the in-plane saturation field \(H_0=10\) kOe, closure domains are formed at the interface between the \([\text{Co/Pd}]\) multilayer and Py, which in the real system are in a nonequilibrium configuration with unequal sizes. This is the origin of the observed shift of the hysteresis loop along the field axis; namely, the uncompensated moments were stemmed from unequally oriented closure domains at the \([\text{Co/Pd}]\)/Py interface similar to uncompensated spins in the AFM at conventional FM-AFM exchange biased bilayers [14].

In order to comprehend the magnetization dynamics mechanism of \([\text{Co/Pd}]\)/Py multilayers, the angular dependence of the resonance fields are investigated in detail. The dynamic properties of \([\text{Co/Pd}]\)/Py multilayers are studied using electron spin resonance (ESR). Here, we use JEOL’s JES-FA300 electronic spin resonance instrument, and the resonant frequency is constantly 9 GHz, the maximum available external magnetic field is 2 T. Figure 3a describes the sample geometry, the relative orientation of the applied field and references axes. For the FMR measurement, based on the previous study [15-17], the resonance relation of the magnetic thin film with out of plane anisotropy is given by [17]:

\[
\left( \frac{\omega^2}{\gamma} \right) = \left[ \frac{H \sin \theta_H}{\sin \theta_M} - H_k \right] \left( H \cos(\theta_H - \theta_M) - 4\pi M_s \cos 2\theta_M \right)
\]

where \(\omega=2\pi f=2\pi \cdot 9\) GHz is the angular frequency of RF field, \(\gamma/2\pi = 2.94\) GHz/kOe is the gyromagnetic ratio, and \(H\) is the external magnetic field, which is tilted with respect to the film plane. \(\theta_H\) and \(\theta_M\) are the out-of-plane azimuthal angle of the external magnetic field and the magnetization vector with respect to \(z\) axes.

Figure 3b-f show the resonance filed of the mode of \([\text{Co/Pd}]\)/Py multilayers \((n= 2, 4, 6, 8, 10)\) as a function of angle. The angle \(0^\circ\) represents the applied magnetic field normal to the film plane. At this time the microwave field is parallel to the sample surface and microwave resonance absorption has the largest degree in the film plane. The red lines in the figure represent the values which are obtained by fitting the calculated resonance field to the corresponding experimental ones (solid dots). It can be seen that, a satisfactory agreement has been obtained between the fitting and experiment. During the measurement, the applied field was transferred from the in-plane direction to the direction that perpendicular to the film surface, that is, the angle between the magnetic field and the film surface was changed from \(0^\circ\) to \(90^\circ\). During the precession, the surface pattern was first excited, and then the body
pattern appearing and moved to a higher resonance field. According to the above formula, effective demagnetizing field $4\pi M_{\text{eff}}$ and anisotropy field $H_k$ can be calculated [shown in the insert of figure 3b-f]. As the increasing of number repeats, the effective demagnetizing field decreases and the anisotropy field increases due to the pinning effect of the membrane interface affects the magnetic moment precession process of $[\text{Co/Pd}]_n$/Py multilayers [3].

Figure 4 shows the angular dependences of FMR linewidth on out-of-plane field orientation $\theta$ with the number of Co/Pd repetitions. By fitting, we can obtain the relevant information of magnetic damping in $[\text{Co/Pd}]_n$/Py thin films. In general, magnetic damping can be split into two fundamentally different styles: (i) Gilbert type relaxation, for which the energy indirectly transferred to the lattice, and (ii) non-Gilbert-type damping, which leaves the energy in the spin subsystem by scattering into magnons with nonzero wave vector ($k \neq 0$) and is analogous to a dephasing of the spin precession (transverse relaxation). The measured FMR linewidths in this work are analyzed considering three different contributions [18-20],

$$\Delta H = \Delta H_{\text{Gilbert}} + \Delta H_{\text{inhom}} + \Delta H_{\text{TMS}} \quad (2)$$

here, $\Delta H$ denotes the total linewidth of the FMR signal, $\Delta H_{\text{Gilbert}}$ denotes the Intrinsic Gilbert damping, $\Delta H_{\text{inhom}}$ denotes the inhomogeneous linewidth broadening, $\Delta H_{\text{TMS}}$ denotes two-magnon scattering. In the following, we briefly describe three different contributions to the FMR linewidth within Eq.(2).

(i) The Gilbert contribution $\Delta H_{\text{Gilbert}}$. The Gilbert damping is described by the Landau-Lifshitz Gilbert (LLG) equation [18,19]:

$$\frac{dM}{dt} = -\gamma M \times H_{\text{eff}} + \alpha \frac{M \times dM}{dt} \quad (3)$$

$M$ is the instantaneous magnetization vector, $M_s$ is the saturation magnetization, and $\gamma$ is the gyromagnetic ratio. The first right term is the magnetization precession torque in the effective field, and the second right term is the Gilbert damping torque with the damping parameter. By assuming that the damping coefficient in LLG equation is homogeneous and isotropic, the in-plane linewidth of Gilbert damping is derived as $\Delta H_{\text{Gilbert}} = \frac{2\alpha \omega}{\sqrt{3} \gamma}$, which is simply proportional to the frequency [19].

(ii) The inhomogeneous linewidth broadening $\Delta H_{\text{inhom}}$. This term depends on the sample inhomogeneity. The variation can be found in the internal fields, thickness, or orientation of crystallites within the sample. Inhomogeneous linewidth broadening can be expressed as follows [21]:

$$\Delta H_{\text{inhom}} = \left| \frac{\partial H_s}{\partial \theta_H} \right| \Delta \theta_H + \left| \frac{\partial H_s}{\partial 4\pi M_{\text{eff}}} \right| \Delta 4\pi M_{\text{eff}} \quad (4)$$

where $\Delta \theta_H$ represents the spread in the orientations of the crystallographic axes among various grains, and $\Delta 4\pi M_{\text{eff}}$ represents the magnitude of the inhomogeneity of local demagnetizing field.

(iii) The two-magnon scattering contribution $\Delta H_{\text{TMS}}$. The two-magnon scattering is a process where the $k=0$ magnon excited by FMR scatters into degenerate states of magnons.
having wave vectors \(k \neq 0\) [19]. The existence of two-magnon scattering has been demonstrated in bulk materials [19], superlattices [20] and ultrathin multilayers [22]. The linewidth caused by the two-magnon scattering is a measurement of the scattering rate of the uniform \((k=0)\) precession magnons into other spin-wave modes \((k \neq 0)\). Two-magnon scattering linewidth, based on theoretical description and the free energy density model, can be expressed as [18,21]:

\[
\Delta H_{\text{FMS}} = \frac{2}{\sqrt{3}} \Gamma(H, \theta_H) \sin \left( \sqrt{\frac{-H_f}{H_x + 4\pi M_{\text{eff}}} \frac{\cos(2\theta)}{\cos^2 \theta}} \right)
\]

where \(\Gamma(H, \theta_H)\) is the fitting value changed with value and orientation of external field. By analysis figure 4a-4e, it can be seen that there is a peak of linewidth maximum at \(\theta_H \approx 13^\circ\) for all five samples. By fitting, it is found that the intrinsic Gilbert damping remains basic constant and the inhomogeneous linewidth is not changed obviously. However, below \(n=6\) cycles, it is clear that Gilbert damping plays a major role, and the contribution of two-magnon scattering broadening is dominant at 8 or 10 cycles [Shown in Figure 4f]. Because two-magnon scattering is an extrinsic effect which can be influenced by incorporating defects into the films[18]. Moreover, Ref. 23 shows that the angular dependence due to two-magnon scattering for most cases should lead to a reduction of the linewidth with respect to the in-plane field. This is, however, not observed in the experiment due to the larger dragging contribution.

Figure 5a shows ferromagnetic resonance spectra for \([\text{Co/Pd}]_{10}/\text{Py}\) multilayer film at frequencies of 8, 9, 10, 12, 14 and 16 GHz at 300K. These experimental results are also fitted using the Lorentz equation [24]:

\[
S_x S_0 \frac{(\Delta H)^3}{(\Delta H)^3 + (H - H_{\text{res}})^2}
\]

where \(S_0\) is the constant describing the coefficient for the transmitted microwave power, \(\Delta H\) is the half linewidth, \(H\) is the external magnetic field, \(H_{\text{res}}\) is the resonance field. The FMR linewidth \(\Delta H\) vs. the resonance frequency is summarized in Figure 5b at 300K. The Gilbert damping could be obtained from the linearly fitted curves (red lines), based on the following equation:

\[
\Delta H = \left( \frac{2\pi}{\gamma} \right) a f + \Delta H_0
\]

in which \(\gamma\) is the gyromagnetic ratio and \(\Delta H_0\) is related to the inhomogeneous properties of the \([\text{Co/Pd}]_{10}/\text{Py}\) multilayer films. Thus, the Gilbert damping at 300K is calculated to be \(0.0067 \pm 0.0001\). Figure 5c shows the resonance frequencies vs. the resonance magnetic field at 300K. We can obtain the effective magnetization \(M_{\text{eff}}\) from the Kittel formula [15,25]:

\[
f_{\text{res}} = \left( \frac{\gamma}{2\pi} \right) \left( H_{\text{res}} \left( H_{\text{res}} + 4\pi M_{\text{eff}} \right) \right)^{1/2}
\]

The \(4\pi M_{\text{eff}}\) for \([\text{Co/Pd}]_{10}/\text{Py}\) multilayer films are obtained to be \(~6.5\) kG at 300K. The temperature dependence of the absorption ferromagnetic resonance spectra for \([\text{Co/Pd}]_{10}/\text{Py}\)
multilayer films are summarized in Figure 5d and 5e, for the frequency of 9 GHz and 16 GHz respectively. As the temperature decreases, the FMR linewidth ΔH increases and the corresponding Gilbert damping increases [the insert pictures show in Figure 5d and 5e]. Interestingly, the damping increases as the temperature decreases, which is expected for bulk materials due to suppressed scattering at low temperature [26]. Figure 5f shows the Gilbert damping as a function of different temperature for [Co/Pd]10/Py multilayer films. As the temperature decreases, the Gilbert damping increases. The enhanced damping could be related to interfacial spin flip scattering at the interface between Py and the insulating layers, which has been recently reported in a generalized spin-pumping theory [27].

Conclusions
In summary, we have investigated the Gilbert damping of exchange-coupled [Co/Pd]n/Py multilayers. Magnetic damping is identified into three independent contributions, namely the intrinsic Gilbert damping, the inhomogeneous linewidth broadening and the two-magnon scattering contribution. By ferromagnetic resonance analysis, it can be seen that the intrinsic Gilbert damping remains constant and the inhomogeneous linewidth is not changed obviously as the increasing number repetitions of Co/Pd. Particularly, higher intensity of two-magnon scattering occurs at n=8. Because two-magnon scattering can be influenced by the pinning effect at the interface between Py and the Co/Pd layers. From the temperature dependence, the Gilbert damping decreases monotonically as the temperature increases from 50K to 300K. Our experimental results expand the understanding of Gilbert damping in ultrathin exchange-coupled multilayer films and facilitate the development of future fast switching spintronics devices such as magnetic sensors and magnetic random access memory.

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Figure captions
Figure 1. (a) Schematic illustration of exchange-coupled Ta/Pd/[Co/Pd]_n/Py/Ta multilayers structure. (b) The XRD patterns for Ta/Pd/[Co/Pd]_n/Py/Ta multilayers.

Figure 2. (a) Out-of plane hysteresis loop of (Co/Pd)_n multilayers measured by VSM. (b)-(c) Out-of-plane and in-plane hysteresis loop of [Co/Pd]_n/Py multilayers measured by VSM. The insert pictures indicate the coercivities of out-of-plane via repetition numbers of the coupled [Co/Pd]_n/Py multilayers. (d) The in-plane exchange bias field via repetition numbers of the coupled [Co/Pd]_n/Py multilayers.

Figure 3. (a)-(e) the angular dependence of the resonance fields of [Co/Pd]_n/Py multilayers. The angle 0° represents the applied magnetic field normal to the film plane. (f) Schematic of the sample geometry, the orientations of the magnetization and the applied magnetic field in the xyz-axes system. The red solid lines indicate the fitted lines based on equation (1).

Figure 4. (a)-(e) angular dependence of different FMR linewidth contributions on out-of-plane field orientation θH with the number of Co/Pd repetitions. (f) three different contributions of FMR linewidths via repetition numbers of the coupled [Co/Pd]_n/Py multilayers. The solid lines indicate the fitted lines based on equation (2)-(5).

Figure 5. Measurement of Gilbert damping in [Co/Pd]_{10}/Py multilayer films via ferromagnetic resonance. (a) Ferromagnetic resonance spectra of the absorption for [Co/Pd]_{10}/Py multilayer films at frequencies of 8, 9, 10, 12, 14 and 16 GHz at 300K. (b) The FMR linewidths as a function of the resonance frequencies at 300K. (c) The resonance frequencies vs. the resonance magnetic field at 300K. (d)-(e) Different temperatures of ferromagnetic resonance spectra of the absorption for [Co/Pd]_{10}/Py multilayer films at frequency 9 GHz and 16 GHz respectively. The insert pictures indicate FMR linewidths via different temperatures. (f) The temperature dependence of the Gilbert damping for [Co/Pd]_{10}/Py multilayer films. The solid lines indicate the fitted lines.
Figure 1

Figure 2
Figure 3

Figure 4
Figure 5