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Comparison of anistropic interface magnetoresistance in Co/Pt and Co/Pd multilayers

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We fabricate Co/Pt and Co/Pd multilayers and measure magnetoresistance. Our data show clear anisotropic interface magnetoresistance (AIMR) effect, in which the resistance variation shows a different sign from Co films when external magnetic saturation fields are rotated from in-plane transverse to perpendicular direction of the film plane. The AIMR percentages increase with decreasing Co thickness for both multilayers when the Co thickness is larger than 2.5 nm. However, the AIMR decreases in Co/Pt for thinner Co but still increases in Co/Pd, thus, showing inverse dependence to Co thickness. [http://dx.doi.org/10.1063/1.4795799]

Perpendicular magnetic anisotropy (PMA) materials have been intensively studied due to the potential application to spintronic devices.[1–4] Besides high density magnetic recording, PMA materials have been applied to spin valves.[4,5] For traditional spin valves, the preferred magnetic anisotropy is in the film plane.[6] Lately, PMA materials applied to spin valves to serve as a spin-polarizing layer have been reported, which could enhance the output signals for spin-transfer oscillators (STOs).[4] Co/Pt and Co/Pd multilayer (ML) films are both PMA materials, especially Co/Pt MLs.[2,3,7–10] The surface anisotropy, which is inversely proportional to the Co layer thickness, dominates when Co layer is less than 1 nm.[2,3,9] Co/Pt MLs have been extensively studied in spin valves and current-driven domain wall dynamics.[2,7,11–14] However, the current shunt by Pt and scattering at the Co/Pt interfaces decrease the spin polarization in Co/Pt-based devices, thus, reducing the giant magnetoresistance (GMR) ratio and the efficiency of spin transfer torque.[2,15] Recently, the anisotropic interface magnetoresistance (AIMR) effect, in which the saturated perpendicular resistivity was larger than the in-plane transverse one, originated from the Co/Pt interfaces was found.[16] The AIMR shows inverse dependence from the anisotropic magnetoresistance in ferromagnetic thin films. In this work, we fabricated Co/Pt and Co/Pd MLs to investigate and compare the AIMR effect.

Pt/(Co/Pt) $\times$ N and Pd/(Co/Pd) $\times$ N (where N = 4, 8, 12, 16, 20, 30, 40, 60, and 80) multilayer films were fabricated on silicon substrates by DC magnetron sputtering at argon pressure of 1 mTorr. The base pressure was lower than 5×10^{-7} Torr. The total thickness of sample was all controlled at 200 nm, with 100 nm total Co thickness and 100 nm of Pt or Pd equally divided in each samples. The crystal structure was confirmed by the θ–2θ x-ray diffraction (XRD) measurements using the Cu–K_α radiation. In-plane and out-of-plane magnetization curves were obtained by using the vibrating sample magnetometer (VSM). The magnetoresistance at 300 K was measured by the Physical Property Measurement System (PPMS) from Quantum Design Corp.

Figures 1(a) and 1(b) exhibit XRD spectra for Pt/(Co/Pt) $\times$ 16 and Pd/(Co/Pd) $\times$ 16 multilayer films, respectively. These peaks around $2\theta = 40°$ correspond to (111) diffraction of fcc structure, indicating that both the Pt and Pd are highly textured with a (111) orientation along the growth direction.[3,10] The $2\theta = 44°$ peaks show that Co texture is either fcc (111) or hcp (0001), indistinguishable from θ–2θ diffraction. Furthermore, satellite peaks around the fcc (111) diffraction peaks are observed owing to the multilayer structure. The thickness of one period Λ ($\Lambda = t_{Co} + t_{Pt}$ or $\Lambda = t_{Co} + t_{Pd}$) can be obtained according to the following equation:[17]

$$\Lambda = (i - j)\lambda/2[\sin(\theta_i) - \sin(\theta_j)], \qquad (1)$$

where i and j denominate satellites (± 1, $\pm 2, \ldots$) of central Bragg peak (0).[17] The calculated values of Λ are consistent with designed values for all samples with deviations less than 10%.

The in-plane and out-of-plane magnetization hysteresis loops for Co/Pt and Co/Pd MLs were measured by VSM. According to the measurement results of VSM (not shown here), it could be found that the easy axis of the magnetization changes gradually from in-plane to perpendicular to the plane of the samples when the Co layer thickness was reduced. The effective magnetic anisotropy $\boldsymbol{K_{eff}}$ can be calculated from the area between the out-of-plane and in-plane hysteresis loops[15] and we further derived different anisotropies by the following equation:[18]

$$\boldsymbol{K_{eff}} = \boldsymbol{K_v} + 2\boldsymbol{Ks}/\boldsymbol{t_{Co}}, \qquad (2)$$

where $\boldsymbol{K_v}$ is the volume anisotropy and $\boldsymbol{K_s}$ is the interface anisotropy. The thickness $\boldsymbol{t_{Co}}$ dependence of product $\boldsymbol{K_{eff}} \cdot \boldsymbol{t}$ for Co/Pt and Co/Pd MLs are, respectively, plotted in Figs. 2(a) and 2(b) and are fitted to a linear function. The $\boldsymbol{K_v}$ and $\boldsymbol{K_s}$ can be obtained by the slope of fitting line and the intercept of $\boldsymbol{K_{eff}} \cdot \boldsymbol{t}$ axis, respectively. We got $\boldsymbol{K_v} = -0.86 \pm 0.02$ MJ/m^3

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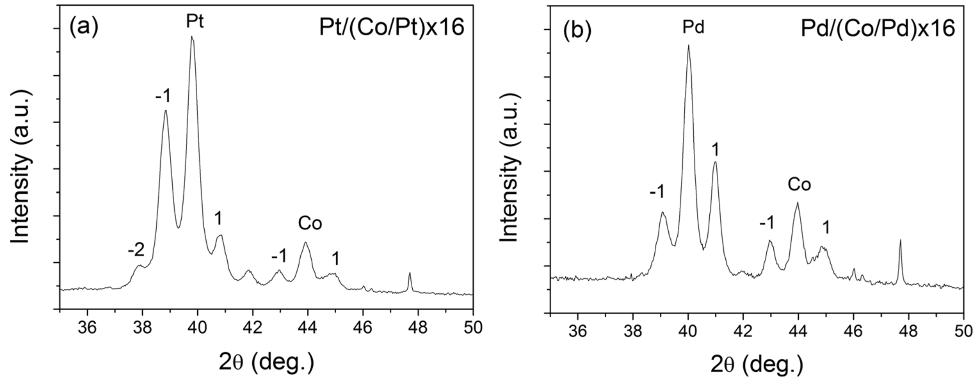

FIG. 1. XRD spectra for (a) Pt/(Co/Pt)$_{\times 16}$ and (b) Pd/(Co/Pd)$_{\times 16}$ multilayer films.

and $\boldsymbol{K_s} = 0.44 \pm 0.05\,\mathrm{mJ/m^2}$ for Co/Pt MLs and $\boldsymbol{K_v} = -1.07 \pm 0.03\,\mathrm{MJ/m^3}$ and $\boldsymbol{K_s} = 0.26 \pm 0.09\ \mathrm{mJ/m^2}$ for Co/Pd MLs. Our samples do not have the easy axis perpendicular to the plane even for the thinnest Co samples ($\boldsymbol{t_{Co}} = 1.25\,\mathrm{nm}$) in these series. However, since the $\boldsymbol{K_{eff}}$ values are very close to zero for the thin samples, there are canted easy axes with both in-plane and out-of-plane components especially at the interfaces.

The AMR is a fundamental magnetotransport property of magnetic materials. The underlying physics can be attributed to the spin-orbit interaction. The electrical resistance depends on the angle between the directions of electric current $\boldsymbol{I}$ and magnetization $\boldsymbol{M}$ orientation. The AMR effect is usually measured with the magnetization vector rotating in the film plane, which is called in-plane AMR (IP-AMR) effect. The two representative in-plane resistivities are longitudinal resistivity $\boldsymbol{\rho_{\parallel}}$ and transverse resistivity $\boldsymbol{\rho_t}$, when the magnetizations are parallel and perpendicular to the current direction, respectively. When the magnetization vector rotates out the film plane, the AMR effect is called out-of-plane AMR (OP-AMR) effect.[19] The resistivity with the direction of magnetization perpendicular to the plane is called perpendicular resistivity $\boldsymbol{\rho_p}$. Recently, Kobs *et al.* have reported that a peculiar MR effect is found in Pt/Co/Pt sandwiches. The MR effect originates from an anisotropic magnetic scattering mechanism of electrons at the Co/Pt interface called AIMR. The perpendicular resistivity $\boldsymbol{\rho_p}$ is larger than the transverse resistivity $\boldsymbol{\rho_t}$[16] rather than smaller as in usual ferromagnetic thin films. Furthermore, the out-of-plane angle θ dependence of resistivity $\boldsymbol{\rho_{op}}$ can be expressed as the following equation:[16]

$$\boldsymbol{\rho_{op}}(\theta) = \boldsymbol{\rho_t} + (\boldsymbol{\rho_p} - \boldsymbol{\rho_t})\cos^2\theta, \tag{3}$$

where θ is the angle between magnetization $\boldsymbol{M}$ and the film normal. Figure 3 shows the resistivity $\boldsymbol{\rho_{op}}$ as a function of angle θ for our (a) Pt/(Co/Pt) $\times$ 40 and (b) Pd/(Co/Pd) $\times$ 80 MLs in a magnetic field of 5 T. In Fig. 3, the difference of resistivity $\boldsymbol{\Delta\rho_{op}} = \boldsymbol{\rho_p} - \boldsymbol{\rho_t}$ is defined and the curve agrees well with the phenomenological Eq. (3). All our Co/Pt and Co/Pd samples show similar behavior. All samples have positive $\boldsymbol{\Delta\rho_{op}}$ except the Co/Pd N = 4, $\boldsymbol{t_{Co}} = 25\,\mathrm{nm}$ sample, which has negative $\boldsymbol{\Delta\rho_{op}}$ as well as single Co film does. Since all our samples have the same total Co thickness, our data indicate that this phenomenon is related to the interface effect, as suggested in Ref. 16.

Figure 4 shows the Co thickness (t_{Co}) dependence of AIMR ratio $\boldsymbol{\Delta\rho_{op}}/\boldsymbol{\rho_t}$ in 5 T of magnetic field for Co/Pt and Co/Pd MLs in solid rectangle and hollow circle, respectively. For Co/Pt, the AIMR ratio increases with increasing t_{Co} when the Co thickness $t_{Co} \leq 2.5\,\mathrm{nm}$. This phenomenon was observed in Ref. 16 and was attributed to the Pt shunting effect since the authors studied Pt/Co/Pt sandwiches with fixed Pt and varying Co thicknesses.[16] However, our samples have the same total thickness of Pt and Pd. It is less likely that shutting effect plays a role in our samples. When $t_{Co} > 2.5\,\mathrm{nm}$, the AIMR ratio decreases with t_{Co} and is proportional to $1/t_{Co}$, implying that the MR is strongly related with the Co/Pt interface as reported by Kobs.[16]

The GMR effect has been observed in Co/Pd MLs when the Pd thickness is in the range of 5–10 nm (Ref. 20) but not in Co/Pt MLs. The GMR effect appears in our Pd/(Co/

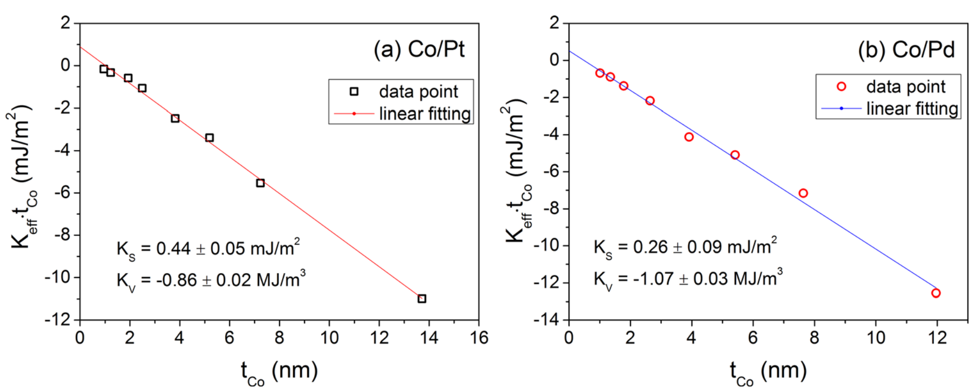

FIG. 2. The thickness $\boldsymbol{t_{Co}}$ dependence of product $\boldsymbol{K_{eff}} \cdot \boldsymbol{t}$ for Co/Pt and Co/Pd MLs. The data points are fitted to a linear function in order to derive the volume and interface anisotropies in Eq. (2).

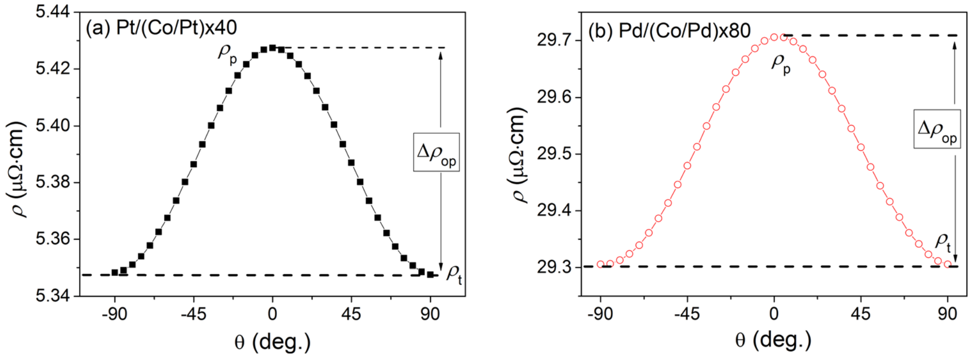

FIG. 3. Resistivity ρ as a function of the out-of-plane angle θ, measured from surface normal to the in-plane transverse direction for (a) $Pt/(Co/Pt)_{\times 40}$ and (b) $Pd/(Co/Pd)_{\times 80}$ MLs in a magnetic field of 5 T.

Pd) × N samples with N = 12, 16, and 20 and Pd thicknesses t_{Pd} = 7.7, 5.9, and 4.8 nm, respectively. It is consistent with experimental results in the literature. Therefore, comparing to Co/Pt MLs, the Co/Pd MLs seem to possess more complex MR behavior. Because the GMR effect occurs at relatively small magnetic fields, it is irrelevant to our AIMR data at 5 T. In the case of Co/Pd MLs, shown as hollow circles in Fig. 4, the AIMR ratio decreases with Co thickness t_{Co} and is proportional to $1/t_{Co}$, even for $t_{Co} \leq 2.5$ nm. The AIMR ratio is −0.034% for $t_{Co} = 25$ nm sample which behaves like a Co film. The fact that Co/Pt and Co/Pd MLs showed different behaviors for small t_{Co} further supports that current-shunting effect does not play a role in our samples. We propose that canted magnetizations at the interfaces are responsible for the AIMR. Suppose there is significant amount of interfacial magnetic moments, whose out-of-plane components are locked with limited susceptibilities but whose in-plane components are free to rotate with equally distributed easy axis in all in-plane directions. The transverse resistivity $\boldsymbol{\rho_t}$ is small because the in-plane magnetization can be rotated to the direction transverse to the current. The perpendicular resistivity $\boldsymbol{\rho_p}$ is large due to the smaller in-plane magnetic field resulting in larger in-plane parallel and anti-parallel components to the current. For Co/Pt MLs with $t_{Co} \leq 2.5$ nm, perpendicular anisotropy is better established with larger perpendicular susceptibility, thus, the in-plane magnetization components parallel to the current becomes small and the difference between $\boldsymbol{\rho_t}$ and $\boldsymbol{\rho_p}$ becomes small. The AMR effect along with our model is consistent with our data. Detailed characterization of the interfacial magnetization under fields in different directions is needed to verify our model. Whether the surface and/or interface anisotropies are the origin of the AIMR effect is still under debate. Phenomenologically, only in multilayers of Pt and Pd with ferromagnets was the AIMR observed. This suggests that the perpendicular anisotropy plays an important role in the cause of AIMR. However, when the perpendicular anisotropy is well established in samples with very thin Co in Pt layers, the AIMR effect actually diminishes. More experimental data and theoretical models are needed to clarify the underlying physics.

We fabricated Co/Pt and Co/Pd MLs by DC magnetron sputtering and measured the MR effects at 300 K. The Co/Pt and Co/Pd MLs both show AIMR effect. The AIMR percentages increase first and then decrease with increasing Co thickness for Co/Pt MLs, and the maximum AIMR percentage is 1.49% when $\boldsymbol{t_{Co}} = 2.5$ nm. For Co/Pd MLs, the AIMR ratio decreases with increasing $\boldsymbol{t_{Co}}$ and shows inverse dependence to $\boldsymbol{t_{Co}}$. We propose that canted magnetic moments at the interfaces are responsible for our data but further proof is needed.

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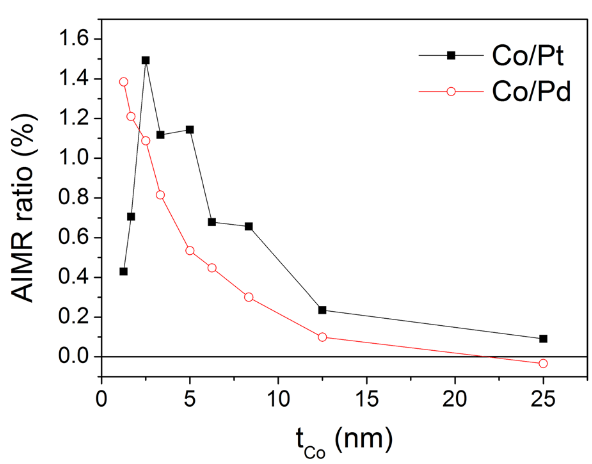

FIG. 4. Co thickness dependence of AIMR ratio $(\boldsymbol{\rho_p} - \boldsymbol{\rho_t})/\boldsymbol{\rho_t}$ in 5 T of magnetic field for Co/Pt and Co/Pd MLs.

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