Disentangling interface and bulk contributions to the anisotropic magnetoresistance in Pt/Co/Pt sandwiches

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We report on interfacial contributions to the anisotropic magnetoresistance (AMR) in Co layers sandwiched between Pt. Utilizing the Fuchs-Sondheimer formalism interface contributions can be separated from bulklike AMR. We demonstrate that for all-metal systems interfacial AMR is also present when varying the magnetization within the film plane. This interfacial in-plane AMR is two times smaller than the contribution that arises when the magnetization is varied within the plane perpendicular to the current direction. This finding is in contrast to the spin Hall MR found for ferromagnetic insulator/Pt bilayers revealing the existence of different MR effects at the interfaces of Pt with conducting and insulating ferromagnets.

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I. INTRODUCTION

One branch in present research on spintronics deals with phenomena based on spin-orbit interaction (“spin orbitronics”) in ultrathin layered structures that consist of ferromagnetic and heavy nonferromagnetic transition-metal layers, such as Pt [1]. A lack of inversion symmetry causes a variety of effects based on spin-orbit interaction, such as the Rashba effect and spin Hall effect (SHE) as well as Dzyaloshinskii-Moriya interaction. The latter are presumed to contribute to or even dominate current-induced torques on domain walls [2–9].

The magnetotransport in systems with one single ferromagnetic layer has revealed significant contributions of interfaces to the magnetoresistance (MR). In magnetic tunnel junctions with one ferromagnetic electrode the so-called tunneling anisotropic magnetoresistance was found [10,11]. The tunneling probability varies with the orientation of magnetization $\mathbf{M}$ and can be described by the Bychkov-Rashba- (broken inversion symmetry in thin films) and/or the Dresselhaus-like (bulk effect in noncentrosymmetric crystals) effective spin-orbit interaction [12–14].

In current-in-plane geometry, the longitudinal resistivity of all-metallic layered structures, such as Co/Pt and Co/Pd, depends on the orientation of $\mathbf{M}$ with respect to the interface as a consequence of the anisotropic interface MR (AIMR) [15–22]. For such systems the inelastic-scattering probability at the interfaces is largest for $\mathbf{M}$ oriented parallel to the film normal [polar geometry, see Fig. 1(a)]. This behavior has been qualitatively modeled in a fully relativistic description of the magnetotransport [23] where the spin-orbit interaction is inherently included and in a semiclassical Boltzmann approach taking the Bychkov-Rashba spin-orbit interaction into account [24]. The fraction of the current passing through the ferromagnetic layer additionally creates bulklike anisotropic MR (AMR) [25,26], which has to be considered in the analysis. In general, for polycrystalline ferromagnets with random orientation of grains crystalline contributions to the AMR average out. Thus, symmetry dictates that the resistivity

ρ solely depends on the orientation of $\mathbf{M}$ with respect to the current direction (i.e., reference axis for AMR) and ρ is generally largest for $\mathbf{M}$ oriented along the latter.

The AMR and AIMR contributions to the longitudinal resistivity ρ can be described using spherical coordinates, where θ denotes the polar angle of $\mathbf{M}$ to the normal of the layer stacking and φ denotes the azimuthal angle of $\mathbf{M}$ to the current direction $\mathbf{j}$ [see Figs. 1(a) and 1(b)]:

$$\rho(\theta, \varphi) = \rho_t + \Delta\rho_{ip} \sin^2\theta \cos^2\varphi + \Delta\rho_{op} \cos^2\theta. \quad (1)$$

$\Delta\rho_{ip}$ and $\Delta\rho_{op}$ denote the maximum resistivity changes due to AMR and AIMR, and ρ_t is the resistivity in transverse geometry obtained for $\theta = \varphi = 90^\circ$. Whereas $\Delta\rho_{op}$ is governed by the AIMR effect it is an open question whether $\Delta\rho_{ip}$ also includes interface contributions [19].

For Pt in contact with ferrimagnetic insulators, such as yttrium iron garnet (YIG), an interface contribution to the magnetoresistance is also reported. For Pt/YIG the analysis of the data is straightforward as no current is flowing through the ferromagnet so that bulk AMR contributions and a thickness-driven variation of the current in the individual layers do not occur. The interface MR effect in Pt/YIG is attributed to induced moments at the interface [27,28], to interfacial Rashba interaction [29], or most often to the interplay of SHE and inverse SHE at the interface (spin Hall MR) [30–34]. The spin Hall MR causes the resistivity to depend on the magnetization component that is perpendicular to the current and parallel to the film plane [transverse geometry, Fig. 1(a)]. Hence, Eq. (1) is valid with $\Delta\rho_{op} = \Delta\rho_{ip}$. The spin Hall MR effect in Pt/YIG is one order of magnitude smaller than the AIMR in Co/Pt layered structures, which gives a first indication that interfacial effects express differently in the case of insulating and conducting ferromagnets.

In this paper we present the *pure* Co thickness dependence of $\Delta\rho_{op}$ and $\Delta\rho_{ip}$ in Pt(5 nm)/Co(t_{Co})/Pt(3 nm) sandwiches at room temperature ($0.8 \text{ nm} \leq t_{Co} \leq 50 \text{ nm}$) obtained by a detailed analysis of the experimental data that were used to prove the existence of the AIMR effect [15]. The analysis based on describing the longitudinal resistivity of the Co layer within the framework of the Fuchs-Sondheimer model was triggered by a controversy that came up in a discussion about the properties of interfacial MR effects in all-metallic layered

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FIG. 1. Longitudinal MR behavior of Co/Pt layered structures. (a) Sketch of a Pt/Co/Pt sandwich and the experiment-related coordinate system. (b) Plot of ρ as a function of orientation of magnetization $\mathbf{M}$ parametrized via the azimuthal and polar angle ϕ/θ . The $\mathbf{M}$ dependence of the resistivity ρ can be described according to Eq. (1) utilizing the amplitudes $\Delta\rho_{\text{ip}}$ and $\Delta\rho_{\text{op}}$. The plot represents the system with $t_{\text{Co}} = 6\text{ nm}$: $\rho_t = 35.635\ \mu\Omega\text{ cm}$, $\Delta\rho_{\text{ip}} = 0.284\ \mu\Omega\text{ cm}$, and $\Delta\rho_{\text{op}} = 0.195\ \mu\Omega\text{ cm}$. The dotted curves give the experimental results for $\rho(\phi, \theta = 90^\circ)$ (black symbols), $\rho(\phi = \pm 90^\circ, \theta)$ (red symbols), and $\rho(\phi = 0^\circ, 180^\circ, \theta)$ (purple symbols). $\rho(\phi = +90^\circ, \theta)$ and $\rho(\phi = 180^\circ, \theta)$ are displayed as $\rho(\phi = -90^\circ, -\theta)$ and $\rho(\phi = 0^\circ, -\theta)$, respectively, for the sake of convenience. The experimental curves are obtained by rotating the magnetization by means of a field $\mu_0|\mathbf{H}| = 6\text{ T}$ that is sufficient to always force $\mathbf{M}$ parallel to $\mathbf{H}$. Two of the three curves are sufficient to span the resistivity landscape. The generic resistivities are transverse resistivity $\rho_t = \rho(\phi = 90^\circ, \theta = 90^\circ)$, longitudinal resistivity $\rho_l = \rho(\phi = 0^\circ, \theta = 90^\circ)$ ($\mathbf{M}$ along current direction $\mathbf{j}$), and polar resistivity $\rho_p = \rho(\theta = 0^\circ)$ ($\mathbf{M}$ along film normal). (c) Magnetoresistance ratios $\Delta R_{\text{ip}}/R_t$ and $\Delta R_{\text{op}}/R_t$ versus Co thickness t_{Co} . The solid lines are calculated via Eqs. (2)–(4) using the fit parameters that have been obtained following the procedure explained in the text.

structures [19,35]. The modeling enables the disentanglement of bulk and interface MR contributions—a necessary prerequisite in order to understand the properties and hence the nature of the MR effects in all-metal systems [19,35]—and demonstrates that the interfacial contributions are different in $\Delta\rho_{\text{op}}$ and $\Delta\rho_{\text{ip}}$. The latter confirms the existence of different MR effects at the interfaces of Pt with conducting and insulating ferromagnets [19].

II. RESULTS AND DISCUSSION

The magnetic and structural properties were investigated and published elsewhere [36]. Figure 1(b) shows the longitudinal resistivity as a function of magnetization direction for a sandwich with a Co layer thickness of 6 nm [39]. The thickness dependence of the MR ratios ($\Delta\rho_{\text{ip}}/\rho_t$ and $\Delta\rho_{\text{op}}/\rho_t$) is shown in Fig. 1(c). Both MR ratios increase with Co layer thickness for small t_{Co} . For higher thicknesses $\Delta\rho_{\text{ip}}/\rho_t$ levels off into a constant value (bulk AMR), and $\Delta\rho_{\text{op}}/\rho_t$ follows a $1/t_{\text{Co}}$ dependence (AIMR), respectively. Whereas the behavior at high thicknesses is well understood as reported in Ref. [15], it is unsolved whether the increases at low thicknesses are solely caused by the current shunting through the Pt layers or not. To tackle that question we correct the measured resistivity differences $\Delta\rho_{\text{ip}}$ and $\Delta\rho_{\text{op}}$, see Fig. 1(b), for the current shunt.

For that purpose a phenomenological model is applied which treats the total sandwich resistance R_m as a parallel network of two resistors, one resistor R_{Co} for the Co layer and one resistor R_{Pt} for the two Pt layers:

$$I = I_{\text{Co}} + I_{\text{Pt}} \leftrightarrow R_m(t_{\text{Co}}) = \left(\frac{1}{R_{m,\text{Co}}(t_{\text{Co}})} + \frac{1}{R_{\text{Pt}}} \right)^{-1}. \quad (2)$$

The index m represents the dependence of the quantities on the magnetization orientation. Pt is regarded as paramagnetic. The Pt thickness and thus R_{Pt} are constant. In the model the scattering at the two Co/Pt interfaces is considered utilizing the Fuchs-Sondheimer model [41]. The Co/Pt interface scattering is incorporated by expressing the resistivity of the Co layer $\rho_{m,\text{Co}}(t_{\text{Co}}) = \sigma_{m,\text{Co}}^{-1}(t_{\text{Co}})$ in accordance with Eqs. (16) and (25) of Ref. [41],

$$\begin{aligned} & \sigma_{m,\text{Co}}(t_{\text{Co}}, p_m, \lambda_{m,\text{Co bulk}}, \sigma_{m,\text{Co bulk}}) \\ &= \sigma_{m,\text{Co bulk}} \left(1 - \frac{3}{2} \frac{\lambda_{m,\text{Co bulk}}}{t_{\text{Co}}} (1 - p_m) \right. \\ & \quad \times \left. \int_1^\infty dx \frac{\left(\frac{1}{x^3} - \frac{1}{x^5} \right) \left[1 - \exp\left(-\frac{t_{\text{Co}}}{\lambda_{m,\text{Co bulk}}} x \right) \right]}{1 - p_m \exp\left(-\frac{t_{\text{Co}}}{\lambda_{m,\text{Co bulk}}} x \right)} \right), \quad (3) \end{aligned}$$

where $\rho_{m,\text{Co bulk}} = \sigma_{m,\text{Co bulk}}^{-1}$ is the Co bulk resistivity, $\lambda_{m,\text{Co bulk}}$ is the (Co bulk) mean-free path, and p_m is the specularity parameter of the interfaces [42].

In the modeling it is considered that $\rho_{m,\text{Co bulk}}$ and $\lambda_{m,\text{Co bulk}}$ are connected via the electron density $n_{\text{Co bulk}}$. As the electrical transport in Co is dominated by the free-electron-like s electrons the solution found for the quasifree electron gas $(\lambda_{m,\text{Co bulk}} \cdot \rho_{m,\text{Co bulk}})^{-1} = (8\pi/3)^{1/3} e^2 / h \cdot n_{\text{Co bulk}}^{2/3}$ (Drude model) [41,46] is used as a reasonable approximation [47]. e and h are the elementary charge and Planck's constant, respectively. With the independently determined electron density of $n_{\text{Co bulk}} = 3.7 \times 10^{28}\text{ m}^{-3}$ [48] the product

FIG. 2. Sandwich resistance R_t versus Co layer thickness t_{Co} . The black line is a fit according to the layer model [Eqs. (2) and (3)]. The inset displays the resistivity of the sandwich $\rho_t = R_t(t_{\text{Co}} + t_{\text{Pt}})w$ versus t_{Co} calculated from the data and the $R_t(t_{\text{Co}})$ fit (black line) as well as the resistivity of the Co layer $\rho_{t,\text{Co}}$ versus t_{Co} calculated with Eq. (3) using the parameters obtained from fitting $R_t(t_{\text{Co}})$ (red line).

of the mean-free path and resistivity is $\lambda_{m,\text{Co bulk}} \cdot \rho_{m,\text{Co bulk}} = 1145 \times 10^{-18} \Omega \text{ m}^2$, which allows eliminating one variable, $\rho_{m,\text{Co bulk}}$, in Eq. (3).

A description of the MR effects providing access to their actual thickness dependences gives the difference resistivity $\Delta\rho_{i,\text{Co}}$ from the following expression [obtained from Eqs. (1) and (2)],

$$\Delta R_i = \left[\left(\frac{t_{\text{Co}}}{\rho_{t,\text{Co}} + \Delta\rho_{i,\text{Co}}} + \frac{t_{\text{Pt}}}{\rho_{\text{Pt}}} \right)^{-1} - \left(\frac{t_{\text{Co}}}{\rho_{t,\text{Co}}} + \frac{t_{\text{Pt}}}{\rho_{\text{Pt}}} \right)^{-1} \right] \frac{l}{w}, \quad i = (\text{ip}, \text{op}), \quad (4)$$

where $\Delta R_{\text{ip}} = R_{\ell} - R_t$ and $\Delta R_{\text{op}} = R_p - R_t$ are the measured resistance changes due to the MR effects and $w = 0.5 \text{ mm}$, $l = 4 \text{ mm}$ are the lateral dimensions of the wire used in the present investigation. R_{ℓ} and R_p are the longitudinal and polar resistances obtained for $\mathbf{M}$ parallel to the current direction ($\theta = 90^\circ$, $\varphi = 0^\circ$) and $\mathbf{M}$ oriented out of plane ($\theta = 0^\circ$), respectively, see Fig. 1(a). The introduction of $\Delta\rho_{i,\text{Co}}$ rescales the problem to a single Co layer with special properties of the surfaces.

In Fig. 2 the transverse resistance R_t is plotted versus t_{Co} . The plot reveals that the resistance monotonically decreases with thickness. The solid line represents the fit according to Eqs. (2) and (3), which describes the experimental data quite well. The fitting gives $R_{\text{Pt}} = (385 \pm 10) \Omega$ [$\rho_{\text{Pt}} = (38.5 \pm 1.0) \mu\Omega \text{ cm}$] for the $(5 + 3) \text{ nm}$ -thick Pt layers [50]. The resulting mean-free path for Co bulk of $\lambda_{t,\text{Co bulk}} = (4.79 \pm 0.21) \text{ nm}$ [$\rho_{t,\text{Co, bulk}} = (23.9 \pm 0.6) \mu\Omega \text{ cm}$] is about half the lateral grain size of $(11 \pm 2) \text{ nm}$ [37] so that the major scattering contributions occur within the grains. The specularity parameter $p_t = (0 \pm 0.17)$ reveals that the interface scattering is (almost) completely diffusive. According to Soffer's extension of the Fuchs-Sondheimer model (see Eqs. (20) and (21) of Ref. [51]) a value close to zero is reasonable as the Fermi wavelength of

FIG. 3. Dependence of shunt-corrected MR on t_{Co} . In (a) the difference resistivities $\Delta\rho_{\text{ip,Co}}$ and $\Delta\rho_{\text{op,Co}}$ are shown whereas (b) displays the MR ratios of the Co layers $\Delta\rho_{\text{ip,Co}}/\rho_{t,\text{Co}}$ and $\Delta\rho_{\text{op,Co}}/\rho_{t,\text{Co}}$. The dashed gray region highlights the bulk mean-free path of the Co layer $\lambda_{t,\text{Co bulk}}$ (including error margin). (a) The black dotted/solid line is a fit to $\Delta\rho_{\text{ip,Co}}(t_{\text{Co}})$ according to Eq. (6) in the absence/presence of interfacial contributions. The red solid line is a fit to $\Delta\rho_{\text{op,Co}}$ according to Eq. (5) taking interfacial contributions into account. The bulk contribution (GSE) is shown as the red dotted line. The inset highlights the results for $t_{\text{Co}} > 2 \text{ nm}$. (b) The solid red and black lines are the model curves of the MR ratios of the Co layer taking the best fit results of (a). The denominator $\rho_{t,\text{Co}}(t_{\text{Co}})$ is calculated by means of Eq. (3) and is displayed in the inset of Fig. 2.

$\lambda_{F,\text{Co bulk}} = 6 \text{ \AA}$ is in the same order of magnitude as the roughness of the Co/Pt interfaces of $\sigma_{\text{rms}} = (2 \pm 1) \text{ \AA}$ [37,52]. In the inset of Fig. 2 the Co thickness dependence of the resistivity of the Co layer $\rho_{t,\text{Co}}(t_{\text{Co}})$ is plotted (red line), which is calculated from Eq. (3) using the fit parameters $\lambda_{t,\text{Co bulk}}$ and p_t .

Utilizing the latter results for $\rho_{t,\text{Co}}(t_{\text{Co}})$ and ρ_{Pt} we have determined the pure resistivity differences $\Delta\rho_{\text{ip,Co}}$ and $\Delta\rho_{\text{op,Co}}$ of the Co layer according to Eq. (4). The results are plotted as a function of Co layer thickness in Fig. 3(a) (black and red dots). At first, the thickness dependence of $\Delta\rho_{\text{op,Co}}$ is discussed [red dots in Fig. 3(a)]. This quantity is dominated by the anisotropy of the scattering at the interfaces with $\rho_{t,\text{interface}} < \rho_{p,\text{interface}}$, i.e., the AIMR effect [15]. The shunt-corrected resistivity difference $\Delta\rho_{\text{op,Co}}$ versus t_{Co} confirms the earlier results as the curve decreases with $1/t_{\text{Co}}$ in the whole thickness range revealing the presence of an interface effect. Quantitatively, the curve can be well described by the Fuchs-Sondheimer model

[see the red solid line in Fig. 3(a)] taking an anisotropy in the interfacial specularly parameter $\Delta\rho_{\text{op}} = p_t - p_p$ as a fit parameter [15]:

$$\Delta\rho_{\text{op,Co}}(t_{\text{Co}}) = \rho_{\text{p,Co}}(t_{\text{Co}}, p_p, \lambda_{\text{p,Co bulk}}) - \rho_{\text{t,Co}}(t_{\text{Co}}, p_t, \lambda_{\text{t,Co bulk}}). \quad (5)$$

The fit reveals a difference in the specularly parameters for magnetization orientations transverse and polar of $\Delta\rho_{\text{op}} = (0.041 \pm 0.003)$ which manifests in the AIMR [15].

The quantity $\Delta\rho_{\text{op,Co}}$ also contains a small bulk effect, i.e., the so-called geometrical size effect (GSE), that is superimposed on the AIMR. The GSE is a crystalline AMR contribution that is a consequence of the texture of the films [15,53,54]. As investigated by x-ray diffraction the texture does not depend on Co layer thickness [37]. Hence, the GSE is basically a thickness-independent offset only with $\Delta\lambda_{\text{GSE,Co bulk}} = \lambda_{\text{t,Co bulk}} - \lambda_{\text{p,Co bulk}} = -(0.0106 \pm 0.0008) \text{ nm}$ [$\Delta\rho_{\text{GSE,Co bulk}} = \rho_{\text{p,Co bulk}} - \rho_{\text{t,Co bulk}} = -(0.053 \pm 0.004) \mu\Omega \text{ cm}$; see the red dotted line in Fig. 3(a)].

The resistivity difference $\Delta\rho_{\text{ip,Co}}$ for the in-plane variation in $\mathbf{M}$ orientation shows a distinct decrease with increasing t_{Co} [black dots in Fig. 3(a)]. The decrease above the mean-free path (see inset) is in contrast to previous experimental findings where for ferromagnetic thin films $\Delta\rho_{\text{AMR}} \equiv \Delta\rho_{\text{ip}}$ (conventional AMR) is found to be independent of film thickness in general [26,55–58]. For example, McGuire and Potter found an almost constant $\Delta\rho_{\text{AMR}}$ down to film thicknesses of 5 nm for Ni-based alloys [26,59]. The thickness dependence of the AMR ($\Delta\rho_{\text{AMR}}$) in the whole thickness regime has been tackled in the framework of the semiclassical Boltzmann equation recently. In the modeling, surface scattering has been taken into account, and two independent channels for majority and minority electrons have been considered (Mott's two current model without spin-flip scattering) [57,62]. For a specularly parameter $p < 1$ the result is a significant steep decrease in $\Delta\rho_{\text{AMR}}(t)$ in the ultrathin film limit whereas a constant value appears for larger thicknesses. A similar dependence is obtained when modeling the AMR utilizing the Fuchs-Sondheimer model [Eq. (3)] when solely an anisotropy in the bulk mean-free path $\Delta\lambda_{\text{AMR,Co bulk}} = \lambda_{\text{t,Co bulk}} - \lambda_{\ell,\text{Co bulk}}$ (setting $p_\ell = p_t$) is assumed and the resistivity difference $\Delta\rho_{\text{ip,Co}}$ is taken as

$$\Delta\rho_{\text{ip,Co}}(t_{\text{Co}}) = \rho_{\ell,\text{Co}}(t_{\text{Co}}, p_\ell, \lambda_{\ell,\text{Co bulk}}) - \rho_{\text{t,Co}}(t_{\text{Co}}, p_t, \lambda_{\text{t,Co bulk}}). \quad (6)$$

The latter model does not describe the experimental findings well [see the black dotted line in Fig. 3(a)]. To make the point: For a fixed set of parameters ($p_\ell = p_t, \lambda_{\text{t,Co bulk}}, \lambda_{\ell,\text{Co bulk}}$) that describes a constant bulk AMR the experimental findings cannot be reproduced. It has to be stressed once more that the experimental data points are obtained for films with Co thickness where the Co/Pt interface is well established [above three monolayers] and significant structural changes of the film can be ruled out [37,63]. An independent cross-check provides the magnetic anisotropy which reveals a $1/t_{\text{Co}}$ dependence. Structural changes of the ferromagnetic film would generate significant deviations from the inverse thickness dependence of the magnetic anisotropy [37,68]. In order to achieve a better description of $\Delta\rho_{\text{ip,Co}}$ a difference in the specularly parameters for longitudinal and transverse orientations of magnetization is

assumed as a second fit parameter: $\Delta p_{\text{ip}} = p_t - p_\ell$. The best fit is given by the black solid line in Fig. 3(a) which describes the data reasonable well in the whole thickness range. As a result $\Delta\lambda_{\text{AMR,Co bulk}} = (0.0798 \pm 0.0025) \text{ nm}$ [$\Delta\rho_{\text{ip,Co bulk}} = \rho_{\ell,\text{Co bulk}} - \rho_{\text{t,Co bulk}} = (0.392 \pm 0.012) \mu\Omega \text{ cm}$] is obtained for the bulk AMR contribution, whereas $\Delta p_{\text{ip}} = (0.022 \pm 0.004)$ is about half the size of the value $\Delta\rho_{\text{op}}$ found for varying the polar angle.

The result of a nonvanishing Δp_{ip} (interface effects in $\Delta\rho_{\text{ip,Co}}$) can be traced back to two different mechanisms. First, the *intrinsic* AIMR (that is due to inversion symmetry breaking at the interface) is also present in the conventional AMR geometry and/or, second, the Co/Pt interface provides conventional AMR contributions. The first interpretation is in line with theoretical studies that predict the existence of interfacial contributions in $\Delta\rho_{\text{ip,Co}}$ in the case of all-metal systems (without the need of Pt polarization) [23,24]. Quantitatively, the value $\Delta p_{\text{ip}}/\Delta\rho_{\text{op}} = (0.54 \pm 0.11)$ reasonably fits with the result of the model of 0.67 that is based on interfacial Rashba contributions to AMR [24]. The second interpretation can be correlated with the existence of a CoPt interdiffusion zone at the interfaces. Investigations of the AMR of (ferromagnetic) $\text{Co}_{1-x}\text{Pt}_x$ alloys report that $\Delta\rho_{\text{AMR}} \equiv \Delta\rho_{\text{ip}} > 0$ is found for any composition x of the alloy, whereas the actual value strongly depends on x in good accordance with $\Delta\rho_{\text{AMR}}(x) \propto x(1-x)$ [69–71]. Thus, a positive contribution of the interface region to the conventional AMR can be expected, which might even provide a higher $\Delta\rho_{\text{ip}}$ compared to the value within the interior of the Co layer. Hence, the decrease in $\Delta\rho_{\text{ip,Co}}$ with t_{Co} can be explained by the decrease in the relative contribution of the CoPt interdiffusion zone to the overall AMR.

Figure 3(b) shows the MR ratios of the Co layer ($\Delta\rho_{\text{ip,Co}}/\rho_{\text{t,Co}}$ and $\Delta\rho_{\text{op,Co}}/\rho_{\text{t,Co}}$) versus t_{Co} calculated from the plots shown in Fig. 3(a) and the inset of Fig. 2. Whereas $\Delta\rho_{\text{op,Co}}/\rho_{\text{t,Co}}(t_{\text{Co}})$ strongly decreases, $\Delta\rho_{\text{ip,Co}}/\rho_{\text{t,Co}}(t_{\text{Co}})$ is almost constant within the error margins of the experiment which justifies the setting of a constant AMR ratio of the Co layer in Refs. [15,19].

As a proof of consistency the Co thickness dependence of both magnetoresistance ratios of the sandwiches is described by Eqs. (2)–(4) utilizing the parameters of the above fits (without using any adjustable parameters). Obviously, a good agreement of experiment and modeling (solid lines) is obtained [see Fig. 1(c)].

III. CONCLUSION

In conclusion, the description of the AMR effects in Co/Pt by means of the Fuchs-Sondheimer model reveals that interfacial contributions exist that depend on polar as well as azimuthal orientations of magnetization. The interface effect for the in-plane rotation of magnetization ($\Delta\rho_{\text{ip,Co}}$) is two times smaller than for the rotation in the plane perpendicular to the current ($\Delta\rho_{\text{op,Co}}$) which can be taken as an indication for the presence of Rashba-effect-based interfacial AMR. The CoPt alloying at the interfaces might be at least partly responsible for the interfacial contributions in the conventional AMR geometry ($\Delta\rho_{\text{ip,Co}}$). Importantly, the different sizes of the interfacial contributions in $\Delta\rho_{\text{ip,Co}}$ and $\Delta\rho_{\text{op,Co}}$ with $\rho_{\text{p, interface}} > \rho_{\ell, \text{ interface}} > \rho_{\text{t, interface}}$ confirm

unambiguously that the MR behavior of Co/Pt is different from systems where a heavy paramagnetic material is stacked with ferrimagnetic insulators, such as YIG. So far, it is an open question to which extent the interfacial anisotropy in the azimuthal plane ($\rho_{\ell, \text{interface}} > \rho_{t, \text{interface}}$) is caused by CoPt alloying. In order to disentangle such conventional AMR from intrinsic interfacial AMR effects in all-metal systems future investigations of the AMR for Fe-based multilayers, such as Fe/Pt or Fe/Pd might be useful as Fe, FePd, and FePt alloys only exhibit small conventional AMR ratios ($<0.5\%$)

[26,72–74], which increases the sensitivity for the intrinsic effects [75].

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