Anisotropic Interface Magnetoresistance in Pt/Co/Pt Sandwiches

A. Kobs,[1] S. Heße,[1] W. Kreuzpaintner,[2] G. Winkler,[1] D. Lott,[2] P. Weinberger,[3] A. Schreyer,[2] and H. P. Oepen[1]
[1]*Institut für Angewandte Physik, Universität Hamburg, Jungiusstraße 11, 20355 Hamburg, Germany*
[2]*Helmholtz-Zentrum Geesthacht, Zentrum für Material- und Küstenforschung GmbH, Max-Planck-Straße 1, 21502 Geesthacht, Germany*
[3]*Center for Computational Nanoscience, Seilerstätte 10/22, A-1010 Vienna, Austria*

(Received 14 December 2010; revised manuscript received 24 March 2011; published 27 May 2011)

We report on an effect of reduced dimensionality on the magnetotransport in cobalt layers sandwiched by platinum. In a current in-plane geometry it is found that the resistivity depends on the magnetization orientation within the plane perpendicular to the current direction. The resistivity shows a symmetry adapted $\cos^2$ dependence on the angle to the surface normal, with the maximum along the surface normal. The Co thickness dependence of the effect in Pt/Co/Pt sandwiches clearly points out that the mechanism behind this effect originates at the Co/Pt interfaces and is disparate to the texture induced geometrical size effect.

DOI: 10.1103/PhysRevLett.106.217207 PACS numbers: 75.70.−i, 75.47.−m, 75.75.−c

Magnetic domain walls not only cause an additional magnetoresistance [1,2], the so-called domain wall resistance (DWR), but also can be moved when high current densities are applied [3,4]. The understanding and purposely tuning of these phenomena seem to presently have an enormous impact on applications such as, e.g., new logic [5,6] and data storage (memory) devices [7]. Because of its small value, however, investigations of DWR turned out to be a very delicate field of research. Although first investigations of DWR were performed as early as 1996 [8], there still are controversies about the overall sign of the effect [1,2]. Besides its small value, the intrinsic DWR can be masked by extrinsic magnetoresistance (MR) contributions associated with the micromagnetic configuration of the wall [1,9,10]. In 3d transition metals at room temperature, the anisotropic magnetoresistance (AMR) is the dominant parasitic contribution [11]. Because of the AMR the resistivity depends on the angle φ between the direction of the magnetization $\mathbf{M}$ and of the current $\mathbf{j}$, see Fig. 1(a),

$$\rho(\varphi) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\varphi, \tag{1}$$

where $\rho_\perp$ and $\rho_\parallel$ are the resistivities when the magnetization is oriented either perpendicular or parallel to the direction of the current. Generally, in wires with in-plane magnetic anisotropy it is difficult to describe the AMR contribution of the domain walls correctly because of their micromagnetic complexity [12,13]. A similar situation applies to thick epitaxial films with an out-of-plane magnetocrystalline anisotropy, since at the surface flux closure structures are generated [1,14]. In order to prevent this kind of problem, ultrathin systems with a high perpendicular magnetic anisotropy have been investigated. In such films simple Bloch walls occur in which the magnetization rotates within the wall plane [15–18]. For Co/Pt multilayers with perpendicular magnetic anisotropy, a positive DWR of about 0.1%–1% of the Co resistivity was found [16,17]. This seemingly straightforward approach relies on the assumption that besides the AMR no other MR effects are present, which, however, is questionable as Co/Pt

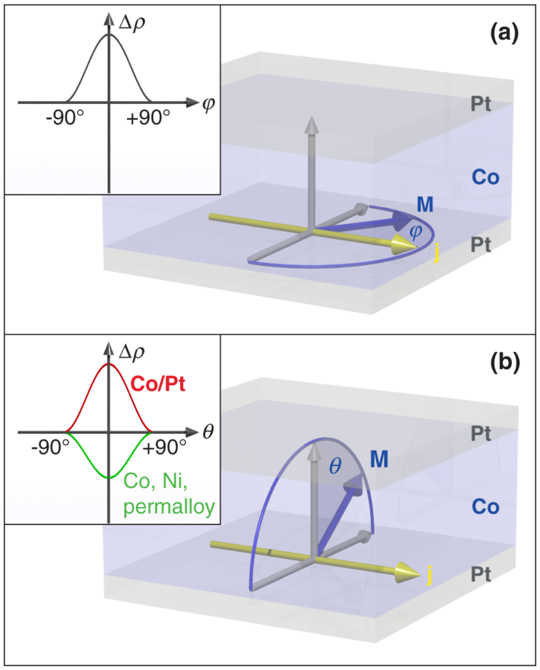

FIG. 1 (color online). (a) Rotating the magnetization $\mathbf{M}$ in the film plane the resistivity is smaller for a magnetization pointing perpendicular to the current $\mathbf{j}$ (transverse geometry) than for $\mathbf{M}$ being parallel to the current (longitudinal geometry). This situation refers to the conventional AMR effect. (b) Rotating $\mathbf{M}$ in a plane perpendicular to the current, it appears that in Co/Pt thin films the resistivity in transverse geometry is smaller than for $\mathbf{M}$ being perpendicular to the film surface (polar geometry). The GSE exhibits the same characteristic but is of opposite sign (see curve for Co, Ni, and permalloy in the inset).

multilayers have distinct geometrical features like texture and alterations of materials in the perpendicular direction, both of which can cause contributions to the MR. In fact, contrary to the respective bulk behavior, in textured films of Co, Ni, and permalloy, the resistivity depends on the direction of magnetization perpendicular to the current. The values for the transverse resistivity ρ_t (**M** oriented in the film plane) differ from the polar resistivity ρ_p (**M** oriented perpendicular to the film plane) [19–21]; see Fig. 1(b). The magnitude of the so-called geometrical size effect (GSE) is in the same range as the AMR, and does not depend on the film thickness: it is caused by texture [21]. Stacking of the Co/Pt layers can yet be another source for geometry induced MR effects as the thickness of the ferromagnetic layers is in the range of the electron mean free path, and, furthermore, Pt is an easy magnetically polarizable material.

We report on a MR effect we discovered in sputter deposited and electron-beam evaporated Co/Pt films in the temperature range from 1.6 to 300 K, for which in contrast to GSE the transverse resistivity ρ_t is smaller than the polar resistivity ρ_p; see the curve for Co/Pt in Fig. 1(b). In this Letter we present the results for the simplest structure of sputter deposited films which consist of one ferromagnetic Co layer sandwiched by Pt layers (for details see [22]), and we restrict ourselves to room temperature investigations. The MR of the films has been studied by sweeping the magnetic field in longitudinal (**M** oriented parallel to the current), transverse, and polar directions and by rotating the samples in a saturation field [24]. To reveal the physical origin of the magnetoresistance anisotropy ($\rho_p > \rho_t$) we varied the Co layer thickness from 0.8 to 50 nm. The results were fitted making use of the Fuchs-Sondheimer approach [25–27]. We will show that the $\rho_p > \rho_t$ effect originates from the Co/Pt interfaces; thus we call the effect anisotropic interface magnetoresistance (AIMR).

In Fig. 2 the magnetoresistance results for a Pt/Co/Pt sample with a Co thickness of $t_{\mathrm{Co}} = 6$ nm are shown. In Fig. 2(a) the two in-plane curves (longitudinal and transverse geometry) are dominated by magnetization reversal via domain wall movements causing the steep resistivity changes at small fields (< 100 mT). For the magnetic hard axis (polar geometry) the curve indicates a coherent rotation of the magnetization, which is completed at about 1.3 T. At large fields, with field aligned magnetization, all three curves exhibit an identical linear decrease which is usually referred to as the spin-disorder MR caused by the suppression of spin waves with increasing field strength [11]. The resistivity difference in saturation for **M** oriented in plane, $\Delta\rho_{\mathrm{ip}} = \rho_{\parallel} - \rho_t$, refers to the conventional AMR effect as for both orientations of the magnetization effects due to texture or interfaces are identical. The resistivity difference in saturation for **M** perpendicular to the current, $\Delta\rho_{\mathrm{op}} = \rho_p - \rho_t$, is nonzero, indicating an additive contribution to the MR similar to GSE. In contradiction to GSE, however, it has a positive sign. For all samples with $t_{\mathrm{Co}} \leq 30$ nm the resistivities exhibit the same behavior, namely, $\rho_{\parallel} > \rho_p > \rho_t$. For the sake of completeness it should be mentioned that in $\Delta\rho_{\mathrm{ip}}$ and $\Delta\rho_{\mathrm{op}}$ contributions arising from the anisotropic nature of the Lorentz MR are negligibly small compared to the MR effects reported in this Letter and are considerably smaller than the error margins of the data (see Fig. 3) [11].

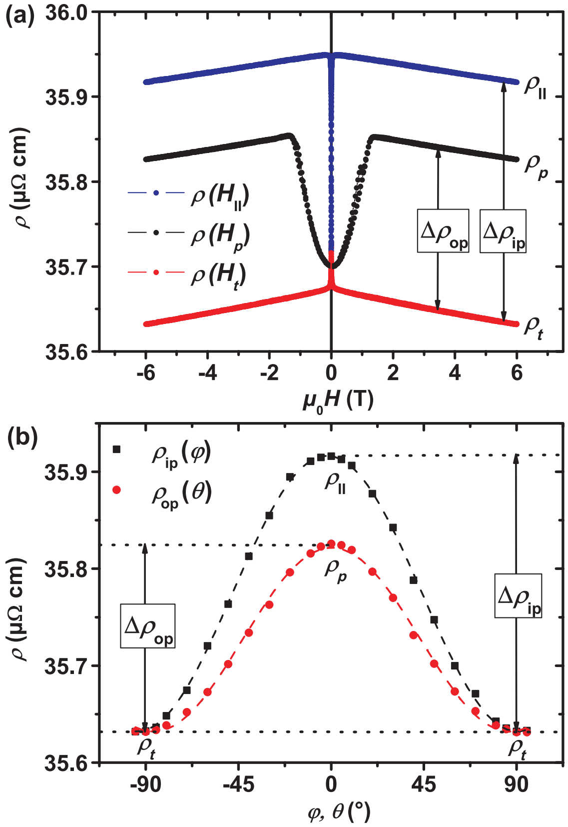

FIG. 2 (color online). (a) Resistivity ρ as a function of the applied field $\mu_0 H$ for the three principle directions of the field with respect to the current direction and film orientation for a $\mathrm{Pt}_{5\ \mathrm{nm}}/\mathrm{Co}_{6\ \mathrm{nm}}/\mathrm{Pt}_{3\ \mathrm{nm}}$ film recorded at room temperature. The differences in resistivities (above technical saturation $M_S \| H$) are labeled as $\Delta\rho_{\mathrm{ip}} = \rho_{\parallel} - \rho_t$ and $\Delta\rho_{\mathrm{op}} = \rho_p - \rho_t$. The slight deviation from the parabolic shape of the polar curve can be related to an unavoidable small misalignment of the magnetic field direction with respect to the normal of the film. (b) Resistivity ρ as a function of the in-plane angle φ, see Fig. 1(a), and of the out-of-plane angle θ, see Fig. 1(b). The field strength is 6 T, causing **M** to be field aligned. The dashed lines represent $\cos^2$ fits.

To investigate the angular dependence of the resistivity with respect to the orientation of the magnetization, the samples were rotated in a field of 6 T. This field strength is sufficient to fully align the magnetization in the field direction; see Fig. 2(a). In Fig. 2(b) the resistivity is displayed as a function of the orientation of the magnetization when **M** is rotated either in plane or perpendicular to the

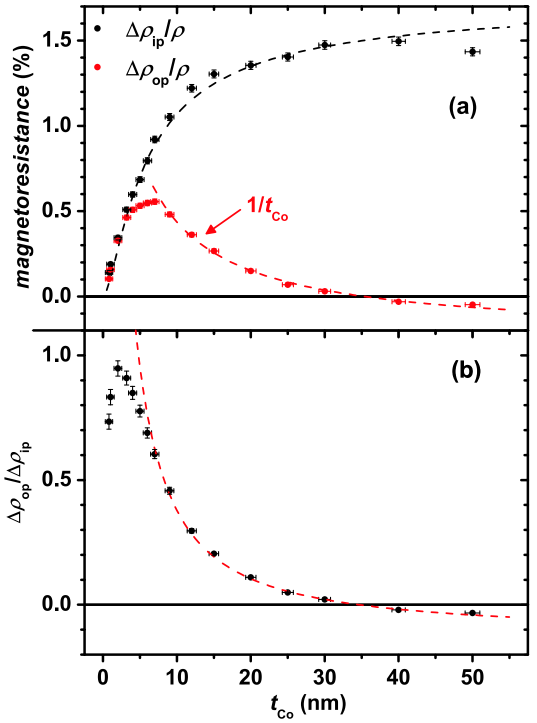

FIG. 3 (color online). (a) Co thickness dependence of $\Delta\rho_{op}/\rho$ and of $\Delta\rho_{ip}/\rho$. The dashed lines represent fits. The behavior of $\Delta\rho_{ip}/\rho$ (AMR) is due to an increase of the current in the Co layer whereas the shunting through the Pt layer decreases. The $1/t_{Co}$ dependence of $\Delta\rho_{op}/\rho$ indicates that the effect originates from the Co/Pt interfaces. At 35 nm the AIMR effect ($\rho_p > \rho_t$) equals the thickness independent GSE ($\rho_t > \rho_p$). (b) Ratio of $\Delta\rho_{op}$ and $\Delta\rho_{ip}$, which corresponds to the ratio of AIMR + GSE and AMR effect, respectively. The curve is fitted utilizing the Fuchs-Sondheimer model for $t_{Co} \geq 7$ nm.

current direction. The functional shape of ρ_{ip} is typical for the AMR; see Eq. (1). If θ denotes the angle between $\mathbf{M}$ and the film normal, then the same kind of angular dependence as in Eq. (1) is found, namely,

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

In Fig. 3(a) $\Delta\rho_{ip}/\rho$ and $\Delta\rho_{op}/\rho$, ρ being the resistivity of the Pt/Co/Pt sandwich, are plotted versus Co thickness t_{Co}. Up to a Co thickness of 15 nm $\Delta\rho_{ip}/\rho$ increases strongly; for $t_{Co} \gg 15$ nm a limiting value of about 1.5% is approached. The apparent increase of the AMR ratio and its subsequent flattening out with increasing Co thickness can be explained quantitatively with the decreasing influence of the Pt shunt on the resistivity ρ: The corresponding dashed line shows the fit of the $\Delta\rho_{ip}/\rho$ data to a simple parallel current model for Co and Pt resistors using the Fuchs-Sondheimer formalism [28]. The fit yields an AMR ratio for the Co layer of $(1.7 \pm 0.1)\%$.

Obviously $\Delta\rho_{op}/\rho$ shows quite a different behavior: for small Co thicknesses ($t_{Co} < 7$ nm) $\Delta\rho_{op}/\rho$ increases continuously and is comparable to the AMR ratio ($\Delta\rho_{ip}/\rho$). For $t_{Co} \geq 7$ nm, however, $\Delta\rho_{op}/\rho$ decreases proportional to $1/t_{Co}$ as indicated by the $1/t_{Co}$ fit (dashed line). This implies that the interior of the Co layer does not contribute to this particular MR effect, which in turn means that it is caused essentially by the Co/Pt interfaces [29]. Therefore, it is appropriate to refer to this effect as anisotropic interface magnetoresistance. To stress the point: The AIMR shows a completely different signature than any other MR effect found in polycrystalline films up to now.

In Fig. 3(b) the ratio of the data of Fig. 3(a) ($\Delta\rho_{op}/\Delta\rho_{ip}$) is displayed versus t_{Co}. The normalization to $\Delta\rho_{ip}/\rho$ removes the more or less arbitrary scaling of $\Delta\rho_{op}/\rho$ with respect to the sandwich resistivity ρ and thereby eliminates the influence of the Pt shunt from data under the prerequisite that the AMR ratio of the Co layer does not depend on thickness. A closer look at $\Delta\rho_{ip}/\rho$ in Fig. 3(a) reveals that for thin Co layers there is a strong relative difference between the experimental data points and the ideal fit, while for $t_{Co} \geq 7$ nm the relative difference is acceptably small ($< 10\%$). This means that only for sufficiently large thicknesses ($t_{Co} \geq 7$ nm) the assumption of a constant AMR ratio of the Co layer is reasonable and $\Delta\rho_{ip}/\rho$ is only suitable to describe the Pt shunt sufficiently well in this thickness regime. As the parasitic shunt of the Pt layers is eliminated in $\Delta\rho_{op}/\Delta\rho_{ip}$ for $t_{Co} \geq 7$ nm, we can deal with the scattering in an effective single Co layer approximation. To quantify the anisotropy of the magnetic scattering at the Co/Pt interface, the Fuchs-Sondheimer formalism is used [28,30]. Fitting the curve in Fig. 3(b) for $t_{Co} \geq 7$ nm, we obtain a change of 0.04 ± 0.01 in the specularity parameter when the magnetization orientation switches from polar to transverse geometry. This implies that the diffusive scattering probability of the electrons at the Co/Pt interfaces [28] varies by 4% when changing the magnetization from in plane to out of plane.

For $t_{Co} > 35$ nm, $\Delta\rho_{op}/\Delta\rho_{ip}$ as well as $\Delta\rho_{op}/\rho$ become negative (see Fig. 3), revealing the existence of another MR contribution, which is of opposite sign compared to the AIMR. This contribution also exhibits a $\cos^2\theta$ dependence, does not depend on the Co thickness, and seems to be typical for the GSE, which can be attributed to the hcp (0001) texture of the Co layer [21,22]. Since we find a GSE which is lower than the value reported previously, this might indicate a more pronounced texture in the studies of Ref. [21].

In conclusion, it was shown that in contrast to the bulk case in thin Co/Pt films, a contribution to the MR arises from the reduced dimensionality in layered systems. The characteristic dependence of the AIMR on $1/t_{Co}$ strongly suggests the presence of an anisotropic magnetic scattering mechanism of electrons at the interface. It is found that when the orientation of the magnetization is perpendicular to the direction of the current the resistivity depends on the orientation of $\mathbf{M}$ to the interface and is largest for the magnetization perpendicular to the film plane. Utilizing the Fuchs-Sondheimer formalism it turns out that the phenomenological specularity parameter is nonvanishing and varies as a function of the orientation of the magnetization. Further investigations are needed to learn about the microscopic mechanism behind the AIMR. It should be pointed out that the interface of the investigated films is not abrupt but mainly determined by a region of interdiffusion, i.e., a gradual transition from Co to Pt (see [22]). In the thickness regime where Co/Pt systems exhibit a perpendicular easy axis of magnetization, the AIMR is in the same order of magnitude as the AMR. This finding is important also in the light of recent efforts to study domain wall resistance in the framework of spintronics.

Financial support via SFB 668 and Landesexzellenzinitiative Hamburg, cooperation with S. Knott and M. Schmidt, and valuable discussions with Y. Mokrousov and S. Hankemeier are gratefully acknowledged.

[1] A. D. Kent, J. Yu, U. Rudiger, and S. S. P. Parkin, J. Phys. Condens. Matter **13**, R461 (2001).
[2] C. H. Marrows, Adv. Phys. **54**, 585 (2005).
[3] A. Yamaguchi, T. Ono, S. Nasu, K. Miyake, K. Mibu, and T. Shinjo, Phys. Rev. Lett. **92**, 077205 (2004).
[4] G. Tatara, H. Kohno, and J. Shibata, Phys. Rep. **468**, 213 (2008).
[5] D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit, and R. P. Cowburn, Science **309**, 1688 (2005).
[6] Peng Xu, Ke Xia, Changzhi Gu, Ling Tang, Haifang Yang, and Junjie Li, Nature Nanotech. **3**, 97 (2008).
[7] S. S. P. Parkin, M. Hayashi, and L. Thomas, Science **320**, 190 (2008).
[8] M. Viret, D. Vignoles, D. Cole, J. M. D. Coey, W. Allen, D. S. Daniel, and J. F. Gregg, Phys. Rev. B **53**, 8464 (1996).
[9] H. G. Roberts, S. Crampin, and S. J. Bending, Phys. Rev. B **76**, 035323 (2007).
[10] D. Elefant and R. Schafer, Phys. Rev. B **82**, 134438 (2010).
[11] T. R. McGuire and R. I. Potter, IEEE Trans. Magn. **11**, 1018 (1975).
[12] M. Klaui, J. Phys. Condens. Matter **20**, 313001 (2008).
[13] S. Hankemeier, A. Kobs, R. Frömter, and H. P. Oepen, Phys. Rev. B **82**, 064414 (2010).
[14] J. F. Gregg, W. Allen, K. Ounadjela, M. Viret, M. Hehn, S. M. Thompson, and J. M. D. Coey, Phys. Rev. Lett. **77**, 1580 (1996).
[15] B. Leven and G. Dumpich, Phys. Rev. B **71**, 064411 (2005).
[16] A. Aziz, S. J. Bending, H. G. Roberts, S. Crampin, P. J. Heard, and C. H. Marrows, Phys. Rev. Lett. **97**, 206602 (2006).
[17] C. Hassel, M. Brands, F. Y. Lo, A. D. Wieck, and G. Dumpich, Phys. Rev. Lett. **97**, 226805 (2006).
[18] K. M. Seemann, M. C. Hickey, V. Baltz, B. J. Hickey, and C. H. Marrows, New J. Phys. **12**, 033033 (2010).
[19] T. T. Chen and V. A. Marsocci, J. Appl. Phys. **43**, 1554 (1972).
[20] T. G. S. M. Rijks, S. K. J. Lenczowski, R. Coehoorn, and W. J. M. deJonge, Phys. Rev. B **56**, 362 (1997).
[21] W. Gil, D. Gorlitz, M. Horisberger, and J. Kotzler, Phys. Rev. B **72**, 134401 (2005).
[22] The polycrystalline Co/Pt films are grown at room temperature at a base pressure of $<2 \times 10^{-9}$ mbar. Via ion beam sputtering utilizing an electron cyclotron resonance source, first a 4 nm thick Pt seed layer is deposited on a 300 nm thick insulating SiO_2 substrate, followed by a 1 nm Pt film grown via dc magnetron sputtering immediately before depositing Co using the same method. The Co is then capped by a 3 nm thick magnetron sputtered Pt layer. At a Co thickness of about 1.1 nm we observe a spin reorientation transition from the perpendicular easy axis of magnetization to the easy plane (see [23]). X-ray diffraction measurements reveal that the films are polycrystalline with a grain size of (10 ± 5) nm. The films are fcc Pt (111)/hcp Co (0001) out-of-plane textured. X-ray reflectometry measurements show that the interfaces are very smooth, the roughness being only about one atomic layer (2 ± 1) Å. The interdiffusion of Co and Pt at the interface is (5 ± 2) Å.
[23] H. Stillrich, C. Menk, R. Frömter, and H. P. Oepen, J. Appl. Phys. **105**, 07C308 (2009).
[24] The current in-plane MR measurements were performed in a four-point probe geometry using fields of up to ± 6 T, with accuracy of $\Delta R/R = 10^{-5}$.
[25] K. Fuchs, Proc. Cambridge Philos. Soc. **34**, 100 (1938).
[26] E. H. Sondheimer, Adv. Phys. **50**, 499 (2001).
[27] X. G. Zhang and W. H. Butler, Phys. Rev. B **51**, 10 085 (1995).
[28] In the Fuchs-Sondheimer model the scattering at the interface or surface is phenomenologically included in the so-called specularity parameter p. The scattering at the interfaces can vary from purely specular ($p = 1$) to purely diffusive ($p = 0$). The thickness dependence of the conductivity is given by Eqs. (16) and (25) in Ref. [26]. The number of fitting parameters is reduced by introducing charge conservation in the free-electron model [see G. Fischer, H. Hoffmann, and J. Vancea, Phys. Rev. B **22**, 6065 (1980)]. Fitting the dependence of the sandwich resistivity ρ on Co thickness (not shown) yields a Co bulk resistivity of $(25 \pm 1)\ \mu\Omega$ cm. With these parameters one obtains the AMR ratio of the Co layer by fitting the data points in Fig. 3(a).
[29] M. A. M. Gijs and G. E. W. Bauer, Adv. Phys. **46**, 285 (1997).
[30] Using Eqs. (16) and (25) of Ref. [26] and the values obtained for the Co bulk resistivity and the AMR ratio of the Co layer by fitting Fig. 3(b), one obtains two different specularity parameters with a difference of 0.04 ± 0.01.