Theoretical study on the electric field effect on magnetism of Pd/Co/Pt thin films

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Based on first principles calculations we investigate the electronic and magnetic properties of Pd layers in Pd(001)/Co/Pt thin film structures exposed to an external electric field. Due to the Co underlayer, the surface Pt layers have induced moments that are modified by an external electric field. The field induced changes can be explained by the modified spin-dependent orbital hybridization that varies non-linearly with the field strength. We calculate the x-ray absorption and the x-ray magnetic circular dichroism spectra for an applied external electric field and examine its impact on the spectra in the Pt layer around the L\textsubscript{2} and L\textsubscript{3} edges. We also determine the layer dependent magneto-crystalline anisotropy and show that the anisotropy can be tuned easily in the different layers by the external electric field.

I. INTRODUCTION

The control of the magnetization of a system by an external electric field, which is known as magneto-electric effect, has been widely investigated during the last years experimentally as well as theoretically, due to its potential application in spintronics \cite{1-3}. The magneto-electric effect was investigated in particular for bulk magnetic compounds with non-collinear magnetic structures \cite{4-6}, magnetic semiconductors \cite{7, 8} and multi-ferroics \cite{9-12}. Within these studies, the modification of the magnetic properties by an external electric field has been associated with various electronic mechanisms, such as the shift of the Fermi level or a change in the charge carrier density.

Recent studies have reported that an external electric field may affect the physical properties of layered systems in a very pronounced way \cite{13, 14}. For example, for thin films of Pd, it was shown that the electric field induces a phase transition from the para- to the ferromagnetic state. This finding could be explained by the Stoner instability caused by the applied electric field that leads to a change in the occupation of the electronic states and shifting that way the Fermi level to a position with a high density of states (DOS). In the case of magnetic systems, an electric field changes their magnetic properties first of all due to its influence on the spin polarization of the valence electrons. Such a manipulation of the magnetic state by the electric field can lead to interesting and important effects concerning possible applications \cite{15-17}. Performing first principles calculations, it was demonstrated, that a well defined change in the magnetic moment can be observed in the case of a ferromagnetic free-standing thin Fe, Ni or Co film, for which the magnetic moments show a linear dependence on the strength of the external electric field \cite{18}. In this case the electron populations in the different spin channels are varied and thus the balance of majority- and minority-spin electrons is distorted leading in turn to a change of the spin magnetic moment in the system. Apart from the spin magnetic moment many other magnetic properties may be controlled by an applied electric field as for example the orbital moment and its anisotropy as well as the magnetic anisotropy energy \cite{18, 20}.

In case of the Co/Pt bilayer system it was demonstrated by means of anomalous Hall effect measurements that the Curie temperature of the Co layer can be controlled by an electric field \cite{21}. For the Curie temperature of the bulk 3d transition metal alloys a Slater-Pauling like behavior was found from first principles calculations \cite{22}. However, experimental results on thin films showed that the Curie temperature is increasing with an increasing number of valence electrons and does not follow the Slater-Pauling like behavior \cite{21}. This finding indicates that in the case of thin films - when compared to the bulk situation - other mechanisms can play an important role for the magnetic properties in the presence of an electric field.

Paramagnetic metals, such as Pt and Pd, that are close to the Stoner instability, have substantial induced moments due to the proximity effect when deposited on magnetic substrate layers. In the case of Pd deposited on the Pt/Co bilayer system, it was demonstrated experimentally and theoretically that the induced magnetic moment of the Pd layer can be controlled by an applied electric field \cite{14}. The inter-relation between the influence of an electric field on the magnetic state and the electronic structure of Pt deposited on a magnetic substrate was investigated in a recent work by exploiting the component-specific x-ray absorption spectroscopy (XAS) together with the x-ray magnetic circular dichroism (XMCD) \cite{13}.

The XMCD is one of the most powerful probe for investigating the magnetization of layered systems in an element resolved way \cite{23}. The XMCD spectra give for a magnetized sample the difference in absorption for left
and right-circularly polarized x-rays. XMCD spectra are often analyzed on the basis of the XMCD sum rules, which link the integrals of the XAS and XMCD spectra to the spin and orbital magnetic moments of the absorbing atom [24–28].

Motivated by a recent experimental XMCD study by Yamada et al. [13], we investigated the electronic and magnetic properties of Pt layers in the surface film system Pd(001)/Co/Pt in the presence of an external electric field by means of first principles calculations. This way, we investigated how the electric field influences the electronic states, magnetic moments, XMCD spectra of the Pt layers and the magnetic anisotropy in the case of the considered systems.

The paper is organized as follows. In Sec. II the computational methods used are briefly sketched while in Sec. III the results are presented and discussed. Finally, in Sec. IV we summarize our results.

II. COMPUTATIONAL DETAILS

All calculations were performed within the framework of density functional theory, relying on the local spin-density approximation (LSDA). For the exchange correlation potential the parametrization of Vosko, Wilk and Nusair was used [29]. The electronic structure is described on the basis of the Dirac equation, accounting for all relativistic effects coherently this way. Electronic states were represented by means of the corresponding Green function calculated using the spin-polarized Körning-Kohn-Rostoker (KKR) Green function formalism as implemented in the SPR-KKR code [30–32]. The potentials were treated on the level of the atomic sphere approximation (ASA) and for the self-consistent calculations an angular momentum cut-off of $l_{\text{max}} = 3$ was used. All necessary energy integrations have been done by sampling 32 points on a semicircle contour in the upper complex energy semi-plane. Furthermore, the k-space integration was done using 750 points in the irreducible part of two dimensional Brillouin zone.

We investigated the Pd(001)/Co$_n$/Pt$_m$ thin film surface system, where $n$ and $m$ denote the number of Co and Pt layers, respectively. The first considered model system consisted of three Pd layers, $n = 2$ or 5 Co layers, $m = 2$ Pt layers and three layers of empty spheres embedded between a semi-infinite Pd substrate and a semi-infinite vacuum region. For the second model system the number of Pt layers was varied with the system consisting of two Pd, $n = 5$ Co layers, $m = 1$, 4 Pt layers and three layers of empty spheres embedded between the semi-infinite Pd and vacuum regions. For Pd, Co, Pt and empty layers ideal epitaxial growth was assumed on a fcc(001) textured substrate with the experimentally in-plane lattice constant of Pd, $a_{\text{Pd}} = 3.89$ Å. Structural relaxations were neglected in all cases.

From the obtained self-consistent potentials the X-ray absorption coefficients $\mu_\lambda(\omega)$ for the photon energy $\hbar \omega$ and polarization $\lambda$ were calculated using the SPR-KKR Green function method on the basis of Fermi’s Golden rule [33]. The corresponding XMCD signal,

$$\Delta \mu(\omega) = \frac{1}{2} \left( \mu_+ (\omega) - \mu_- (\omega) \right),$$  \hspace{1cm} (1)

is defined as the difference in the absorption for left and right circularly polarized radiation. The broadening of the experimental spectra was simulated by a Lorentzian broadening function with a width parameter of 1 eV. In addition to the XMCD spectra, the magnetic anisotropy (MAE) was obtained by means of magnetic torque calculations [34–35].

The effect of a homogeneous external electric field was modeled by a periodic array of point charges in the vacuum region that behave essentially like a charged capacitor plate. In the present calculations the array of point charges or capacitor plate, respectively, was placed in the last vacuum layer. This set-up leads to a homogeneous electric field of strength,

$$E = \frac{Q}{a_0^2 \epsilon_0},$$  \hspace{1cm} (2)

where $Q$ is the charge of the capacitor in unit of the electron’s charge, $\epsilon_0$ is the permittivity of vacuum and $a_0^2$ is the area of the unit cell for the Pd(001) plane. Here, the applied electric field is perpendicular to the surface and for the positively charged condensed plate it points from the vacuum towards the surface increasing this way the spill-out of the electrons from the Pt layers to the vacuum with increasing electric field strength.

III. RESULTS

A. Variation of the thickness of the Co layer

To investigate the impact of an external electric field on the electronic structure of the Pd(001)/Co$_n$/Pt$_m$ system, we focus first on Pd(001)/Co$_2$/Pt$_2$, corresponding essentially to a system composed of 0.5 nm Co and 0.4 nm Pt films, as studied recently in Ref. [13]. These experiments have been accompanied by theoretical work, however, considering in contrast to the present study a (111)-oriented surface. From the self-consistent calculations we obtained the spin magnetic moments of the layers as a function of the electric field. The spin-magnetic moments of the Co layers without an external electric field ($E = 0$) are $m_{\text{Co}_1} = 1.92 \mu_B$ and $m_{\text{Co}_2} = 1.89 \mu_B$ for Pd(001)/Co$_2$/Pt$_2$, where the indices of the Co layers start at the Pd/Co interface.

To see an impact of the thickness of the ferromagnetic film on the spin and orbital polarization of the Pt film, the calculations have been performed also for Pd(001)/Co$_5$/Pt$_2$. In this case, the magnetic moments for four Co layers (for $E = 0$) are very close to each other, $m_{\text{Co}_2} \sim m_{\text{Co}_3} \sim m_{\text{Co}_4} \sim m_{\text{Co}_5} \sim 1.8 \mu_B$, while for the
Co layer at the Pd/Co interface the magnetic moment is the largest one, \( m_{\text{Co}} \sim 1.9 \mu_B \). For both systems the change of the magnetic moment of the Co layers induced by the electric field is negligible.

In the Pt layers induced spin moments are formed due to the proximity effect caused by the Co layer with the value of the induced moment being largest for the Pt layer at the Pt/Co interface. In the presence of the external electric field the magnetic moments in the Pt film are modified. This modification is depending on the thickness of the Co film, as can be seen in Fig. 4 showing the sum of the spin magnetic moments of the Pt layers, \( \sum m_{\text{Pt}} \), as a function of the electric field for both considered systems. Nevertheless, for both systems the magnetic moment decreases with increasing positive electric field in spite of the different number of Co layers. Moreover, in contrast to calculations for free standing ferromagnetic thin films [15], the Pt spin-magnetic moment in the present case does not vary linearly with the field strength.

In order to understand the impact of an external electric field on the electronic structure of the Pt layer we calculated the density of states (DOS) for the systems in the presence of the electric field. Figure 2 shows for various electric field strengths the spin resolved DOS projected on to s, p and d states for the topmost Pt layer in Pd(001)/Co2/Pt2. The applied electric field strengths have the value \( \pm 7 \text{ V/nm} \) denoted as +E and −E in the following. One can see, that the external electric field slightly modifies the electronic states of the Pt layer. A positive electric field shifts the s, p as well as d states of Pt down, while a negative field shifts the states up in energy. Moreover, one can see that these shifts increase with the energy of the electronic states as they are more affected by the electric field due to their weaker localization. Due to the difference of the DOS for the two spin channels, these shifts lead to a change of the magnetic moments, which depend on the sign of the electric field. It should be noted that in contrast to the work on a free standing film in Ref. [13] the Fermi level is fixed in our case as we deal with a half-infinite substrate. Accordingly, the value of the Fermi energy is that of the Pd substrate for all applied electric fields. Another effect of the electric field seen in Fig. 2 is the change of the amplitude of the DOS due to the change of hybridization of the electronic states of Pt and Co layers, or as it was pointed out in Ref. [13] the hybridization of the sp-states and the d-states of Pt. As the hybridization is spin dependent, this also results in a change of the magnetic moments induced by the electric field.

As discussed in the literature [13], the above-mentioned field-induced changes of the electronic structure and magnetic properties can be probed in a detailed way using XAS/XMCD spectroscopy. Focusing here on the magnetic properties of the Pt layers, the absorption spectra at the Pt L2 and L3 edges have been calculated both for Pd(001)/Co2/Pt2 and Pd(001)/Co5/Pt2. The XAS and XMCD spectra without the influence of an external electric field are given in Fig. 3 showing only tiny differences between the two systems.

The modification of the XAS spectra for these systems by the electric field \( \pm E \), are represented in Fig. 4 showing the field-induced changes, \( \mu(\pm E) - \mu(0) \), of the total XAS and of XMCD signals, \( \Delta \mu(\pm E) - \Delta \mu(0) \) for the Pt layers in Pd(001)/Co2/Pt2 and Pd(001)/Co2/Pt4. Although only tiny differences are found for both systems, one can see that the changes are more pronounced at the L3 edge in both cases. This finding is in line with the previously reported experimental results [13] and can be explained as follows. As an electric field will in particu-
lar shift electronic states below or above the Fermi level, pronounced field induced changes have to be expected first of all at the absorption edges of the spectra. As the Pt d-states in that energy region have primarily $d_{5/2}$-character and as the $L_3$ and $L_2$ spectra are dominated by their $d_{5/2}$- and $d_{3/2}$-contributions, respectively, it follows that an electric field has a much stronger impact for the $L_3$ than for the $L_2$ spectrum.

The modifications of XAS and XMCD spectra depend directly on the direction of the electric field as this determines the direction of the field-induced shift of the electronic states with respect to the Fermi energy. Due to the screening of the electric field with increasing distance from the surface, the field-induced changes of the XAS and XMCD signals are most pronounced for the surface Pt layer and decrease towards the interface. This behavior can be seen clearly in Fig. 4 showing the layer resolved results for Pd(001)/Co$_2$/Pt$_2$. The same trend is found also for Pd(001)/Co$_5$/Pt$_2$.

### B. Variation of the thickness of the Pt layer

In order to investigate how the electric field effect changes with an increasing thickness of the Pt film, calculations have been performed for the Pd(001)/Co$_5$/Pt$_m$ system, where the thickness of the capping Pt layer was varied between $m = 1$ and $m = 4$. The top panel of Fig. 5 shows the calculated spin moments of the individual layers in Pd(001)/Co$_5$/Pt$_1$ (a) and Pd(001)/Co$_5$/Pt$_4$ for various electric fields. In the case of Pd(001)/Co$_5$/Pt$_1$ the Pt spin moment is $m_{Pt_1} = 0.22 \mu_B$. For Pd(001)/Co$_5$/Pt$_4$ the induced moment of the Pt layers significantly decreases away from the Co interface while the Pt layer at the Co interface possesses the largest induced moment with $m_{Pt_4} = 0.18 \mu_B$ coupled ferromagnetically to that of Co. The spin magnetic moment of the next Pt layer is $m_{Pt_2} = 0.06 \mu_B$ and is also ferromagnetically aligned to the Co moments. The remaining very small magnetic moments for the third and fourth Pt layers are antiferromagnetically oriented with respect to the Co layers.

The Pt spin-magnetic moment in Pd(001)/Co$_5$/Pt$_1$ increases in case of a positive electric field ($+E$) while it decreases for $-E$ with the value $0.23 \mu_B$ and $0.21 \mu_B$, respectively. This dependency on the electric field is opposite to that of Pd(001)/Co$_n$/Pt$_2$ shown in Fig. 1 and can be attributed to the screening of the electric field that gets more important for an increasing thickness of the Pt film. In particular, one can see rather strong field-induced changes of the spin magnetic moments of the interface and next-to-interface Co layers in Pd(001)/Co$_5$/Pt$_1$. In this case the spin moment of the Pt layer follows the changes of the spin moment of Co at the Co/Pt interface. Obviously, the impact of the electric field on the Co spin moment significantly de-
FIG. 5. Top panel: Calculated layer resolved magnetic spin moments of the individual atomic layers in Pd(001)/Co5/Pt1 (a) and Pd(001)/Co5/Pt4 without electric field and in the presence of a positive and negative electric field. Bottom panel: Calculated difference for the minority and majority density of states of the interface Co layer between positive and negative electric field for different thicknesses of the capping Pt layer.

While the field induced changes of the spin polarization (i.e. $m_{\text{spin}}(\varepsilon) = n^+(-\varepsilon) - n^-(-\varepsilon)$ and $m_{\text{spin}}(\varepsilon) = n^+(-\varepsilon) - n^-(-\varepsilon)$), the XAS and XMCD spectra at the L3- and L2-edges of Pt in Pd(001)/Co5/Pt$_n$ with $n = 1$ and 4 and its dependence on the thickness $n$ of the Pt film. First, we consider in Fig. 7 (top panel) the layer resolved XAS spectra calculated without including an external electric field. One can see a weak dependence of the XAS spectra on the position of Pt layer in the Pd(001)/Co5/Pt$_4$...
system. However, the XMCD spectra shown in Fig. 7 (bottom panel), exhibit a rather pronounced decrease, when going from the interface (Pt₁) to the surface (Pt₄) layer. Note that the XMCD signal of the surface Pt layer even changes sign in line with the sign change for the induced spin moment in this layer (see discussion above). The strongest XMCD signal occurs for the interface Pt layer reflecting the largest induced spin moment due to proximity to the ferromagnetically ordered Co layers.

The changes of the XAS and XMCD spectra of Pt in Pd(001)/Co₅/Pt₁ and Pd(001)/Co₅/Pt₄ that are caused by the applied electric field are presented in Figs. 8 (a) and (b), respectively. Similar to the systems with 2 ML of Pt, one finds that the change of the spectra reverses its sign if the orientation of the electric field is reversed. In addition, one can see the asymmetry of these modifications with respect to a change in the orientation of the electric field. The most pronounced changes occur for the Pt L₃ edge signal, similar to the results obtained for Pd(001)/Co₂/Pt₂. The intensities of the layer-resolved changes of the XAS spectra for Pt in Pd(001)/Co₅/Pt₄ gradually decrease when going from the Pt surface to the interface layer. As discussed above, this can be attributed to the screening of the electric field in the surface region. However, the XMCD spectra change non-monotonously towards the interface layer as a consequence of a competition of the decreasing electric field strength and the increasing impact of the neighboring Co layers controlling the Pt spin magnetic moment via the proximity effect.

In addition to the impact of an electric field on the XMCD spectra, its influence on the layer resolved MAE was investigated. Figure 9 shows the layer resolved MAE of Pd(001)/Co₅/Pt₁ and Pd(001)/Co₅/Pt₄, respectively, for no electric field present as well as for an applied electric field with positive and negative sign, respectively.

The definition for the MAE used implies an out-of-plane and in-plane anisotropy for a positive or negative, respectively, sign of the MAE.

In an earlier study [19] it was already found that an electric field may strongly affect the magneto-crystalline anisotropy of free-standing transition metal mono-layers, as a result of the distortion of the electronic structure by the applied electric field. The authors point out that in these systems the electric field breaks the z-reflection symmetry, lifting that way a degeneration in the cross-points of the energy bands via the field-induced hybridization between the d and p orbitals that contribute to these states.

As Fig. 9 illustrates, an electric field also strongly modifies the MAE for the systems considered here despite the lack of z-reflection symmetry for the field-free case. As a reference, the figure also shows the total and layer resolved MAE for Pd(001)/Co₅/Pt₁ and Pd(001)/Co₅/Pt₄ for zero-field conditions. As one can see, Pd(001)/Co₅/Pt₁ has a total MAE corresponding to an in-plane anisotropy with dominating contributions from the Co layers in the middle of the Co film, while the positive contribution from the interface Co/Pt layer
is rather small. Pd(001)/Co5/Pt4, on the other hand, has out-of-plane anisotropy with its MAE dominated by the contribution from the Co layer at the Co/Pt interface. It should be noted that a strong dependence of the MAE on the thickness of the over layer was discussed already previously for several systems [30-37]. Figures 10 and 11 illustrate the contributions to the MAE from the interface Co and Pt layers, represented as a function of occupation of energy bands in case of Pd(001)/Co5/Pt1 system. Bottom panel: Field-induced changes of the contribution to the magnetic anisotropy energy from the Co5 layer, MAE(±E)- MAE(0).

FIG. 9. Calculated layer-resolved magnetic anisotropy energy (MAE) of Pd(001)/Co5/Pt1 (top panel) and Pd(001)/Co5/Pt4 (bottom panel) for no electric field present as well as for an applied electric field with positive and negative sign, respectively. The results have been obtained from fully relativistic calculations (SOC ≠ 0) and calculations with the strength of the spin-orbit coupling in the Pt layers set to zero (SOC = 0).

FIG. 10. Top panel: Contribution to the magnetic anisotropy energy from the Co5 and Pt layers (without SOC scaling and with SOC = 0 in the Pt layers), represented as a function of occupation of energy bands in case of Pd(001)/Co5/Pt1 system. Bottom panel: Field-induced changes of the contribution to the magnetic anisotropy energy from the Co5 layer, MAE(±E)- MAE(0).

FIG. 11. Top panel: Contribution to the magnetic anisotropy energy from the Co5 and Pt layers (without SOC scaling and with SOC = 0 in the Pt layers), represented as a function of occupation of energy bands in case of Pd(001)/Co5/Pt4 system. Bottom panel: Field-induced changes of the contribution to the magnetic anisotropy energy from the Co5 layer, MAE(±E)- MAE(0).
substrate is common to both systems considered, the difference in the MAE has to be attributed to the details of the electronic structure of these systems associated with a different thickness of the Pt surface film. As a result, switching the SOC on the Pt atoms artificially off leads for the Pt film to a strong weakening of the dependence of its electronic structure on the magnetization direction and in turn of the MAE. This is seen in Figs. 10 and 11, respectively, indicating that the contribution of the Co interface layer to MAE drops down by about one order of magnitude when the SOC is switched off for Pt. For this situation, the layer resolved MAE for both systems is rather similar (see Fig. 9). The difference between the results for the two systems can be attributed to some extent to a different hybridization of the Co and Pt related electronic states, which is obviously dependent on the thickness of the Pt film. Based on these results, one can expect that the field induced changes to the MAE should be associated first of all to the influence of the electric field on the Pt related electronic states.

Analysing the field-induced changes of the total and layer resolved MAE of Pd(001)/Co$_5$/Pt$_1$ and Pd(001)/Co$_5$/Pt$_4$, the most pronounced changes are found at the interface, although the changes for the other layers are not negligible. Despite the pronounced screening effect in case of Pd(001)/Co$_5$/Pt$_4$ with 4 MLs of Pt, the field-induced change of the Co interface contribution to the MAE is significant, indicating a key role of the electronic structure changes occurring in the Pt film due to the electric field. The field induced changes of the MAE in the systems with 1 and 4 Pt monolayers are associated primarily with the Co/Pt interface contribution. Corresponding results for the interface layers are plotted in Figs. 10 and 11 respectively, as a function of the occupation. From these figures one can see that for most of the occupation numbers the MAE changes have opposite sign for the opposite orientation when the electric field is reversed. The origin of these changes of the MAE can be attributed first of all to the modification of the electronic structure of the Pt film, i.e. the electric field controlled hybridization of the $d$ and $p$ orbitals, as discussed in Ref. 19.

IV. CONCLUSIONS

In conclusion, in this work we examined the influence of an electric field effect on the magnetic properties in the Pt layer of Pd(001)/Co$_n$/Pt$_m$ thin film structures by performing first-principles calculations. For this purpose, a homogeneous external electric field was modeled by a charged plate in front of the surface. From the self-consistent calculations, we determined the spin magnetic moment and XMCD spectra in the presence of an electric field. We found that in case of Pd(001)/Co$_2$/Pt$_2$ and Pd(001)/Co$_5$/Pt$_2$ that the spin-magnetic moments are varying independently from the number of Co layers roughly quadratically as a function of the electric field strength. An inspection of the angular momentum resolved DOS reveals that the electric field slightly shifts the $s$ and $p$ states around the Fermi level. From the calculated XMCD spectra, it was found that the electric field has its major impact for the L$_3$ edge spectra. We also investigated dependency of the electric field effect on the thicknesses of the Pt layer. In case of Pd(001)/Co$_5$/Pt$_1$ as well as Pd(001)/Co$_5$/Pt$_4$, the electric field induced change of the XMCD spectra is most significant for the L$_3$ edge, independent on the thickness of the Pt capping layer. In addition, the layer dependent MAE and its dependency on an electric field was examined. It was found that the electric field strongly modifies the MAE. It turned out in particular that this change is still considerable for deeper lying layers.

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[1] G. A. Prinz, Science 282, 1660 (1998)
[2] O. O. Brovko, P. Ruiz-Díaz, T. R. Dasa, and V. S. Stepnyuk, Journal of Physics: Condensed Matter 26, 093001 (2014)
[3] H. Zhang, M. Richter, K. Koepernik, I. Opahle, F. Tasnádi, and H. Eschrig, New Journal of Physics 11, 043007 (2009)
[4] I. Dzyaloshinsky, J. Phys. Chem. Solids 4, 241 (1958).
[5] T. Moriya, Phys. Rev. Lett. 4, 228 (1960).
[6] H. Katsura, N. Nagaosa, and A. V. Balatsky, Phys. Rev. Lett. 95, 057205 (2005)
[7] D. Chiba, M. Sawicki, Y. Nishitani, Y. Nakatani, F. Matsukura, and H. Ohno, Nature 455, 515 (2008)
[8] Y. Yamada, K. Ueno, T. Fukushima, H. T. Yuan, H. Shimotani, Y. Iwasa, L. Gu, S. Tsukimoto, Y. Ikuhara, and M. Kawasaki, Science 332, 1065 (2011)
[9] T. Lottermoser, T. Lónkai, U. Amann, D. Hohlwein, J. Ihringer, and M. Fiebig, Nature 430, 541 (2004)
[10] A. J. Hearmon, F. Fabrizi, L. C. Chapon, R. D. Johnson, D. Prabhakaran, S. V. Streltsov, P. J. Brown, and P. G. Radaelli, Phys. Rev. Lett. 108, 237201 (2012)
[11] D. Lebeugle, A. Mougin, M. Viret, D. Colson, and L. Ranno, Phys. Rev. Lett. 103, 257601 (2009)
[12] P. Babkevich, A. Poole, R. D. Johnson, B. Roessli, D. Prabhakaran, and A. T. Boothroyd, Phys. Rev. B 85, 134428 (2012)
[13] K. T. Yamada, M. Suzuki, A.-M. Pradipto, T. Koyama, S. Kim, K.-J. Kim, S. Ono, T. Taniguchi, H. Mizuno, F. Ando, K. Oda, H. Kakizaki, T. Moriyama, K. Nakamura, D. Chiba, and T. Ono, Phys. Rev. Lett. 120,
[14] A. Obinata, Y. Hibino, D. Hayakawa, T. Koyama, K. Miwa, S. Ono, and D. Chiba, Sci. Rep. 5, 14303 (2015).

[15] P.-J. Hsu, A. Kubetzka, A. Finco, N. Romming, K. von Bergmann, and R. Wiesendanger, Nature Nanotechnology 12, 123 (2017).

[16] M. Schott, A. Bernand-Mantel, L. Ranno, S. Pizzini, J. Vogel, H. Béa, C. Baraduc, S. Auffret, G. Gaudin, and D. Givord, Nano Letters 17, 3006 (2017).

[17] H. Yang, O. Bouille, V. Cros, A. Fert, and M. Chshiev, Scientific Reports 8, 12356 (2018).

[18] C.-G. Duan, J. P. Velev, R. F. Sabirianov, Z. Zhu, J. Chu, S. S. Jaswal, and E. Y. Tsymbal, Phys. Rev. Lett. 101, 137201 (2008).

[19] K. Nakamura, R. Shimabukuro, Y. Fujiiwara, T. Akiyama, T. Ito, and A. J. Freeman, Phys. Rev. Lett. 102, 187201 (2009).

[20] D. Chiba, Y. Nakatani, F. Matsukura, and H. Ohno, Appl. Phys. Lett. 96, 192506 (2010).

[21] D. Chiba, S. Fukami, K. Shimamura, N. Ishiwata, K. Kobayashi, and T. Ono, Nat. Mat. 10, 853 (2011).

[22] C. Takahashi, M. Ogura, and H. Akai, Journal of Physics: Condensed Matter 19, 365233 (2007).

[23] J. Okabayashi, Y. Miura, and H. Munelata, Scientific Reports 8, 8303 (2018).

[24] B. T. Thole, P. Carra, F. Sette, and G. van der Laan, Phys. Rev. Lett. 68, 1943 (1992).

[25] P. Carra, B. T. Thole, M. Altarelli, and X. Wang, Phys. Rev. Lett. 70, 694 (1993).

[26] M. Altarelli, Phys. Rev. B 47, 597 (1993).

[27] A. Ankudinov and J. J. Rehr, Phys. Rev. B 51, 1282 (1995).

[28] C. Ederer, M. Komelj, M. Fähnle, and G. Schütz, Phys. Rev. B 66, 094413 (2002).

[29] S. H. Vosko, L. Wilk, and M. Nusair, Can. J. Phys. 58, 1200 (1980).

[30] H. Ebert, D. Ködderitzsch, and J. Minár, Rep. Prog. Phys. 74, 096501 (2011).

[31] H. Ebert and R. Zeller, The SPR-TB-KKR package, http://olymp.cup.uni-muenchen.de (2006).

[32] R. Zeller, P. H. Dederichs, B. Ujfalussy, L. Szunyogh, and P. Weinberger, Phys. Rev. B 52, 8807 (1995).

[33] H. Ebert, Rep. Prog. Phys. 59, 1665 (1996).

[34] J. B. Staunton, L. Szunyogh, A. Buruzs, B. L. Gyorfy, S. Ostanin, and L. Udvardi, Phys. Rev. B 74, 144411 (2006).

[35] S. Bornemann, J. Minár, J. B. Staunton, J. Honolka, A. Enders, K. Kern, and H. Ebert, The European Physical Journal D 45, 529 (2007).

[36] P. Beauvillain, A. Bounouh, C. Chappert, R. Mgy, S. OuldMahfoud, J. P. Renard, P. Veillet, D. Weller, and J. Corno, Journal of Applied Physics 76, 6078 (1994).

[37] B. Ujfalussy, L. Szunyogh, P. Bruno, and P. Weinberger, Phys. Rev. Lett. 77, 1805 (1996).

[38] C. Andersson, B. Sanyal, O. Eriksson, L. Nordström, O. Karis, D. Arvanitis, T. Konishi, E. Holub-Krappe, and J. H. Dunn, Phys. Rev. Lett. 99, 177207 (2007).

[39] O. Šipr, J. Minár, S. Mankovsky, and H. Ebert, Phys. Rev. B 78, 144403 (2008).

[40] Okabayashi Jun, Koyama Tomohiro, Suzuki Motohiro, Tsujikawa Masahito, Shirai Masafumi, and Chiba Daichi, Scientific Reports 7, 46132 (2017).