PHYSICAL REVIEW B **77**, 064411 (2008)

Interface effects, magnetic, and magneto-optical properties of Al/Co/V/MgO(100) structures

Y. Huttel,[1,2] C. Clavero,[2] G. van der Laan,[3,4] P. Bencok,[4,5] T. K. Johal,[3] J. S. Claydon,[3,6] G. Armelles,[2] and A. Cebollada[2]
[1]*Instituto de Ciencia de Materiales de Madrid, Consejo Superior de Investigaciones Científicas (CSIC) C/Sor Juana Inés de la Cruz, 3 28049 Madrid, Spain*
[2]*Instituto de Microelectrónica de Madrid-IMM (CNM-CSIC), Isaac Newton 8 (PTM), 28760 Tres Cantos, Madrid, Spain*
[3]*Magnetic Spectroscopy Group, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom*
[4]*Diamond Light Source Ltd, Chilton, Didcot, Oxfordshire OX11 0DE, United Kingdom*
[5]*European Synchrotron Radiation Facility, 6 rue Jules Horowitz, BP 220, F-38043 Grenoble Cedex, France*
[6]*Department of Electronics, The University of York, Heslington, York YO10 5DD, United Kingdom*

(Received 7 September 2007; published 11 February 2008)

The magnetic and magneto-optical properties of Al/Co/V/MgO(100) structures and the influence of the Co/V interface for different thicknesses of the Co and V layers have been studied experimentally. From the element-specific hysteresis loops obtained by x-ray magnetic circular dichroism (XMCD) at the Co and V L_3 edges we find that the V layers are magnetically polarized antiparallel to the Co layers and that magnetization reversal occurs at the same magnetic field in both layers. The effect of the V atomic volume and the relative thicknesses of V and Co layers on the magnetic moments of the V and Co atoms are also studied. Contrary to what might be expected, the atomic magnetic moments of the V and Co atoms do not depend on the V atomic volume, however they depend strongly on the thicknesses of the V and Co layers. From the trend in the Co and V atomic magnetic moments as a function of Co and V thicknesses and the absence of any spectroscopic evidence for the formation of a VCo alloy, a long-range spin polarization of the V atoms is proposed. The extracted magneto-optical (MO) constants of V and Co as a function of photon energy clearly evidence a large amount of polarization in the V films in agreement with the XMCD results, which is indicative of the magnetic coupling between Co and V. The experimental MO results and simulations also show the strong influence of these polarized V layers in the MO properties of the complete system. These results, given the absence of spectroscopic evidence for the formation of a VCo alloy, support a long-range magnetization of the V atoms and a reduction of the Co atomic magnetic moments.

DOI: 10.1103/PhysRevB.77.064411

PACS number(s): 75.70.−i, 78.70.Dm

I. INTRODUCTION

Magnetic interactions at interfaces between nonmagnetic and magnetic elements and—in some cases—magnetic polarization of nonmagnetic elements at these interfaces are challenging topics in materials science. The understanding of magnetic phenomena in such systems is an important issue for fundamental science as well as for potential applications such as magneto-optical (MO) high-density data storage devices and sensors. Recent *ab initio* density-functional calculation results from Carrillo-Cázares *et al.*[1] have clearly illustrated the complexity of the interaction between 3*d* transition-metal adatoms (Ni, Fe, Mn, Sc, Ti, V, and Cr) deposited on a Co(001) surface and the substrate Co atoms. In particular, these authors have shown that the magnetic behavior of the adatoms do not only depend on their specific nature but also on the coverage, especially in the submonolayer regime. Among the 3*d* transition-metal–Co interfaces, the V/Co interface has attracted particular interest in recent years. This interest is partly driven by the fact that V is paramagnetic in its bulk body centered cubic (bcc) form, but could become ferromagnetic in low-dimensional systems or in contact with ferromagnetic materials.

Although it is quite well accepted that the magnetic properties of V in alloys and low-dimensional systems, such as surfaces and clusters, do strongly depend on the local geometry (i.e., coordination number, site symmetry, and neighbor distance) and resulting electronic structure,[2–6] the experimental results still display a plethora of magnetic behavior. For example, V on surfaces has been predicted to be without net spin,[2] ferromagnetic,[7] antiferromagnetic,[8–10] and paramagnetic,[11] whereas experimental results evidence ferromagnetic,[12] antiferromagnetic,[13,14] and nonferromagnetic[15,16] behavior. On the other hand, results for the magnetic properties of small V clusters[2–5,13] are also contradictory and very little is known about the magnetic properties of V compounds and alloys.[17,18]

While the V/Fe system has been extensively studied,[19–27] less is known and understood about other systems,[17,18,28–32] in particular the V/Co system. This also holds for V/Co multilayers, for which the existence of an antiferromagnetic coupling with V thickness (i.e., the spacing between adjacent Co layers) of 9 Å,[33] but also an interlayer ferromagnetic coupling independent of the V thickness[34] was reported. In these systems, a coupling strongly dependent on the atomic structure of the layers and on the sharpness of the V/Co interfaces was also reported.[35] Furthermore, the superconducting properties of these systems and in particular the transition temperature of V/Co multilayers was found to oscillate with Co thickness.[36] Such results clearly demonstrate the importance of the V/Co interface and the V and Co layer thicknesses for phenomena such as oscillatory magnetic coupling, giant magnetoresistance, and superconductivity in systems made of thin V and Co layers. Despite the important role of the V/Co interface in the physical properties of V/Co multilayers, only a few studies exist in the literature relating to the role of the V/Co interface in the properties of V/Co multilayered structures. Recently, we reported the magnetic properties of V/Co and Co/V interfaces grown on Cu(100) surfaces and for very low V and Co coverages.[37] In particular, we showed that Co atoms induce a strong magnetic moment on the V atoms with opposite magnetization direction. The trends in the magnetic moments vs Co and V thicknesses showed that the Co magnetic moments decrease with decreasing Co and increasing V coverages. On the other hand, the V magnetic moment was found to increase with increasing Co coverage and to decrease with increasing V coverage. The experimental results have been partially reproduced by recent theoretical approaches developed by Carrillo-Cázares *et al.*[1,38–40] and Jisang Hong.[41–43] All these theoretical results confirmed a strong polarization of the V atoms in contact with Co and the antiparallel alignment of the magnetization in V and Co layers. Carrillo-Cázares *et al.*[1,38–40] have performed a number of theoretical calculations in order to simulate the V/Co and Co/V interfaces and VCo alloys and to extract the atomic magnetic moments of Co and V atoms in these systems. They found that the highest magnetic polarization of the V atoms is achieved in a VCo alloy in which the averaged V and Co magnetic moments[44] are $-1.82\mu_B$ and $1.56\mu_B$, respectively (in the first four Co layers in contact with the VCo alloy).[40] They also performed calculations for n monolayer (ML) Co/VCo alloy/V/Cu(001) systems (n $=1$, 2, 3, and 4) in order to simulate the formation of VCo alloy at the Co/V interface[40] and found magnetic moments (averaged over the slabs[44]) of $-0.2\mu_B$ and $1.48\mu_B$ for V and Co, respectively, in 4 ML Co/VCo alloy/V/Cu(001). Jisang Hong[41–43] found a strong decrease of the Co magnetic moment upon adsorption of V atoms on the Co(100) face centered cubic (fcc) surface. The highest magnetic moment of the V atoms ($-1.94\mu_B$) was obtained for 0.5 ML V coverage, while for a surface alloy a magnetic moment of the V atoms of ($-1.19\mu_B$) was deduced. The corresponding averaged Co atomic magnetic moments were respectively $1.48\mu_B$ (in the two Co layers in contact with the 0.5 ML V) and $1.38\mu_B$ (including the alloy and the two layers below the alloy layer). The same author predicted the existence of perpendicular magnetic anisotropy for 0.5 ML V adsorbed on Co(100) and also the vanishing atomic V moment for V coverages $\geqslant 1$ ML. It should be noted that both groups found a rapid decrease of the V atomic magnetic moment upon increasing V thickness in all the considered structures.

In this paper we present a combined x-ray magnetic circular dichroism (XMCD) and MO spectroscopic Kerr study on 30 Å Al/n Å Co/m Å V/MgO(100) structures, where $n=10$, 20, 40, 50, and 200 and $m=10$, 20, 40, and 80. The use of these two complementary dichroism techniques allows exploring in detail the electronic structure and magnetism of the fabricated structures. While XMCD is more sensitive to the atomic element environment due to the nature of the atom-specific electronic transitions probed, MO Kerr spectroscopy probes electronic states that are more delocalized, yielding complementary information. Detailed crystallographic and electronic structure studies of V deposited on MgO(100) have been reported elsewhere,[45–47] as well as the crystallographic structure study of Co deposited on V/MgO(100) substrates.[48]

From the element-specific hysteresis loops monitored by XMCD we obtain direct evidence of the antiparallel magnetization of the V and Co layers in the systems studied. We also show that the magnetic field at which magnetization reversal occurs coincides for both V and Co layers. Evidence of in-plane magnetization is also given together with results for the trend in the V and Co atomic magnetic moments as a function of Co and V thicknesses and V atomic volume. In the systems investigated here, the V layers have bcc structure and the Co layers have hexagonal close packed (hcp) structure. The results are tentatively compared with those obtained by recent theoretical calculations on similar systems, even though in the so-far published calculations, the Co in contact with V has an fcc structure. In particular, the possible formation of a VCo alloy is discussed in the light of the XMCD, Kerr, and x-ray absorption spectroscopy (XAS) experimental results.

II. EXPERIMENTAL DETAILS

All samples were grown in an ultrahigh vacuum system using both triode sputtering and laser ablation facilities. Series of samples with the same structure, i.e., 30 Å Al/n Å Co/m Å V/MgO(100), were grown. Prior to V deposition, a 10 nm MgO buffer layer was grown by laser ablation at 450 °C on the substrate to planarize the surface. The thin V films were deposited at different temperatures [from room temperature (RT) to 500 °C] and the Co films were deposited at RT, both using triode sputtering. Subsequently, a 30 Å thick Al capping layer was deposited at RT to protect the samples against oxidation. Effectiveness of the Al capping layer was checked by polar Kerr spectroscopy with reproducible measurements performed at a 2 years interval, which confirmed the stability of the structures. Two series of samples were grown: in the first series all V thin layers were grown at RT, while for the second series the thin V layers with fixed thickness of 40 Å were deposited at different temperatures with the purpose to obtain different V atomic volumes.[45,47] In all cases, V grows in bcc structure, while Co grows in hcp structure, forming two domains rotated by 90°. The c axis of the hcp domains are located in the plane of the deposited thin layers. A detailed description about the structural characterization of these samples can be found elsewhere.[48]

XMCD characterization of the magnetic structures was performed by measuring the XAS signal in total electron-yield (TEY) mode on beamline ID08 of the European Synchrotron Radiation Facility (ESRF) at Grenoble, France. The applied magnetic field (up to 7 T) was parallel to the incident x-ray beam and its direction was reversed between successive photon-energy scans. Also, the circular polarization of the incident light was reversed in order to correct for possible changes in the XAS signal due to the optical elements in the beamline or the influence of the magnetic field on the TEY. The degree of circular polarization was $99.9\pm0.1\%$ and the absence of any contaminants was verified using XAS.

To obtain element-specific hysteresis loops the XMCD signal was measured by scanning the magnetic field and recording the intensity difference between the Co or V L_3 edge

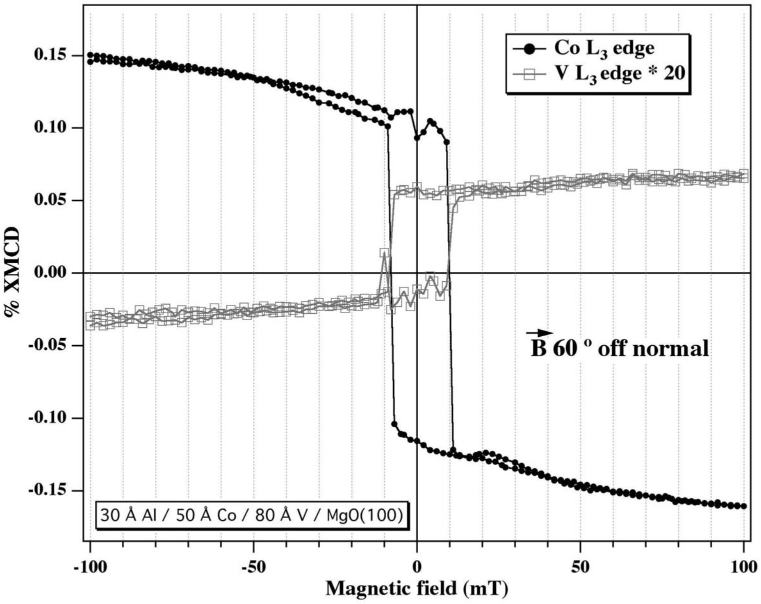

FIG. 1. Representative XMCD element-specific hysteresis loops measured at the Co L_3 and V L_3 edges of the 30 Å Al/50 Å Co/80 Å V/MgO(100) structure. The loops have been measured with the magnetic field at 60° from the surface normal.

and a background reference intensity measured a few eV below the L_3 absorption edge. The measurements were performed by both reversing the light helicity and the magnetic field direction. By cross-checking the obtained scans the artificial magnetic background in the dichroic spectra could be suppressed (or at least strongly diminished) as explained elsewhere.[49,50] No additional manipulation of the experimental data was performed.

The MO properties were studied using a polar Kerr MO spectrometer, similar to the one described elsewhere.[51] For the polar configuration, a magnetic field high enough to magnetically saturate the sample is applied in the direction perpendicular to the surface. The interaction between the light and magnetic material results in elliptically polarized reflected light, with ellipticity ε_k and rotation of the polarization plane by an angle θ_k. Polar Kerr loops were measured by recording the Kerr rotation angle using normal-incident light with a wavelength of 530 nm. Magnetic saturation was achieved in all cases. The rotation and ellipticity polar Kerr spectra obtained in the spectral range from 1.4 to 4.3 eV were analyzed using theoretical tools, such as the transfer-matrix formalism[52,53] with the thin film approximation,[54] which are able to describe the optical and MO response of systems consisting of a number of continuous layers stacked along the growth direction.

III. RESULTS AND DISCUSSION

A. X-ray magnetic circular dichroism

XMCD has become an established technique in materials science for the investigation of magnetic properties of thin films and nanostructures. The element selectivity, i.e., the possibility to probe the magnetic properties of a chosen element in a complex material, has transformed XMCD into a powerful and complementary technique for the unraveling of magnetic properties of materials. In many studies, the atomic magnetic moment values (both orbital and spin moments) are extracted from the XMCD spectra using the sum rules.[55,56] In some studies, the element-specific hysteresis loops of the investigated systems have been extracted.[49,50,57–62] The limited number of publications originates from the difficulty of measuring the hysteresis loops, which requires high photon flux combined with high beam stability. The element selectivity of XMCD allows separating the V and Co contributions to the magnetic behavior in our structures. Below we expose the results of such studies, presenting the element-specific hysteresis loops of Co and V, as well as studies of the trend in Co and V atomic magnetic moments as a function of V atomic volume and the V and Co thicknesses. Since recent theoretical results[40,43] have suggested the formation of VCo alloy at the Co/V interface, we also discuss this issue in the light of XAS and XMCD results together with published crystallographic results.[48]

1. Element-specific XMCD hysteresis loops

Figures 1 and 2 display some representative element-specific hysteresis loops of selected samples. In Fig. 1 we show the loops for 30 Å Al/50 Å Co/80 Å V/MgO(100). The hysteresis loop at the V L_3 edge provides an unambiguous proof of the magnetic polarization of V in this structure, where the V layer is much thicker that a few ML. This extends the results previously reported for very thin V layers in contact with Co.[1,37–43] The opposite sign for the XMCD signals of the hysteresis loops for V and Co in Fig. 1 provide direct evidence for the opposite magnetization of the V and Co thin layers, also in agreement with published results.[1,37,40–43] Furthermore, from the loops in Fig. 1 it can be seen that the Co and V magnetizations switch at the same magnetic field, which is close to 10 mT (100 Oe), similar to the value measured by Kerr in the same structures[48] and indicative of the magnetic coupling between both layers. Thus the Co and V layer magnetizations are coupled antiparallel. It further appears from Fig. 1 that the magnetization of both the V and Co layers do not saturate at 100 mT. No

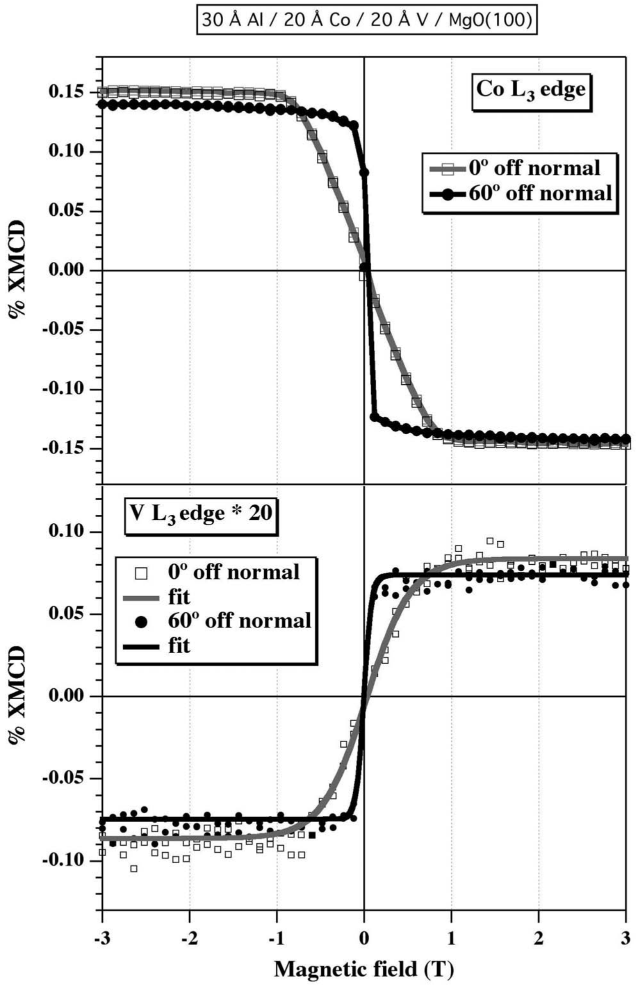

FIG. 2. Representative XMCD element-specific hysteresis loops measured at the Co L_3 (top panel) and V L_3 (bottom panel) edges of the 30 Å Al/20 Å Co/20 Å V/MgO(100) structure. The hysteresis loops have been measured with a magnetic field at 0° and 60° to the surface normal.

remanence could be observed when applying the magnetic field parallel to the surface normal (not shown here), therefore indicating the existence of an easy axis of magnetization in the thin film planes, consistent with Kerr measurements.[48]

Additional information about the magnetization process has been obtained by measuring XMCD hysteresis loops of both V and Co for a wider range of the magnetic field strengths and orientations along different directions. The corresponding hysteresis loops, presented in Fig. 2, clearly show that for a fixed field orientation, both Co and V layers reach the saturation magnetization at the same field strength. For a field oriented parallel to the surface normal (0° off normal) the magnetization is saturated at ~1 T, while for the hysteresis loops measured with a magnetic field oriented at 60° off normal, saturation of the magnetization is reached at much lower fields.

Therefore the element-specific hysteresis loops measured at low and high magnetic fields (Figs. 1 and 2, respectively) clearly show that the V and Co layers are exchange coupled and that the V layer is magnetically polarized antiparallel to the Co thin film. Their behavior under external magnetic field is opposite although both layers display the same coercive field and orientation of the easy axis of magnetization which lies in the plane of the thin films, following the easy axis of magnetization of the hcp Co (the *c* axes of the hcp domains are in the plane of the thin films[48]) in agreement with transverse[48] and polar Kerr measurements (see Sec. III B).

2. Atomic magnetic moments: Effect of V atomic volume

The atomic magnetic moments are expected to be quite dependent on the atomic structure and the corresponding electronic structure that can be altered by tiny changes in the surrounding environment.[40] These expectations have motivated, e.g., the search of magnetic properties of V surface layers and small clusters as discussed in the Introduction. Here we present the study of the trend in the atomic magnetic moments of Co and V in the fabricated structures as a function of the V deposition temperature which is directly correlated to the V atomic volume. A series of samples with the structure 30 Å Al/20 Å Co/40 Å V/MgO(100) were measured with XMCD. In these samples the Al capping layers and Co layers were grown at RT, while the thin V layers were grown at different temperatures, favoring the expansion or compression of the V atomic volume depending on the growth temperature. In fact, we recently showed that the growth temperature of V thin layers is a key parameter that can be used to control the V atomic volume.[45,47] In a 4 nm thick layer deposited on MgO(100), V grows under in-plane compression, having a coherent interface with the MgO, as the 45° in-plane lattice rotation implies an almost perfect match with the MgO lattice. On the other hand, the out-of-plane V lattice parameter for films deposited at RT, 100 °C, and 200 °C appears expanded with the highest value for RT deposition, adopting the bulk value for samples grown at 300, 400, and 500 °C. As a consequence of the evolution of the in- and out-of-plane lattice parameters, the V atomic volume displays a continuous dependence on deposition temperature. In particular, the V atomic volume has a maximum expansion when the deposition is performed at RT (~1.6% compared to the V atomic bulk volume) and it continuously decreases as the deposition temperature increases.[45,47] The maximum compression (~2.8% compared to the V atomic bulk volume) is reached for the 400 °C deposition temperature. Therefore depending on deposition temperature, the V atomic volume can be tuned over nearly a 4.5% range around the V atomic bulk volume, which might modify the atomic Co and V magnetic moments at the Co/V interface. We used this flexibility in the V atomic volume of the 30 Å Al/20 Å Co/40 Å V/MgO(100) system to investigate the effect of the atomic structure on the magnetic properties of the Co/V interface.

The Co atomic magnetic moments were extracted from XAS spectra with opposite alignment of magnetization direction and light helicity vector by using the sum rules.[55,56] The relation between the orbital moment μ_L spin moment μ_S, magnetic dipole term T_z, and number of 3*d* holes n_h (all per atom) in the ground state and the intensities of the difference

$\Delta A_{2,3}$ and sum $A_{2,3}$ spectra integrated over the corresponding $L_{2,3}$ edges is given as[55,56]

$$\frac{\mu_L}{n_h} = -\frac{4}{3}\frac{\Delta A_3 + \Delta A_2}{A_3 + A_2}, \tag{1}$$

$$\frac{\mu_S + 7T_z}{n_h} = -2\frac{\Delta A_3 - 2\Delta A_2}{A_3 + A_2}. \tag{2}$$

Theoretical results[63] indicate that $7T_z/\mu_S < 0.1$, so that neglecting T_z gives an error in μ_S up to 10%. Here, we have extracted the Co magnetic moments by assuming that $T_z=0$ and that the mixing of the $2p_{3/2}$ and $2p_{1/2}$ core levels as well as transitions to the *sp* valence band states can be neglected in the $L_{2,3}$ XMCD spectrum. In very thin Co layers deposited on V, the Co-V hybridization can induce a charge transfer between the two metals and as a consequence, n_h can vary with layer thickness.[37] However, here the thicknesses of the layers allow us to use a standard n_h value, where we have chosen $n_h=2.49$, which is the value of hcp Co.[56,64] For the Co and V layer thicknesses considered here, saturation effects might affect the determination of the atomic magnetic moment values. Saturation effects are difficult to calculate in multilayered structures such as those studied here. In fact, they involve several photon-energy dependent parameters such as the x-ray absorption coefficients of the various layers in the structures and the mean-free paths of the photoelectrons traveling through the various elements (Co, V, Al, and aluminium oxide of the capping layer) and the corresponding interfaces before escaping into the vacuum. According to Nakajima and co-workers,[65,66] saturation effects become increasingly important for increasing thickness and at grazing angles of the incident light. In order to reduce the saturation effects, all quantitative analysis has been performed here on data acquired with normal-incident light. Furthermore, a reference sample with 30 Å Al/200 Å Co/MgO(100) structure was measured in order to evaluate the impact of the saturation effects on the Co atomic magnetic moment determination. The magnetic moments extracted from the experimental data for this bulk hcp Co were $1.57\mu_B$ and $0.13\mu_B$ for μ_S and μ_L, respectively, giving a total Co magnetic moment of $1.70 \pm 0.04\mu_B$ per atom, which is very close to the expected value of $1.77\mu_B$.[56] Since the sample with 30 Å Al/200 Å Co/MgO(100) structure is the one with the thickest Co layer studied here and the extracted magnetic moment is very close the expected value for a bulk hcp Co, we assumed that saturation effects were not relevant in our determination of the Co atomic magnetic moments.

Extraction of the V atomic magnetic moment from XMCD is more problematic than that of Co due to the saturation effects and overlap between the L_3 and L_2 peaks, which are separated by a relatively small $2p$ spin-orbit splitting. In the case of V, saturation effects are expected to be more relevant than for Co because the x-ray absorption coefficient of V is approximately twice that of Co,[67] and also the mean free path of the photoelectrons extracted from the V layers is slightly lower than that from the Co layers.[68] The combined effect of both variables artificially enhances the signal from the V layers that are in contact with the Co layers. Consequently, the extracted V magnetic moments should only be considered to determine the trends in the moments and not their absolute value. The magnetic moments have been extracted following the procedure used for VCu alloys,[18] where we assumed that the maximum of the normalized dichroic signal is proportional to the magnetic moment with the scaling factor obtained using a reference sample with known magnetic moment. Although this procedure might give a systematic uncertainty (a detailed discussion on the validity and limitations of the procedure has been presented in Ref. 18), it has been successfully used for alloys with very low V concentration where μ_L and T_z can give large contributions,[69] while here these contributions are expected to be smaller since the V concentrations are higher than for the $Cu_{0.967}V_{0.033}$ alloy.[18]

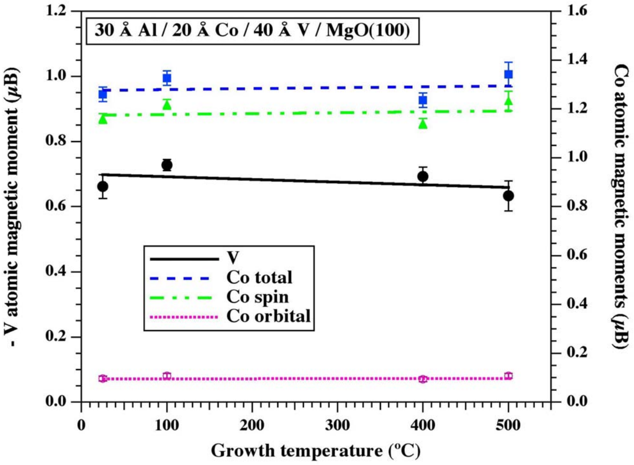

FIG. 3. (Color online) V and Co atomic magnetic moments as a function of V deposition temperature, which is correlated with V atomic volume expansion, in the 30 Å Al/20 Å Co/40 Å V/MgO(100) structure. Lines are guides to the eye.

The atomic magnetic moments of V and Co extracted for the 30 Å Al/20 Å Co/40 Å V/MgO(100) structures, where the V layers are grown at different temperatures, are collected in Fig. 3. It can be clearly observed that the V deposition temperature does not induce major changes in the atomic magnetic moments of V and Co. Despite a difference in the V atomic volume expansion of nearly 4.5° between V layers grown at RT and 400 °C, it appears that there are no changes in the atomic magnetic moments of V and Co.

Note that in this case saturation effects will not modify the trends in the atomic magnetic moments of Co and V because the Co and V layer thicknesses are kept constant. Furthermore, the above mentioned sensitivity to V layers in contact with Co layers should increase the sensitivity to the changes in the V atomic magnetic moments. Therefore the trends in the Co and V magnetic moments are a clear indication that the atomic volume of V is not of relevance for the magnetic properties of the studied systems. As we shall see below, the situation is rather different concerning the V and Co layer thicknesses.

3. Atomic magnetic moments: Effect of V and Co thicknesses

For the V/Co/Cu(100) system, the effect of the V and Co thicknesses on the atomic magnetic moment values has been

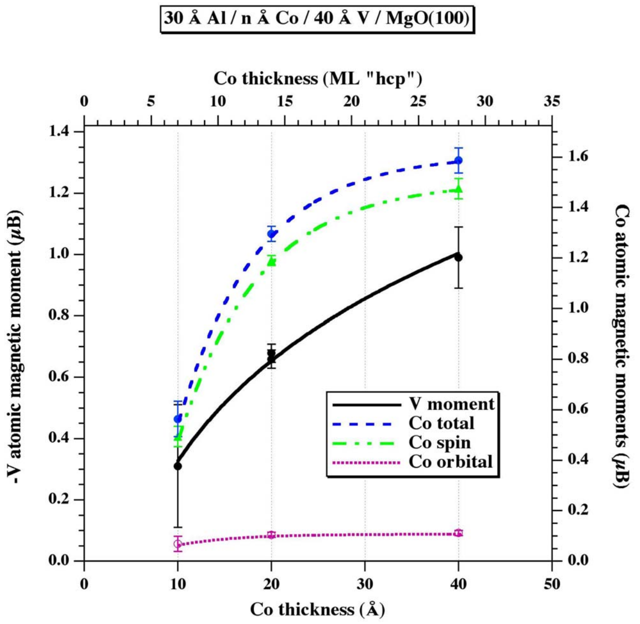

FIG. 4. (Color online) V and Co atomic magnetic moments as a function of Co thickness. The magnetic moments have been measured in the 30 Å Al/n Å Co/40 Å V/MgO(100) structures, where $n=10$, 20, and 40. Lines are guides to the eye.

found to be mandatory.[37] In our previous work, the V and Co thicknesses were restricted to a few ML (see Ref. 37) and the magnetic polarization of the V was found to be an interface effect. Hence the effect of the V or Co thicknesses on the measured values of the V and Co magnetic moments was found to be very important. Also the theoretical results from Carrillo-Cázares *et al.*[1,38–40] and Jisang Hong[41–43] have highlighted the strong interface character of the V magnetic polarization. In particular, these authors have predicted a very low (nearly zero) averaged magnetic moment of the V atoms in thick V layers (>1 ML thick) due to the predicted high magnetic moment of the V atoms in the V layer in contact with the Co layers and the rapidly vanishing V atomic magnetic moment for the other V layers. This implies that the contribution of the V layers, not in contact with the Co layer, to the averaged V atomic moment should be very low, reducing drastically the averaged V atomic magnetic moment in the slabs used in the calculations.

Here we extend our previous study[37] performed on very thin V and Co layers to structures involving thicker V and Co layers and investigate the trend in the atomic magnetic moments as a function of V and Co thicknesses. Figure 4 displays the trend as a function of Co layer thickness. The magnetic moment values displayed in Fig. 4 were measured in the 30 Å Al/n Å Co/40 Å V/MgO(100) structures, where $n=10$, 20, and 40, and extracted using the procedure described in Sec. III A 2. The Co thickness (in ML) in the top scale of the figure has been calculated assuming hcp atomic arrangement of the Co deposited on the V layer with the c axis in the plane of the Co layer and the $[11\bar{2}0]$ direction parallel to the sample surface normal, in agreement with recent results.[48]

As can be seen from Fig. 4, both Co and V magnetic moments are strongly dependent on the thickness of the Co layer. The increase in the Co atomic magnetic moment upon increasing Co thickness is mainly due to the increase of the spin magnetic moment. It can be observed that both Co and V magnetic moments increase by a factor close to 3 when the Co thickness goes from 10 Å (=7 MLs) to 40 Å (=28 MLs). These trends in the magnetic moments upon increasing Co thickness are in agreement with our previous results on thinner Co and V films.[37]

TABLE I. Co and V total atomic magnetic moments (in μ_B) for the structures 30 Å Al/20 Å Co/n Å V/MgO(100) with $n=10$, 20, and 40. Numbers in brackets are the experimental uncertainties of the last digit of each number.

n	10	20	40
Co	1.3(1)	1.32(6)	1.29(3)
V	−0.83(2)	−0.74(2)	−0.67(3)

The present results suggest that the magnetic polarization of the V layer and the reduction of the Co magnetic moments are not strictly limited to the Co/V interface and that more Co and V layers are involved in the mechanism than just the very first layers at the interface. In fact, if only the first Co layer at the Co/V interface would be affected by the interface, as suggested by theoretical results,[1,38–43] additional Co layers would induce only a small change in the magnetic moments. This is particularly true for thicknesses explored here which are much larger than the thicknesses required to saturate the effect of the interface on the averaged magnetic moments of Co and V, as expected from recent theoretical results.[1,38–43] Note that even extremely strong saturation effects in the order of 10-20 % (Refs. 65 and 66) would not modify the observed trends in the Co and V atomic magnetic moments. Also the suggested formation of an interface alloy located at the V/Co interface[1,38–43] is not likely to explain the observed trend in the magnetic moments upon increasing Co layer thickness. A more profound discussion on the presence or absence of a VCo alloy is presented in (Sec. III A 4).

Complementary information can be obtained from Table I, where both the Co and V magnetic moment values are given as a function of V layer thickness for the 30 Å Al/20 Å Co/n Å V/MgO(100) structures, where $n=10$, 20, and 40. From Table I it can be seen that the Co atomic moment is nearly constant while the V atomic magnetic moment suffers a reduction of nearly 20% from $-0.83\mu_B$ to $-0.67\mu_B$ for V thicknesses of 10 and 40 Å, respectively. Assuming that the magnetically polarized V atoms are located in the first V layers (forming either or not an alloy) and taking into account that XMCD with sum rule analysis gives the average value of the magnetic moment (averaged over all V layers probed) and a magnetic moment value that is normalized to the number of V atoms, we would expect a strong decrease of the magnetic moment value with increasing V thickness. Let us now give a simple estimation by considering that the V magnetic moment extracted from the 20 Å Co/10 Å V sample corresponds to a system where the first two layers of V in contact with Co are magnetically polarized and the remaining five layers are not polarized. The V magnetic moment for 20 Å Co/20 Å V would therefore cor-

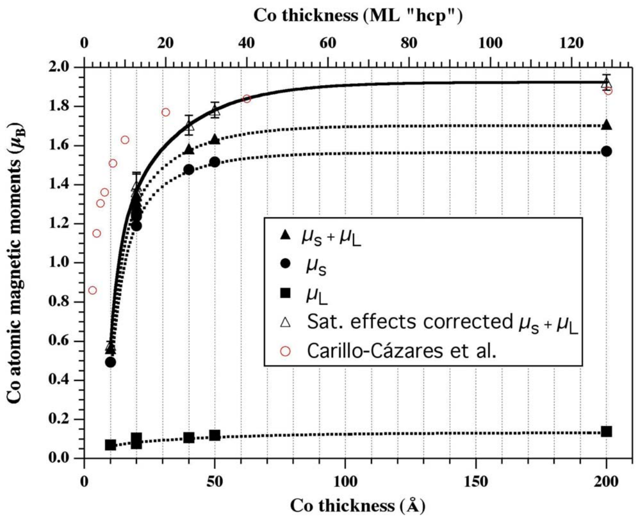

FIG. 5. (Color online) Co atomic magnetic moments as a function of Co thickness. Experimental results for the total atomic magnetic moment are displayed with and without taking into account saturation effect corrections for the purpose of comparison. Also theoretical results from Ref. 40 are represented for comparison (see text for details). Lines are guides to the eye.

respond to a system where the first 2 MLs of V are magnetically polarized and the other 13 MLs are not polarized. Since the XMCD gives a magnetic moment normalized to the number of V atoms, this means that the magnetic moment value should be reduced by a factor of 2 since with the above assumption, the number of magnetically polarized V atoms is the same while the total number of V atoms is doubled. Following the same reasoning, we deduce that for 20 Å Co/40 Å V, the V magnetic moment should be reduced by a factor of 4, or by 75%, which is far from the observed 20% reduction. The above results clearly show that the magnetic properties of the Co/V system are not driven only by the first Co and V layers located at the interface. The V and Co layers far away from the interface also modify the magnetic moment values of V and Co in the Co/V system independent of the possible formation of an interface alloy that has been proposed in the case of the V/Co fcc/Cu(100) system. This is further illustrated in Fig. 5, which shows the trend in the Co atomic magnetic moments as a function of Co thickness for a wider range of Co thicknesses.

The experimental results have been displayed with and without correcting for saturation effects, together with the theoretical results obtained for the V/Co fcc/Cu(100) system.[1,39,40] The saturation effects[65,66] have been considered here to illustrate their rather limited impact on the extracted magnetic moments and to clearly show the lack of impact of these effects on the trends of the magnetic moments upon increasing Co thickness. The experimental results have been tentatively compared to very recent theoretical results.[40] We have chosen to display only the most recent theoretical results and more specifically those that consider the presence of a CoV alloy at the Co/V interface and the best fit to previously published experimental results.[37] Apart from the fact that theoretical results have been performed only (as far as we know) for VCo systems, where the Co layers have fcc structure, we have assumed that in the comparison between theory and experiment, the difference in Co crystalline structure (fcc in the theoretical case and hcp for the present study) is not a major issue. This is partially supported by the discussion in Sec. III A 2, where we have shown that an expansion of the V atomic volume does not induce changes in the Co and V magnetic moments, and we argue that, in a more general sense, the atomic order or atomic structure is not very relevant in the process of magnetization reduction of the Co atoms and magnetic polarization of V atoms at the Co/V interface. The theoretical Co magnetic moment values displayed in Fig. 5 have been extracted from Table 4 of Ref. 40 in the following way: the 2 Co/CoV/V, 3 Co/CoV/V, and 4 Co/CoV/V systems have been considered as being similar to 3 ML Co/V, 4 ML Co/V, and 5 ML Co/V, respectively. The magnetic moment of the Co atoms from the different layers have been averaged in order to be comparable to the XMCD results. For thicker Co layers, i.e., n ML Co/V with $n > 5$, the averaged Co magnetic moments have been obtained by considering a system with the first layers identical to the 5 ML Co/V case with additional Co layers on top, all with Co atoms having a magnetic moment equal to $1.91\mu_B$. The trend in the experimental Co atomic magnetic moments vs Co thickness clearly shows that the reduction of the Co magnetic moments propagates into the Co layers and is not only limited to the first Co layer in contact with the V layers.

The above results strongly suggest a long-range reduction of the magnetic moment for the Co atoms as well as a long-range magnetic polarization of the V atoms. On the other hand, the formation of a VCo alloy at the V/Co interface[40–43] has been recently suggested, a topic discussed in Sec. III A 4.

4. On the formation of a VCo alloy

As mentioned above, in this case the assumption of the formation of a VCo alloy does not permit us to recover the experimental values of the Co and V atomic magnetic moments. This is because a better agreement between theoretical and experimental V and Co atomic magnetic moment values and trends could only be obtained by assuming V and/or Co diffusion in most of the sample volume. Such a diffusion necessarily implies very high diffusion factors at RT, which is probably not the case due to the rather similar atomic radii of V and Co. On the other hand, crystallographic studies[48] have clearly identified the presence of hcp Co on top of bcc V and therefore it should be assumed that the strong diffusion of V and/or Co proceeds without the destruction of crystallographic order, which is also unlikely to occur. Finally, direct experimental evidence of the formation of a VCo alloy could not be found from the XAS spectra, which also contradict the formation of a VCo alloy.

XAS is in fact a very sensitive technique to detect changes in the electronic structure (expected on alloy formation) since it involves x ray excited electronic transitions from V 2p and Co 2p core levels to unoccupied valence states. The latter are strongly affected by electronic structure changes as a consequence of chemical bonding or atomic environment modifications. For example, changes in the Co

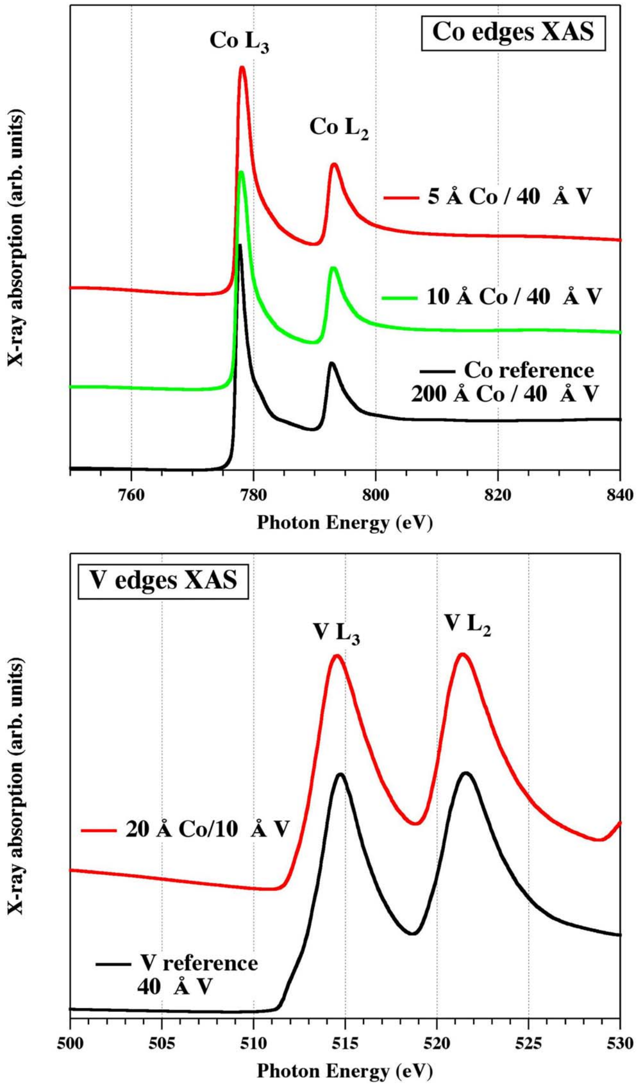

FIG. 6. (Color online) Isotropic Co $L_{2,3}$ XAS spectra as a function of Co thickness (top panel) and V $L_{2,3}$ XAS spectra as a function of V thickness (bottom panel). All the measured structures were deposited on an MgO(100) substrate and capped with a 30 Å thick Al layer.

$L_{2,3}$ edges have been clearly observed in Co_2MnSi Heusler alloys,[70,71] Co-doped ZnO,[72] $Zn_{1-x}Co_xO$ nanorods,[73] and Co/CoO interfaces,[74] depending on the atomic environment of the Co atoms. Also changes in the spectral shape of the V $L_{2,3}$ edges have been clearly observed in VCu alloys,[18] and it has been emphasized by XAS studies that Co atoms in catalysts significantly disturb the different V environments.[75] Hence the formation of a VCo alloy should be clearly observable in the Co $L_{2,3}$ and V $L_{2,3}$ XAS spectra. In Fig. 6 we show the XAS spectra measured from reference Co and V thin films and in structures where the Co or V layer thickness has been intentionally reduced in order to highlight the presence of such a possible alloy. As can be observed in Fig. 6, there is no evidence of any change in the electronic structure. XAS spectra of thin Co layers (5 and 10 Å thick) in contact with 40 Å thick V layer do not display significant differences when compared with a 200 Å thick Co reference thin-film layer. The lack of evidence of the formation of a VCo alloy is further evidenced by the XAS measured at the V $L_{2,3}$ edges (bottom panel of Fig. 6) where no changes in the spectral shape can be observed when comparing a pure V layer (40 Å thick) and a thinner V layer (10 Å thick) in contact with a Co layer. Since a strong diffusion (at RT) of the V and/or Co would induce the formation of an alloy, and as a consequence strong changes in the electronic structure of the systems with the corresponding modification in the spectral shape of the Co and V $L_{2,3}$ XAS, we instead suggest the presence of long-range spin polarization of the V in contact with Co, which in addition would explain the measured Co and V atomic magnetic moments.

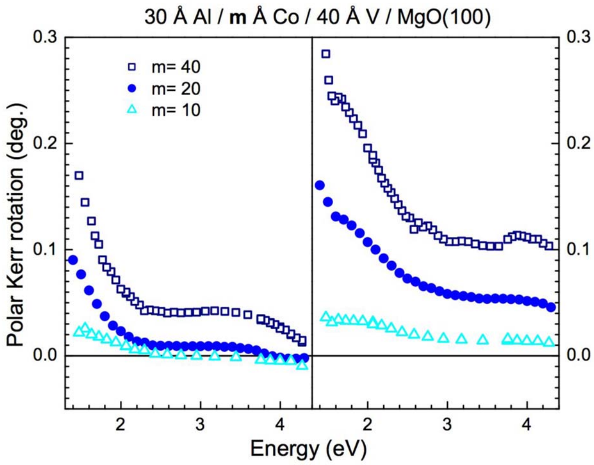

FIG. 7. (Color online) Polar Kerr rotation and ellipticity spectra from the 30 Å Al/*m* Å Co/40 Å V/MgO(100) structures, where $m=10$, 20, and 40.

B. Magneto-optical properties

Figure 7 displays the complex Kerr rotation and ellipticity spectra measured from the 30 Å Al/*m* Å Co/40 Å V/MgO(100) systems with $m=10$, 20, and 40. A progressive reduction in rotation and ellipticity intensities over the entire spectral range is observed with decreasing Co thickness.

Additionally, the spectra measured from the 30 Å Al/20 Å Co/*n* Å V/MgO(100) structures, where $n=10$, 20, and 40, are shown in Fig. 8. In this case, despite that the Co thickness is kept constant, a progressive increase in rotation and ellipticity intensity is observed for decreasing V thickness, with the rotation spectra even undergoing a sign change.

In order to understand the contributions that determine the MO activity of these systems, we developed, as a first step, simulations of the rotation and ellipticity spectra by considering only the contribution from the Co layers. These simulations were performed by means of the transfer-matrix formalism[52,53] where the MO constants of Co were obtained from a reference 1.2 nm thick Co film[76] grown under identical conditions as the Co/V samples. The agreement between the simulated spectra and the experimental data was not satisfactory, even when taking into account the reduction

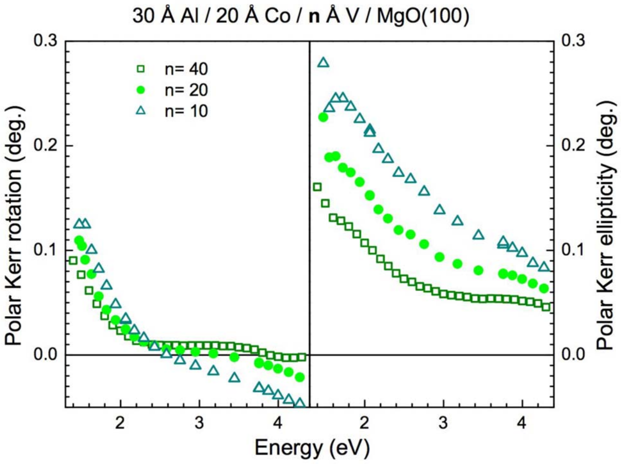

FIG. 8. (Color online) Polar Kerr rotation and ellipticity spectra from the 30 Å Al/20 Å Co/n Å V/MgO(100) structures, where $n=10$, 20, and 40.

of the magnetic moment (observed by XMCD) in the Co films, which was introduced by a proportional decrease of the MO constants. Such a disagreement clearly evidences the strong influence of the polarized V layers on the MO properties. From the measured polar Kerr rotation and ellipticity spectra of the Co/V samples, and by using the transfer-matrix formalism we can extract the MO constants of polarized V. The results are presented in Fig. 9, where the MO constants have been obtained assuming a homogeneous magnetic moment distribution in both the Co and V layers. Moreover, according to the XMCD results, the average magnetic moments of Co and V depend on the sample, and therefore the MO constants of the Co and V films in each system have been associated to a unique set of reference MO constants for Co and V, by using

$$\varepsilon_{xy} = \frac{\mu}{\mu_{\text{ref}}} \varepsilon_{xy}^{\text{ref}}, \tag{3}$$

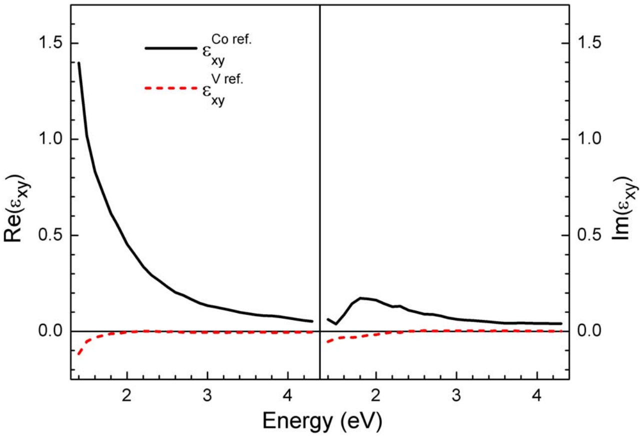

FIG. 9. (Color online) Reference MO constants for V extracted from the rotation and ellipticity spectra (dashed line) together with the reference MO constants for Co (drawn line).

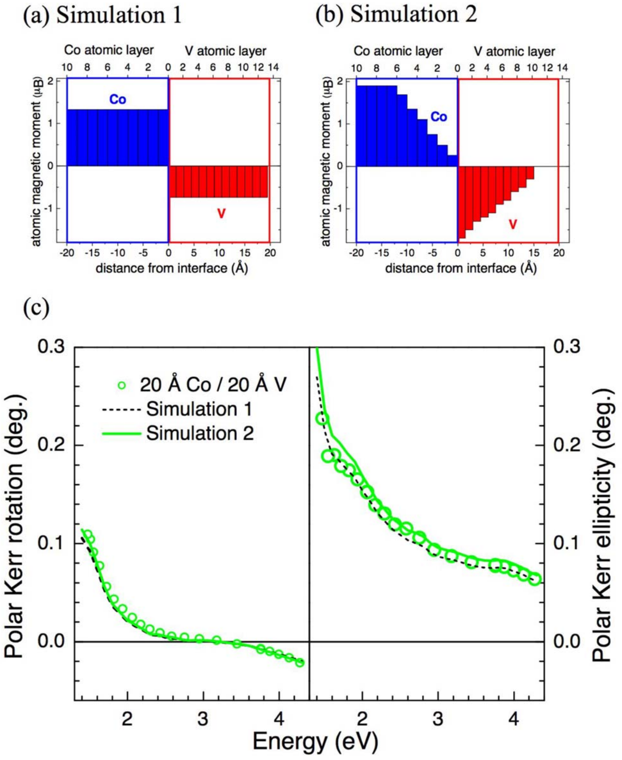

FIG. 10. (Color online) (a) Magnetic moment distribution considered in simulation 1, in which films with homogeneous magnetic moments were assumed. A more realistic model was considered in simulation 2 (b) with an exponential decay (increase) of the magnetic moment of Co (V) as the distance to the interface decreases. (c) Polar Kerr rotation and ellipticity spectra data and simulations performed according to the models described.

where ε_{xy} and $\varepsilon_{xy}^{\text{ref}}$ are the MO constants of the magnetic film and reference material (Co or V), respectively, and μ and μ_{ref} are the average magnetic moment per atom (measured using XMCD) of the homogeneous film and the reference material, respectively. In the case of Co, the MO constants extracted from the 1.2 nm Co film[76] were fixed as reference MO constants (Fig. 9), assuming a magnetic moment value of $\mu_{\text{ref}}^{\text{Co}}=1.77\mu_{\text{B}}$/atom.[56] For V we arbitrarily set the reference magnetic moment to $\mu_{\text{ref}}^{\text{V}}=1\mu_{\text{B}}$/atom.

As can be observed, the absolute values of the MO constants of polarized V are lower than those of Co. Moreover, the sign is opposite to that of Co, which is in agreement with the antiferromagnetic coupling between the Co and polarized V films.

As a second step, we have explored the influence of the magnetic moment distribution within the films on the MO activity of a selected representative system, [30 Å Al/20 Å Co/20 Å V/MgO(100)]. This was done by comparing the results obtained within the previous approximation, in which the atomic moments were considered to be constant inside the films [simulation 1, Fig. 10(a)], and with a more realistic configuration considering an exponential decay (rise) of the Co (V) magnetic moments as a function of the distance from the Co/V interface [simulation 2, Fig. 10(b)]. In both cases the total magnetization values were adjusted to those measured by XMCD. For this purpose, the rotation and ellipticity spectra were calculated using the transfer-matrix formalism, considering both models and the reference MO constants shown in Fig. 9. As can be observed in Fig. 10(c), very similar results were obtained within both approximations and also an excellent agreement with the experimental measurements was achieved. This result shows that for the investigated thickness range the MO optical activity does not strongly depend on the distribution of the magnetic moments inside the Co and V films, and therefore the results obtained in the first step of the analysis, in which homogeneous films were considered, remain still valid. This implies that the existence of homogeneous magnetization in the V and Co layers or the presence of exponential decay (rise) of the magnetization as a function of the distance from the Co/V interface cannot be inferred directly from the MO experimental results and simulations. However, it is worth noticing the need to consider in both models a large amount of polarization in the V films in order to obtain a satisfactory agreement with the experimental spectra. Such a large amount of polarization in the V films would be more compatible with the formation of a CoV alloy, as long as the alloy has propagated through most of the structures. However, no spectroscopic evidence of alloy formation could be found from XAS (cf. Sec. III A 4) or from crystallographic studies.[48] Therefore a model that includes a gradual decay (rise) of the magnetizations as a function of the distance from the Co/V interface is favored.

IV. CONCLUSIONS

We have presented a study of the magnetic and magneto-optical (MO) properties of multilayered Al/Co/V/MgO(100) structures. The experimental XMCD results have provided direct evidence of the magnetic polarization of the V atoms through element-specific hysteresis loops measured at the V L_3 edge. Also the antiparallel alignment of the magnetization between the V and Co layers was evidenced. A careful investigation of the influence of the V atomic volume and the Co and V layer thicknesses on the atomic Co and V magnetic moment values has been reported. While—contrary to expectations—no effect of the V atomic volume on the atomic Co and V magnetic moments could be observed, a clear effect of the Co and V layer thicknesses on the magnetic moments has been found. In particular, it has been shown that the reduction of the Co magnetic moments propagates into the Co layers and that more than one layer of V is magnetically polarized, in contrast to recent results from theoretical calculations. Also the formation of VCo alloy has been found to be very unlikely for the V_{bcc}/Co_{hcp} system. The MO experimental results and simulations clearly show the strong influence of the polarized V layers in the MO properties of the multilayers. In all MO simulations a large amount of polarization in the V films has been found, in agreement with the XMCD results. The combined XMCD and MO results suggest a long-range magnetization of the V atoms and a reduction of the Co atomic magnetic moments. We hope that the present experimental work will stimulate theoretical studies.

ACKNOWLEDGMENTS

We acknowledge the European Synchrotron Radiation Facility (ESRF) for the provision of x rays and would like to thank N. B. Brookes for assistance during experiments on beamline ID08. Excellent technical assistance from the ESRF staff, in particular from K. Larsson, is greatly acknowledged. Y.H. acknowledges the Spanish Ministerio de Ciencia y Tecnología, Comisión Interministerial para la Ciencia Y la Tecnología–CICYT under Contract No. MAT2005-05524-C02, the "Ramón y Cajal" program, and Consejo Superior de Investigaciones Científicas (CSIC) for financial support. C.C. acknowledges financial support from the Spanish Ministerio de Educación y Ciencia through the FPI program. The Comunidad Autónoma de Madrid (CAM) under Project No. S-0505/MAT/0194 NANOMAGNET is also acknowledged.

---

[1] T. A. Carillo-Cázares, S. Meza-Aguilar, and C. Demangeat, Surf. Sci. **601**, 1763 (2007).

[2] B. V. Reddy, M. R. Pederson, and S. N. Khanna, Phys. Rev. B **55**, R7414 (1997).

[3] V. S. Stepanyuk, W. Hergert, P. Rennert, K. Wildberger, R. Zeller, and P. H. Dederichs, J. Magn. Magn. Mater. **165**, 272 (1997).

[4] S. E. Weber, B. K. Rao, P. Jena, V. S. Stepanyuk, W. Hergert, K. Wildberger, R. Zeller, and P. H. Dederichs, J. Phys.: Condens. Matter **9**, 10739 (1997).

[5] K. Lee and J. Callaway, Phys. Rev. B **49**, 13906 (1994).

[6] S. Blügel, Appl. Phys. A: Mater. Sci. Process. **63**, 595 (1996).

[7] J. S. Moodera and R. Meservey, Phys. Rev. B **40**, 8541 (1989).

[8] D. R. Grempel and S. C. Ying, Phys. Rev. Lett. **45**, 1018 (1980).

[9] S. Bouarab, H. Nait-Laziz, C. Demangeat, A. Mokrani, and H. Dreyssé, J. Magn. Magn. Mater. **104-107**, 1765 (1992).

[10] C. L. Fu, A. J. Freeman, and T. Oguchi, Phys. Rev. Lett. **54**, 2700 (1985).

[11] S. Ohnishi, C. L. Fu, and A. J. Freeman, J. Magn. Magn. Mater. **50**, 161 (1985).

[12] C. Rau, C. Liu, A. Schmalzbauer, and G. Xing, Phys. Rev. Lett. **57**, 2311 (1986).

[13] H. Akoh and A. Tasaki, J. Phys. Soc. Jpn. **42**, 791 (1977).

[14] H. Beckmann, F. Ye, and G. Bergmann, Phys. Rev. Lett. **73**, 1715 (1994).

[15] R. L. Fink, C. A. Ballentine, J. L. Erskine, and J. A. Araya-Pochet, Phys. Rev. B **41**, 10175 (1990).

[16] M. Finazzi, F. Yubero, P. Bencok, F. Chervrier, K. Hricovini, F. Ciccacci, and G. Krill, J. Magn. Magn. Mater. **165**, 78 (1997).

[17] S. L. Qiu, R. G. Jordan, A. M. Begley, X. Wang, Y. Liu, and M. W. Ruckman, Phys. Rev. B **46**, 13004 (1992).

[18] Y. Huttel, G. van der Laan, C. M. Teodorescu, P. Bencok, and S. S. Dhesi, Phys. Rev. B **67**, 052408 (2003).

[19] J. Izquierdo, A. Vega, O. Elmouhssine, H. Dreyssé, and C. Demangeat, Phys. Rev. B **59**, 14510 (1999).

[20] B. A. Hamad and J. M. Khalifeh, Surf. Sci. **470**, 149 (2000).

[21] P. Fuchs, K. Totland, and M. Landolt, Phys. Rev. B **53**, 9123 (1996).

[22] M. Finazzi, E. Kolb, J. Prieur, Ch. Boeglin, K. Hricovini, G.

Krill, C. Chappert, and J.-P. Renard, J. Magn. Magn. Mater. **165**, 373 (1997).

[23] G. R. Harp, S. S. P. Parkin, W. L. O'Brien, and B. P. Tonner, Phys. Rev. B **51**, 3293 (1995).

[24] M. M. Schwickert, R. Coehoorn, M. A. Tomaz, E. Mayo, D. Lederman, W. L. O'Brien, T. Lin, and G. R. Harp, Phys. Rev. B **57**, 13681 (1998).

[25] A. Scherz, H. Wende, P. Poulopoulos, J. Lindner, K. Baberschke, P. Blomquist, R. Wäppling, F. Wilhelm, and N. B. Brookes, Phys. Rev. B **64**, 180407(R) (2001).

[26] A. Scherz, P. Poulopoulos, R. Nünthel, J. Lindner, H. Wende, F. Wilhelm, and K. Baberschke, Phys. Rev. B **68**, 140401(R) (2003).

[27] M. Sacchi, A. Mirone, C. F. Hague, J.-M. Mariot, L. Pasquali, P. Isberg, E. M. Gullikson, and J. H. Underwood, Phys. Rev. B **60**, R12569 (1999).

[28] F. Song and G. Bergmann, Phys. Rev. Lett. **88**, 167202 (2002).

[29] B. A. Hamad and J. M. Khalifeh, Surf. Sci. **481**, 33 (2001); **492**, 161 (2001).

[30] A. V. Ponomareva, L. V. Pourovskii, E. I. Isaev, Yu. Kh. Vekilov, B. Johansson, and I. A. Abrikosov, J. Magn. Magn. Mater. **258-259**, 128 (2003).

[31] V. Korenivski, K. V. Rao, J. Birch, and J.-E. Sundgren, J. Magn. Magn. Mater. **140-144**, 523 (1995).

[32] L. T. Baczewski, P. Pankowski, A. Wawro, K. Mergia, S. Messoloras, and F. Ott, Phys. Rev. B **74**, 075417 (2006).

[33] S. S. P. Parkin, Phys. Rev. Lett. **67**, 3598 (1991).

[34] R. Krishman, T. Catinaud, M. Seddat, M. Porte, and M. Tessier, J. Magn. Magn. Mater. **159**, 175 (1996).

[35] J. Du, M. Lu, L. N. Tong, W. Ji, H. R. Zhai, and H. Xia, J. Magn. Magn. Mater. **177-181**, 1209 (1996).

[36] Y. Obi, M. Ikebe, T. Kubo, and H. Fujimori, Physica C **317-318**, 149 (1999).

[37] Y. Huttel, G. van der Laan, T. K. Johal, N. D. Telling, and P. Bencok, Phys. Rev. B **68**, 174405 (2003).

[38] T. A. Carillo-Cázares, S. Meza-Aguilar, and C. Demangeat, J. Magn. Magn. Mater. **290-291**, 110 (2005).

[39] T. A. Carillo-Cázares, S. Meza-Aguilar, and C. Demangeat, Eur. Phys. J. B **48**, 249 (2005).

[40] T. A. Carillo-Cázares, S. Meza-Aguilar, and C. Demangeat, Solid State Commun. **144**, 94 (2007).

[41] Jisang Hong, Surf. Sci. **600**, 2323 (2006).

[42] Jisang Hong, J. Magn. Magn. Mater. **303**, 191 (2006).

[43] Jisang Hong, J. Korean Phys. Soc. **49**, 1586 (2006).

[44] We refer here to averaged magnetic moments of Co and V in the sense that the magnetic moments of the same element have been averaged over all the layers considered in the slabs used in the calculations. The averaged moments are more suitable for further comparison with XMCD results since this technique gives the averaged magnetic signal within the sample probing depth which is always higher than the thickness of the slabs considered in the theoretical approaches.

[45] Y. Huttel, E. Navarro, and A. Cebollada, J. Cryst. Growth **273**, 474 (2004).

[46] E. Román, Y. Huttel, M. F. López, R. Gago, A. Climent-Font, A. Muñoz-Martín, and A. Cebollada, Surf. Sci. **600**, 497 (2006).

[47] Y. Huttel, J. I. Cerdá, J. L. Martínez, and A. Cebollada, Phys. Rev. B **76**, 195451 (2007).

[48] J. F. Calleja, Y. Huttel, M. C. Contreras, E. Navarro, B. Presa, R. Matarranz, and A. Cebollada, J. Appl. Phys. **100**, 053917 (2006).

[49] C. T. Chen, Y. U. Idzerda, H.-J. Lin, G. Meigs, A. Chaiken, G. A. Prinz, and G. H. Ho, Phys. Rev. B **48**, 642 (1993); Y. U. Idzerda, H.-J. Lin, G. Ho, G. Meigs, A. Chaiken, G. A. Prinz, and C. T. Chen, J. Appl. Phys. **75**, 5808 (1994).

[50] D. R. Lee, Y. Choi, C.-Y. You, J. C. Lang, D. Haskel, G. Srajer, V. Metlushko, B. Ilic, and S. D. Bader, Appl. Phys. Lett. **81**, 4997 (2002).

[51] W. S. Kim, M. Aderholz, and W. Kleemann, Meas. Sci. Technol. **4**, 1275 (1993).

[52] M. Schubert, Phys. Rev. B **53**, 4265 (1996).

[53] M. Schubert, T. E. Tiwald, and J. A. Woolam, Appl. Opt. **38**, 177 (1999).

[54] Š. Višňovský, M. Nývlt, V. Prosser, R. Lopušník, R. Urban, J. Ferré, G. Pénissard, D. Renard, and R. Krishnan, Phys. Rev. B **52**, 1090 (1995).

[55] B. T. Thole, P. Carra, F. Sette, and G. van der Laan, Phys. Rev. Lett. **68**, 1943 (1992); P. Carra, B. T. Thole, M. Altarelli, and X. Wang, *ibid.* **70**, 694 (1993); G. van der Laan, Phys. Rev. B **57**, 112 (1998).

[56] C. T. Chen, Y. U. Idzerda, H.-J. Lin, N. V. Smith, G. Meigs, E. Chaban, G. H. Ho, E. Pellegrin, and F. Sette, Phys. Rev. Lett. **75**, 152 (1995).

[57] J. Dresselhaus, D. Spanke, F. U. Hillebrecht, E. Kisker, G. van der Laan, J. B. Goedkoop, and N. B. Brookes, Phys. Rev. B **56**, 5461 (1997).

[58] G. Lauhoff, J. Lee, J. A. C. Bland, J. Ph. Schillé, and G. van der Laan, J. Magn. Magn. Mater. **177-181**, 1253 (1998).

[59] H.-Ch. Mertins, S. Valencia, W. Gudat, P. M. Oppeneer, O. Zaharko, and H. Grimmer, Europhys. Lett. **66**, 743 (2004).

[60] E. Goering, A. Fuss, W. Weber, J. Will, and G. Schütz, J. Appl. Phys. **88**, 5920 (2000).

[61] J. Lindner, A. Scherz, P. Poulopoulos, C. Rüdt, A. N. Anisimov, H. Wende, K. Baberschke, P. Blomquist, R. Wäppling, F. Wilhelm, and N. B. Brookes, J. Magn. Magn. Mater. **256**, 404 (2003).

[62] J. H. Dunn, O. Karis, C. Andersson, D. Arvanitis, R. Carr, I. A. Abrikosov, B. Sanyal, L. Bergqvist, and O. Eriksson, Phys. Rev. Lett. **94**, 217202 (2005).

[63] A. Scherz, H. Wende, K. Baberschke, J. Minár, D. Benea, and H. Ebert, Phys. Rev. B **66**, 184401 (2002).

[64] R. Wu, D. Wang, and A. J. Freeman, Phys. Rev. Lett. **71**, 3581 (1993); R. Wu and A. J. Freeman, *ibid.* **73**, 1994 (1994).

[65] R. Nakajima, Ph.D. thesis, Stanford University, Stanford, 1998.

[66] R. Nakajima, J. Stöhr, and Y. U. Idzerda, Phys. Rev. B **59**, 6421 (1999).

[67] B. L. Henke, E. M. Gullikson, and J. C. Davis, At. Data Nucl. Data Tables **54**, 181 (1993).

[68] D. Briggs and M. P. Seah, *Practical Surface Analysis* (John Wiley & Sons, Chichester, 1990).

[69] P. Gambardella, S. S. Dhesi, S. Gardonio, C. Grazioli, P. Ohresser, and C. Carbone, Phys. Rev. Lett. **88**, 047202 (2002).

[70] J. Schmalhorst, M. D. Sacher, V. Höink, G. Reiss, A. Hütten, D. Engel, and A. Ehresmann, J. Appl. Phys. **100**, 113903 (2006).

[71] N. D. Telling, P. S. Keatley, G. van der Laan, R. J. Hicken, E. Arenholz, Y. Sakuraba, M. Oogane, Y. Ando, and T. Miyazaki, Phys. Rev. B **74**, 224439 (2006).

[72] S. Krishnamurthy, C. McGuinness, L. S. Dorneles, M. Venkatesan, J. M. D. Coey, J. G. Lunney, C. H. Patterson, K. E. Smith, T. Learmonth, P.-A. Glans, T. Schmitt, and J.-H. Guo, J. Appl.

Phys. **99**, 08M111 (2006).

[73] J. W. Chiou, H. M. Tsai, C. W. Pao, K. P. Krishna Kumar, J. H. Chen, D. C. Ling, F. Z. Chien, W. F. Pong, M.-H. Tsai, J. J. Wu, M.-H. Yang, S. C. Liu, I.-H. Hong, C.-H. Chen, H.-J. Lin, and J. F. Lee, Appl. Phys. Lett. **90**, 062103 (2007).

[74] T. J. Regan, H. Ohldag, C. Stamm, F. Nolting, J. Lüning, J. Stöhr, and R. L. White, Phys. Rev. B **64**, 214422 (2001).

[75] J. A. Lopez-Sanchez, J. K. Bartley, A. Burrows, C. J. Kiely, M. Hävecker, R. Schlögl, J. C. Volta, M. Poliakoff, and G. J. Hutchings, New J. Chem. **26**, 1811 (2002).

[76] C. Clavero, L. Martínez, A. García-Martín, García-Martín, Y. Huttel, N. D. Telling, G. van der Laan, A. Cebollada, and G. Armelles (unpublished).