Magnetic circular dichroism study of Fe/Co/Cu(001) using electron yield x-ray absorption spectroscopy with different probe depths

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To obtain depth-resolved magnetic information from Fe films grown on fcc Co/Cu(001), we have used various signal sources for the detection of x-ray absorption spectroscopy. These include total electron yield (TEY) and partial electron yield (PEY) of inelastic electrons at various kinetic energies between 70 and 470 eV as well as PEY using photoelectrons at a fixed binding energy (constant initial state: CIS) near the Fermi level. Inelastic electron yield at electron emission angles up to 87° from the surface normal was found to be as nonsurface sensitive as TEY, however, the CIS mode shows a shorter information depth, comparable to the inelastic mean free path of photoelectrons. No difference in the dichroic signal at the Fe L_3 edge was found between the CIS and TEY modes for a 2-monolayer (ML) Fe/Co film, but an 8-ML Fe/Co film showed a much higher dichroic signal in the CIS mode than that in the TEY mode. This is consistent with a homogeneous magnetic film at an Fe thickness of 2 ML and a nonhomogeneous magnetic film with a live ferromagnetic layer on the surface with nonferromagnetic underlayers at an Fe thickness of 8 ML. Thus, it is possible to extract depth-resolved magnetic information from x-ray magnetic circular dichroism by combining the surface sensitive CIS mode with other detection modes with less surface sensitivity. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1915518]

I. INTRODUCTION

Recent applications of magnetic multilayers such as magnetic random access memory (RAM) and the promising future of spin electronics have inspired extensive research into magnetic thin films and their interfaces. These films will often grow in a metastable structure, which can be different at different layers. Since the magnetic properties of a material are sensitive to its structure, the magnetic properties may thus vary as a function of depth. Fe films grown on fcc Cu(001) are a good example exhibiting different structures and magnetic properties at different Fe thickness ranges.[1] In particular, Fe films have complicated depth-dependent magnetic properties at 5-11-ML thickness.[1] Similar observations were made on Fe films grown on fcc Co/Cu(001) with a possible magnetic Fe/Co interface at a similar thickness range, making the situation even more complicated.[2,3] A depth-resolved technique for magnetic analysis is thus desirable for such nonhomogeneous magnetic films.

X-ray magnetic circular dichroism (XMCD) spectroscopy, as a variant of x-ray absorption spectroscopy (XAS), has become a powerful standard tool for element-resolved quantitative analysis of magnetic properties.[4] As the samples under study in most cases are not thin enough for transmission experiments, especially for transition metals, alternative methods measure the decay products of the core hole created by the absorption process. The 2*p* core hole decays via two pathways: the Auger process and to a much lesser extent fluorescence decay. The Auger process generates an avalanche of electrons including a large number of inelastically scattered secondary electrons. All these electrons and the fluorescence intensity can be used as signal sources for the XAS experiments with different probing depths.[5] This offers the possibility of obtaining depth-resolved information by combining different detection modes for XAS with different probe depths. The most widely used XAS modes are the total electron yield (TEY) and fluorescence yield (FY). The detected electrons in TEY mode are dominated by secondary electrons generated by the inelastic scattering of Auger electrons through different channels as well as photoelectrons. The probe depth of TEY-XAS depends on the escape depths of both secondary electrons and Auger electrons, the latter being a function of the kinetic energy of Auger electrons.[6] With TEY-XMCD alone, however, one cannot resolve the magnetic distribution in a film of several monolayers (ML) thickness, such as the Fe/Co/Cu(001) system. Thus, a more surface sensitive detection mode is necessary for XMCD to solve this problem.

In practice, TEY measurements are performed by either measuring the sample current or by detecting the electrons emitted from the sample using a multichannel plate. For the latter case, Amemiya *et al.* reported that applying a large negative retarding voltage on the plate at grazing angle limited the detection of electrons to kinetic energies higher than the retarding voltage and increased the surface sensitivity.[7,8] By varying the detection angle, various probe depths could be obtained.[7] This already belongs to the so-called partial electron yield (PEY) mode, since only electrons within a certain energy range are detected. The probing depth of XAS

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in such a case is a complicated average of the mean free paths of all electrons involved, and good surface sensitivity is only achieved at very grazing angles. This method requires changing the detector angle precisely with very good angular resolution, which cannot be done without a special design.[7]

An electron energy analyzer is a widely used device to detect electrons with good angular resolution and high-energy resolution, and often is available in the same experimental station in which the absorption measurements are carried out. It seems thus natural to use an electron energy analyzer for partial yield detection of XAS in order to get information with different depth sensitivity. The direct detection of the primary Auger electrons, Auger PEY, as signal source for XAS should result in a shorter probe depth compared to TEY (Ref. 9) due to the short inelastic mean free path (IMFP) of Auger electrons with kinetic energies of several hundred eV, typically less than 10 Å.[10] The problem with Auger electron detection, especially in multielement samples, is that during a photon energy scan photoelectrons from another element often move through the energy window set to the fixed kinetic energy of the Auger electrons, thus creating artifacts in the absorption spectrum.

In this paper we explore alternatives to Auger electron detection for measuring the x-ray absorption cross section. We investigate the surface sensitivity of several ways of partial electron yield measurements using an electron energy analyzer with the goal of reaching a higher surface sensitivity compared to TEY detection. We measured the Fe and Co $L_{2,3}$-edge absorption of an ultrathin Fe/Co bilayer on Cu(001), using the following detection schemes: (i) standard total electron yield, measured by the drain current from the sample holder (TEY); (ii) partial electron yield of inelastically scattered electrons at several fixed kinetic energies and emission angles (inelastic electron yield, IEY); and (iii) partial electron yield at a kinetic energy corresponding to zero binding energy of photoelectrons, also for different emission angles. In this mode we are only detecting electrons that have not undergone inelastic scattering events, namely, Auger electrons at the absorption resonances and photoelectrons from the Fermi edge. Because this last mode is technically identical to photoelectron measurements for constant initial state (CIS), where photon and analyzer energies are scanned in parallel, we will refer to mode (iii) simply as "CIS." We find that the IEY mode (ii), for all values of electron energy and emission angles under investigation, does not show a probing depth any different from TEY, while the CIS mode is more surface sensitive by nearly a factor of 3.

Finally, we applied both, the TEY and CIS modes, to measure the XMCD of 2- and 8-ML Fe films grown on Co/Cu. It is known that a 2-ML Fe film on Co/Cu(001) is homogeneously magnetized, whereas in an 8-ML Fe film the surface layers are ordered ferromagnetically, while the atomic layers underneath are not ferromagnetic.[2,3,8] We indeed observe the same size of dichroic signals at the L_3 edge from both modes in a 2-ML film, but a distinctly larger dichroic signal in the CIS mode compared to the TEY mode in the 8-ML film. These results prove the potential application of XMCD in the CIS mode as a flexible surface sensitive magnetic analysis tool.

II. EXPERIMENT

The experiments were carried out at the UE56/2–PGM2 beamline of the Berlin synchrotron radiation facility BESSY. Partial electron yield detection was performed using a commercial hemispherical electron energy analyzer (HAC 150, VSW Scientific Instruments Ltd.) to collect electrons from the sample with an angular acceptance angle of ±3°, and TEY is measured by the sample current. The photon beam and the analyzer are in the horizontal plane with a fixed angle of 45° between the incident light and the emitted electrons detected by the analyzer. The sample can be rotated around a vertical axis. In this way, the emission angle and incidence angle can be changed. The detailed experimental setup can be found elsewhere.[3] For the present experiments, the pass energy of the analyzer was set to 90 eV, which corresponds to an energy window of about 9 eV due to the adding of four signals from four different channeltrons in the multichannel analyzer. The photon energy resolution was set to about 0.15 eV. Before the XMCD experiments, the sample was magnetized by a current pulse in a magnetic coil in the horizontal plane. The dichroism is then obtained by reversing either the helicity of the circularly polarized light or the sample magnetization direction. All spectra are presented in the following for a magnetization direction along the in-plane component of the light polarization vector for positive helicity.

The samples were grown by deposition of Fe films after evaporation of 5-8-ML Co films on a Cu(001) substrate at room temperature using water-cooled electron-beam evaporation sources. Before evaporation, the substrate was prepared by cycles of Ar^+-ion sputtering and annealing. During evaporation, the thickness of the film was first monitored by medium energy electron-diffraction (MEED) oscillations to calibrate the evaporation rates. In the thickness dependence study, the evaporated Fe film thickness was then calculated from the previous calibrated rate by measuring the deposition time under the same evaporation conditions. Auger electron spectroscopy (AES) was used to check the film cleanliness before and after evaporation. The film thickness uniformity was also checked by AES at different sample positions.

III. RESULTS AND DISCUSSION

A. Inelastic electron yield (IEY)

Figure 1 shows a series of Fe L-edge XAS spectra for a 3-ML Fe film grown on Co/Cu(001) using TEY and IEY at three different kinetic energies: 70, 130, and 470 eV, respectively. These energies were chosen to have no direct photoemission signal from all the three elements in the sample during the photon energy scan around the Fe $L_{2,3}$ edges. The spectra were shifted vertically for clarity and normalized to the same edge jump value at higher photon energies above the L_2 edge, where no dichroism is expected. The spectra were measured at normal emission with a photon incidence angle of 45°. The dashed and solid lines show the spectra for positive and negative helicity, respectively. All the spectra in Fig. 1 show a clear dichroic signal, and further analysis reveals that they have about the same value of dichroic asym-

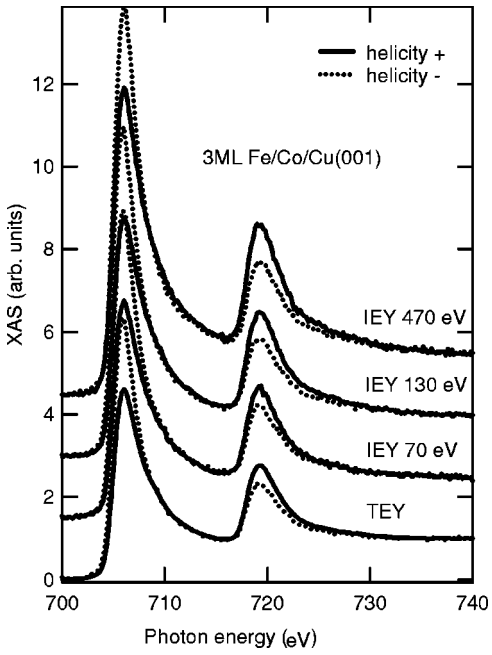

FIG. 1. Fe L-edge x-ray absorption spectra for a 3-ML Fe film grown on Co/Cu(001) measured with different methods. The spectra were shifted vertically for clarity. From bottom to top, the spectra shown are for the TEY mode and the IEY mode at kinetic energies of 70, 130, and 470 eV. In each group of spectra, the dashed and solid lines indicate positive and negative helicities, respectively.

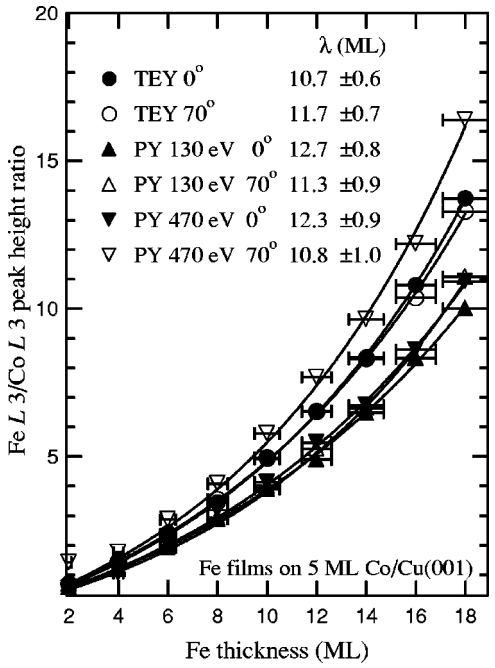

FIG. 2. The ratio between Fe L_3 peak height and Co L_3 peak height as a function of Fe thickness using different detection modes at two different angles. The solid lines are experimental curves fitted to the data using the equation described in text. The fitting parameters λ are given in the legend.

metry at both edges. However, the two L-edge peak heights in Fig. 1 are different for the different spectra and increase with increasing kinetic energy of the inelastic electrons for IEY. It is known that the two peaks are due to the transition from 2p levels into empty 3d states, and that the transition to unoccupied 4s states gives rise to the steplike background.

The TEY spectrum, which is almost identical to those reported in the literature by transmission measurements,[11,12] has the lowest $L_{2,3}$-edge peak heights. It is also noticed that the ratio between the two absorption peak heights is about the same for all the spectra. The reason for this nonproportionality of electron yield and x-ray absorption cross section, at least for the two different types of transitions, $p \rightarrow s$ and $p \rightarrow d$, is not clear. Henneken *et al.* demonstrated that the increasing number of primary electrons for higher photon energies can destroy the proportionality between the TEY signal and the product of absorption coefficient and photon energy.[13] However, the energy range for the present spectra is only about 40 eV, so this effect should be small. Saturation effects[11] can also not explain this difference, since for the extremely small film thickness (3 ML corresponds to about 5.6 Å) and 45° incidence, saturation effects influence the peak height less than 2%.[14] Furthermore, saturation effects are stronger for the higher peaks, and thus should change the peak ratio, which, however, is not the case here. A similar kinetic-energy dependence is also observed in the lineshape of the Co $L_{2,3}$-edge absorption spectra using the IEY mode of measurement. We think that this nonproportionality might be related to the Co underlayer and Cu substrate in the studied system. The 3d transition metals have more localized 3d electrons and delocalized 4s electrons, which could lead to a different space distribution of the generated core holes after excitation of the 2p electrons into these two different types of final states in the absorption process and thus could cause a difference in IEY. Further, our studies revealed a similar kinetic-energy dependence at the Fe $L_{2,3}$ edges in the background to peak ratio in IEY for Fe/Cu(210), while no big difference between the IEY and TEY spectra was found for Fe/Si(001).

We now come back to the main point of the present investigation, namely, the probing depth of the TEY and IEY modes of detection. To determine the probing depth, a series of spectra for the Fe and Co $L_{2,3}$ edges were performed at different Fe overlayer thicknesses. The films were grown on a 5-ML Co/Cu(001) at room temperature, and the emission angle was set either at normal emission or at 70° to the surface normal. Figure 2 shows the ratio between the Fe L_3 peak height and the Co L_3 peak height as a function of Fe thickness for different detection modes at these two angles. In Fig. 2, the circles, upward triangles, and downward triangles indicate TEY and IEY at 130 eV and IEY at 470 eV, respectively. The solid and open symbols are for data at normal emission and at an emission angle of 70°, respectively. The data were fitted to an exponential function $C[\exp(t_{\mathrm{Fe}}/\lambda)-1]$, where C is a constant depending on the cross sections of both Fe and Co L_3 absorption edges, λ is the exponential probing depth for the XAS absorption signal, and t_{Fe} is the Fe film thickness. These fits are shown as solid lines in Fig. 2, and they fit the data quite well.

From the obtained fit parameters λ as given in Fig. 2, it is clear that IEY does not show a better surface sensitivity than TEY, as their probing depth is similar even at an emission angle of 70°. Further experiments showed similar results even at a grazing angle of 87°. This is definitely unexpected from the point of view of the electron IMFP, which should be

only of the order of a few monolayers at kinetic energies of 130 and 470 eV. This does not mean that the inelastic electrons are much less attenuated in the solid than the other electrons, since scattering processes in the solid cannot distinguish the origin of electrons. The reason lies in the fact that these inelastic electrons themselves are generated by inelastic scattering processes of the primary electrons. The intensity of inelastic electrons at a certain kinetic energy is determined by two contributions: a negative one, which reduces the intensity, is inelastic scattering of the electrons of this energy to lower energies, and a positive one, which increases the intensity, is inelastic scattering of electrons from higher kinetic energies. Due to the second effect, the intensity of inelastic electrons thus seems to be less attenuated than that of primary electrons at the same energy after a certain path length. Increasing the path length of the electrons inside the solid by increasing the emission angle will initiate more scattering processes but not necessarily attenuate the intensity of those inelastic electrons for the same reason. The electrons that reach the detector under a certain emission angle are scattered into that direction only after the last of many inelastic scattering events. In each scattering the memory about the propagation direction of the parent electron is lost. Thus, the probing depth of the IEY mode is insensitive to the emission angle, which is verified by Fig. 2. Recently, Zharnikov *et al.* have also found that their PEY mode has a quite large probing depth with more contributions from inelastically scattered electrons when reducing the retarding voltage on a multichannel plate,[15] although they still detect both primary and inelastically scattered electrons. Reference 7 also shows that the small probing depth for such a method is only realized at grazing angles of only a few degrees, and we believe the reduced probing depth at grazing angle in Ref. 7 is, in fact, due to the attenuation of primary electrons. As the inelastic electron scattering involves multiscattering processes, a Monte Carlo calculation is necessary to give a quantitative explanation for the larger probe depth of these electrons including its complicated angular dependence, which can serve as a guide for further experiments. From the above discussion, we conclude that IEY can serve as a suitable signal source for XMCD measurements, however, it is intrinsically not more surface sensitive than TEY.

B. Partial yield detection of elastic electrons [constant initial state (CIS) measurement]

In the so-called "constant initial state" (CIS) mode of photoemission measurements the analyzer kinetic energy is shifted in the same way as the scanned photon energy. This leads to the detection of emitted electrons at a fixed *binding* energy scale. Using this mode for the detection of the absorption signal avoids the problem of detecting direct photoemission signal from other elements.

To explore the applicability of CIS mode for XMCD measurements, we have chosen a 2-ML Fe film as sample, because of its known homogeneous magnetic properties.[2,3] Figure 3(a) shows the Fe *L*-edge x-ray absorption spectra measured at room temperature of a 2-ML Fe film on Co/Cu(001) using electron detection at a binding energy

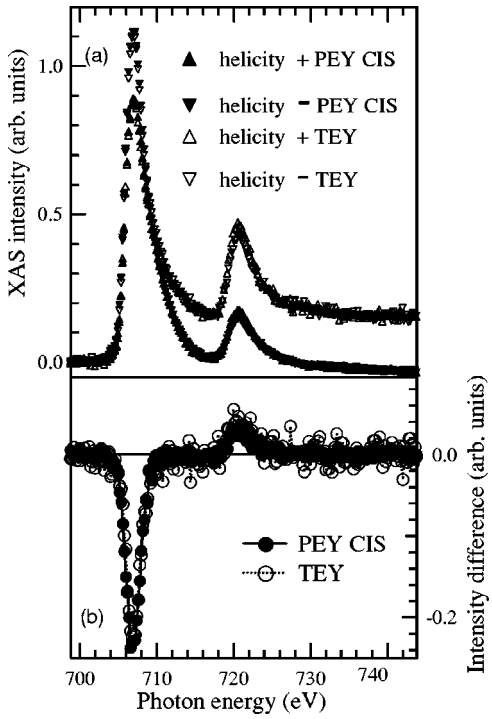

FIG. 3. (a) Fe *L*-edge X-ray absorption spectra of a 2-ML Fe film on Co/Cu(001) in CIS mode using electrons from close to the Fermi energy (filled symbols) and TEY (open symbols). Spectra for both helicities are represented by the upward and downward triangles, respectively. (b) The dichroism spectra calculated from (a) as intensity difference shown by the filled and open symbols for the CIS and TEY modes, respectively.

window centered at 5-eV binding energy, close to the Fermi level. Spectra for both helicities are represented by different orientation of the open triangles. For comparison, the Fe $L_{2,3}$-edge TEY spectra for the same sample are also shown in Fig. 3(a) with the upward and downward solid triangles for the two helicities, respectively. For a better quantitative comparison between the two modes, the sum of the two L_3 peaks from the XAS spectra with both helicities at each mode were normalized to have the same value of 2. The spectra were measured at an emission angle of 23° and a light incident angle of 22°. The sample was magnetized in the horizontal plane before the experiment. One can see that now the peak intensity ratio between the L_3 and the L_2 peak is different for the two modes of detection, and the steplike background from the $d \rightarrow s$ transitions is not present in the CIS spectrum. This is due to the influence of the Auger peaks that are measured at resonance, which dominate the electron signal close to the Fermi level. The intensity reduction of the L_2 peak with respect to the L_3 peak can be understood in terms of Coster–Kronig transitions. As discussed in Ref. 16, the L_2MM Auger transition is far less intense than the L_3MM transition due to the fact that the Coster–Kronig decay channel $L_2L_3M_{4,5}$ rapidly transfers the L_2 hole into an L_3 hole and thus decreases the L_2MM Auger intensity. This has also been verified experimentally by Auger photoelectron coincidence spectroscopy.[17] All in all, the signal in the CIS mode is thus not proportional to the x-ray absorption. However, if the spectra are scaled to equal height of the L_3 peaks, as in Fig. 3(a), the dichroism signal at L_3, i.e., the difference between the spectra recorded for opposite helicity, is identical. This is

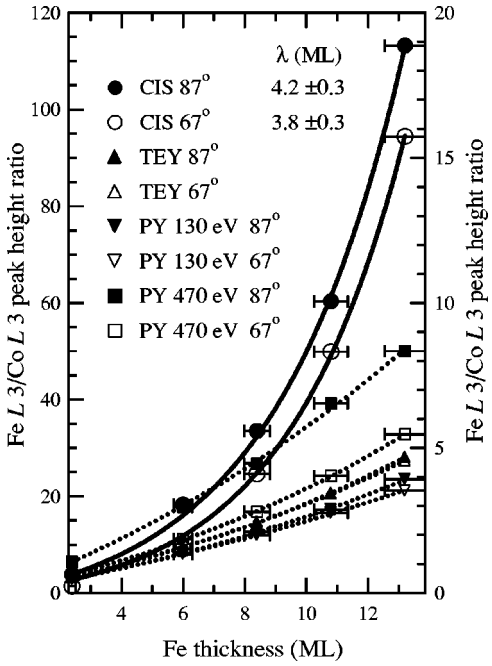

FIG. 4. (a) The ratio between Fe L_3 peak height and Co L_3 peak height (right scale) as a function of Fe thickness using CIS mode at two grazing angles: 67° and 87°. The solid lines are the curves fitted to the data using the equation described in text. The fitting parameters λ were also shown. As a comparison, data for TEY and IEY (left scale) at two kinetic energies (130 and 470 eV) are also shown. The dashed lines are the curves fitted to the data using the same equation.

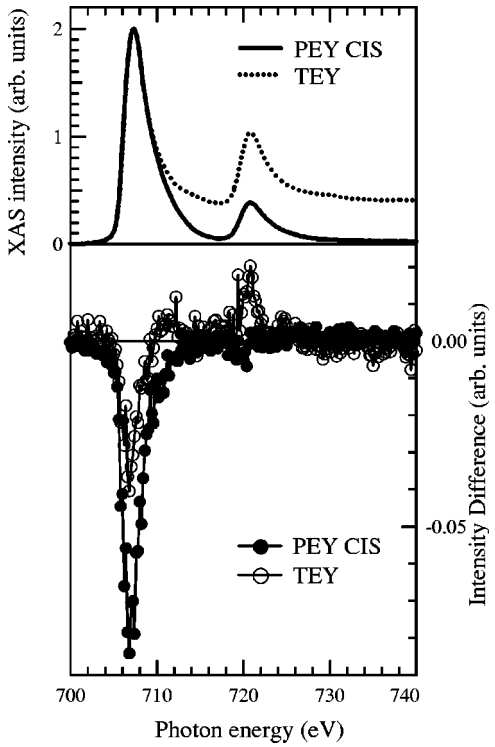

FIG. 5. (a) Fe $L_{2,3}$-edge x-ray absorption spectra of an 8-ML Fe on Co/Cu(001) in CIS mode using electrons from close to the Fermi level and in TEY mode. (b) The calculated dichroism spectra as intensity difference shown by the open and filled symbols for the CIS and TEY mode, respectively.

shown in Fig. 3(b), which shows these difference curves, calculated from Fig. 3(a), by the filled and open symbols for the CIS and TEY modes, respectively. This can be explained by the dominant Auger process in the resonant photoemission, which is proportional to the absorption cross section. This is also true for the Co spectra. Although the dichroic signal is smaller at the L_2 edge compared to the L_3 edge due to the same reason as mentioned before, CIS indeed works well for XMCD measurements and could provide the necessary qualitative magnetic information from the size of the dichroic signal at the L_3 edge, although spin and orbital moments cannot be obtained in a straightforward way by applying the sum rules because of the nonproportionality of the detected signal to the x-ray absorption cross section if the entire spectrum is regarded.

We now turn to the surface sensitivity of the CIS mode. As for IEY in Sec. III A, a series of Fe and Co $L_{2,3}$-edge XAS spectra using this method has been acquired for different Fe thicknesses to obtain the probe depth. As a comparison, TEY and IEY at two kinetic energies (130 and 470 eV) were also recorded at the same time. Figure 4 shows the ratio between the Fe L_3 peak height and the Co L_3 peak height as a function of Fe thickness for the three detection modes at emission angles of 67° and 87°. In Fig. 4, the circles, upward triangles, downwards triangles, and squares indicate CIS, TEY, and IEY at 130 eV and IEY at 470 eV, respectively. The solid and open symbols are for data at emission angles of 87° and 67°, respectively. The fitting curves for the CIS mode and other modes are shown as solid and dashed lines, respectively. The fitting curves generally fit the data quite well. Because the thickness dependence here has been measured only up to an Fe thickness of about 13 ML, the fitting parameters λ found for the other modes, which are larger than 11 ML, exhibit a big uncertainty, and are not reported in Fig. 4. It is, however, clear that even at emission angles of 87°, the IEY mode is less surface sensitive than the CIS mode. The fitting parameters λ for the CIS mode show values of about 4 ML, which are similar to the IMFP of photoelectrons at a kinetic energy of about 700 eV. No big difference was found for the λ values for the two angles, which, however, could be also just due to the experimental error. From Fig. 4, we conclude that the surface sensitivity of CIS is comparable to AES and greater than TEY and IEY by a factor of nearly 3 and could be used for investigations of the depth distribution of magnetic properties. Note that Amemiya *et al.*, using high-pass selected partial electron yield detection using a channel plate obtained only a factor of less than 2 enhancement in the surface sensitivity at 90° grazing emission.[7]

C. Depth selective magnetic information by combining TEY and CIS

In order to prove that depth-resolved magnetic information can be derived by combining the different surface sensitivities of XMCD using TEY and CIS modes of detection, an 8-ML Fe film has been prepared on Co/Cu(001). At this thickness, the magnetic properties are known to be depth dependent.[2,3,8] Figure 5(a) shows Fe $L_{2,3}$-edge x-ray absorption spectra for this film using CIS and TEY modes represented by solid and dashed lines, respectively. Because the

dichroic difference at the two edges in this sample is much smaller than for a 2-ML Fe film (Fig. 3), only the sum of the both helicities in each mode is shown. As before in Fig. 3(a), the sum of the two L_3 peaks from the XAS spectra for both helicities at each mode was normalized to have the same value of 2. The electrons are detected at the same binding energy as in Fig. 3 for the CIS mode. The spectra were measured at a temperature of 200 K with an emission angle of 67°. In Fig. 3(b), the calculated dichroism spectra as intensity difference are shown by the filled and open symbols for the CIS and TEY modes, respectively. Compared to Fig. 3(a), the shape of the XAS spectra for each mode are the same, however, Fig. 5(b) shows much reduced dichroic signals for both modes, with a larger dichroic signal for the CIS mode than for the TEY mode at the L_3 edge. Compared to the dichroic signal of the TEY mode it is noticed that the dichroism in the CIS mode at the L_2 edge in Fig. 5(b) has almost vanished. In terms of sum rule analysis this would imply an enhanced orbital to spin moment ratio. One has to keep in mind, however, that the signal-to-noise ratio is comparably low at the L_2 edge, and that the direct application of the sum rules to the CIS mode spectra, as mentioned above, is not straightforward. The observed reduced dichroic signal in the TEY mode is consistent with literature.[2,3,8] When considering the different probe depths of the two modes, it is clear that the larger dichroic signal in the CIS spectrum of the 8-ML Fe film at the L_3 edge should come mainly from the surface due to its higher surface sensitivity compared to that of the TEY spectrum. Because the probe depth of TEY is larger than CIS, the higher intensity contribution from the non ferromagnetic underlayers will reduce the whole dichroic response of the film. Thus, Fig. 5 confirms the presence of a live ferromagnetic layer at the surface for this Fe film thickness. We hence conclude that combining the two detection schemes, sample current total electron yield and partial electron yield at fixed zero binding energy using a standard electron energy analyzer, surface sensitive magnetic information can be obtained in a single photon energy scan of the absorption spectrum.

IV. CONCLUSION

Partial electron yield detection of x-ray absorption with high surface sensitivity using an electron energy analyzer in samples containing different elements seems to be only possible by detecting electrons at energies corresponding to fixed binding energy. At zero binding energy only elastic electrons, photoelectrons from close to the Fermi level and Auger electrons at the absorption resonance, are detected that have not undergone multiple inelastic scattering events (CIS mode). Using the intensity of these electrons as signal source, the surface sensitivity is enhanced by a factor of nearly 3 compared to the total electron yield detection. Measurements of inelastic electrons at different fixed kinetic energies and different, even quite grazing, emission angles, on the other hand, do not show any significant increase in surface sensitivity. We discuss this as being due to the scattering processes, by which angular information of the parent scatterers is lost. A certain drawback is the lack of proportionality of the partial electron detection schemes to the x-ray absorption cross section over an entire $L_{2,3}$ absorption spectrum we observed. The $L_{2,3}$ absorption peak height to background ratio in IEY has a strong dependence on the kinetic energy of the detected electrons, the reason for which is not fully understood. In the CIS mode, detection of elastic electrons, the background from $d \rightarrow s$ transitions is strongly suppressed due to the strong influence of the resonantly detected Auger electrons. Nevertheless, if one only considers the magnetic circular dichroism of the L_3 peak, it is possible to extract valuable information about the magnetic depth distribution by comparing it to the dichroism of the total electron yield-detected absorption spectrum. While there is no difference in the dichroic signal for a 2-ML Fe/Co film, an 8-ML Fe/Co film has a much higher dichroic signal in the CIS mode than in the TEY mode. This finding is consistent with a homogeneous magnetic film at an Fe thickness of 2-ML and a nonhomogeneous magnetic film with a live ferromagnetic layer at the surface and nonferromagnetic underlayers. Further systematic studies using this method are necessary to better understand the Fe/Co/Cu(001) system.

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[1] S. Müller, P. Bayer, C. Reischl, K. Heinz, B. Feldmann, H. Zillgen, and M. Wuttig, Phys. Rev. Lett. **74**, 765 (1995); S. Müller, P. Bayer, A. Kinne, C. Reischl, R. Metzler, and K. Heinz, Surf. Sci. **331–333**, 723 (1995); K. Heinz, S. Müller, and P. Bayer, *ibid.* **337**, 215 (1995).
[2] W. L. O'Brien and B. P. Tonner, Surf. Sci. **334**, 10 (1995); Phys. Rev. B **52**, 15332 (1995); J. Appl. Phys. **79**, 5629 (1996).
[3] X. Gao, M. Salvietti, W. Kuch, C. M. Schneider, and J. Kirschner, Phys. Rev. B **58**, 15426 (1998).
[4] 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); W. L. O'Brien and B. P. Tonner, Phys. Rev. B **50**, 12672 (1994).
[5] F. M. F. de Groot, J. Electron Spectrosc. Relat. Phenom. **67**, 529 (1994).
[6] B. H. Frazer, B. Gilbert, B. R. Sonderegger, and G. de Stasio, Surf. Sci. **537**, 161 (2003).
[7] K. Amemiya, S. Kitagawa, D. Matsumura, T. Yokoyama, and T. Ohta, J. Phys.: Condens. Matter **15**, S561 (2003).
[8] K. Amemiya, S. Kitagawa, D. Matsumura, H. Abe, T. Ohta, and T. Yokoyama, Appl. Phys. Lett. **84**, 936 (2004); K. Amemiya, D. Matsumura, H. Abe, S. Kitagawa, T. Ohta, and T. Yokoyama, Phys. Rev. B **70**, 195405 (2004).
[9] T. Kendelewicz, P. Liu, C. S. Doyle, G. E. Brown, Jr., E. J. Nelson, and S. A. Chambers, Surf. Sci. **453**, 32 (2000).
[10] M. P. Seah and W. A. Dench, Surf. Interface Anal. **1**, 2 (1979). Compilation of experimental data determined with various energies for large variety of materials.
[11] R. Nakajima, J. Stöhr, and Y. U. Idzerda, Phys. Rev. B **59**, 6421 (1999).
[12] C. T. Chen *et al.*, Phys. Rev. Lett. **75**, 152 (1995).
[13] H. Henneken, F. Scholz, and G. Ulm, J. Appl. Phys. **87**, 257 (2000).
[14] Using Eq. (7) of Ref. 11, an XAS signal source probe depth of 2 nm and x-ray penetration depths at the L_3 edge (L_2 edge) of 20 nm (40 nm) (Ref. 12), one obtains an effect of 2% (1%) on the intensity of the L_3 edge (L_2 edge).
[15] M. Zharnikov, S. Frey, K. Heister, and M. Grunze, J. Electron Spectrosc. Relat. Phenom. **124**, 15 (2002).
[16] J. G. Tobin and G. D. Waddill, J. Appl. Phys. **75**, 6369 (1994).
[17] C. P. Lund, S. M. Thurgate, and A. B. Wedding, Phys. Rev. B **55**, 5455 (1997).