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Soft x-ray resonant magneto-optical Kerr effect as a depth-sensitive probe of magnetic heterogeneity: Its application to resolve helical spin structures using linear *p* polarization

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We have calculated the soft x-ray resonant Kerr intensities as a function of the incident grazing angle of linearly *p*-polarized waves from the model spin structures, where the chirality (handedness) of the spin spirals (twist in depth) in a magnetic layer and the periodicity of a unit spiral are designed to vary. Variations in the chirality and the periodicity lead to noticeable changes in the Kerr intensity versus the grazing angle, which is due not only to a large sensitivity of the Kerr intensity of the linear *p* polarization to both the magnitude and direction of the transverse components of magnetizations, but also to a large dependence of the depth sensitivity on the grazing angle at the resonance regions. The measurement and analysis of the specular Kerr intensity are relatively straightforward in determining the inhomogeneous spin structures in depth, compared to those of the Kerr rotation and ellipticity. This is proven to be a convenient and useful probe to determine the handedness of spin spiral structures, as well as to resolve the detailed magnetic heterostructures in depth in ultrathin-layered films. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1806535]

I. INTRODUCTION

Recently, ultrathin magnetic films have attracted much attention because of their intriguing physical properties and technological applications to ultrahigh-density information storage and other spintronic devices.[1–3] In layered nanostructures of such films, a rich variety of magnetic fine structures are invariably present, caused by the multiple-length scales of various magnetic interactions in conjunction with the reduced dimension (geometry confinement) of the films.[3–6] For instance, the magnetic heterostructures varying in depth, such as a spiral spin structure with a left or right handedness (the chirality of a helical structure), have been found in exchange-spring magnets that consist of soft and hard magnetic layers.[4,7,8] In addition, a depth-varying exchange-bias behavior in an ultrathin Co layer, sandwiched between a Pd capping layer and an antiferromagnetic FeMn layer, was observed in an earlier work.[9]

Visible light or x-ray magneto-optical (MO) effects, such as the Kerr rotation θ_K and ellipticity η_K, have been widely used to investigate a rich variety of magnetic states in magnetic heterostructures, because the MO effect is significantly sensitive to the small amount of magnetic moments in their magnitude and direction.[10–16] In particular, a synchrotron x-ray MO spectroscopy is emerging as a powerful cutting-edge technique, becoming a popular method to investigate the various magnetic properties being associated with nanostructures because of its several unique characteristics such as element specificity, magnetic sensitivity, and large resonant enhancement in the vicinity of the absorption edges, as well as the ongoing growths in the measurement and/or analysis techniques.[13–18] Specifically, the θ_K and η_K spectra, as a function of the grazing angle of incidence ϕ for different photon energies $h\nu$s near the resonance regions, provide invaluable information on magnetic heterostrutures, such as depth-varying spin directions, so that these spectra are very informative to determine the depth-dependent spin structure inherently present in the magnetic multilayer films that consist of several ultrathin layers of different elements. While neutron scattering,[19] and resonant specular[20] and off-specular[21] reflectivity have been a tool to study the magnetic heterogeneity in the films imposed by chemical inhomogeneity.

Despite the great advantages of using the θ_K and η_K signals in the study of magnetization reversals, it is somewhat difficult to measure these signals because one needs to analyze the polarization states of reflected beams, which are changed by interactions between the incident waves and magnetic heterogeneity in a given volume. The θ_K and η_K measurements thus rely on the special polarization analyzers that are designed for specific spectral energy ranges, and rely on the elaborate alignments of the polarizers with respect to a propagation direction of incident x rays,[16–18] although the Kerr intensity, the Kerr rotation, and ellipticity measurements, together, provide more magnetic information than the intensity measurement alone does. Such phase-sensitive MO properties make it difficult and time consuming to measure

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the θ_K and η_K spectra, particularly with continuously varying ϕ or $h\nu$, even if the appropriate equipments are available for the measurements.

Keeping these points in mind, in order to examine/resovle complex spin structures in which the spin directions vary in depth in an ultrathin layer, we devise a simple, reliable, and powerful probe that monitors a specular Kerr intensity reflected directly from a sample of interest, instead of monitoring the θ_K and η_K signals through the polarization analysis of the reflected beams from a polarization analyzer. The results in our model simulations show that *p*-polarized soft x-ray resonant specular intensity (hereafter called the Kerr intensity I_K) is very sensitive to the handedness and periodicity of a helical spin structure. It has been found that this is due not only to a large sensitivity of the I_K spectra of the *p* polarization at a grazing incidence to both the sense and size of the transverse components of magnetizations *M*, but also to a noticeable depth sensitivity and its ϕ dependence as well.

II. MODEL CALCULATIONS AND RESULTS

A. Variation of I_K spectra with spiral spin configurations

For the model calculations, first, we illustrate a model structure of the spin spirals having half a periodicity in which the in-plane *M* rotates gradually in depth in a given magnetic layer, so that the top and bottom spins are oppositely oriented in a given axis. Such a structure will hereafter be called a helical structure that can be characterized by three different parameters. The first parameter is the periodicity (Λ) of a unit spiral—a complete 360° winding of the in-plane *M* along the depth (one turn of twist). The second one is the handedness that represents the winding orientation of the in-plane *M*. The case of a clockwise winding, starting from the top toward the bottom, is referred to as the right handedness and denoted as *R*, whereas the opposite, the counter-clockwise case, is referred to as the left handedness, *L*. The third parameter is the orientation of the top spin. The various helical spin structures with $1/2\Lambda$ in a given thickness are illustrated in Fig. 1(a) and denoted for convenience by three alphabet characters. The first two characters, for example, of *pxR* indicate that the direction of the most top spin is oriented to the positive *x* direction, whereas the last character *R* indicates its right handedness. The first and second rows in Fig. 1(a) display the *R* and *L* series, respectively. The helical structures denoted as *pxR* and *pxL* can be rotated clockwise by 90° to yield *pyR* and *pyL*, respectively. The structure *pyR* turns to *nxR* by another 90° clockwise rotation and finally to *nyR* by one more rotation. For the opposite handedness, the structure *pyL* turns to *nxL* and finally to *nyL* by analogous steps. The individual configurations of four different orientations in each of the *R* and *L* series are equivalent in the light of their handedness.

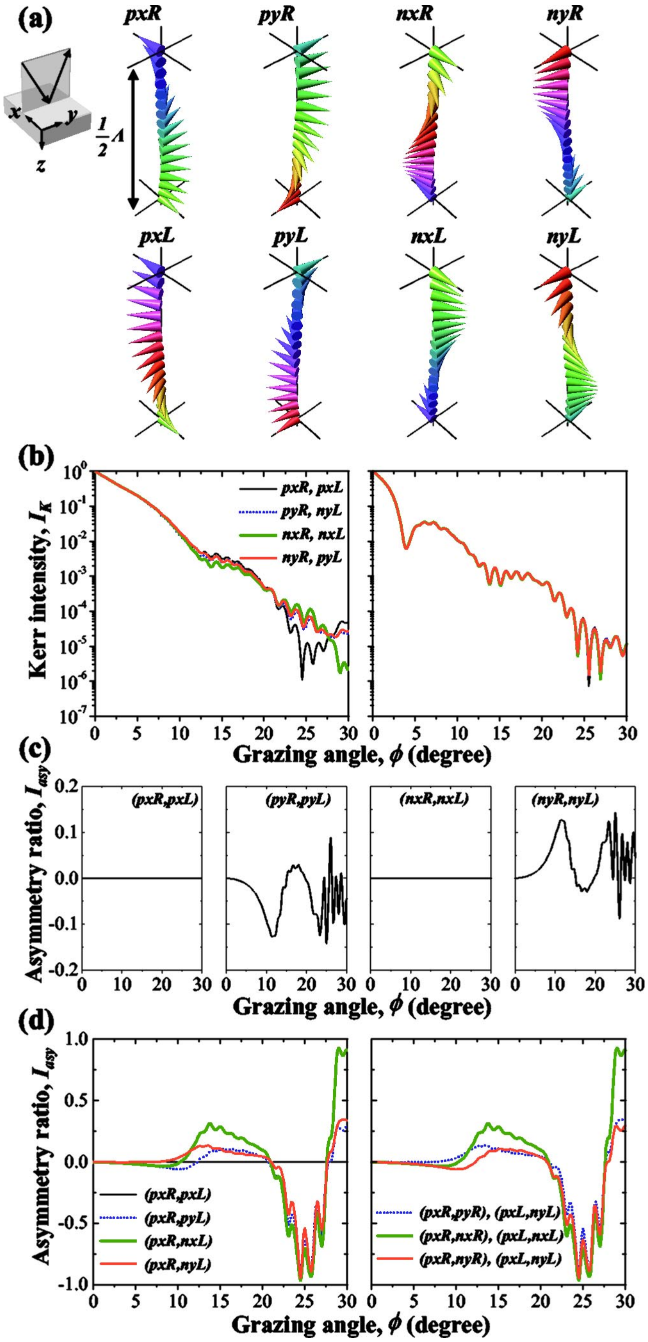

FIG. 1. (Color online) (a) Helical spin structures of half a periodicity $1/2\Lambda$ of a unit twist with right (R) and left (L) handednesses of four different orientations. The in-plane orientation of magnetization gradually changes in depth in a 35-Å-thick Co layer. (b) shows the I_K spectra vs ϕ for both the $h\nu$=778.1 and 770.0 eV, which are calculated from these various helical structures in a model layered structure of Si/SiO$_2$(1500 Å)/Ta(50 Å)/Ni$_{81}$Fe$_{19}$(80 Å)/Fe$_{50}$Mn$_{50}$(200 Å)/Co(35 Å)/Pd(15 Å). Each inset shows the same calculations from a different but simple layered structure of Si/SiO$_2$(1500 Å)/Co(35 Å)/Pd(15 Å). (c) shows the asymmetry ratio spectra (the difference of the two I_K spectra normalized by their sum) for each pair of the counterpart *R* and *L* with the same orientation. In (d), the left and right panels show the asymmetry ratios for the pairs of *pxR* and each of the different orientations of *pxL*, *pyL*, *nxL*, *nyL* of the same *L* handedness, and those between the different orientations of the same handedness, respectively.

For the calculations of the I_K spectra versus ϕ for various helical structures shown in Fig. 1(a), we use a layered structure of Si substrate/SiO$_2$(1500 Å)/Ta(15 Å)/Ni$_{81}$Fe$_{19}$(80 Å)/Fe$_{50}$Mn$_{50}$(200 Å)/Co(35 Å)/Pd(15 Å).[22] The model helical structures shown in Fig. 1(a) correspond to the spin configurations in the 35-Å-thick Co layer. For two different energies, $h\nu$=778.1 eV (the Co L_3 edge) and 770.0 eV, the I_K spectra versus ϕ are calculated, as shown in Fig. 1(b). Those two different $h\nu$ spectra are contrasting. The spectra for the different helical structures at $h\nu=770$ eV show their negligible contrast, whereas the spectra at the Co L_3 edge exhibit a distinct difference between them, around $\phi=15°$ and 25°. These results indicate that the Co resonant Kerr intensity can resolve the variation of the M directions with depth in a Co layer. However, the same spectra, even at the Co L_3 edge, are also found for the following pairs of (pxR,pxL), (pyR,nyL), (nxR,nxL), and (nyR,pyL), as revealed in Fig. 1(b), indicating that those different spin configurations in each pair are equivalent in the viewpoint of the p-polarized Kerr intensity. Rapid oscillations in the I_K spectra versus ϕ are ascribed to the interference effect in the complex-layered structure of this model, which are compared with those calculated from a simpler model structure of the Si substrate/$\mathrm{SiO_2}$(1500 Å)/Co(35 Å)/Pd(15 Å), as shown in each inset of Fig. 1(b). The rapid oscillatory behavior disappears in the spectra for the simpler structure.

In the following, we focus only on the Co L_3 spectra, because the specular intensities contrast for the different configurations of a spin spiral structure in a Co layer. A valuable indication of the difference between the two I_K spectra is the asymmetry ratio $I_{asy}=(I_a-I_b)/(I_a+I_b)$ that is defined as their difference divided by their sum. The I_{asy} spectra for each of the (R,L) pairs of the same orientation are displayed in Fig. 1(c) to clearly show the differences and similarities in the two I_K spectra. For the (pxR,pxL) and (nxR,nxL) pairs, there is no difference in the I_K spectra, whereas the (pyR,pyL) and (nyR,nyL) pairs show noticeable differences in those spectra. These plots clearly show large enhancements or reductions around 12° and 25° in the I_{asy} spectra and this dependence on the orientation of the helical structure. Based on these simulation results, it is evident that the p-polarized soft x-ray resonant I_K measurements, with the varying orientation of the helical structure, is powerful to resolve/determine the handedness and details of an unknown helical structure. It should be noted that the I_K spectra of the p-polarized soft x rays, as a function of ϕ in the vicinity of the resonance edges, provide invaluable information on such depth-varying spin structures.[10,11]

We replot the I_{asy} spectra in the left panel of Fig. 1(d), for the L series of different pxL, pyL, nxL, and nyL orientations with respect to a fixed pxR orientation. The right panel in Fig. 1(d) shows the I_{asy} spectra for the pairs of different orientations but with the same handedness. Comparisons between these I_{asy} spectra show that only the four I_{asy} spectra are distinctly distinguishable, which indicates the presence of the equivalent helical structures with respect to a p-polarized incident wave of $h\nu=778.1$ eV. In order to clarify the origin, Fig. 2 displays the M components projected on the transverse (x) and longitudinal (y) axes that vary in depth for the pairs of the two different helical spin structures from which the ϕ versus I_K spectra are equivalent. In comparisons of both the transverse and longitudinal components for the counterpart helical structures in each pair, it is found that the equivalent spectra are due to the same distribution of the transverse components in depth, together with the same distribution of the magnitude of the longitudinal components.

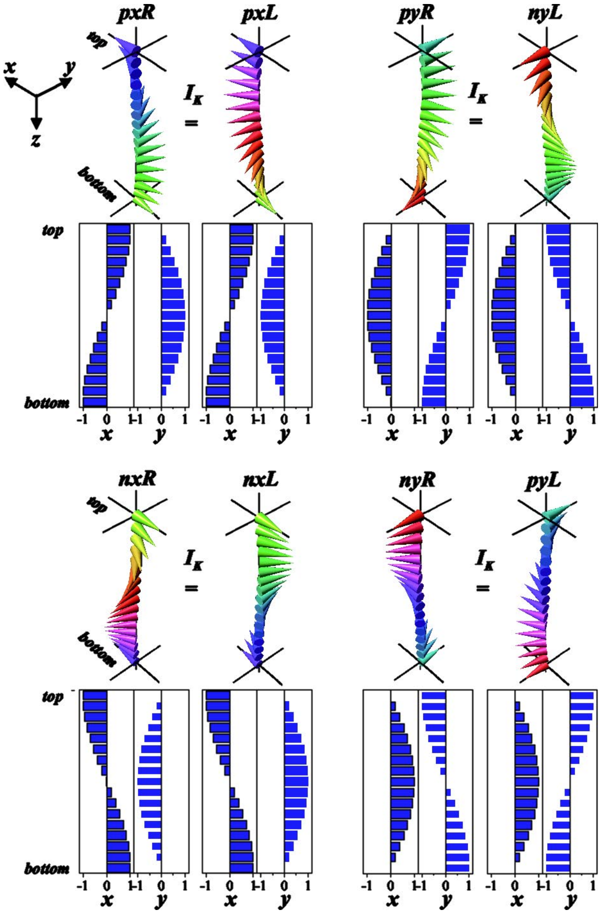

FIG. 2. (Color online) Each pair shows the counterpart helical spin structures from which the same I_K spectrum is obtained. Below each structure, the transverse (x) and longitudinal (y) components of the magnetizations distributed in depth are redrawn.

B. Dependence of I_K spectra on the periodicity of helical spin structures

Next, in order to examine how the I_K spectra change with Λ, we calculate the I_K spectra for different Λs illustrated in Fig. 3(a). The resultant I_K spectra at the Co L_3 edge show their differences for the different Λs. Weak oscillations in each I_K spectrum are ascribed to the interference effect in such a complex-layered structure, as proven in the comparison of the I_K spectra for the different layered structures as shown in Fig. 1(b). In Fig. 3(c), we plot the I_{asy} spectra for various Λs, with respect to $n=0$, as an alternative way in order to clearly show those contrasting I_K spectra. Large oscillatory behaviors clearly appear together with the layer-structured related oscillations. The large-scale oscillation peak increases in its magnitude with an increasing ϕ for each spectrum. The width between the oscillation peaks is likely to depend on Λ, i.e., the period of the oscillations increases with a decreasing Λ. The changes in the amplitude, as well as in the period of the oscillations, implicate much information on the unit structure and/or the periodicity of the helical spin configurations. The I_K spectra versus ϕ from the various spin spiral structures can thus be used as a depth-sensitive probe to resolve those different structures.

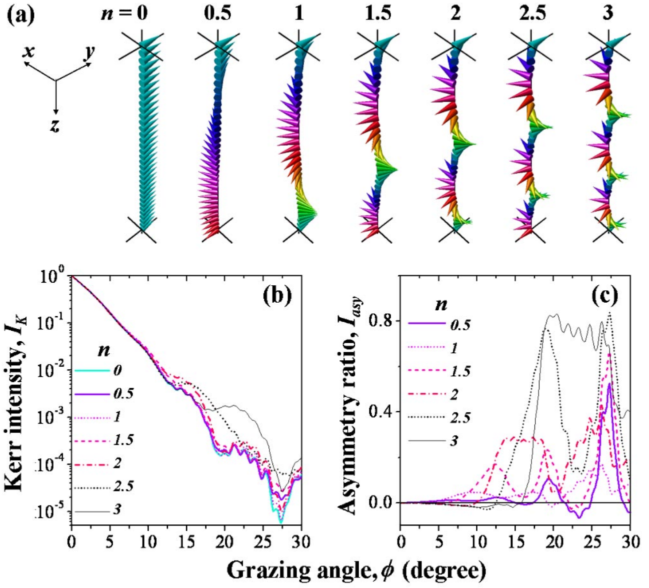

FIG. 3. (Color online) (a) Helical spin configurations of *pyL* with various periodicity. The repeating number $n=t/\Lambda$ of a complete 360° winding of a spin spiral in a given thickness t varies as $n=0$, 0.5, 1, 1.5, 2, 2.5, and 3. The I_K spectra for a linear p polarization from these spin structures are calculated at $h\nu=778.1$ eV, as shown in (b), and their I_{asy} spectra with respect to $n=0$ in (c). The model-layered structure used is the same as that in Fig. 1, but the Co layer used in this calculation is 70-Å thick.

C. I_K sensitivity to the orientation and magnitude of magnetizations

In order to elucidate how the soft x-ray resonant I_K spectra for a linear p polarization are dependent upon the handedness and periodicity of a helical spin structure or detailed depth-varying spin structures in ultrathin films, we attempt to calculate the sensitivity of I_K for the p polarization to the sense and size of M uniformly oriented in a Co layer, as well as to the depth in a given magnetic Co layer. In the top panels of Fig. 4, three different orientations of M denoted as $[m_x,m_y,m_z]$ are displayed. In Fig. 4(a), only the longitudinal M component m_y varies as +1, −1, and 0 with holding the other components $m_x=m_z=0$, whereas in Fig. 4(b), only the transverse component m_x varies as +1, −1, and 0 with keeping $m_y=m_z=0$. The resultant I_K and I_{asy} spectra versus ϕ calculated from these different structures are shown in the middle and bottom panels, respectively. It is clearly found that the I_K spectra for $m_y=-1$ and +1 are the same, but different for $|m_y|=1$ and $m_y=0$, as confirmed by their I_{asy} spectra. In contrast, for all the cases of $m_x=+1$, −1 and 0, their I_K spectra are different, as shown in Fig. 4(b). The results evidently reveal that the resonant I_K for a linear p polarization has no sensitivity to (i.e., does not change with) the sense of m_y, but a large sensitivity to the magnitude of m_y, whereas the I_K is noticeably sensitive to the change in both the size and sense of the transverse M component.[23]

The mentioned p-polarization I_K sensitivity to m_y and m_x allows to understand the presence of equivalent I_K spectra for certain different helical spin structures, as shown in Fig. 2, as well as to resolve/determine the similarity and difference in the various spin configurations through the resonant I_K spectra. In contrast to such properties, the intensity magnitude of the I_K spectra for $m_x=+1$ and −1 are not symmetric with respect to that of the I_K for $m_x=0$, as shown in the bottom panel of Fig. 4(b), but their asymmetry increases with an increasing ϕ. This asymmetric contrast can lead to a vertical shift with respect to zero M in the magnetization hysteresis loops obtained through the I_K contrast, because such asymmetric characteristic can distort true M reversals in the measurements, thus yielding incorrect results and interpretations. Such artifacts can be avoided by careful measurements and normalization. We note here that a care should be taken in the investigation of the M reversals using the I_K, because this signal has different sensitivities to the magnitude and orientation of M as well as its asymmetric contrast for reversing transverse components.

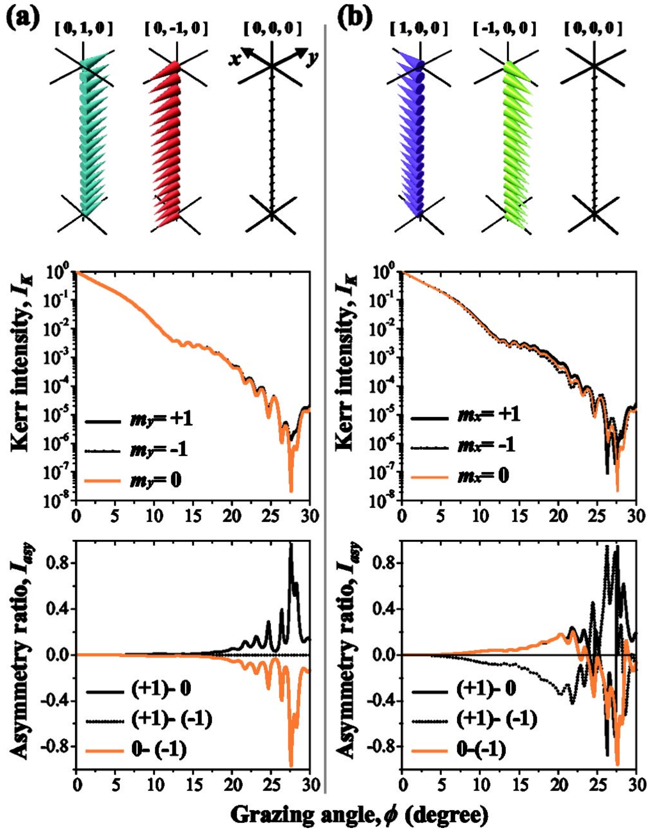

FIG. 4. (Color online) Top panels of (a) and (b) show the model spin configurations uniformly oriented through the entire Co thickness. The uniformly oriented M are denoted as $[m_x,m_y,m_z]$ with each component of $m_{x(y,z)}$ along $x(y,z)$-axis. In (a), m_y varies as +1, −1, 0 with $m_x=m_z=0$. In (b), m_x varies as +1, −1, 0 with holding $m_y=m_z=0$. The middle and bottom panels in (a) and (b) show the I_K and I_{asy} spectra at $h\nu=778.1$ eV as a function of ϕ, respectively, which are calculated from the spin configurations illustrated in the top panels with the same conditions used in Fig. 1.

D. The sensitivity of I_K to a specific depth

We noted that rapid oscillations in the calculated I_K spectra are associated closely with the interference effect in the complex-layered structures. Such interference effect in conjunction with the resonant features of the MO effect together causes enhancements or reductions in I_K, due to different weights of contributions of each layer in depth, thus influencing the overall I_K signals. This effect is also remarkably dependent on ϕ. For instance, the I_{asy} values around ϕ

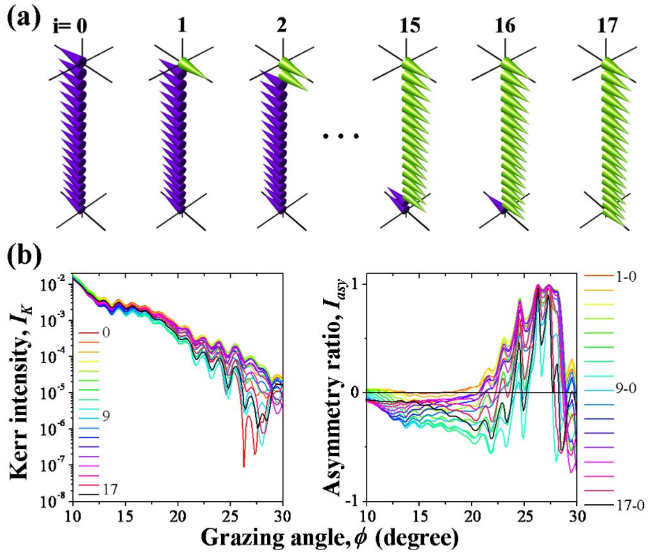

FIG. 5. (Color online) (a) Various spin configurations in which only the transverse component exists, i.e., $|m_x|=1$ and $m_y=m_z=0$. The spins uniformly oriented toward the $+x$ direction flip layer by layer to the opposite direction of $-x$, starting from the top. In this model, the layered structure is the same as that used in Fig. 1. The individual spins have a constant magnitude of $m_x=1$ through the entire Co layer in order to examine just the depth sensitivity to the transverse component. (b) the I_K spectra versus ϕ calculated from each spin configuration illustrated in (a) for an incident linear p polarization at $h\nu=778.1$ eV, and their I_{asy} spectra with respect to $i=0$.

$=28°$ are approaching 1, which is due to a strong enhancement caused by the interference effect. This, which offers an extremely large depth sensitivity into I_K, enables us to resolve the depth-varying spin structures, as demonstrated in Fig. 1. To better clarify the depth sensitivity of I_K, we calculate the I_K spectra, as a function of ϕ, from the spin configurations illustrated in Fig. 5(a), where the individual spins oriented to the $+x$ direction are flipped layer by layer to the opposite direction, —x. In addition to the large sensitivity of the p-polarized I_K to the transverse M component, its depth sensitivity is also proven to be considerably large, according to the I_K and I_{asy} spectra shown in Fig. 5(b).

III. DISCUSSION

It was found in an earlier work[9] that a rich variety of the interference effects inherently present in the ultrathin-layered films provide an extremely large depth sensitivity and its ϕ dependence into I_K in the resonance regions. These MO properties are very useful to determine the depth-varying spin structures by fitting the measured specular I_K versus ϕ to those calculated from the various model configurations, as used in x-ray/neutron scattering experiments and analysis of the structural refinements.[19–21] The specular Kerr intensity reflected from a magnetized film in the vicinity of the resonance thresholds is a kind of an x-ray resonant magnetic scattering. As reported in Ref. 24, the resonant and nonresonant charge scattering, and the resonant magnetic scattering contribute differently to the reflected intensities according to the polarization vectors of the incident and reflected x rays, as well as the direction of magnetizations. Particularly, easy measurements of the specular intensity can make such a probe popular in making a refinement of the unknown spin structures of the magnetic heterogeneity in depth, whereas the nonspecular case is useful in the structural refinements of a lateral heterogeneity.[21] These emerging tools will be as powerful as the neutron-scattering experiments and analyses.

IV. CONCLUSION

In conclusion, the ϕ versus I_K spectra of the incident p polarization in the vicinity of the resonance thresholds are noticeably sensitive to the size and sense of the transverse magnetization component, and show a remarkable depth sensitivity. These MO properties, which are assisted by a rich variety of the interference effects near the resonance regions, can be applied to determine/resolve the fine structures of the magnetic heterogeneity in depth. For instance, the measurement and analysis of such spectra allow to determine the handedness and periodicity of a helical spin structure as well as the magnetic properties confined to the surface or interface and its related depth-varying magnetism in the ultrathin layered films.

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[22] This model layered structure is the same as that of the real sample reported in Ref. 9, but the model spin configurations can be different. From a simple layered structure of $\mathrm{Si/SiO_2(1500\ \AA)/Co(35\ \AA)/Pd(15\ \AA)}$, we also calculated the I_K spectra and obtained similar results, as described in text. In this paper, we report the I_K spectra calculated from the complex layered structure described in the text because such a complex structure is often synthesized for the use in the current spintronic devices such as a spin valve.

[23] In fact, in contrast to the *p* polarization, the resonant I_K spectra of a linear *s* polarization have different sensitivities. Further elaborate calculations revealed that the I_K spectra of the *s* polarization show no sensitivity to the sense and size of m_x and the sense of m_y, but show a relatively weak sensitivity to only the size of m_y.

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