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Atomic-scale depth selectivity of soft x-ray resonant Kerr effect

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By the use of resonant soft x-ray Kerr rotation measurements with its varying incident angle and energy, we observed various shifts of the exchange bias field of a 3.5-nm-thick Co layer in oppositely exchange-biased $Ni_{81}Fe_{19}/Fe_{50}Mn_{50}/Co/Pd$ films. The results in conjunction with their model simulations clearly reveal that the measurements enable one to resolve varying magnetization with depth in the individual magnetic layers of such a multicomponent ultrathin layered structure on the atomic scales. Significant interference effects combined with penetration depth of resonant soft x rays, which are closely associated with their absorptive and refractive contributions, offer remarkably different depth sensitivities into the Kerr effects depending on grazing angle and resonance energy. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1622123]

Current miniature magnetic devices, such as spin valve sensors and nonvolatile memory cells applicable to ultrahigh-density information storages,[1] consist of complex multicomponent ultrathin layers having nanometer-scale thickness or less. The magnetic properties or functions of those films are known to be determined crucially by structural and magnetic properties at many interfaces and are known to be varying with depth in the individual layers.[2–5] In order to better understand their intriguing properties associated with interfaces, it is essential to examine the depth dependence of magnetic information. However, many measurement techniques average various magnetic characteristics in the film plane.

There have been several attempts to separately investigate the magnetic properties of individual layers in ultrathin layered structures.[6–9] In these works, the different magnetic properties of the individual layers have been resolved by visible or soft x-ray magneto-optical Kerr effects. In earlier work,[3] we also attempted to resolve depth-varying magnetic properties of a Co layer by the use of standing waves generated from a well-ordered multilayer on top of which the Co layer is deposited. Here we report that soft x-ray Kerr rotation, θ_K, versus incident grazing angle, ϕ, and energy, $h\nu$, measurements can provide an extremely large depth selectivity on the atomic scales even in a ultrathin single layer, simply by choosing appropriate ϕ and $h\nu$ around the resonant regions. For instance, both the experimental and simulation results of ϕ vs θ_K measurements are presented for depth-varying magnetization reversals in a 3.5-nm-thick Co layer of NiFe/FeMn/Co/Pd films.

The sample of a structure of SiO_2 (150 nm)/Ta (5 nm)/$Ni_{81}Fe_{19}$ (8 nm)/$Fe_{50}Mn_{50}$ (20 nm)/Co (3.5 nm) has oppositely oriented exchange bias between two ferromagnetic (F) NiFe and Co layers with an antiferromagnetic (AF) FeMn layer, as seen in visible Kerr loop shown in the inset of Fig. 1(a). The oppositely oriented exchange bias was locked in by cooling through a Blocking temperature with their antiparallel remanent magnetizations oppositely saturated above the Blocking temperature in a high vacuum chamber with a base pressure of 2×10^{-8} Torr. Details of the sample growth, representative characteristics, and exchange-bias setting will be reported elsewhere.[10] We notice here that a Pd capping layer was deposited to prevent oxidation after the formation of the opposite exchange bias in NiFe/FeMn/Co films. After the Pd deposition, the Co magnetization reversal becomes nonuniform, rather shows varying exchange bias field, H_{eb}, as seen in a vibrating sample magnetometer (VSM) loop [see Fig. 1(a)]. While, NiFe exchange bias remains unchanged after the Pd deposition since the NiFe layer is far away in distance from the Pd capping layer.

The nonuniform Co reversal is likely to be modified by Pd proximity effect on the Co surface. To clarify the true origin of the observed nonuniform reversals, we have employed a technique of resonant soft x-ray ϕ vs θ_K measurements that enable to resolve magnetization reversals of different elements and their depth varying reversals in complex multicomponent layered structures. The measurements were carried out on the beamline 8.0 at the Advanced Light Source at Lawrence Berkeley National Laboratory. The details have been described elsewhere.[11]

Figure 1(b) shows Co-resolved magnetization loops measured via soft x-ray θ_K at different ϕ as noted for somewhat different $h\nu$ around the Co L_3 edge. Various H_{eb}, coercivity, H_c, and slopes of the loops are clearly seen depending on ϕ. Those different values that are characteristic of each ϕ loop, are associated with different parts of the entire Co reversal shown in the VSM loop. Among those, H_{eb} for $\phi = 7°$ is almost zero, apparently indicating nonexchange biasing. For other ϕ loops, Co exchange biasing is present, and in particular, H_{eb} for $\phi = 10°$ is exactly the same as that of the Co reversal observed from that sample without Pd deposition. It is quite interesting how ϕ dependent θ_K loop measurements give almost narrow single switching loops with different H_{eb}, H_c, and slopes that are resolved from the

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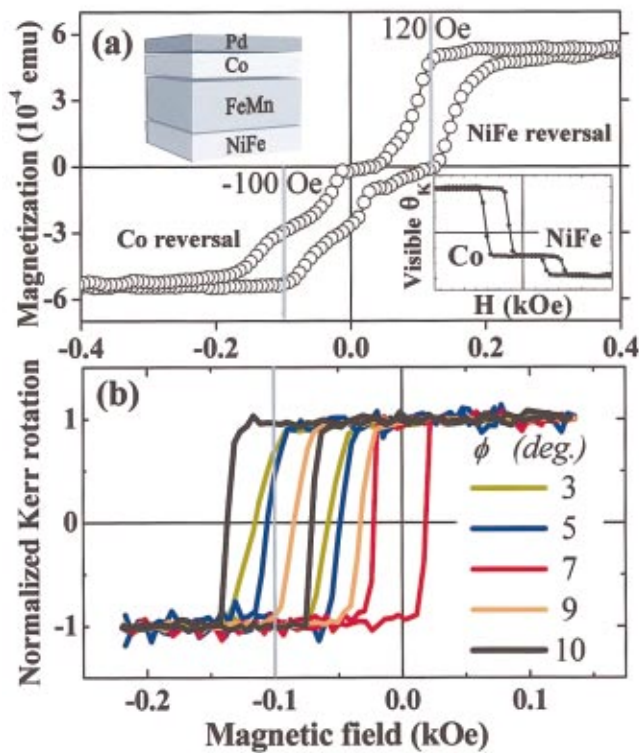
FIG. 1. (Color) (a) Magnetization reversals of NiFe and Co layers which are oppositely exchange biased to a FeMn layer. The lower inset shows magnetization reversals of both NiFe and Co layers measured with visible Kerr effect in a high vacuum chamber prior to deposition of a Pd capping layer. The two vertical gray lines indicate H_{eb} values for the Co (-100 Oe) and NiFe (120 Oe) reversals. The visible Kerr loop has opposite sense in the magnitude and different sensitivity to layers. (b) Co resolved magnetization reversals measured via soft x-ray θ_K at different ϕ as noted and somewhat different $h\nu$ near the Co L_3 edge. The sign and magnitude of θ_K are normalized with the saturation value at a positive saturation field. The vertical gray line is placed at -100 Oe which is the same as H_{eb} of a part of the entire Co reversal shown in the VSM loop.
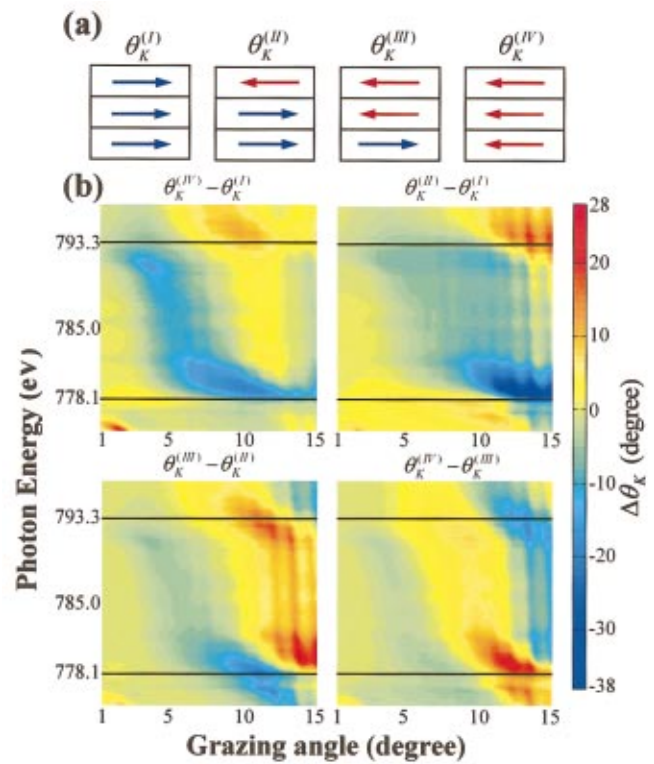

FIG. 2. (Color) (a) A spin flip model where the directions of spins placed at three different depths reverse incoherently in depth as schematically illustrated. (b) Calculated contrasts in θ_K for independent spin flips, plotted as contour against ϕ and $h\nu$. $\theta_K^{(IV)} - \theta_K^{(I)}$ represents the contrast in θ_K for a spin flip from one direction to the other opposite one coherently through the entire Co thickness, whereas $\theta_K^{(II)} - \theta_K^{(I)}$, $\theta_K^{(III)} - \theta_K^{(II)}$, and $\theta_K^{(IV)} - \theta_K^{(III)}$ correspond to the contrasts in θ_K for each of the individual spin flips at different top, middle, and bottom depths, respectively.

mixed, multiple Co switching shown in the VSM loop. Such measurements should inform on depth-varying heterogeneity in the magnetization reversals of a ultrathin Co layer with sufficient depth resolutions.[12]

In order to verify it, we calculate θ_K versus both ϕ and $h\nu$ from some model spin structures illustrated in Fig. 2(a). In this model, we divide the 3.5-nm-thick Co layer into three different regions of the same thickness and use a spin flip model where the magnetization directions of three different regions are independently flipped. For calculations of θ_K from the model structures around the Co L_3 and L_2 edges, $+/-$ helicity dependent complex refractive indices, $n_{+/-}(h\nu)$, should be used for Co, which are obtained from right and left circularly components of Co absorption spectra measured versus $h\nu$ and their Kramers–Kronig transformations.[13] For $n(h\nu)$ of other layers such as NiFe, FeMn, Pd, etc., we use tabulated Henke data[14] since the Co resonant region of interest in this calculation corresponds to their nonresonant $h\nu$ regions as for those elements. We also use the real part of $-r_{ps}/r_{ss}$ for θ_K, where $r_{ss(ps)}$ is the reflection coefficient from $s(s)$ to $s(p)$ polarization.

From calculated θ_K against both ϕ and $h\nu$ from each spin configuration noted as (I), (II), (III), and (IV) in Fig. 2(a), their differences in Fig. 2(b) are remarkably contrasting
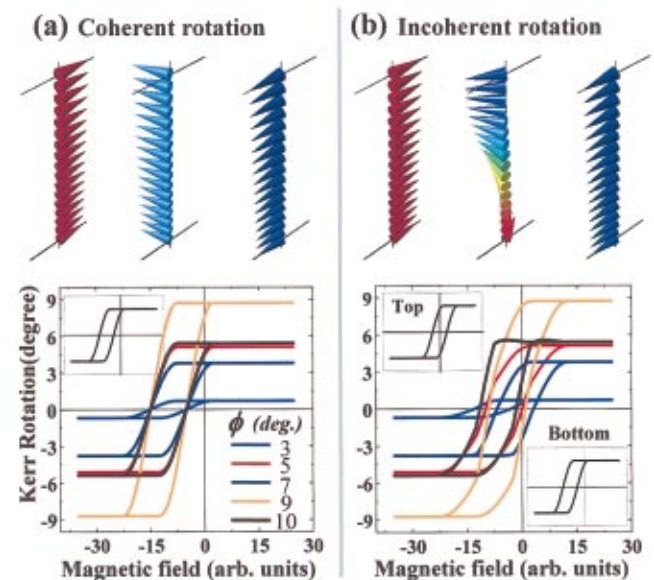

FIG. 3. (Color) Model spin structures within a Co layer for coherent and incoherent magnetization reversals and calculated θ_K loops based on the models. In (a), the inset shows the model hysteresis loop of a coherent reversal with a certain H_{eb} of the same value for all the individual spins. In (b), the upper and lower insets indicate the model hysteresis loops, respectively, of top and bottom layer spins, which are assumed to have different H_{eb} as shown in the insets.

at certain ϕ and $h\nu$ around the resonant regions for the independent spin flips, indicating that θ_K has a significant depth sensitivity. Also, the noticeable changes in the magnitude and sign of those contrasts on the $\phi-h\nu$ plane exhibit a large variation of the depth sensitivities of θ_K depending on ϕ and $h\nu$. This origin is ascribed to strong interference effects in conjunction with penetration depth that are associated closely with absorptive and refractive nature of soft x rays in response to such a complex multilayer film.[13]

It was revealed earlier that Co-specific θ_K is strongly sensitive to depth at which magnetization reversal occurs. This sensitivity is also distinctly different with varying ϕ and $h\nu$ near the Co absorption edges. With these regards, to verify that varying H_{eb} observed by soft x-ray ϕ vs θ_K is caused by depth varying exchange bias, we simulate θ_K loops for several different ϕ at certain $h\nu$ from two distinct models of coherent and incoherent rotations in depth within a single Co layer, as shown in Fig. 3. All the calculated θ_K loops at different ϕ and $h\nu$ from the coherent model represented by a hysteresis loop shown in the inset, exhibit the same H_{eb} and H_c as expected, but different magnitudes and signs depending on ϕ and $h\nu$ because of their related interference effects. While, an incoherent rotation in depth shows a remarkable change in H_{eb} depending on ϕ or $h\nu$ because of the different depth sensitivities as a function of ϕ and $h\nu$, as evidently shown in Fig. 2. These confirm that for a uniform magnetization reversal, ϕ vs θ_K measurements do not show any change in H_{eb}, whereas nonuniform magnetization reversals evidently yield changes in H_{eb} depending on ϕ.[15]

The simulation results, hence, provide a clear evidence that the experimental result of depth-resolved exchange bias holds true and can be obtained from ϕ vs θ_K measurements. Here we notice that we neither intend to simulate the exact shapes of experimentally observed loops and nor intend to determine the exact spin structure in the Co layer during the reversal. The observed nonuniform exchange bias itself is quite interesting because the spin structure of a F layer coupled to an AF layer is typically assumed to be uniform inside the F layer in most previous models of exchange bias. Also, the nonuniform exchange bias inside the Co layer should give rise to incoherent rotation in depth during the reversal. In this work, even though we cannot determine the exact spin structure of Co, our experimental observation of depth-resolved, Co-specific loops supports that at least a part of spring-like (twist) spin structure might be present within the Co layer during the reversal. Probably, the incoherent rotation in such an ultrathin Co layer may be possible for the case of much reduced Co exchange coupling compared to that of the bulk. Not only Pd proximity but also many *in situ* measurements during the Co growth seem to cause such reduction in Co exchange coupling in our sample.

Finally, in order to examine to what extent depth resolution can be obtained in a single magnetic layer, we also calculate θ_K with varying ϕ from a simple Co/Pd bilayer structure. Figure 4 shows the calculated contrasts in θ_K vs ϕ for Co spin flips independently at top, middle, and bottom layers of one monolayer thickness. The contrast at $\phi=6.0°$ is almost zero for the spin flip of the bottom layer, while largest for the top spin flip. Thus, at that angle any spin reversal at
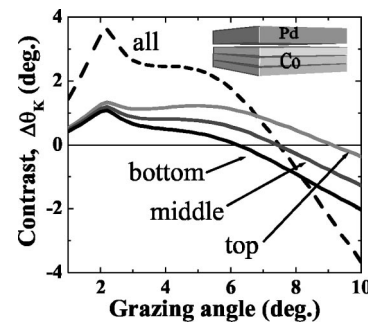

FIG. 4. Calculated contrasts in θ_K as a function of ϕ at $h\nu=778.5$ eV for spin flips independently at top, middle, and bottom depths within the 0.6-nm-thick Co layer of a Co (0.6 nm)/Pd (1.5 nm) bilayer structure.

the bottom layer cannot be measured, but the top spin reversal can be resolved sensitively via θ_K since its largest sensitivity. In contrast, the depth selectivity at $\phi=9.2°$ is reversed for the top and bottom spin reversals. By choosing not only appropriate ϕ but also $h\nu$ in the θ_K measurements, thus we can resolve magnetization reversals at different depths even in a few monolayer thick layers.

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[12] We believe that the size of soft x-ray beam is much larger than that of many magnetic domains of somewhat different H_{eb} so that the measured Kerr signal is average over slightly different H_{eb} of the individual domains at each ϕ. If experimentally observed nonuniform exchange bias were caused by a possible lateral heterogeneity, every ϕ loop would show nonuniform reverslas as well, as observed by a VSM.
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[15] In this model, while H_{eb} varies with depth, H_c and slopes for different depths are assumed to be the same. Therefore, H_c does not vary with ϕ, but the loop slopes somewhat change with depth since different H_{eb} with depth assumed in the model contribute to each loop at a given ϕ. In experimental results, the variations in H_c and slope as well as H_{eb} with ϕ are possible due to likely depth varying H_c in the Co layer of the sample used in this work.