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Switchable Uncompensated Antiferromagnetic Spins: Their Role in Exchange Bias

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We report element-resolved and interface-sensitive magnetization reversals investigated from an oppositely exchange-biased NiFe/FeMn/Co structure by employing soft x-ray resonant Kerr rotation measurements. We have found not only switchable uncompensated antiferromagnetic regions with its sizable thicknesses at both interfaces of the FeMn layer but also their strong coupling to the individual ferromagnetic layers. These experimental results provide a better insight into experimentally observed reductions in exchange-bias field on the basis of an interface-proximity model proposed in this work.

Key words : Exchange bias, Soft x-ray resonant Kerr rotation, Uncompensated

1. Introduction

Since the exchange bias (EB) effect was first discovered by Meiklejohn and Bean [1], its underlying physics has been intensively studied for the past two decades [2]. One of unsolved issues in this research area is about experimentally observed reductions in the EB field, H_{eb}, in coupled ferromagnetic/antiferromagnetic (F/AF) metallic systems. The typical values are two orders of magnitude less than the theoretical values [2]. Some earlier models proposed so far seem to predict well the reduction of H_{eb}, but their underlying physics are still controversial [3-8].

In this article, we report element-resolved and depth-sensitive magnetization **M** reversals for interfacial uncompensated (UC) regions in an AF layer and two F layers, and their strong coupling in an oppositely exchange-biased NiFe/FeMn/Co structure, investigated by soft x-ray resonant Kerr rotation measurements. We have found that *switchable* UC Fe spins at both interfaces of the FeMn layer are sizable in its thickness, F in character, and coupled strongly to the reversals of the individuals of exchange-biased NiFe and Co. Here, we address a likely role of the switchable UC region in the EB effect and suggest the origin of the reduction of H_{eb} on the basis of our model calculations in the framework of an interface-proximity effect proposed in this work.

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2. Experiments

The sample studied here is as follows: Si/SiO_2(150 nm)/Ta(5 nm)/$Ni_{81}Fe_{19}$(8 nm)/$Fe_{50}Mn_{50}$(20 nm)/Co(3.5 nm)/Pd(1.5 nm). The two F NiFe and Co layers were oppositely exchange-biased by the single AF FeMn layer, set during a special cooling procedure. Details of each layer growth, and sample characterizations, the EB setting have been reported elsewhere [9]. From this oppositely exchange-biased sample, we measured soft x-ray resonant Kerr rotation θ_K loops at different values of the grazing angle of incidence, φ, and photon energy, $h\nu$, of linearly *s* polarized soft x-rays in the vicinity of each element resonance.

3. Results and Discussion

The resonant features of the individual magnetic elements, and their dependence on φ selected in the measurements evidently appear in the Kerr intensity I_K spectra at $\varphi = 9°$ and 10°. This result clearly exhibits the element specificity of the soft x-ray Kerr effect [10, 11].

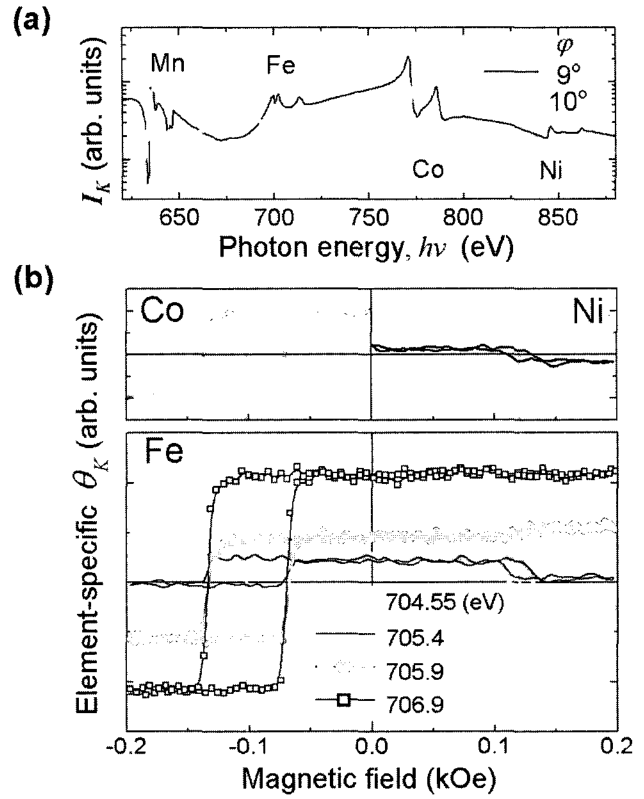

Fig. 1. (a) I_K spectra measured in the $h\nu$ range covering the resonance regions of all the constituent magnetic elements. The $h\nu$ values shown in (a) are not corrected. (b) Co-, Ni-, and Fe-resolved θ_K loops measured at $\varphi = 9^\circ$ for Ni and Fe, and at $\varphi = 10^\circ$ for Co.

Together with this capability, a much improved depth selectivity has been also proved in our earlier works [12, 13]. By combining these two abilities, we can investigate element-specific and depth-sensitive magnetization **M** reversals in such complex magnetic multilayer films. Figure 1(b) shows the resultant hysteresis loops of Co, Ni, and Fe specific **M** reversals, measured at different φ and $h\nu$ values as noted. From these separated loops, we can identify the **M** reversals of the individual constituent F layers, i.e., Co- and Ni-resolved loops, which are shifted to $H_{eb} = -100$ and +120 Oe, respectively. This opposite shift of the two Co and NiFe loops represents that both layers are oppositely exchange-biased as designed by a previous cooling procedure. The Fe-resolved loops, which are considerably dependent on $h\nu$, are contributed from the three different parts: the NiFe layer and the two interfacial UC regions. Due to the oppositely oriented exchange-biasing between the two F layers, we can resolve the reversals of UC Fe spins at both interfaces of the FeMn layer, which are coupled to the oppositely oriented reversals of the two F layers. The negatively shifted Fe loops themselves manifest that the interfacial Fe spins adjacent to the Co layer are F in character, i.e., UC at the corresponding interface, and also coupled strongly to the Co reversal. As for the opposite side, the Fe loops originate from the interfacial UC Fe in the proximity to the NiFe layer as well as from Fe in the same NiFe layer, indicating that both are also coupled at the FeMn/NiFe interface. From these element-resolved loops, we can identify the individual switching behaviors of constituent layers and both interfacial UC AF regions, and their couplings.

The depth sensitivity of soft x-ray resonant Kerr rotation with an atomic-scale resolution found in our earlier works [12, 13] is then applied to determine the effective thicknesses t_{UC} of switchable UC regions. By making an elaborate analysis of the Fe resolved loops measured at different values of $h\nu$, which are contrasting for slighty different $h\nu$ values, t_{UC} are estimated to be 13 ± 2 Å and 6 ± 4 Å at the FeMn/Co and NiFe/FeMn interfaces, respectively. Details of the determination of t_{UC} have been reported elsewhere [14]. Such sizable t_{UC} values indicate the presence of a magnetically distinguishable layer from the interior of the nominal AF and F layers. Such distinct layer can be formed in a variety of hybrid systems due to the proximity effect at various interfaces [15-17]. This proximity effect at F/AF interfaces has been ignored to explain significantly reduced H_{eb} observed typically in experiments. This layer may influence the size of H_{eb} and H_c as an additional buffer that plays a crucial role in the EB effect, hence should be explicitly considered in modeling.

4. An Interface-proximity Model

Here we propose an interface-proximity model, as depicted in Fig. 2(a). J_F and J_{AF} are different exchange coupling constants at different interfaces of UC/F and AF/UC, respectively. The magnetocrystalline anisotropy (MCA) constant K and the saturation magnetization M are also defined for the individual F and UC layers. By assuming the Stoner-Wohlfarth (i.e., coherent rotation) reversal, total energy E_{tot} divided by an interface area γ is given as

$$E_{tot}/\gamma = -J_{AF}\cos\phi_{UC} - J_F\cos(\phi_{UC} - \phi_F) - M_{UC}t_{UC}H\cos(\phi_{UC} - \phi_H) - M_F t_F H\cos(\phi_F - \phi_H) - K_{UC}t_{UC}\cos^2\phi_{UC} - K_F t_F\cos^2\phi_F,$$

where the first and second terms are the exchange interaction energies, the third and fourth the Zeeman energy terms, and the fifth and sixth the in-plane MCA terms for the individual F and UC layers.

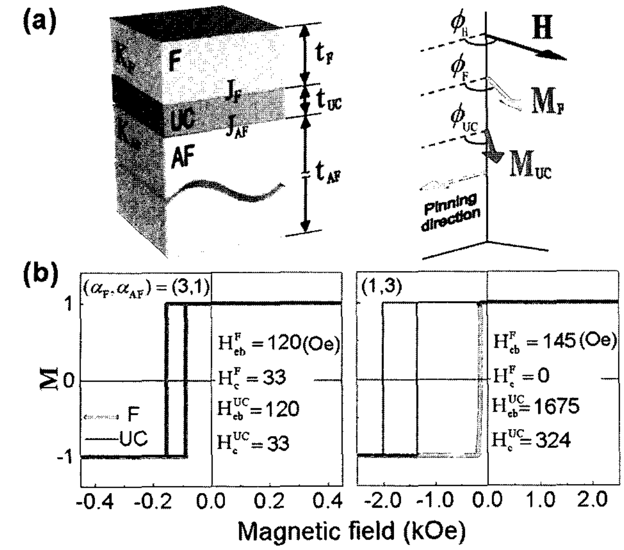

Fig. 2. (a) An interface-proximity model and relations of ϕ_F, ϕ_{UC} and ϕ_H. The physical parameters relevant to this model are as follows: $M_F = 1500$, $M_{UC} = 800$ emu/cm^3, $K_{AF} = 30000$ erg/cm^3, $K_F t_F = \eta(K_{UC} t_{UC} \cdot J_F)^{1/2}$, $K_{UC} t_{UC} = \eta(K_{AF} t_{AF} \cdot J_A)^{1/2}$ with $\eta = 0.16$. (b) Normalized **M** reversal curves of F and UC layers, calculated for $t_{AF} = 20$, $t_{UC} = 1.2$, and $t_F = 3.5$ nm at $\phi_H = 0$ at both cases of $(\alpha_F, \alpha_{AF}) = (3, 1)$ and $(1, 3)$.

In order to correctly predict typically observed enhancements in H_c of an F layer in coupled F/AF systems just by using the above equation without any additional models [18-20], we adopt an induced K for a coupled F layer instead of its intrinsic bulk value. On the basis of the microscopic MCA origin [21], we finally deduce $K_F t_F = \eta(K_{UC} t_{UC} \cdot J_F)^{1/2}$ and $K_{UC} t_{UC} = \eta(K_{AF} t_{AF} \cdot J_{AF})^{1/2}$ as described [22].

Under given physical parameters and a certain condition of ϕ_H and H, the equilibrium values of ϕ_F and ϕ_{UC} can be determined by finding local minima of E_{tot}. From the found values of ϕ_F and ϕ_{UC} as a function of H at various values of ϕ_H, the **M** reversal curves of both F and UC layers can be determined for two cases of $J_F > J_{AF}$ and $J_F < J_{AF}$ as shown in Fig. 2(b). For $(\alpha_F, \alpha_{AF}) = (3, 1)$ at $\phi_H = 0°$ (where $J_{AF} = J_0 \alpha_{AF}$, $J_F = J_0 \alpha_F$ with $J_0 = 0.08$ erg/cm^2), H_{eb} and H_c values for both F and UC layers are clearly found as noted and those values are comparable to their experimental ones for a Co/FeMn interface of our sample [14]. This is because we use a weak exchange coupling of $J_0 = 0.08$ erg/cm^2 in this calculation. In that case, the F and UC spins simultaneously switch because the coupling between both layers is stronger than that between the UC and nominal AF layers. For $(\alpha_F, \alpha_{AF}) = (1, 3)$, the UC layer switches at higher fields while the F layer switches at lower fields, hence H_{eb} values for the two layers are not equal.

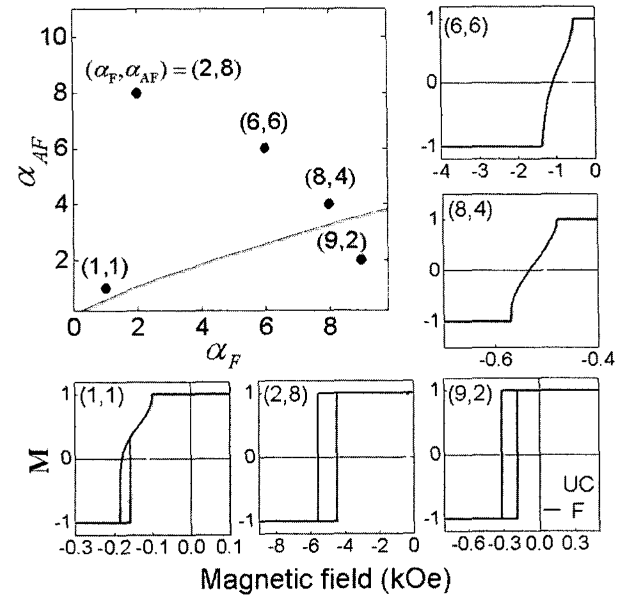

Fig. 3. Normalized **M** reversal curves at given values of (α_F, α_{AF}) as noted. The remaining physical parameters used in this calculation are the same as those in Fig. 2(b). The gray-shaded area represents simultaneous switching of the F and UC layers.

For different relative strengths of J_F and J_{AF}, we also calculate the **M** reversals of individual F and UC layers. For J_F and J_{AF} values outside the gray-shaded area in Fig. 3, the F and UC reversals are quite different and do not switch simultaneously. In contrast, for J_F and J_{AF} within the gray-shaded area, both layers switch simultaneously. Their characteristic loop shapes for various (α_F, α_{AF}) values as noted are given in Fig. 3. In the case of the simultaneous reversals, the switchable UC Fe spins apparently do not pin the F layer during exchange biasing since the UC region switches together with the F reversal. However, the UC region is still coupled to the nominal AF layer, according to the interface-proximity model and experimental observations of element- and depth-resolved loops. Thus, it is certain that the F layer is not exchange-biased directly by the AF layer, but through the UC region. Such strongly coupled reversals between the interfacial UC AF and F layers have been observed because J_F is typically stronger than J_{AF} in metallic F/AF real samples.

Figure 4 displays calculations of H_{eb} and H_c versus both α_F and α_{AF} using the interface-proximity model [23]. It is quite interesting that for $\alpha_{AF} \le 1$, H_{eb} remains almost constant, i.e., independent of α_F even up to $\alpha_F = 10^3$. For the larger values of α_{AF}, H_{eb} monotonically increase with α_F up to its certain value and then saturate above that value. These results indicate that significantly reduced α_{AF} can lead to the reduction of H_{eb} even for α_F being as

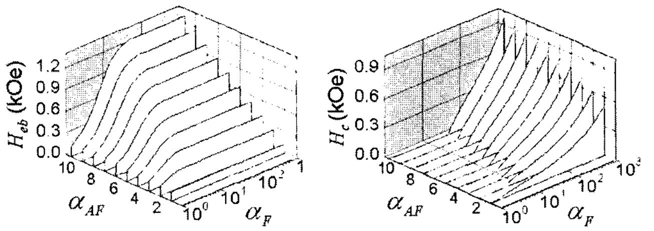

Fig. 4. Calculations of H_{eb} and H_c versus α_F and α_{AF} for the F layer with the same remaining parameters as those shown in Fig. 2.

large as 10^3. Typically observed reductions in H_{eb} have not been well explained in terms of such a theoretical large value of J simply using the MB model [1], but are well predicted by the interface-proximity model proposed in our earlier work [22]. Furthermore, our model seems to explain well experimentally observed enhancements in H_c by solving E_{tot} without any additional models [18-20].

5. Conclusion

We suggest that the experimental reduction of H_{eb} be caused by J_{AF} much weaker than J_F, driven by a magnetically modified UC region with its sizable thickness, and that the experimental estimations of J in exchange-coupled F/AF samples through H_{eb} could be J_{AF} not J_F for the general case of $J_F > J_{AF}$ in metallic systems. Possible imperfections of the rigidity of an AF layer in real samples can be implemented into an effective value of J_{AF} for our model. The conditions of sample preparations as well as EB setting would affect the relative strength of J_F and J_{AF}, and t_{UC}, as well.

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