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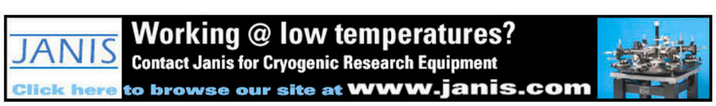

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Probing the magnetization reversal in epitaxial Fe/IrMn exchange biased bilayers using angle-dependent anisotropic magnetoresistance

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We investigated the detailed magnetotransport properties of epitaxial Fe/IrMn exchange biased bilayers by angle-dependent anisotropic magnetoresistance measurements over a wide temperature range. Irreversible resistance jumps and smooth transitions are observed when measuring along different angles with respect to the bias at certain temperatures. The angular dependence of the switching fields shows good agreement with a domain wall (DW) nucleation model. The exchange bias, the induced uniaxial anisotropy, and the intrinsic 90° DW nucleation energy are further extracted from the angle-dependent measurements. A linear temperature dependence is observed for both the exchange bias and the induced uniaxial anisotropy, while the intrinsic 90° DW nucleation energy is independent of the temperature. © *2012 American Institute of Physics*. [doi:10.1063/1.3675179]

I. INTRODUCTION

The exchange bias (EB)[1] of ferromagnetic (F)/antiferromagnetic (AF) bilayers has been extensively studied in the past few decades due to its key role in magnetic recording technologies. The EB typically occurs due to the interfacial exchange coupling at the F/AF interface, which gives rise to a hysteresis loop shift (H_{eb}), and an enhancement of the coercivity (H_c).[2,3] Phenomenologically, competing anisotropies have been used to give quantitative interpretations. By considering a unidirectional anisotropy, K_{eb}, and an induced uniaxial anisotropy, K_u, for many polycrystalline EB systems the value of H_{eb} and H_c can be numerically fitted by a coherent rotation model.[4]

Despite extensive research, there are still ongoing controversies about the fundamental magnetization reversal mechanisms in EB systems. Recent experimental works on epitaxial (002) exchange biased Fe/MnF$_2$,[5] Fe/MnPd,[6,7] and Fe/IrMn (Ref. 8) bilayers show inconsistency with the coherent rotation protocol. In contrast, a domain wall (DW) nucleation model showed good agreement with all of the experiments.[7] Recently, by using Lorentz TEM, Wang *et al.* also directly observed that the magnetization reversal in epitaxial Fe/IrMn bilayers occurs through DW nucleation and propagation.[9] For quantitative interpretations, the angular dependent magnetic measurements are usually performed by using the vector magneto-optic Kerr effect,[10,11] which offers a comprehensive understanding of the magnetic reversal processes by independently probing both the longitudinal and transverse magnetization components. With this technique, the magnetization reversal behavior of epitaxial (002) EB systems at room temperature (RT) have been systematically studied.[5–8] Symmetric and asymmetric multistep loops were observed and attributed to the DW nucleation and propagation along the different Fe cubic easy axes directions. However, such magnetic properties at low temperatures, and the temperature dependent reversal behavior, remain unexplored. Previous experimental works,[9,12,13] along with the theoretical ones[14] only studied the temperature dependence of H_{eb} and H_c along the bias direction. In this paper, we measured the angular dependence of the magnetization reversal over a wide temperature range from 10 to 300 K, probed by an anisotropic magnetoresistance (AMR) measurement, using a Quantum Design physical property measurement system (PPMS) with an in-plane rotator. The AMR is advantageous over other magnetometry in studying the magnetization reversal due to its better sensitivity to the magnetization distribution during the reversal process.[15,16]

II. EXPERIMENT

Epitaxial Fe(10 nm)/IrMn(4.2 nm) bilayers in the shape of a Hall bar were deposited through a shadow mask on MgO(001) substrates under our well-defined recipe.[8] A Ta layer (5 nm) was used as a capping layer. A permanent magnet generating a field of ~300 Oe was employed along the Fe [010] easy axis throughout the sample deposition and cooling process (to RT), to define the EB direction. The AMR measurement was performed using the PPMS with a horizontal rotator. The conventional 4–probe technique was applied with a DC current flowing along the bias direction; see Fig. 1. The sample was first field-cooled from 300 to 10 K under a 5 KOe field parallel to the bias. Subsequently, the angle-dependent AMR data was acquired at 10 K, and at temperature steps of 20 K from 20 to 300 K. Specifically, at each temperature, the magnetoresistance (MR) signals versus the applied field, H_{ext}, $R(H)$, were measured at different ϕ, defined as the angle between H_{ext} and the Fe[010] easy axis (Fig. 1). The AMR originates from the anisotropic spin-orbit coupling effect that results in a resistance maximum when the magnetization is aligned along the direction of the current flow and a minimum when they are mutually orthogonal. The critical field, H_{crit}, at which the MR switches from a

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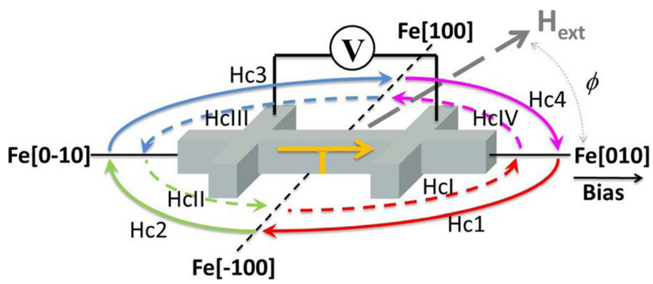

FIG. 1. (Color online) Geometry of the AMR experimental setup with the relative orientation of the bias, DC current, external magnetic field, H_{ext}, and the various switching fields between different Fe easy axes.

high to a low resistance (or vice versa) indicates the 90° DW nucleation process. Previous works have shown that the magnetization reversals are achieved via nucleation of either 90° or 180° DWs with propagation along the different Fe easy axes.[7] Depending on the initial and final remanent directions, with respect to the crystallographic orientation involved in a magnetic transition, we refer to the corresponding switching fields of 90° magnetization reversal as H_{c1} to H_{c4} (clockwise) and H_{cI} to H_{cIV} (counterclockwise); see Fig. 1. Note that AMR is only sensitive to 90° magnetization reversals and the 180° magnetization reversal via DW nucleation cannot be probed because there is no resistance change from the parallel to the antiparallel configuration of the magnetization with respect to the current.

III. RESULTS AND DISCUSSIONS

The $R(H)$ signals at 10 K at various representative ϕ are displayed in Figs. 2(a)–2(b), showing the two-step magnetic reversal by two successive 90° DW nucleations. At $\phi = -30°$ [Fig. 2(a)], for the decreasing field process (square), the magnetization was originally saturated along the Fe[010], parallel to the current direction, and displayed a high resistance state. Upon the first switching, the magnetization is abruptly reversed at H_{cIV} to the intermediate state in which the Fe spins are oriented along Fe[100], perpendicular to the initial and final remanent axes. In this case, the magnetization is perpendicular to the current leading to a low resistance state. Then, upon the second switching, it smoothly reversed to Fe[0–10] at H_{cIII} and displayed a high resistance state. It is worth noting that the reversal in each step takes place in a different manner. In the first step, the magnetization reversed mainly via a sharp irreversible transition, indicating that the reversal is mainly governed by nucleation and propagation of magnetic domains; in the second one, smooth reversible transitions were observed, indicating that the magnetization rotation is the relevant process during reversal. The magnetization reversals for the increasing field (circle) follow the same semicircle with the decreasing field, marked by the switching fields, H_{c3} and H_{c4}, according to our model.[7] Perpendicular to the bias, $\phi = -90°$ [Fig. 2(b)], the reversal process for the decreasing and increasing field is symmetric with respect to the $H = 0$ (*x-axis*), and only sharp irreversible transitions were observed. The intermediate states for $\phi = -90°$ are mediated by the Fe spins oriented along the easy axis given by the bias,

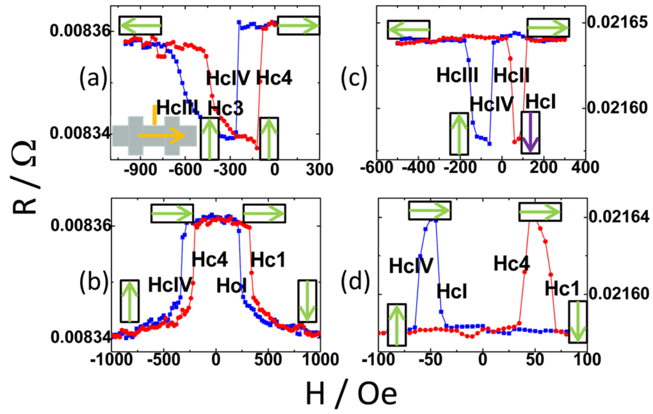

FIG. 2. (Color online) Angle-dependent $R(H)$ signals at (a) $\phi = -30°$, and (b) $\phi = -90°$ at 10 K; and at (c) $\phi = -30°$, and (d) $\phi = -90°$ at 300 K. The orientations of the Fe spins in the switching processes are represented by the arrows enclosed in a square.

i.e., Fe[010], parallel to the current. As a result, the high resistance state was observed at the intermediate states. For comparison, the $R(H)$ signals at 300 K and at the same ϕ are shown in Figs. 2(c)–2(d). Here, only sharp irreversible transitions were obtained at all ϕ. Certain magnetization reversals are observed at different switching fields when compared to the data at 10 K. This is due to the different semicircles involved during the switching along the decreasing and increasing fields, respectively.[8] Specifically, the magnetization reversal route for the decreasing and increasing field lies in opposite semicircles for $\phi = -30°$, and lies in the same semicircle for $\phi = -90°$. Note that this asymmetry is developed within an all DW-nucleation protocol, and is different from the earlier reports where DW nucleation and coherent rotation both exist but take place along different reversal branches.[17]

The ϕ-dependence of the switching fields at 10 and 300 K is summarized in Fig. 3, and subsequently interpreted by the DW nucleation model. The model considered the intrinsic 90° DW nucleation energy, $\varepsilon_{90°}$, the exchange anisotropy, K_{eb}, and the induced uniaxial anisotropy, K_u. The equations for the theoretical switching fields can be found in Ref. 7. The results of the fitting for the data at 10 K shows relatively good agreement, with the fitting parameters, $K_{eb}/M = 206$ Oe, $\varepsilon_{90°}/M = 85$ Oe, and $K_u/M = 40$ Oe, where M is the magnetization. Overall, the angle-dependent behavior is well-reproduced by the DW nucleation model. However, deviations exist for the switching fields H_{c2}, H_{c3}, H_{cII}, and H_{cIII} at $-45° < \phi < 45°$, and H_{cI} and H_{c4} at $-135° < \phi < -45°$. Taking a look back at the $R(H)$ signals, smooth reversible transitions, rather than sharp ones, were observed at these corresponding ϕ for these switching fields, which indicated that the magnetization reversal was mainly achieved via coherent rotation rather than DW nucleation. For the data at 300 K, all of the switching fields can be well reproduced under the single DW nucleation model, with the fitting parameters $K_{eb}/M = 10$ Oe, $\varepsilon_{90°}/M = 50$ Oe, and $K_u/M = 5$ Oe.

Similar angular dependence measurement and analysis has been performed at each temperature from 20 to 300 K, in steps of 20 K. For 200 K $< T <$ RT, the magnetization reversal

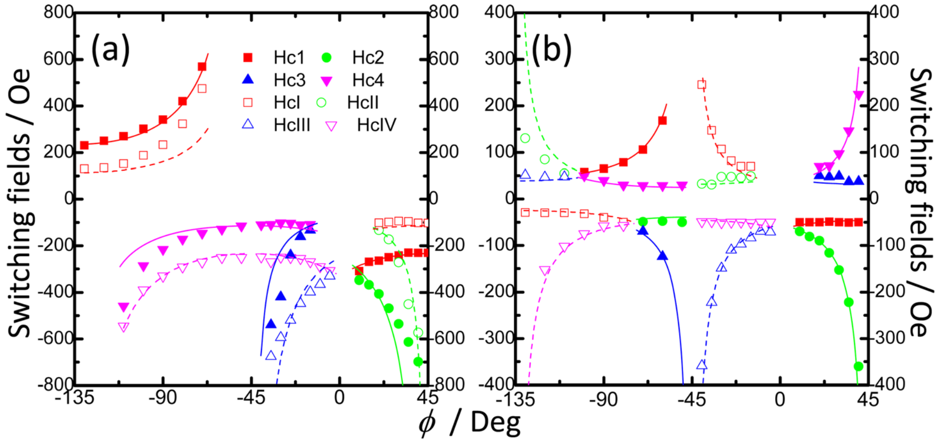

FIG. 3. (Color online) Angular dependence of the experimentally observed switching fields (symbols) and the corresponding theoretical fitting results (curves) at (a) 10 K, and (b) 300 K. The switching fields, represented by different symbols and curves, correspond to the magnetic transitions between the different initial and final Fe easy axes orientations.

close to the bias occurred via one-step (180°) transitions, and thus, was not accessible by AMR measurements. The derived parameter, K_{eb}/M, $\varepsilon_{90°}/M$, and K_u/M for $10\ K < T < 200\ K$ is summarized in Fig. 4. The bias field, K_{eb}/M, decreased linearly with increasing temperature. The uniaxial anisotropy field, K_u/M, also showed a similar linear dependence, confirming the bias induced nature of the K_u. For some Fe based EB systems, it is possible to induce a perpendicular coupling at the F/AF interface.[18] A non-linear temperature dependence of the EB due to this perpendicular coupling has been reported and a negative K_u was also indicated.[18] However, in our Fe/IrMn system, a linear temperature dependence was found and is in good agreement with the Malozemoff model for the EB[12,13,19] that considers a parallel F and AF coupling. The all-positive K_u values determined from our fitting also showed no evidence of any perpendicular coupling, even at low temperature. On the contrary, it is noted that the 90° DW nucleation energy, $\varepsilon_{90°}/M$, does not show a significant temperature dependence. Our previous work showed this term being strongly dependent on the AF layer thicknesses.[7,8] Such thickness dependence is likely attributed to the fourfold anisotropy induced by the AF layer[20] that was superimposed on the intrinsic Fe cubic anisotropy. However, even this induced fourfold anisotropy does not show a significant temperature dependence, recent experiments on the CoO/Fe/Ag(001) system[20] showed that the induced anisotropies and bias field actually come from different origins of the AF spins. We believe a similar phenomenon occurs in our Fe/IrMn system. With a decrease in temperature, the bias field increases due to the enhanced effective pinning at the interface. However, those AF spins that account for the fourfold anisotropy do not change much with the temperature. Finally, our results also show that the AMR is a good tool to study the temperature-dependent anisotropy in a single-crystalline system.

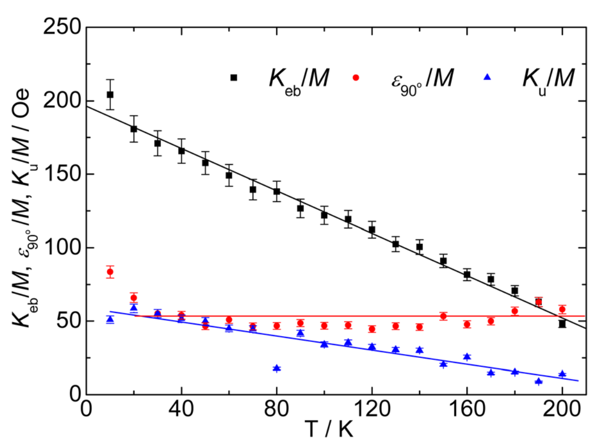

FIG. 4. (Color online) Temperature dependence of the parameters, $\varepsilon_{90°}/M$, K_{eb}/M, and K_u/M, given by the fitting for the angular dependent switching fields. Linear lines are guides to eye.

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