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Magneto-optical study of magnetization reversal asymmetry in exchange bias

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The asymmetric magnetization reversal in exchange biased Fe/MnF_2 involves coherent (Stoner-Wohlfarth) magnetization rotation into an intermediate, stable state perpendicular to the applied field. We provide here the experimentally tested analytical conditions for the unambiguous observation of both longitudinal and transverse magnetization components using the magneto-optical Kerr effect. This provides a fast and powerful probe of coherent magnetization reversal as well as its chirality. Surprisingly, the sign and asymmetry of the transverse magnetization component of exchange biased, low-anisotropy MnF_2 and high-anisotropy FeF_2 change with the angle between cooling and measurement fields. © *2006 American Institute of Physics*.
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A ferromagnetic (FM) layer in contact with an antiferromagnetic (AFM) one experiences a shift of the hysteresis loop along the field axis due to the so-called exchange bias (EB).[1,2] One of the intriguing features of EB is a pronounced asymmetry in the hysteresis loops, a very unusual phenomenon in magnetism since all other magnetic materials exhibit symmetric reversal. The most prominent example of an asymmetric reversal occurs in Fe/MnF_2, which exhibits a pronounced step on only one side of the hysteresis loop.[3] Polarized neutron reflectometry (PNR) showed that this step is related to coherent rotation of the magnetization,[3,4] which is pinned in a potential minimum transverse to the applied magnetic field. As PNR is not sensitive to the direction of the transverse moment it cannot determine the chirality of the magnetization vector upon magnetization reversal.

Although asymmetric magnetization reversal has been claimed from PNR,[4] viscosity,[5] and anisotropic magnetoresistance[6] measurements, vector magnetometry and especially magneto-optical Kerr effect (MOKE), i.e., vector MOKE, have not yet been performed. MOKE studies, accessing both longitudinal and transverse magnetization components, are scarce for exchange biased systems.[7–9] It is therefore important to analyze how coherent magnetization rotation manifests itself in a well-defined MOKE signal.

Here, we use MOKE in separate longitudinal and transverse geometries to study magnetization reversal in the model exchange bias system Fe/MnF_2(110). This fast technique allows us to determine the chirality of the magnetization reversal via the *sign* of the transverse magnetization component. We derive analytical conditions to unambiguously identify in the experiment the Kerr signature of pure longitudinal (M_L) or transverse (M_T) magnetization components. These conditions allow for the determination of the orientation and relative magnitude of the in-plane magnetization components at all fields during magnetization reversal. Surprisingly, the hysteresis loop asymmetry critically depends on the angle φ_H between the in-plane measurement field and the cooling field direction. Within a few degrees M_T changes its sign. For 90° it appears on both sides of the loop with the same sign of rotation, contrary to a Stoner-Wohlfarth (360°) reversal process. For the analogous case of exchange biased epitaxial, twinned FeF_2(110),[4] which has a 20 times higher anisotropy than MnF_2(110),[10] this angular dependence is narrowed down dramatically.

Polycrystalline Fe on epitaxial, twinned, MnF_2(110) has been grown in the structure MgO(100)/ZnF_2(110)/MnF_2(110)/Fe/Al with thicknesses of ⋯/25/65/12/3 nm, respectively. Details of the sample preparation and structural characterization are given elsewhere.[3]

MOKE measurements were performed with an in-plane magnetic field H_{ext} oriented horizontally [Fig. 1(a)] and at 45° with respect to the [001] direction of the AFM twins. This is crucial to observe the asymmetry in the hysteresis loop.[3] Kerr loops were taken in two separate configurations [Fig. 1(a)]. In the horizontal configuration (I) the plane of incidence is horizontal, i.e., parallel to the longitudinal magnetization M_L, as in longitudinal Kerr effect. In the vertical configuration (II) the plane of incidence is parallel to the transverse magnetization M_T. For both configurations the linearly polarized incident light can be continuously rotated from *s* to *p* polarization using a λ/2 retarding plate. Kerr rotation of the reflected laser beams can be simultaneously detected in both configurations. For detection [Fig. 1(b)], the beam reflected from the sample passes a Glan-Thompson polarizing beam splitter, where it is separated into two orthogonal polarized beams which are focused by lenses onto diodes A and B of a diode bridge. The light intensities at the diodes, I_A and I_B, and the difference signal I_{A-B} are simultaneously measured using a lock-in amplifier. Prior to each measurement the diode bridge is balanced ($I_{A-B}=0$) using a λ/2 retarding plate. All Kerr loops were taken at $T=20$ K

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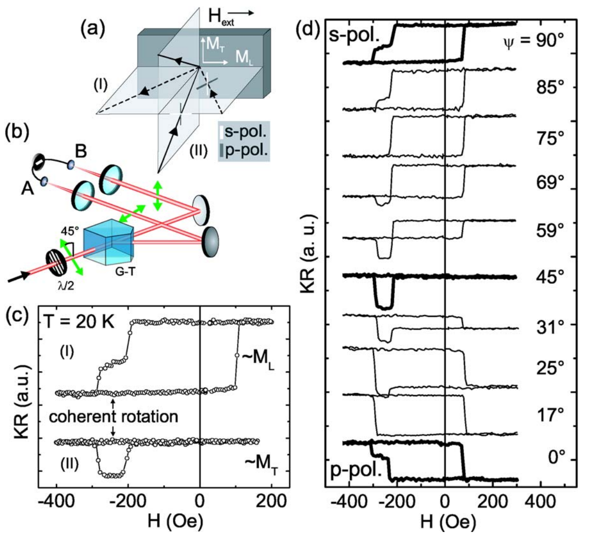

FIG. 1. (Color online) (a) MOKE setup in horizontal (I) and vertical (II) configurations. (b) Diode bridge detector for MOKE (λ/2=half-wave plate, G-T=Glan-Thompson prism, which separates orthogonal linear polarizations). The light reflected from the sample enters from the lower left side. MOKE loops of Fe/MnF_2 at T=20 K for (c) *s*-polarized incident light in the horizontal (I) and the vertical (II) configurations and (d) different polarization directions of the incident beam in the horizontal (I) configuration.

after field cooling (FC) through the Néel temperature (T_N =78 K) in H_{FC}=1 kOe in the film plane at 45° to the twins aligned along the [001] direction of $MnF_2(110)$.

Figure 1(c) shows Kerr rotation (I_{A-B}) data using *s*-polarized incident light for both MOKE configurations (*s*-polarization for each plane of incidence). For the horizontal configuration (I) we observe a strongly asymmetric hysteresis loop with a distinct plateau on the negative field side of the loop. The loop shape is identical to that taken with a superconducting quantum interference device magnetometer under identical conditions (not shown), indicating that this Kerr loop is a measure of M_L. In the vertical configuration (II) a pronounced peak is observed only in the field range where the longitudinal signal shows the horizontal plateau. Elsewhere, the Kerr rotation is zero. Such a peak was observed earlier, on an identical sample, by PNR, and was shown to originate from M_T. Thus, MOKE in the vertical configuration (II) probes unambiguously the transverse magnetization component M_T due to coherent magnetization rotation with respect to H_{ext}.

Figure 1(d) shows a series of Kerr loops [all taken in the horizontal configuration (I)] as a function of the incident polarization direction from *s*- to *p*-polarized state (ψ =90° to 0°). The observation of identically shaped loops but with reversed sign for pure *s*- and *p*-polarized light is an intriguing feature. Even more surprisingly, the loop at ψ =45° is very similar to the one in the transverse configuration [Fig. 1(c)]. In transverse MOKE, however, the M_T component is predicted[11] to appear for *p* polarization, i.e., at ψ =0°.[11] This indicates that both M_L and M_T can actually be measured in a single geometrical setup simply by changing ψ, but with additional conditions (see below). For all other ψ, the Kerr loops appear to be a superposition of the loops taken at ψ=0° and 45°.

More detailed results are summarized in Fig. 2 in both horizontal (left panel) and vertical (right panel) configurations, for ψ=90° [*s* polarization, Figs. 2(a) and 2(d)], 45°

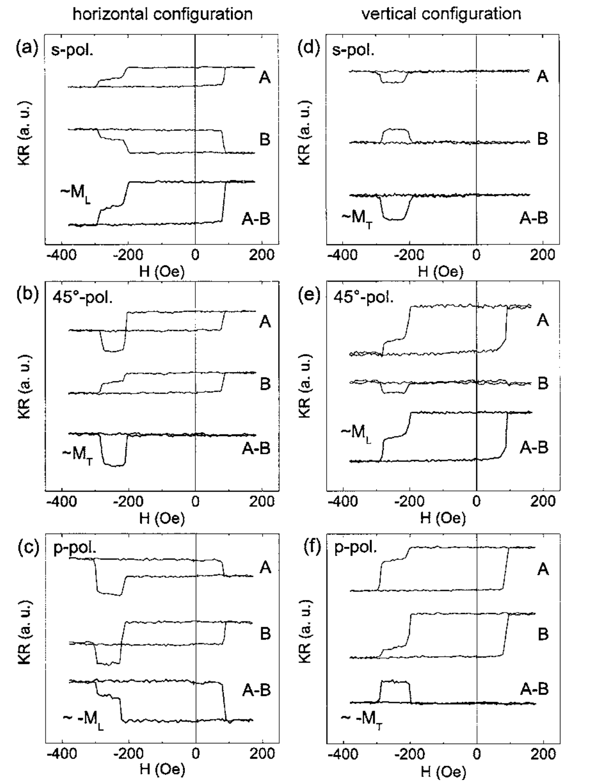

FIG. 2. MOKE loops of $Fe/MnF_2(110)$ at T=20 K in the horizontal (left panel) and vertical (right panel) configurations for different incident polarization directions. Both diode signals I_A and I_B and their difference signal I_{A-B} are shifted and shown for each polarization.

[Figs. 2(b) and 2(e)], and 0° [*p* polarization, Figs. 2(c) and 2(f)]. In the vertical configuration the Kerr loops (I_{A-B}) are identical for *s* and *p* polarizations except for their sign. In addition, the loop at ψ=45° has the shape found for *s* polarization in the horizontal configuration.

Most previous analytical MOKE descriptions deal with Kerr rotation detection with a crossed analyzer,[12–15] as opposed to our diode bridge technique. Here, we derive analytical expressions for observations of the pure components M_L and M_T.

In the *horizontal configuration* the optical path is given by[13]

$$\frac{\vec{E}}{E_0} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} 1+M_T T & M_L L \\ -M_L L & S \end{bmatrix} \begin{bmatrix} \cos\psi \\ \sin\psi \end{bmatrix}, \quad (1)$$

with $S=r_{ss}/r_{pp}$, $T=\Delta r/r_{pp}$, and $L=r^l_{sp}/r_{pp}$, where r_{pp} and r_{ss} are the isotropic Fresnel reflection coefficients for (ψ=0°) *p*- and (ψ=90°) *s*-polarized incident light and Δr and r^l_{sp} are the transverse and longitudinal magneto-optic coefficients, respectively. ψ is the polarization angle of the incident laser beam (as defined above) and α is the angle of polarization rotation, which is required to balance the diode bridge. For ψ=0° $I^L/I_0=|E/E_0|^2$ at the diodes is given by

$$\frac{I^L_{A,p}}{I_0} = M_T\,\mathrm{Re}(T) - M_L\,\mathrm{Re}(L) + \cdots ,$$

$$\frac{I^L_{B,p}}{I_0} = M_T\,\mathrm{Re}(T) + M_L\,\mathrm{Re}(L) + \cdots .$$

Higher order terms in M have been neglected. Interestingly, the difference $I^L_{A-B,p}$ is a measure of M_L only because

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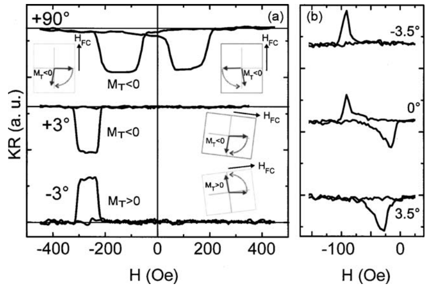

FIG. 3. Sensitivity of transverse MOKE signal at 20 K and field cooling in 1 kOe of (a) $Fe/MnF_2(110)$ and (b) $Fe/FeF_2(110)$ to variations of the angle between the directions of the cooling and measurement fields.

$$\frac{I^L_{A-B,p}}{I_0} = -2M_L\,\mathrm{Re}(L), \tag{2a}$$

consistent with Fig. 2(c). For other polarizations

$$\frac{I^L_{A-B,45°}}{I_0} = M_T\,\mathrm{Re}(T) + M_L\,\mathrm{Re}(L)(1+\mathrm{Re}(S)) + M_L\,\mathrm{Im}(L)\mathrm{Im}(S) \tag{2b}$$

and

$$\frac{I^L_{A-B,s}}{I_0} = -2M_L\,\mathrm{Re}(L)\mathrm{Re}(S) - 2M_L\,\mathrm{Im}(L)\mathrm{Im}(S). \tag{2c}$$

If $I^L_{A-B,s}=-I^L_{A-B,p}$ (condition 1) is satisfied [Fig. 1(d)], the intensities become

$$\frac{I^L_{A-B,45°}}{I_0} = M_T\,\mathrm{Re}(T) \tag{3a}$$

and

$$\frac{I^L_{A-B,s}}{I_0} = 2M_L\,\mathrm{Re}(L). \tag{3b}$$

Hence, for $\psi=45°$, $I^L_{A-B,45°}$ [Fig. 2(b)] is a pure measure of M_T. In the *vertical configuration* at $\psi=45°$, we find that $I^T_{A-B,45°}$ is a pure measure of M_L if $I^T_{A-B,s}=-I^T_{A-B,p}$ (condition 2), which is also satisfied experimentally [Fig. 2(e)].

We point out that the pure M_T signal in the horizontal configuration, or the pure M_L signal in the vertical configuration, will appear at $\psi \neq 45°$ if $I^{L,T}_{A-B,s} \neq -I^{L,T}_{A-B,p}$. Although the determination of this angle is beyond the scope of this letter, we do stress the fact that incorrect conclusions may be obtained if "conditions 1 and 2" are not met. Note that this measurement technique is not quantitative vector MOKE because the ratio of the transverse and longitudinal magnetization components depends on the ratio of the magneto-optic coefficients Re(L) and Re(T) in Eqs. (2a), (3a), and (3b) which are not known.

Most surprisingly, varying the in-plane applied magnetic field by $\varphi_H=\pm 3°$ with respect to the cooling field direction the transverse magnetization component changes sign, i.e., its chirality reverses [Fig. 3(a)]. The fact that for $\varphi_H=\pm 3°$ no M_T signal appears on the right side of the hysteresis loop does not, however, imply that the magnetization reversal proceeds via domain wall nucleation and propagation.[16] At an applied field direction of, e.g., $\varphi_H=90°$ the transverse component appears on both sides of the loop with the same sign, i.e., rotating within the same half plane $[M_T(H)<0]$ in contrast to the full 360° rotation of a Stoner-Wohlfarth reversal.

The types of reversal modes observed for finite φ_H in twinned $MnF_2(110)/Fe$ confirm qualitatively the theoretical predictions for an untwinned EB system.[17] In this model the absence of a transverse component ($M_T=0$) on one side of the loop is attributed to a nonuniform reversal mode.

The similar measurement procedure applied to $Fe/FeF_2(110)$ shows in Fig. 3(b) in between the two transverse components of opposite sign at −3.5° and +3.5°, a full rotational signature at 0° of the Stoner-Wohlfarth type. Moreover, for angles of +5° and −5° (not shown) we find two peaks each of negative and positive sign, respectively. This is in contrast to Fig. 3(a) where this occurs at ±90°. The reason is the higher anisotropy of FeF_2 [Fig. 3(b)] compared to MnF_2 [Fig. 3(a)], giving rise to a rather complex phase diagram as function of the angle between the cooling field and the hysteresis loop-measuring field.[16]

In conclusion, systematic MOKE investigations on the model exchange bias system $Fe/MnF_2(110)$ provide straightforward unambiguous experimental and analytical identifications of well-defined pure transverse and longitudinal magnetization components. Direct comparison with an analytical model yields conditions that allow for the unambiguous decomposition of the magnetization into its longitudinal and transverse components. We observe a strong dependence of M_T on the angle between cooling and measuring fields. These observations confirm theoretically predicted reversal modes.

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