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Out-of-plane stray field at magnetization reversal in epitaxial magnetite thin films

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Abstract

With a μ-Hall sensor array we have studied the local behavior of the out-of-plane stray field component for different magnetic states in Fe_3O_4 thin films on $MgAl_2O_4$ and MgO substrates for fields applied parallel to the main surface. The results indicate a narrow field region where a nearly step-like response and Barkhausen jumps of the out-of-plane stray field are measured. The hysteresis of the local field and its amplitude depend on the magnetic state condition of the film.

Keywords: Magnetite; Magnetization reversal; Micromagnetism; Domain dynamics

In general, for fields applied parallel to the main surface of a ferromagnetic thin film the magnetization reversal is determined by domain nucleation (mainly at the edges) and domain-wall propagation with partial rotation of the magnetization in some of the domains. One aspect of the magnetization reversal process in thin films has not yet been reported, namely the behavior of the magnetization component transverse to the main area of the film. Due to the very large demagnetization factor perpendicular to the plane of the film, the precession of the magnetization **M** is within a cone with an eccentricity of the order of 100. This is the reason for the one-dimensional treatment used in the past and successfully applied to understand ferromagnetic resonances [1]. We may expect that in the process of magnetization reversal under an external field a magnetic torque **T** is active which can produce a tilting of the magnetization vectors of the domains.

The aim of this work is to demonstrate the use of a novel technique to study the out-of-plane component of the stray field which appears in the process of magnetization reversal of an in-plane magnetized film. This out-of-plane component may arise from the stray fields near domain walls, or from perpendicular magnetization components due to, either a perpendicular easy axis or from tilting of the magnetization in the domains. For this study we use a μ-Hall sensor array recently developed to study the dynamics of vortices in high-T_c superconductors [2], with an active area of $10 \times 10 \mu m^2$ for each sensor. We have selected magnetite (Fe_3O_4) as model substance because the orientation of the magnetic easy axis in the low-temperature phase can be very well controlled by cooling the sample through the Verwey transition at $T_V \sim 120\,K$ in an applied magnetic field. Below the Verwey transition magnetite has a monoclinic structure with a magnetic easy axis along the *c*-direction; during field cooling Fe_3O_4 aligns its easy axis with the field parallel to a $\langle 1\,0\,0 \rangle$ direction [3].

The films were prepared by pulsed laser deposition onto (0 0 1)-MgO (sample #1) and $MgAl_2O_4$ (#2) substrates from a ceramic magnetite target using an Excimer Laser ($\lambda = 248\,nm$) operating at 10 Hz with a pulse energy of 1020 mJ. The thickness of the films was

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300 nm (120 nm) for sample #1 (#2). X-ray studies showed an epitaxial and relaxed growth of the films [4,5]. Conversion electron Mössbauer spectroscopy revealed that the films were highly stoichiometric. Magnetization measurements showed a Verwey transition at $T_V \simeq 120\,K$. Fig. 1 (a) shows the in-plane magnetization hysteresis loops along the [1 0 0] direction of the films #1 (#2) at $T = 40\,K$ (10 K) in zero field cooled (ZFC) and in-plane field cooled (FC) states. Whereas the coercive field is independent of the cooling procedure, the switching field distribution is much broader in the ZFC than in the FC state.

The local magnetic fields B_{local} at the Hall sensors were determined by measuring the Hall voltage using a DC or an AC current at 66 Hz. A resolution better than 0.1 G was achieved. The film was fixed with a small amount of wax on the sensor chip which was located at the center of the film (of size $2 \times 2\,mm^2$). The system sample-sensor was thermally anchored on a rotatable sample holder of a magnetocryostat system. Because the out-of-plane field component is much smaller than the applied magnetic field, a parallel orientation of the sample-sensor system with respect to the applied field is necessary. This orientation was adjusted with an accuracy of better than 0.01°, resulting in a small but measurable field dependence of the Hall voltage due to the misalignment.

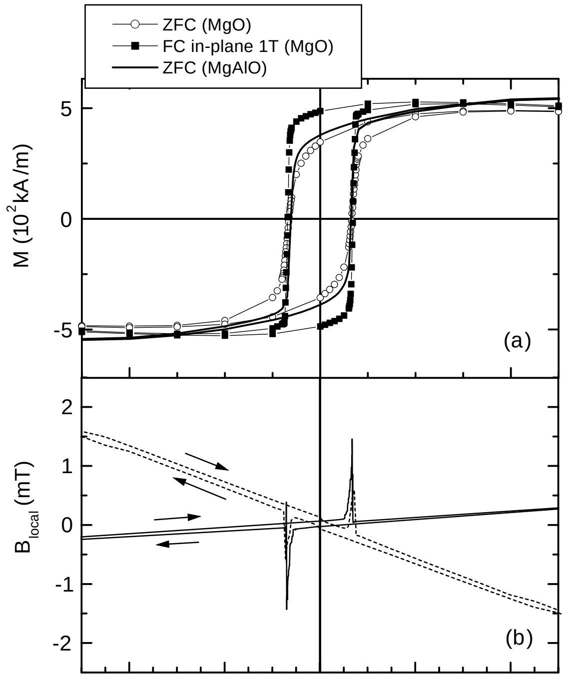

Fig. 1. (a) Magnetization loops as a function of the in-plane applied field measured at $T = 40\,K$ (10 K) for samples #1(#2) in FC (in plane $\mu_0 H = 1\,T$, sample #1) and ZFC (#1 and #2) states. (b) Local field out-of-plane component as a function of the in-plane applied field for two runs with different misalignment angles giving rise to different background slopes of the Hall voltage. The sample has been FC with an in-plane field of 1 T. Note the reproducibility of the features at the coercive fields of the sample. The arrows indicate the direction of the field sweep.

Fig. 1(b) shows the measured local field as a function of the in-plane field for the FC state at two misalignment angles for sample #1. Due to the small misalignment a Hall voltage proportional to the applied field is measured. This signal ($\mu_0 H_z$) is considered as background and is subtracted from the data presented below. The measurements reveal a local field different from zero in a narrow applied field region near the coercive field $\mu_0 H_c = 0.068\,T$, see Figs. 1(a) and (b) and 2 (a). It is important to note that the feature around H_c depends neither on the magnitude nor on the direction of the misalignment field component within the investigated angle range of $\pm \sim 0.02°$. The features depicted in Fig. 1(b) are highly reproducible from run to run as can be seen in Fig. 2(a). Our measurements reveal clearly

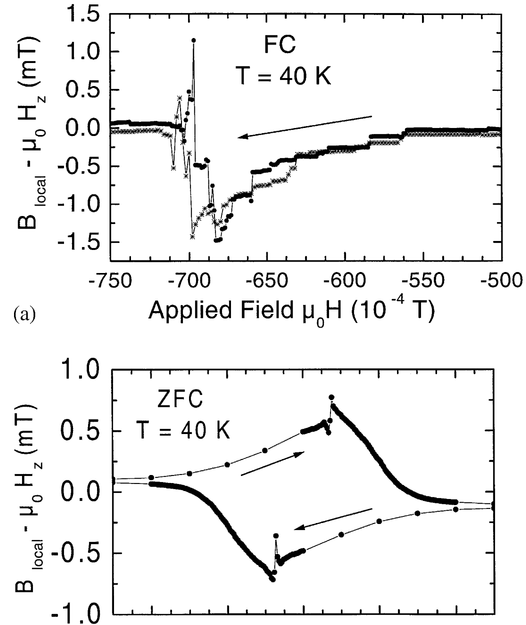

Fig. 2. (a) Local field as a function of the in-plane applied field near the coercive field for two independent runs at $T = 40\,K$. The sample #1 was FC with an in-plane field of 1 T. Note the reproducibility between the two runs and the oscillatory behavior observed just above H_c. (b) Out-of-plane component as a function of the applied in-plane field at $T = 40\,K$ for the same sample but in ZFC state.

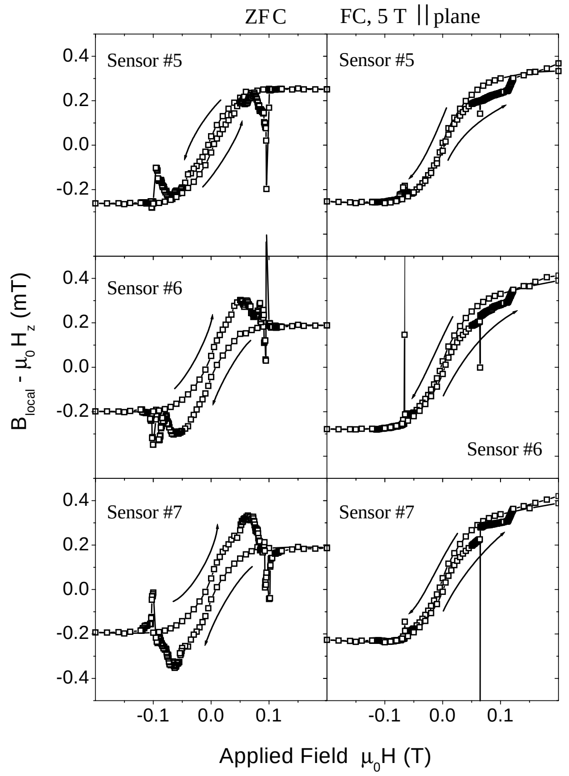

Fig. 3. Local field results from three sensors of sample #2 taken in the ZFC and FC states at $T = 10\,\mathrm{K}$. During FC a 5 T field was applied in-plane along [1 0 0].

that the behavior of B_{local} is influenced by Barkhausen jumps, see Fig. 2(a).

By sweeping the in-plane field from the single domain and saturated state at $|H| \gg |H_c|$, the number of domains under the sensor active area increases when the field decreases in magnitude or increases in the opposite direction at $|H| < |H_c|$ where $|B_{\mathrm{local}}|$ increases slowly with $|H|$, reaching a maximum at $|H_c|$, see Fig. 2(a). A further increase in the same direction of the in-plane field leads to a sharp decrease often accompanied by an overshoot behavior with change of sign. This last process occurs abruptly, causing the asymmetry of the feature measured around H_c.

Fig. 3 shows the Hall sensor response of sample #2 at 10 K in the ZFC and FC states. The signal of three adjacent sensors is presented. In the FC state sharp spikes can be seen superimposed on a smooth and only weakly hysteretic background. In the ZFC state broad stray-field components appears. These features agree with the global magnetization measurements in Fig. 1(a). Whereas the stray fields display the same overall shape in the FC state for the three sensors, clear differences are discernible in the ZFC state. This indicates a more heterogeneous magnetic state after ZFC. Measurements after FC in an out-of-plane field yielded similar results as ZFC.

One may try to infer the origin of the stray fields from the differences observed between ZFC and in-plane FC. Both samples, see Figs. 2 and 3, show sharper features and larger stray field spikes in the FC states. On the other hand, on average a large hysteresis is seen in the ZFC state. One might tentatively conclude that the stray field spikes near the coercive field arise from stray fields of domain walls which are driven past the sensors. The hysteretic signal in the ZFC state might arise from perpendicular magnetization components within the domains due to perpendicular easy axis orientation, as torque measurements showed [6].

To corroborate this picture let us estimate the stray field produced by a single wall crossing the area of a μ–Hall sensor. Taking into account MFM results [7] and the thickness of our films, the domain walls in our samples are very probably of Bloch type with a domain-wall thickness $\sim 0.1\,\mu\mathrm{m}$. From Fig. 3 we may assume a single Bloch wall of length $\leq 10\,\mu\mathrm{m}$. If the stray field profile is approximated by a square profile with $B_z = M_s$ at the domain-wall and $B_z = 0$ otherwise, then an integrated stray field signal $B_{\mathrm{stray}} \leq (0.1\,\mu\mathrm{m}/10\,\mu\mathrm{m})\ M_s = 0.01 M_s$ is obtained. With $M_s = 0.58\,\mathrm{T}$, we estimate a stray field $B_{\mathrm{stray}} \leq 5.8\,\mathrm{mT}$ which is of the same order of magnitude as observed, see Fig. 2.

In summary, we have shown that it is possible to study magnetization reversal dynamics locally by the measurement of the out-of-plane stray field using μ–Hall sensor arrays.

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