Magnetization dynamics of a CrO$_2$ grain studied by micro-Hall magnetometry

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Micro-Hall magnetometry is employed to study the magnetization dynamics of a single, micron-size CrO$_2$ grain. With this technique we track the motion of a single domain wall, which allows us to probe the distribution of imperfections throughout the material. An external magnetic field along the grain’s easy magnetization direction induces magnetization reversal, giving rise to a series of sharp jumps in magnetization. Supported by micromagnetic simulations, we identify the transition to a state with a single cross-tie domain wall, where pinning/depinning of the wall results in stochastic Barkhausen jumps.

Studying the behavior of small magnetic particles is important both from the fundamental point of view – for testing basic concepts of ferromagnetism – and for potential applications in high-density magnetic storage, magnetic sensing, spintronics, or in biology. In order to simplify the analysis of magnetization behavior to an accessible level many experimental studies have been performed on small arrays or even on single nanometer-scale particles. On the other hand, calculations and numerical simulations have revealed pivotal insight into possible modes of magnetization reversal, see e.g. [2–5]. For the magnetization behavior of systems, which are larger than the critical size of coherent magnetization reversal, domain walls (DWs) play a decisive role. Again, it is often beneficial to study a single entity, small enough that its magnetization dynamics is governed by a single DW. One reason is that DW motion may yield indications of the intrinsic defect structure of a magnetic particle. The calculation of magnetic key quantities, such as the coercivity and the remanence, in turn requires knowledge of the nature of imperfections in the material and how they contribute to the various energy terms, as well as the distribution of imperfections throughout the material.

Many of the previous single-wall studies were performed on either permalloy or garnet films [9,12]. In this Letter, we report results of magnetization measurements of an individual, single-crystalline CrO$_2$ grain of rod-like shape with dimensions of approximately $(7 \times 1.2 \times 0.5) \mu$m$^3$, see inset of Fig. 1. CrO$_2$ has been known as a non-volatile magnetic-storage material for a long time and has attracted renewed interest [13] as an almost completely half-metallic ferromagnet ($T_C \approx 393$ K) being explored as a potential candidate for spintronics applications. For this material, in particular, the magnetotransport properties of grains, nanowires and thin films being influenced by the dynamics of magnetic DWs have been subject of recent interest [14–16]. CrO$_2$ has the tetragonal rutile structure and a uniaxial magneto-crystalline anisotropy with the easy magnetization direction (EMD) along the [001] direction [17,18]. This direction coincides with the longest dimension of our rod such that magneto-crystalline and shape anisotropy simply superpose. High-purity crystallites for this study were grown in a two-step process using a new route of synthesis that allows to control the grain size and shape [19].

The motivation for our study was to gain a quantitative understanding of the magnetization reversal of a single CrO$_2$ grain. In micromagnetic simulations carried out for a rod-like grain with rectangular surfaces and the dimensions of our sample we find that the ground state (demagnetized state) corresponds to a single cross-tie DW along the long axis of the grain. Experimentally we observe that in the regime of single DW motion, the magnetization reversal in the CrO$_2$ micro-grain takes place through a series of sharp Barkhausen jumps, which we attribute to stochastic pinning and depinning of the DW. Accordingly, the magnetic flux densities emanating from both ends of the grain are strictly correlated and change in opposite directions.

For the magnetic measurements, we analyzed [4,5] the Hall response of a two-dimensional electron gas (2DEG) to the $z$-component of the stray field $B_z$ emanating from a CrO$_2$ grain positioned on top of the 2DEG, cf. inset of Fig. 1. To allow for simultaneous measurement of the stray fields at both ends of the grain, we use Hall crosses of active area $(5 \times 5) \mu$m$^2$ whose separation was chosen to correspond to the grain length. The magnetic measurements were performed with external magnetic field $\mu_0 H_{\text{ext}}$ applied along the $x$- and $y$-directions, $i.e.$ almost parallel (EMD) and perpendicular (hard axis) to the long axis of the grain, respectively.

Figure 1 shows the hysteresis loops of the grain measured at $T = 5$ K for both directions of $H_{\text{ext}}$. The expected pronounced anisotropy is obvious. For the easy-axis magnetization we find a relatively low coercive field of $H_c \approx 3.5$ mT which is consistent with the values reported for bulk and thin films [19,20]. Analyzing the magnetization curve measured along the magnetically...
hard direction in terms of reversible magnetization rotation the anisotropy field \( \mu_0 H_a \sim 250 \text{ mT} \) can be obtained. This value yields an effective uniaxial anisotropy constant of \( K_{\text{eff}} = H_a J_s/2 \sim 7.3 \times 10^4 \text{ J/m}^3 \), where \( J_s \approx 0.74 \text{ T} \) is used for the spontaneous polarization at low temperatures \([21]\). The shape anisotropy constant \( K_z = (N_\perp - N_\parallel) J_s^2 / 2 \mu_0 \) for the grain is found to be \( \sim 6 \times 10^4 \text{ J/m}^3 \). Therefore, the uniaxial magnetocrystalline anisotropy constant \( K_1 \) is \( \sim 1.3 \times 10^4 \text{ J/m}^3 \) which is consistent with the values of \( 1.4-6 \times 10^4 \text{ J/m}^3 \) reported in the literature \([15,18,20,22,23]\). For both field directions, we observe that the magnetization changes through a series of sharp jumps. Assuming the motion of a single DW for the EMD, see below, the change in the average stray field \( \langle B_z \rangle \) due to the DW displacement \( \Delta y \) within the grain is described by \( \Delta \phi = 2M_s d \Delta y \), where \( \phi \propto \langle B_z \rangle \) is the flux emanating from the grain (approximated by a rod of thickness \( d \)) \([24]\). The upper left inset of Fig. 1 indicates that the displacement of the DW occurs in discrete steps \( \Delta y \) of order of a few nm. The smallest step we have observed corresponds to \( \Delta y \approx 0.8 \text{ nm} \), demonstrating the high resolution of the present magnetization measurement technique.

Figure 2 shows the hysteresis loops measured at both ends of the grain for the external magnetic field along the EMD. The magnetic signal at the two ends are oppositely directed. For the hysteresis loops, we identify two regimes of magnetization behavior: below and above \( \mu_0 H^* \approx \pm 20 \text{ mT} \), where a large jump in magnetization occurs. The transition field \( H^* \) is not stochastic and essentially temperature independent up to the highest temperature of our experiment of 100 K. All other discontinuous magnetization changes occur at random, \( i.e. \), in a stochastic manner.

For \( |H_{\text{ext}}| < H^* \), the magnetization changes according to Barkhausen jumps which are of opposite sign and strictly correlated for the flux through crosses 1 and 2. This correlation is clearly seen in Fig. 2(b), panels 1B and 2B, where the identical field values at which jumps are detected from the two ends of the grain are highlighted by vertical arrows. We attribute this part of the hysteresis curve to pinning/depinning of a single DW. Beyond the large jump, \( i.e. \) for \( |H_{\text{ext}}| > H^* \) (panels 1A and 2A of Fig. 2(b)), the magnetization changes through rotation of magnetic domains and Barkhausen jumps, which are mostly uncorrelated for both ends of the grain.

Micromagnetic simulations \([25]\) support the conjecture of the existence of these regimes which are related to two distinct states, correspondingly labeled A and B in Fig. 3. For the simulations an exchange stiffness constant

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**FIG. 1.** (Color online) Hysteresis loops measured for magnetic fields applied almost parallel and perpendicular to the easy magnetization direction (EMD). Lower right inset: SEM image of the CrO2 grain placed between two Hall crosses (labeled 1 and 2). Upper left inset: Barkhausen jumps corresponding to the displacement of a single domain wall (see text).

**FIG. 2.** (Color online) (a) Easy-axis hysteresis loops simultaneously measured at two grain ends (crosses 1 and 2) at \( T = 5 \text{ K} \). The sweep direction is indicated by the arrows. The apparent negative remanence (see also Fig. 1) is due to the specific nature of the stray field \( \langle B_z \rangle \) to which our Hall crosses respond. The different regimes A and B of magnetization reversal (indicated by the shaded areas) correspond to different domain configurations, see text and Fig. 3. (b) Magnification of the hysteresis loops in regions A (\( |\mu_0 H_{\text{ext}}| > 20 \text{ mT} \)) and B (\( |\mu_0 H_{\text{ext}}| \leq 20 \text{ mT} \)). The jumps at the grain ends are strictly correlated within regime B, \( i.e. \), they appear at exactly the same field values for identical sweep directions (panels 1B and 2B). In contrast, jumps are mostly uncorrelated for regime A (panels 1A and 2A, jumps without counterpart are highlighted by question marks).
of \( A = 4.6 \times 10^{-12} \text{ J/m} \) has been used \cite{22} together with the anisotropy constant \( K_1 \) and the spontaneous magnetization \( J_s \) as mentioned above. The simulation volume is discretized in unit cells of cubic shape with an edge length of 18 nm. The magnetization configurations are obtained in the quasistatic regime after relaxation of the initial configuration. The configuration B is obtained from a two-domain configuration with magnetization oppositely oriented along the easy axis. During relaxation the magnetic moments close to the wall between the two domains curl forming a cross-tie wall. Alternatively, configuration B can be obtained from A by applying a small field anti-parallel to the main magnetic domain. Configuration B is the ground state of the system, with a total energy about two third of configuration A. Configuration A is obtained after relaxation of a three-domain configuration imposed as initial state. A similar state to configuration A is attained by relaxation of the single domain configuration (here: a single DW), when pinned to one of these local minima and saddle points is involved. A domain configuration (here: a single DW), when pinned to one of these local minima, is depinned by the application of \( H_{\text{ext}} \) which leads to the observed Barkhausen jumps. The synchronous magnetization changes at both ends are also found for the hard axis magnetization (not shown) and for temperatures \( T \leq 100 \text{ K} \), whereas both the number of Barkhausen jumps and their magnitude decrease with increasing temperature, indicating a thermal contribution to the (de)pinning. A detailed statistics of the Barkhausen jumps depending on temperature and magnetic field orientation will be published elsewhere. The finite slope between the Barkhausen discontinuities observed in our experiment may suggests a significant elastic bending of the DW, or likewise, reversible rotation within the grain and/or growth of the endcaps. From the number of Barkhausen jumps occurring in the specific field interval at low temperatures we estimate a density of pinning centers (of a certain strength sufficient to be detected within our resolution) of \( 1 \times 10 \mu \text{m}^{-3} \), which implies a high purity of the investigated grain.

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\[ |J_s| = 6 \times 10^{-12} \text{ J/m} \]

\[ \text{m}^{-3} \]

\[ \mu \text{m} \]

\[ 1 \times 10 \mu \text{m}^{-3} \]

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