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Permalink
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Journal
JOURNAL OF APPLIED PHYSICS, 103(7)

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Publication Date
2008-03-11

DOI
10.1063/1.2837888

Peer reviewed
Identifying reversible and irreversible magnetization changes in prototype patterned media using first- and second-order reversal curves

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(Presented on 9 November 2007; received 12 September 2007; accepted 17 November 2007; published online 11 March 2008)

Arrays of nanomagnets have important potential applications as future generation ultrahigh-density patterned magnetic recording media, in which each nanomagnet constitutes a single bit. We introduce a powerful technique to identify and quantify reversible and irreversible magnetization changes, a key challenge in characterizing these systems. The experimental protocol consists of measuring a few families of second-order reversal curves along selected profiles in the first-order-reversal-curve diagram, which then can be decomposed into truly irreversible switching events and reversible magnetization changes. The viability of the method is demonstrated for arrays of sub-100-nm Fe nanomagnets, which exhibit complex magnetization reversal processes.


Having the potential to reach unprecedented recording densities of 1 Tb/in.\(^2\) and beyond, patterned magnetic recording media have attracted a lot of interest in the last decade.\(^1,2\) In future patterned media, the data are to be stored in arrays of nanomagnets such that, ideally, each nanomagnet holds 1 bit. With the lithographic techniques already available,\(^3\) fundamental nonmagnetic parameters of the arrays such as grain size and nanomagnet spacing can be varied in a controlled fashion, which allows one to systematically study the effects of these parameters on the magnetic properties. Arrays of nanomagnets therefore also offer a unique opportunity to experimentally validate theoretical models of switching behavior, particle interactions, and thermal activation effects. To tackle these problems on a quantitative level, it is necessary to have a method that allows one to separate measured magnetization changes into contributions from irreversible and reversible processes.

We here propose an effective method for this task, which involves first-order and second-order reversal curves (FORCs and SORCs). A FORC (Refs. 4–8) is a magnetization curve \(M(H_r,H)\), which originates at some reversal field \(H_r\) from the major loop \(M(H)\), and SORCs (Ref. 4) are magnetization curves \(M(H_r,H_q,H)\) branching off a given FORC at the second reversal field \(H_q\). FORCs were originally introduced\(^9\) to experimentally measure the Preisach distribution. Later, it was recognized that FORCs measured on magnetic systems consisting of curvilinear hysterons, such as the Stoner-Wohlfarth assemblage, cannot be fitted accurately by linear Preisach models. To overcome this limitation, Mayergozy and Friedmann\(^4\) suggested to measure also higher-order reversal curves in addition to FORCs, in particular, SORCs, and to fit a nonlinear, generalized Preisach model to both sets of curves.

Rather than fitting a model to measured sets of FORCs and SORCs, we here take a different approach and extract the amount of reversible and irreversible changes directly from the FORC and SORC data. For a given set of ascending FORC (increasing \(H\), starting from \(H_r\)), the separation of reversible from irreversible magnetization changes can be performed only near the descending branch of the major loop, that is, for \(H \rightarrow H_r\). Here, the irreversible change is the vertical difference between the major loop \(M(H)\) and the FORC \(M(H_r,H)\),

\[
dM^{ir}(H_r) = \lim_{H \rightarrow H_r} [M(H) - M(H_r,H)],
\]

while the reversible change is

\[
dM^{rev}(H_r) = \lim_{H \rightarrow H_r} [M(H_r,H) - M(H_r)].
\]

The normalized difference \(dM^{rev}(H_r)/dH\), where \(dH=H-H_r>0\), is also referred to as the reversible ridge.\(^10\) To decompose the magnetization change along an ascending FORC at any \(H>H_r\) into irreversible and reversible contributions, we suggest measuring a set of \(N\) descending magnetization curves \(M[H_r,H_q(i),H]\), \(i=1,\ldots,N\) branching off the particular FORC \(M(H_r,H)\) after a second field reversal at \(H_q(i)>H_r\). The amount of irreversible change in magnetization per field change \(dH=H_q-H>0\) that occurred along the FORC near \(H_q\) is then the (vertical) difference between the SORC and the FORC

\[
dM^{ir}(H_r,H_q) = \lim_{H \rightarrow H_q} [M(H_r,H_q,H) - M(H_r,H)],
\]

while the reversible change is obtained as

\[
dM^{rev}(H_r,H_q) = \lim_{H \rightarrow H_q} [M(H_r,H_q) - M(H_r,H_q,H)].
\]

To numerically determine the \(dM\) values from measured data sets, we fit a line to the initial segment of each reversal curve, that is, the first \((f+1)\times dH\) field steps from the reversal point onward, where \(f\) can be considered a smoothing
large positive peaks offset from the $H=−H_r$ axis, about which they are symmetrically positioned. These two offset peaks—at $(H,H_r)=(1.3,0.1)$ and $(0.1,−1.4)$ kOe—result in a constricted major loop. The magnetization mechanisms underlying the two peaks are annihilation of a vortex from the same side as it was nucleated (upper peak) and nucleation of a vortex from negative saturation (lower peak). The FORC diagram exhibits another interesting feature, a positive peak centered at $H=−H_r≈1.5$ kOe flanked by two smaller negative peaks. This negative-positive-negative trio of features can be explained statistically by a history-dependent distribution of annihilation fields,17 or microscopically, by some shape anisotropy that leads to field polarity dependent annihilation fields.15 Finally, there is a positive ridge centered at the $H=−H_r$ axis, extending from $H=0$ to $H=1$ kOe, which is related to coherent switching of single-domain particles in the sample. To clarify the nature of the prominent features in the FORC diagram in terms of reversible and irreversible processes, we measured sets of SORCs for several values of $H_r$ and performed the decomposition into reversible and irreversible contributions according to Eqs. (3) and (4). An example is shown in Fig. 2 for $H_r=40$ Oe. It turns out that most of the magnetization changes for $H$ near $H_r$, that is, $H_q<1$ kOe in Fig. 2(b), are due to reversible processes, manifestated by the overlapping SORCs shown in Fig. 2(a).

Irreversible processes (true switching events, on the other hand, are found to be associated with the upper of the two offset peaks in the FORC diagram, located at $(H,H_q)=(1.3,0.1)$ kOe, corresponding to the annihilation of vortices15 that had nucleated at reversal field $H_r>40$ Oe.

In Fig. 3, the rate of irreversible (a) and reversible (b) changes is shown for four different sets of SORCs, attached to the FORCs originating at $H_r=+40$, −490, −940, and −1390 Oe, respectively. In (a), it can be clearly seen from the positive values that for those FORCs reversing at $H_r<0$, irreversible changes do occur during recoil to $H=0$, which means that the remanent magnetization $M(H_r,0)$ is not identical to the irreversible magnetization $M^r(H_r)$ for $H_r<0$. Moreover, the location of the left irreversible peak in each
The peak location is almost stationary. Figure 3 defines by while figure for comparison.

Every fifth data point is marked with a plot symbol. The slopes for the major derivative $\frac{dM}{dH}$ in $Q$ shows no apparent history dependence is the quadrant that the reversible slopes are not history independent, unlike positive and negative regions in the other quadrants of the theoretical models. To identify the characteristic of the reversible slopes from Fig. 3 and find that the negative and positive regions centered about $H \sim H_r \sim -1.4$ kOe and $\sim +60$ Oe, respectively, are due to reversible processes, while those lobes of the two peaks at $(H, H_r) = (1.3, 0.1)$ and $(0.1, -1.4)$ kOe that are just outside $Q_{r, -}$ are due largely, but not solely, to irreversible processes (vortex nucleation and annihilation). These results demonstrate that the combination of FORC and SORC techniques can give very detailed information about the history-dependent irreversibility of magnetization changes.

We thank C. P. Li, I. V. Roshchin, and I. K. Schuller for the sample used in this study, and G. T. Zimanyi for useful discussions. This work was supported in part by BaCaTec, ACS (No. PRF-43637-AC10), and the Alfred P. Sloan Foundation.