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# Superparamagnetic behavior of μm-sized permalloy disks

M. A. Schofield[1], M. Beleggia[1], J. W. Lau[1,2] and Y. Zhu[1]

[1] Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton NY 11973-5000
[2] currently, National Institute of Standards and Technology, Gaithersburg MD 20899

Understanding magnetization reversal dynamics in patterned ferromagnetic elements, representing the fundamental building blocks of more complicated structures, is crucial to the development of modern magnetic storage media and spintronic devices. In our lab, we fabricate patterned magnetic arrays and shapes in a UHV thin-film deposition system by lithographic and shadow-mask techniques. We have a state-of-the-art, field-emission TEM equipped with a custom-made objective lens (JEOL 2100F-LM) dedicated for field-free magnetic imaging and electron holography applications [1]. Some of our research efforts have been to develop quantitative methods to measure the local magnetization of a specimen using electron holography and Lorentz microscopy in order to understand the magnetic properties and shape-effect of individual elements, and the interaction behavior of neighboring elements. Recently, however, we have observed by Lorentz-TEM spontaneous thermally-activated remnant-state switching of μm-sized permalloy disks in certain patterned arrays. Surprisingly, the disks appear to switch from the clockwise (C) to the anti-clockwise (AC) vortex states with a measurable frequency in the range between 0.1 and 10 Hz.

The samples under study are nominally 20nm thick Permalloy disks grown by shadow-mask techniques on an amorphous carbon substrate, and capped with 2nm carbon to reduce oxidation. The samples were grown by e-beam evaporation in our UHV chamber, where the shadow-mask consists of 1μm holes in a square array with 5μm periodicity. Figure 1a shows two Lorentz images extracted from a real-time recording of a portion of the array showing the switching phenomenon at room-temperature. Interpretation of the Lorentz contrast (black vs. white) in the sequence indicates the vorticity of the disk as being in either the AC (white) or the C (black) state. Figure 1b shows the change of vorticity in one of the disks as a function of time over a period of one and a half minutes. The time average shows that this particular disk stays preferentially (68% of the time) in the C state. Indeed, individual disks show varied switching behavior that is generally non-symmetric in the sense that the C and AC states do not appear energetically degenerate. However, the non-degeneracy is also not systematic: some disks might prefer C, some others might prefer AC, and there does not appear to be any strong correlation between the particular states of neighboring disks.

The reversal mechanism, i.e. the pathway followed by the element over the energy landscape from the C to AC state, is currently unknown. An idealized energy landscape, however, showing the two minima corresponding to the C and AC states, with a barrier $E_0$ in between, is sketched in Fig. 2. In principle, the states C and AC should have the same energy, but we assume for a given disk that the specific irregularities in shape, surface roughness, grain size and orientation, defect structure, etc. play a role in determining the preferred "ground-state" of an individual disk. The average energy barrier separating the C and AC states can be estimated by analyzing the temperature dependent switching behavior within a standard Arrhenius framework for thermal fluctuations. We have modeled the switching frequency as $f(T)=f_0\exp(-E_0/KT)$, where the phenomenological parameter $f_0$ is the "attempt frequency", $E_0$ is the average barrier height, K is Boltmann's constant and T is the temperature of the system. Data segments were recorded directly to DVD (29.97 frames per second) at various temperatures (85K, 103K, 134K, 163K, 200K, 234K, 258K and 300K) by use of a cooling stage. At 200K, nearly all of the switching phenomena ceased. Between 234K and room temperature, there was a marked dependence on temperature for the switching rate of individual disks. From a statistical analysis of the switching frequency, we find an average barrier height of $E_0=(413\pm19)$meV and intrinsic attempt frequency of $f_0=(1.2\pm0.7)\times10^8$Hz. Typically, the "ground-state" energy difference between the C and AC state was found to be around $\Delta E\sim10\text{-}20$meV, but showed a wide distribution of values, with the equal possibility of being either positive or negative, depending on the specific disk.

Using micromagnetic simulation and theoretical calculations, we are addressing the possible mechanisms for the observed thermal switching in these disks, as well as reasons for the difference in the low-energy C and AC states for a given disk. These results will be presented at the conference. In order to facilitate additional modeling, however, we carried out electron energy loss measurements of the thickness profile for these disks. Figure 3 is a sketch of the measured profile, and indicates that the "disks" are actually very shallow hills (~1nm high) on a roughly uniform thin film (~5nm) of permalloy. Energy calculations applied to permalloy "disks" with the observed thickness profile suggest that the high-energy intermediate state corresponding to the barrier $E_0$ is consistent with a vortex displaced to the edge of the disk. [2]

References

[1] M. A. Schofield, M. Beleggia, Y. Zhu and G. Pozzi, submitted to Ultramicroscopy, 2006.
[2] Supported by US Department of Energy BES, under contract No. DE-AC02-98CH10886.

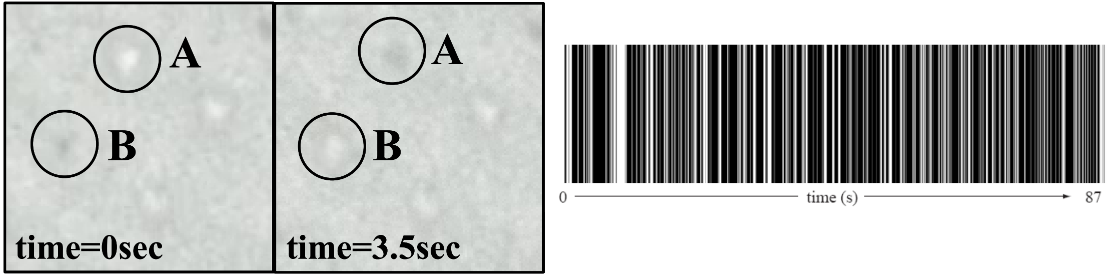
FIG.1(a)
FIG.1(b)

FIG.2

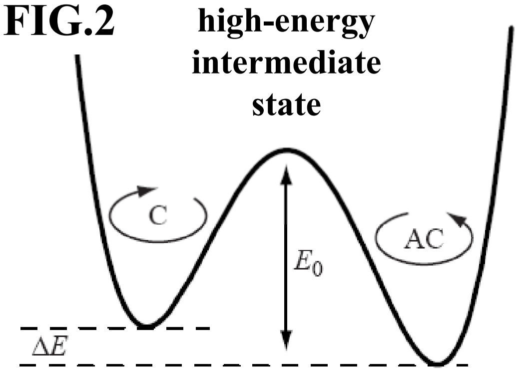

FIG.3

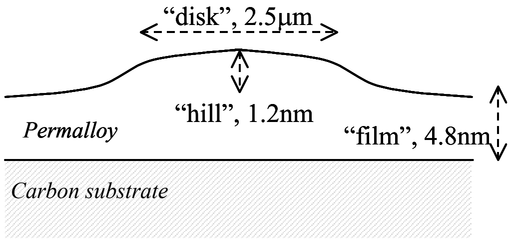

**FIG.1.** (a) Two frames extracted from DVD recording of the switching behavior in permalloy disks at room temperature. The time between successive images is 3.5s, and regions A and B show disks that have switched vorticity. (b) Vorticity of a particular disk at room temperature over a span of 87 seconds. Black corresponds to C state, while white refers to the AC state of the disk.
**FIG.2.** Idealized energy landscape separating the C and AC states. $E_0$ is the average energy barrier, and ΔE is the energy difference between the states, which in principle should be zero.
**FIG.3.** Schematic of the thickness profile obtained from EELS measurements for these disks showing that the sample consists of a roughly uniform thin film (~5nm) with a periodic array of ~20% thickness modulation.