Electronic Supplementary Information

New Reversal Mode in Exchange Coupled Antiferromagnetic/Ferromagnetic Disks: Distorted Viscous Vortex

Dustin A. Gilbert,[a] Li Ye,[a] Aïda Varea,[b] Sebastià Agramunt-Puig,[c] Nuria del Valle,[c] Carles Navau,[c] José Francisco López-Barbera,[c, d] Kristen S. Buchanan,[e] Axel Hoffmann,[f] Alvar Sánchez,[c] Jordi Sort,[c, g] Kai Liu,[a, *] and Josep Nogués[c, d, g,*]

[a]Physics Department, University of California, Davis, CA, USA

[b]MinD-in2UB, Electronics Department, Universitat de Barcelona, Martí i Franquès 1, 08028, Barcelona, Spain

[c]Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain

[d]ICN2 – InstitutCatala de Nanociencia i Nanotecnologia, Campus UAB, 08193 Bellaterra (Barcelona), Spain

[e]Department of Physics, Colorado State University, Fort Collins, CO, USA

[f]Materials Science Division, Argonne National Laboratory, Argonne, IL, USA

[g]Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain

[*]Corresponding authors: kailiu@ucdavis.edu, Josep.Nogues@uab.cat.

Details of the first order reversal curve (FORC) measurements:

First, the sample is saturated in a positive field. Then, the field is reduced to a scheduled reversal field, H_R, and the magnetization is recorded as the applied field, H, is swept back to positive saturation, hence tracing out a single FORC. This sequence is repeated for decreasing values of the reversal field until negative saturation is reached, measuring a family of FORCs where the magnetization, M, is recorded as a function of both H and H_R. The FORC distribution, $\rho(H,H_R)$ is then calculated by applying a mixed second order derivative:

$$\rho(H, H_R) = -\frac{1}{2M_S}\frac{\partial^2 M(H, H_R)}{\partial H_R \partial H}, \tag{1}$$

where M_S is the saturation magnetization. The resulting distribution is only non-zero for irreversible switching processes. Recognizing that sweeping H probes the up-switching events and stepping H_R probes the down-switching events, new coordinates can be defined: the local bias $H_B=(H+H_R)/2$ and local coercivity $H_C^*=(H-H_R)/2$.

Anatomy of the FORC features for vortex, biased vortex and tilted-vortex reversals:

A schematic of a standard vortex FORC is shown in Fig. S1(a). For a magnetic vortex in a symmetric structure, such as a circular dot, the three main features correspond to (i) nucleation from positive saturation (at $H_R^{(i)}$) and annihilation to positive saturation (at $H^{(i)}$), (ii) annihilation to negative saturation (at $H_R^{(ii)}$) and nucleation from negative saturation (at $H^{(ii)}$), and (iii) subsequent annihilation to positive saturation (at $H_R^{(iii)}=H_R^{(ii)}$, $H^{(iii)}=H^{(i)}$). Feature (ii) is accompanied by a negative feature, extending in the $-H$ direction relative to the positive feature. In the vortex state, the magnetization varies continuously in response to the magnetic field ($dM/dH\neq0$), whereas in the saturated state the magnetization remains constant ($dM/dH=0$). These 'unmatched' dM/dH slopes [30] leads to a negative feature. The different reversal modes can be distinguished as follows.

Non-biased vortex: the nucleation and annihilation fields will be symmetric for positive and negative saturation, thus $H_R^{(i)}=-H^{(ii)}$, $H^{(i)}=-H_R^{(ii)}$ and $H^{(iii)}=H^{(i)}$. Transforming these into (H_C,

H_B) coordinates as described above, $H_C^{(i)}=H_C^{(ii)}$, and $H_B^{(i)}=-H_B^{(ii)}$; feature (iii) occurs at $H_B=0$ at $H_C=H_A$ [Fig. S1(a)].

Uniformly exchange biased vortex: as shown in Fig. S1(b), the coordinates of the FORC features can be calculated to be $H_C^{(i)}=H_C^{(ii)}$, and $H_B^{(i)} + H_B^{(ii)}=2H_E$. The FORC features retain their relative arrangement, just offset along the H_B axis by H_E.

Tilted vortex: as shown in Fig. S1(c), the nucleation fields are equally biased, but not the annihilation fields. Thus $H_R^{(i)}+H_E=-H^{(ii)}+H_E$ and $H^{(i)}+H_E \neq -H_R^{(ii)}+H_E$, and features (i) and (ii) will no-longer remain aligned. Further, feature (iii) will still be intimately coupled to both features, manifesting at ($H_R^{(ii)}$, $H^{(i)}$).

Distorted viscous vortex reversal: as shown in Fig. S1(d) the nucleation and annihilation events both can change and thus (i) and (ii) will not be aligned. However, since the exchange field is very small, the entire FORC distribution is still centered around H_B~0.

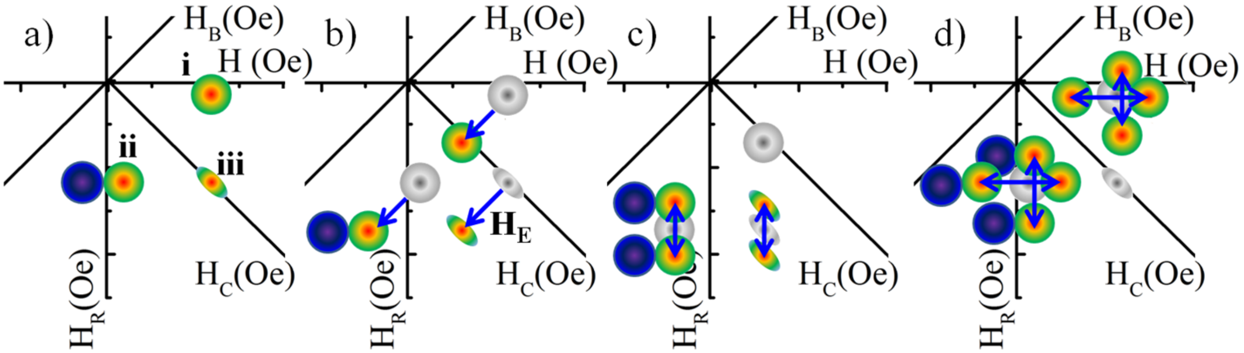

Fig. S1. Schematic FORC diagrams for (a) unbiased vortex, (b) biased vortex, (c) tilted vortex, and (d) distorted viscous vortex. Arrows indicate the shift of the major FORC features due to changes in the nucleation and annihilation fields.