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Memory-bit selection and recording by rotating fields in vortex-core cross-point architecture

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In one of our earlier studies S.-K. Kim *et al.*, [Appl. Phys. Lett. **92**, 022509 (2008)], we proposed a concept of robust information storage, recording, and readout, which can be implemented in nonvolatile magnetic random-access memories and is based on the energetically degenerated twofold ground states of vortex-core magnetizations. In the present study, we experimentally demonstrate reliable memory-bit selection and recording in vortex-core cross-point architecture, specifically using a two-by-two vortex-state disk array. In order to efficiently switch a vortex core positioned at the intersection of crossed electrodes, two orthogonal addressing electrodes are selected, and then two Gaussian pulse currents of optimal pulse width and time delay are applied. Such tailored pulse-type rotating magnetic fields which occur only at the selected intersection are a prerequisite for a reliable memory-bit selection and low-power-consumption recording of information in the existing cross-point architecture. © 2011 American Institute of Physics. [doi:10.1063/1.3551524]

Energy-efficient, ultrahigh-density, ultrafast, and non-volatile solid-state universal memory has been a long-held dream in the field of information storage technology. Magnetic vortices in patterned magnetic dots are among the most promising candidates for practical storage device applications,¹ not only because of the energetically stable twofold ground states of their core magnetizations,^{2–8} but also due to the easily controllable low-power-consumption core switching through resonant vortex-core excitation.^{9–17} However, an experimental demonstration of the technologically important process of information writing in an array of vortex-core memory bits has yet to be achieved. To further the realization of magnetic random-access memory using an array of vortex-state dots (hereafter called VRAM) proposed conceptually earlier,⁹ we experimentally demonstrate in the present study reliable memory-bit selection and energy-efficient recording by particularly optimized rotating magnetic fields in an existing basic cross-point architecture.

For the experimental realization of the VRAM (Refs. 9 and 18), we used the two-by-two vortex-state disk array as illustrated in Fig. 1. Permalloy (Py: Ni₈₀Fe₂₀) disks of identical radii ($R=2.5\ \mu\text{m}$) and thicknesses ($L=70\ \text{nm}$) were positioned at intersections of Au electrodes. The disks were fabricated by magnetron sputtering at a base pressure of less than 5×10^{-9} Torr, subsequent patterning by standard electron-beam lithography (Jeol, JBX9300FS), and lift-off processes. Each disk was capped in vacuum with 2-nm-thick Pd layers to prevent oxidation. The four intersection areas of the crossed electrodes were 50 nm thick and $10\ \mu\text{m}$ wide, as shown in the optical microscopy image (see Fig. 1 inset). To allow for sufficient soft x-ray transmission through the sample, the Au electrodes were deposited onto a 200-nm-thin silicon nitride membrane of a $5\times 5\ \text{mm}^2$ window by

electron-beam evaporation under base pressures of less than 1×10^{-8} Torr.

For reliable memory-bit selection and efficient manipulation of vortex-core orientations in this cross-point architecture, we employed pulse-type rotating fields that can be produced by Gaussian pulse currents applied along the orthogonally arranged electrodes, as shown in Fig. 1. Such rotating fields are not perfect circular-rotating fields of constant magnitude and single-harmonic frequency ω_H rotating either counterclockwise (CCW) or clockwise (CW) on the film plane.^{9,15,19} In principle, such ideal circular-rotating fields can be produced locally at the intersection of crossed electrodes by the superposition of only two equivalent harmonic oscillating fields generated by alternating currents

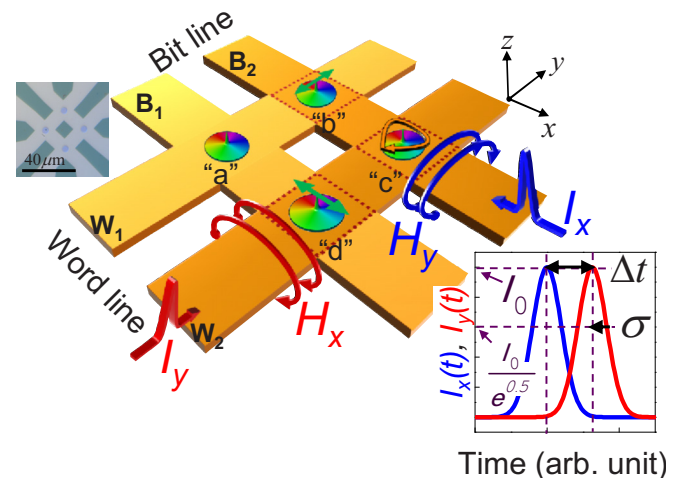


FIG. 1. (Color online) Two-by-two cross-point architecture. At each intersection there is positioned a single vortex-state Py disk of $R=2.5\ \mu\text{m}$ and $L=70\ \text{nm}$. The left inset shows an optical microscopy image of the 50-nm-thick Au crossed striplines of $10\ \mu\text{m}$ width, with the Py disks at the intersections. The right inset shows two Gaussian pulse currents of equal width σ and a certain time delay Δt , as applied along the x and y axes.

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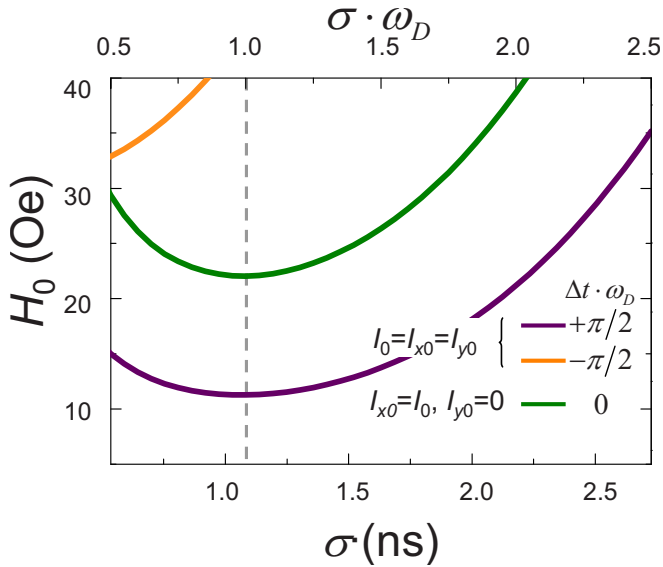


FIG. 2. (Color online) Analytical calculation of the threshold strengths required for upward-to-downward core switching as function of σ with Py disk of same dimensions as real sample, $R=2.5 \mu\text{m}$ and $L=70 \text{ nm}$. The purple (orange) curve indicates H_{th} of a CCW (CW) rotating field, whereas the green one is that of a linear field. The gray vertical dashed line is at $\sigma = 1.09 \text{ ns}$ ($\sigma=1/\omega_D$).

flowing along two orthogonal electrodes. As reported in earlier studies,^{9,15,17,19} the CCW (CW) rotating field is most efficient for selectively switching only the upward (downward) core to its reversed orientation with the lowest threshold strength if the field frequency ω_H is tuned to the vortex angular eigenfrequency ω_D . In this study, as we use nonideal rotating fields produced by orthogonally applied *Gaussian-pulse* currents (see Fig. 1), it is necessary to optimize pulse parameters of width σ and time delay Δt so as to achieve low-power-consumption vortex-core switching. In our earlier paper,²⁰ the optimal values were reported to vary only with ω_D , such that $\sigma=1/\omega_D$ and $\Delta t=\frac{\pi}{2}p/\omega_D$, where p is the polarization of the initial vortex state, $p=+1$ (-1), corresponding to the upward (downward) core magnetization. The positive and negative values of Δt correspond to CCW and CW rotating fields, respectively, while $\Delta t=0$ corresponds to a linear field (see Ref. 20).

The operating mechanism for memory-bit selection and recording in the cross-point architecture, in the present study, is based on the fact that the threshold field strengths H_{th} required for vortex-core switching differ distinctly with Δt , that is, with the polarization of the pulse-type rotating fields (the linear field, the CCW, and CW rotating fields). Figure 2 plots the results of the analytical calculation of the H_{th} values versus σ for the indicated different polarizations of the applied pulse fields for Py disks of the same dimensions as those of a real sample. The purple (orange) line indicates the result with $\Delta t=+\frac{1}{2}\pi/\omega_D$ ($\Delta t=-\frac{1}{2}\pi/\omega_D$), whereas the green indicates that with a Gaussian pulse applied along only one electrode, where $\omega_D/2\pi=146 \text{ MHz}$ is used in the calculation. Apparently, the threshold fields vary significantly for the different field polarizations. H_{th} was lowest at $\sigma = 1.09 \text{ ns}$ for $\Delta t=+\frac{1}{2}\pi/\omega_D$ (purple line: CCW rotating field) and for the upward core orientation as an initial state. The minimum H_{th} for the linear (green) field was higher by a factor of almost 2 than that for the CCW rotating field: 22.1 versus 11.3 Oe. The CW rotating field (orange line:

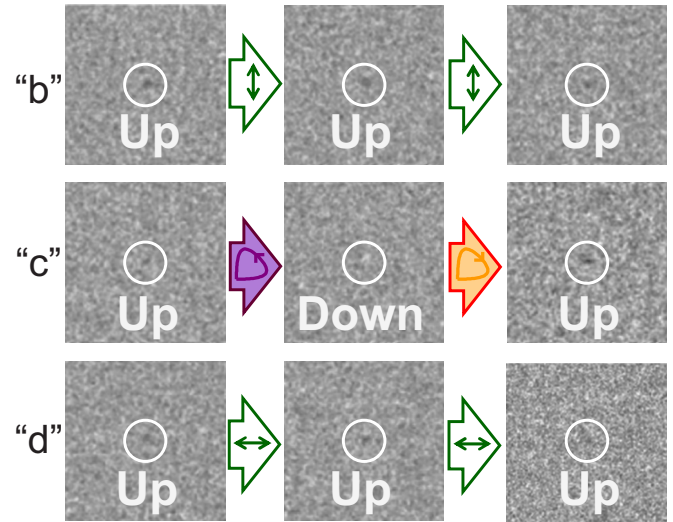


FIG. 3. (Color online) XMCD images of the three different disks' vortex-core regions marked as b, c, and d (see Fig. 1). The dark and white spots indicate the upward and downward core orientations, respectively. The initial core magnetization (see the left column) was upward for all of the disks. The polarization of the applied fields at each intersection is indicated by the arrows. The strength of the applied fields along the x and y axes is $H_0 = 11.5 \text{ Oe}$. The first column represents the initial state at each Py disk, the second column shows the state after applying orthogonal currents of $\Delta t = +2.0 \text{ ns}$, and the third column indicates the state after applying orthogonal currents of $\Delta t = -2.0 \text{ ns}$.

$\Delta t = -\frac{1}{2}\pi/\omega_D$) required a much higher strength than 43 Oe at $\sigma = 1.09 \text{ ns}$, already four times higher than $H_{\text{th}} = 11.3 \text{ Oe}$ of the CCW rotating field. This remarkable difference in H_{th} between the different field polarizations enables reliable memory-bit selection in the basic cross-point architecture, without the typical half-selection problem²¹ of conventional magnetic random-access memory, simply by choosing two electrodes at the intersection of which a vortex core is to be switched, as shown in Fig. 1.

To verify experimentally the above concept, we imaged directly the out-of-plane core magnetizations before and after vortex-core switching events by high-resolution magnetic transmission soft x-ray microscopy (MTXM), where x-ray magnetic circular dichroism (XMCD) at the Fe L_3 edge²² served as contrast mechanism. Figure 3 shows MTXM images of the vortex-core regions of three different Py disks marked as “b,” “c,” and “d” (see Fig. 1). The dark and white spots indicate the upward and downward core orientations, respectively, in our experimental setup. By monitoring those spots in such images, we could readily determine whether vortex-core switching events had occurred for a given pulse field of different polarization and strength. In the real sample, the minimum value of H_{th} for $\Delta t = +2.0 \text{ ns}$ (-2.0 ns) was 11.0 Oe for the upward (downward) core switching. By applying two pulse currents with optimal values $\Delta t = +2.0 \text{ ns}$ (CCW rotating field) and $\sigma = 1.27 \text{ ns}$ (Ref. 23) along the two striplines marked as “W₂” and “B₂” only the upward core located at position c, was switched. In this case, as confirmed by the x-ray images, only at the cross-point the upward core orientation switched once, with a further increase to 11.5 Oe. As expected, the reversed downward core was not switched by the same CCW rotating field, even with further increasing H_0 . By contrast, at locations b and c, neither the upward nor the downward core was switched with

$H_0=11.5$ Oe, because the linear field of insufficient strength was applied at those locations.

Next we note a possible readout mechanism. As consistent with the asymmetry of the switching behaviors that rely on the relative core orientation and the rotation sense of applied pulse-type rotating fields, a large asymmetry in the vortex-core gyration amplitude has been found as reported in one of our earlier studies.¹⁹ For the upward core orientation, only the CCW field affects large-amplitude vortex-core gyrations, but the CW field does not. Accordingly, large-amplitude vortex-core gyrations could yield large deviations of in-plane curling magnetizations from the vortex ground state, which in turn gives rise to the marked difference in magnetizations between the free and fixed vortex layers (e.g., in spin valve structure). If the rotation sense of the applied fields is known, the core orientation in response to those applied fields can be identified by the tunneling magnetoresistance (TMR). Thus, given a typical spin valve structure that includes a magnetic tunneling junction, the change in TMR would be used as a readout means for detecting either vortex-core orientation (for detail, see Ref. 20).

The present experimental demonstration of reliable energy-efficient recording of a memory bit selected in vortex-core cross-point architecture by optimally designed rotating fields promises practical nonvolatile information storage and recording functions. This technological achievement in fundamental vortex-core switching dynamics thus imparts further momentum to efforts to realize unique-vortex-structure-based VRAM with its novel dynamic properties, and is a critical milestone on that path.

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