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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 [Appl. Phys. Lett. **92**, 022509 (2008)], we proposed a concept of robust information storage, recording and readout, which can be implementaed 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 information 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 occurs only at the selected intersection is prerequisite for a reliable memory-bit selection and low-power-consumption recording of information in the existing cross-point architecture.

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Energy-efficient, ultrahigh-density, ultrafast and nonvolatile 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[9,18] we used the two-by-two vortex-state disk array as illustrated in Fig. 1. Permalloy (Py: $Ni_{80}Fe_{20}$) disks of identical radius (R = 2.5 μm) and thickness (L = 70 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, and subsequent patterning by standard e-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 μm 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 mm-by-5 mm 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 simple Gaussian pulse currents applied along the orthogonally arranged electrodes, as shown in Fig. 1. Such rotating fields are not ideal circular-rotating fields of constant magnitude and single-harmonic frequency $\omega_{\mathbf{H}}$ rotating either counter-clockwise (CCW) or clockwise (CW) on the film plane .[9,18] In principle, such ideal circular-rotating fields can be produced locally at the intersection of crossed electrodes by the superposition of two harmonic oscillating fields generated by alternating currents flowing along orthogonal electrodes.[9,18] As reported in earlier studies,[9,17,18] 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 $\omega_{\mathbf{H}}$ is tuned to the vortex angular eigenfrequency ω_D.[9,15,17,19] As we use non ideal pulse-type rotating fields produced by orthogonally applied alternating currents (see Fig. 1), one has 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] we reported optimal values 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.[20] The positive and negative values of Δt correspond to a CCW and CW rotating field, respectively, while Δt =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 and the CW and CW rotating fields). Figure 2 plots the results of the analytical calculations 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 is that with a Gaussian pulse applied along only one electrode, where $\omega_D/2\pi$ = 146 MHz is used in the calculation.

Apparently, the threshold fields vary sigificantly for the different field polarizations. H_{th} was lowest at σ = 1.09 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 two than that for the CCW rotating field: 22.1 versus 11.3 Oe. The CW rotating field (orange line: $\Delta t = -\frac{1}{2}\pi/\omega_D$) required a much higher strength than 43 Oe at σ = 1.09 ns, already four times higher than H_{th} = 11.3 Oe for 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 problem[21] 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 this concept, we imaged by high-resolution magnetic transmission soft x-ray microscopy (MTXM) where x-ray magnetic circular dichroism (XMCD) at the Fe L_3 edge[22] served as contrast mechanism directly the out-of-plane core magnetizations before and after vortex-core switching events, 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 a different polarization and strength. In the real sample, the minimum value of H_{th} for $\Delta t =$ + 2.0 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 ns (CCW rotating field) and σ = 1.27 ns [Ref. 23] along the two striplines marked “W_2” and “B_2,” 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. Reversely, with H_0 = 11.5 Oe, neither the upward nor the downward core at locations “b” and “c” was switched, because a linear field of insufficient strength was applied at those locations.

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 non-volatile 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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[23]The value σ = 1.27 ns, used in the experiment, differed from that (σ = 1.09 ns) used in the analytical calculation. The $\omega_D / 2\pi$ value for the real sample seemed to be slightly less than that ($\omega_D / 2\pi = 146$ MHz) used in the analytical calculation.

Figure captions

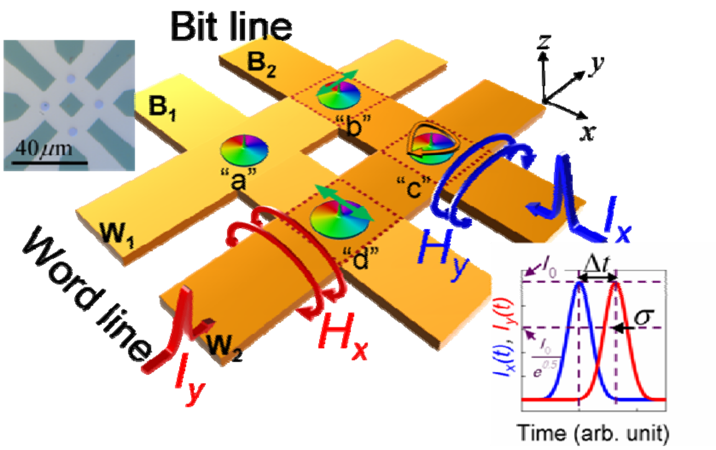
FIG. 1. (Color online) Two-by-two cross-point architecture. At each intersection there is positioned a single vortex-state Py disk of R = 2.5 μm and L = 70 nm. The left inset shows an optical microscopy image of the 50-nm-thick Au crossed striplines of 10 μm width, with the Py disks at the intersections. 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.

FIG. 2. (Color online) Analytical calculation of 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 μm and L = 70 nm. The purple (orange) line indicates the 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 σ = 1.09 ns.

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

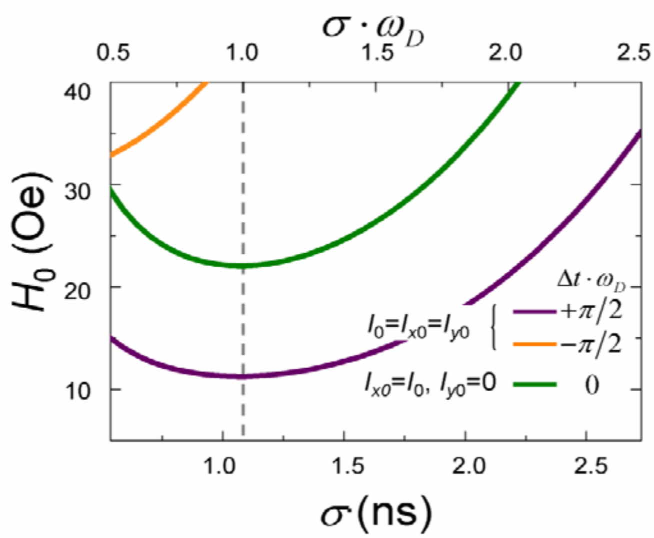
column) was upward for all of the disks. The polarization of the applied fields at each intersection is indicated by the arrows. The strength of the applied fields along the x and y axes is H_0 = 11.5 Oe. The first column represents the initial state at each Py disk, the second column shows the state after applying orthogonal currents of $\Delta t =$ + 2.0 ns, and the third column indicates the state after applying orthogonal currents of $\Delta t =$ - 2.0 ns.

FIG. 1.



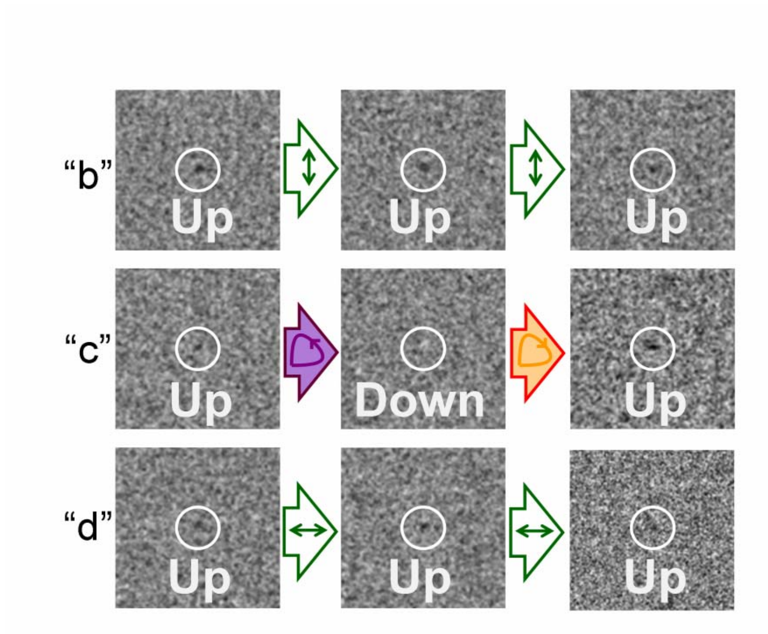
Bit line
B₂
B₁
40μm
"a"
"b"
"c"
"d"
W₁
W₂
Word line
z
y
x
I_x
H_y
H_x
I_y
I_0
Δt
σ
$I_x(t)$, $I_y(t)$
Time (arb. unit)

FIG. 2.



σ · ω_D
0.5
1.0
1.5
2.0
2.5
40
30
20
10
H_0 (Oe)
Δt · ω_D
+π/2
−π/2
I_0=I_x0=I_y0
I_x0=I_0, I_y0=0
0
1.0
1.5
2.0
2.5
σ (ns)

FIG. 3.



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