A Multi-level Single-bit Data Storage Device

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I. MOTIVATION

- Magnetoresistive Random Access Memory (MRAM) allows fast data access and non-volatile data storage needed for a universal computer memory.
- Figure 1(a) shows a schematic of a MRAM proposal using ring-shaped ferromagnetic structures. It is possible to have circular memory cells in a vertical MRAM (Figure 1b).

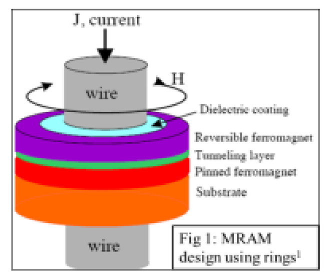


Fig 1: MRAM design using rings[1]

Fig 1b: Bit line with ring-shaped memory cells[2]

- Ring-based MRAMs can use magnetoresistive measurements on two lowest energy configurations, i.e. the clockwise and counterclockwise (CW/CCW) vortex states. Figure 2 shows CW/CCW vortex states in rings.

Fig 2: 2 state bit configuration

II. OOMMF SIMULATIONS

- Object Oriented MicroMagnetic Framework (OOMMF) iteratively solves the **Landau-Lifshitz-Gilbert equation**

$$\frac{\partial \vec{M}}{\partial t} = -\frac{\gamma}{1+\alpha^2}\vec{M}\times\vec{H}_{eff} - \frac{\gamma\alpha}{(1+\alpha^2)M_s}\vec{M}\times(\vec{M}\times\vec{H}_{eff})$$

  α is a phenomenological damping parameter, γ is the gyromagnetic ratio
- We apply a circular magnetic field as if from an infinite wire passing through the center of ring-based structures.
- Magnetic parameters for permalloy**:** Saturation of magnetization Ms = 8.6 x 10^5 A/m, Exchange parameter A = 1.3 x 10^{-13} J/m, Crystalline anisotropy = 0, and T = 0 K.

III. PREVIOUS EXPERIMENTS

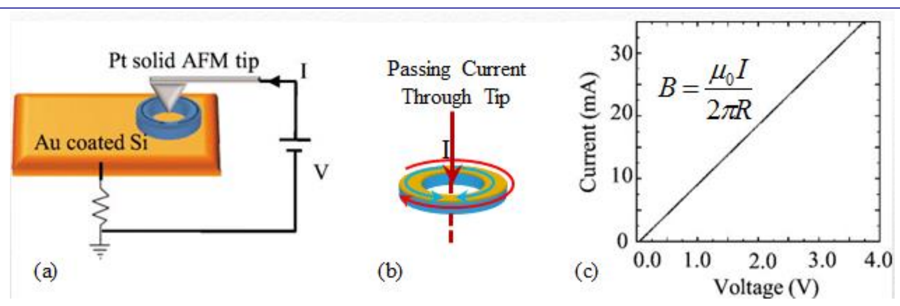
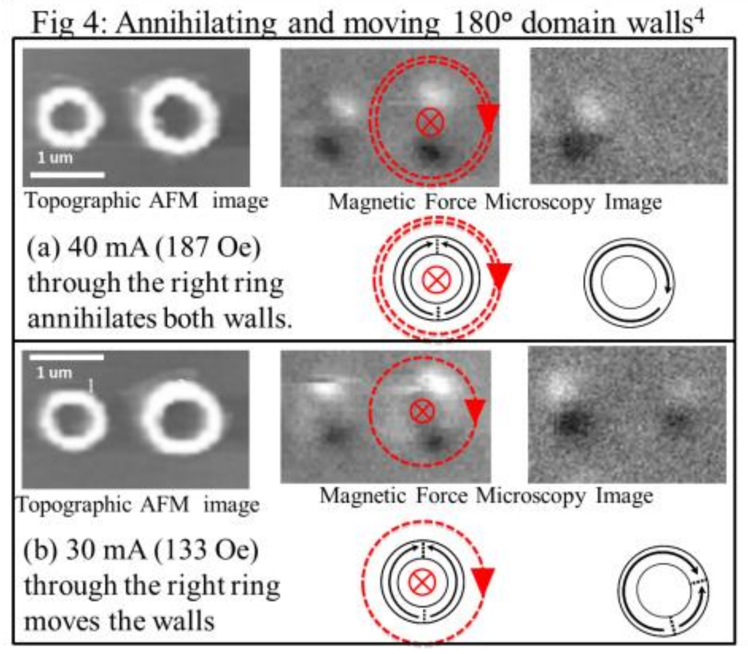


Fig 3 (a) Schematic of the experimental setup. (c) A current-voltage plot generated directly from the experimental setup in (a).[3]

We have passed current through thin rings using the setup shown in Figure 3.

We have annihilated and moved domain walls as shown in Figure 4.

Fig 4: Annihilating and moving 180° domain walls[4]



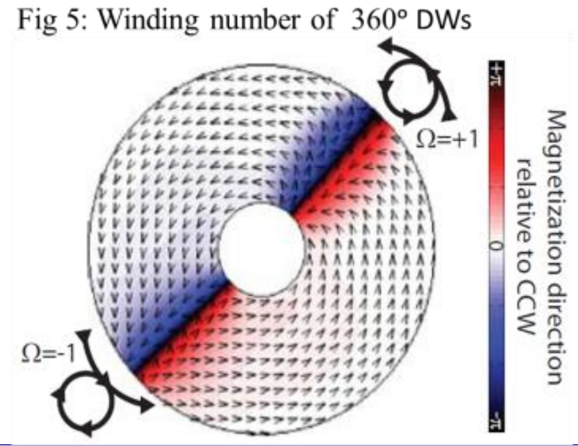
IV. VORTEX SWITCHING AND 360° DOMAIN WALLS (DWs)

TOPOLOGICAL WINDING NUMBER

Equation for DW exchange energy and winding number (Ω)[4] :

$$E_{ex} = \frac{\mu_0 M_s^2 t l_{ex}^2}{2} ln(\frac{R_2}{R_1})[2\pi(1+2\Omega) + \int_0^{2\pi}(\frac{\partial\phi}{\partial\theta})^2 d\theta]$$

Fig 5: Winding number of 360° DWs



Winding Number Ω

Ω =+1 same ciculation
Ω =-1 opposite circulation
Ω =+1 annihilates first, i.e . wall with **same circulation annihilates first**

Figure 5 shows magnetization for +1 and -1 360° domain walls.

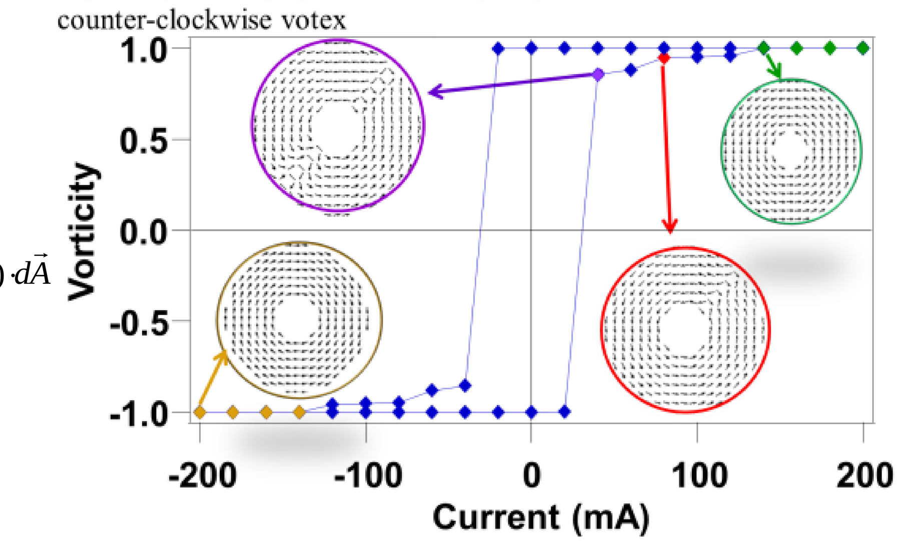
HYSTERESIS CURVE FOR RINGS

Figure 6 shows a hysteresis curve for a 5 nm thick ring. The outer diameter is 800nm and inner diameter is 200nm.

Vorticity is given by:

$$V = -\frac{1}{A}\int_A(\hat{r}\times\vec{M})\cdot d\vec{A}$$

Fig 6: Hyteresis graph for switching rings from clockwise to counter-clockwise votex



The clockwise (CW) vortex has a vorticity of -1. As we apply a counter-clockwise (CCW) field, we get **two 360° domain walls**. Stronger CCW field annihilates the Ω =+ 1 wall first and then the Ω = -1 wall is annihilated. Finally, we have a counter-clockwise vortex with vorticity +1.

ENERGY GRAPHS Ω=+1 and Ω=-1

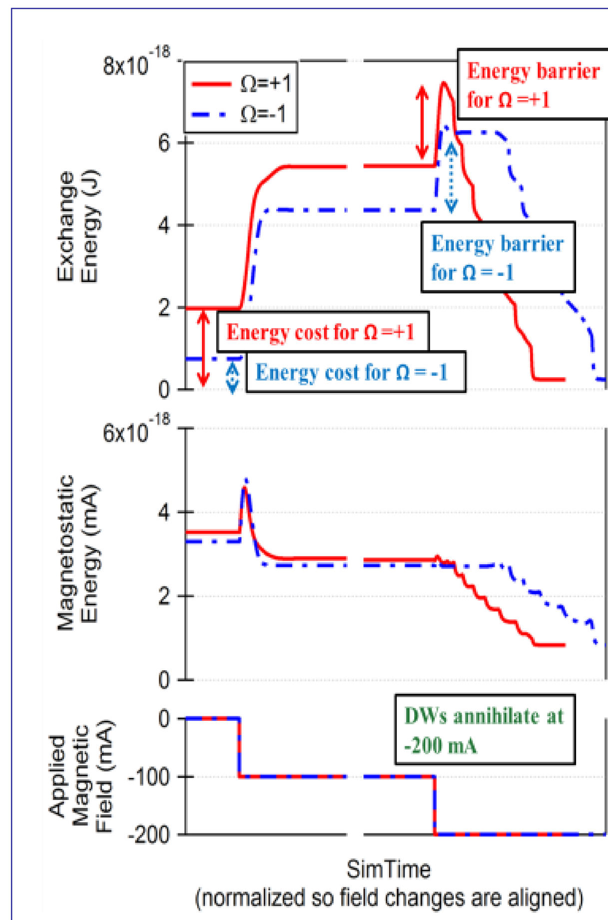


Fig 7: Energy graphs for 360° domain walls

Figure 7 shows energy vs. simulation time for a +1 and -1 360° DWs as magnetic field increases.

Exchange energy cost for the +1 DW is higher than for the -1 DW. Exchange energy barriers and magnetostatic energy costs and barriers for the two DWs walls are almost same.

The exchange energy controls DW annihilation. Although magnetostatic energy peaks at -100mA, the DW only decreases in width. At -200mA, the exchange energy peaks, both energies decrease, and the DW annihilates.

V. MULTI-LEVEL BIT: CREATING 4 NON-DEGENERATE STABLE DWs

CENTERED ELLIPSE CREATES 2 PAIRS OF DEGENERATE DWs

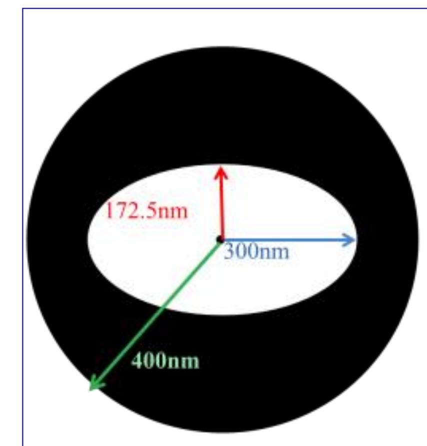


Fig 8 : Elliptical hole centered inside a circle

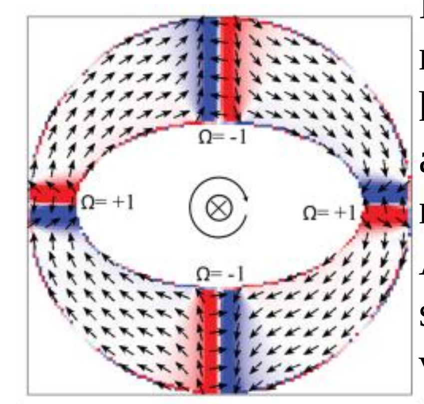


Fig 9: 4 Domain Walls in a centered ellipse.

Figure 8 shows a circle of radius 400 nm. The ellipse has a major axis of 300 nm and minor axis of 172.5 nm long.

As we apply CW field to switch from CCW to CW vortex, we get four 360° domain walls (two Ω = +1 and two Ω = -1) as shown in Fig 9.

OFF-CENTERED ELLIPSE TO BREAK LENGTH DEGENERACY: 0 to 2 DWs

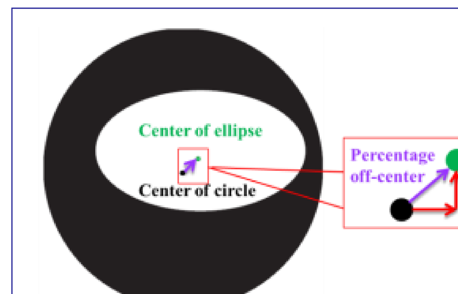


Fig 10 : Off-centered ellipse.

Domain Wall energy is proportional to domain wall length. Therefore, we can use a ccombination of DW length and winding number to create DWs that annihilate at different fields. Figure 10 shows an off-centered ellipse in a circle so that the DWs on the major axis and minor axis have different lengths.

1.78% OFF-CENTERED ELLIPSE: 2 NON-DEGENERATE STABLE DWs

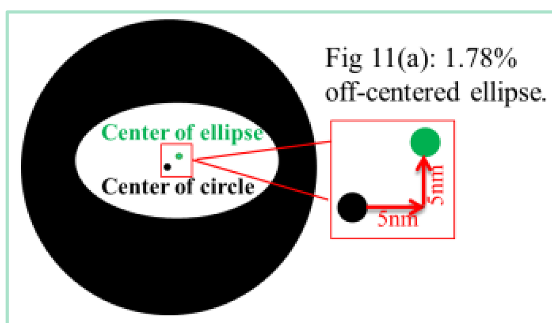


Fig 11(a): 1.78% off-centered ellipse.

Fig 11(a) shows a possible setup to annihilate 4 domain walls at different fields. However, as shown in the transtion for Fig 11(b), 2 of the 4 walls annihilate during the transition. Thus, we are left with only 2 DWs.

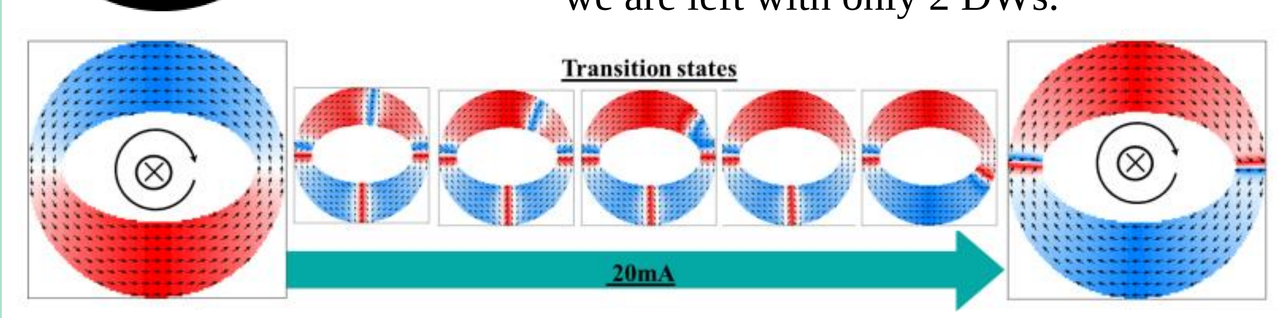


Fig 11 (b) : 1.78% off-centered ellipse forms 2 domains walls.

7% OFF-CENTERED ELLIPSE: 0 DOMAIN WALLS

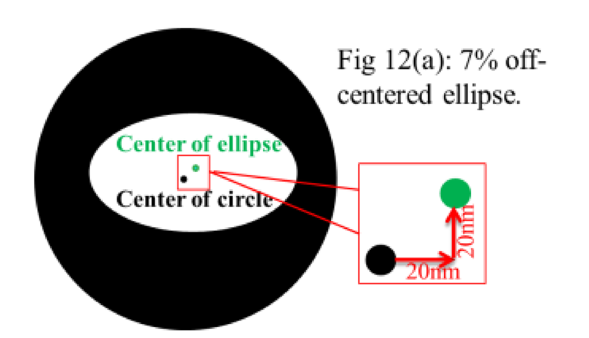


Fig 12(a): 7% off-centered ellipse.

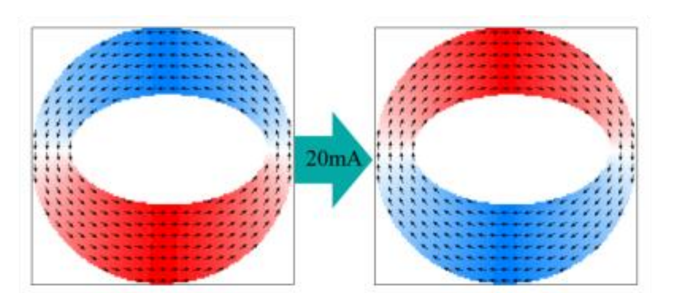


Fig 12 (b) : 7% off-centered ellipse has no domains walls

Fig 12(a) shows a more off-centered ellipse to create non-degenerate DWs. However, Fig 12(b) shows that no stable DWs form as we switch vorticity.

ADDING NOTCHES TO GET 4 NON-DEGENERATE STABLE DWs

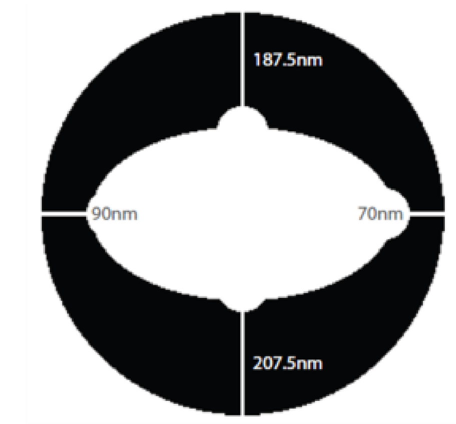


Fig 13(a): Centered ellipse with 4 notches

Figure 13 (a) shows 100 nm diameter circular notches inserted into the ellipse 40 *nm*, 30 *nm*, 20 *nm*, and 10 *nm* (clockwise from top) to make 4 stable DWs with different lengths.

Figure 13 (b) shows the formation and annihilation of four domain walls in the mask shown in Fig 13 (a).

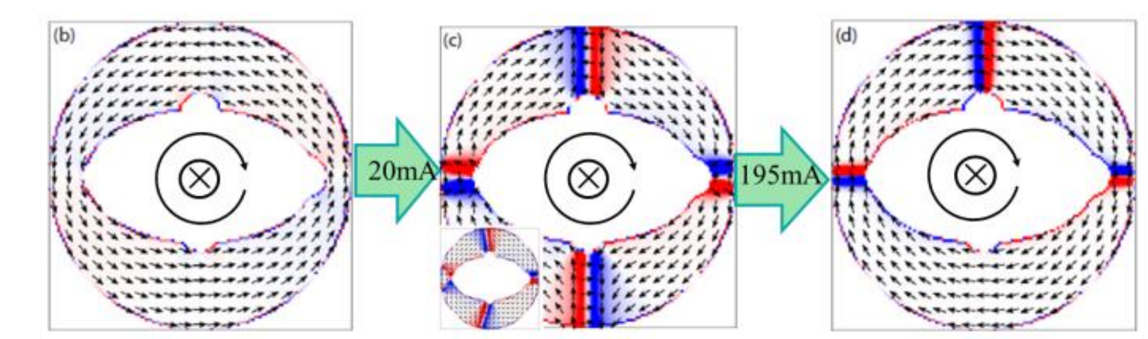
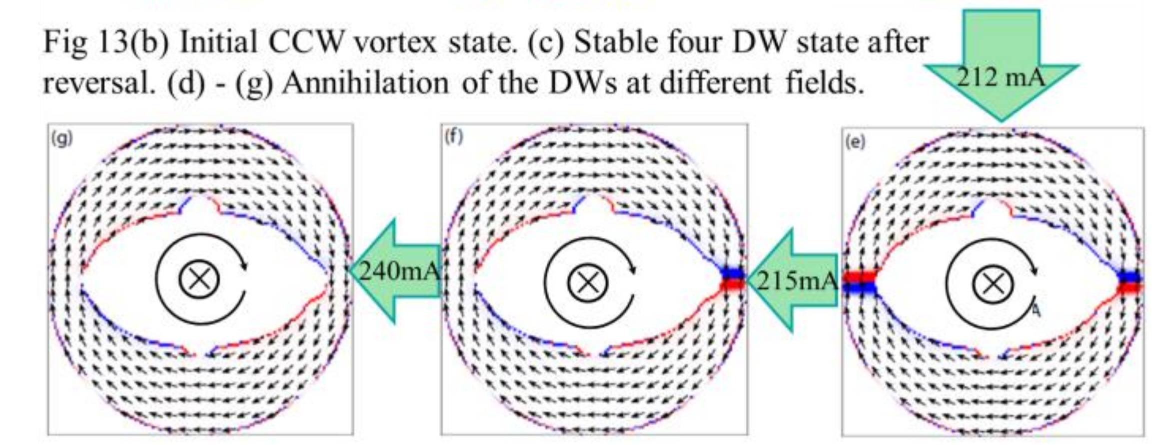


Fig 13(b) Initial CCW vortex state. (c) Stable four DW state after reversal. (d) - (g) Annihilation of the DWs at different fields.



VI. CONCLUSIONS

- The switching process between vortex states in thin rings occurs through pairs of DWs with opposite winding number. The DW energy depends on both DW winding number and DW length.
- We can use a careful combination of variation in DW winding number and DW length to get 4 non-degenerate DW. We have used a circular ring with an elliptical center and 4 notches to get 4 non-degenerate stable DWs.
- Our simulations demonstrate a proof of concept for multi-level bit storage device. However, fabricating nanorings with precise geometries and notches is experimentally challenging.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

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