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 shows a schematic of a MRAM design proposal that uses ring-shaped ferromagnetic structures.
- Ring-based MRAMs can use magnetoresistive measurements on two lowest energy configurations, i.e. the clockwise and counterclockwise (CW/CCW) vortex states. Figure 2 a) shows CW/CCW vortex states. Figure 2b) shows bit line ina vertical MRAM.

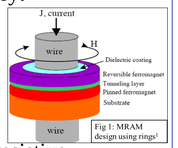


Fig 1: MRAM design using rings[1]

Fig 2(a): 2 state bit configuration

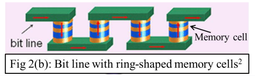


Fig 2(b): Bit line with ring-shaped memory cells[2]

II. METHODS

EXPERIMENTS

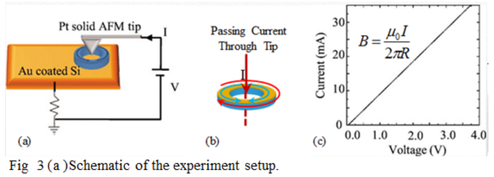
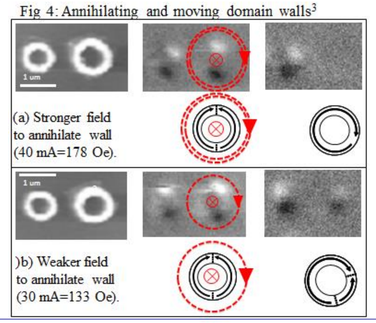


Fig 3 (a)Schematic of the experiment setup.
(c) A current-voltage plot generated directly from the experimental setup in (a).[3]

Fig 4: Annihilating and moving domain walls[3]



OOMMF SIMULATIONS

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

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

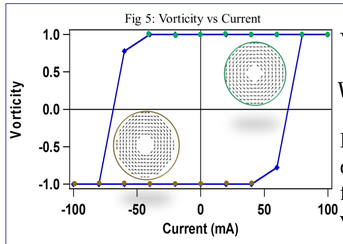
Magnetic parameters for permalloy:

Saturation of magnetization $Ms = 8.6 \times 10^5$ A/m, Exchange parameter of $A = 1.3 \times 10^{-13}$ J/m, Zero crystalline anisotropy and $T = 0$ K.

III. 360° DOMAIN WALLS AND TOPOLOGICAL WINDING NUMBER

HYSTERESIS CURVE

Fig 5: Vorticity vs Current



Vorticity given by::

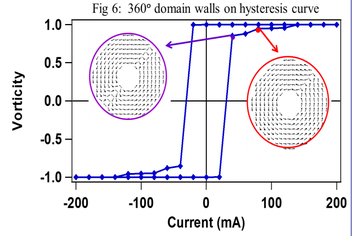
$$V = -\frac{1}{A}\int_A (\hat{r}\times\vec{M})\cdot d\vec{A}$$

Figure 5 shows a plot of vorticity vs. current for CW and CCW vortex states.

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

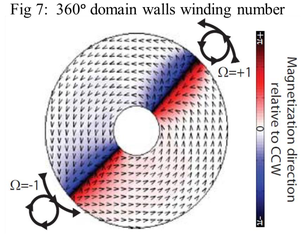
We an see the evolution of 360° domain walls.

Fig 6: 360° domain walls on hysteresis curve



ENERGY GRAPHS Ω=+1 and Ω =-1

Fig 7: 360° domain walls winding number



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

Figure 7 shows magnetization for +1 and -1 360° domain walls.

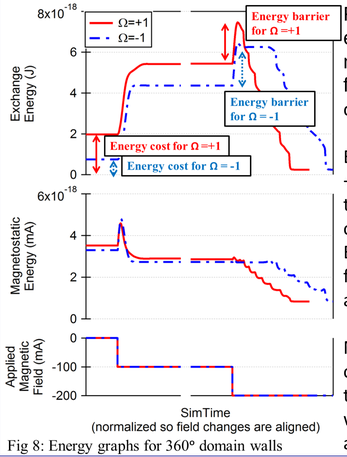


Figure 8 shows exhange and magnetostatic energy for +1 and -1 360° domain walls.

Exchange energy cost for +1 domain wall is higher than the exchange energy cost for -1 domain wall. Exchange energy barriers for the two walls are almost same.

Magnetostatic energy costs and barriers for the two walls with different winding numbers are almost same.

Fig 8: Energy graphs for 360° domain walls

IV. ANNIHILATING FOUR DOMAIN WALLS AT DIFFERENT FIELDS

CENTERED ELLIPSE INSIDE CIRCLE: 4 DOMAIN WALLS

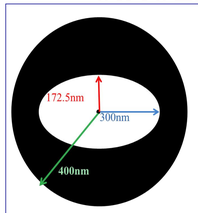


Fig 9(a) : Elliptical hole centered inside a circle

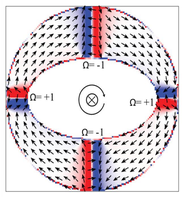


Fig 9(b) : 4 Domain Walls in a centered ellipse.

Figure 9(a) shows a circle of radius 400 nm. For ellipse, the major axis is 300 nm long and minor axis is 172.5 nm long.

Figure 9(b) shows four 360° domain walls: two Ω = +1 and two Ω = -1.

OFF-CENTERED ELLIPSE INSIDE CIRCLE: 0 to 2 DOMAIN WALLS

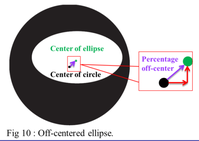


Fig 10 : Off-centered ellipse.

Figure 10 shows an off-centered ellipse in a circle. The motivation for this was to make different length domain walls so that each of the four domain walls may be annihilated at different fields.

1.78% OFF-CENTERED ELLIPSE: 2 DOMAIN WALLS

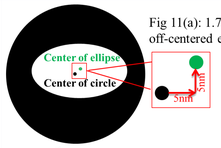


Fig 11(a): 1.78% off-centered ellipse.

Fig 11(a) and (b) show a possible setup to annihilate 4 domain walls at different fields, but we do not get 4 domain walls with this setup.

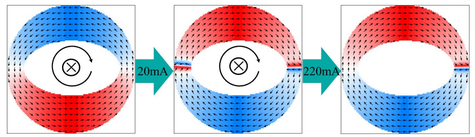


Fig 11 (b) : 1.78% off-centered ellipse has only 2 domains walls, not four.

7% OFF-CENTERED ELLIPSE: 0 DOMAIN WALLS

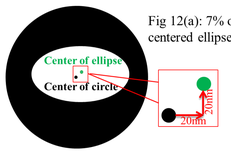


Fig 12(a): 7% off-centered ellipse.

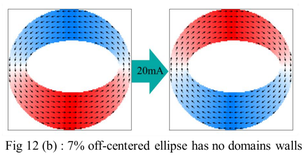


Fig 12 (b) : 7% off-centered ellipse has no domains walls

Fig 12(a) and (b) show a another possible setup to annihilate 4 domain walls at different fields, but we get no domain walls to start with.

4NOTCHES

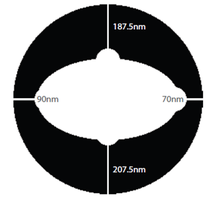


Fig 13(a): Centered ellipse with 4 notches

Figure 13(a) shows circular notches of *diameter* = 100*nm* are inserted into the ellipse (clockwise from top) 40 *nm*, 30 *nm*, 20 *nm*, and 10 *nm* to make four different domain wall lengths.

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

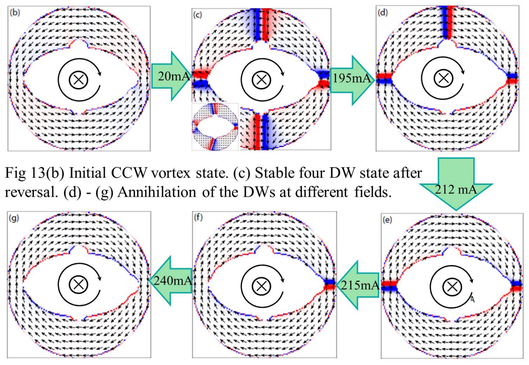


Fig 13(b) Initial CCW vortex state. (c) Stable four DW state after reversal. (d) - (g) Annihilation of the DWs at different fields.

V. CONCLUSIONS

1. We have given a proof of concept for multi-level bit storage device using six different magnetic states.
2. We investigated different aspects of domain wall winding number and domain wall length to form and annihilate four domain walls.
3. We conclude that a circular ring with and an elliptical center and notches may allow us to get six different magnetic states. Whereas, an off-centered elliptical hole inside a circular ring hinders the formation of all four walls.

VI. ACKNOWLEDGEMENTS

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3. Center for Nanoscale Systems (CNS) at Harvard University.

VII. REFERENCES

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[3]T. Yang, KEA, *APL*, **98**, 242505 (2011).