Logic operations and data storage using vortex magnetization states in mesoscopic permalloy rings, and optical readout

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Abstract. Optical coatings applied to one-half of thin film magnetic rings allow real-time readout of the chirality of the vortex state of micro- and nanomagnetic structures by breaking the symmetry of the optical signal. We use this technique to demonstrate data storage, operation of a NOT gate that uses exchange interactions between slightly overlapping rings, and to investigate the use of chains of rings as connecting wires for linking gates.

1. Introduction
Magnetic elements are a promising basis for development of smart memory and low-power applications. Magnetic random access memory chips, while much more expensive than competing technologies, have found markets where power minimization and data retention upon power-down are essential. However, the devices rely on very tight manufacturing control over the oxide barriers in the tunnel junctions, and there are scaling issues related to cross-talk between the current-carrying control wires [1, 2]. Several other paradigms are being considered for magnetic computation[3-6].

The use of magnetic vortex states has received increased interest, with both the chiral state of rings, and the state of the cores of magnetic disks being explored for data storage purposes[7-9]. Under the influence of a magnetic field, rings with diameters from micrometer to nanometers exhibit saturation, relaxation to an “onion state” and a circumferential (vortex) state of either clockwise (CW) or counterclockwise(CCW) chirality, as shown in Fig 1a. The CW and CCW states can be used to represent the logical values of 0 and 1. For rings in which a vortex is the ground state, the stability of data can be controlled by variation of the geometry and materials chosen for the ring. In this paper, we demonstrate the use of these vortex magnetic states for data storage and simple logic operations. We describe operation of a NOT gate and investigate interconnects and majority gate designs for employing multi-ring structures in the equivalent of null-convention logic cellular automata.

2. Experimental methods
Proof-of-concept devices were fabricated using e-beam and photolithography and thermal evaporation of Permalloy (Py), aluminum, and zinc sulfide coatings. Individual rings of Py, 5 microns in diameter with a central hole of 3 microns, and 45-50 nm thick, were

Figure 1 a) schematic hysteresis loop of ring  b) measurement geometry
deposited onto silicon (100) wafers. All samples were measured using a commercially manufactured small-spot magneto-optic Kerr effect (MOKE) measurement system with computer controlled coils capable of delivering arbitrary 2-dimensional global field signals to the sample [10]. A 5 mW diode laser operating at 635 nm, and with a 10 micron spot size, was used to illuminate the sample at an incidence angle of 45 degrees. Figure 1b shows the measurement geometry. The magnetization-induced polarization shift was measured using a combination of a quarterwave plate (to remove phase shifts) and an analyzing polarizer [11]. The analyzer was set at a 2-3 degrees off extinction, and typical measurements presented here were averaged over 200-500 cycles of the magnetic field to improve signal to noise ratios.

The small spot size of our system and the diameter of the rings chosen for these studies are matched so that we can determine the magnetic behavior of rings that are touching or in close proximity. In this way, we can look at cascading magnetization behavior in systems of rings. Although these experiments have been performed by changing the fields globally, strip-line activation of individual rings will ultimately allow us to control multiple inputs in an addressable manner.

In order to measure the response reliably, we needed to control the chirality of the rings. Following Nagatani [12], a segment of the ring was removed from the pattern, as shown in figures 1b and 2a. The chord of this segment was aligned perpendicular to the incoming light beam (transverse, y-axis) as shown in figure 1b. When exposed to a 2-3 second pulse of a 300 Oe transverse magnetic field, the shape anisotropy of the narrow region of the ring results in retention of a preferred direction during subsequent longitudinal field cycling. The retained magnetization sets the chirality (CW or CCW) when the ring collapses into the vortex state. This permitted us to set and characterize a particular state deterministically.

One half of each ring was overcoated (lower half in figure 2a) with an antireflection (AR) layer of ZnS 60 nm thick, which is a quarterwave for the angle of incidence we are using.

3. Results and Discussion

3.1. Single rings

Figure 2b shows the hysteresis loop measured for one of these clipped rings, without the AR coating present as a reference. For the uncoated ring, the usual plateaus near zero field show that the magnetization, averaged over the ring, is zero for the vortex states. It is not possible to determine whether the ring is in the CW or CCW state. With the addition of the AR coating over half of the ring, the symmetry of the optical signal is broken. The amplitude of the signal from the coated half is increased by a factor of 2-3x (depending on the coating thickness and measurement conditions) and undergoes a phase change of ~180 degrees due to the coating [13, 14]. Using A as the value of the signal from the uncoated half of the ring, the values for saturation in the positive and negative directions will be -2A (-3A+A) and +2A respectively. For a CCW vortex state (figure 2c), the
contribution of the upper half will be $A$ and the bottom half will be $3A$, leading to a larger signal than either saturation condition. For a CW vortex state (figure 2d), the value will be $-4A$, below both saturation values. Using the transverse pulses described above, we were able to set the rings controllably to either the CW or CCW state, and read out these values using the MOKE signal, demonstrating their potential as data storage elements. Stripline setting of the narrow region of the ring, or thermally-assisted switching could be used to load data, and multiple beams (with a reference, so that the offset from saturation is determined) would allow optical readout.

3.2. NOT gates

Combining data storage with modest processing power ("smart memory") is of interest for many applications where the bus between the processor and the data storage blocks of a computer becomes the limiting factor in processing. We have demonstrated reliable operation of the simplest logic operation – an inversion. A clipped ring is connected to a uniform ring (with an indeterminate vortex chirality), which switches at a slightly lower longitudinal field value. As the field is reduced from saturation, the clipped ring switches first, and drives the state of the attached ring to the opposite state. We fabricated samples that had coatings on the top and bottom halves of rings joined at a 45 degree angle to the applied fields, and measured the response of each ring separately. The hysteresis loop for the input and output rings of such a NOT gate are shown in figure 3. Note that because the coating of the output ring is on the top half of the ring, there is a sign change from the input signal which has the coating on the bottom. After a positive transverse pulse, the input ring always drops into a CW state. The output ring has a similar loop, but due to the coating being on the top, this is identified with a CCW state, and inversion is confirmed. It is noteworthy that for the CW state of the input ring, the vortex state is retained to higher value of the applied field for the increasing-field portion of the cycle. This is because the overlap region is magnetized in an overall positive direction with the CW state. When the field is increasingly negative, there is a conflict between the applied field and the vortex-induced magnetization in the central region that results in an earlier conversion to the onion state. This is shown by the different widths of the two vortex states. In the CCW state, the relative width of these two states is reversed.

3.3. Signal transfer

In the design of cellular automata, in addition to logic gates, it is essential to demonstrate fan-out capability, and to be able to transfer information through signal lines from one gate to another. We tested fan-out capability using the pattern shown in Fig 4a. When a transverse pulse set the signal in the clipped ring to the CW state, CCW output was observed in both of the symmetric rings on the right. Signal transfer is accomplished through a linked series of rings that will undergo cascading inversions when

![Figure 3](image_url) a) SEM b) input readout and c) output ring readout for the NOT gate

![Figure 4](image_url) a) fan-out ring configuration; b) transfer line configuration
triggered by a switching event. We made preliminary investigations of chained rings to determine the feasibility of making gate connections this way. Rings with different orientations with respect to the measurement field, and different diameters were tested. The most successful pattern is shown in Fig 4b. In this case, a CW input to the clipped ring at the top (using a transverse field, as usual) resulted in reliable conversion of the bottom (output ring) to the CW state, demonstrating signal transfer. We used a smaller inner diameter for the final ring to displace the switching threshold for the final ring. Using the standard overlap and the same geometry for each of the rings resulted in less reliable output. Further investigations on reducing overlap and changing the contact angle between rings are planned to improve these characteristics.

4. Summary
In this work, we have shown that vortex states in physically connected rings can be used for data storage and that the information can be read out optically. We demonstrate operation of a NOT gate using global fields to set the inputs. Preliminary investigations on rows of connected rings were presented. These studies form the basis for future work into more complicated logic gates and circuits made of linked rings. The single layer construction is robust, and stability of data structures can be designed in via the geometry of the rings. Future work will include use of striplines for input, and production of a majority logic gate.

References
[1] Freescale Semiconductor Press Release, http://www.flashmemorysummit.com/English/Collaterals/Press_Releases/2008/20080226_Freescale.pdf, 2008.
[2] Orlov, A, Imre, A, Csaba, G, Ji, L, Porod, W, Bernstein, G H, 2008 J. of Nanoelectronics and Optoelectronics 3 55-68.
[3] Cowburn, R P, Welland, M E, 2000 Science 287 1466-1468.
[4] Csaba, G, Imre, A, Bernstein, G H, Porod, W, Metlushko, V, 2002 IEEE Trans. on Nanotechnology 1 209-213.
[5] Cui, Z, Rothman, J, Klau, M, Lopez-Diaz, L, Vaz, C A F, Bland, J A C, 2002 Microelectron. Eng. 61-2 577-583.
[6] Klau, M, Lopez-Diaz, L, Rothman, J, Vaz, C A F, Bland, J A C, Cui, Z, 2002 J. Magn. Magn. Mater. 240 7-10.
[7] Black, W C, Das, B, 2000 J. Appl. Phys. 87 6674-6679.
[8] Imre, A, Csaba, G, Bernstein, G H, al, e, 2003 Superlattices and Microstructures 34 513-518.
[9] You, C Y, Bader, S D, 2000 J. of Appl. Phys. 87 5215-5217.
[10] Durham Magneto Optics Ltd, http://www.durhammagnetooptics.com/index_files/Products.htm, in.
[11] Allwood, D A, Xiong, G, Cooke, M D, Cowburn, R P, 2003 J. of Phys. D Appl.Phys. 36 2175-2182.
[12] Nakatani, R, Yoshida, T, Endo, Y, Kawamura, Y, Yamamoto, M, Takenaga, T, Aya, S, Kuroiwa, T, Beysen, S, Kobayashi, H, 2004 J. Appl. Phys. 95 6714-6716.
[13] Allwood, D A, Xiong, G, Cooke, M D, Faulkner, C C, Atkinson, D, Cowburn, R P, 2004 Appl. Phys. 95 8264-8270.
[14] Bowden, S R, Ahmed, K K L, Gibson, U J, 2007 Appl. Phys. Lett. 91 232505.