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ABSTRACT
Past studies have demonstrated that logic states can be represented using the rotation of the magnetization at flux-closed remanence in individual ferromagnetic disks. In this work, we present the results of micro-magnetic simulations of touching circular elements that can be used for room operable magnetic quantum cellular automata. Like gears in a mechanical system, the chirality of the magnetization alternates from element to element, as determined through interaction with neighbors. The switching of touching symmetric elements occurred when the applied field was removed, meaning minimal energy loss during the process. Maintaining coherence of opposite chirality in chains of elements could be achieved with the introduction of a biasing element to eliminate the bidirectionality of interaction.

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I. INTRODUCTION

Interest in viable alternatives to standard transistor-based computing is increasing as scaling nears its limit. Currently, only three major chip makers are in the race to bring the 7 nm transistor process node to market.\(^1,2\) Ferromagnetic materials have long been considered as a potential successor, especially in the areas of high-density storage and magnetic random-access memory (MRAM); their major advantages are non-volatility, higher packing density, and extremely low power dissipation. By extension, their potential use as room temperature magnetic quantum cellular automata (MQCA) has been studied and it has been shown that logic states can be represented using the direction of the in-plane magnetization.\(^4\) In the case of symmetric elements such as Permalloy disks, the rotation of the disk’s magnetization in the clockwise or anti-clockwise direction can be used to represent logic 1 or 0. The rotation in this “vortex state” happens at flux-closed remanence when the applied field has been removed. Additionally, in symmetric rings, a third state known as an “onion” or reset state is present. This state is a superposition of the two rotational states, and it occurs when magnetization is driven to saturation by an external field.\(^4\) Circular magnetic elements are particularly good candidates for MQCA since it is known that magnetization reversal depends on the element aspect ratio and symmetry.\(^5\) In addition, with the vortex state at flux-closed remanence, switching can be achieved with minimal power dissipation.\(^7\)

Bringing two or more elements in proximity to one another means that quantum entanglement can be introduced into the system, and of course, the strength of interaction between elements can be tunable depending on how close they are to one another, i.e., slightly apart, or just touching at the edges. The magnetic field lines between the elements are coupled because of the quantum exchange force that aligns neighboring magnetic spins in parallel. Opposite chirality of magnetization at remanence in each element then occurs as domain walls form at the free edges, giving rise to edge-driven switching. The correlated end state of the elements in a linear chain means that a basic NOT gate or magnetically coupled wire can be realized.\(^4\)

Currently, common measurement techniques like Magnetic Force Microscopy (MFM) or Scanning Hall Probe Microscopy
(SHPM) are capable of imaging magnetic samples but they are limited to zero field measurements. In the case of MFM, the tip–sample interaction can potentially change the magnetization state of the sample itself. An in-field technique such as Lorentz microscopy is not ideal either since repeatable measurements are difficult to obtain due to the shifting electron beam. These methods only offer spatial resolution analysis. They do not possess the temporal resolution necessary to capture the dynamics of the magnetization reversal process, which is on the order of picoseconds. On the other hand, temporal techniques like the magneto-optic Kerr effect lack the necessary spatial resolution. Hence, simulations are done to bridge the gap by providing an understanding on the formation, motion, and annihilation of the domain walls that enable the switching process itself.

II. SIMULATION PARAMETERS

The open source Object Oriented Micro-Magnetic Framework (OOMMF) from the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce, was used to simulate the elements in this study. The material was Permalloy of saturation magnetization $860 \times 10^3$ A/m with an element diameter and a thickness of 400 nm and 25 nm, respectively. The dimensionless damping factor $\alpha$ in the Landau–Lifshitz–Gilbert (LLG) solver has been experimentally established to be $\ll 1$ for ferromagnetic materials. The damping factor for disks and large aspect ratio rings was 0.0312 and for small aspect ratio rings, it was 0.011. These numbers were chosen to allow the elements to end in flux-closed remanence. The discretized mesh, which is determined by the magneto-static exchange length in Permalloy was 5 nm in the xyz axes. This was used for the smaller aspect ratio rings, but was increased to 25 nm in the z-axis for disks and the larger aspect ratio rings to reduce total simulation time. We do not believe that the use of a larger z-axis mesh affected the results of the simulated disks or larger aspect ratio rings.

III. RESULTS AND DISCUSSION

A. Individual circular elements

Shown in Figs. 1(a)–1(c) are the OOMMF representations of a disk going from saturation to a remanent vortex state through the formation of two domain walls at the edges of the disk. Previous studies have shown that domain walls move perpendicular to the applied field and that the probability of a clockwise or anti-clockwise chirality at remanence is 50\%. The stray out-of-plane component of the vortex core, also known as the demagnetizing field, then rotates in-plane until it finally settles in the disk center. Work done by Zhu et al. showed that vortex-type magnetization becomes harder to maintain as the diameter of the disk shrinks since the exchange energy becomes comparable to the magnetostatic self-energy at 100–200 nm diameter. They, instead, proposed using a ring element to eliminate this instability of the vortex core which can cause the demagnetizing field to flip in either the +z-axis or −z-axis as the disk shrinks.

Simulations in Figs. 1(e), 1(f), 1(h), and 1(i) of 400 nm rings with 40 nm and 100 nm holes, respectively, settled into full vortex at remanence without the residual vortex core. The onion states are shown in Figs. 1(d) and 1(g), but it should be noted that other representations of this state are possible. Like the disks, both rings formed two domain walls that moved perpendicular to the applied field. Although not shown here, it was found that the rings of aspect ratio <4 did not settle into vortex at remanence, as the types of domain wall formed were a mixture vortex and transverse —head-to-head or tail-to-tail—type walls. The magnetostatic free energy of transverse walls is higher than that of the vortex; hence, annihilation of all domains within the ring does not take place. This non-zero coercivity indicates that the ring was not fully demagnetized at remanence, meaning that switching occurs at a non-zero field. The rings of aspect ratio <4 were therefore not considered when simulating multi-ring systems.

B. Touching disks

When two elements are brought together within the range of the magnetostatic exchange length, the exchange energy’s alignment of the magnetic moments at the contact edge keeps domain walls from forming at that edge. With the magnetization there effectively pinned, the far edges of both elements begin to form vortex-type walls. In the case of touching disks, both begin to switch, ending up with remanent magnetizations of opposite chirality in Fig. 2. The two elements put together can be thought of as an implementation of a logical NOT gate.

The bidirectional nature of the switching seen with two elements becomes problematic when three or more elements are in play. In a three-disk chain, the two outermost disks begin to switch with vortex walls at the free edges, while the central disk’s magnetization is pinned at both of its edges. The outer disks resolve into
their remanent vortex states, while the central disk’s magnetization is left in a superposition of two competing chiralities as in Fig. 3(a). Adding an elongated biasing element to the three-disk chain as shown in Fig. 3(b) imposes a unidirectional order on the switching process. Like disks, switching in elongated elements starts from the edges and magnetization reversal occurs at higher switching fields. Being in contact with one of the disks mean that magnetization can be pinned and reversal delayed in that disk, allowing unidirectional switching.

The biasing element used here was an elongated diamond of $400 \times 100 \text{ nm}^2$. In Fig. 3(b), the leftmost disk still has domain walls, while the rightmost disk resolves its remanent vortex state first. The other two disks then follow, resolving themselves simultaneously. The system ends with the magnetization moments of the disks at the contact edges going in the same direction as in Figs. 3(c) and 3(d). A correlated disk chain could, therefore, be used as a magnetically coupled wire.

However, this method for imposing unidirectional switching does not work for larger chains of disks as the magnetizations of the leftmost disk and the biasing element did not end up in the same direction, although all the disks are correlated and the switching was unidirectional. The image shown in Fig. 4 suggests the correlated volume, the number of elements that can remain magnetically coupled in this system is four. This was also confirmed in our simulations for five, six, and seven-disk systems. In these cases, the disks became uncorrelated at random points in the chain, even though they all ended in remanent vortex states. Decreasing the $z$-axis mesh to 5 nm did not change these results.

C. Touching rings

For touching rings, experimental studies have shown that multiple touching rings demonstrated correlated chiralities. In our simulations, we found that even numbered chains of rings ended in correct correlation. Figure 5 shows the correlated states of two touching rings with 40 nm and 100 holes, respectively. In a four-ring chain with 40 nm holes, switching began from the two end rings and propagated inward to the inner rings as seen in Figs. 6(a) and 6(b). A biasing element was not needed because the influence of the demagnetizing field on the switching process is reduced due to the missing vortex core. We found that the correlation was shown for up to six rings with 40 nm holes as in Fig. 6(c). However, not shown here, we also found that the odd numbered ring chains suffered from the same problem of the unbiased disks, with the center ring not reaching a resolved vortex state. The addition of a biasing element did not change this result and neither did decreasing the simulation mesh in the $z$-axis to 5 nm.

In four-ring chains with 100 nm holes, our simulations showed a different switching mechanism. In Fig. 7, the two inner rings settled into their correlated vortex states first followed by the two outer rings. It is known that the symmetry strongly influences the switching of rings and that small deformations can be nucleation sites for domain walls. Given that all elements in this work were symmetric, we also now see that the aspect ratio plays a significant role in the switching process for a linear chain. This ring chain took significantly longer time to form domain walls and begin the switching process with the damping factor in the micro-magnetic solver being 0.011. This is because of the reduced influence of the vortex core as the damping factor in the four-ring chains was 0.0312. The fact that there is less space for a vortex-type domain wall to form as the hole size increases also confirms this. As mentioned earlier,
FIG. 4. A 4-disk chain with biasing element. Although the disks end in a correlated state, the leftmost disk is not correlated with the biasing element unlike in the 3-disk chain.

FIG. 5. (a) Correlated vortex states of 400 nm Permalloy rings with a 40 nm hole. (b) Correlated vortex states of 400 nm Permalloy rings with a 100 nm hole.

FIG. 6. Four-ring chains with 40 nm holes in the switching process (a). In correct correlation without biasing element (b). Six-ring chain in correct correlation (c).

FIG. 7. Four-ring chains with 100 nm holes in the switching process (a). In contrast to its 40 nm hole counterpart, the two inner rings switch first followed by the two outer rings. The chain in correct correlation (b).
the rings with the aspect ratio <4 did not form vortex-type domain walls.

Keeping this in mind, putting together a mix of large and small aspect ratio rings could be used to implement a majority logic gate where the state of the output is determined by the majority input. Just as in standard transistor-based logic where inputs are decided and stable before an output can change, the large aspect ratio rings can be used to implement stable inputs, while the smaller aspect ratio rings can be used for the output. Since chirality control of the rings has been shown to be possible by shifting the location of the hole, this could then be achieved.

IV. CONCLUSION

Our simulations show that circular elements are a good candidate for MQCA. They offer stable ground states that can be used to represent logic 1 or 0. Circular rings have an additional onion state that can be used as a reset. When in contact, magnetic moments line up in parallel at the point of contact allowing for edge-driven correlated switching to take place. Our simulations show that magnetically coupled wire and basic NOT gate can be achieved, the limiting factor being the magnetic correlated volume for the wire. It may be possible to use a mixture of rings with different aspect ratios to implement stable inputs and outputs to a complex majority gate.

SUPPLEMENTARY MATERIAL

Simulation videos with hysteresis loops for Figs. 2–7 can be found in the supplementary material.

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