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A multi-level single-bit data storage device

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One method to increase bit density in magnetic memory devices is to use larger structures that have multiple states in which to encode information rather than the typical two state system. A ferromagnetic nanoring with multiple domain walls that annihilate at different applied magnetic fields could serve as such a bit. This paper examines the formation and annihilation of four 360° domain walls (DWs) using micromagnetic simulations. To create the walls, one can apply circular magnetic fields to asymmetric nanoring structures. Nanorings with circular notches on a centered elliptical hole enable the formation of stable DWs in specific locations with known characteristics. By considering the impacts of both domain wall length and topological winding number on domain wall energy, one can create a nanostructure with four stable domain walls that annihilate at different applied magnetic fields. With two stable vortex configurations, such nanorings could theoretically encode up to ten different states. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4867603]

The prevalence of portable electronics and growing need for mass storage motivate research efforts to create smaller, stable memory structures. However, as bit density continues to increase, it becomes difficult to address individual nanobits. One possible solution is to use a multi-level bit. Multi-level bits are larger magnetic nanostructures that encode information not in a two state system but in a system with a greater number of distinct, identifiable magnetic states.[1,2]

In recent years, ring-shaped ferromagnetic structures have been proposed in magnetoresitive random-access memory (MRAM) designs,[3,4] using the lowest energy configurations, the clockwise/counterclockwise (CW/CCW) vortex states, and magnetoresistive readout to enable the fast data access and non-volatility of MRAM. In the case of thin nanorings ($\approx$5 nm), the reversal process from one stable vortex to the other occurs via the creation and annihilation of 360° domain walls (DWs).[5,6] Such 360° DWs have been seen experimentally in both rings[7–11] and other closed nanostructures[12,13] and have been studied computationally.[5,11,14,15] If n stable 360° DWs could be created in a single nanoring that annihilates at different energies, this would lead to a nanoring with 2+ n DW states that could theoretically be used as a multi-level bit. In this paper, we examine a nanoring with four distinct 360° domain walls that annihilate sequentially at different applied magnetic fields. We use circular rings with elliptical centers and consider the effects of the length and winding number on the annihilation of such walls.

Calculations were performed with OOMMF,[16] which iteratively solves the Landau-Lifshitz-Gilbert equation in order to find the minimum energy state. The magnetic parameters were set for permalloy, with a saturation magnetization of $M_s = 8.6 \times 10^5\,\mathrm{A/m}$, a six-nearest neighbor exchange parameter of $A = 1.3 \times 10^{-13}\,\mathrm{J/m}$, and no crystalline anisotropy, and calculations were performed at $T = 0\,\mathrm{K}$ in order to reduce simulation time. Previous studies have shown that 360° DWs in symmetric nanorings will form at room temperature.[4,5,14] The rings studied here have an outer diameter (OD) of 800 nm and the inner hole is an ellipse with a major axis of 600 nm and a minor axis of 345 nm. The thickness of the rings is 5 nm and a grid of $3.2 \times 3.2 \times 5$ nm/cell was used. The applied circular magnetic field simulates the effect of current passing through an infinite wire in the center of the ring, such that the magnetic field is proportional to the current and the inverse of the distance between the calculated point and the wire.

In order to make a multi-level bit, we must first form multiple domain walls and then control their annihilation at different applied fields. Figure 1(a) shows a nanoring with four 360° domain walls. There are two types of 360° DWs which are identified by their topological winding number, Ω. The left and right DWs have a topological winding number of $+1$, because the rotation of spins in the 360° DW is in the same direction as the underlying vortex (both are CW). In the top and bottom DWs, the rotation of spins in the DW is in the opposite direction (CCW) of the underlying vortex (CW) resulting in $\Omega = -1$. 360° DWs form in pairs of opposite winding numbers during magnetization reversal in a circular magnetic field.[6] In Figure 1(a), the ring was initialized with a CCW magnetic structure and then an azimuthal magnetic field of that would result from a current of $I = -30\,\mathrm{mA}$ was applied to reverse the magnetization, creating transition states which then form 360° DWs. The transition states consist of a central rotated domain bounded by two 180° DWs of opposite winding number, as seen in the schematic in Fig. 1(b). As the switched center region grows, the 180° DWs propagate away from the central region until they meet the 180° DW. As adjacent domains rotate in opposite directions for magnetostatic and topological reasons, the 180° DWs that meet have the same winding number and so combine to form a single 360° DW, such as the one at the center

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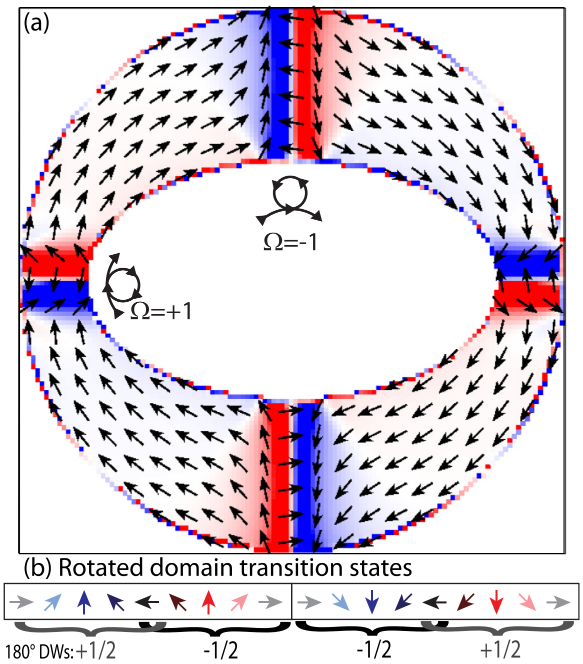

FIG. 1. (a) Four DW state in an 800 nm outer diameter ring with a 600×345 nm elliptical hole at $I = -30$ mA. The magnetization was initially CCW and has reversed such that it is mostly in the CW direction. Four 360° DWs formed in the reversal process, two with $\Omega = +1$, and two with $\Omega = -1$. (b) Schematic of two rotated domain transition states, which formed on the lower left and lower right domains of (a) and comprised two 180° DWs. As these 180° DWs meet those of adjacent domains, they form the 360° DWs seen in (a).

boundary in Fig. 1(b). A pair of rotated domains will form one 360° DW of $\Omega = +1$ and one of $\Omega = -1$. As the rotated domains always occur in pairs, the result is always an even number of DWs in pairs of $\Omega = +1$ and -1. For more details of this process please see Ref. 6.

Creating four stable DWs is the first step towards a multi-level bit. Figure 1(a) has two pairs of identical DWs: the top and bottom DWs and the left and right DWs. Therefore, the energy degeneracies must be broken so that the four DWs annihilate at four different applied magnetic fields. DW energy is a function of the exchange and magnetostatic energies and these energies are impacted by both the DW length and the topological winding number.[14] We can determine domain wall energy by calculating the change in magnetostatic and exchange energy before and after DW annihilations. For otherwise identical 360° DWs in a symmetric nanoring of 800 nm outer diameter and 320 nm inner diameter, we find the exchange and magnetostatic energies of a +1 to be -1.7×10^{-18} J and -2.7×10^{-18} J, respectively. These values are higher than those of the -1 DW, which are -0.5×10^{-18} J and -2.5×10^{-18} J, respectively, in agreement with previous work.[5,14] As the outer diameter of the ring shrinks, increasing the curvature, the relative contribution of the exchange and magnetostatic energies to the total energy changes. As the length of the DW is decreased but the curvature is held constant, the total energy of the wall decreases. However, in all cases, the +1 has a higher energy than then -1 DW. Thus, we can adjust the DW energy by varying the DW length and winding number.

An initial attempt to make four non-degenerate DWs is to ignore the winding number and simply create four DWs of different lengths by using an inner elliptical hole that is off-center. However, only two or zero DWs form due to the asymmetry of the structure. When the elliptical hole is off-centered, the rotations that form the transition states begin at different times due to the lack of uniformity of the applied magnetic field along the inner boundary. The applied magnetic field is the driving force behind rotation and is strongest at the inner boundary, where it must overcome the energy barrier of the magnetostatic energy that resists rotation of

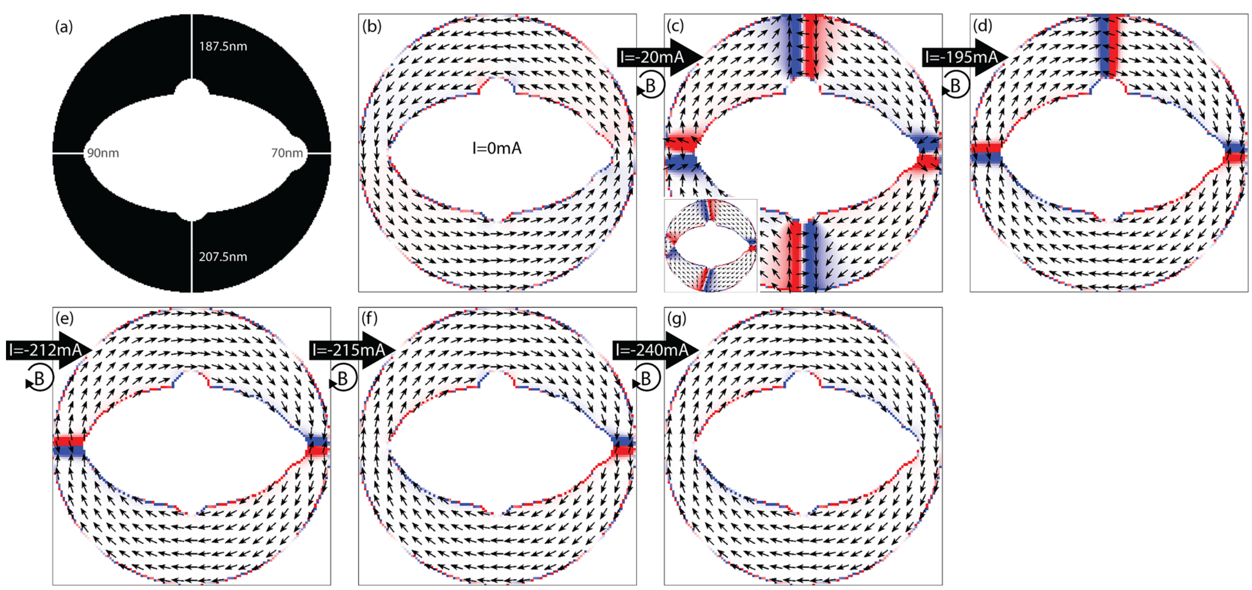

FIG. 2. 800 nm outer diameter nanoring with a 600×345 nm elliptical hole. Circular notches of $d = 100$ nm are inserted into the ring (clockwise from top) ≈40 nm, 30 nm, 20 nm, and 10 nm to make four different domain wall lengths as seen in (a). (b) Initial CCW vortex state. (c) Stable four DW state after reversal. The inset shows a snapshot of the formation of the DWs, revealing the effect of the pinning sites. (d)–(g) Sequential annihilation of the DWs at increasing field strengths.

spins at the boundary. For a perfectly centered current in a ring with a circular, centered hole, the magnetic force on the spins at the inner boundary from the applied magnetic field is uniform. As the hole is changed into an ellipse, the magnitude of the force of the applied magnetic field on the spins at the inner boundary changes as a function of position. This lack of uniformity means that some of the 180° DWs bordering the rotated domain transition states begin propagating before the neighboring domains fully form 180° DWs. Instead of forming 360° DWs, the propagating 180° DWs annihilate those that have not fully formed and fewer 360° DWs are created. The asymmetry may also lead to DWs forming at positions other than the stable and metastable positions defined by the major and minor axes of the ellipse. When this occurs, the DW moves to minimize its length by approaching the stable position defined by the major axis of the ellipse, and two domain walls of opposite winding number will annihilate if they meet at this position.

In order to create four stable DWs, we instead used pinning sites. Different configurations of notches and antinotches have successfully been used as pinning sites for magnetic domain walls either to keep them from moving[17,18] or to control where they form.[19] Figure 2(a) is the profile of the same ring as in Fig. 1, with the inclusion of four circular notches. Each notch has a diameter of 100 nm and has been inserted into the ring by 10–40 nm.[20] The nanoring is initialized with a CCW magnetic vortex structure as seen in Fig. 2(b). The magnetic field is created by passing current through the center of the nanoring, and the current is initially increased in 10 mA steps until $I = -90$ mA, then in 5 mA or 1 mA increments in order to see the order of DW annihilation. At $I = 20$ mA, the four domain walls form, as seen in Fig. 2(c). The inset shows the effect of the notches at a snapshot during the magnetic relaxation at $I = 20$ mA. Even though the DWs form slightly to the left of the top and bottom notches, the notches keep both DWs pinned rather than allowing them to collapse to the narrowest point of the ring.

There is no change in the DW structure as the current is increased to $I = -190$ mA except that, as the Zeeman field gets stronger, the DWs narrow slightly as can be seen by comparing the DW width in Figs. 2(c) and 2(d). The longest DW, at the bottom of the ring, annihilates at $I = -195$ mA, followed by the top DW at $I = -212$ mA, the left DW at $I = -215$ mA, and the right DW at $I = -240$ mA. Thus, if we are only considering that the DW energy is a function of length, the DWs annihilate in the correct order. To understand the small field difference between the DWs at the top of the ring and the left of the ring, we have to consider the winding number. The top wall is almost double the length of the left wall, however, the left wall has an $\Omega = +1$ rotation. Because +1 DWs cost more energy than −1, DWs of the same length, the top and left walls annihilate at similar fields. It is also not possible to force the longer walls to have +1 winding and the shorter walls to have −1, because the +1 DWs cost more energy and so form in locations where their length is minimized.

Overall, we have shown that it is possible to make structures with four stable DWs that can be annihilated at different currents. The asymmetry in off-centered, elliptical holes destroys the ability to form four stable walls. However, pinning with notches in a centered elliptical hole allows the four domain walls to form and forces them to stay at the axial positions of the ellipse. In terms of creating these structures experimentally, the fabrication considerations to meet the geometric requirements may limit the utility of such structures.

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[20] It should be noted that, in the formation of the profile, all sizes were rounded to the nearest grid size of 3.2 nm in order to keep the edges of the notches and the ellipse as uniform as possible.