Bit Storage by 360° Domain Walls in Ferromagnetic Nanorings

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Abstract

We propose a theoretical design for the magnetic memory cell which allows an efficient storage, recording, and readout of information on the basis of thin film ferromagnetic nanorings. The information bit is represented by the polarity of a stable 360° domain wall introduced into the ring. Switching between the two magnetization states is achieved by the current applied to a wire passing through the ring, whereby the 360° domain wall splits into two charged 180° walls, which then move to the opposite extreme of the ring to recombine into a 360° wall of the opposite polarity.

Index Terms: magnetoresistive random access memory (MRAM), ferromagnetic rings, topological domain walls, current-induced switching, micromagnetic modeling

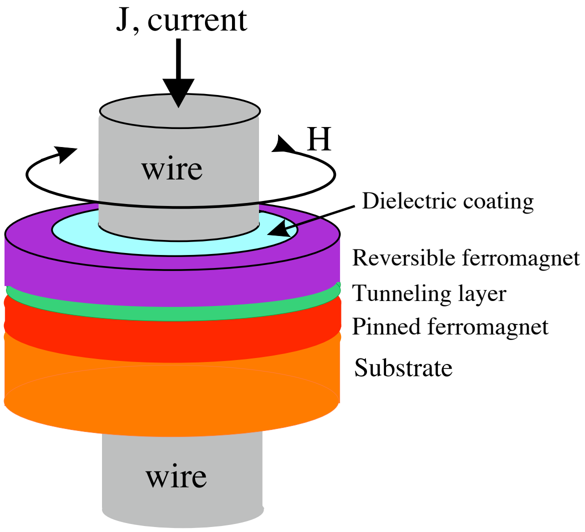

FIG. 1: Schematics of the proposed design.

Magnetoresistive Random Access Memory (MRAM) has long been considered as one of the main contenders to replace the current semiconductor-based devices as a universal, non-volatile computer memory [1–4]. Nevertheless, despite recent developments of commercially available products [1], MRAM technology is yet to deliver a device that would truly compete with the existing semiconductor technologies.

In the current MRAM cell designs the storage element is a sandwich structure which contains two ferromagnetic layers separated by a thin tunneling layer; the magnetization is fixed in one of the ferromagnetic layers, but is free to move in the other [1, 3]. The bit of information is encoded as a monodomain magnetization state of the free ferromagnetic layer which can be switched as a whole by the magnetic field generated by the current passing through the "write" lines. Readout is achieved by measuring the tunnel current through the storage element, which depends on the magnetization state. The main difficulty in designing an MRAM cell is to be able to reliably write bits of information to a specified cell. One important issue is the problem of 1/2-bit select due to the close proximity of the "write" lines to the free magnetic layer in the cross-point addressing scheme [1]. Another issue is the need to use rather strong currents to generate the magnetic fields required for switching, which makes these devices quite power-hungry.

Recently, a growing interest was attracted by a new MRAM cell design concept in which the storage element is made in the shape of a submicron-sized ring [5–19]. As was proposed in Ref. 5, the bit may be encoded by the direction of the vortex magnetization state in a ferromagnetic thin film ring. A difficulty associated with this design has to do with switching between the two vortex states, since it requires creating magnetization poles at the ring boundaries. Hence a rather elaborate writing scheme using paired word lines [5] or the use of spin-polarized current [16, 20–23] were called for. Note that in the latter case the current densities required to affect the magnetization state are found to be quite high (exceeding 10^8 A/cm^2) [16, 21, 23]. Another proposal has been to pass a current of variable polarity vertically through the sandwich structure, so that the resulting circular magnetic field favors a particular orientation of the vortex or the asymmetric "onion" magnetization state [7, 13].

Here, we propose a new principle for the design of a robust MRAM cell based on thin film ferromagnetic nanorings (see Fig. 1 for schematics). In contrast to similar previous designs [7, 24], which are based on twisted onion states (see e.g. Figs. 2b,c of [7]), we propose to use the polarity of the tightly localized 360° domain wall (see Fig. 2 below) in the free ferromagnetic layer to encode the bit of information. Existence and stability of such domain walls for certain ranges of parameters was recently demonstrated by us via micromagnetic modeling and simulations [25]. Winding domain walls, including 360° walls, are also frequently observed experimentally in cobalt nanorings [9, 10, 12]. We further propose to use the circular field generated by a wire passing through the ring to switch between the two polarities of the 360° wall. In addition, we suggest to use a material with a moderate four-fold anisotropy to further stabilize the wall.

The basic idea of the proposed design is that in the presence of a 360° wall the magnetization pattern looks like a vortex state in most of the ring, except a small region where the wall is localized (see Fig. 2). Nevertheless, in contrast to the vortex states, its topological degree (i.e. the winding number of the magnetization vector along a closed loop traced counter-clockwise inside the ring) is zero, since inside the wall the magnetization rotates in the direction opposite to the direction of rotation in the rest of the ring (for vortex states the topological degree is +1). Thus, both states corresponding to the ±360° walls are accessible by smooth in-plane rotation of the magnetization vector from the "onion" state [2, 6, 8, 16], the native magnetization state in the ring following saturation by an in-plane field. Switching between these states can be achieved by passing a current of variable polarity through a wire running perpendicularly to the ring plane through its center, generating a circular mag-

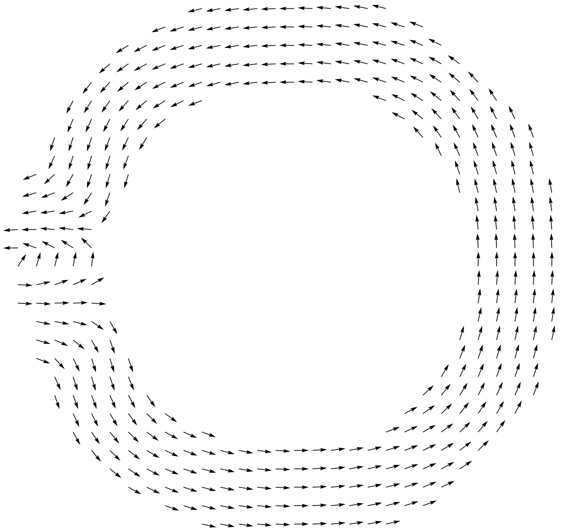

FIG. 2: Bit-encoding magnetization state with a −360° wall on the left. The other bit is encoded by the mirror image of this magnetization pattern, with the +360° wall on the right, respectively. From the numerical solution of (3), see the text for details.

netic field in the ring, and readout can be performed, as in previous designs, by arranging the ferromagnetic nanoring to be part of a magnetic tunnel junction sandwich, with fixed ferromagnetic ring layer in a vortex state. Note that this design is free from the 1/2-select problem, as was already pointed out in Ref. 7.

Let us demonstrate the feasibility of the proposed design by a micromagnetic study of the Landau-Lifshits-Gilbert equation [4] for the magnetization vector $\mathbf{M} = \mathbf{M}(\mathbf{r}, t)$ in the ferromagnetic ring (denoted by $\Omega \subset \mathbb{R}^3$):

$$\frac{\partial \mathbf{M}}{\partial t} = -\frac{g|e|}{2mc}\left(\mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s}\mathbf{M} \times \mathbf{M} \times \mathbf{H}_{\text{eff}}\right), \tag{1}$$

with Neumann boundary condition on the material boundary $\partial\Omega$. The effective field $\mathbf{H}_{\text{eff}} = -\frac{\delta E}{\delta \mathbf{M}}$, with

$$\begin{aligned} E[\mathbf{M}] = &\int_{\Omega}\left(\frac{K}{2M_s^4}M_1^2 M_2^2 + \frac{A}{2M_s^2}|\nabla \mathbf{M}|^2 - \mathbf{H} \cdot \mathbf{M}\right) d^3\mathbf{r} \\ &+ \frac{1}{2}\int_{\mathbb{R}^3}\int_{\mathbb{R}^3} \frac{\nabla \cdot \mathbf{M}(\mathbf{r})\, \nabla \cdot \mathbf{M}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|}\, d^3\mathbf{r}\, d^3\mathbf{r}'. \end{aligned} \tag{2}$$

Here we assumed the four-fold anisotropy typical of epitaxial films, e.g., cobalt films [26]. When the film thickness d is sufficiently small, this equation can be reduced [25, 27] to an effective equation for the angle θ between the magnetization vector in the film plane and an

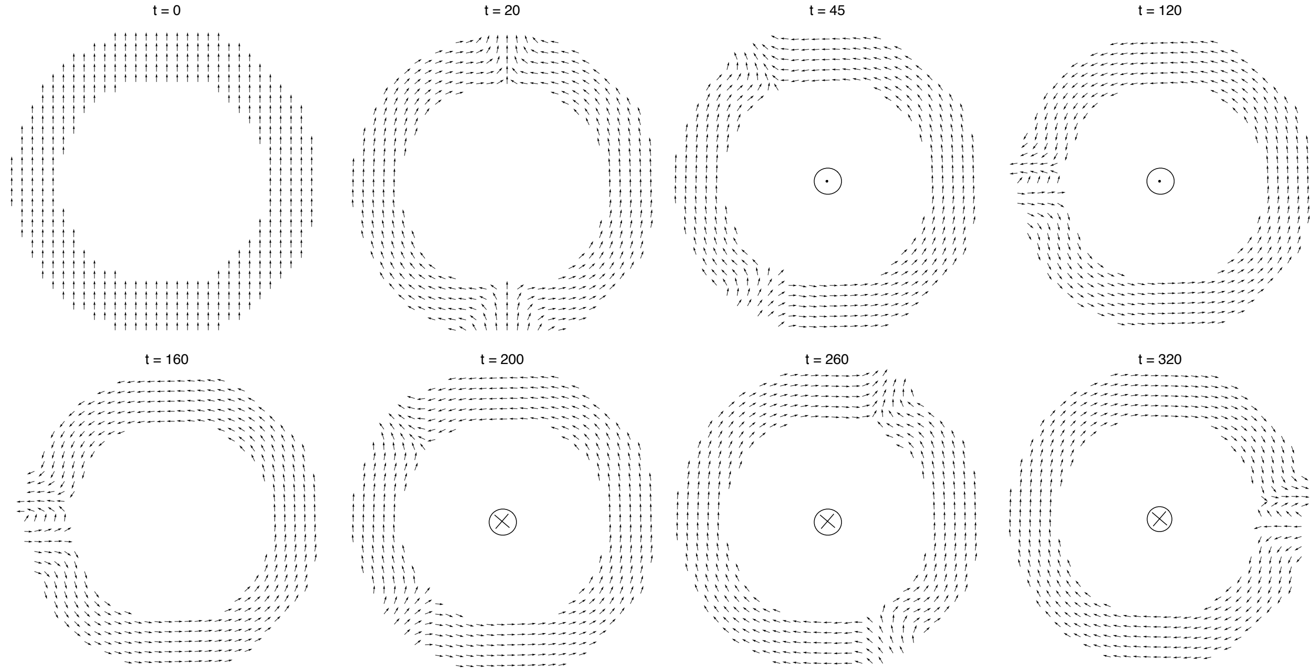

FIG. 3: The dynamics of the magnetization reversal in a ferromagnetic nanoring subject to the magnetic field from a wire passing through the ring center. Results of the numerical simulations of (3) (see text for details).

easy direction:

$$\begin{aligned} \theta_t &= \Delta\theta - \tfrac{1}{4}\sin 4\theta - h_1\cos\theta - h_2\sin\theta \\ &\quad +\nu\varphi_x\cos\theta + \nu\varphi_y\sin\theta, \qquad (3) \\ \varphi &= \tfrac{1}{2}(-\Delta)^{-1/2}\left(\theta_x\cos\theta + \theta_y\sin\theta\right) \\ &\quad +\text{boundary terms}, \qquad (4) \end{aligned}$$

where lengths were rescaled by $L = (A/K)^{1/2}$, and the thin film parameter $\nu = d/(lQ^{1/2})$ was introduced [27], where $l = (A/4\pi M_s^2)^{1/2}$ is the exchange length and $Q = K/(4\pi M_s^2)$ is the material's quality factor.

We now investigate the process of switching in a ferromagnetic nanoring by performing a numerical simulation of (3) in a ring of diameter 30 and width 5, with $\nu = 10$, and $h_1 = \mp 3.2y/(x^2+y^2)$, $h_2 = \pm 3.2x/(x^2+y^2)$, or $h_{1,2} = 0$, depending on the current through the central wire (all quantities are dimensionless, see the following paragraph for a physical interpretation; the details of the numerical method are as in Ref. 25). At $t = 0$, the magnetization is saturated by a field along the y-axis. As the field is removed, the magnetization settles into the symmetric onion state (Fig. 3, $t = 20$). Then, a positive current is applied through the wire, generating a counter-clockwise magnetic field, which drives the poles of the onion and the associated charged 180° walls towards each other on the left side of the ring. At $t \simeq 100$ these two walls collide to form a 360° wall (Fig. 3, $t = 120$). Importantly, when the current is stopped, the resulting 360° wall maintains its integrity and does not break up (Fig. 3, $t = 160$, same as Fig. 2, consistently with our earlier studies of 360° walls [25]). Applying a negative current leads, in turn, to a breakup of the 360° wall. The resulting charged 180° walls propagate along the ring to collide at the opposite extreme on the right and form a new 360° wall of opposite polarity (Fig. 3, $t = 320$). As before, when the current is switched off, the wall remains in its place (not shown). Note that no magnetic poles need to be created during switching, the existing poles simply move back and forth along the ring boundaries.

In conclusion, we have demonstrated the feasibility of storage and writing of a bit in the form of ±360° walls in a thin film ferromagnetic ring. The dimensionless parameters used in the simulation can be translated, e.g., to those of a cobalt ($l = 3.37$ nm, $M_s = 1400$ emu/cm^3, $Q = 0.08$ [6, 26]) ring of diameter 350 nm, width 60 nm, and thickness $d = 9.6$ nm. The current producing the required circular magnetic field is $J = 27$ mA, corresponding to a moderate current density of 6×10^7 A/cm^2. Note that a way to further reduce the switching current density is to use a softer material (with smaller Q and d), at the expense of increasing the ring diameter. We emphasize that this design is expected to be very robust, in view of the stability of the underlying 360° walls [25] and the topologically constrained switching process. Finally, note that the proposed cell geometry allows to stack the rings vertically by interrupting the vertical wire with horizontal lines of alternating directions, suggesting a possibility to greatly increase the memory capacity by harnessing the third dimension.

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