Transitions Between Vortex and Transverse Walls in NiFe Nano-Structures

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This paper investigates the possible transitions between transverse and vortex type domain walls in magnetic domain wall trap memory elements, induced by a rotating magnetic field. A phase relation is shown to exist relating the final domain wall configuration to the field strength and field rotation frequency. Thus, it is possible to controllably switch from a transverse domain wall to either a clockwise or counterclockwise one.

***Index Terms*—Domain wall transitions, domain wall traps, magnetic random access memory (MRAM), memory elements.**

I. Introduction

DOMAIN wall traps for magnetic memory and sensor elements were proposed by McMichael and co-workers [1]. These memory elements may provide magnetic random access memory (MRAM) with reproducible switching behavior and low switching fields that is nonvolatile, reliable, fast, and secure. Two stable states for switching are provided by two knees in a magnetic nanowire, which act as traps for the domain wall (see Fig. 1). Switching between the two positions is achieved with an in-plane static magnetic field along the x direction. The total energy contains contributions from the magnetostatic, exchange, and Zeeman energies [2], and it is the balancing of these competing terms in the Energy Hamiltonian in order to minimize the total energy that leads to the stable micromagnetic configuration of the sample.

Because no magnetic domain nucleation step is required to move the domain wall between the two traps, the switching fields are much lower than in single-domain magnetic memory elements. In conventional memory elements based on rectangular or elliptic shapes, the high reversal fields may induce nonuniform switching modes with a wide distribution of switching fields.

The three typical wall structures that may occur are shown in Fig. 2, which give an enlarged view of the magnetization configuration near the right knee: the transverse wall, the counterclockwise vortex wall, and the clockwise vortex wall. If it were possible to reliably switch between domain wall structures as well as the positions of the domain walls in the trap structure, then it may be possible to store more information bits per storage unit. For example, the two stable domain wall positions and the three types of domain walls will give six different states or more than two bits per unit.

The stability of domain wall configurations is important for the correct functioning of the magnetic memory elements, so it is important to understand the mechanisms and conditions for transitions between different types of domain wall. The total energy of a domain wall in a nanowire depends on the dimensions

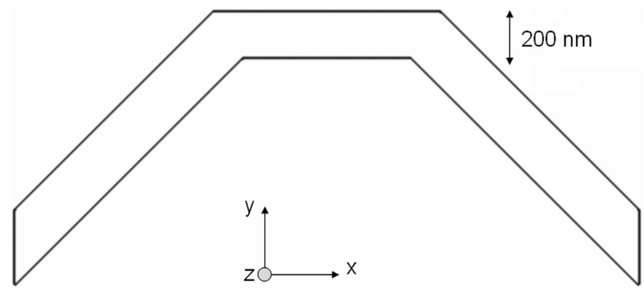

Fig. 1. Domain wall trap memory element with two central knees that provide stable positions for head to head domain walls that separate the two oppositely aligned regions of the magnetic nanowire.

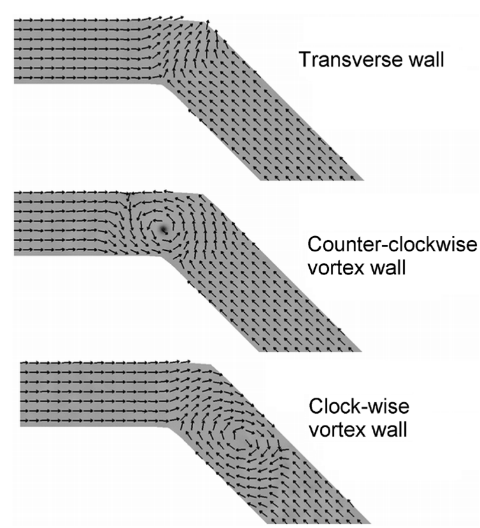

Fig. 2. Three possible domain wall configurations at the knee of a NiFe nano-wire. The width and the thickness of the wire are 200 and 20 nm, respectively. The magnetization configurations were obtained solving the Landau–Lifshitz–Gilbert equation with different initial states.

of the nanowire. McMichael and co-workers [3] showed that nanowire width is of particular importance, but in the memory elements suggested, which have width 200 nm, a transverse domain wall always has higher energy than a vortex wall, which is thus more stable. An energy barrier exists between the two

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states that might be overcome due to thermal effects at high temperature. The transverse to clockwise vortex and transverse to anticlockwise vortex transitions will have different associated energy barriers as the transitions require the sample to pass through different magnetization configurations.

II. Numerical Experiments

The Landau–Lifshitz–Gilbert (LLG) equation is solved numerically using a finite-element method [4]. Initial configuration files are chosen for transverse and clockwise vortex domain walls. These initial configurations are prepared by splitting the sample into a number of sections and designating each section with a particular magnetization direction. The sample is then allowed to relax in zero field into a stable remanent state. This technique results in the controlled generation of many different stable configurations, including the transverse and vortex domain walls required.

A clockwise rotating magnetic field is simulated in the plane of the sample. This introduces three variables; maximum field strength H, field rotation frequency f, and number of rotations n_{rot}. Throughout this investigation, a value of $n_{\mathrm{rot}} = 2$ has been used. After the rotations, the sample is allowed to relax to a stable configuration in zero field. H and f are varied to test for a phase relation between their values and the final domain wall configuration and condition of the sample memory element. Thermal energies are not considered, with temperature set at 0 K.

Energy barriers between the transverse and vortex states are calculated using an elastic band nudge method [5] for zero applied field.

III. Results and Discussion

Using the rotating magnetic field, it is possible to change a transverse head to head domain wall into a vortex domain wall, and also to control precisely whether the vortex is clockwise or counterclockwise around its core. Fig. 3 shows the approximated phase diagram obtained. A region exists where the frequency of the field rotations is low enough that the field can act along the length of the nanowire for an extended period of time, allowing it to move the domain wall to the end of the nanowire or even expel it completely. This results in a homogeneous magnetization which settles down with shape anisotropy of the memory element. Wall expulsion becomes even easier as the field strength is increased. An upper-left region exists where the frequency is so high that the magnetization is unable to follow the field direction. This is more significant when the field strength is low. In between these two regions the transition from transverse walls to vortex walls is observed, and by controlling the field strength it is possible to choose the result. Field strengths below about 230 Oe produce clockwise vortex walls while above 230 Oe counterclockwise vortices are formed. These regions are consistent and well-formed, providing a reliable, controlled method for transverse to vortex domain wall transitions.

Applying a rotating field to a vortex domain wall does not produce a useful phase relation. Again, a central region exists where the desired transition is possible. Vortex to transverse transitions are seen within this region but not, it seems, in a consistent, correlated manner. The vortex state is more energetically favorable, even if the energy barrier between the two states is overcome. Therefore, unlike transverse to vortex, a vortex to transverse transition cannot be considered probable or certain within this region.

Applying a constant static field of 150 Oe to the memory element structure with transverse wall demonstrates the switching process of the domain wall traps (Fig. 4).

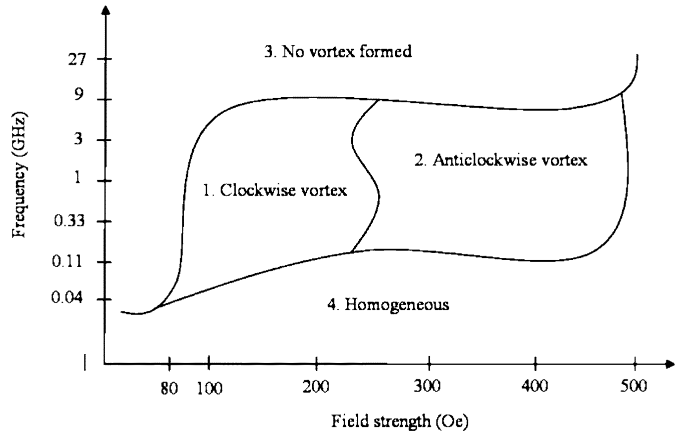

Fig. 3. Approximate schematic phase relation (based on clusters of data points) between maximum field strength H and field frequency f of a clockwise in-plane rotating magnetic field that has been applied to a transverse domain wall, showing distinct regions for the final domain wall configuration. These regions show that controlled transitions from transverse domain walls to clockwise or counterclockwise vortex domain walls are possible.

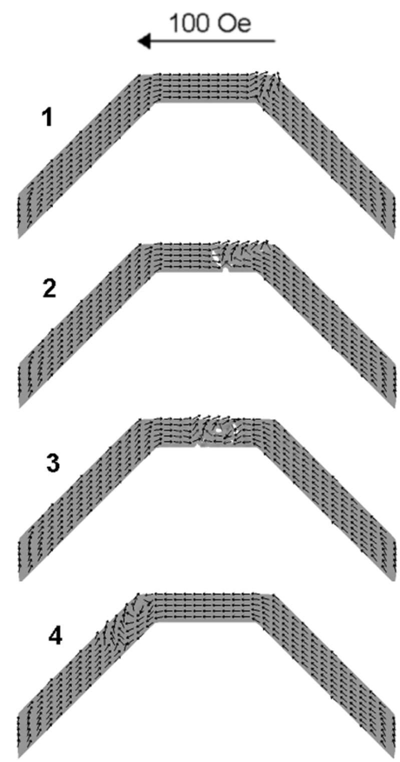

Fig. 4. Steps in the switching process of a domain wall trap memory element, from simulation. (1) The initial stable zero-field domain wall configuration is transverse. (2) The applied field pushed the domain wall away from the right-hand trap. This requires the added energy from the field. (3) The domain wall has entered the centre segment of the nanowire but the added energy has also allowed it to drop into a more favorable vortex configuration. (4) The domain reaches the second trap and is unable to pass through it. It is then allowed to relax in zero field, with the second trap providing a stable resting position.

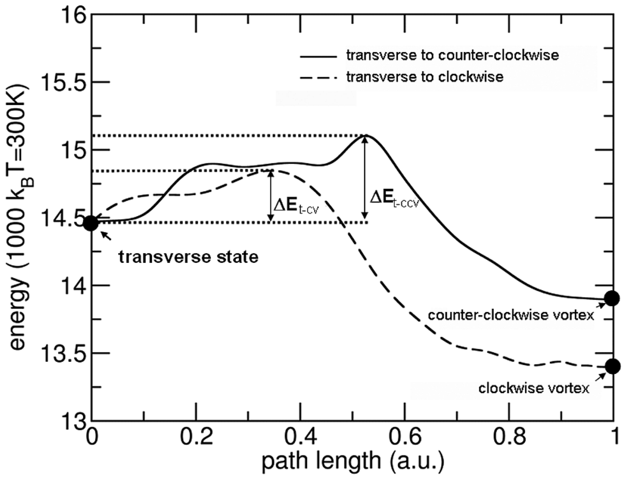

Fig. 5. Minimum energy path for the transitions between the transverse domain wall to the clockwise vortex domain wall (dashed line) and between the transverse domain wall to the counterclockwise vortex domain wall (solid line).

The total time for the process shown in Fig. 4 is below 2 ns. Thus, data rates in memory or logic operations using domain wall trap devices may well exceed 500 MHz.

In addition to the switching dynamics, we characterized the energy landscape for different domain structures using the nudged elastic band method [4]. The total sample configurational energies for the different domain wall states of Fig. 2 were calculated at zero applied field. The counterclockwise vortex state has the lowest configurational energy. The energy of the counterclockwise vortex state is 3.9% higher and the energy of the transverse state is 7.9% higher than the reference energy (clockwise vortex state). The transverse state and the vortex state are separated by an energy barrier. The energy barriers are $\Delta E_{t-\mathrm{cv}} = 380\mathrm{k_B T}$ and $\Delta E_{t-\mathrm{ccv}} = 640\mathrm{k_B T}$ for the transition from the transverse to the clockwise vortex state and from the transverse to the counterclockwise vortex state, respectively. The configurational energy of the sample depends on the exact position of the domain wall along the nanowire, so our result shows some disagreement with experimental data [6] where the resulting vortex wall finds a resting position in a slightly different part of the sample, resulting in the transverse to clockwise transition having a lower energy barrier. This difference in final vortex position is possibly related to the choice of the initial stable configuration in the simulation.

Fig. 5 shows the calculated minimum energy paths. In these calculations, a sequence of magnetic states is constructed in such a way as to form a discrete representation of a path from the transverse state to one of the vortex states. An optimization algorithm is applied until at any point along the path the gradient of the energy is only pointing along the path. This path is called the minimum energy path and gives the most likely transition between the two states under the influence of thermal fluctuations.

IV. Summary

The possible domain wall configurations in NiFe bent nanowires were investigated. Domain walls become trapped at the knees of the wire and form either a transverse, clockwise vortex, or counterclockwise vortex structure. Dynamic micromagnetic simulations showed that a rotating in-plane field can be used to switch between the three different domain wall states. Controllable switching was achieved for transitions from the transverse to either of the vortex states. Further work will be to investigate a more consistent method of triggering vortex to transverse domain wall transitions.

Acknowledgment

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