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Injecting, Controlling, and Storing Magnetic Domain Walls in Ferromagnetic Nanowires

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Invited Paper

Injecting, controlling, and storing magnetic domain walls in ferromagnetic nanowires

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ABSTRACT

Domain walls in ferromagnetic nanowires are important for proposed devices in recording, logic, and sensing. The realization of such devices depends in part on the ability to quickly and accurately control the domain wall from creation until placement. Using micromagnetic computer simulation we demonstrate how a combination of externally applied magnetic fields is used to quickly inject, move, and accurately place multiple domain walls within a single wire for potential recording and logical operations. The use of a magnetic field component applied perpendicular to the principle domain wall driving field is found to be critical for increased speed and reliability. The effects of the transverse field on the injection and trapping of the domain wall will be shown to be of particular importance.

Keywords: micromagnetic simulation, domain wall dynamics, ferromagnetic nanowires, magnetic devices

1. INTRODUCTION

Spintronic devices exploit the spin of the electron and its associated magnetic moment to sense, transport and store information. Recently there has been a particular interest in developing devices that depend on the magnetic properties of long, thin wires where the logical information is encoded by the transition between two magnetic domains. The transition region, the domain wall, can be moved to change the logic value[1]. Essentially controlling the motion of the domain wall is critical for realizing new fast, high-density non-volatile data storage devices[2]. Control includes injection/nucleation, moving, and stopping/positioning the domain wall precisely with speed and reliability.

In a long, thin, narrow nanowire the magnetic moments of the material lie primarily in the plane and along the long axis of the wire. A single magnetic domain state is energetically favorable in nanowire geometries but a domain wall transition can be created to separate two head to head or tail to tail oriented domains. The simplest domain wall is a transverse, or 180°, domain wall – a 180° rotation of the magnetization in the plane of the wire[3]. In thicker wires a more complex vortex wall can be created. There are two primary techniques available to manipulate domain walls, external magnetic fields and spin polarized currents[4]. Each technique has its advantages, and are therefore likely to be used in combination in devices, but in principle the details of the wall motion are independent of the driving mechanism. Here we attempt to demonstrate full control of the injection, motion, and precise positioning of multiple domain walls in single wire with externally applied magnetic fields.

A primary advantage to the use of magnetic fields is the speed at which a domain wall can be moved. In Figure 1 we show the speed of a transverse domain wall as a function of long axis driving field. The maximum speed of the transverse domain wall is greater than 500 m/s; roughly an order of magnitude greater than one typically finds with current induced motion and field induced motion for vortex walls[5]. Interestingly, the maximum speed of the wall occurs at a relatively small magnetic field strength. Above this critical field, called the Walker field, the internal structure of the domain wall changes which leads to low average wall speeds[6, 7]. Because of this effect we attempt to fully control our domain walls by never exceeding the Walker field along the long axis of the wire to ensure fast, reliable domain wall motion. The reliability is achieved because the domain wall maintains a constant, known magnetic structure crucial for improving its control.

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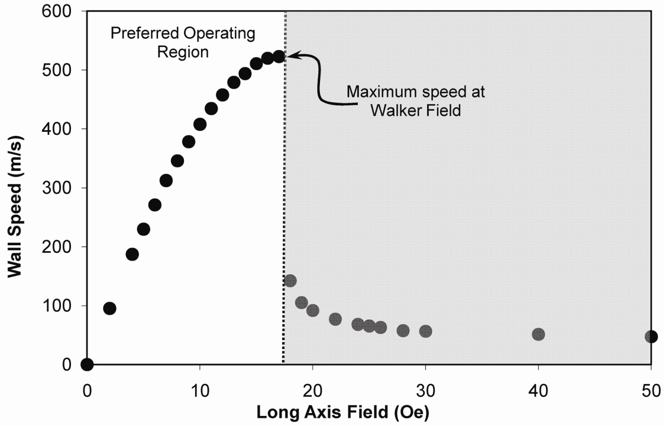

Figure 1. Typical field driven domain wall speeds. For fast device operation and increased domain wall control, it is preferred to keep the longitudinal fields below the critical Walker field.

Controlling moving domain walls makes it possible to reliably write information. In Figure 2 we show the final magnetic state representing eight different written three-bit sequences each written from the initial state shown in Figure 2a in less than 6.2 ns each. We have arbitrarily defined a value of "0" to be when no magnetic transition (domain wall) is found at a notch location in the wire and a "1" to correspond to the presence of a domain wall at a notch. Alternatively it is possible to use the magnetization direction itself to encode that data; this would lead to a smaller overall device areal footprint.

As shown in Figure 2, a structure that can hold three bits is sufficient to create eight distinct states, making it the minimum size necessary for a device. We will detail the steps necessary to quickly inject the domain wall into the wire, to quickly move the domain wall to its desired location, and to position the wall at its final position. In Figure 2 the domain wall is observed to be the transition region between the dark and light regions within the wire region. Arrows are added to the figure to show more completely the direction of the magnetic moments in the plane of the wire and in particular in the domain wall interior. Magnetic fields are applied in the plane of the wire, along the long axis to inject and move the wall (called injection and driving fields), and perpendicular to the wires length (called transverse fields) to control the orientation of the magnetic moments in the wall to ease the injection process, speed up the wall in the wire, and to move it to the desired stopping point. The time to write a triple sequence depends on the number of walls injected and the distance that each wall must travel from the injection point to the trapping point. In Figures 2b) – 2d) a single domain wall is present in the wire and each of these states takes under 2 ns to write. The states 2e) through 2g) involve a second wall and take under 4 ns to complete. This is a significant improvement in writing time compared to an earlier model that contained 8 notches[8]. In previous work, writing the three transitions could take 20 – 30 ns although the

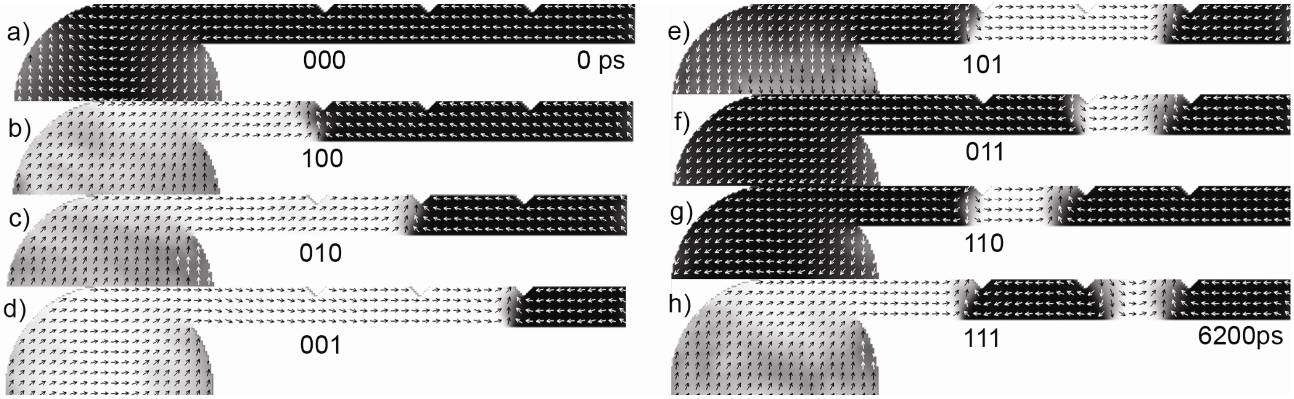

Figure 2. The eight possible unique bit sequences written from the initial state Figure 2a). The maximum writing time represented by the state h) is about 6 ns. A "1" is defined to be the location where a domain wall is located at a notch. If no wall is present at the notch it is a "0".

overall spatial footprint of the device would grow due to the fact that eight pads are necessary to store information instead of one larger device. Using the magnetization to encode the date requires one fewer wall which decreases the writing time as well as the size.

2. MICROMAGNETIC SIMULATION DETAILS

In this work we use computer simulation to investigate techniques to reliably control domain walls. The simulations offer concurrent nanometer spatial and picosecond temporal resolution allowing for detailed investigations of the important interactions that take place in the structures. Additionally lithography can be expensive and time consuming so simulation is useful for quickly exploring different patterned structures.

Micromagnetic simulation involves integrating the three-dimensional standard Landau-Lifshitz equation of motion for each of the magnetic moments m_i in the wire

$$\frac{\partial \vec{m}_i}{dt} = -\gamma \vec{m}_i \times \vec{H} - \frac{\alpha\gamma}{M_s} \vec{m}_i \times \left(\vec{m}_i \times \vec{H}\right)$$

where γ is the gyromagnetic ratio and M_s is the saturation magnetization of the material[9]. The first term on the right hand side of the equation is the precession term which rotates the magnetic moments about the direction of the local field, and the second term is the damping term which relaxes the magnetization into the direction of the applied field. The rate at which the damping occurs is controlled by the damping parameter $\alpha = 0.008$ which is typical for permalloy. The total magnetic field H consists of the local ferromagnetic exchange field, the long range magnetostatic dipole interaction and all externally applied magnetic fields. The materials parameters are also for permalloy with no crystalline anisotropy, an exchange constant $A = 1.3 \times 10^{-6}$ erg/cm, and saturation magnetization of $M_s = 800$ emu/cm^3.

The simulation requires that the structures be discretized into small blocks to approximate the local magnetization. Here the blocks are typically identical cubes with an edge length of no greater than 5 nm. In each of the images shown the wires have a 100 x 5 nm^2 rectangular cross section with lengths ranging from 1.5 microns to 10 microns. The time intergration is carried out using a 4th order predictor corrector technique with a time step of around half a picosecond.

The injection, driving, and capture of the domain wall are all controlled by varying externally applied magnetic fields. The primary injection and driving fields are applied along the long axis of the wire (x-axis) as shown in Figure 3 and never exceed 15 Oe which is less than the Walker breakdown field. This is important for fast motion and reliable control of the wall due to its constant internal magnetic structure. Perpendicular in-plane fields (y-axis) are also applied. The modest strength of these transverse fields (< 150 Oe) does not alter the breakdown field but is useful for creating domain walls of a known orientation which eases the injection process, leads to increased speed, and can be used for precision control of the final location[8,10,11]. The use of a transverse field is critical for each aspect of domain wall control as described below.

3. DOMAIN WALL CONTROL

Full control of a domain wall can be demonstrated by its creation, motion, and placement. Additionally, most devices require the use of more than one domain wall so controlling a second (third, fourth, etc.) domain wall in the presence of the first is also necessary. The following steps will show that full control can be obtained with the use of externally applied magnetic fields.

3.1 Injection

In a long, thin ferromagnetic nanowire the magnetization lies in the plane of the wire due to the strong shape anisotropy. Additionally, a domain wall is energetically unfavorable so it must be either nucleated or injected from the ends. Nucleation of a domain wall from the end of the wire involves large magnetic fields 30 – 50 times greater than the Walker field therefore the speed of the injected walls is low and the structure is unknown[10]. Improvement can be made by using an injection pad attached to one end of the wire, however in the typical geometry the injection field is still an order of magnitude greater than the critical field for fast, reliable motion[10,12]. Recently we reported that by attaching the

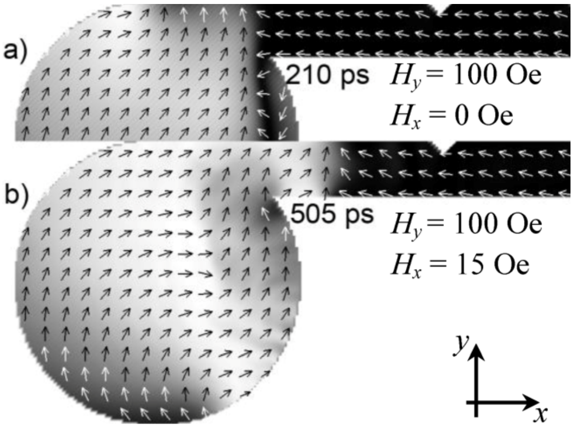

Figure 3. The injection of a domain wall from a 500nm diameter pad attached to a 100 nm wide wire. A field is initially applied along the y-axis in a) to rotate the magnetization in the pad at which point the injection field is applied in b). The injection process is fast (< 1/2 ns) and guarantees a known domain wall structure which improves control.

wire to the top or bottom of the injection pad a significant decrease in the injection field could be realized[10]. Additionally an addition field applied transverse to the injection field could be used to lower the injection field strength to well below the breakdown field. The transverse field is used to control the direction of the magnetic moments within the domain wall, and to preferentially select which walls are injected.

In Figure 3 we show two steps in the domain wall injection process. Initially the magnetic configuration is shown in Figure 2a) with the moments in the wire primarily aligned along the –*x*-axis. The wire is long, 100 nm wide and 5 nm thick, creating a large demagnetization field that holds the moments in the plane of the wire. The magnetization of the pad is unchanged when a 100 Oe field is applied along the +y-axis. This transverse field quickly rotates the magnetization of the 500 nm diameter injection pad, placing the domain wall at the injection site as shown in Figure 2a). About 0.2 ns after the transverse field is applied, the injection field is turned on along the +x-axis and the domain wall quickly enters the wire at which point it can be moved and placed appropriately. By reversing the direction of the transverse field and the injection field, a second wall can be placed into the wire. This process can be repeated reliably as many times as is necessary.

3.2 Motion

A transverse domain wall can be moved rapidly and reliably along the wires length by a field applied along the long axis. To create the final states shown in Figure 2b) – 2d) from that of Figure 3b) the domain wall must be accurately controlled.

The applied transverse field and the interaction of the domain wall with the notch combine to systematically pass and capture domain walls[8,13]. In Figure 4 we show plots of the position of a transverse wall as a function of time as it is driven along a 100 x 5 nm^2 cross-sectional area wire. A notch is placed at the center of the wire to capture the domain wall. The dashed line shows the behavior of the wall when no transverse field is applied. The wall moves rapidly at 412 m/s along the wire until it reaches the notch at 16 ns, at which point it becomes trapped. When a field is applied transverse to the wires long axis and in the direction of the magnetic moments of the domain wall, the wall speeds up[11,14]. In Figure 4 we show the increase in speed as external fields of 50 Oe and 100 Oe are applied perpendicular to the driving field. When 50 Oe is applied the wall speed increases but not enough to avoid capture at the notch, however, the 100 Oe field is sufficient to keep the domain wall moving. The speed of the wall with the 100 Oe field is about 100 m/s faster than without a transverse field leading to a significant increase in the kinetic energy of the domain wall. The potential barrier created by the notch is lower than this new kinetic energy and the wall passes. The potential barrier does briefly slow the wall but it is not high enough to stop it and the wall passes and is driven away.

To create the image shown in Figure 2b) the transverse field is turned off immediately after the injection takes place. This leads to a reduction in the speed of the domain wall which allows it to be captured by the notch. To create figure 2c) the transverse field is turned off after the wall passes the first notch and likewise 2d) is created by turning off the transverse field after the second notch is passed.

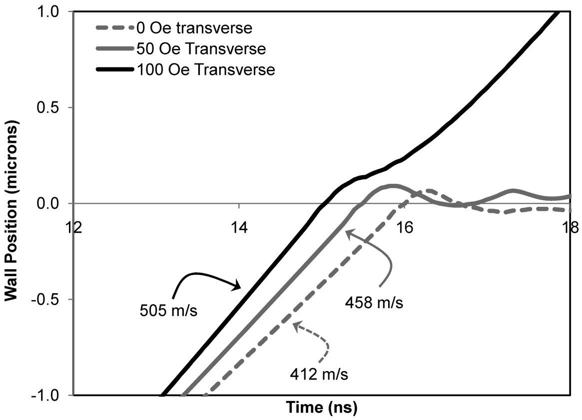

Figure 4. Position of a transverse domain wall as a function of time in a wire with a 100 x 5 nm^2 cross-sectional area. In each case a driving field of 10 Oe is placed along the wires long axis with different strength transverse fields. A small triangular notch is placed along the edge of the wire at a position of 0 μm to capture the wall. The transverse field is used to increase domain wall speed which can give it enough kinetic energy to avoid being captured by the notch.

3.3 Trapping

In Figures 2 and 3 it should be noted that the notches are placed along the top edge of the wire. It is just as easy to place the notches along the bottom edge of the wire but when this is done the domain walls are always captured at the first notch. Previously we have explained this behavior with a topologic model for the domain wall which can be briefly summarized[15,16]. A transverse domain wall is a composite topologic structure consisting of two equal and opposite topologic charges associated with each end of the wall. In Figures 2 and 3 the positive topologic charge is located on the top of the wire for each domain wall. To pass the domain wall beyond a notch the charge must be weakly bound. In Figure 5 we show identical domain walls being driven toward a notch, one located on the top of the wire and the other on the bottom of the wire. Unlike Figures 2 and 3, the positive topologic charge is one the bottom edge of the domain wall. In each example the domain wall is trapped and we plot the domain wall energy as a function of time (which can be further correlated with the domain wall position) as the wall is trapped. It is clear that the domain wall energy is significantly reduced when captured by the notch on the top of the wire as compared to the notch on the bottom of the wire. This behavior demonstrates that a notch inscribed into a wire is more effective at trapping a negative topologic defect than a positive one, therefore in order to selectively pass and trap domain walls the notches must be placed in locations where positive defects will be present.

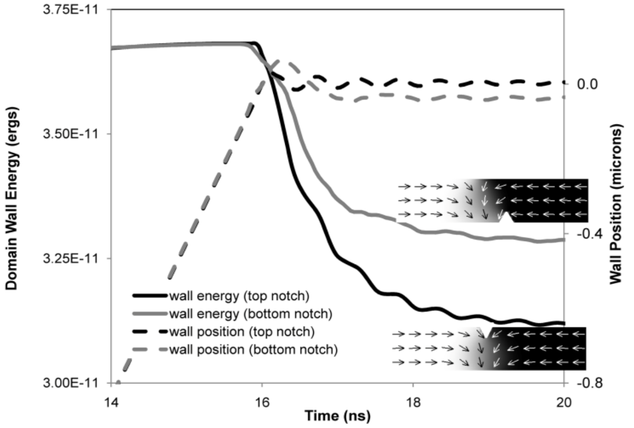

Figure 5. Notch location and domain wall structure determine the trapping ability of the notch. In this case identical domain walls are driven toward a notch located in the center of the wire (one on top of the wire, one on the bottom of the wire) and captured. The domain wall configuration and notch location lead to different trapping behavior which is apparent in by the trapping location as shown in the inset and the significant difference in the domain wall energy.

The asymmetry in the trapping potential is really due to a difference in the magnetostatic energy of the domain wall in each case. This can be realized somewhat by looking at the magnetic pole density at each of the notches shown in Figure 5. For the bottom notch the pole density, and therefore the magnetostatic energy, is quite large along the right side of the notch and again at the bottom left corner of the notch. Additionally these two poles have the same sign leading to a further increase in energy. When the notch is placed at the top of the wire, there is a reduced pole density along the edges of the notch, and a strong pole at the center of the notch. However these poles have opposite sign and therefore lead to an overall reduction in the energy. This leads to a much more stable pinning potential which is best avoided if passing and trapping behavior is needed. Because the kinetic energy of the wall is needed to drive past a notch, both structures are effective at holding the domain wall once captured. The loss of the kinetic energy means that strong longitudinal fields to overcome the pinning barrier to subsequently release the domain wall.

The transverse field applied during the injection process allows for the creation of known domain wall structures and therefore the creation of topologic charges in the correct location. This is important because different geometries can be simulated that will alter the location of the topologic charges and therefore the probable pinning locations. Additionally the transverse field is necessary to increase the wall speed to give it enough energy to pass undesired notches. The transverse field is critical for each step demonstrated in the precise control of a domain wall travelling through the magnetic nanowire structures shown.

4. DISCUSSION AND CONCLUSION

The discussion so far allows for the creation of the states shown in Figure 2a) – 2d) but states 2e) – 2h) require additional domain walls to be injected into the wire. The effectiveness of the domain wall trap is important in this process. To inject a second domain wall, the long axis field must be reversed. If the first domain wall is not trapped it will begin to move back toward the injection site due to the reversal in the driving field. A notch with the appropriate size to capture or pass domain walls is an effective enough trapping location under the field reversal process. To inject the second domain wall, the injection process described above is repeated with both the transverse and injection fields reversed to ensure that a domain wall will be injected with a positive topologic charge on the top of the wire. Because the first wall is trapped at a notch and therefore has no kinetic energy it will remain in place as the second notch is injected and moved, as described above, into place to create Fig 2e) – 2g)[8]. As a general rule, the injection takes a bit less than a nanosecond and placing the wall takes about a nanosecond, so the injection and placement of each wall takes 2 ns. The first three states are created in less than 2 ns, the second three states are created in less than 4 ns, and the final state which can be created exactly like the first state takes about 6 ns.

The structure shown in Figure 2 is fast, with a writing time of 2 – 6 ns. The size is perhaps large with an overall area of 0.75 μm^2 the footprint of which could be effectively reduced by clever positioning. Currently we are investigating ways to decrease both the size of the injection pad and wire dimensions. A modification of the domain wall injection pad allows for easier domain wall injection which allows for the use of smaller pads and smaller wires. This is important because the domain wall dimensions depend on the wire dimensions so that the domain walls can be more densely packed. Shrinking the dimensions without a significant change in domain wall speed also increases the timing moderately.

Full control of a domain wall has been demonstrated, from its injection to its placement, including in the presence of multiple other domain walls. All of this has been demonstrated by the use of externally applied magnetic fields which are beneficial due to the high speed at which they can move a domain wall. Additionally, the strength of the driving and injection fields has been kept below the important Walker breakdown field where complicated domain wall dynamics and low average wall speeds affect the useful behavior. The in-plane transverse field is essential for knowledge of the domain wall structure, which is important for precise control the domain wall motion and placement in the wire.

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