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Controlled motion of 180° and 360° domain walls along planar nanowires is presented. Standard Landau — Lifshitz micromagnetic modeling has been used to simulate the response of the domain walls to the application of an external magnetic field. A 180° wall is quickly and easily moved with the application of an applied. field along the axis of the wire but a 360°domain wall is stationary in the same case. An oscillatory applied field can be used to continually move the wall along the wires axis. The speed at which the 360° domain wall is found to be several times slower than a similar 180° domain

wall and is limited by interaction between the magnetization of the domain wall and the external field.

Section 1: Introduction

A magnetic domain wall is the transition region between oppositely magnetized domains. This transition region can be put into motion with the application of an external magnetic field or with a spin-polarized current via a spin-torque effect[1,2]. Each driving mechanism has its advantages over the other but in principle the dynamics of the moving wall are the same and ultimately a combination of the two effects is likely to be necessary. Several spintronic devices in logic, recording, and sensing have been proposed which utilize the motion of a domain wall along the axis of a thin, narrow nanowire to transmit or store information[3,4]. The realization of these devices depends in part on the ability to control the location of the domain wall in the wire.

In a thin enough nanowire there is essentially one type of domain wall, a transverse or 180° domain wall where the magnetization rotates in the plane of the wire as it transitions from one direction to the other as shown at the top of Figure 1 [5]. The bottom image shows two transverse walls which have been pushed together to create a full rotation of the magnetization. This extremely stable structure is called a 360° domain wall and it considered a transition between two aligned domains. Arrows representing the direction of the magnetic moments are included in Figure 1 to show how the transition occurs. The red and blue shading correspond to the direction of the long axis magnetization and the scheme remains the same throughout this manuscript.

Controlling a domain wall requires involves both moving the wall and stopping it. For device operation it is preferential to move the wall quickly. The 180° domain wall is easily, and quickly, moved with the application of an external magnetic field oriented along the long axis of the wire. The wall moves as the domain in the direction of the applied field grows at the expense of the oppositely magnetized domain, which leads to an overall reduction in Zeeman energy. A 360° domain wall is not easily moved however. When a field is applied along the main magnetization direction, to the right in Figure 1, the left and right

walls remain stationary, essentially pushing up against each other. The robustness of the 360° wall to applied fields is a desired feature for recording information therefore moving the wall to a desired location is critical. If the field is applied in the reverse direction, to the left, the walls separate but they move with the same speed so the "center" of the overall transition region remains stationary. A current might be useful in this case as it has been shown that currents move domain walls in the same direction, although typically an order of magnitude slower than a field moves the wall. Here we present a technique for moving the 360° domain wall with applied fields with minimum speeds equivalent to that found in fast current driven cases[1].
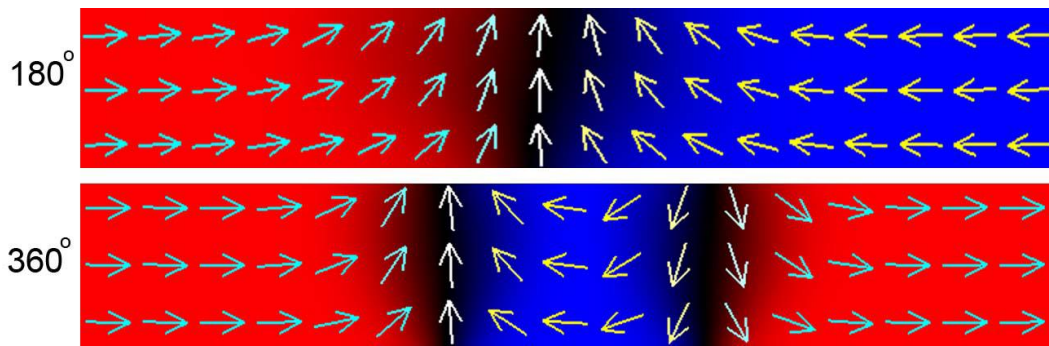

Figure 1: Representations for the magnetic moments of a 180° and 360° domain wall in a 100 nm wide wire

Once a simple transverse wall is in motion there are several techniques available for stopping it. Most techniques rely on a change to the physical shape or magnetic structure of the wire, often a notch or protrusion in the wire itself[8,9]. Because these artificial defects must be added ahead of time, during the manufacturing of the wire, precision control of the domain walls can be obtained but there is no possibility of changing the trapping locations. Additionally, a trapped domain wall is often difficult to release, requiring large fields or currents to put the wall into motion again[10]. Additional control of domain wall pinning locations could be realized if the pinning sites could be moved as opposed to set when built. Recently it was proposed that domain walls could be used as traps for other domain walls in neighboring wires[11,12]. The domain walls would couple together across the wires and could allow for an additional degree of control if the 360° walls could be reliably moved. In this work we present our

technique for controlling the location of a 360° domain wall. Our technique controls the location of the wall by systematically controlling the external field pulse durations and directions used to move the wall.
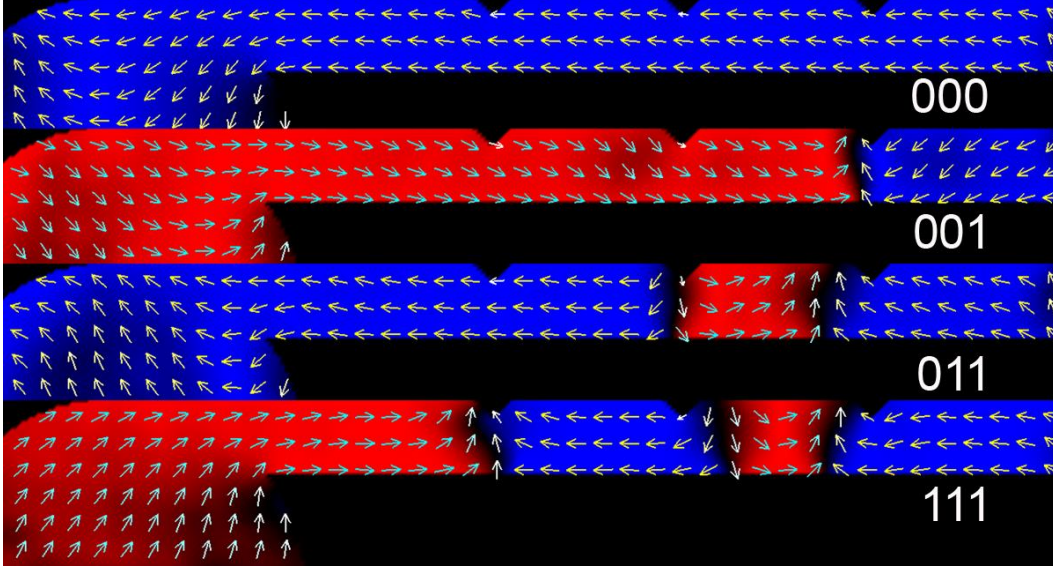
Figure 2: Time lapse sequence of domain walls being injected and trapped in a wire with magnetic fields.

Section 2: Simulation Details

We simulate the motion of a domain wall with standard three-dimensional micromagnetic simulation. The simulations follow the standard Landau-Lifshitz equation of motion for the magnetic moments *m* in the wire

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

where γ is the gyromagnetic ratio, M_s is the saturation magnetization and H is the total magnetic field acting on a magnetic moment[13]. The materials parameters are for permalloy. The simulated wires have a length of 10 microns and a 100×5 nm^2 rectangular cross-section. The wire is discretized into identical cubes, no larger than 5nm on edge and integrated with a 4th order predictor corrector technique with a

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simulated integration time step of less than a picoseconds. The magnetic damping parameter is α=0.008.

To put the walls in motion magnetic fields are applied along the long axis of the wire. We keep the moving wall field strength below the so-called Walker breakdown field to maintain the domain walls of a known shape and because this is the field range for which the walls move the quickest.
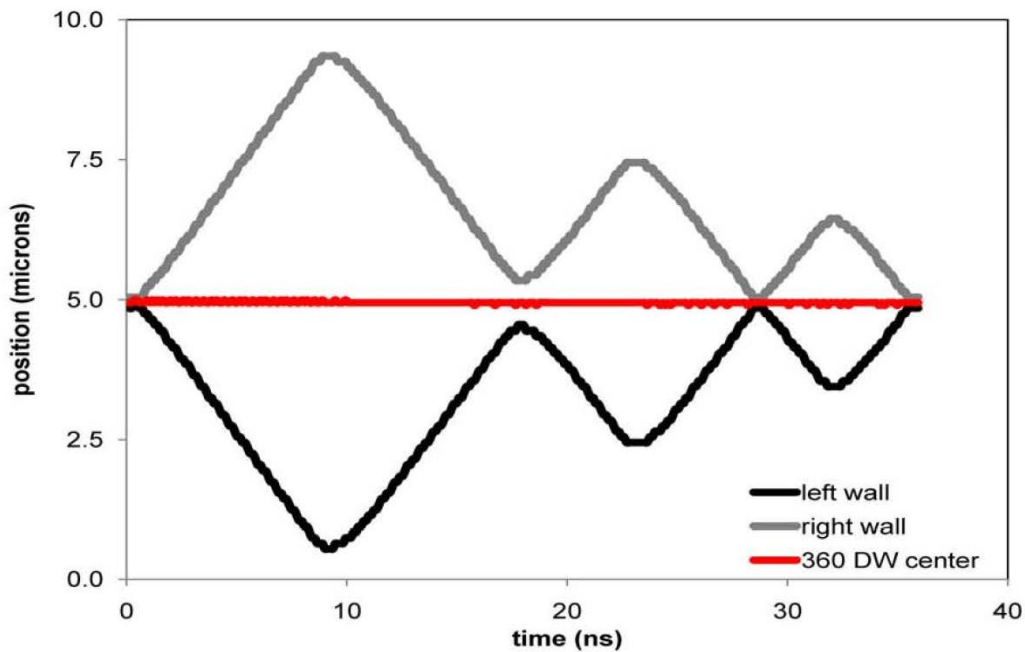
Figure 3: Position of the 360° wall components when moved by a longitudinal field. The composite walls center is stationary.

Section 3: Domain Wall Control

3.1 180° Walls

A time lapse sequence of a series of domain walls which were injected, transmitted, and trapped is shown in Figure 2 by using only magnetic fields[14]. The combination of effects described above for transverse walls shows how these ideas come together to demonstrate the ability to write information. First a domain wall is injected into the

wire from the pad on the left. The wall is then quickly driven along the length of the wire until it is trapped at a notch. The elapsed time between "0 0 0" and "0 0 1" was under 2 ns. The now trapped wall is stationary as the subsequent domain walls are injected and moved in to location. A three bit sequence, in [Figure 2](#) a "1" or a "0" depends on the presence of a domain wall at a trapping point, has 8 possible states so this structure represents the minimum necessary for writing information quickly and reliably. Four of the eight representations are shown. The final "1 1 1" sequence was written in under 6 ns.

3.2 360° Walls

Stopping a 360° domain wall is as easy as letting the two transverse walls collide under a compressive field (field that moves the walls toward each other). The two colliding transverse walls couple together to create a robust 360° domain wall. [Figure 3](#) shows the difficulty in moving a 360° domain wall. The plot shows the position of the left and right walls as a function of time as a magnetic field is applied along the long axis of the wire. Initially the field drives the walls quickly apart. When the field is later reversed, the domain walls turn around and move together.
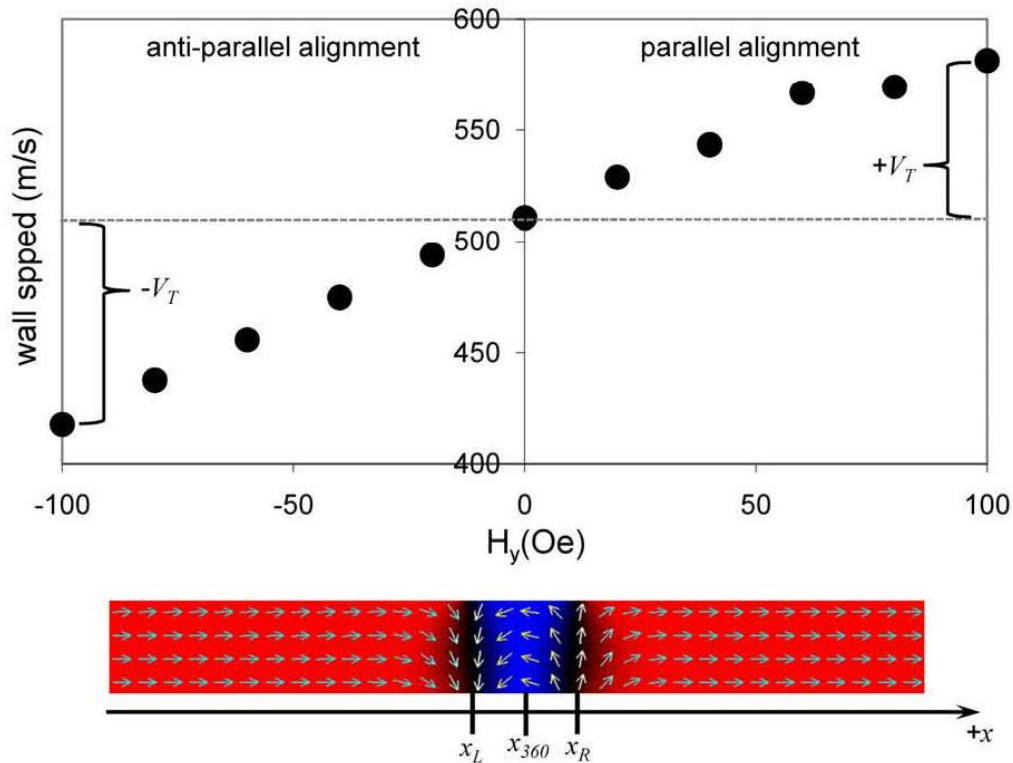
Figure 4: There is an asymmetry in the speed of a domain wall when transverse in-plane fields are used with longitudinal driving fields. The effect depends on the relative alignment of the transverse field and the magnetic moments in the domain wall.

The average location (called the 360 DW center) is shown to be essentially constant for the entire trial. The reason the wall center is stationary is that the left and right walls have the same speed and because they travel in opposite directions the velocity is zero.

An extra component of magnetic field applied in the plane of the wire but perpendicular to the long axis of the wire has previously demonstrated to significantly change the speed of a domain wall based on the relative alignment of the transverse field and magnetic moments in the domain wall[15,16]. Figure 4 shows that when the transverse field is positive (parallel to the magnetization of the right wall) the wall travels faster. The opposite is true when the two are anti-aligned. The effect is almost linear such that for a given

transverse field strength that each walls speed changes by the same magnitude V_T. This allows for the systematic control of a 360° domain wall as shown in Figure 5. Initially, along path A, a magnetic field is applied along the long axis of the wire to separate the two walls and a transverse field is used to move the right wall more quickly than the left wall. The fields are reversed causing the walls to move back toward each other. This time the reversal of the transverse field, along path B, moves the left wall quicker than the right so that when the two walls approach each other at C. This process is repeated until the wall has been moved a 2.5 microns. The average speed of the domain wall center is roughly 85 m/s. This is about an order of magnitude less than the 500 m/s a single transverse wall moves but it is consistent to the maximum speed observed for a single wall driven by an electric current and the first report of moving a 360° domain wall with applied fields.
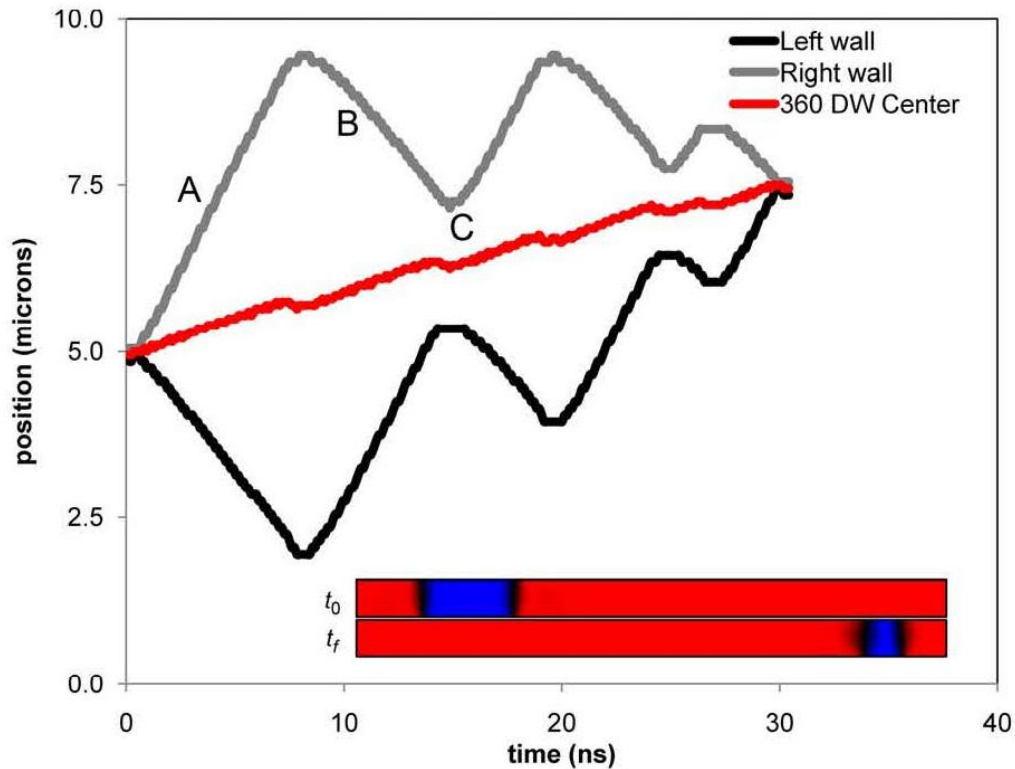
Figure 5: Transverse fields are used to move 3600 domain walls significant distances by oscillating the field components. The wall averages 85 m/s.

Section 4: Discussion

The maximum speed of a 360° domain wall is a function of the transverse field. Larger transverse fields should lead to faster overall speeds. As shown in Figure 4 we define the center of the domain wall, x_{360}, to be the average position of the left, x_L, and right, x_R. walls

$$x_{360} = \frac{x_L + x_R}{2}.$$

The position of each wall as a function of time is $x(t)_{R,L} = v_{R,L}t$ where the subscripts correspond to the left and right walls individually. When a transverse field is applied parallel to the moments in the right wall (anti-parallel to the left) the velocity of each wall changes in proportion by

$$v_R = v_0 + V_T$$
$$v_L = -(v_0 - V_T) = -v_0 + V_T.$$

Where v_0 is the speed with no transverse field and V_T is the speed change due to the transverse field. This means that the domain wall center is located at

$$x_{360} = \frac{(-v_0 + V_T)t + (v_0 + V_T)t}{2} = V_T t.$$

When the field are reversed the velocities of the walls change in magnitude and direction such that

$$v_R = -(v_0 - V_T) = -v_0 + V_T$$
$$v_L = v_0 + V_T$$

the center of the domain wall continues to move forward with the speed gained by the application of the transverse field

$$x_{360} = (\frac{v_0 + V_T)t + (-v_0 + V_T)t}{2} = V_T t.$$

This simple calculation shows that the 360° wall cannot move without the transverse fied. Additionally it is instructive to compare the results of the simulation with this simple calculation. We measure V_T=110m/s in this trial, whereas we measure a speed for the domain wall of 85 m/s which is in good agreement. The bulk of the difference comes from the reversal of the domain walls as noticed in [Figure 5](#). When the fields are reversed the walls stop and turn around slowing the overall progress. The simple calculation above represents the maximum speed a 360° domain wall could move which will be slowed by the necessary field reversals. In a long wire the reversals could be minimized because there would be more room for the walls to move, whereas in our 10 micron simulation we had to reverse the fields to keep the walls from leaving the ends of the wire.

Section 5: Conclusion

Magnetic fields are used to quickly move and control the location of 360° domain walls in thin, narrow nanowires. A 360° domain wall moves with a maximum speed determined by the strength of a transverse field which is necessary to propagate the wall. This speed is slower than typically found for a 180° domain wall but still fast when compared to similar efforts using electric currents as the driving mechanism. The precise location of the 360° domain wall can be controlled without making physical changes to the wire. Instead controlling the length of the field pulse determines how far the wall will move which gives an extra degree of control for tuning the wall location.

Acknowledgments

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