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Application of Local Transverse Field for Domain Wall Control in Ferromagnetic Nanowire Arrays

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Application of local transverse fields for domain wall control in ferromagnetic nanowire arrays

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In ferromagnetic nanowire arrays, where each wire contains multiple domain walls, it will be necessary to select an individual domain wall (DW) to move. In the field driven DW case, the field is typically applied globally affecting all of the domain walls in the system. We present micromagnetic simulation results demonstrating selectivity and control of an individual DW in such an array of nanowires using a combination of global and locally generated magnetic fields. Arranging the orientation of the local field allows for selectivity of a specific DW and its controllable movement to a new location.
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The dynamical motion of a magnetic domain wall in a nanowire has been intensely investigated in part due to some interesting physical phenomena and potential applications in recording and logic technologies.[1–4] In order to better understand domain wall dynamics, the focus has primarily been on moving a single domain wall through a single wire. In two wire systems, the preliminary focus has been on the interactions of domain walls in neighboring wires.[5–7] However, most of the potential applications will consist of arrays of nanowires, each containing multiple domain walls, and it will be necessary to develop techniques to select and control an individual domain wall in such systems. It will also be important for the domain walls to move quickly, which is typically the case when driven by magnetic fields. In this work, we present the results of micromagnetic simulations which demonstrate a technique that uses magnetic fields to reliably select and quickly move an individual domain wall in a wire or nanowire array. The technique uses a combination of a locally applied field, generated by a current carrying wire under the ferromagnetic wire, oriented transverse to the wire to select the domain wall, and a globally applied longitudinal field to drive the domain wall.

In a long, thin nanowire, the shape anisotropy determines that the magnetic moments in the wire align primarily in the plane, and along the long axis, of the nanowire. Domains can form in, or be injected into, the wire with either a head to head or a tail to tail orientation of magnetic moments. In this work, we will focus on the transverse domain wall that forms between the domains.[8] The transverse wall can be moved by the application of an external magnetic field or by running a current through the wire.[9] In the field driven case, the domain wall will be driven quickly along the wires length with weak magnetic fields; large fields cause the domain wall to precess about the wires axis slowing its speed significantly.[10] The domain wall dynamics are similar in the current driven case, although the average domain wall speeds tend to be significantly lower.[11,12] If multiple domain walls exist in the wire, the neighboring domain walls will move in opposite directions when driven by a magnetic field, and all domain walls move in the same direction when driven by a current.[13,14] In either case, all of the domain walls in the wire respond to the stimulus, and all are put into motion unless held in place; this is typically accomplished by patterning a series of notches along the wire's length.[15–17] As we will show, a transverse magnetic field, applied in the plane of, but perpendicular to, the wire's long axis, is useful in selecting an individual domain wall to control. In multiple wire systems, it is necessary to locally generate the transverse field which increases the level of domain wall selectivity.

The domain wall dynamics and the field driven motion of a magnetic moment $\vec{m}$ are described by the Landau Lifshitz (LL) equation

$$\frac{\partial \vec{m}}{\partial t} = -\gamma(\vec{m} \times \vec{H}) - \frac{\alpha\gamma}{M_s}\vec{m} \times (\vec{m} \times \vec{H}), \tag{1}$$

where γ is the gyromagnetic ratio, M_s is the saturation magnetization, and H is the total magnetic field acting on a magnetic moment. The material parameters are for permalloy ($M_s = 800\,\text{emu/cm}^3$, $A = 1.3\,\text{erg/cm}$, $K = 0$). The simulations do not include the effects of finite temperature which would act to improve the results. In particular, thermal fluctuations increase the breakdown field due to the randomness imparted in the magnetic moments in the domain wall and would decrease the depinning fields slightly allowing for weaker driving fields and currents. A reduction in the current needed to create the local transverse field further decreases any potential heating problems.

In this work, each individual ferromagnetic wire has a total length of $5\,\mu$m with a rectangular cross-sectional area of $100 \times 5\ \text{nm}^2$.[18] In the simulated nanowire arrays, the ferromagnetic wires are separated by 100 nm of empty space. This spacing is chosen to minimize the interaction of the domain walls in neighboring wires. The domain wall dynamics are modeled in our simulations by discretizing each wire into identical cubes, 5 nm on edge, and integrating with a 4th order predictor corrector technique. The integration time step is less than a picosecond. The magnetic damping parameter is $\alpha = 0.008$. In order to demonstrate control, an initial domain configuration is created in the wire and the domain walls are trapped at specific locations along the wire to ensure no unwanted motion. The domain walls are held in place by notches separated by a micron, each an isosceles triangle with base and height of 30 nm apiece.

In ferromagnetic nanowires, a transverse magnetic field, in combination with a longitudinal driving field, has been shown to have a variety of behaviors that are useful in controlling a domain wall. The transverse field component can be used to assist the domain wall injection process[19,20] and to speed up or slow down a domain wall.[21–24] The ability of the transverse field to change the domain wall speed also impacts the ability of a notch to trap a domain wall, in that fast moving walls can pass a notch that is capable of trapping a slower moving wall.[25–27] When the transverse field component is applied parallel to the direction of the magnetic moments within the domain wall, it will speed up, and if applied anti-parallel, it will slow down.[22] Similarly in Fig. 1, we show that the longitudinal field necessary to release a trapped domain wall varies with the magnitude and direction of the transverse field.

The curves in Fig. 1 represent the driving field necessary to release a captured head to head domain wall (the equilibrium magnetic orientation of the trapped domain wall is represented in the diagrams) for the two possible notch locations on the wire. When the notch is located along the top edge of the wire, the domain wall is more strongly trapped than when the notch is located along the bottom edge of the wire. The difference in trapping ability is due to the characteristic triangular shape of the transverse domain wall and its related magnetic charge distribution.[8,15,28,29] The transverse field causes the domain wall to expand when the field and moments are parallel and to contract when aligned anti-parallel.[22] The change in the domain wall dimensions leads to a redistribution of the magnetic charge within the domain wall affecting the pinning potential of the notch.

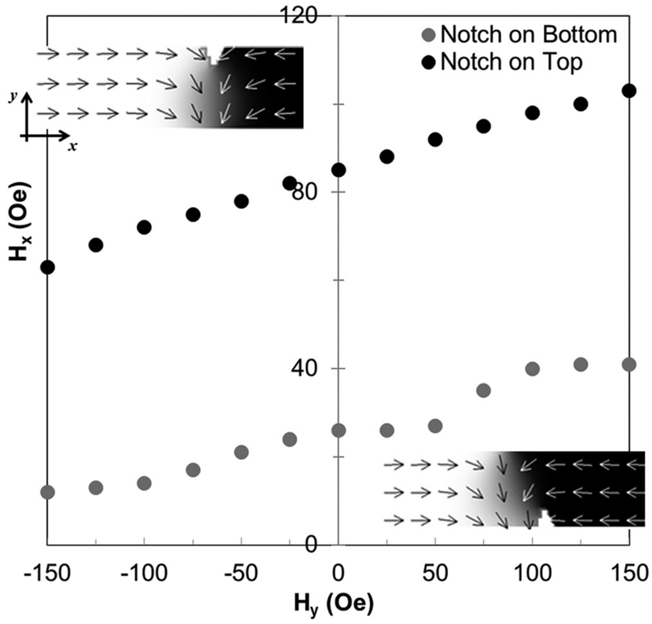

FIG. 1. The driving field needed to release a domain wall from the specific notch geometry shown as a function of transverse field is plotted. The transverse field assists the depinning process when the field is in the direction of the magnetic moments in the domain wall ($-y$ axis) and holds the domain wall more strongly when anti-aligned ($+y$ axis).

The case in which the domain wall is more weakly trapped at the notch, when the notch is located along the bottom edge of the wire, is of particular interest because when the transverse field is applied parallel to the domain wall (along the $-y$ – axis), the domain wall can be released by a driving field (H_x) that is less than the critical Walker breakdown field.[22] This means that the domain wall can be quickly released from the notch and moved to another location along the wire without undergoing any internal transformations, improving control of the moving domain wall. Thermal fluctuations would act to decrease the magnetic field necessary to release the domain wall slightly. This would allow for lower driving fields or currents, or improve the reliabilityof the depinning process at the given fields.

The ability of a transverse field to control an individual domain wall in a single nanowire is demonstrated in Fig. 2. The magnetic domain structure for a piece of a single wire with four notches located along the bottom edge of the wire is shown in each of the images at different times. At $t = 1$ ns, two domain walls with opposite magnetic orientation are pinned at the two outside notches even though a global driving field of 14 Oe has been applied to the wire. The total magnetic configuration is similar to that of a 360° domain wall and can be created using an injection pad.[19,20] The plot in Fig. 2 shows the magnetic field components applied to the wire as a function of time. A constant 14 Oe field is applied along the long (x-) axis of the wire while 150 Oe transverse field pulses are applied first in the $-y$ direction and then the $+y$ direction. Note that no motion occurs until the transverse field pulses are applied. The total time between the start of the pulse and the domain wall becoming trapped at the next notch is about 2 ns for this separation, although the temporal separation between subsequent pulses is longer than this to demonstrate that the represented states are stable. The negative transverse field assists in the release of the left wall, while also helping to hold the right wall in place, while the longitudinal field drives the wall to the next notch, shown at $t = 6$ ns. When the transverse field is subsequently applied along the $+y$ axis, the left wall is held in place while the

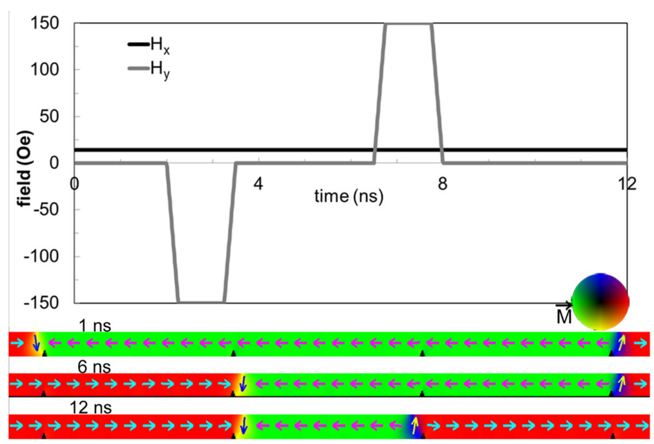

FIG. 2. The magnetic domain configuration of a 100 nm wide wire and the magnetic field applied to the wire as a function of time. The driving field is a constant 14 Oe applied along the +x axis and transverse pulses are applied. The transverse pulses are used to select which individual domain wall to move. The first pulse selects the domain wall on the left, and the second pulse selects the domain wall on the right.

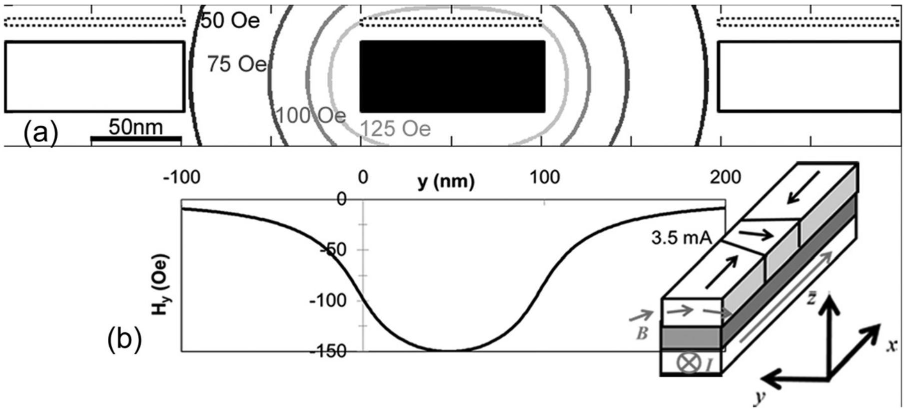

FIG. 3. (a) The Oersted field map for a current running through a 100 nm wide, 40 nm thick wire (solid black rectangle). The solid rectangles represent the locations of neighboring current carrying wires and the dashed rectangles are locations of the ferromagnetic separated from the current carrying wires by 10 nm of insulating material (b) The magnitude of the transverse magnetic field component at the locations of the ferromagnetic wires for a 3.5 mA current in the central wire.

right wall is moved to the next notch, shown at $t = 12$ ns. The length of the field pulses is related to the separation of the notches; if the notches were separated by a greater distance, the pulses could be of greater time duration. The current pulses used to create the transverse fields are a nanosecond in duration and can be off for many nanoseconds before reapplication to move the next wall, so the heating effects should be minimal. Reversal of the longitudinal field with a combination of the same transverse fields allows the walls to be moved back to their starting location.

The transverse field allows for selectivity of an individual domain wall when more than one exists in a given wire. However, in an array of wires, unless this field is applied locally, a number of domain walls may be put into motion. A local field can be generated by a current carrying wire grown above or below the ferromagnetic wire.[30] A map of the calculated Oersted field created by a 100 nm wide, 40 nm thick current carrying wire (the black rectangle) is shown in Fig. 3(a). The clear rectangular boxes represent the locations of neighboring current carrying wires, each separated by 100 nm, and the dashed rectangles are the locations of the ferromagnetic wires in this array, one located above each potential current carrying wire. The ferromagnetic wires are separated from the current carrying wire by 10 nm of insulating material. The plot in Fig. 3(b) shows the transverse component of the field at the locations of the ferromagnetic wires due to a 3.5 mA current running through the central wire. The current in the central wire generates a 150 Oe transverse field at the center of the ferromagnetic wire. As previously shown, 150 Oe is a transverse field of sufficient strength to release a trapped domain wall when use in combination with a driving field less than that of the critical breakdown field.[22] A 3.5 mA current represents a current density which is lower than the critical failure current density for a gold nanowire.[31,32] Additionally, the current pulses only need to be applied for short durations further limiting the effects of heating. Increasing the thickness of the current carrying wire or decreasing the thickness of the insulating layer would lead to further reductions in the current density which would act to minimize heating effects. As shown in Fig. 3(b), the transverse field is relatively uniform throughout the magnetic nanowire and quickly drops off outside the wire so that neighboring wires are largely unaffected. In this work, we use the calculated field distributions to simulate the effects of running a current through one of the wires, and a current through multiple wires, in the nanowire arrays. Changing the direction of the transverse field, necessary to select domain walls with a different orientation, is accomplished by reversing the direction of the current.

In Fig. 4(a), we show the initial state of a three wire system, where each wire contains a pair of oppositely oriented domain walls as discussed previously. Schematic representations of the transverse field pulses applied to each individual wire and the subsequent magnetic equilibrium state in each wires are shown in Figs. 4(b)–4(f). The large arrows on the left represent the direction of the global driving field applied to each of the wires during the step. To change from the state shown in Fig. 4(a) to that of Fig. 4(b), a negative transverse field pulse was applied to the top wire. This field pulse was simulated by assuming a current was run under the top wire. At the same time, a field pointing to the right was applied to the entire system. This combination of fields selects only the top left domain wall and it is driven to the second notch on the top wire. The other five domain walls in the system remain at rest. The global field is reversed as a current is

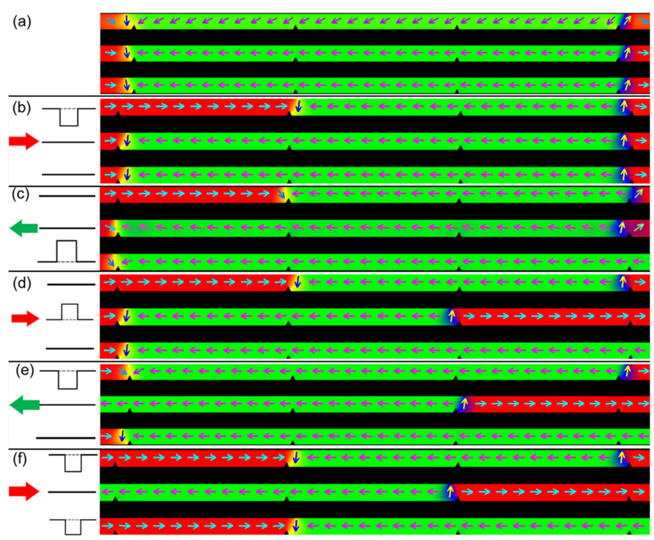

FIG. 4. (a)-(f) Time lapse sequence of the magnetic domain state for a three wire system. The central 3 μm length of each wire is shown. Each wire is 100 nm wide and separated from its neighbors by 100 nm. Schematics of the applied transverse field pulses ($\pm$150 Oe) and the direction of the global driving field ($\pm$14 Oe) represented by the large arrows shown on the left. The final magnetic domain states, after the application of the given fields in the step, from the previous state, are shown.

applied under the bottom wire, selecting the domain wall on the lower right and driving it out of the figure as shown in Fig. 4(c). Switching the global field and running a current under the central wire lead to the image in Fig. 4(d). Another field reversal and a current pulse applied under the top wire allow the first domain wall to be driven back to its original location, Fig. 4(e). In the final image, Fig. 4(f), two domain walls have been driven by running simultaneous current pulses under each of the top and bottom wires. We have previously demonstrated that the transverse field could be applied longer which would allow domain walls to move more than one notch at a time.[25] The technique of using a locally applied transverse field pulse could also be used in the current driven case. In this situation, a current in a ferromagnetic wire would provide the driving force and the local transverse field could be used to select which domain wall to move, similar to the process shown in Fig. 2. A combination of fields and currents can be used to efficiently and quickly move and control domain walls.

In summary, domain walls can be moved with magnetic fields applied along the axis of a wire, but selection and control of an individual domain wall are accomplished with the use of a magnetic field applied in-plane but transverse to the long axis of the wire. Domain walls held in place by notches can be pinned more strongly or released more easily by the transverse field. This behavior means that the transverse field can be used to select a single domain wall within an individual nanowire and when the transverse field component is created locally, a single domain wall in an array of wires each containing multiple domain walls can be reliably selected and moved. This element of control is important for a variety of applications requiring fast domain wall motion in arrays of ferromagnetic nanowires.

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