Magnetic Behavior of 360° Domain Walls
in Patterned Magnetic Thin Films

by

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Abstract

$360^\circ$ transverse domain walls (360DWs), which form readily from transverse $180^\circ$ domain walls (180DWs) of opposite sense, demonstrate qualitatively distinct behaviors from their constituent 180DWs and are therefore of interest both from a physics perspective and for their applications in future domain wall devices. This thesis presents experimental and modeling-based investigation of the properties and behaviors of 360DWs including formation, magnetostatic behaviors, and response to field, AC, and DC driving forces.

The formation of 360DWs is first examined by simulation in a model nanowire. An injection system capable of producing 360DWs from a wire and an injection pad is presented and its behavior is analyzed both by simulation and experimentally through magnetic force microscopy and scanning electron microscopy with polarization analysis.

Next, a model multilayer system is used to demonstrate the magnetostatic behavior of 360DWs, demonstrating a much reduced stray field compared to 180DWs and a strong interlayer pinning behavior that allows the 360DW to act as a programmable pinning site. The richness of this magnetostatic behavior is analyzed experimentally in a rhombic ring system which readily generates 360DWs during reversal. The action of 360DWs is shown to dominate the reversal process, reducing switching fields and showing multiple reversal pathways with a strong dependence on field history.

Simulations are used to explore the response of the 360DW to field and DC and AC currents. This highlights 360DW behaviors quite distinct from those of 180DWs, including the inability to be positioned by an applied field and the ability to be destroyed in place. 360DWs are shown to have an intrinsic resonant behavior in the GHz range, the exact frequency of which is broadly tunable by an applied field. Resonance can be excited by an applied AC current, and in conjunction with DC can be used to pin and gate 360DW propagation at a geometric pinning site, using globally applied currents and without impact on nonpinned domain walls.
Thesis Supervisor: Caroline Ross
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Chapter 1

Introduction

1.1 Motivation

The discovery of giant magnetoresistance (GMR) in 1988[1] has led to great strides in magnetic storage technology and sparked interest in the field of spintronics, electronic devices which incorporate both spin and electrical charge in their function. In the 15 years since their introduction, sensors based on the GMR effect have become ubiquitous in conventional hard drives, leading to ever-greater data densities. However, as the extensive interest in spintronic research should indicate, the technological applications of magnetoresistance (MR) are hardly limited to conventional magnetic recording media.

Magnetoresistive random access memory (MRAM) employs MR effects to directly encode data in the magnetization of a small multilayer device containing a magnetically soft/free layer and a hard/fixed layer. Different relative orientations of the layers produce different resistance states (see sec. 2.6) which encode a 0 or 1. MRAM devices promise significant improvements over conventional flash memory: write times superior by orders of magnitude, reduced power consumption, and no write-cycle wear limitations.[2] It is unsurprising that MRAM designs have been the focus of significant
scientific interest.

One pathway to these future memory technologies focuses on discrete elements of uniform magnetization. This exploits the simplest possible magneto-resistive behavior in which layers are entirely parallel or antiparallel (sec. 2.6) and two distinct resistance states are available. Each discrete element can then encode one bit, which can be read with a sensing current. MRAM designs based on the spin torque effect,[3] which use applied current to directly manipulate the magnetic state without reliance on a magnetic field, allow tightly controlled addressing of individual bits in large arrays at very high densities, all at lower power than field-driven MRAM. Spin torque transfer MRAM shows great promise as a future memory technology; successful prototypes have already been demonstrated and commercialization is underway.

There is a second pathway to novel magnetic memories which focuses on direct manipulation of magnetic domain walls (DWs) within a larger piece of magnetic material, such as a nanowire. As a single nanowire can contain multiple domain walls at arbitrary positions, an individual magnetic element can encode a much greater amount of data. The entire contents of the nanowire can then be driven by an applied current. However, magnetostatic interactions between domain walls limit the data density that can be achieved in this way.

It has been shown that domain walls can be employed in the design of not only memory systems, such as the “racetrack memory” famously proposed by Stuart Parkin (sec. 8.3),[4, 5] but also novel logic devices.[6, 7] For example, in the method proposed by Allwood et al.[6] traditional logic circuit elements such as fanouts, crossovers, AND and NOT gates, which are sufficient to produce all other logic gates, can be created simply by using particular geometries of magnetic material through which the domain wall propagates. In this scheme, a rotating magnetic field is used to drive one or more domain walls through the circuit. Basic circuits such as an oscillator and a shift register have been demonstrated experimentally.
To avoid the difficulties of generating strong localized or rotating magnetic fields, ultimately, the spin-torque effect is again the preferred method of domain wall manipulation. A thorough understanding of domain wall physics and current-driven behavior is therefore necessary to develop these technologies, and it is unsurprising that the current-driven behavior of 180° domain walls (180DWs) (sec 2.2) has been thoroughly investigated. Additionally, in examining the current-driven behavior of domain walls in nanowires we observe many phenomena of fundamental interest to magnetic science, such as Walker breakdown (sec. 2.4.3).

The coupled-180DW structures known as 360° domain walls (360DWs) (sec 2.5), previously observed for example during reversal of ring devices[8] and unpatterned thin films,[9] present an especially interesting line of inquiry. 360DWs form spontaneously from 180DWs of opposite chirality on close approach, and thus should be expected to form in any domain wall device pushing the limits of density. It has been observed that these structures display behaviors quite distinct from the 180DWs which compose them,[10, 11] which can have a significant impact on the magnetic behavior of a sample. Additionally, 360DWs exhibit a strong flux closure (sec. 5) which results in a greatly reduced stray field; as a result, the stable packing density for 360DWs may be greater than that of 180DWs despite the 360DWs greater width. An understanding of 360DWs is therefore of great interest for the design of domain wall devices. In this thesis, we explore the magnetostatic behavior of 360DWs thoroughly, in particular the influence of 360DWs on multilayer structures.

While the magnetic behavior of 360DWs has been studied to some extent, we will show in sec. 7.2.2 that there are additional behaviors unique to the 360DW that have yet to be thoroughly investigated, including an intrinsic resonant behavior with no analogue in 180DWs. Additionally, we note that the effect of current on 360DWs is entirely unexplored. Given the significant difference between 180DW and 360DW magnetostatic and field-driven behavior, as well as the distinct topology of 360DWs,
a unique current-driven behavior may be expected. This is not only an open question in magnetic physics; as current-driven control of magnetization is the goal for future logic and memory technology, it is also a critical line of inquiry for technological development.

1.2 Thesis Outline

Chapter 2 presents a review of magnetic energies, the physics of magnetic domain walls, and relevant equations in micromagnetic simulation. Chapter 3 describes experimental and simulation methods. Chapter 4 discusses the formation of 360DWs from 180DWs and demonstrates a system designed to create 360DWs using an alternating magnetic field. Chapter 5 explores the magnetostatic behavior of 360DWs and their influence on magnetic reversal through analysis of the rich response of the rhombic ring system. Chapter 6 discusses the influence of fields and currents on 360DWs. Chapter 7 summarizes key results and discusses future work.

The appendices contain documentation for various programs written over the course of this research to facilitate working with the OOMMF micromagnetic simulator [12].
Chapter 2

Background and Literature Review

First, magnetic energy terms relevant to understanding thin film domain wall behavior are summarized. Next, an overview of domain wall structure is provided, followed by a discussion of domain wall formation, and then domain wall motion by driven by magnetic field and current. Fifth, a summary of 360° domain wall formation and characteristics is provided. Finally, magnetoresistance is briefly reviewed. As this thesis concerns the applications of 360DWs to magnetoelectronic devices, in particular devices in which current is used to sense the magnetization or presence of domain walls, we focus on the physics of ferromagnetic transition metals.

2.1 Summary of Magnetic Energy Terms

The structure and evolution of domain walls and other magnetic configurations can often be readily understood in terms of the balance between of various magnetic energies. 360° domain walls in particular are most easily understood as a balance between exchange and demagnetization energies. Additionally, proper understanding of these terms is essential in interpreting micromagnetic simulations. Accordingly, several principal magnetic energy terms are introduced briefly before discussing domain wall structure.
Exchange Energy

In a ferromagnetic material, it is energetically favorable for adjacent magnetic moments to lie parallel. Any deviation from this orientation incurs an energy penalty proportional to the misalignment. Exchange energy is defined over pairs of spins: in terms of two adjacent spins, this is described by the equation \[ (2.1) \]

\[ E_{\text{ex}} = A \left( \frac{\partial \theta}{\partial x} \right)^2 \]

in which \( \theta \) is the angle between spins; \( x \) is the separation between spins; and \( A \) is a material constant called the exchange stiffness, in units of energy per length, which incorporates the exchange integral and crystal structure. Integrating this expression over all spin pairs in three dimensions gives the total exchange energy of the system. \[ (2.2) \]

\[ E_{\text{ex}} = A \int_V (\nabla \vec{m})^2 dV \]

Since OOMMF uses rectangular unit cells, for each spin only the six orthogonally adjacent nearest neighbors cells are considered in calculating the exchange energy.

Magnetostatic Energy

The magnetostatic energy captures the interaction of a magnetized body with the magnetic field (“demagnetizing field”) generated by its own magnetization. The magnetostatic energy can be calculated with the expression \[ (2.3) \]

\[ E_{\text{shape}} = -\frac{1}{2} \int_V \vec{H}_D \cdot \vec{M} dV \]

where \( \vec{H}_D \) is the demagnetizing field generated by magnetic surface poles. For ellipsoids, shape anisotropy can be linearly related to the magnetization through
demagnetization factors. Calculation of demagnetizing fields for samples of different geometries is quite complex; a thorough discussion can be found in O’Handley.[13]

In non-spherical geometries, the demagnetizing field creates easy axes based on the geometry; this is the shape anisotropy. Phenomenologically, for the purposes of this work we can consider a simple result: it is energetically favorable for magnetization to point along the longest axis of a geometric form, as this reduces the area of surface poles and thus the stray magnetic field. In thin films, in the absence of a strong out-of-plane magnetocrystalline anisotropy, is is extremely favorable for $\vec{M}$ to lie in the plane of the film; in nanowires, $\vec{M}$ generally follows the wire. In this way, the stray fields generated are minimized.

**Anisotropy Energy**

For crystalline materials, the energy may vary with the orientation of the magnetization with respect to the crystalline axes. This is the magnetocrystalline anisotropy, which results from spin-orbit interactions. This energy term is closely tied to the symmetry of the system, and is expressed by

$$E_{ani} = \int_V u_{ani}(\frac{\vec{M}}{M_S})dV$$

(2.4)

where $u_{ani}$ is a spherical harmonic suitable to the symmetry of the system and $M_S$ is the saturation magnetization. These solutions can become quite complicated, but there is a simple first-order approximation for $u_{ani}$ in the case of uniaxial anisotropy:[13]

$$u_{ani} = K_1 sin^2 \theta + K_2 sin^4 \theta + ... \approx K_1 sin^2 \theta$$

(2.5)

where $K_n$ are materials constants and $\theta$ is the angle between $\vec{M}$ and the favored (“easy”) axis. This energy is minimized when $\vec{M}$ lies along the easy axis.

This work concerns itself with polycrystalline films, which have no global mag-
netocrystalline anisotropy easy axis. However, individual grains still have easy axes; in this way, anisotropy provides a set of local variances that can have a symmetry-breaking effect on an otherwise symmetric effect. This may be observed as, for example, a domain wall in a ring preferentially depinning in a certain direction when a field is applied. When performing micromagnetic simulation, the first-order simplified version of the anisotropy energy presented in Eq. 2.5 is used.

**Zeeman Energy**

The Zeeman energy captures the interaction of the magnetization $\vec{M}$ with an externally applied magnetic field $\vec{H}_{\text{ext}}$. It is easily understood intuitively: it is energetically favorable in a ferromagnet for the magnetization to align with an applied field. Zeeman energy is minimized when $\vec{M} \parallel \vec{H}_{\text{ext}}$, and can be calculated by the following equation:[14]

$$E_Z = -\int V \vec{H}_{\text{ext}} \cdot \vec{M} dV$$  \hspace{1cm} (2.6)

### 2.2 Structure of Domain Walls

Domains and domain walls form to reduce the magnetostatic energy of a sample. Formation of multiple, differently-oriented domains can create internal flux closures to reduce or eliminate the stray field by eliminating surface poles. The walls that bound these domains are defined by a gradual rotation of spins across the width of the wall, to minimize the exchange penalty. A typical closure domain structure for a system with cubic anisotropy is shown in Fig. 2.1.
2.2.1 Simple Bulk Materials: Bloch Walls

A 180° domain wall is so named because it separates two domains with magnetizations 180° apart, that is, antiparallel. The simplest possible 180° domain wall bounds two domains in an infinite bulk sample with uniaxial anisotropy. Between two adjacent domains, the magnetizations are antiparallel. If the plane of the wall contains the anisotropic easy axis, no stray field is generated, and if the magnetization rotates parallel to the plane of the wall, there is no effective magnetic charge inside the wall.[14] This generates zero stray field and is thus magnetostatically optimal. The width of the domain wall is a balance between exchange energy, which favors a broad domain wall with a small spin-angle gradient, and anisotropy energy, which favors alignment with the easy axis. The wall thickness is therefore a function of these two energies, and $\delta_{DW} = \pi \sqrt{\frac{A}{K_u}}$ where $A$ is the exchange stiffness and $K_u$ the uniaxial anisotropy energy coefficient. [13] This form of domain wall is called a Bloch wall, and it is the typical domain wall in bulk samples. A schematic ferromagnet containing a 180° Bloch domain wall is shown in Fig. 2.2.
2.2.2 Thin Films: Néel Walls

In the case of thin films, the structure of the domain wall can be significantly different. In forming a 180° domain boundary in a very thin sample, the Bloch wall structure would result in the magnetization inside the domain wall pointing through the thickness of the sample, generating a significant stray field (in a flat sheet, the demagnetization factor in this case approaches 1, such that $H_{\text{demag}} = M_s$). In films with thickness comparable to the Bloch wall width, a different wall structure is formed in which the spins rotate in the plane of the surface, rather than the plane of the wall. In this case, the domain wall still forms a dipole, but is directed out the thin edge of the sample, rather than the broad surface. This structure is called a Néel wall. Schematic Bloch and Néel walls are shown in Fig. 2.3.

In typical materials, the Néel wall is stable up to 50 or 60 nm thicknesses, with stability and wall width increasing with decreasing thickness due to the reduction in magnetostatic energy.[13] Néel walls are governed by magnetostatics rather than anisotropy; while the precise width depends on sample geometry and to some extent anisotropy, the general scale of width is given by $\delta_{DW} = \pi \sqrt{\frac{2A_{\text{eff}}}{\mu_0 M_s}}$ where $M_s$ is the saturation magnetization.[13] A precise calculation of domain wall width as a function...
The transverse Néel walls is the two typical domain wall structures in thin film nanowires; the other is the vortex wall. In the vortex wall structure, the Néel wall cuts diagonally across the wire with a vortex core at the center of the wire. Vortex domain walls are favored when the nanowire is particular thick or wide, as shown in the partial phase diagram in Fig. 2.5. In this thesis, we employ thin and narrow nanowires that are well within the transverse phase region, and from this point on we therefore consider only transverse domain walls. These domain walls are treated more thoroughly in the following sections.

2.3 Creation of Domain Walls

From this section onward, we focus on transverse 180° Néel domain walls in nanowires and other patterned devices of high aspect ratio, as this leads naturally to the discussion of 360DWs. The magnetization reversal process naturally leads to the formation of one or more domain walls: as shape anisotropy prevents coherent rotation of the magnetization in a nanowire, reverse domains must be created to initiate the reversal process. Reverse domains can be nucleated anywhere in the nanowire, though edges are particularly favored, and these domains expand to complete the reversal process.
As the boundary of the reverse domain meets the edge of the wire, a transverse domain wall will be left behind.

Simulation of the reversal of a permalloy nanowire is shown in Fig. 2.6. At the very edges of the bar, the exchange penalty for rotation of the spins is reduced and the demagnetizing field causes the magnetization to cant slightly. As a result, this is low-energy site for reverse domain nucleation; a reverse domain nucleates at each end of the bar in Fig. 2.6(b-d). In (e), two transverse 180DWs are clearly established, and in (e-g) reversal continues by the shrinking of the initial (right-magnetized) region.
Figure 2.5: Top: A vortex domain wall simulated in a 2 nm thick, 250 nm wide permalloy strip. Bottom: Partial phase diagram of head to head domain wall structures in thin magnetic films. $\delta$ is the magnetostatic exchange length and $w$ and $t$ are the width and thickness of the wire, respectively. Reprinted from McMichael and Donahue, IEEE Transactions on Magnetics 33:5 4167 (1997). ©1997 IEEE.

Since these two 180DWs have the same directional sense, when they collide in (g) they simply annihilate, completing reversal. The fully reversed bar is shown in (h).

If reversal is arrested, for example if a propagating domain wall is trapped at a pinning site, additional reverse domains may be nucleated to continue the process. This can introduce many additional domain walls, and thus choosing a structure that readily pins propagating domain walls can generate domain-wall-rich configurations. These are discussed more in section 6.

2.4 Domain Wall Motion

The position of domain walls can be manipulated by an external magnetic field, by magnetostatic interactions with other domain walls,[15, 16] or by the application of a current via the spin-torque effect. We will begin by considering only field-driven effects, in which case the evolution of the magnetic state is governed by the Landau-
Lifshitz-Gilbert equation\[17\]

\[
\frac{d\vec{m}}{dt} = -\gamma \vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{d\vec{m}}{dt}
\]  \hspace{1cm} (2.7)

where $\vec{m} = \frac{\vec{M}}{M_s}$, $\gamma$ is the gyromagnetic ratio, $\vec{H}_{eff}$ is the applied field, and $\alpha$ is a material-dependent damping term known as the Gilbert damping parameter. The first term on the right-hand side, the precessional term, indicates the precession of the magnetic moment about the applied field. The second term, the damping term, indicates the loss of energy by the system through the damping parameter $\alpha$, causing the magnetic moment to eventually align with the applied field.
2.4.1 Field-Induced Motion

Field-driven domain wall motion at low fields is intuitive, easily understood by considering the Zeeman energy (we will discuss the complex case at higher driving forces in section 2.4.3). Consider the case of a 180DW in an infinite wire, shown in Fig. 2.7.

Here, an applied magnetic field directed to the left or right can reverse the magnetization by rotating the magnetization near the domain wall, effectively sliding the DW along the wire. When a field is applied, the domain wall will travel with a constant velocity until it leaves the end of the bar, completing reversal of the magnetization. Up to a point, the domain wall velocity is simply linear with the applied field,[18, 19] as shown in Fig. 2.8. Beyond this point, the behavior is significantly more complex; this regime is discussed in section 2.4.3.
2.4.2 Current-Induced Motion

Domain walls can also be manipulated by an applied current through the spin transfer torque (STT) effect. As a current passes through a magnetic layer, it becomes partially polarized. In the simplest explanation of this effect, as current crosses the domain wall, causing the spins of conducting electrons to rotate, there is a torque between conducting electrons and the local magnetization. As a result, regardless of the magnetization of the sample or the sense of the DW, the DW is driven down the wire in the direction of electron flow.

Capturing this behavior requires a modification to the LLG equation (Eq. 2.7) to incorporate the effects of the current. Considering the case in which current is flowing along a wire oriented along the x axis, this introduces two new terms as follows:

\[
\frac{d\vec{m}}{dt} = -\gamma \vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{d\vec{m}}{dt} + (\vec{u} \cdot \vec{\nabla})\vec{m} + \beta \vec{m} \times [(\vec{u} \cdot \vec{\nabla})\vec{m}] \tag{2.8}
\]

or, when simply considering current flowing along a wire oriented along the x axis,

\[
\frac{d\vec{m}}{dt} = -\gamma \vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{d\vec{m}}{dt} + u \cdot \vec{m} \times (\vec{m} \times \frac{\partial\vec{m}}{\partial x}) + \beta \cdot u \cdot \vec{m} \times \frac{\partial\vec{m}}{\partial x} \tag{2.9}
\]

where \(\vec{u}\) is the spin current in units of \(\frac{m}{s}\) and \(\beta\) is a dimensionless nonadiabatic parameter. The spin current is in turn described by:

\[
\vec{u} = \vec{J}P \frac{g\mu_B}{2eM_s} \tag{2.10}
\]

where \(\vec{J}\) is is the current density, \(P\) the material-dependent polarization, \(g\) the Landé factor, \(\mu_B\) the Bohr magneton, \(e\) the elementary charge, and \(M_s\) the saturation magnetization.

The first additional term, \(u \cdot \vec{m} \times (\vec{m} \times \frac{\partial\vec{m}}{\partial x})\), describes the spin angular momentum.
transfer from polarized conduction electrons to the spins within the domain wall.[22] This is the spin torque mentioned earlier, called the adiabatic spin torque. However, there is an additional term $\beta \vec{m} \times [(\vec{u} \cdot \vec{\nabla})\vec{m}]$, directed along an axis orthogonal to the adiabatic spin torque. This is the nonadiabatic spin torque, incorporating the previously mentioned nonadiabatic parameter $\beta$. The microscopic origin of this torque term is debated, but the nonadiabatic spin torque has a significant influence on the behavior of current-driven domain walls.[22, 21] $\beta$ can be determined experimentally; here we treat it as an additional parameter that may be varied to give insight into the micromagnetic behavior.

### 2.4.3 Walker Breakdown

When a 180DW is subjected to a driving force above a certain critical point, whether that force is field- or current-based, the motion of the 180DW becomes irregular. The DW travel is no longer smooth and linear, but has a lopsided oscillating velocity component.[23] Additionally, the chirality of the DW alternates continually due to an antivortex core traversing the width of the wire; effectively, the DW which is normally locked in plane rotates about the wire at a frequency proportional to the driving force.[24] At this point, the 180DW has entered Walker breakdown.

At the onset of Walker breakdown, the net forward velocity of the domain wall decreases sharply, but linearity is recovered at a lower proportionality as the driving force continues to increase.[19] After the onset of Walker breakdown, the 180DW undergoes an oscillatory motion, though with a net forward velocity (Fig. 2.9).[25, 26, 27, 28] This characteristic velocity variation is readily demonstrated experimentally, as shown in a field-driven 180DW is shown in Fig. 2.10. Exhaustive simulations of current-driven domain wall motion were performed by Thiaville et al.[21], showing this behavior in the case where $\beta > \alpha$. Simulated current-driven domain wall velocities for varying $\beta$ are shown in Fig. 2.11.
Figure 2.9: Simulated magnetization configuration of a domain wall propagating a 550 nm long section of wire with $H_x = 100$ Oe and $H_y = 0$ Oe. (a)–(j) show Walker breakdown with 0.2 ns resolution, while (j)–(m) show the following breakdown event with 0.6 ns resolution. (n) Instantaneous domain wall velocity $v(t)$ during Walker breakdown with $H_x = 25$ Oe and $H_y = 0$ Oe. Reprinted with permission from Journal of Applied Physics 103:7, 073906 (2009). Copyright 2008, American Institute of Physics.[10]
Figure 2.10: Velocity data for a domain wall driven by an applied magnetic field in a 600nm-wide NiFe wire. Straight solid lines are linear fits to data below 5 Oe and above 25 Oe. Inset shows detail. Reprinted by permission from Macmillan Publisher Ltd: Nature Materials 4 741-744 (2005), copyright 2005.[19]

Figure 2.11: Simulated domain wall propagation velocity under spin current $\vec{u}$, assuming a perfect wire and constant domain wall width and taking the Gilbert damping parameter $\alpha = 0.02$. At $\beta = \alpha$, the behavior is linear; for $\beta > \alpha$ Walker breakdown is observed. Reprinted with permission from “Micromagnetic understanding of current-driven domain wall motion in patterned nanowires,” Europhysics Letters 69 (6), 990 (2005) (http://epljournal.edpsciences.org/). Reproduced by permission of the AAS.
The irregularity of motion during Walker breakdown is generally undesirable in DW devices, where precise control of DW position is key. The Walker breakdown behavior can be suppressed if injection of the antivortex into the wire can be suppressed, that is, if the 180DW can be prevented from rotating out of the plane. For a single transverse 180DW, this can be done with an applied field oriented along the direction of the domain wall core, which increases the mean DW velocity substantially by reducing or eliminating antivortex injection events.[23] Alternatively, sample geometry can be engineered to prevent Walker breakdown; for example, a comb structure has been demonstrated in which a regularly-spaced series of cross-shaped intersections along the nanowire maintained the original DW chirality and increased propagation velocity by a factor of four.[29]

2.5 360° Domain Walls

360° domain walls are metastable structures, which have been observed in thin films and nanowires, comprising two 180° domain walls of similar rotational sense (in wires, opposite orientation) which have been brought together. Typically, these are Néel domain walls, but 360DWs based on Bloch walls have also been observed in thin films.[30] They are so named because the domains they separate have parallel magnetization, that is, the magnetization rotates a full 360° across the domain wall. Just as transverse 180DWs have an 'up' or 'down' sense, 360DWs have a chirality defined by the sense of their rotation. Unlike 180DWs, 360DWs have no net magnetization, and thus have a topology such that they can be created or destroyed in place.[10]

2.5.1 360° Domain Walls in Thin Films

360DWs can be generated during magnetization reversal in very thin films when a Néel wall passes across a (typically nonmagnetic) defect, trapping a Bloch line.[31, 14] The
domain wall cannot propagate across the defect, and the domain wall is folded about
the defect, creating a 360DW anchored at the defect site. This is shown in a simulated
Co thin film in Fig. 2.12. The domain wall so formed is metastable and cannot
be removed except at very high magnetic fields depending on the strength of the
pinning site; for the 360DW in Fig. 2.12, an external field of 280 kA/m≈3500 Oe
was required. 360DWs can also be formed during reversal without the presence of
defects[32] due to local variations in anisotropy[9] or even small variations in the
shape of a patterned film.[33] Finally, in multilayer films, 360DWs may form due
to interlayer magnetostatic interactions; this allows formation of 360DWs at layer
thicknesses greater than those for which 360DWs are observed in single layers.[34]

360DWs may also be formed during reversal of thin films containing multiple
domains. When a domain is energetically disfavored and shrinks, a 360DW may
be formed based on the nature of the bounding domain walls.[35] If the bounding
domain walls have opposite rotational sense, called unwinding walls, they experience
attraction and can be annihilated topologically without a large energy barrier.[14] If
the bounding domain walls have similar rotational sense, called winding walls, the
bounding walls repel and do not have a low-energy path to annihilation. If a winding
wall pair is forced together by an external field driving elimination of the domain that
the walls bound, a 360DW is formed. Again, this structure is stable to very large
fields relative to other critical fields for motion and annihilation in a given sample.

From this point forward, we focus on 360DWs in magnetic stripes, which have
slightly different properties due to the strong stray field of transverse domain walls.

2.5.2 360° Domain Walls in Stripes

Consider two transverse Néel 180DWs in a magnetic stripe interacting via stray field.
If they are of identical sense (analogous to opposite rotation in unpatterned films),
they can interact and annihilate; if they are of opposite sense (analogous to similar ro-
Figure 2.12: Simulation of the formation of a 360° domain wall in a thin Co film. An external field of $H_{ext} = 160 \text{ kA/m} \approx 2000 \text{ Oe}$ is applied in the positive $y$ direction. The grey scale plots of the left and right columns depict the $x$ and $y$ components of the magnetization, respectively. Reprinted with permission from J. Appl. Phys. 87:9 5517 (2000).[31] Copyright 2000, American Institute of Physics.

tation), they can form a 360DW. However, unlike 360DWs in unpatterned thin films, opposite-sense (360DW-forming) transverse 180DWs walls attract each other by stray field, as they have opposite dipolar characteristics. Similarly, similar-sense transverse 180DWs repel, but will be annihilated if forced together by an applied field. Therefore, in patterned thin films of narrow linewidth 360DWs can form spontaneously by 180DW coupling in the absence of an applied field. A clockwise schematic 360DW in
Figure 2.13: Micromagnetic simulation image of an equilibrium 360DW in a thin film nanowire 200 nm in width.

Figure 2.14: Time-lapse sequence of two domain walls being driven by a 10 Oe field aligned along the +x-axis in a 5 nm thick wire. In (a) the elementary topologic charges are given. Opposite topologic charges annihilate. Reprinted with permission from Applied Physics Letters 94:13, 132502 (2009). Copyright 2009, American Institute of Physics.[10]

A wire is shown in Fig. 2.13.

Transverse 360DWs are therefore created from transverse 180DWs whose cores are directed along opposite directions, that is, which have opposite topological charges; the simulated collision of two oppositely-oriented 180DWs is shown in Fig. 2.14.

The two constituent 180DWs are strongly coupled by dipolar interactions, as the 180DWs can be viewed as opposite dipoles in close proximity; the dipolar field favors
a very narrow domain wall. The structure is stabilized by the exchange interaction, which discourages rapid rotation of the magnetization across a given distance. This favors a very wide domain wall, creates a large energy barrier preventing the 360DWs from combining and annihilating. The 360DW thus has an equilibrium width (in the absence of an applied field) set by the balance of these energies, as well as the Zeeman energy of any applied field.[11, 36]

Due to flux closure between the two constituent 180DWs, the 360DW has a reduced stray field and more rapid stray field decay. Simulation of the in-plane stray field magnitude in a 200 nm x 5 nm cross-section nanowire is shown in Fig. 2.15.

A lack of net magnetization also indicates that unlike a 180DW, a 360DW does not move under an applied magnetic field. Instead, the 360DW is compressed or expanded by a longitudinal applied field. In a typical nanowire system, an applied field directed along the core region of the 360DW (blue in Fig. 2.13) can dissociate the 360DW very easily, with a field of just a few tens of Oe; an applied field in the opposite direction will annihilate the 360DW, but only at a strength of hundreds or thousands of Oe.[8, 11] The precise fields necessary depend on the structure and equilibrium width of the domain wall, and therefore have a complex dependence on sample geometry.

2.5.2.1 Formation and Influence on Reversal Behavior

We have previously discussed the formation of 360DWs in thin films, which can typically be attributed to defects that trap propagating domain walls during reversal. In patterned thin films, however, 360DW formation is generally the result of coupling of two distinct 180DWs. For example, 360DWs may form in reversal of ring shapes, which at remanence after saturation contain two 180DWs of opposite sense.[8] A schematic ring reversal is shown in Fig. 2.16. At remanence after saturation, thin film rings exist in the ‘onion’ state, with two 180DWs of opposite sense at opposite
Figure 2.15: In-plane stray field magnitude for a 180° domain wall (left) and a 360° domain wall (right) in a permalloy nanowire of 200 nm x 5 nm cross section. Red indicates off-scale high values very near the domain wall core, up to 3000 Oe (180DW) and 2500 Oe (360DW).
ends of the ring. When a reverse field is applied, these domain walls propagate around the ring, and reversal may proceed by rotation or by formation of (in all rings, Fig. 2.16 top) vortex or (in smaller rings, Fig. 2.16 bottom) twisted states.[8] In the twisted state, the two onion state domain walls have combined to form a 360DW. If a twisted state is formed, the 360DW is annihilated at a higher field to create the vortex state. A sample reversal via the twisted state is shown in MFM micrographs is shown in Fig. 2.17.

In rings with sharp corners to act as pinning sites, such as rhombic rings, reversal can proceed by buckling mechanisms that generate many additional reverse domains. This can result in the formation of up to four 360DWs over the course of a single reversal, shown in Fig. 2.20.[37]

In this thesis, we show that 360DWs may be also be created using deliberately tailored domain wall injection systems, discussed in section 4.2.

Since 360DWs are not eliminated until very high fields, they can play a significant role in the magnetic behavior of ring-shaped elements.
Figure 2.17: Formation of the twisted state in a thin film cobalt ring with 520 nm diameter and 200 nm linewidth. (a) AFM image of the nanoring. (b) MFM image of the ring after saturation and application of a 28 Oe reverse field. The onion state remains. (c, d) Formation of the twisted state at 162 Oe reverse field, which persists at 267 Oe. (e) Elimination of the 360DW, leaving the vortex state. (f) Formation of the reverse onion state, nucleating two new 180DWs. Figure from [8].

Figure 2.18: Buckling reversal mechanism in a Co thin film rhombic ring generating multiple 360DWs. Field increases from left to right. Magnetization along the straight arms buckles with increasing field, eventually generating multiple reverse domains. The newly formed 180DWs then propagate and combine to form multiple 360DWs, leaving the magnetization of the ring structure almost completely reversed. Figure from [37].
role in future reversals of such devices.\cite{32} During the reversal process, 360DWs can dissociate into pairs of 180DWs spanning a reverse domain, enabling reversal at fields much lower than those necessary to generate reverse domains.

The behavior of 360DWs in nanowires and other patterned thin film systems is only partially understood. In sections 5 and 6, we explore the magnetostatics of 360DWs and their influence on the reversal behavior of multilayer systems.

\subsection{2.5.2.2 Resonance}

It has previously been demonstrated that 180DWs can be resonated in an externally defined potential well.\cite{38} 360DWs in thin film stripes instead exhibit an intrinsic resonant behavior, governed by the balance between demagnetization and exchange and the internal structure of the domain wall, in which an oscillating field can resonate the equilibrium spacing when applied along the 360DW core axis (translational mode) or the size of each constituent 180DW when applied along the 180DW core axis (breathing mode).\cite{39} When considering higher-order modes, in addition to translation and breathing the 360DW can also exhibit wobbling resonant modes, with each constituent 180DW rotating back and forth across a small angle in the plane of the wire. The effect of this resonance on the behavior of the 360DW has not been thoroughly considered. In this work, we demonstrate that the first-order translational (width-oscillating) mode occurs at a resonant frequency which is broadly tunable with an applied field. We additionally examine the use of high-frequency AC to activate the first-order translational mode and consider its effects on 360DW motion, annihilation, and pinning behavior.
2.6 Magnetoresistance

Magnetoresistance (MR) effects are a category of phenomena in which the electrical resistance of a magnetic material or structure varies with the direction of magnetization in that structure. Magnetoresistance is broadly divided into four categories with different physical origins: anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), tunneling magnetoresistance (TMR), and colossal magnetoresistance (CMR). We consider the first three below, as they are most relevant to this work. For all methods, we define the MR ratio as $\frac{\Delta R}{R_{\text{min}}}$, where $\Delta R$ is the magnitude of the resistance change in the structure and $R_{\text{min}}$ the minimum resistance. Magnetoresistance has applications in both characterization and devices; in this work, we focus on AMR and GMR for characterization, and so explore them in greater detail.

2.6.1 Anisotropic Magnetoresistance

Anisotropic magnetoresistance was the first observed mode of magnetoresistance, measured by Lord Kelvin in nickel and iron samples over 150 years ago.[40] AMR is observed in transition metal ferromagnets, causing a shift in resistance depending on the angle between the direction of magnetization $\vec{M}$ and the direction of electron flow $\vec{I}$ due to Hall effect deflection of carriers away from the current direction. AMR produces a relatively small magnetoresistive effect, with commonly observed MR ratios of 1.5 to 4%.[41, 42] though values up to 50% have been achieved experimentally.[43] When considering AMR, the maximum value of resistance $R_{\parallel}$ is achieved when $\vec{M}$ is parallel or antiparallel to $\vec{I}$, and the minimum value $R_{\perp}$ is achieved when $\vec{M} \perp \vec{I}$. This is attributed to enhanced electron scattering between the s and d orbitals when electrons are traveling parallel to the applied magnetic field;[13] strong internal fields in magnetic materials give rise to a significant resistance change. AMR in a simple
bar therefore follows the relation[44, 13]

$$R(\theta) = R_\perp + [R_\parallel - R_\perp] \cdot \cos^2 \theta$$

(2.11)

where $\theta$ is the angle between $\vec{M}$ and $\vec{I}$.

AMR is valuable as a measurement technique; simple resistance measurements can in this way read aspects of the magnetic configuration of a simple single layer of magnetic material. For example, AMR is very effective in detecting the presence or absence of domain walls in nanowires: the magnetization deviates from following the wire, necessarily reducing the resistance in a narrow region. However, the small resistance changes involved make it unsuitable for domain wall memory and logic devices.

2.6.2 Giant Magnetoresistance

GMR is a magnetoresistive effect observed in multilayer thin film structures in which two ferromagnetic layers are separated by a nonmagnetic (but conductive) spacer layer, whereby the resistance varies based on the angle between the magnetization of the two layers.[1] GMR gives rise to a much larger $\Delta R$ than AMR, though the MR ratio varies widely; while typical values have been reported of a few to tens of percent[41] ratios as high as 220% have been demonstrated.[45] When considering GMR, the maximum value of resistance is achieved when the two magnetic layers are parallel, and the minimum value achieved when they are antiparallel.[13] GMR is observed both when the current is in the plane of the magnetic layers (Current In Plane, or CIP) and when it is perpendicular to the layers (Current Perpendicular to Plane, or CPP).

The GMR effect is attributed to magnetization-dependent scattering processes in the two ferromagnetic layers, particularly at the interfaces. Electrons with spins
antiparallel to the material magnetization scatter more readily due to the difference in the density of states at the Fermi energy (Fig. 2.20(a, b, d)); accordingly, the magnetic layers have different effective resistances for electrons of different spins (Fig. 2.20(c, e)).

We can consider GMR using a two-current model, treating a non-polarized current as two distinct fully polarized currents $I_\uparrow$ and $I_\downarrow$. Each magnetic layer has a distinct resistance for each polarized current: when a layer is magnetized in a given direction, the density of states for carriers of with spin opposite that direction is increased and the resistance for those carriers is lowered. If the magnetization is parallel in both layers, this results in a conductive channel for one spin current (Fig. 2.20(e)). However, if the magnetization is antiparallel, there is very strong interfacial scattering[13] and no preferred spin conduction channel, increasing the total resistance (Fig. 2.20(c)). This is shown schematically in Fig. 2.19.

GMR also follows a simple relation[13]

$$R(\theta) = R_\parallel + [R_{\text{anti}} - R_\parallel](1 - \cos\theta)$$  \hspace{1cm} (2.12)

where $R_{\text{anti}}$ is the maximum resistance (layers antiparallel) and $\theta$ is the angle between the magnetizations of the two magnetic layers.
Figure 2.20: (a) Density of 3d and 4s spin-up (teal) and spin-down (orange) states for an unmagnetized (left) and ferromagnetic (right) sample. (b) Schematic trilayer where the magnetic layers have antiparallel (high-resistance) magnetization, showing spin-dependent density of states as in (a). (c) Schematic resistance for the two spin conduction channels of (b). (d, e) as (b, c) for parallel (low-resistance) magnetization states. Figure adapted from [46].

GMR is a very practical, high-signal method for determining the magnetic state of suitable multilayer systems, for example in the permalloy/copper/cobalt rhombic ring structures discussed in section 6. The only requirement for a GMR system is a pair of ferromagnetic layers separated by a conductive nonmagnetic layer, with typical layer thicknesses significantly below 10 nm. The ferromagnetic layers need not be identical, and the stack need not be symmetric, which is a critical consideration for GMR devices: to usefully employ GMR in a magnetic sensor, an asymmetric structure is necessary. A magnetically soft layer is used to sample a magnetic field (or store
a bit of information) and a fixed or hard layer is used as a reference, such that the resistance is controlled by reversal of the soft layer.

The ferromagnetic layers need not be the same material, and more complicated stack structures may be used in devices: in the spin valve (SV) structure, the fixed layer is pinned by an adjacent antiferromagnetic layer; in the pseudo-spin valve (PSV) structure, a harder magnetic material is used for the fixed layer. GMR sensors are very mature, and GMR quickly became the dominant method for hard drive readback,[2] though in the past five years TMR sensors have taken over this role. For these reasons we consider GMR and potentially TMR as methods for reading the state of future domain wall devices.

### 2.6.3 Tunneling Magnetoresistance

TMR is a magnetoresistive effect that occurs when electrons tunnel across a junction comprising two magnetic layers and a very thin (a few atomic layers) insulating spacer in the CPP configuration. This configuration is called a magnetic tunnel junction (MTJ). TMR produces the largest $\Delta R$ among the magnetoresistive effects; first observed to generate a conductance ratio of roughly 14% at low temperature,[47] recent experiments with MgO barriers have generated MR ratios as high as 604% at room temperature and over 1100% at low temperature.[48] Consider again a spin-dependent density of states at the Fermi energy, as in GMR. When the two layer magnetizations are parallel, tunneling can occur without a spin flip, electrons of spin opposite to the magnetization can tunnel very readily, and the net resistance is greatly decreased. When the layers have opposite magnetization, the polarized part of the current is restricted to the less favorable spin-flip tunneling, and the overall resistance is greatly increased depending on the degree of current polarization.

Just as GMR sensors replaced AMR sensors, the great sensitivity of TMR offers significant advantages in a sensor device, and since 2005 TMR sensors have taken over
as the preferred readback method for hard drives.[49] MTJs are extremely promising as the basis for MRAM devices, and such memories are already being explored commercially.[50] Given the high sensitivity and demonstrated viability of tunnel junction devices, we consider TMR as a potential readback method for data-storing domain wall devices in this thesis.

2.7 Open Questions

While 360DWs have been known in thin films since 1962,[35] the study of 360DWs in patterned films is much more recent. The magnetic physics of transverse 360DWs in stripes has been investigated to some extent, but much remains to be explored. For example, it is known that 360DWs can significantly impact the reversal of unpatterned multilayer films, as previously discussed. However, a thorough study of 360DW magnetostatics in multilayer nanowire systems to examine the details of interlayer interactions and their effects on reversal has yet to be performed. Additionally, it has been observed that 360DWs possess an intrinsic resonance with no analogy in 180DWs;[51] although the behavior has been identified, its effects on the stability and propagation of the 360DWs have not been studied.

Finally, and most critically, the effects of current on 360DWs are entirely unexplored. The complex response of 180DWs to current, including the Walker breakdown effect, have been thoroughly investigated. However, 360DWs possess a distinct topology that is incompatible with the antivortex-core motion of 180DW-type Walker breakdown and which may significantly impact the current response of the 360DW. Since current-driven motion is key to the operation of domain wall devices, and as we will show 360DWs are well-suited to a role in domain wall devices, exploring and understanding the response of 360DWs to DC and AC current is of significant importance for future magnetic devices.
Chapter 3

Experimental and Modeling Methods

In this chapter, we will describe procedures for fabricating samples, methods of measurement and testing, and simulation parameters.

3.1 Fabrication

All samples were fabricated on low-conductivity silicon wafers with 50 Å thermal oxide.

3.1.1 Optical Lithography

Large electrodes for DC measurements were fabricated using optical lithography. For adhesion, an initial layer of hexamethyldisilazane (HMDS) was applied. A few drops of HMDS were spun at 60 RPM to cover the wafer, allowed to dry for one minute, and then spun at 6000 RPM to remove excess. Immediately thereafter, Shipley 1813 photoresist was applied and spun at 6000 RPM with a typical thickness of 1 µm. Wafers were then baked on a hot plate at 90° C for 2 minutes. The resist was
exposed in a Tamarack mercury lamp system for 20 seconds and developed in Shipley 352 developing solution for 60 seconds. Samples were rinsed with deionized water and dried with nitrogen.

3.1.2 Electron Beam Lithography

Samples, waveguides, and portions of electrodes directly contacting samples were patterned using electron beam lithography. Poly(methyl methacrylate) (PMMA) (950k molecular weight) was used as the e-beam resist, spun at 3500 RPM with a typical spun-on thickness of 150 nm. Following spinning, deposited wafers were either baked in a flow oven at 155°C for 45 minutes or on a hot plate at 155°C for two minutes to drive off moisture.

Samples were exposed on a Raith 150 electron beam lithography tool at 10 kV with a 6 mm working distance and a 20 µm aperture. Dosage varied between samples. For rectangular patterning, a simple rastering method was used. For curved shapes (including rhombic rings), concentric vector paths were generated such that the inner and outer edges of the sample were each defined with a single pass along a path defined by the edges. This improved size and shape control and reduced edge roughness.

The exposed resist was developed in a 3:1 (by volume) solution of isopropanol:methyl isobutyl ketone. Depending on the sample and dose, either a 90 or 120 second developing time was used, following which samples were rinsed with isopropanol and dried with nitrogen gas.

3.1.3 Deposition

Large-electrode deposition was performed by staff in the MIT NanoStructures Laboratory using electron beam evaporation. Patterned magnetic samples, nanoscale electrode components, and waveguides were deposited in a single sputtering cham-
ber offering magnetron sputtering, ion beam sputtering, and ion milling. Multilayer samples were deposited without breaking vacuum.

3.1.3.1 Electron Beam Evaporation

Optically patterned electrodes were provided by the NanoStructures Laboratory using an electron beam evaporation system. A 5 nm titanium layer was initially deposited to promote adhesion with the oxidized surface, followed by a 45 nm gold layer forming the bulk of the electrode. Patterning was completed by liftoff for ten minutes in 145 °C 1-methyl-2-pyrrolidinone (NMP) with agitation.

3.1.3.2 DC Magnetron Sputtering

Permalloy, gold, titanium, and tantalum layers in patterned samples, electrodes, and waveguides were deposited using argon plasma sputtering with a DC magnetron to confine the plasma and increase the sputtering rate. A schematic DC magnetron sputtering setup is shown in Fig. 3.1.

The system base pressure typically ranged between $7 \times 10^{-9}$ Torr and $2 \times 10^{-8}$ Torr, but was never higher than $5 \times 10^{-8}$ Torr. Deposition was carried out with an argon pressure of 1 mTorr. Plasma voltage was typically 60V with a current of 2 A. DC magnetron power was fixed at 100W. Targets were presputtered for at least one minute before exposing the sample to the flux.

While direct deposition rate monitoring was not available, the deposition rate of each sputtering gun was calibrating using atomic force microscopy (AFM) on a clean test wafer exposed for a fixed time. Calibrated deposition rates ranged from 1 (Cu) to 9 (Au) Å per second, and deposition times were accurate to within one second. This corresponds to an error range of 2.5% to 5% for typical layer thicknesses.

When adhesion layers were deposited, a few seconds of ion milling were first performed to scrub the surface and remove remaining resist without performing signifi-
3.1.3.3 Ion Beam Sputtering

Cobalt layers in patterned samples were deposited using argon plasma ion beam sputtering. A schematic ion beam sputtering setup is shown in Fig. 3.2. Unlike magnetron sputtering, the plasma is generated remotely and ions are then accelerated from the ionization chamber towards the target. This results in a much lower deposition rate, in this case approximately 0.1 Å per second.

Ion beam sputtering was performed in the same chamber as DC magnetron sputtering, without breaking vacuum. The deposition argon pressure was $4 \times 10^{-5}$ Torr. The beam voltage was set to 100 V, the accelerator voltage to 250 V, and the discharge voltage to 40 V. The beam current was fixed at 35 mA with the cathode current varying as needed.
3.1.4 Liftoff

Liftoff was performed in N-methyl-2-pyrrolidinone (NMP). A small amount of NMP was heated to 135°C and samples were immersed with agitation for five minutes. Depending on the delicacy of the patterned sample, at this point sonication was sometimes performed for eight seconds. Samples were then immersed in fresh NMP for an additional five minutes, and sonication was sometimes performed again. Samples were then rinsed in isopropanol and dried with nitrogen.

3.2 Micromagnetic Simulation

For micromagnetic simulation, the open-source Object Oriented MicroMagnetic Framework (OOMMF) package[12] developed by the National Institute of Standards and
Technology (NIST) was used. This simulation package implements the LLG equation (Eq. 2.7) with uniaxial spin-torque terms (Eq. 2.9). Materials parameters for all materials used are shown in Table 3.1.

A rectangular mesh was used with unit cell sizes symmetric in the x-y plane but potentially different along the z (through-thickness) dimension, in cases where two-dimensional simulation was desired. In all cases, simulation cell sizes were chosen so that the cell length in the xy plane was smaller than the exchange length of any magnetic material present. Specific simulation mesh cell sizes are provided along with each result.

For quasistatic simulations, the Gilbert damping parameter $\alpha$ was set to 0.5. For dynamic simulations in Permalloy, $\alpha = 0.01$. The spin torque nonadiabaticity $\beta$ is treated as a variable parameter, but where not otherwise specified was set to $3\alpha = 0.03$.

Since we expect samples grown under our experimental conditions to be densely polycrystalline, anisotropy was randomly oriented per mesh unit cell. The primary role of anisotropy in these calculations was to provide internal variation that would provide a sort of symmetry-breaking texture. For example, when reversing a magnetic ring as briefly described in section 2.5.2.1, the onion state domain walls are initially in a metastable state; one must depin and propagate along one half of the ring. Anisotropy causes one direction to be favored, discouraging the experimentally unlikely metastable state and ensuring a more physically reasonable reversal field.

### Table 3.1: Materials parameters for micromagnetic simulation. For convenience, both mks and cgs units are provided.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Permalloy</th>
<th>Cobalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation Magnetization $M_s$</td>
<td>$860 \times 10^3$ $\text{A/m}$</td>
<td>$1400 \times 10^3$ $\text{A/m}$</td>
</tr>
<tr>
<td>Uniaxial Anisotropy Constant $K$</td>
<td>$500 \times 10^3$ $\text{erg/cm}^3$</td>
<td>$5.2 \times 10^6$ $\text{erg/cm}^3$</td>
</tr>
<tr>
<td>Exchange Stiffness (with self) $A$</td>
<td>$13 \times 10^{-12}$ $\text{J/m}$</td>
<td>$30 \times 10^{-7}$ $\text{erg/cm}$</td>
</tr>
</tbody>
</table>

*Except where it is explicitly stated that anisotropy was neglected.*
3.2.1 Micromagnetic Giant Magnetoresistance Calculation

When using simulations to calculate GMR, each stack of cells along the z (through-thickness) direction was considered as a single resistor. Following Eq. 2.12, arbitrary values were assigned to $R_∥$ and $R_⊥$ and the angle between the magnetizations of the two magnetic layers in the given cell was calculated. Using this method a resistance map can be calculated, assigning a value to each cell in the simulation.

In the case of simple bar-like nanowire structures, the total effective resistance can be calculated by an appropriate summation of the cells in the resistance map in series and in parallel. While this gives a result in arbitrary units, a self-consistent set of calculations using a particular geometry with varying field can be used to show a qualitatively accuracy description of the reversal behavior.

In the case of rhombic structures, described in section 6, a more complex calculation must be performed. First, the resistance map was rotated such that a given straight segment of the rhombic ring (corners excluded) lies along the x axis. Nearest-neighbor interpolation was used to compute this result. From this point, the resistance of the arm can be calculated by considering a sheet of resistors in series and parallel, as above.

To calculate the resistance across the rhombic ring corners, a method developed by Helmut Körner and modeled after Bogart and Atkinson[52] was used. The cells composing the corner were divided into a series of line-pairs, such that each line-pair met at the same angle as the rhombic shape itself, no cell appeared in more than one line-pair, and at least 99% of cells appeared in a line-pair. Each line-pair was treated as a wire, with the resistances summed in series, and then the set of line-pair resistances were summed in parallel.

With each corner and straight segment mapped to a particular resistance, the sample was treated as a simple circularly-linked chain of resistors. It was assumed that current partitioned evenly into both halves of the rhombic ring, that is, current
partitioning based on the relative states of the two current pathways was neglected. Given the position of current and voltage electrodes, in this way it was possible to compute an effective resistance value for rhombic ring geometries that could be compared directly with experimental measurements.

3.3 Characterization

3.3.1 MFM

Magnetic force microscopy was performed on a Veeco/Digital Instruments atomic force microscope. Commercial low-moment tips were employed to minimize the influence of the tip stray field on the magnetization of the sample, as it has been observed that conventional tips may significantly perturb softer materials such as permalloy. Scan heights were varied between 20 nm and 100 nm.

3.3.2 SEMPA

Direct imaging of 360° and higher-degree domain walls was performed at NIST using scanning electron microscopy with polarization analysis (SEMPA). SEMPA directly detects the spin of secondary electrons emitted from the near-surface region of the sample (~1 nm). In ferromagnets, spin-polarization of these secondary electrons directly represents the magnetization. The SEMPA system applies an electron beam to the surface of the sample, and the secondary electrons generated are captured by two orthogonal low-energy polarization analyzers, allowing the full three-dimensional spin of a given electron to be measured. A magnetization map of the surface is built by rastering the electron beam across the sample. A detailed treatment of this technique is available in a review by Scheinfein et al.[53]

SEMPA measurements were made in ultrahigh vacuum with a base pressure below $3 \times 10^{-8}$ Pa. To ensure the sample itself was being imaged, sample surfaces were
cleaned and lightly etched by 800-1000 eV argon ions to remove the protective gold capping layer as well as oxide and hydrocarbon contamination. Surface composition was continuously monitored with Auger spectroscopy to ensure only the minimal etching was performed. Application of magnetic fields was performed in an adjoining vacuum chamber without breaking vacuum, and then samples were imaged at remanence.

3.3.3 Magnetoresistance Measurements

GMR measurements were performed using two separate systems. In both systems, samples were mounted on a custom circuitboard with static shock protection which connected electrodes via spring pins to BNC-compatible plugs. Both two-point and four-point measurement configurations were used, with narrow gold electrodes routed from optically-patterned outer pads to inner electrodes. A sample electrode layout is shown in Fig. 3.3, and a sample chip layout is shown in Fig. 3.4.

Resistance was measured by applying a 1 kHz, 10 $\mu$A sensing current using a Keithley 6221 current source. This sensing current was detected by a Stanford Research Systems SR830 DSP lock-in amplifier, with readings taken when the phase angle was stable and less than 1°. Instrument outputs were read via a GPIB-connected National Instruments BNC-2090A DAQ system.

Slow, low-noise readings were performed using a Lakeshore ferrite-core magnet backed by a 100 A power supply capable of generating over 5000 Oe. The magnetic field was read by a Lakeshore 450 Hall probe and monitor/controller system. At each designated field point, the magnetic field was matched precisely to the target value by a feedback loop between the magnet power supply and the hall probe output voltage. As a result, measurements were quasistatic; there was no continuous field variation.

Rapid measurements for statistical analysis of reversal behavior were performed using a hand-wound ferrite-core electromagnet backed by a Kepco BOP 20-10M bipo-
Figure 3.3: Electrode configuration for GMR measurements on a rhombic ring. (a), scanning electron micrograph of a sample. (b), schematic electrode configuration.

Lar power supply. The magnetic field was read by the same Hall probe system, but in this case, the magnetization was varied continually via a control current applied by the BNC-2090A. The magnetic field was swept at a target rate of approximately 30 Oe/s and the actual applied field and resistance were simultaneously measured.
Figure 3.4: Example sample measurement chip layout highlighting electrodes. Bottom left: optically patterned contact pads. Top left: Inner contact electrodes patterned by electron beam lithography. Right: scanning electron micrograph showing inner region. Figure from [37].
Chapter 4

Creation of 360° Domain Walls

We first consider methods of generating one or more 360DWs. Often, 360DWs are formed as a result of pinning or magnetostatic attraction of 180DWs; it is for this reason that 360DWs form readily in magnetic rings as discussed in section 2.5.2.1. Accordingly, we first discuss coupling of 180DWs in wire systems. Second, we discuss one method of deliberately forming domain walls, using specifically-designed injection systems. An additional method of creation is discussed in chapter 6, in which we consider the complex multilayer rhombic ring system, which readily forms 360DWs due to corner pinning and rich interlayer magnetostatic interactions.

4.1 Formation in Nanowires

Simulation of an infinite nanowire allows a very straightforward study of 360DW formation. When multiple 180DWs are present in a wire, we expect them to attract or repel based on the relative orientations of the domain wall cores, that is, on the domain wall chiralities. We note that 180DWs emit a stray magnetic field that is the sum of a dipolar and a monopolar field, as shown in Fig. 4.1. If the domain wall cores are parallel (same chirality), the stray field from each domain wall repels the other: the domain walls behave like parallel dipoles and separate. When the domain wall
cores are antiparallel (opposite chirality), the stray field from each 180DW attracts the other and a 360DW is formed. In a perfect wire, the absence of pinning sites allows 180DWs to couple into 360DWs from any distance or repel to arbitrarily large separation. In a single-layer permalloy wire with 200 nm x 5 nm cross section and with very rough edges, 180DWs spontaneously coupled from and repelled to a distance between 500 and 600 nm, at which point the rough edge provided sufficient pinning strength to halt motion. This is a key result for domain wall devices: this large interaction distance limits the packing of 180DWs and indicates that in 180DW-based devices, spontaneous 360DW formation will almost certainly occur. We will show shortly that after coupling into 360DWs the stray field is much reduced and the packing density can be improved.

The equilibrium structure of the 360DW depends upon the balance between exchange and demagnetization energies. As the wire width increases at fixed thickness, the total exchange energy increases while the dipolar energy decreases. As a result, the equilibrium 360DW width has a strong geometry dependence. We demonstrate
Figure 4.2: Variation of 360° domain wall width at equilibrium. The equilibrium separation is defined as the distance between the constituent 180° domain wall cores. This measure is smaller than the true 360DW width by exactly one 180DW width under any chosen metric for the width of 180DWs.

this with simulations of a 4 nm thick permalloy nanowire discretized into 4 nm x 4 nm x 4 nm unit cells. Anisotropy was neglected. The 180DW equilibrium separation was defined as the x-axis distance between the points representing the minimum and maximum y-axis magnetizations. Results are shown in Fig. 4.2.

4.2 Formation in Injection Systems

This chapter covers work done in collaboration with the National Institute of Standards and Technology. Devices described herein were designed by Youngman Jang, who also performed MFM characterization and performed initial simulations. SEMPA analysis was performed by Sam Bowden. Additional simulations and simulation anal-

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1Sections of this chapter, including some figures and subfigures, have been previously published in Appl. Phys. Lett. 100 062407 (2012) available at http://link.aip.org/link/?apl/100/062407. Reprinted with permission from Applied Physics Letters 100 062407 (2012). Copyright 2012, American Institute of Physics.[54]
ysis, including stray field analysis, was performed by the author.

As 360DWs are formed from coupled 180DWs, we expect that it should be possible to experimentally demonstrate controlled 360DW formation in a system in which 180DWs of controlled chirality can be injected. Such a structure is described here. A circular pad is attached asymmetrically to a gently curved wire, in contrast to the symmetrical structures used by Diegel et al.[55] and Kunz et al.[56] This is shown in Fig. 4.3. The circular pad was 1.2 µm in diameter and the wire was 250 nm wide, with layer thicknesses Ti(5 nm)/Co(6 nm)/Au(5 nm).

The asymmetrical structure allowed control of the chirality of 180DWs formed by cycling of a uniaxial (bidirectional) field directed perpendicular to the wire axis. This is in contrast to the biaxial field employed by Kunz[56] and the rotating field employed by Diegel[55], providing an injection system which is simpler to implement experimentally.

4.2.1 Micromagnetic Simulation

To verify the formation of 360DWs in the structure, micromagnetic simulations were performed for a Co nanostructure with a smaller linewidth, comprising a circular pad of 1.2 µm diameter connected to a curved wire of 120 nm width and 2 µm length. The model used rectangular unit cells of 2 nm × 2 nm × 4 nm and standard material parameters of Co: 1400 \( \text{emu/cm}^3 \) for saturation magnetization, 0.01 for the Gilbert damping parameter, and 3.0 × 10^{-6} erg/cm for exchange stiffness. After saturation with an in plane y-direction magnetic field \( (H_y) \) of 3000 Oe, a head-to-head transverse 180DW was formed in the wire at remanence, shown in Fig. 4.4(a). To inject a second transverse 180DW, \( H_y \) was increased from 0 Oe to -119.4 Oe in 24 steps of 1 ns duration. Injection of the second 180DW occurred at \( H_y = -50 \) Oe and the two 180DWs combined into a 360 DW (Fig. 4.4(c)), but the field was then increased to -119.4 Oe in order to eliminate the vortex from the injection pad, which was necessary.
before additional 180DWs could be injected on subsequent cycles. The 360DW was stable at 119.4 Oe. This process could therefore be used to stack several 180DWs into the wire by alternating $H_y$ between $\pm 119.4$ Oe (Fig 4.4(d)).

### 4.2.2 Experimental Results

To demonstrate the formation of 360DWs in an experimental system, a sample was saturated at $H_y = 3000$ Oe, returned to remanence to form a 180DW, and then $H_y$
Figure 4.4: OOMMF model of formation of 360DW in a wire attached to a circular pad. (a) After 239 kA/m saturation along y, a 180° wall formed in the wire, shown at remanence. (b) A further field of -4.0 kA/m along y produced a second 180DW. (c) the remanent state showing a 360DW. (d) repeated alternating field of magnitude 9.5 kA/m along y generated multiple domain walls. Red and blue represent the sign of the x-component of the magnetization.

-200 Oe was applied to inject a second 180DW. Fig. 4.5(a) shows an MFM image at 20 nm tip height of the remanent 360DW, indicated by the dark-light contrast. A SEMPA image of the same sample is shown in Fig. 4.5(b). This is a direct image of the surface magnetization of the sample, which displays a continuous rotation of the magnetization angle on traversing the wall. Fig. 4.5(c) plots the angle of the magnetization as a function of distance across the wire, showing that the DW has ‘tails’ extending along the wire similar to the tails of a 180DW. The equilibrium width of the 360DW (estimated as the distance within which the magnetization angle changes by 80% of 360°, i.e. from -144° to +144°), was ≈350 nm. Note that this is a different rule than was used for the calculation in Fig. 4.2, which is calculated
based on 50% of a full rotation and gives a smaller result. The equilibrium width is determined by a balance between the magnetostatic interaction between the two component 180DWs which pulls the 180DWs together, and the exchange energy at the center of the 360DW which pushes them apart.

4.2.3 MFM Contrast

The origin of the MFM contrast can be understood by modeling the stray field of the 360DW. A micromagnetic simulation of the 360DW is shown in Fig. 4.6(a) based on a wire shape modeled using a mask created from two rectangles joined with a 20° angle to approximate the curve in the wire, digitized into 2 nm x 2 nm x 6 nm thick Co cells. Fig. 4.6(b) shows the in-plane magnitude \((H_x^2 + H_y^2)^{0.5}\) of the stray field of the 360DW calculated at a height of 3 nm above the surface of the Co film, and Fig. 4.6(c) shows the out-of-plane component \(H_z\). The 360DW produced a field similar to that of a superposed dipole and quadrupole. The stray field was substantial in the vicinity of the wire but decayed rapidly away from the wire. The MFM contrast is sensitive to the \(H_z\) component at the scan height, and produced a dark-light contrast which is asymmetrical with respect to the axis of the wire.[8] The magnetization angle vs. distance along the wire is shown in Fig. 4.5(c) and agrees well with the experimental data.

4.2.4 Alternate and Higher-Degree Structures

In contrast to the 360DW of Fig 4.5(b), whose structure agrees well with that of the micromagnetic simulation in Fig. 4.6(a), we also observed a wider structure shown in Fig. 4.5(d) in a different sample. The MFM image of this sample, measured at a scan height of 100 nm, is shown as the inset of Fig. 4.5(a). The two component 180DWs are separated from each other, presumably as a result of pinning in the wire, and this structure does not represent an equilibrium 360DW. Unlike the equilibrium 360DW,
Figure 4.5: (a) MFM data of a 360DW imaged at a tip height of 20 nm. The 360DW shows as two contiguous bright and dark contrast regions and the shape of the wire and injection pad are evident. The inset shows part of the wire segment of another sample imaged at a height of 100 nm in which two spatially separated 180DWs are present, indicated by arrows, one with bright contrast and one with dark contrast, but they do not form a 360DW. The contrast is weaker but a larger separation between the dark and light contrast is evident. (b) SEMPA image of the sample of (a) with the in-plane magnetization direction indicated on a color wheel. (c) The angle between the magnetization and the axis of the wire, measured along the dashed line shown in (b) (green), and calculated from the micromagnetic simulation of Fig. 4.6(a) (blue). (d) SEMPA image of the sample in the inset of (a), showing a pair of separated 180DWs. The uncertainty in the magnetization direction for the SEMPA data is $17.1^\circ$ (one standard deviation).
Figure 4.6: (a) OOMMF simulation of a 360DW in a wire with 120 nm linewidth. The magnetization directions are plotted on a color wheel. (b) In-plane stray field magnitude calculated at a height of 3 nm above the surface of the sample. The white arrows represent the in-plane direction of the field at its greatest magnitude. (c) Calculated z-component of the stray field at a height of 3 nm above the surface of the sample. Red and blue represent up and down directions.
the structure of Fig. 4.5(d) was destroyed during MFM scanning at a tip height of 90 nm, presumably because the tip field displaced the 180DWs and facilitated their recombination.

The injection pad/wire structure could also be used to demonstrate the formation and stability of more complex DWs, as predicted in Fig. 4.4(d). A 540DW was formed by applying field steps in the SEMPA vacuum chamber before imaging. \( H_y = 1684 \text{ Oe} \) was used to create the initial 180DW and subsequent 180DWs of opposing chirality were injected by applying fields of \( |H_y| = 178 \text{ Oe} \) in alternating directions. A SEMPA image of a stable 540DW is shown in Fig. 4.7(a). In this case the applied field values were +1684 Oe, -178 Oe, +178 Oe, and -178 Oe (this field sequence could have feasibly nucleated a 720DW). MFM imaging of the same sample cycled in a similar manner showed only a 180DW, suggesting that the field from the MFM tip destabilized the 540DW and led to a collapse into a simpler structure.

Fig. 4.7(b) is a SEMPA image of the sample of Fig. 4.7(a) after injection of a fourth 180DW. The additional wall is of the correct chirality to form a 720DW, but it was pinned before reaching the 540DW. The sample was then reset at \( H_x = -1000 \text{ Oe} \) and cycled to introduce three 180DWs which formed another 540DW of opposite rotation sense to the first one, shown in Fig. 4.7(c). The additional 180DW on the right of Fig. 4.7(c) is believed to be the remains of the original 540DW which was not completely eliminated at -1000 Oe. Simulations of a 540DW show that it can persist until at least \( H_x = 2010 \text{ Oe} \). These results demonstrate the possibility of creating DWs of \( n\pi \) rotation (where \( n \) is an integer) in Co nanowires.

### 4.3 Summary

In nanowires, transverse 180DWs of opposite sense couple over long range by stray field interaction to form 360DWs. Once formed, 360DWs do not interact by stray field
Figure 4.7: (a) SEMPA image of a 540DW. (b) SEMPA image after injecting an additional 180DW. (c) A 540DW of opposite sense to that of (a) adjacent to a 180DW. Magnetization directions are indicated on a color wheel. The uncertainty in the SEMPA angular data is 7.4° (one standard deviation). Scale bars are 250 nm.

unless otherwise driven to a separation of approximately the 360DW width, allowing a 720DW to form. However, a free 180DW may interact with a 360DW to form a 540DW.

Formation of 360° and 540° domain walls has been demonstrated experimentally using a circular injection pad connected to a curved wire. These domain walls were analyzed with MFM and SEMPA, showing excellent qualitative agreement with micromagnetic simulation of 360DW structure and stray field distribution. We have experimentally demonstrated that 360DWs have a well-defined size, persist over a wide
field range, and are distinguishable from two closely-spaced (but separately pinned) 180DWs.
Chapter 5

Magnetostatics Physics of 360° Domain Walls in Multilayer Nanowires\textsuperscript{1}

An understanding of magnetostatic behaviors in simple, controlled systems is critical in understanding the behavior of more complex multilayer systems, as discussed in section 6. In this chapter, we will show that 360DWs have a profound impact on the reversal of multilayer systems due to strong interlayer interactions between 360DWs, which do not move under an applied field, and propagating 180DWs in adjacent layers. In examining a pseudo-spin-valve multilayer bar, we will show that the stray field of a 360DW in the hard layer can have two major effects on the soft layer: strong pinning of propagating domain walls and low- or zero-field nucleation of reverse domains. Additionally, we will demonstrate that a variety of interlayer interactions are possible depending on the relative orientations of the 360DW and 180DW, which give rise to different reversal pathways and distinct switching fields.

\textsuperscript{1}Sections of this chapter, including figures, have been previously published in Appl. Phys. Lett. 96 162501 (2010) available at http://link.aip.org/link/?apl/96/162501. Reprinted with permission from Applied Physics Letters 96 162501 (2010). Copyright 2010, American Institute of Physics.\textsuperscript{[57]}

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We examine here simulations of a magnetic nanowire 2050 nm in length and 200 nm in width, of layer composition Co(5 nm)/Cu(5 nm)/NiFe(5 nm), with no edge roughness. The unit cell was 2x2x5 nm and simulations were performed quasistatically ($\alpha = 0.5$), with equilibrium at each field step defined as no unit cell magnetization rotating faster than 0.12 degrees per ns. The five unit cells at each extremum of the bar were fixed, and a magnetic field applies along the wire was varied in 1 Oe steps up to 500 Oe.

We consider the cases in which a 180DW propagating in the NiFe layer, driven by a magnetic field, approaches a 360DW in the Co layer. The 360DW in the Co layer can be described as two closely-spaced 180DWs of opposite orientation, which we will label as right (or R) and left (or L) (Fig. 5.1(a)). This allows for four distinct interaction cases: the magnetizations of the cores of the NiFe 180DW and the right side of the Co 360DW may be oriented parallel or antiparallel, and the magnetizations of the Co and NiFe layers may be initially oriented parallel or antiparallel. These cases are summarized in table 5.1, and discussed in detail later. For each of the cases in which the Co and NiFe magnetizations are initially antiparallel, we will furthermore show that two different reversal paths are possible.

For a single NiFe layer, a 180DW propagates at a field below 1 Oe, as expected in a geometrically perfect wire. For a single Co layer, a field parallel to the Co magnetization direction compresses the 360DW and annihilates it at approximately

<table>
<thead>
<tr>
<th>Case#</th>
<th>1</th>
<th>2</th>
<th>3a</th>
<th>3b</th>
<th>4a</th>
<th>4b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co and NiFe magnetization initially</td>
<td>P</td>
<td>P</td>
<td>AP</td>
<td>AP</td>
<td>AP</td>
<td>AP</td>
</tr>
<tr>
<td>Orientation of NiFe 180DW core vs. Co 360DW near edge</td>
<td>P</td>
<td>AP</td>
<td>P</td>
<td>P</td>
<td>AP</td>
<td>AP</td>
</tr>
<tr>
<td>Orientation of NiFe 180DW core vs. reverse-domain-bounding DW</td>
<td>-</td>
<td>-</td>
<td>AP</td>
<td>P</td>
<td>AP</td>
<td>P</td>
</tr>
<tr>
<td>Field to reverse NiFe layer (Oe)</td>
<td>168</td>
<td>153</td>
<td>128</td>
<td>122</td>
<td>146</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 5.1: The four cases of 180°-360° domain wall interaction in a magnetic multilayer stripe. P indicates parallel orientation, AP, antiparallel orientation.
1700-1800 Oe, whereas an antiparallel field dissociates the 360DW into its two component 180DWs, which move apart, reversing the Co layer at about 40 Oe.

5.1 The Four Possible Interlayer 360DW-180DW Interactions

We first discuss case 1 in which the NiFe and Co layers are initially magnetized parallel to each other, and the core of the approaching NiFe 180DW is oriented parallel to the core of the right side of the Co 360DW, along +y. Fig. 5.1 shows a series of equilibrium states at different applied fields. Even at remanence, there is a significant distortion in the NiFe magnetization directly above the Co 360DW, as seen clearly in Fig.5.1(a), resulting from the stray field of the 360DW, which can exceed 1000 Oe near the top surface of the NiFe. The stray field calculated 5 nm above the NiFe layer, evaluated along the lower edge of the bar (y = 0), is shown in Fig. 5.2.

When a field is applied, the NiFe 180DW initially starts to propagate at a field of a few Oe but its movement is impeded when it reaches a position above the Co 360DW (Fig. 5.1(b)). Completion of the NiFe reversal does not occur until a considerably higher field is applied. The 360DW dissociates at a field of 51 Oe (Fig. 5.1(c)), forming a reverse domain in the Co. The reversal of the NiFe is completed at ∼168 Oe by the formation and expansion of a reverse domain in the NiFe directly above the R 180DW in the Co. A residual 360DW remains in the NiFe layer with the same chirality as the original 360DW in the Co (Fig. 5.1(d)). The NiFe 360DW is dragged along the +x direction by the propagating R 180DW in the Co (Fig. 5.1(e)). Reversal at the left of the stripe does not complete because of the boundary condition at the left hand edge. It is evident that the 180DW that propagates in the NiFe layer has an opposite core magnetization (Fig. 5.1(e)) compared to the initial 180DW (Fig. 5.1(a)).
Figure 5.1: Reversal of a multilayer bar with a 360DW in the hard layer and a 180DW in the soft layer. In the model, the NiFe layer is located above the Co layer, separated by 4 nm Cu, but in the figure the layers are separated for clarity. The figure illustrates Case 1 in which the core of the 180DW and of the right side of the 360DW are parallel, indicated by arrows in (a). Equilibrium configurations at (a) 1 Oe, (b) 11 Oe, (c) 51 Oe, the 360DW dissociates, (d) 159 Oe, a 360DW remains in the NiFe, (e), the 360DW in the NiFe is translated by the right 180DW in the Co. The L 180DW in the Co does not exit the stripe due to the boundary conditions at the end of the stripe.

Repeated simulations lead to a broadly similar reversal process that differs in detail because the Co magnetocrystalline anisotropy is reset randomly each time the simulation is initiated. In one example (not shown), the NiFe reversal completed by propagation of the NiFe 180DW over the R 180DW in the Co without leaving a residual 360DW in the NiFe. Despite these differences, in all the simulations, a 360DW in the Co layer prevents reversal of the NiFe layer until the applied field is
Figure 5.2: Stray field magnitude calculated 5 nm above the surface of the NiFe film, measured along the lower edge (y=0) of the bar. The heavy dashed line indicates the magnitude of the field component in the plane of the bar; light dashed line, the component normal to the plane of the bar.

over 150 Oe, well above the field required to dissociate the 360DW, and considerably higher than the <1 Oe field needed to propagate a NiFe 180DW in the absence of the Co 360DW.

In case 2, when the core of the approaching NiFe 180DW is oriented antiparallel to that of the R side of the Co 360DW, the 360DW provides an attractive potential. The NiFe 180DW moves at fields as low as 1 Oe to a position directly above R (Fig 5.3). At 68 Oe the 360DW dissociates and L moves to the left, forming a reverse domain in the Co. The NiFe 180DW and the R side of the Co 360DW separate at the upper edge of the stripe at 99 Oe, then at the lower edge of the stripe at 153 Oe, allowing the reversal of both layers to complete. Again, this occurs well above the field at which the Co 360DW dissociates.

Cases 3 and 4 are analogous to cases 1 and 2, respectively, except that the Co and NiFe layers are initially oriented antiparallel to each other. In both cases, at remanence, the stray field from the Co 360DW nucleates a small reverse domain in
Figure 5.3: Reversal of a multilayer stripe with a 360DW in the hard layer and a 180DW in the soft layer, antiparallel to the near edge of the 360DW. This corresponds to case 2 in which the core of the 180DW and of the R side of the 360DW are antiparallel, indicated by arrows in (a). Equilibrium configurations at (a) 1 Oe, the 180DW has already moved to a position above the R side of the Co 360DW, (b) 68 Oe, the 360DW expands to form a reverse domain in the Co, (c) 99 Oe, the NiFe 180DW and R separate at the top edge of the stripe, (d) 150 Oe, extension of the 180DW, (e) 153 Oe, separation of the NiFe 180DW and R, and completion of the NiFe reversal. The walls do not exit the stripe due to the boundary conditions at the end of the stripe.

The NiFe directly above it, seen in Fig. 5.4(a). This can be understood as a result of the dipolar stray field from the Co 360DW, which destabilizes the magnetization in the NiFe directly above it, and in the geometry studied here, is sufficient to promote the formation of a reverse domain in the NiFe. The reverse domain appears to form stochastically on either side of the NiFe stripe, and the core of the DW that bounds it can be oriented in one of two directions, i.e. along +y or -y.

In case 4, the core of the NiFe 180DW is oriented antiparallel to the core of the R side of the Co 360DW. The reversal process is shown in Fig. 5.4. In Fig. 5.4(a,b,c),
the core of the propagating 180DW in the NiFe is antiparallel to the core of the DW bounding the reverse domain, which is indicated by a ‘U’-shaped arrow in Fig. 5.4(a). The 180DW propagates until it reaches the reverse domain, as shown in Fig. 5.4(b). At higher fields, the reverse domain expands to span the bar to form two parallel 180DWs; the left-hand one propagates to the left, completing the reversal of the NiFe layer at 146 Oe applied field, leaving a 360DW in the NiFe layer. The orientation of the core of the NiFe 180DW is reversed during this process, from -y in Fig. 5.4(a) to +y in Fig. 5.4(c). Unlike cases 1 and 2, the applied field compresses the Co 360DW, which is not eliminated until the field reaches >1700 Oe.

Fig. 5.4(d,e,f) shows a different reversal path when the core of the propagating 180DW in the NiFe is parallel to the core of the DW bounding the reverse domain. Here the 180DW combines with the reverse domain at 39 Oe, forming a single 180DW which is pinned above the Co 360DW (Fig. 5.4(e)). A field of 71 Oe unpins the 180DW (Fig. 5.4(f)) and the NiFe reversal is complete at 72 Oe. It is significant that the field required to reverse the NiFe layer differs by a factor of two depending on the configuration of the reverse domain that forms above the Co 360DW.

We now come to case 3, in which the Co and NiFe layers are initially antiparallel and the core of the NiFe 180DW is oriented parallel to the R side of the Co 360DW. As in case 4, two reversal processes were observed depending on the detailed configuration of the NiFe reverse domain (not shown). When the cores of the 180DW and the DW bounding the reverse domain are parallel, the field required to fully switch the NiFe was 122 Oe, which is higher than that of the corresponding path in case 4 (72 Oe). This occurs because in case 3, the 180DW in the NiFe is oriented antiparallel to L, and is therefore pinned more strongly over the L side of the Co 360DW. In contrast, when the cores of the 180DW and the DW bounding the reverse domain are antiparallel, the switching field was 128 Oe in case 3 compared to 142 Oe in case 4, i.e. case 3 shows a lower switching field. This is different from the previous result because the
Figure 5.4: Effect of field on a multilayer stripe with a 360DW in the Co layer and a 180DW in the NiFe layer, in which the Co and NiFe are initially magnetized antiparallel, corresponding to case 4. (a-c) In one reversal path, a reverse domain forms in the NiFe bounded by a DW in which the magnetization of the core is oriented along +y, antiparallel to the core magnetization in the NiFe 180DW. (a) at 1 Oe, (b) at 46 Oe, the NiFe 180DW moves adjacent to the reverse domain, (c) at 146 Oe the reverse domain expands, completing reversal of the NiFe but leaving a residual 360DW. (d-f) In another reversal path, a reverse domain forms in the NiFe bounded by a DW in which the magnetization of the core is oriented along -y, parallel to the core magnetization in the NiFe 180DW. (d) at 1 Oe, (e) at 39 Oe, the propagating 180DW combines with the reverse domain, leaving a 180DW in the NiFe that is pinned by the stray field of the underlying Co 360DW. (f) at 71 Oe, the 180DW depins, and reversal completes at 72 Oe.
orientation of the propagating wall, and therefore its interaction with L, was reversed as it moved past the 360DW.

5.2 Summary

A system consisting of a spin-valve stripe with a 360DW in the hard layer and a 180DW in the soft layer shows a rich reversal behavior. Four possible cases can be distinguished based on whether the hard and soft layers are initially magnetized parallel or antiparallel, and on the relationship between the magnetization directions at the centers of the walls. The fields required to propagate the 180DW along the NiFe are summarized in Table 5.1.

These results are caused fundamentally by the strong magnetostatic interaction between the Co 360DW and the NiFe. The stray field is sufficient to distort the magnetization in the NiFe layer, and even to nucleate a reverse domain if the Co and NiFe layers are initially magnetized antiparallel. When a NiFe 180DW approaches the site of the Co 360DW, it is either attracted or repelled based on the orientation of its core with respect to that of the nearer side of the 360DW, and it also interacts with the magnetization distortion or reverse domain formed in the NiFe directly above the Co 360DW. In some cases, reversal of the NiFe layer leaves a residual 360DW in the NiFe layer, which affects the response to subsequent field cycling. The orientation of the core of the propagating 180DW may also be reversed. The reversal process is determined by the initial DW configurations, though stochastic formation of a reverse domain can be important. While the results presented here are specific to the simulated geometry, it is expected that magnetostatic interactions will play a similarly important role in other patterned multilayer systems.

These results have implications in the operation of domain-wall devices. For example, a 360DW may be used as a programmable pinning site which can control the
reversal of a soft layer. DW pinning is commonly accomplished using geometrical features in a bar, such as notches [58, 59, 60], but these are permanent features. In contrast, a 360DW can be created by concatenation of 180DWs, for example in a ring-shaped stripe[8], and destroyed using a field or an applied current (section 7.2.1), enabling it to be used to ‘gate’ the response of a soft layer. In addition, if a 360DW were used as a token for data processing or storage, the presence of the 360DW and even its chirality could be detected by measuring the response of a 180DW of known orientation in an adjacent soft layer.
Chapter 6

Rich Behavior of 360° Domain Walls: the Rhombic Ring System

As described in section 2.5.2.1, 360DWs form readily in rhombic ring structures due to the presence of sharp corners and buckling reversal modes. In chapter 5 we demonstrated in simulation that 360DWs have a profound effect on the reversal behavior of multilayers. In this chapter, we show that in the multilayer rhombic ring system these two effects give rise to a rich behavior with many reversal pathways which is dominated by the influence of 360DWs. We first use micromagnetic simulation to explore the reversal pathways of single layer and multilayer rings. By comparing GMR calculated from simulation with experimental GMR measurements, we demonstrate a qualitative match between simulation and experiment. This allows us to use simulation to break down the complex reversal behavior into several types of events, which can be understood in terms of previously discussed 360DW behavior, and identify occurrences of these events in the experimental data. Finally, we discuss the statistical prevalence of different reversal pathways in the experimental data as a function of

\footnote{Sections of this chapter, including sections of some figures, have been previously published in Appl. Phys. Lett. 98 252506 (2011) available at http://link.aip.org/link/?apl/98/252506 and are copyright 2011 the American Institute of Physics. Reprinted with permission from Applied Physics Letters 98 252506 (2011). Copyright 2011, American Institute of Physics.}
field history.

Rhombic rings 2 $\mu$m x 1 $\mu$m in length and 200 nm in linewidth were examined in simulation and experiment. In single-layer rings, the magnetic layer thickness was 4 nm; in multilayer rings, the nominal layer thicknesses were NiFe(6 nm)/Cu(4 nm)/Co(5 nm)/Au(5 nm). The top Au layer was included to ensure good electrical contact of the overlaid electrodes. Three such samples were fabricated, designated A, B, and C; an example device is shown in Fig. 3.3. Samples were initialized at $\pm$ 800 Oe, and cycled up to a maximum field of $\pm$100 to $\pm$500 Oe Sample A was measured with the the most extensive set of field extrema ($\pm$100, 150, 200, 300, 350, 400, 500 Oe), while other samples were measured at $\pm$300, $\pm$350, and $\pm$400 Oe. Each experiment comprised 2500 loops, or 5000 reversals. Additionally, high-field behavior was measured in the range of $\pm$5000 Oe; statistical experiments were not performed in this case.

6.1 Reversal of Elliptical Rings

We will first briefly review the well-studied behavior of elliptical rings in order to highlight the features of the rhombic ring system that are distinct from smoothly-curved rings. In single-layer elliptical rings, reversal proceeds analogously to the mechanism described for circular rings in section 2.5.2.1. From the initial onion state, the two domain walls are displaced and propagate around the ring. Depending on how they approach, the twisted state containing a 360DW may be formed, or the domain walls may annihilate, leaving the vortex state. If the twisted state is formed, at higher fields, the 360DW is annihilated, leaving the vortex state. From the vortex state, a reverse domain is nucleated and the two 180DWs bounding the reverse domain propagate to the end of the ring, leaving the reverse onion state. This process is shown in Fig. 6.1.
The asymmetry of the elliptical ring has an impact on the process: when the field is applied along the long axis, generation of a twisted state (and thus a 360DW) is less likely and the vortex state is stable over a narrower field range, but when the field is applied perpendicular to the long axis, the twisted state is observed more frequently and the stability of the vortex state is reduced.\cite{62} The rhombic rings examined in this chapter were only subjected to fields oriented along the long axis of the ring.

Multilayer elliptical rings present a more complex behavior. Here we consider simulation of a PSV structure 600 nm long, with a 3:2 aspect ratio, 50 nm linewidth, and layer composition Co(4 nm)/Cu(4 nm)/NiFe(4 nm).\cite{37} Soft layer walls are initially displaced from the ring ends due to the stray field from the hard layer domain walls. The stray field from the hard layer then nucleates additional domain walls in the soft layer, which always generates a twisted state. The hard layer then assumes an intermediate state containing between two and four 360DWs, which may persist even into the reverse onion state.

### 6.2 Reversal of Rhombic Rings

Rhombic rings differ from elliptical rings in that (a) they very readily form multiple 360DWs on reversal even in single-layer systems and (b) Co rhombic rings reverse by buckling, rather than pure DW depinning and propagation. These 360DW structures are stable to at least 1400 Oe in NiFe and at least 2300 Oe in Co. We consider first single-layer rings of both permalloy and cobalt.

#### 6.2.1 Single-Layer Rings

Simulated reversal of a single-layer NiFe rhombic ring is shown in Fig. 6.2(a-d). Two 360DWs were formed in the device, which reverses by both DW nucleation and displacement of the original onion state DWs. Since the OOMMF model does not
Figure 6.1: Left column: simulated magnetization distributions in a Co elliptical-ring structure with long axis of 930 nm, short axis of 620 nm, and width of 110 nm. The five images (A-E) correspond to fields 0 Oe, 650 Oe, 700 Oe, 750 Oe, and 850 Oe, respectively. Right column: schematic representation of the different magnetic states. Reprinted with permission from “Magnetization reversal in elliptical ring nanomagnets,” Journal of Physics D 36, 2031 (2003) (http://dx.doi.org/10.1088/0022-3727/36/17/301). Reproduced by permission of the AAS.[62]
Figure 6.2: (a-d), reversal of a NiFe single-layer rhombic ring. (a), remanence. (b), state just prior to reversal onset. (c), formation of two 360DWs. Based on the DW orientations, the onion-state DWs both depinned in the downward direction; the top 360DW therefore formed by nucleation of additional DWs. (d), first 360DW is eliminated. Note the compression of the remaining 360DW. (e-j), reversal of a Co single-layer rhombic ring. (e), remanence. (f), onset of buckling. (g), formation of first reverse domain, pinned by corners. (h), formation of additional reverse domains. (i), completed reversal including four 360DWs. (j), elimination of one 360DW.

include thermal effects and the anisotropy is set to zero, this was the only reversal mode observed in simulation. However, since we know the direction of domain wall breakaway from corners is in principle stochastic, we also expect a reversal mode that forms zero 360DWs.

Simulated reversal of a single-layer Co rhombic ring is shown in Fig. 6.2(e-j). Four 360DWs were formed in the device, which reverses primarily by DW nucleation in a buckling method. Simulations with randomized anisotropy indicate the buckling method favors formation of a large even number of 360DWs, with formation of four being the most common (5 of 9 simulations), followed by two (1 of 9), and zero (1 of 9). While no odd 360DWs counts were observed, the nucleation patterns observed in
the simulations do not rule out the formation of an odd number of 360DWs.

6.2.2 Multilayer Rings

Reversal of the multilayer structure from saturation is shown in Fig. 6.3. Although no 360DWs structures are present at saturation, two form during reversal of the soft layer due to coupling of domain walls during reversal of the pseudo-onion state. One of these provides a pinning site that influences hard layer reversal, resulting in the formation of four 360DWs in the hard layer.

Reversal of the GMR structure from an initial state containing 360DWS is shown in Fig. 6.4. In this case, the soft layer contains one and the soft layer four 360DWs. A complex interaction with formation of mirror domains results in a completely different reversal behavior, giving two 360DWs in the hard layer and three in the soft layer.

From these two rhombic ring results, we can calculate the GMR behavior of these multilayer devices and compare with experimental data, which in turn will allow us to analyze the more complex reversal behaviors. We observe two qualitatively distinct reversal patterns shown in Fig. 6.5(a,b). In the first pattern, designated block-type reversal, a single, broadly stable peak is observed. In the second, designated step-type reversal, an asymmetric GMR trace is observed with an initial high-resistance plateau and an additional intermediate plateau stable over a significant field range. Experimental GMR measurements support this general picture of reversal, as shown in Fig. 6.5(c,d).

In experimental traces showing block-type reversal, the resistance rises to the maximum value over a relatively narrow field range, below 30 Oe. While initial switching is gradual, distinct steps are not generally observed. At a higher field, around 110 Oe in experiments, reversal completes almost instantaneously and the resistance returns to the baseline value.

In experimental traces showing step-type reversal, the initial switching is similar,
reaching maximum resistance in a narrow field range below 35 Oe. Around 55 Oe the resistance decreases sharply to an intermediate plateau. This plateau is stable for typically tens of Oe, and then hard layer reversal completes abruptly at a variable higher field around 90 Oe, significantly lower than the 110 Oe block-type reversal field.

We observe these two types of reversal due to the presence of geometric pinning sites in the rhombic ring. Pinning of onion-state domain walls allows the buckling-
Figure 6.4: Reversal of a NiFe/Cu/Co multilayer rhombic ring from an unsaturated state containing 360DWs. Positive field is directed to the right. The left column shows the hard layer and the right the soft layer. (a) Initial state containing four 360DWs in the hard layer and one in the soft layer. (b) In the top left branch of the hard layer, the closest edges of the two 360DWs have the same sense. When increasing field allows the 360DWs to expand, the entire structure is annihilated. (c) Mirror domain structures form in the soft layer at remanence. The soft layer also begins reversal by reverse domain nucleation at the leftmost extremum due to the hard layer stray field. (d) Reversal of the hard layer. Formation of a complex mirror domain structure has resulted in a soft layer configuration with many 360DWs. The hard layer is beginning to buckle. (e) Hard layer reversal continues by buckling. A pair of parallel 180DWs in the soft layer annihilate. (f) Total hard layer reversal, eliminating adjacent parallel 180DW structures. At a slightly higher field, the two 360DWs in the lower right arm of the hard layer annihilate due to parallel near edges. The result is two 360DWs in the hard layer and three in the soft layer.

type reversal mode, in which reverse domains are nucleated in the ring arms, and the additional 180DWs may go on to form 360DWs. 360DWs act as interlayer pinning sites, significantly influence reversal behavior, and persist to significant applied fields, larger than were applied in the majority of experiments. Block-type reversal is observed when there are few leftover 360DWs in the hard layer, and the soft layer undergoes complete reversal, followed by the hard layer. Narrow steps or gradual
Figure 6.5: The two general reversal modes of the rhombic ring system shown in simulation (a,b) and experiment (c,d). The reversal is from negative to positive field. (a) and (c) show block-type reversal; (b) and (d) show step-type reversal with a pronounced intermediate state.

Switching may be observed during the two major switching events due to short-lived pinning at corners, but otherwise, this behavior qualitatively resembles elliptical ring reversal. Step-type reversal is observed when many 360DWs are present before cycling. Reversal is initiated at an abnormally low field by 360DW dissociation in a manner that will be discussed later, and domain wall propagation is then blocked by corners and interlayer 360DW interactions. This halts reversal until a significantly higher field is applied, creating a broadly stable intermediate resistance plateau. The layers do not necessarily reverse separately; in fact, the maximum resistance state can be a complex state with multiple mirror domains, in which the magnetization is antiparallel almost everywhere but neither layer is reversed.

Even within these two patterns, reversals show significant variability in initial and ultimate switching fields and in the presence, stable field ranges, and number of additional steps. Without the ability to directly image the sample, we can only
understand the sample state by analysis of GMR trace patterns. We will show by comparison to simulations that a given experimental reversal can be understood from its GMR trace in terms of a number of discrete events and phenomena, discussed individually below.

### 6.3 GMR Analysis of Reversal Subevents

#### 6.3.1 Early Soft Layer Switching

During reversal, significant switching may be observed even before the forward field is fully removed, as evidenced by a significant increase in GMR before crossing zero field. This is illustrated in simulation and experiment in Fig. 6.6. A measurable increase can be detected at fields as low as -60 Oe when reversing from negative towards positive field. Simulations indicate three possible origins of this phenomenon.

First, DWs at the ring extrema can be displaced by mutual magnetostatic repulsion. A small portion of the soft layer near one of the long axis extrema is reversed in the soft layer, creating an antiparallel region that significantly elevates GMR from the saturation/fully parallel case. An onion state DW may also be attracted to a nearby DW of opposite sense in the opposite layer, as shown in Fig. 6.6(c,d).

Second, when 360DWs are present, as the forward field magnitude is decreased, the equilibrium width of the 360DW is increased, giving an increase in resistance. 360DW expansion alone gives only a very small increase, but when other pinning sites are nearby, or interlayer interactions with another DW are favorable, it is possible for a leftover 360DW to fully dissociate as the forward field is decreased. This can even result in the reversal of a significant portion of the ring before zero field is reached. This extreme case is illustrated in Fig. 6.7(b), in which a 360DW has expanded to a corner of the ring before the forward field is removed.

Third, the presence of a domain wall in one layer significantly distorts the mag-
Figure 6.6: (a) Calculated GMR trace from simulation of a rhombic ring brought from positive saturation to -400 Oe to +400 Oe. Total resistance, rather than simulated four-point resistance, is shown to avoid distracting electrode-placement artifacts. The marked point highlights an increase in resistance as 360DWs expand to partially reverse the ring. (b) Experimental GMR trace demonstrating the same shape at the highlighted point. The field was repeatedly cycled between ±200 Oe. (c) Simulation image at -400 Oe. 360DWs are present in the hard layer. (d) Simulation image at the marked point (-128 Oe), showing the soft layer on the left and the hard layer on the right. The four 360DWs have expanded substantially around corners of the ring. Distortion of the soft layer due to the stay fields from hard layer 180DWs is more pronounced. Magnetostatic attraction of the right soft layer DW to the nearby hard layer 360DW is also a contributing factor.

Magnetostatic attraction in an adjacent layer, creating a site for assisted DW nucleation. In this case leftover 360DWs, in addition to facilitating reversal by opening and dissociation, can encourage nucleation of reverse domains in the opposite layer, further decreasing the switching field. A simulation example of DW-facilitated nucleation even before the forward field is removed is shown with its GMR trace in Fig. 6.7. This example also displays a significant amount of 360DW expansion; it is not possible to show an example of this effect without including 360DW expansion, as it is 360DWs that provide the nucleation sites. Note that even when soft layer DWs are trapped by interlayer magnetostatic pinning, the nucleation field is sufficiently low that the soft
Figure 6.7: (a) Calculated GMR trace from simulation of a rhombic ring brought from positive saturation to -400 Oe to +400 Oe. Resistance at the marked point is elevated from the baseline due to 360DW expansion as well as nucleation of multiple domains in the soft layer. (b) Simulation image at -400 Oe. The hard layer contains four 360DWs and the soft layer two. (c) Simulation image at the marked point (-48 Oe). A reverse domain has been nucleated in the top-right arm of the soft layer. Two hard layer 360DWs have combined into one domain by expansion, with 180DWs of similar orientation annihilating.

layer reversal process still takes place over a narrow field range.

Experimental results suggest that only the second and third proposed mechanisms occur. In experiment, elevated resistance at remanence never occurred on the first reversal after saturation, but occurred in approximately 50% of reversals to ±200 Oe thereafter. Since 360DWs are not present immediately after saturation, this suggests that experimental observation of elevated resistance at remanence is most likely due to the action of 360DWs, but a GMR trace is not sufficient to distinguish 360DW dissociation and assisted nucleation. Both mechanisms remain possible explanations. That the first proposed mechanism is observed only in simulation may also help to explain why calculated GMR curves show a greater degree of this elevated resistance effect than experimental curves, which is typical in our results and demonstrated in Fig. 6.6.
6.3.2 Formation of Mirror Domains

Experiments on extended films have shown that interlayer coupling causes the formation of mirror domains between coupled layers[63]. The same phenomenon is readily observed in our rhombic ring simulations, which form mirror domains even under significant applied fields which should favor one domain orientation. This is closely tied to and an extreme case of reverse domain nucleation and 360DW expansion. In fact, while the maximum resistance state of an elliptical ring indicates antiparallel bidomain states, the maximum resistance state of a rhombic ring can indicate a complex multidomain state with total formation of mirror domains. While the magnetization is still almost totally antiparallel, this is a very high-energy state that presents a huge number of pinning and nucleation sites that influence future reversal behavior. Unlike the elliptical ring case, we note the resistance level is in no way sufficient to deduce the domain configuration. A simulated GMR curve and simulation images of its maximum resistance state are displayed in Fig. 6.8. A full mirror domain state is achieved at remanence and persists up to an applied field between 140 and 160 Oe.

6.3.3 Low-Field Hard Layer Switching and the Intermediate Resistance Plateau

One of the two rhombic ring reversal modes shows a broadly stable intermediate resistance plateau. An example GMR trace in simulation and experiment is shown in Fig. 6.9(a,b). This state occurs when 360DWs dissociate, when 180DWs are nucleated with magnetostatic assistance, or when 180DWs are displaced from a pinned position in the maximum resistance state (either bidomain or complex mirror domain). Hard layer reversal is thus initiated at a much lower field than is associated with the buckling process. Newly freed DWs then propagate significantly before being trapped by other pinning sites, such as corners and 360DWs in the opposite magnetic layer; while the
Figure 6.8: (a) Calculated GMR trace from simulation of a rhombic ring brought from positive saturation to -900 Oe to +900 Oe. On the negative-to-positive reversal, a nearly-maximal resistance state is achieved at remanence. (b) Simulation image at the marked point (zero applied field on the negative-to-positive reversal). A combination of 360DW expansion and assisted reverse domain nucleation have left the ring in a near-fully-antiparallel state containing six domains in each layer in a mirror domain configuration.

reversal initiation field is reduced, this low field is not sufficient to allow propagating DWs to escape all pinning sites, leading to a stabilized multidomain intermediate state. Figure 6.9(c) is a picture from the simulation in (a) at the marked point, showing a simple case in which the soft layer is DW-free and the propagating domain in the hard layer is pinned at corners. Fig. 6.9(d), from a different simulation (not shown) at +180 Oe (increasing positive field), shows a similar intermediate state where hard layer reversal is impeded by both corners and soft layer domain walls. This intermediate state persists up to a field at which a reverse domain can be nucleated or a DW can escape the pinning potential and continue propagation. We will later show that the occurrence of this state shows a strong dependence on field history,
6.3.4 Reduced Ultimate Switching Field in Step-Type Reversal

At sufficient fields the ring transitions to the low-resistance state, in which the layers are magnetized parallel apart from the presence of residual 360DWs. In over 90% of the measured loops, this occurs at a lower field in step mode reversal compared to block mode reversal. This is illustrated in Figs. 6.6(b) and 6.5(c,d), where the block mode reversal completes at a field magnitude of about 110 Oe in both examples, while the step mode reversal completes at 80 Oe. As discussed above, the high resistance indicating the influence of 360DWs.
state of the ring contains considerably more DWs during step mode reversal, and the lower field for completion of reversal is attributed to the expansion or unpinning of these features. In some measurements the reversal occurred via several intermediate steps, and was not complete until the field reached 220 Oe.

Early reversal does not always occur in association with step-type switching. Figure 6.10(c) shows a domain wall strongly pinned with no opposite-layer domain wall available for assisted nucleation. In this case, even when the majority of the ring reverses and the resistance decreases below the intermediate level, a portion of the ring remains unreversed until a significantly higher field enables reverse domain nucleation, giving a three-step behavior. A pair of GMR traces displaying this phenomenon in simulation and experiment are shown in Fig. 6.10(a,b). Less than 1% of experiments...
showed reversal in which a single intermediate state was stable up to the block-type
switching field; while not observed in simulation, this most likely indicates a strongly
pinned intermediate state with no opportunity for assisted nucleation. These are mi-
nority cases; again, greater than 90% of reversals with intermediate states also display
early ultimate switching.

6.4 Statistics of Rhombic Switching and Field His-
tory Effects

To understand the conditions under which step and block mode reversals occur, the
rings were cycled within a variety of field ranges. The maximum fields applied were
insufficient to saturate the ring, leaving residual DWs that influence the reversal mode
on subsequent cycling.

In the field range of ±250 Oe, the ring showed an asymmetrical behavior in which
the ascending and descending branches of the loop alternated between step and block
modes, as shown in Fig. 6.6(b). This behavior was stable over hundreds of cycles,
but in 0.04% of the field scans, the step mode/block mode sequence reversed sponta-
neously, e.g. the ascending branch changed from step mode to block mode and the
descending branch from block mode to step mode. In 0.12% of the cycles, the GMR
remained high (i.e. over 30% of the total magnetoresistance) at the maximum field
of 250 Oe, which is indicative of a multidomain state being trapped. Following such
an event, the subsequent half loop showed a gradual rise to high resistance followed
by a drop back to the minimum resistance, and the next half-loop randomly showed
a step or block mode.

During cycling at ±300 Oe, the probability of a high resistance state increased
to 2.56%, while the probability of a spontaneous change in the reversal pattern re-
mained at 0.04%. The alternating behavior at this field extremum is shown in Fig.
Figure 6.11: (a) Ten sequential minor loops to ±300 Oe showing alternating block/step behavior. (b) Demonstration of a switch in the reversal pattern by an elevated baseline resistance. After the block-type 1 ends in an elevated resistance state, another block-type reversal 2 occurs. Trace 2 shows a normal baseline resistance, and trace 3 shows a step-type pattern and a return to alternating behavior. (c) Probabilities of the block- and step-type reversal modes as a function of cycling field extrema.

6.11(a), and reversal of the pattern by an elevated resistance state in (b). The overall reproducibility of the behavior at ±250 and ±300 Oe suggests that in the great majority of cycles, consistent domain structures are formed in each half-loop which are not eliminated at the maximum field, leading to repeatable switching behavior. The rare changes in reversal sequence or trapping of multiple domain structures might be
attributed to variations in the thermally activated depinning of DWs between field cycles.[64]

As the field range increased, the behavior became more variable and the alternating block and step reversal within each half loop is no longer observed. At ±350 Oe, block reversal occurred in 47.8% of half loops and step reversal occurred in 38.6%, with the remaining reversals showing multiple steps. The selection of the block or step mode was random. Block reversal occurred in 78.2% of half loops at ±400 Oe. The probability of observing an elevated resistance at maximum field increases to 30.0%, and in this case, a step reversal mode followed in most (80.0%) of the subsequent half loops. For cycles performed in large field ranges, 5000 Oe, block reversal was observed. The statistics of the reversal process are shown in Fig. 6.11(c). These results suggest that block reversal becomes the dominant reversal mode for larger field amplitudes, in which more of the reverse domains and DWs are eliminated, but step reversal is promoted if multiple domains and DWs are present in the ring at the field maximum.

6.5 Summary

The magnetoresistance of 2 um long, 200 nm wide Co/Cu/NiFe rhombic rings has been used to demonstrate the role played by domain wall interactions and residual 360DWs in the magnetic reversal of multilayer patterned structures. Micromagnetic simulations show that rhombic rings readily generate 360DWs during reversal, which are not eliminated until fields of over 1000 Oe, and predict that these metastable structures dominate subsequent reversal processes, for example by opening to form a reverse domain, or by interacting with the other magnetic layer, pinning propagating 180DWs or promoting the nucleation of reverse domains. Experimental measurements of GMR show two major reversal modes, block mode, in which the resistance
rises then falls over narrow field ranges, and step mode, where stable intermediate resistance plateaux occur. Simulations reproduce these results, and show that the block mode is expected for reversal from saturation, while the step mode occurs when multiple metastable domain structures are present in the ring. The simulation also reproduces details of the experimental results, such as low-field increases in resistance or differences in switching fields between the modes. This agreement suggests that the 360DW-mediated reversal predicted by the simulation is representative of the magnetic behavior of the sample.

Repeated minor loop cycling of the rings shows a systematic change in the reversal mode as a function of the maximum applied field, with a change from an alternating step/block mode at 250 and 300 Oe to a dominant block mode at 400 Oe and above. The results support the view that the reversal process is dominated by the interlayer magnetostatic interactions between domain walls, and in particular by the 360DWs which remain at the end of each field cycle.
We now discuss the unique behaviors of the 360DW as compared to the 180DW. We consider field-, DC current-, and AC current-driven behaviors separately; unique effects under multiple driving forces are discussed in section 7.3.

7.1 Field-Driven Behavior

As discussed in section 2.5, unlike 180DWs, 360DWs do not move under an applied field due to their zero net magnetization. Instead, there are two possibilities depending upon the sense of the applied field with respect to the magnetization of the 360DW core. Note that only components of the field parallel to the wire are considered here. For a field perpendicular to the wire, the cores of the component 360DWs widen or shrink depending on the orientation of the field, but the 360DW is largely unaffected until the field overcomes the shape anisotropy of the wire and cants the magnetization of the sample as a whole.
**Dissociation**

When a field along the wire is applied parallel to the 360DW core, the core region widens and the 360DW is expanded. This reduces the exchange energy in the system, while increasing the stray field penalty due to separation of the dipoles. Even a modest field applied along this direction is sufficient to escape the dipolar interaction potential well, dissociating the 360DW into its constituent 180DWs and propagating them in opposite directions. Though the critical dissociation field depends on 360DW width and accordingly on sample geometry, it is typically within the tens of Oe; for example, in the 200 nm-wide Co nanowires considered in section 5, a 360DW can be dissociated by a mere 40 Oe reverse field. For the remainder of this chapter, an external magnetic field oriented along the 360DW core will be called an expansive field.

**Annihilation**

When a field is applied antiparallel to the 360DW core, the 360DW is compressed. This increases the energy of the system substantially, in particular due to the heightened exchange penalty. However, there is no simple pathway for elimination of the 360DW purely by applied field, and the metastable 360DW persists to extremely high fields. As with dissociation, the critical field varies with sample geometry, but annihilation occurs in a typical thin film nanowire at fields over 1000 Oe; in the same Co nanowire previously mentioned, a 360DW is stable to 1700-1800 Oe. Once the annihilation field is exceeded, the 360DW’s constituent 180DWs join at one end, and the structure collapses in a burst of spin waves. For the remainder of this chapter, an external magnetic field oriented antiparallel to the 360DW core will be called a compressive field.
7.2 Current-Driven Behavior

For this section, we consider a permalloy nanowire of dimensions 5048 nm x 100 nm x 5 nm, discretized into 4 nm x 4 nm x 5 nm unit cells. Anisotropy was neglected, the polarization factor $P$ was taken to be 0.04, and the nonadiabaticity parameter $\beta$ was varied between 0.02 and 0.05. An initial state was generated by manually defining a DW placed approximately 2 $\mu$m from the left end of the stripe and allowing this configuration to equilibrate. This placement, as well as the boundary condition of a 24 nm fixed-spin layer at each end of the bar, ensured the influence of the stray field from the end of the bar would be negligible. The locations of 360DWs as a function of time and the positions at which they annihilated were determined from the value of the transverse ($y$-axis) component of the magnetization as a function of distance along the stripe. The equilibrium 360DW structure is shown in Fig. 7.2(a).

7.2.1 DC Current-Driven Behavior

7.2.1.1 Manipulation

The simulations show that 360DWs translate under an applied current, showing an approximately linear increase in velocity with current density. Fig. 7.1(a) gives the velocity calculated at zero applied field as a function of spin current velocity $u$. The spin current velocity is proportional to the applied current density as described in equation 2.10. At zero field the DW velocity for the 360DW is similar to that obtained for a 180DW for spin current velocities up to $\sim$200 m/s. As this simulation is performed for nonzero $\beta$ parameter and zero anisotropy in a geometrically perfect wire, there was no critical current density for DW motion.

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Figure 7.1: A comparison of domain wall velocities for 360° and 180° domain walls (a) at zero applied field with varying spin current velocity and (b) at fixed spin current velocity $u=100$ m/s with varying applied field. The parameter $\beta = 0.03$ in all cases. Positive field and velocity are directed to the right, along $+x$.

Fig. 7.1(b) shows the effect on DW velocity of a magnetic field applied along the stripe (x-axis field) for $u = 80$, 100, and 120 m/s for both 180DWs and 360DWs. The 180DW showed the expected Walker behavior in which the velocity increased with field then dropped abruptly at a field near 14 Oe. In contrast, the velocity of the 360DW had no detectable dependence on the field along the stripe in the range of -25 Oe to +50 Oe. Below -25 Oe, the 360DW dissociated to form a reverse domain, while at much higher positive fields (1438 Oe), the 360DW collapsed. The velocities of the 180DW and the 360DW were identical at zero applied field, consistent with Fig.7.1(a), i.e., for moderate current densities (i.e. those below the current required to cause annihilation of the 360DW described below) a 360DW under any applied field propagated with the same velocity as a 180DW at zero field.
7.2.1.2 Annihilation

At a spin current density of $u=238 \text{ m/s}$, the 360DW exhibited an annihilation process which is qualitatively different from the Walker breakdown exhibited by the 180DW at $u=400 \text{ m/s}$ at zero applied field. In agreement with prior work,[25, 26, 27] Walker breakdown of the 180DW at high current or field occurred by the emission of an antivortex core from the stripe edge and an oscillation in the magnetic configuration and the velocity of the 180DW, but the 180DW was not destroyed. In contrast, the annihilation of the 360DW was an irreversible process which occurred by the creation of a vortex core at one edge of the stripe resulting in the formation of a single 180DW enclosing a U-shaped reverse domain on the other edge of the stripe, as shown in Fig. 7.2(c). At this point the velocity of the DW along the stripe fell to zero, and the U-shaped reverse domain contracted, Fig. 7.2(d). As the shrinking reverse domain approached the edge of the wire, it began to accelerate along $-x$, opposite to the initial propagation direction, Fig. 7.2(e). Eventually, the reverse domain vanished, releasing a burst of spin waves. The current-induced 360DW annihilation also differed from the annihilation process of a 360DW caused by a field in the absence of a current, which occurs via the formation and movement of multiple vortex cores accompanied by the emission of spin waves.

The nonadiabaticity parameter $\beta$ had a significant influence on the critical current density for breakdown. This is shown in conjunction with the effects of applied field in Fig. 7.5(b) in section 7.3. We note two distinct annihilation regimes: perturbed breakdown, in which the 360DW collapsed when it encountered the fixed-spin boundary condition at the end of the bar, and spontaneous breakdown, in which the 360DW collapsed during propagation without an accompanying perturbation. As $\beta$ decreases, the critical current densities for perturbed and spontaneous annihilation increase significantly, and the range of the perturbed annihilation regime increases. For $\beta=0.02$ no spontaneous annihilation was observed even at $u=350 \text{ m/s}$, corre-
Figure 7.2: Annihilation process of a current-driven 360DW. (a), Part of stripe showing the equilibrium transverse 180DW structure. Axes are indicated. (b), the equilibrium 360DW structure at zero field. (c), part way through the annihilation process of a 360DW showing a reverse domain bounded by a U-shaped 180DW. (d), (e), successive snapshots of the 360DW annihilation process.
sponding to a current density of \(1.25 \times 10^{13} \text{A/m}^2\). This \(\beta\) dependence is in general agreement with previous work on 180DW motion, in which increasing \(\beta\) for \(\beta > \alpha\) led to higher velocities at a given field, explained by the greater field-like torque provided by increasing \(\beta\),[66] as well as lower breakdown velocities.[21]

These results correspond to a permalloy stripe with cross-sectional area 100 nm x 5 nm. Simulations of other geometries indicated that the results are quantitatively similar for stripes in which the 360DW equilibrium structure resembles that of Fig. 7.2(b), in which the cores of the two component 180DWs lie approximately antiparallel to each other. For example, changing the stripe width from 100 nm to 50 nm lowered the zero-field annihilation spin current density from \(u=238 \text{ m/s}\) to \(u=236 \text{ m/s}\), and the DW velocity decreased from 435 to 429 m/s at \(u=150 \text{ m/s}\). However, for stripe widths above \(~\sim 120 \text{ nm}\), the two component 180DWs developed mirror-image curvatures so that the equilibrated 360DW was narrower at one side of the stripe than the other, and the current required to annihilate the 360DW was lowered significantly.

### 7.2.2 AC Current-Driven Behavior

As AC current contributes no net electron flow, it is no surprise that it produces no net domain wall motion, only a very short-range oscillatory motion. However, also induces an expansion and contraction of the domain wall width, corresponding to a trade of wall energy between demagnetization and exchange, oscillating about the equilibrium width. Such oscillatory excitations have previously been observed for field-excited 360DWs in thin-film stripes[51] and thick films,[39].

#### 7.2.2.1 Intrinsic Resonance

The 360DW is analogous to two masses in a (complex) system of springs derived from the exchange and dipolar terms, and so it stands to reason that this system should have a resonant frequency. Indeed, when a field is applied or removed, this
oscillation occurs with a characteristic frequency in the absence of any externally-defined potential, in field or current, unlike the resonance induced in constrained 180DWs.\cite{67, 68} This is shown in Fig. 7.3(a).

### 7.2.2.2 Tunability in Resonance

Though the difference is subtle, Fig. 7.3 (a) demonstrates two different characteristic frequencies, one while the field is applied and another when it is absent. Additional simulations confirm that the resonant frequency varies with the instantaneous applied field, but not with the previous state, field history, etc. This is shown in Fig. 7.4. These results suggest the resonant frequency is a function only of the immediate equilibrium width of the 360DW, which is a function of sample geometry and applied field. In a given sample, then, the resonant frequency of a 360DW can be tuned over a wide range with modest external fields, from 1.5 GHz at -25 Oe (just before dissociation) to 3.3 GHz at +50 Oe. Although the effect is nonlinear, with \( \frac{d\omega}{dH} \) decreasing with increasing H, the very high compressive field stability of the 360DW suggests that much larger resonant frequencies could be achieved.

### 7.2.2.3 Resonant AC Current

We expect that this resonant mode should be accessible with AC current, as it induces translational and width oscillations in the 360DW. When an AC current is applied, oscillations in demagnetization and exchange energies were also observed, but at \textit{twice} the frequency of the applied current. This occurs because the 360DW is slightly compressed and expanded as it reverses direction, corresponding to the translational mode observed by Roy et al. under field excitation.\cite{51} Each AC cycle causes the domain wall to reverse direction twice, at the case at the minimum and maximum of each current cycle, and therefore each AC cycle produces two of these compression-expansion events which characterize the resonance. Higher-order peaks
Figure 7.3: (a), Oscillations in demagnetization (solid line) and exchange (dashed line) energies in a 360DW. A field of +20 Oe was applied at time=0 and removed at time=5 ns with no applied current. The vertical axis represents the difference in energy compared to its value at equilibrium in zero field. (b), Steady-state energy oscillation amplitude in a 360DW subjected to an applied field and current as a function of field strength and current frequency. The amplitude of the current was fixed at $u=240 \text{ m/s}$ or $J = 8.57 \cdot 10^{12} \text{ A/m}^2$. 
were only weakly present in the FFT data, and may simply correspond to higher-order translational modes; no measurable wobbling was detected.

In the presence of an AC current, the amplitude of the oscillations in energy reached a steady state value determined by the frequency of the AC current and the magnitude of the applied field. This is shown in Fig. 7.3(b). The amplitude of the oscillation was maximized when the 360DW was excited at its resonant frequency by applying an AC current at half the resonant frequency; when an applied field was introduced, the resonant point varied as expected based on the previous measurements of resonant behavior. Simulations over a range of fields and current frequencies showed the highest amplitude oscillations in energy and width when the AC current frequency was within 1% of the resonant frequency determined at zero current.
7.3 Behavior under Multiple Driving Forces

One case of this behavior has already been covered: combining AC and field adjusts the 360DW’s resonant frequency, as discussed previously. This leaves us with three other cases: Field/DC, AC/DC, and all three driving forces.

7.3.1 Annihilation Control with Field and DC

The critical current for annihilation as a function of field and $\beta$ is shown in Fig. 7.5. An expansive field is found to increase the critical velocity, and as previously discussed, the domain wall velocity depends only on the applied current. As such, the maximum domain wall velocity can be tuned by an applied field, with an increase of up to 15% above the zero-field critical velocity when the domain wall is nearly dissociated. A compressive field destabilizes the domain wall against the current-induced destruction mode, and the critical current density and maximum stable propagation velocity are reduced accordingly.

7.3.2 Resonant Depinning with AC and DC

A superposed AC current has no effect on a DC driving current, which controls the behavior. We suspected that the energy input from resonant AC might facilitate pushing the domain wall out of micropinning sites, for example due to edge roughness. However, simulations in both rough and straight bars showed identical domain wall velocity no matter what the frequency or magnitude of the AC current. AC current also had no effect on the stability of the 360DW. Simulations were performed in a straight wire in which the largest possible noncritical DC current was applied; annihilation could not then be induced by any frequency or magnitude of AC current, even though the domain wall velocity momentarily exceeded its critical value. We conclude that AC and DC have essentially orthogonal effects.
Figure 7.5: (a), The behavior of a 360DW subjected to an applied field and DC current. Filled diamonds indicate the boundary between spontaneous and perturbed annihilation; open diamonds, between stable propagation and perturbed annihilation. (b), the behavior of a 360DW subjected to an applied field and DC current for varying values of $\beta$. Diamonds indicate $\beta=0.03$, circles indicate $\beta=0.04$, and squares indicate $\beta=0.05$. For each $\beta$ value, filled symbols indicate the boundary between perturbed and spontaneous annihilation and open symbols the boundary between stable propagation and perturbed annihilation.

However, we see a significant effect when we examine a wire with a strong pinning site, such as a notch. A 360DW was allowed to equilibrate in a permalloy nanowire 100 nm wide and 5 nm thick. The nanowire was discretized into 4 nm x 4 nm x 5 nm unit cells. A DC bias current of $u=140$ m/s was applied, which was sufficient to propagate the domain wall but not to escape the geometric pinning site. The equilibrium condition of a 360DW pinned at the notch is shown in Fig. 7.6(inset).
When an AC current is superposed on the DC current, a side-to-side wobbling motion of the domain wall is induced, while the top of the domain wall remains pinned at the notch. For certain frequencies and magnitudes of AC current, the domain wall is ejected from the notch and propagates along the wire at the velocity expected for DC $u=140 \text{ m/s}$. This is roughly analogous to the reduction in pinning field for a geometrically pinned 180DW subjected to resonant current observed by Debau et al, [38] though in this case depinning occurs only when the 360DW moves coherently instead of wobbling and expanding/contracting, and so depinning is tied to the intrinsic resonance of the domain wall.

Running a large number of simulations varying the magnitude and frequency of the AC component shows that the depinning events trace at least one clear resonant peak (Fig. 7.6); the minimum depinning current magnitude occurs at a frequency close to the resonant frequency of a free 360DW in a wire. This variation from the...
original resonant frequency is expected, as it is clear that the confined 360DW has changed shape somewhat, which we have shown is the determining factor for resonance conditions.

Since AC has no effect on a free domain wall, we have shown that a global AC current superposed on a global DC current can be used to selectively depin and thus gate the propagation of 360DWs. This is a very simple method of control, and we will consider its applications to domain wall devices later.

### 7.3.3 Resonant Depinning with Field, DC, and AC

Consider the same case with the addition of an external magnetic field. We have shown that the magnetic field alters the 360DW shape, which in turn alters the resonant frequency. We might expect, then, that an applied field will alter the depinning characteristics of this domain wall. The same simulations shown in Fig. 7.6 were executed again with a 50 Oe compressive field, and the results are shown in Fig. 7.7. The compressive field shifts the resonant peak to a higher frequency, as expected, and also lowers the critical current overall. This may be related to the reduced critical destruction current induced by a compressive field, as this depinning event does require an antivortex core to enter the bar near the notch, similar to the current-driven destruction process.

### 7.4 Summary

In this chapter, we have shown that 360DWs are immobile under an applied field, but can be dissociated by a weak (<100 Oe) expansive field or annihilated by a strong (>1000 Oe) compressive field. When DC current is applied, at low current densities, the 360DW translated stably at a velocity similar to a 180DW at zero field; at higher current densities, the 360DW can be annihilated in place when it encounters a pertur-
Figure 7.7: Depinning of a 360DW from a notch by application of resonant AC current with a DC bias current, with and without a compressive bias field. Black dots indicate depinning at the indicated conditions without a bias field; green circles indicate depinning with the bias field. Depinning from minor pinning sites is controlled by AC current, DC current, and magnetic field; stability of the 360DW against spontaneous annihilation is controlled and at still higher current densities, the 360DW is spontaneously annihilated. Multiple driving forces applied simultaneously have partially independent effects; and at still higher current densities, the 360DW is spontaneously annihilated.

Example: progress of domain walls past a notch can be gated with globally-applied driving force. For many cases local behavior can be modulated by a globally-applied driving force. For example, progress of domain walls past a notch can be gated with globally-applied driving force. For many cases local behavior can be modulated by a globally-applied driving force. For many cases local behavior can be modulated by a globally-applied driving force.
AC current, while the velocity of domain walls that have passed the notch remains
unaffected. It may also be possible to achieve synchronous depinning of 360DWs from
multiple pinning sites, potentially allowing a coherent “ratcheting” motion between
pinning sites. The partial independence of driving forces is the key result for the
utility of 360DWs in domain wall devices.
Chapter 8

Summary, Device Applications, and Future Work

8.1 Summary of Key Results

In this thesis, we have discussed the creation, manipulation, and destruction of 360° transverse domain walls in thin film metallic magnetic stripes. We have examined their effects on domain wall propagation and reversal in both single- and multi-layer structures.

360DWs in stripes are formed by two transverse 180DWs of opposite sense. We have demonstrated their formation in a typical nanowire and shown that the equilibrium width varies linearly with the wire width. In addition to the well-known formation method in ring structures, we have demonstrated formation in a specifically designed device combining a circular injection pad and a curved nanowire. This result was confirmed with SEMPA, MFM, and micromagnetic simulation results, which showed excellent agreement on the structure and extent of the 360DW. This injection system additionally supports creation of complex nπ domain walls using a small alternating field; experimentally, a 540° domain wall has been demonstrated.
360DWs have a stray field consistent with the superposition of a dipolar and quadrupolar field. At a given distance, this stray field is much reduced compared to that of a typical 180DW. However, it is still significant at a very small length scale, allowing 360DWs to influence reversal in other magnetic layers of multilayer devices. A 360DW can act as a strong pinning site for a propagating domain wall in an adjacent magnetic layer, with the ultimate pinning strength dependent on the relative orientation of the 360DW and 180DW. In the 200 nm wide nanowire studied in chapter 5, for expansive fields, pinning continues until the 360DW is dissociated. For compressive fields, pinning strength is 72-168 Oe for our typical NiFe(5 nm)/Cu(5 nm)/Co(5 nm) multilayer stack.

These magnetostatic effects, as well as the overall effects of 360DWs on reversal, were demonstrated by investigating single-layer and multilayer rhombic rings using GMR measurements and micromagnetic simulations. The sharp corners of these rings act as pinning sites, typically requiring reversal by nucleation of reverse domains, leading to the formation of up to (and most commonly) four 360DWs during reversal of simple single-layer rings. In the multilayer system, a rich reversal behavior dominated by the influence of 360DWs was observed. Reversal pathways showed multiple metastable states and formation of complex mirror domains between layers. Experimental GMR responses were matched with calculated GMR responses to give insight into the experimental behavior, which showed a strong correlation and suggests several phenomena at play during reversal:

1. 360DWs generally reduce the switching field of both the soft and hard layers. When 360DWs are present in a given layer, switching can proceed at low fields by dissociation; when 360DWs are present in an adjacent layer, the strong (but highly localized) stray field produces a favorable reverse domain nucleation site.

2. Unlike bars (or circular rings), the maximum resistance state does not correspond to simply one (two) antiparallel domain(s) in each layer; due to pinning
of propagating domain walls by domain walls in other layers, complex systems of mirror domains can form instead.

The reversal behavior was shown to have a strong field history dependence, with certain GMR curves shown to typically follow others, indicating repetition of certain patterns of 360DW formation.

We have shown that the response of 360DWs to field and current driving forces is qualitatively distinct from that of the constituent 180DWs. Due to their zero net magnetization, 360DWs are not translated by an applied field. Instead, they are compressed (and at high fields $> 1000$ Oe, destroyed) or expanded (and at modest fields $< 50$ Oe, dissociated) by fields directed along the 360DW core and are unaffected by fields perpendicular to the core. When modest DC currents are applied at any applied field, a 360DW is translated at the same velocity as a 180DW would be at zero field. At higher DC currents, instead of the Walker breakdown behavior and oscillatory motion observed in 180DWs, a 360DW is destroyed in place by traversal of a vortex core across the wire, releasing the domain wall energy in a burst of spin waves. The critical current and therefore maximum 360DW propagation velocity can be controlled by the applied field, with expansive fields increasing the critical current and compressive fields decreasing it. By applying a field nearly sufficient to dissociate the 360DW, the maximum velocity can be increased up to 15% over the zero-field case.

The 360DW displays an intrinsic resonance behavior governed by the interaction between demagnetization and exchange energies, which is directly observable as an oscillation in the domain wall width. When perturbed by a particular applied field, the 360DW oscillates at a characteristic frequency which depends inversely upon the domain wall width, and accordingly upon the applied field and sample geometry. Applying a high-frequency alternating current induces an oscillation of the 360DW width at twice the current frequency; calculating the energy absorbed by the wall
per cycle as a function of current frequency shows that AC can be used to excite the resonant mode and confirms the shift of the resonant frequency by an applied field.

By investigating all combinations of multiple simultaneous driving forces, we reach the following three conclusions concerning 360DW behavior:

1. An applied field cannot translate the domain wall, but can influence its stability and maximum DC-driven velocity, and additionally controls its resonant frequency.

2. A DC current translates the domain wall and, at a certain critical current, destroys it.

3. An AC current cannot translate or destroy the domain wall and has no impact upon its stability.

Additionally, a method for combining AC and DC current (and optionally field) to produce selective depinning from notches was demonstrated. Using only globally applied currents, propagation of domain walls across a notch can be gated using pulses of resonant AC. The flexibility granted by these orthogonal “handles” for controlling 360DWs suggest that 360DWs may be put to excellent use in domain wall devices.

8.2 Future Work: Experimental Demonstration of 360DW Current-Driven Behaviors

The behavior of 360DWs under Ac and DC current has been established only by simulation; the clear next step is to attempt to replicate these results experimentally, and work is underway to this end. Additional samples similar to the 360DW injection system described in section 4.2 have been patterned. Electrodes will be attached such that the current crosses the long injection wire, influencing the 360DW that forms in the middle of the wire.
A 3 GHz current source capable of sending single pulses with a rise time less than 20 picoseconds will be employed to provide sufficiently fast current pulses. Accordingly, a 3 GHz waveguide electrode has been designed to be compatible with a 150 µm G-S-G probe to allow controlled pulse injection. By using AMR measurements, the presence or absence of a 360DW can be detected, in principle allowing determination of when a 360DW has been annihilated. However, in the precise setup described in section 4.2, there is nothing to prevent the 360DW from being ejected out the end of the wire, which is indistinguishable in magnetoresistance measurements from the case where it was destroyed in place. Modifying the tapered end of the wire to include a notch or a sudden widening of the wire should provide sufficient pinning to block all further 360DW motion, though additional work will be necessary to determine the correct geometry. Once a suitable system is designed, it will be possible to use this injection system to directly measure the field, AC, and DC-driven behaviors previously discussed.

8.3 Future Work: 360° Domain Walls in Domain Wall Devices

The magnetostatics and AC- and DC-driven behaviors of 360DWs offer many advantages in existing domain wall memory and logic devices, as well as offering the potential for new types of devices.

Energetics of 360° Domain Walls

A 360DW in a 200 nm x 5 nm wire contains approximately 38 eV of stored energy, with 12 eV stored as exchange energy and 26 eV stored as demagnetization energy. This is about $\frac{1}{3}$ the energy per switch of a 32 nm-process Si transistor at 1 GHz, and is comparable to the ITRS target for 11 nm-process transistors at the same
frequency.[69] Creation and destruction of a 360DW at 1 GHz dissipates 6.1 nW of energy as spin waves. Additionally, this energy is dissipated over several microns of wire length as the spin waves are damped out slowly. Even assuming significant inefficiency in 360DW generation, this suggests that a rapidly-switching domain wall device based on 360DWs is viable. This idea is further supported by considering that the wall energy will decrease somewhat with decreasing wire width and therefore decreasing 360DW size.

**Racetrack Memory**

Racetrack memory is a design for domain-wall-based magnetic storage famously proposed by Stuart Parkin.[4] In this design, data is stored in a magnetic wire, encoded by multiple domain walls at arbitrary spacing. A readback system, for example a TMR or GMR stack using the magnetic wire as the free layer, is placed at the center of the wire. Pulses of DC current are applied to shift the data back and forth along the wire, and the orientation of the wire magnetization above the sensor is read to recover the stored data. This is shown schematically in Fig. 8.1. It has been shown that domain walls can be created, injected, and manipulated en masse in this system;[5, 4] however, many limitations make a 180DW-based racetrack technology difficult to realize.

First, formation of 360DWs must be considered. To achieve any reasonable data density, domain walls must be tightly packed, but we have previously shown that 180DWs can couple at a distance several times their own width, depending on wire roughness. As a result, coherent motion of 180DWs cannot be assumed for any reasonable data density, as the 180DW stray fields will overlap and interact. Additionally, 180DWs of parallel core orientation can annihilate, and so 180DWs must be kept well-separated. Though the results presented by Parkin concern vortex domain walls, these walls also have a polarity that allows for magnetostatic attraction or repulsion.
It has been proposed that the coherent motion problem can be avoided by the use of regularly-spaced triangular pinning sites in the wires.[4] However, this increases the difficulty of fabrication, and is not sufficient to solve the problem. Even with only one domain wall, repeated pulses of fixed length did not depin the domain wall every time;[4] we cannot assume either perfect coherent motion or perfect coherent depinning, and as a result, data will become corrupted.

This is further complicated by a second problem, the response of the system to external magnetic fields. A 180DW in a wire may be translated by just a few Oe, and in a system with multiple 180DWs, adjacent domain walls must necessarily move in opposite directions under an applied field. Even if perfect depinning and motion are assumed, a small external field could move the system out of metastability and cause
coupling of adjacent domain wall pairs, corrupting all data.

A third problem concerns writing of data. Topologically, a 180DW cannot be created or removed in place, as the magnetization on either side of it is opposite. To modify a piece of data, then, it is necessary to rewrite the entire contents of the wire. If it were possible to modify data in-place, without creating a new magnetization state from scratch, power consumption and read/write latency in many cases could be improved.

Fortunately, use of 360DWs as the data token alleviates these problems. First, we have shown that the stray field of 360DWs falls off rapidly due to flux closure, allowing tighter packing even allowing for the much greater width of the 360DW. In a very rough wire, 180DWs of opposite sense could couple from initial separation over 500 nm, while 360DWs whose near edges had opposite sense had no interaction at any separation down to the 360DW width. While 360DWs can couple into higher-order domain walls, this coupling is much weaker than 180-180 coupling and requires a much closer approach. Additionally, 360DWs are not propagated by external fields, and are sensitive to current only; this makes the device more robust. Finally, the distinct topology of the 360DW allows the data to be edited one 360DW at a time, in place, with no need to rewrite a larger portion of the data stream. However, this assumes a suitable injection system for releasing 360DWs into a wire, as discussed in section 8.3. With additional research into creating and injection 360DWs, more practical approaches to racetrack memory may be discovered.

**Injection of a 360° Domain Wall into a Data Racetrack**

To make practical use of the 360DW injection system, it must be possible to extract the generated 360DW from the wire. As only DC current can be used to translate a 360DW, this must be the basis of our injection system. In order to achieve this, we need an insertion point for a domain wall into a wire; an example device is shown in
Figure 8.2: A schematic system for injecting a 360DW into a wire already carrying multiple 360DWs. The point “A” indicates where a notch in the injection system wire may be used to gate the release of 360DWs into the main wire.

Fig. 8.2. A 360DW can be created using an alternating field in the indicated direction without impacting propagation of the two domain walls in the bus wire.

When a 360DW must be injected into the bus wire, there are two possibilities. In the simplest case, a DC current can be applied between the injection pad and the right end of the bottom wire, pushing the domain wall out into the wire where it can be moved by a separate DC current between the left and right ends of the wire. In this case, injection and translation are handled separately, but the ability to apply DC to distinct regions is required. In an alternate scheme, a pinning notch can be introduced at point A and DC can be applied globally from all points marked $V_{DC}$. An AC current may then be applied as indicated to depin the domain wall and release it into the moving stream. This requires fine timing, but uses global currents.

Early simulations indicate that a 360DW can be pushed across this sort of three-way intersection, but only under a limited set of driving conditions that is still poorly understood. Additional research will determine whether this or other varieties of injection system based on this 360DW generator can be experimentally realized.

360° Domain Walls as Gating and Trapping Systems

As discussed in section 5, the local but strong stray field of 360DWs can be used as a mobile, removable pinning site in a multilayer system. 360DWs can be freely created and destroyed in place, and in a multilayer system with a nonconductive spacer
layer, it is possible to use current to manipulate and destroy pinning sites in one layer independently. The orientation of the 360DW with respect to the propagating domain wall also determines whether the 360DW acts as a potential barrier or a potential well, blocking propagation in one direction or halting propagation entirely. For example, this could be employed instead of a notch as a method for gating domain wall injection into the bus wire in the racetrack memory design just described: a 360DW in an adjacent layer can be moved in and out of position with a current (or simply created and destroyed) to gate injection of domain walls into the bus wire. Currently, this behavior has been investigated only in stacked multilayers (which increase fabrication complexity), but it is reasonable to expect a somewhat weaker pinning behavior will be observed for closely-spaced wires in the same plane; examining this behavior for device applications is a topic for further research.

This pinning behavior can also be employed in 180DW-based domain wall devices that assume uniform motion of 180DWs. Densely-packed 360DWs in an adjacent layer can provide a series of periodic magnetostatic energy wells in which 180DWs are trapped. Simulations indicate that if the 360DW layer is subjected to a current, the magnetic configuration in the 180DW layer is dragged along purely by the strength of the magnetostatic information; that is, a 360DW can be used to tow a 180DW, allowing a domain wall device to take advantage of the smooth motion of 360DWs.
Bibliography


Appendix A

OOMMFTools

The OOMMFTools postprocessing utility library was developed to facilitate postprocessing of OOMMF table and vector file output. It was written in Python and was released as open-source under the GPL. It is available linked from the NIST website for OOMMF or directly from http://web.mit.edu/daigohji/projects/OOMMFTools/. Documentation for the software follows.

- OOMMFTools Version 1.1 12/31/2011
- OOMMFDecode Version 1.0 12/31/2011
- OOMMFConvert Version 1.0 12/31/2011
- ODTChomp Version 1.0 12/31/2011

A.1 Introduction

OOMMFTools is a set of utilities designed to assist OOMMF postprocessing with an intuitive, graphical interface. It includes the following subcomponents:

- OOMMFDecode - Converts OOMMF vector files into numpy arrays and/or MATLAB data files
• OOMMFConvert - Converts OOMMF vector files into bitmaps and movies
• ODTChomp - Converts ODT files or subsets thereof into normally-delimited text files

The Py2EXE-wrapped Windows version is designed to be portable and free of external dependencies. Everything necessary is included, including a binary of FFmpeg for OOMMFConvert. The script otherwise has the following dependencies:

• Python (2.6 preferred) [All]
• wxPython (Unicode) [All]
• numpy [OOMMFDdecode]
• scipy [OOMMFDdecode]
• FFmpeg [OOMMFConvert]
• OOMMF [OOMMFConvert]
• Tcl/Tk [OOMMFConvert]

Bug reports and feature requests should be sent to doublemark@mit.edu. Please include log files with any bug report if possibly.

The Py2EXE-wrapped Windows version of this software includes a compiled Windows binary of the FFmpeg library. FFmpeg can be found at http://ffmpeg.org/ and is licensed under the LGPLv2.1, available at http://www.gnu.org/licenses/old-licenses/lgpl-2.1.html. In the interest of complying with the FFmpeg license to the letter, the source code is available at http://web.mit.edu/daigohji/projects/OOMMFTools/ffmpeg-0.6.tar.gz.

### A.2 OOMMFDdecode

OOMMFDdecode batch-processes vector files (omf, ovf, oef, ohf) into numpy arrays. These can then be pickled, for python users, or saved into MATLAB data files, for MATLAB users.
A.2.1 Utilization

The GUI is very simple. Two checkboxes are offered - for making numpy data and for making MATLAB data. Simply check the options for the types of data you want to save and drag one or more OMF files onto the application. The data format (text, binary 4, binary 8) is automatically detected. When the import is finished, you’ll be prompted to save the data for each format you selected.

Dropping a batch of OMF files is primarily designed to automate aggregation of data from various states of a single simulation. The program assumes all files you drop at a time are ”similar” - that is, they have the same grid size and other header data. Please be mindful of this constraint, and if you wish to convert files from several disparate simulations do so in different drop operations.

Some files (such as energy densities) contain only a single value, not a vector. In OOMMF, these outputs are still vector files. The relevant quantity is stored in the X coordinate.

A.2.1.1 MATLAB Data

The output .MAT file contains several variables.

First, a 3-element vector GridSize, which contains the X, Y, and Z span of each cell. This is imported from the OMF file headers, specifically from the first file on the list of dropped files (again, it is assumed all files in one batch are similar).

Second, a vector SimTime, which contains the simulation time associated with each OMF file, if any. The input files are sorted based on SimTime if and only if times are available for all files.

Third and fourth, the vectors Iteration and Stage, which contain the iteration and stage number associated with each OMF file, if any. This is the total iteration number, not the stage iteration number.
The final variable is a 5-D matrix OOMMFData, which can be understood as follows.

OOMMFData(A,B,C,D,E):

A. The index of the OMF file, in simulation time order. If simtime data is not available, the files are in the same order as they were dropped on the program, which is generally the operating system sort order.

B. X coordinate in first-octant coordinates.

C. Y coordinate in first-octant coordinates.

D. Z coordinate in first-octant coordinates.

E. (1,2,3) are the x,y,z components of the vector.

Note that everything is indexed in the OOMMF (first-octant) coordinate system, but row-column matrix notation is fourth-quadrant. Depending on what you’re trying to do, it may be necessary to transform the data accordingly. When in doubt, remember that indices into matrices generated by this program match OOMMF’s own numbers!

A.2.1.2 numpy Data

The output .PNP file can be unpickled into a tuple containing two items: first, a 5-D matrix as documented above; second, a dictionary of header values extracted from the OMF file header data. This latter data is useful for looking up the scale of each cell or the simulation time of a particular file.

A.2.2 Known Bugs

No bugs are currently outstanding.

If the About dialog does not work under Ubuntu, your version of wxPython is outdated. You will want to get a copy and build it - the prebuilt package for Ubuntu is often too old.
A.3 OOMMFConvert

OOMMFConvert is meant to ease converting OOMMF simulation results into bitmaps and movies, especially for Windows users for whom the console is more unfamiliar or difficult. It uses the existing avf2ppm capability of OOMMF, along with the open-source utility FFmpeg for movie conversion.

A.3.1 Utilization

The GUI is divided into five sections as follows.

A.3.1.1 Path to OOMMF - configures Tcl shell calls

The left combo box contains the call necessary to involve tcl. This defaults to and should almost always be left on the value “tclsh”. However, some Windows installations of ActiveTcl/Tk use other commands, such as tclsh85 (which is provided as a dropdown option). If necessary, enter a new value here.

The static text field to the right shows the path to the oommf.tcl file in your OOMMF installation. This is the file that will be called to invoke avf2ppm. You can use the "Load OOMMF" button to locate it, or simply drag the oommf.tcl file anywhere over the program window. This path is recorded in the file oommf.path in the program directory, and this configuration step is only necessary once.

A.3.1.2 Configuration File - shows mmDisp configuration file

This section shows which mmDisp configuration file is going to be used in avf2ppm. You can save an mmDisp configuration file from an mmDisp view with the "Write config..." option in the File menu. You can select a configuration file with the "Load Config" button, or by dragging a file with the extension .conf, .config, or .cnf anywhere within the program window. The text shows the absolute path to the currently
selected config file. This value is not saved between sessions, as it is typically simulation-dependent and unique for different groups of OMF files. To clarify, it is saved between file drops, so you can easily use the same configuration file to convert multiple batches of OMF files without closing the program.

For the magnetization, the maximum value of the vector field is fixed (Ms). For other kinds of fields, such as demag, the maximum value of the vector field may fluctuate from file to file. This could result in clipping unless you happened to use the largest-values of file to produce your config file. If you’re using a field where the maximum value fluctuates significant, check ”generate vector field maxima”. If this is checked, the program will decode the files to be converted and find the maximum vector magnitude among all files. This can add significantly to the runtime, but makes it easy to generate uniformly-scaled pictures for these sorts of fields without clipping.

A.3.1.3 Images - configures bitmap output

This section controls the bitmap file output. If ”Make Bitmaps” is unchecked, no images will be created. It defaults on. ”Image Magnify%” overrides the parameters in the mmDisp configuration file to increase the output bitmap size. It employs a temporary copy of the configuration file, and the original is not overwritten. The value is in percent of the OOMMF default size, usually around 640x480.

A.3.1.4 Movies - configures movie output

This section controls the output of a movie file based on a collection of input OMF files. A movie will be made from each batch of OMF files if ”Make Movies” is checked, but it defaults off.

The leftmost configuration on the bottom row is the FPS of the output movie. You may also consider it ”simulation files per second.” Since FFmpeg uses an awkward
fixed-framerate form, frames will be duplicated to fill in time when the FPS is reduced. These temporary files are cleaned up automatically. This value can be between 1 and 25 FPS, and defaults to 25.

The middle combo box allows the choice of encoding from a number of codecs built into FFmpeg. The default is HuffYUV, which I find gives the best-quality output files for the common red-white-blue color scheme. MPEG4 has some difficulty with the black-on-blue arrows and gives a visibly worse encoding. The HuffYUV decoder does not come standard on most systems (Windows) but is freely available, and I highly suggest using this codec.

The rightmost control is the movie magnification, which functions similarly to the image magnification. However, many codecs are unstable for large input image sizes (above around 140% over the OOMMF default size) and may fail silently. This is a bug in the encoder and cannot be worked around. Therefore, increasing the movie magnification is done at the user’s risk. The default codec HuffYUV is quite robust, and readily supports use of the movie magnification control.

A.3.1.5 Drop OOMMF Files Here! - a friendly reminder

Drag and drop configuration and vector field files here - or anywhere in the program window, but this section is a friendly reminder. Multiple files can be dropped at a time. OMF files are converted to bitmaps using the oommf command line utility avf2ppm and the supplied mmDisp configuration file. If a movie is being made, the batch of simultaneously dropped OMF files is converted to a single movie with the frames in filename order.

A.3.2 Known Bugs

Movie magnification is currently limited, and should only be used in cases where you wish to display the entire simulation, not a window onto a particular part of it. This
is related to how views are specified in mmDisp conf files. A patch should be available soon.

A.4 ODTChomp

ODTChomp takes in ODT data tables, simplifies the name scheme to the extent it it possible, and outputs the desired columns into a text file with a given delimiter. The behavior is rather distinct from odtcols, which is better at fixed-width rather than fixed-delimitation formatting.

A.4.1 Utilization

Begin by loading an ODT file. Drag-and-drop also works. The leftmost panel shows the columns found in the ODT file, using a simplified name scheme that uses the minimum number of uniquely identifying descriptors. The result is generally very human-readable unless the simulation file is extremely complex. The right panel shows which data fields will appear in the output file.

Double-clicking an entry in the left panel, or clicking an entry and then the ”→” button, will mark it for export. Double-clicking an entry in the right panel, or clicking an entry and then the ”←” button, will remove it from the export. The subsequent set of buttons can be used to add or remove all fields from the output file. The ”Move Up” and ”Move Down” buttons affect the item highlighted in the right panel, and are used to reorder the output columns.

The radio buttons between the two panels choose the delimiting symbol for the values in the output. For example, if you want the comma-separated values commonly used by Excel, choose comma. If you choose space as the delimited, spaces that appear in column names will be replaced by underscores in the output.
Finally, the export button writes the selected columns in the selected order to a plaintext file.

A.4.2 Batch Mode

The checkbox just above the Export button enables Batch Mode. Batch Mode is designed to extract the same data fields from a large group of ODT files using drag-and-drop. Batch Mode can only be used once one file has already been loaded and export data has been selected. Even if Batch Mode is checked, if no file has previously been loaded, the first file drop will give non-batch behavior.

Once a file has been loaded and data fields have been chosen, any files dragged and dropped onto ODTChomp with Batch Mode enabled will have the specified fields extracted. The output will be placed in the same folder as the dropped file, with the same filename and the ".txt" extension. Currently, dropping directories is not supported and they will not be recursed.

A.4.3 Known Bugs

No bugs are currently outstanding, but directory recursion will be added.
Appendix B

MIFCraft

MIFCraft is a metaprogramming system designed to wrap the OOMMF MIF file format. It extends batching capabilities and provides input validation. It was written in Python and was released as open-source under the GPL. It is available directly from http://web.mit.edu/daigohji/projects/OOMMFTools/. Documentation for the software follows.

- MIFCraft v0.3 2/01/12

B.1 Introduction

MIFCraft is a Python-based scripting system designed to make writing MIF files easier and more reliable. It wraps the OOMMF-extended Tcl system entirely, and presents a pure-Python interface used to generate files. It provides simple, plain-English warnings if you typo a label, include a non-existent file, or do something else that would generate a verbose OOMMF runtime error later on. Once you’re comfortable with the system, you can (for example) use simple Python looping constructs to rapidly generate groups of simulations that vary one or more parameters. To use MIFCraft, you’ll need to install Python from python.org.
For this manual, it’s assumed that you know OOMMF, but have never used Python. Don’t worry if you don’t know Python; the system is very straightforward and a few examples will go a long way. If you have used Python before, bear with me. MIFCraft has been tested with Python 2.6 and 2.7, but should be compatible with 3.0. You’ll need to copy MIFCraft.py into a Python library folder, or make sure it’s in the same directory as your MIFCraft scripts. This folder is most likely C:\Python26\Lib\site-packages\ for Python 2.6, C:\Python27\Lib\site-packages\ for Python 2.7, etc.

B.2 Getting Started with a Simple Example

Let’s start with a very simple task: defining a rectangular prism of magnetic material and relaxing it from a random initial state. The final result of this is available as test.py in the SimpleExample folder where you unpacked MIFCraft. Follow along by creating your own file, first_try.py.

B.2.1 Some Boilerplate

All MIFCraft scripts start by importing the MIF object from the MIFCraft library. When you create a MIF object, MIFCraft creates a MIF file for OOMMF.

from mifcraft import MIF

In this example, we’re also going to use the mks value of $\mu_0$. We define that constant based on pi, which is available in the Python math library. Later, we’ll use this in our script - no need for [subst] or [expr] as normally seen in MIF files.

from math import pi
Mu0 = pi * 4e-7

Now we’re ready to create our MIF object and file. We’re going to use the filename test_1.mif, with the OOMMF basename test_1. As a reminder, the basename is
the prefix applied to OOMMF output files. Whenever you want to supply a string of text in MIFCraft, surround it with single quotes.

```python
with MIF(filename='test_1.mif', basename='test_1') as myMIF:
```

We now have a MIF object named myMIF and can create Specify blocks in it. If you’re reading along in the example file, you’ll note that every line after this is indented. Unlike Tcl, Python cares about indentation: these indents signify that these lines belong to the the MIF file we opened with `with`. When you stop indenting, that’s a sign that you’re done setting up this MIF file and want it written out.

One last aside: whenever you’d like to provide extra clarity, you can put comments in your MIFCraft files using the `#` character. This causes the rest of the line to be ignored.

### B.2.2 Replacing `Specify`...

In a normal MIF file, you’d probably start with some geometry, something like:

```plaintext
Specify Oxs_BoxAtlas:SomeAtlas {
    xrange { 0 1e-7 }
    yrange { 0 1e-7 }
    zrange { 0 2e-8 }
}
```

In MIFCraft, we create this in myMIF like this:

```python
myMIF.BoxAtlas(xrange=(0, 100e-9),
                yrange=(0, 100e-9),
                zrange=(0, 20e-9))
```

For each `Specify...` statement you can use in OOMMF, there’s a corresponding method in MIFCraft with the same name, minus ‘Oxs_’. Each parameter that needs to be specified in OOMMF as `name value` is specified here as `name=value`. Note how the ranges are grouped with parentheses. A complete manual on how to specify
parameters for each type of Specify block is provided in mifcraft-reference.html, but you’ll find most of them are obvious.

You’ll note this atlas doesn’t have a name (like ‘SomeAtlas’). That name is automatically generated by MIFCraft, and you don’t have to worry about it. What if we want to use this atlas later on? Well, we can capture it like this:

\[
\text{Brick} = \text{myMIF.BoxAtlas}\left(xrange=(0, 100e^{-9}),
\right.
\left.\ yrange=(0, 100e^{-9}),
\right.
\left.\ zrange=(0, 20e^{-9})\right)
\]

This is what’s done in the example file. Now we can reference that atlas by its Python name, ‘Brick’. We do this immediately when we create the mesh:

\[
\text{myMIF.RectangularMesh}(\text{atlas=Brick},
\right.\cellsize=(5e^{-9}, 5e^{-9}, 5e^{-9}))
\]

Remember to indent, and once again, group multiple values with parentheses. Note that Brick isn’t a string and doesn’t need single quotes—it’s a Python name, like myMIF.

We also need our standard parameters: demagnetization and exchange energy.

\[
\text{myMIF.Demag()}
\]
\[
\text{myMIF.UniformExchange}(A=13e^{-12})
\]

Next we need an evolver - we’ll use Oxs_RungeKuttaEvolve. Most parameters have default values here, so we only need one. Let’s do a quasistatic simulation.

\[
\text{myMIF.RungeKuttaEvolve}(\alpha=0.5)
\]

We’d like to move on to our Oxs_TimeDriver, but we know that takes a scalar field for saturation magnetization and a vector field for initial magnetization. We set those up first and assign them labels, then use them directly.

\[
\text{myMs} = \text{myMIF.UniformScalarField}(\text{value}=800e3)
\]
\[
\text{mym0} = \text{myMIF.PlaneRandomVectorField}(\text{min_norm}=1,
\right.\max_norm=1,
\right.\plane_normal=(0, 0, 1))
\]
myMIF.TimeDriver(stopping_dm_dt=0.1,
                stage_count=1,
                Ms=myMs,
                m0=mym0)

Note that we didn’t give the TimeDriver an Evolver, which it needs. MIFCraft
knows you’ll only ever create one Evolver per MIF file, and links the TimeDriver to
it automatically! All we have left to do is set up outputs.

gm.MIF.Destination(label='disp', type='mmDisp')
gm.MIF.Schedule(output='Oxs_TimeDriver:TimeDriver:Magnetization',
                 label='disp', step=50)

All told, your file should now look like this:

from mifcraft import MIF
from math import pi
Mu0 = pi * 4e-7

with MIF(filename='test_1.mif', basename='test_1') as myMIF:
    Brick = myMIF.BoxAtlas(xrange=(0, 100e-9),
                            yrange=(0, 100e-9),
                            zrange=(0, 20e-9))
    myMIF.RectangularMesh(atlas=Brick,
                           cellsize=(5e-9, 5e-9, 5e-9))
myMIF.Demag()
myMIF.UniformExchange(A=13e-12)
myMIF.RungeKuttaEvolve(alpha=0.5)
myMs = myMIF.UniformScalarField(value=800e3)
mym0 = myMIF.PlaneRandomVectorField(min_norm=1,
                                     max_norm=1,
                                     plane_normal=(0, 0, 1))
myMIF.TimeDriver(stopping_dm_dt=0.1,
                 stage_count=1,
                 Ms=myMs,
                m0=mym0)

myMIF.Destination(label='disp', type='mmDisp')
myMIF.Schedule(output='Oxs_TimeDriver:TimeDriver:Magnetization',
                 label='disp', step=50)

Now we can run that file with python first_try.py from the command line, or
by opening and then running it in the IDLE editor that comes with your Python
installation, if you’d rather. I like the command line. (You can also run .py files
directly from the Windows Explorer shell, but you won’t be able to see the debug information if you have any mistakes!) That will create test_1.mif in the same folder, and it looks like this:

```plaintext
# MIF 2.1
# Auto-generated by MIFCraft at 15:19:56 on Tuesday Jan 10 2012
Specify Oxs_BoxAtlas:BoxAtlas {
    xrange { 0.00e+00 1.00e-07 }
    yrange { 0.00e+00 1.00e-07 }
    zrange { 0.00e+00 2.00e-08 }
}

Specify Oxs_RectangularMesh:RectangularMesh {
    cellsize { 5e-09 5e-09 5e-09 }
    atlas BoxAtlas
}

Specify Oxs_Demag:Demag {}

Specify Oxs_UniformExchange:UniformExchange {
    A 1.3e-11
}

Specify Oxs_RungeKuttaEvolve:RungeKuttaEvolve {
    alpha 0.5
    do_precess 1
    allow_signed_gamma 0
}

Specify Oxs_UniformScalarField:UniformScalarField {
    value 800000.0
}

Specify Oxs_PlaneRandomVectorField:PlaneRandomVectorField {
    plane_normal { 0 0 1 }
    min_norm 1
    max_norm 1
}

Specify Oxs_TimeDriver:TimeDriver {
    evolver RungeKuttaEvolve
    mesh RectangularMesh
    Ms UniformScalarField
    m0 PlaneRandomVectorField
    basename test_1
    stage_count 1
}
```

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B.2.3 Debugging with MIFCraft

That’s nice, and it produces a pretty and well-formatted MIF file, but it didn’t save us that much work! We still wrote everything by hand. To see one aspect where MIFCraft comes in handy in this example, let’s deliberately introduce an error in our Python file - let’s change the cell size so that it doesn’t divide cleanly.

```python
myMIF.RectangularMesh(atlas=Brick,
                      cellsize=(5e-9, 6e-9, 5e-9))
```

When we try to run this, we get the following error:

```
(.	est_1.mif) could not be completed:
  In RectangularMesh <RectangularMesh>: ystep invalid: 6e-09 does not evenly divide atlas y size 1e-07
```

We’re given the exact location and nature of the error before we even try loading the file in OOMMF. If we make the same mistake in a MIF file, we instead see:

```
Error loading test_1.mif: Error thrown from inside "Oxs_ExtCreateAndRegister" --- Oxs_Ext initialization error in construction of Oxs_RectangularMesh:RectangularMesh --- Oxs_Ext ERR: Invalid MIF input block detected for object Oxs_RectangularMesh:RectangularMesh: range is not an integral multiple of cellsize.
(LoadProblem)
--------
Message id: crc: 0x0FDE56B5 413
Message src: Oxs_Mif
--------
STACK TRACE:
Error loading test_1.mif: Error thrown from inside "Oxs_ExtCreateAndRegister" --- Oxs_Ext initialization error in construction of Oxs_RectangularMesh:RectangularMesh --- Oxs_Ext ERR: Invalid MIF input block detected for object Oxs_RectangularMesh:RectangularMesh: range is not an integral multiple of cellsize.
while executing
  Oxs_ExtCreateAndRegister $key $init_str ("Oxs_Mif" instance method 'ReadMif' line 108)
```

That is a stack trace, and it's a very useful error message for programmers, but not quite what you want when you're just working on a MIF file. Let's try another error - just delete the yrange part of our BoxAtlas.

(.	est_1.mif) could not be completed:
In BoxAtlas <BoxAtlas>: yrange invalid: mandatory argument 'yrange' not provided.

If a response has to be one of a fixed list, you'll be informed of what the valid options are. If we change the type of our Destination to 'mmLies', we get:

(.	est_1.mif) could not be completed:
In Destination mmLies <disp>: type invalid: mmLies is not one of ['mmDisp', 'mmGraph', 'mmArchive', 'mmDataTable'].

You'll also be warned if you create any Specify blocks that you never use (typically unused atlases), if you reference any files that don’t exist (such as images), or if you don’t set up any output for your simulation. You might have intended this for some reason, so your file will still be created - it’s just a warning.

### B.2.4 Using Names Manually

Sometimes, usually when you want to schedule some kind of output, you may want to supply a name instead of using the hidden MIFCraft auto-names. You can do this by adding the extra argument 'name' to anything.

```plaintext
myMIF.TimeDriver(stopping_dm_dt=0.1,
  stage_count=1,
  Ms=myMs,
  m0=mym0,
  name='MyTimeDriver')
```
In most cases, names will be obvious - the Oxs_TimeDriver is called TimeDriver, the Oxs_UZeeman is called UZeeman, and so on. If you have more than one of a particular energy, though, you may find it helpful to use manual names to set up your output. Note: in the above example, to allow the demonstration code to fit on the page, a method of breaking strings over lines was used. This is not necessary, and you may simply use output='Oxs_TimeDriver:MyTimeDriver:Magnetization'.

B.3 Using Python: A More Advanced Example

Now we can apply control flow concepts that are missing from MIF files, particularly for loops. We’re also going to make some use of Python lists and string substitution.

B.3.1 Python Lists in Five Seconds

A list is surrounded by square brackets []. It can contain any number of items. For example, [1, 2, 3, 4, 5] is a list of numbers. You can make an empty list with []. To add something to a list, use nameOfList.append(something). For example,

```python
foo = [1, 2, 3]
foo.append(5)
```

foo is now the list [1, 2, 3, 5].

In MIFCraft, lists of names of Specify blocks are often handy in creating Multi-Atlases.
B.3.2 Python For Loops in Five Seconds

A for loop repeats a block of code several times, changing the value of a variable each time.

```python
for foo in ["a", "b", "c"]:  
    print foo
```

prints a, then b, then c. We can use this to create multiple MIF files, varying one or more parameters.

B.3.3 Python String Substitution in Ten Seconds

You can use '%s' in a string to copy the value of a variable into that string. The string is followed by % and then the variable names. For example,

```python
foo = 'inserted'
print 'You’ll see the variable %s here.' % (foo)
```

prints 'You’ll see the variable inserted here.' You can use multiple variables like this:

```python
foo = 'see'
bar = 'inserted'
print 'You’ll %s the variable %s here.' % (foo, bar)
```

B.3.4 Python Ranges in Five Seconds

When creating loops, you’ll often want to create a range of evenly spaced numbers for parameter variation. Here you should use the command `range(min, max, step)`, which gives all numbers between min (inclusive) and max (exclusive) separated by the given step. If no step is given, it’s assumed to be 1. For example, `range(1, 6, 2)` gives [1, 3, 5]. Remember the exclusivity: `range(1, 5, 2)` gives [1, 3]. So, instead of
foo = [1, 2, 3]
bar = [1, 3, 5, 7]
for i in foo:
    for j in bar:
        ...

you can conveniently use

for i in range(1, 4):
    for j in range(1, 8, 2):
        ...

B.3.5 Varying Parameters in MIF Files

Let’s assume that for some reason we really want to do the same simulation as in our first example, only we really want to try the simulation at various values for the saturation magnetization, say 500e3 to 1100e3. We don’t want every single one, so let’s do 500e3, 600e3, 700e3, and so on. Let’s modify our script to produce several different MIF files, each the same except for the saturation magnetization. We’ll want to make a MIF file for each one. For convenience, let’s put them all in a subdirectory mifs. We can do this very easily:

```python
for satLimit in range(500e3, 1101e3, 100e3):
    with MIF(filename='mifs/sat_%s.mif' % satLimit,
             basename='sat_%s' % satLimit) as M:
        Brick = M.BoxAtlas ...
...
    satMag = M.UniformScalarField(value = satLimit)
...
```

This will create seven output files in the mifs subdirectory, named sat_500e3.mif, sat_600e3.mif, and so on. The same technique can be used to vary any parameter you like. If you want to explore a two-dimensional parameter space, you can do something like

```python
for firstParam in range(1, 10, 1):
    for secondParam in range(50, 250, 50):
```
with MIF(...)

and all possible pairs will be used. All you need to do is choose appropriate filenames and basenames.

In the HideousExample subfolder, there is an example from my recent research: a permalloy bar with conductive gold pads attached to it at regular intervals. This causes the current density through the bar and the Oersted field generated by the pads to modulate along its length of the bar. Additionally, the geometry of the gold pads can be varied to modulate the current drop vs. the resultant Oersted field... and the pads can be placed above or below the pad, changing the sense of the Oersted field for a propagating domain wall of given chirality. The Oersted field was previously modeled, so it’s just a matter of plugging in numbers. Modulating these parameters means defining plenty of BoxAtlases in each simulation to capture all the different regions!

In this case, my MIFCraft script was just over 100 lines, including some comments. This produced 1,282 distinct simulation files, each over 700 lines long! Good thing OOMMFq can control batches of simulations. When there’s some amount of symmetry in the problem, using loops with MIFCraft can save plenty of work. Take a look at a Python tutorial and see what you can do.

B.4 Common Tricks

B.4.1 Organizing MIF Files and Data

It’s possible to use MIFCraft to generate really enormous volumes of data. I’ve found it’s useful to put all my MIF files in one folder, and all the outputs in another folder with subfolders for each MIF file. For example, if I have MIFs/foo.mif and MIFs/bar.mif, the output will be in data/foo/ and data/bar. Since MIFCraft
generates directories automatically as needed, this is easily accomplished as follows.

```python
for someParameter in range(5):
    with MIF(filename='MIFs/MySim_%s' % someParameter,
             basename='data/MySim_%s/MySim' % someParameter):
        ...
```

Using string substitution in folder names is an easy way to keep data well-sorted.
Appendix C

OOMMFq and OOMMFLink

OOMMFq is a batching system for automatically deploying a series of simulations. OOMMFLink allows remote querying of the status of the service and remote uploading and enqueueing of simulations. It was written in Python and was released as open-source under the GPL. They are available directly from http://web.mit.edu/daigohji/projects/OOMMFq/ and http://web.mit.edu/daigohji/projects/OOMMFLink/. As a warning to users, OOMMFq is in the beta state, and OOMMFLink is still in early alpha. Documentation for OOMMFq follows; OOMMFLink is still in active development.

- OOMMFq Version 0.1 1/11/11

C.1 OOMMFq

OOMMFq is a queuing system for the OOMMF micromagnetic simulation code. It monitors the number of active simulation and allows the user to drag and drop simulation specification MIF files into a queue which will be run as previous simulations finish. It maintains information on the runtime of active and complete sims for reference. It may also be operated as a server for the companion program OOMMFLink,
which allows remote users to upload and enqueue sims or inquire about the state of running sims.

The Py2EXE-wrapped Windows version is designed to be portable and free of external dependencies. The program otherwise has the following dependencies:

- Python (2.6 preferred)
- wxPython (Unicode)
- OOMMF
- Tcl/Tk
- Twisted
- Zope (a Twisted dependency)

### C.1.1 Configuration

Before use, OOMMFq must be informed of the path to oommf.tcl, as well as the correct Tcl shell command (probably `tclsh`, which is the default, but on ActiveTcl 8.5 for Windows, it’s `tclsh85`). You may either use the Load OOMMF button or drag-and-drop the oommf.tcl file itself to provide this path. Like all OOMMFq configuration options, this path is saved to the oommfq.conf configuration file as soon as it is set.

You may also wish to set the number of concurrent simulations in the Active Simulations panel. By default, this number is one-half the number of processors.

To use the OOMMFLink server functionality, you will need to set a port on the OOMMFLink Server panel. You may also change the "Start server automatically" checkbox, which determines whether or not the OOMMFLink server is launched as soon as OOMMFq is run.
C.1.2 Utilization - Scheduler

The Active Simulations panel shows which simulations are currently running, as well as which user enqueued them and how long they’ve been running. Simulations highlighted in red had some kind of error, and the simulation file should be checked. These sims do not count against the running simulation count, and are simply displayed for clarity. You may click the Clear Errors button when you no longer need this information.

To enqueue simulations, you may drag and drop MIF files onto the window or click the Add Sims button. These sims will be enqueued under the username currently in the name box just under the Add Sims button. Sims will be executed in the order they appear, from top to bottom.

To change the priority of simulations, highlight any number of simulations and click the green up or down arrow. To dequeue simulations, highlight any number of simulations and click the red X.

C.1.3 Utilization - Network

OOMMFq can receive remote enqueue requests and file uploads from OOMMFLink clients as long as the server is running. Check your IP/hostname and port in the OOMMFLink Server panel, and click Start Server if the server is not already running. Sims uploaded by users will be automatically enqueued, and uploaded files are placed in the /remote/$USERNAME/$BATCHNAME subdirectory of your OOMMFq directory, where $USERNAME and $BATCHNAME are supplied by the connecting user. In general, server operation should be entirely painless and no maintenance is needed.

When the server is halted with the Stop Server button, existing file transfers are allowed to finish, but no new connections will be accepted.
C.2 Known Bugs

For unknown reasons, OOMMF boxsi processes zombify on Windows around 10% of the time. Since OOMMFq waits for a termination code from a process as the cue to launch another simulation, this can cause batch execution to stagnate. The user must identify which OOMMF instances are using no CPU or have an excessive runtime, and terminate them manually with `kill` or the Windows Task Manager. This will cause them to terminate properly and batch execution will continue.

Tasks cannot currently be batch-deleted. This feature will be added.