Domain wall dynamics in ferromagnetic cylindrical and planar nanostructures

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DOMAIN WALL DYNAMICS IN FERROMAGNETIC CYLINDRICAL AND PLANAR NANOSTRUCTURES

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Summary

This thesis presents a comprehensive study on domain wall (DW) dynamics in NiFe cylindrical and planar nanostructures. In cylindrical nanowires of relatively low aspect ratio, a three dimensional helical DW is found to separate two vortices of opposite chirality. The formation of helical DW is controlled by introducing geometrical modulations along the nanowire. The magnetic charge calculation at the helical DW shows an abrupt transition between two opposite charges (positive to negative or vice versa). To verify the micromagnetic simulations, compositionally modulated nanowires are grown by pulsed electrodeposition at two different potentials. Differential etching of the two layers of NiFe with different compositions leads to the formation of constrictions. The presence of the helical DWs in the constricted cylindrical NiFe nanowires is verified by magnetic force microscopy (MFM) imaging. At high aspect ratio, transverse DWs that are found in sub-50 nm cylindrical nanowires are shown to possess an intrinsic oscillatory behavior in the translational motion. Moreover, in the absence of external energies, the oscillations are governed by the energy transfer from the DW rotations. Such oscillations are self-sustained and unique to the transverse DWs in cylindrical nanowires. By setting up a magnetostatically coupled nanowire system, an infinite oscillation is achieved by the application of current to balance the DW coupling. The sustained oscillation is analogous to simple harmonic motion between a compressed and relaxed state of the DW. Solving the simple harmonic equation unfolds the finite the mass associated with the DW in cylindrical nanowires which was assumed to be mass less in previous studies. The transverse DW pinning and depinning mechanisms are studied at the geometrical

modulations in the planar and cylindrical nanowires. In planar nanowires, DW pinning potential is found to be chirality dependant at an anti-notch structure. The potential barrier undergoes a transition from smooth and gradual to steep and abrupt shape as the dimensions of the anti-notch are varied. In cylindrical nanowires, the DW pinning has shown contrary behaviors with the application of current and magnetic field. Interestingly, an increase in the notch depth results in lowering the depinning current density. The DW deformation and rotation assist the spin-polarized current in depinning process. The degree of DW deformation is higher at the deeper notch and lowers the depinning current density. The DW pinning at the anti-notch has shown two different phenomenon as the height of the anti-notch is varied. At lower dimensions, the pinning mechanism follows the trend similar to the notch. However, at higher dimensions, the DW transformation from transverse to vortex configuration causes the lowering in the barrier height in the field driven case. The barrier potential rises for the current driven case due to the vortex chirality switching within the anti-notch. In planar NiFe nanostructures, the DW injection methods using local Oersted field and the external magnetic field are presented. The key focus is devoted to the transverse DWs in narrow nanowires. Using patterned nanostructures, techniques to control, detect and rectify the DW chirality are presented by using MFM imaging. The selective motion of the vortex core in the presence of the linear magnetic field assists in DW chirality detection. Two different switching mechanisms of the DW within a slanted rectangular structure result in rectifying the chirality of the transverse DW. Finally, a DW based reconfigurable magnetic logic is demonstrated in which a single structure performs all the basic logic operations. Two underlying

principles, transverse DW selective switching and the effect of transverse Oersted field on the DW are verified experimentally by MFM imaging.

Chapter 1

Introduction

Conventional microelectronic devices operate based on the displacement of charge. The semiconductor technology has been dominating the electronics market since the inception of transistor with rapid developments in miniaturizing the size of the devices in the past five decades. But the size of the transistor is reaching its fundamental limits, where the electrons are not able to comply with classical mechanical laws. Quantum mechanical effects assist the electrons to tunnel through the gate causing leakage current. These infinitesimal currents produce enormous heat due to the dense packing of billions of transistors in processors and memory devices. The current trend of charge based devices is approaching the limit where alternative technologies are needed.

Currently, research all over the world is focused on finding a potential alternative to replace the charge based semiconductor technology to store and process data. Besides charge, electron has another property known as “spin”. Spin can be regarded as the fourth dimension of the electron. It is a quantum mechanical angular momentum having two directions unlike the electron charge. It can take one of the two states relative to the magnetic field, generally known as “up” and “down”. These two directions can be assigned to two binary data bits “1” and “0”.

Spin based devices famously known as “spintronic” devices have the potential to outperform the conventional electronic devices due to their remarkable advantages. The spin switching is much faster than the charge transfer. The lower power consumption and high endurance make them attractive. Above all, the spin based devices are non-volatile. One of the most successful spintronic devices is the mass storage hard disk drive. Though

this hard disk technology is successful in providing ultrahigh density at low cost, the rotation speed of the disk limits the data rates. The mechanical positioning of the head on the bits makes it less robust. The permanent call for higher storage densities and faster data rates is pushing this technological approach to its fundamental limits. These limits in miniaturization of the bits as well as of the read-and-write heads pose challenges to the storage density.

Various alternative spintronic technologies were proposed such as MRAM (magnetic random access memory) and STT-MRAM (Spin Transfer Torque MRAM) in the last decade [1]. MRAM is an array of magnetic tunnel junctions (MTJ) in which the data is stored as the magnetization orientation. The Oersted field generated by the strip lines switches the data, and the current passed through the MTJ reads the data. The current strip lines for writing pose both scalability and power issues. The next generation STT-MRAM uses current to switch the magnetization via spin transfer torque (STT) effect between the ferromagnetic layers instead of Oersted field [2]. Currently, a lot of research is going on to overcome the technological challenges to commercialize it as a memory device.

Recently, magnetic domain wall (DW) based memory has been proposed by IBM known as racetrack memory [3,4]. The DWs in a ferromagnetic nanowire are driven by the spin-polarized current via STT effect to move the data along the racetrack [5,6]. The DWs are also promising for the applications in magnetic logic. Alwood *et al.*, [7,8] have demonstrated the first magnetic logic where DW acts as a medium for the logic operation. Memory is to store the data and logic is to process the data. If the DW based memory and logic are combined, a novel spin based integrated circuit can be realized which is a pure

non-volatile technology with ultra-high speed and very low power consumption. Nevertheless, there is a need for better understanding of the DW behavior in ferromagnetic nanostructures. To this end, this thesis focuses on some of the features of the DW dynamics in ferromagnetic nanostructures.

1.1 Basics of Ferromagnetism

To gain an insight into the origin of DWs in ferromagnetic materials, it is imperative to start with basics of ferromagnetism. The origin of ferromagnetism can only be fully described according to the quantum mechanical principles. The classical mechanical approach on ferromagnetism was first given by Weiss based on his molecular field theory [9] in 1907. Weiss postulated that there exists a strong internal interaction field, which aligns the atomic moments in a common direction. Weiss theory could succeed in explaining the spontaneous magnetization of the material and temperature dependent phenomenon, which is known as Curie-Weiss law. However, it remained a mystery that an external field of few tens of A/m is able to switch the magnetization even though the internal molecular field is much stronger in the order of 10^9 A/m. To explain this controversial phenomenon, Weiss proposed the idea of magnetic domains. In each individual domain, the direction of the magnetic moment is dominated by the molecular field, while the overall orientations of domains can be different. The average of all the domains is the total moment. Weiss's theory lays the foundation for the understanding of the ferromagnetic behavior, but the origin of the molecular field theory cannot be fully accounted by the classical mechanics.

Heisenberg addressed the origin of molecular field using a quantum mechanical approach due to electrostatic exchange energy between electron spins in 1928 [10].

Exchange interaction is short-range and usually this effect is considered only between the neighboring spins. In the end, the ferromagnetism has turned out to be an electrostatic phenomenon. Heisenberg exchange theory provides basic understanding of ferromagnetism. However, it is difficult to obtain the properties of the macroscopic materials. Micromagnetism is an appropriate theoretical approach to address these issues.

Micromagnetics deals with magnetic systems as classical continuous objects with boundary conditions. Static and dynamic properties can be described by differential equations, which enable analytical and numerical simulation of magnetization dynamics. Various kinds of energies in a magnet are essential for the micromagnetic equations. In general, there are four types of energies that play crucial role on the properties of a ferromagnetic material:

Zeeman Energy

Exchange Energy

Anisotropy Energy

Demagnetizing Energy

1.1.1 Zeeman Energy:

The energy of interaction between the applied field H_a and the magnetization M of the material is given by the thermodynamic relation of the electrodynamics of continuous media

$$E_z = -\mu_0 \int_V M \cdot H_a dV \quad (1.1)$$

This energy term will be minimum when M is fully aligned with H_a .

If an external field H_a is applied to a dipole, it will align its spin vector with the direction of H_a . In order to rotate the particle to a position where its dipole vector μ makes an angle θ with the direction of the applied field, the amount of work required is equal to

$$e_z = -\mu \cdot H_a = -\mu H_a \cos(\Theta) \quad (1.2)$$

where e_z is called Zeeman energy and Θ is the angle between dipole and magnetic field.

To get overall Zeeman energy (E_z) of a sample of volume V , one needs to sum Eqn. (1.2) over all N_a atoms as

$$E_z = -\sum_{i=1}^{N_a} \mu_i \cdot H_a \quad (1.3)$$

We can generalize this expression to a continuum approximation, assuming the thermodynamic limit of huge N_a :

$$E_z = \int_V e_z dV = -\mu_0 \int_V M \cdot H_a dV \quad (1.4)$$

1.1.2 Exchange energy:

The formation of a ferromagnetic structure in a certain material is mainly due to the exchange interaction of its atoms, which is independent of the direction of the total magnetic moment of the sample. This interaction is a quantum mechanical effect resulting from the symmetry of the wave functions of the system with respect to the interchange of the particles. Macroscopically, this energy can be expressed in terms of the derivatives of M with respect to the coordinates.

$$E_x = A \int_V \sum_{i,j=x,y,z} \left| \frac{\partial m_i}{\partial r_j} \right|^2 dV \quad (1.5)$$

where A is a phenomenological exchange parameter with units of J/m.

This expression can be illustrated using the theoretical atomic dipole model for ferromagnets. The permanent magnetic dipoles of the ferromagnetic materials interact strongly between each other, even in the absence of external magnetic field. So, the spin interaction between nearest neighbors allows atoms in ferromagnets to align with each other. The interaction energy between a pair of neighbor atoms with spins S_i and S_j is often described by the Heisenberg model

$$e_x = -2J_{ij} \cdot S_i \cdot S_j \quad (1.6)$$

This energy is proportional to the dot product of the dipole moments of both atoms, and J_{ij} is the coupling constant between atomic spins. This coupling constant is given by the value of the quantum mechanical exchange integral between the wave function associated with atoms i and j ; hence, it has the units of energy.

Usually it is a good approach to consider J_{ij} as a constant throughout the material. Therefore, J_{ij} can be replaced by J in Eqn. (1.6). For every pair of atoms in a ferromagnetic material, $J > 0$, whereas in Antiferromagnetic substances, $J < 0$. As a result, spins will tend to align anti-parallel to each other in antiferromagnets.

To calculate the total exchange energy of the material (E_x), Eqn. (1.6) has to be summed over all the pairs nearest to the neighbors. This continuum generalization gives us the general expression for this energy term:

$$E_x = \int_V e_x dV = A \int_V \sum_{i,j=x,y,z} \left| \frac{\partial m_i}{\partial r_j} \right|^2 dV \quad (1.7)$$

where A is the material constant

A can be determined by

$$A = \frac{J}{a^2} \quad (1.8)$$

for which a is the lattice constant.

It can be easily seen that E_x and A have same sign. If the magnetization varies too rapidly in a short distance, E_x will be very high. Physically, this energy term will have a smoothing effect on the dipole orientation, introducing a preference for the atoms to remain aligned with each other. The exchange interaction will only dominate in short range, between atoms that are at a distance of the order of the Exchange length L_{ex} . This exchange length is the distance over which the magnetization will be roughly constant, and is approximately determined by

$$L_{ex} = \sqrt{\frac{A}{K_m}} \quad (1.9)$$

where K_m is the energy density given by

$$K_m = \frac{1}{2} \mu_0 M_s^2 \quad (1.10)$$

For permalloy ($\text{Ni}_{80}\text{Fe}_{20}$), $M_s = 8 \times 10^5$ A/m and $A = 1.3 \times 10^{-11}$ J/m, which gives an exchange length of 5.7 nm corresponding to about 17 unit cells.

1.1.3 Anisotropy Energy:

Crystalline materials are magnetically anisotropic because there is a preferential direction for the orientation of the dipoles lying along the main crystallographic axis of the structure. There exists an internal field that forces the net magnetization to align with certain axis of the crystalline structure and K is the anisotropic vector that defines the so called easy direction. For instance, in a hcp crystalline structure, K would be parallel to

the c axis of the hexagonal cell. The magnetocrystalline anisotropy energy (E_k) is defined as the work needed to rotate the sample magnetization to a certain direction from easy direction, and it is determined by a series expansion of trigonometric functions of the angles that the magnetization vector makes with the main crystallographic axis. Two types of magnetocrystalline anisotropies can be defined as

- **Uniaxial anisotropy** occurring in hexagonal crystals such as cobalt.

$$E_k = \int_V (K \sin^2 \Theta) dV \quad (1.11)$$

Here θ is the angle between the $\overset{V}{\text{easy}}$ axis direction and magnetization and K is the energy density (J/m^3). Higher order terms, like $\sin^4 \Theta$ and $\sin^6 \Theta$ can be included, but it has been verified that they are insignificant.

- **Cubic anisotropy** for example, iron and nickel

$$E_k = \int_V K_0 + K_1 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_1^2 \alpha_3^2) dV \quad (1.12)$$

where α_1 , α_2 and α_3 are the direction cosines between the magnetization direction and crystal axis.

Minimization of this energy term causes the magnetization to align with the easy axis and it will also contribute to the memory effect of ferromagnets, called hysteresis, that enable us to store information in hard disk drives even after they are turned off, making the device non-volatile. This hysteresis effect is due to the resistance created by E_k , when the magnetization tries to switch to a direction away from the easy axis. It means that not all the angles are equally probable for the orientation of the magnetic dipoles of

the crystalline substance. So, higher is the anisotropy field, higher is the coercivity (H_c) of M-H loop.

1.1.4 Demagnetizing Energy:

The demagnetizing energy E_d corresponds to the interaction between the magnetization of the material and demagnetizing field H_d . This energy is given by a similar thermodynamic relation to the Zeeman term

$$E_d = -\frac{\mu_0}{2} \int_V (H_d \cdot M) dV \quad (1.13)$$

The factor of $\frac{1}{2}$ is analogous to the calculation of electrostatic energy between two charges. The energy due to the charge on another do not accumulate on each other.

Demagnetizing field

The magnetostatic or the demagnetizing field H_d , originated by M , can be calculated from basic Maxwell's electromagnetic equations

$$\nabla \times H_d = 0 \quad (1.14) \quad \text{and} \quad \nabla \cdot H_d = \nabla \cdot M \quad (1.15)$$

Since the curl of H_d is zero, this field can be given by the gradient of a certain scalar potential – the demagnetizing potential V_d :

$$H_d = -\nabla V_d \quad (1.16)$$

To understand the source of this demagnetizing field, we can think of an electric analogue. If we have a material with a certain polarization P inside it, that polarization creates electric charge on the surface of the material, normal to its vector direction. These charges are responsible for the creation of electrostatic potential,

described in Poisson equation. In a ferromagnet, similar case happens with the magnetization (instead of polarization). Since M is continuous inside the material, there will be an effective magnetic charge density ρ , defined by Poisson's equation:

$$\nabla^2 V_d = \nabla \cdot \mathbf{M} = -\rho \quad (1.17)$$

However, on the surfaces M is no longer continuous because this function jumps abruptly from M_s to 0. As a result, surface magnetic charges appear at the material boundaries with a density σ given by:

$$V_d^{out} = V_d^{in} \quad (1.18)$$

$$\left. \frac{\partial V_d}{\partial \mathbf{n}} \right|_{out} - \left. \frac{\partial V_d}{\partial \mathbf{n}} \right|_{in} = -\mathbf{M} \cdot \mathbf{n} = -\sigma \quad (1.19)$$

where $\mathbf{n}$ is the unitary vector normal to the surface.

Physically, magnetic charges emerge on a surface whenever the magnetization has a component normal to the surface. These charges are the source of demagnetizing field that are opposite to the normal magnetization of the material. Hence, this energy term aligns the magnetization parallel to the surfaces. After computing the charge distribution ρ (r) and σ (r) the solution to our Poisson problem - demagnetizing potential - is calculated as follows

$$V_d(r) = \int_V \frac{\rho(r')}{|r - r'|} dV' + \int_{dA} \frac{\sigma(r')}{|r - r'|} dA' \quad (1.20)$$

The demagnetizing field is given by the symmetry of the gradient of this solution, which upon integration gives E_d as

$$E_d = \int_V e_d dV = -\frac{\mu_0}{2} \int_V H_d \cdot M dV = +\frac{\mu_0}{2} \int_{-\infty}^{\infty} H_d^2 dV \quad (1.21)$$

where the last integral can easily be obtained by parts.

Minimizing this energy E_d corresponds to rotating the magnetic dipoles of the sample so that they create a minimum of magnetic charges on the surfaces, and that causes the material to be divided into different magnetic domains oriented in opposite directions (proposed by Weiss) as shown in Figure 1.1. In this way, the magnetic charges formed by a certain domain compensate the charges of adjacent domain, reducing E_d .

Hypothetically, if demagnetizing energy is the only term present, the material would break itself into smaller and smaller domains resulting in a zero total magnetization. The only thing that stops ferromagnets to do so is their particular exchange energy E_x . This energy term has the opposite effect of the E_d . As it was previously described, the atomic spins tend to align parallel to the orientation of their nearest neighbors. However, this exchange interaction has a very short range. So only the atoms within a distance of L_{ex} (eqn. 1.9) are forced to remain parallel. On the other hand, the magnetostatic forces are of long range, hence the demagnetizing energy has a more significant effect over greater distances, whereas the exchange dominates over short distances.

Figure 1.1 schematic illustration of the of magnetization breakup into domains to reduce the demagnetization field

It is the balance between these two energies that is responsible for the formation of magnetic domains, which are going to be separated by walls. These walls are called domain walls (DW). They are of particular interest because of atomic dipoles that are rotated about 180° from one side of the wall to the other, that is, from the orientation of one domain to the orientation of the adjacent one, as represented in figure 1.2.

The thickness of these DWs, however, will also be influenced by the anisotropy energy. This energy E_k forces the magnetic domains to align along the easy direction. So, supposing we have two antiparallel domains next to each other, lying along the easy axis of the sample, then the magnetic dipoles that remain in the DW will have to rotate 180° (as can be seen in figure. 1.2). Thus, these separating dipoles will take direction outside the easy one, and for that reason the E_k “prefers” to create a very thin wall, while E_x wants to enlarge it.

Figure 1.2 This illustration is a schematic representation of an 180° domain wall.

1.2 Micromagnetic equilibrium- Brown's equation

In a state of constant temperature and external applied field, the minimum of the free energy gives us the equilibrium state [11]. The free energy of the ferromagnetic body can be obtained by summing the various energy terms described in previous section 1.1

$$E_{\text{tot}} = \int_v \left[A(\nabla M)^2 + E_K - M_s m \left(H_a + \frac{H_d}{2} \right) \right] dV \quad (1.22)$$

By considering a first order variation of the free energy, we arrive at the following

$$m \times \left[\frac{2A}{M_s} \nabla^2 m + H_d + H_a + H_K \right] = 0 \quad (1.23)$$

where H_k is anisotropy field.

Equation (1.23) is known as Brown's equation. In the equilibrium, torque is zero everywhere and the magnetization is parallel to an effective field.

$$H_{eff} = \frac{2A}{M_s} \nabla^2 m + H_d + H_a + H_K \quad (1.24)$$

Brown's equation lays basis for the classical micromagnetic approach for solution of stationary problems.

1.3 Micromagnetic dynamics-LLG equation

In order to complete the micromagnetic model, there is a need to describe the evolution of the system by introducing the dynamics equation. In this section, we state the results of Landau and Lifshitz, and the modification made by Gilbert to obtain the Landau-Lifshitz-Gilbert (LLG) equation.

The gyromagnetic precession of a vector field M in the presence of external field is given by

(1.25)

$$\frac{\partial M}{\partial t} = -\gamma M \times H_a$$

where H_a is the external magnetic field and γ the gyromagnetic ratio. When H_a is replaced by the effective field H_{eff} given in Equation 1.25, we get

$$\frac{\partial M}{\partial t} = -\gamma M \times H_{eff} \quad (1.26)$$

This equation describes a continuous precessional motion where dissipative process is not taken into account. Landau and Lifshitz [12] introduced an additional damping term to correct this and the following equation was obtained:

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\lambda}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) \quad (1.27)$$

where $\lambda > 0$ is a constant that is unique to the material.

Figure 1.3: Sketch of the damped magnetization precession under the influence of an effective field.

In 1955, Gilbert [13] reformulated the theory as he realized that the damping term introduced by Landau and Lifshitz cannot account for large damping. The damping term introduced by Gilbert is of the form

$$\frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \quad (1.28)$$

where $\alpha > 0$ is a constant that is unique to the material.

The precessional equation modified by Gilbert, now referred to as the Landau-Lifshitz-Gilbert equation, is

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \quad (1.29)$$

The equation proposed by Landau and Lifshitz and the one reformulated by Gilbert is proved to be equivalent.

1.4 Domain wall energy and thickness

Two semi-infinite domains separated by a 180° Néel wall in a uniaxial sample are considered. The DW thickness is considered to be δ which contains n layers of spins, so that $\delta = na$ where a is the lattice constant. For simplicity, we assume that the angles between neighboring spins in the wall are a constant at $\theta = \pi/n$ and that the anisotropy energy density within the wall is a constant K .

The angle between spins, θ , is small, so that the exchange energy between a pair of spins in equation 1.6 can be approximated [14] as

$$-2JS^2 \cos\theta = JS^2\theta^2 - 2JS^2 \quad (1.30)$$

where the last term is a constant. Since there are n/a^2 number of spins in a unit wall area, The exchange energy of the wall can then be written as

$$E_{ex} = \frac{n}{a^2} (JS^2\theta^2 - 2JS^2) = \frac{\pi^2 A}{na} + C = \frac{\pi^2 A}{\delta} + C \quad (1.31)$$

where $A = JS^2/a$ is known as the exchange stiffness constant and C is a constant. Note that the exchange energy is inversely proportional to the wall thickness ($K \sim 1/\delta$) so that the

exchange energy prefers the DW to be infinitely thick. Since the semi-infinite domains occupy the easy axis directions, the magnetizations in the domain wall are pointing in the hard axis. The cost of the anisotropy energy is in the order of K , the anisotropy constant, per unit volume of wall. This gives us

$$E_a = K \left(\frac{n}{a^2} \right) a^3 = Kna = K\delta \quad (1.32)$$

per unit wall area due to anisotropy. Note here that the anisotropy energy is proportional to the wall thickness ($K\sim\delta$), so that anisotropy compresses the DW to be as thin as possible. We can then obtain the total wall energy per unit area to be

$$E_{wall} \approx \frac{\pi^2 A}{\delta} + K\delta \quad (1.33)$$

In short, the DW thickness is simply a competition between the anisotropy and the exchange energy.

1.4.1 Bloch wall and Néel Wall

There are two kinds of domain walls that exist in the ferromagnetic material depending on the thickness of the thin film. Bloch walls and Néel walls are distinguished by the direction of spin rotation within in the domain wall (DW) [15]. In Bloch wall, the spins rotate out-of-plane [16] (in the wall plane) whereas in the Néel wall spins rotate in-plane (through the wall plane) between two domains of magnetization direction [17, 18].

Figure 1.4 Schematic illustrations of the Bloch wall in thick films and Néel Wall in thin films

1.4.2 Transverse and Vortex domain walls

According to the spin structure within a DW, the Néel wall can be broadly differentiated in two transverse wall and vortex wall [17]. In the transverse DW, the spins rotate in the plane of the structure. An asymmetric width of the DW along the y -axis yields a triangular shaped wall as shown in Figure 1.5 and the transverse component of the wall has two directions which can be defined as chirality of the transverse DW. If the spins point along $+y$ - direction, the DW is said to possess an Up chirality and in the case where the spins point along $-y$ -direction, the DW is said to possess a Down chirality. The vortex wall has a different magnetization configuration. The spins in the wall curl clockwise or counter-clockwise around the vortex core which determines the orientation of the vortex wall with the magnetization pointing out of the plane in the $+z$ or $-z$ direction as shown in Figure 1.5. The types vary with geometry and the material properties. The phase diagram of the energetically stable walls with the geometry has been calculated by M. Donahue [19]. However, further differentiation on the walls has

been proposed by Thiavelli *et al.* [20] which adds a different asymmetry in the transverse wall type. The phase diagram calculated by the later is shown in Figure 1.6.

Figure 1.5 Spin configurations of a transverse and vortex DW

Figure 1.6 Phase diagram of stability of the transverse and vortex DWs in planar nanostrips according to the thickness and width of the nanowire [21].

1.4.3 Magnetic charge possessed by transverse DW

A transverse DW is characterized by the magnetic charge it carries. A head to head (HH) DW in which the two domains converge at the DW (spins pointing towards each

other) possesses a positive charge. A tail to tail (TT) DW in which the two domains diverge at the DW (spins pointing away from each other) possesses negative magnetic charge. The magnetic charge calculations can be performed by taking the divergence of the magnetization along the DW according to this formula

$$Q = -\nabla \cdot \vec{M} \quad (1.34)$$

where Q is the magnetic charge and M is the magnetization.

The transverse DW is defined by a triangular shape [22]. The magnetic charge calculations at the two edges *i.e.* the apex and base of the triangle can be seen in the Figure 1.7. For a HDDW, the base of the triangle contains positive charge and the apex of the triangle has negative charge.

Figure 1.7 Magnetic charge possessed by the transverse (HH) DW in planar nanowire

However, the magnetic volume pole of the nanowire shows that the positive charge dominates and compensates the negative charge. For a TTDW, the base of the triangular shape possesses negative charge and the apex possesses the positive charge

with effective charge being negative. Thus a transverse DW acts as a magnetic monopole. In the transverse DW, 70% of its charge is concentrated at the 20% of triangular base [22]. The stray field exerted by the DW due to the magnetic charge plays a significant role in the interactions due to magnetostatic coupling between the DWs [23-32]. The magnetic charge possessed by the DW decides the type of potential disruption at the pinning sites in nanowires [33-36]. The magnetostatic interaction between the DW and the external nanomagnets allows a remote pinning for DW without creating any pinning sites along the nanowires [37].

1.4.5 Transverse DW chirality

Besides magnetic charge, the transverse DW is also characterized by an additional parameter called “chirality” defined by the direction of the transverse magnetization of the DW. Transverse component is always orthogonal to the magnetization of domains. The transverse magnetization pointing along +y- direction is called “Up” chirality DW. The magnetization pointing along the -y-direction is called “Down” chirality DW. The DW chirality plays an important role in DW based applications due to the unique features such as charge and energy distribution along the transverse component [14,22]. The transverse DW can also be seen as a combination of two topological defects +1/2 and -1/2 [38,39]. The arrangement of the edge defect in the DW can affect the DW interactions [40,41]. When two transverse DWs of opposite magnetic charges (HH and TT) are relaxed close to each other, they attract each other. This attraction can result either in annihilation of the DWs or formation of a bound state depending on the edge defect arrangement of the two DWs as shown in Figure 1.8. When similar kind of edge defects face each other (opposite chirality of the DWs), the two DWs annihilate upon collision. When opposite edge defects

face each other (same chirality of the DWs), they form a 360° DW upon collision even though annihilation is the lowest energy state [42-44].

Figure 1.8 Winding numbers assigned according to the edge defects for transverse DW and effect of the edge defects on the outcome of collision between HHDW and TTDW.

1.5 Spin transfer torque induced domain wall motion

When current is applied to a ferromagnetic material, the conduction electrons become spin-polarized due to spin dependant scattering. These conduction electrons align according to the local magnetization because of the angular momentum transfer from local moments. To conserve the total angular momentum, the conduction electrons exert a torque on the local moments which is called spin transfer torque. This effect is called spin transfer torque (STT) effect. L. Berger, first predicted that spin transfer torque is able to drive the DWs in ferromagnetic materials [45-47]. Though the DW motion is demonstrated in ferromagnetic thin films using a very high current [48,49], the concept was not received much attention for almost a decade. Later, Slonczewski and Berger independently predicted that when current is applied perpendicular to a Giant magneto

resistance (GMR) multilayer, STT can switch the free layer magnetization [50-52]. Later, these results were experimentally confirmed by Tsoi *et al.*, [53]. Slonczewski predicted that the STT either switches the magnetization of the free layer or drives the magnetization into steady state precession as the spin torque may act against the damping torque as shown in Figure 1. 9. His assumption was spin transfer torque is an adiabatic process. However, later experiments proved that there is also a non-adiabatic process which takes place along with the adiabatic process during the STT. The origin of a non-adiabatic term was accounted by various groups in different methods to explain the experimental results including momentum transfer concept [54,55], spin mistracking [56,57], and spin-flip scattering [58].

Figure 1.9 Schematic shows the directions of three different torques acts on the magnetization m under the application of magnetic field and current

The DW motion driven by STT gathered attention recently due to the racetrack memory proposed by IBM [3]. When two neighboring DWs are driven by an external magnetic field, they move in opposite direction to either annihilate or move away [59]. However, when the DWs are driven by STT, they all move in the direction of conduction electrons. In racetrack memory, the information or data bits are stored as the magnetization direction of the domains in ferromagnetic nanowires. The DWs separating these data bits move through the track due to the STT effect by the application of current. The direction of the current demonstrates the motion of the DWs and data bits. The GMR sensor embedded within the nanowire reads the signal and the stray field generated by the strip line on the nanowire writes the bits. The DW motion is precisely controlled by the pinning sites along the nanowire.

1.5.1 Extended Landau-Lifshitz-Gilbert Equation

Though there is no complete understanding on the origin of the current induced STT, it is believed that at least two different mechanisms cause the DW motion. With the spin-polarized current applied to the system, dynamical evolution of the magnetization should include the STT effect on the local magnetization. The modified LLG equation [60] can be written as

$$\frac{\partial \mathbf{M}(t)}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}(t)}{\partial t} - (\mathbf{u} \cdot \nabla) \mathbf{M} + \frac{\beta}{M_s} \mathbf{M} \times [(\mathbf{u} \cdot \nabla) \mathbf{M}] \quad (1.35)$$

where $\mathbf{M}$ is the magnetization, M_s is the saturation magnetization of material u is the electron drift velocity, γ_0 is the gyromagnetic ratio, α is the Gilbert damping constant and β is the non-adiabatic parameter.

The first two terms account for the torque by the effective field H_{eff} and the Gilbert damping torque, parameterized by a dimensionless α as described previously in section 1.3. The rest of the terms are the STT terms which explain the two mechanisms behind the DW motion induced by a current. As proposed by Slonczewski, the first term describes the angular momentum transfer between the conduction electrons and the local spins of the material. In this case, it is assumed that when the electrons move across the DW, they adjust their spin orientations adiabatically to the direction of the local moments while transferring angular momentum to the DW.

The adiabatic STT term can be written as

$$STT_1 = (u \cdot \nabla) M \quad (1.36)$$

where u is the conduction electron velocity quantified by magnitude of the spin transfer torque given by

$$u = \frac{g\mu_B p}{2eM_s} \quad (1.37)$$

for which g , μ_B , and e are the Landè factor, Bhor magnetron, and electron charge, respectively, M_s is the saturation magnetization and p is the conduction electron spin polarization has the value estimates the range from 0.4 to 0.7.

The second term, which is generally called as non-adiabatic STT term can be defined as

$$STT_2 = \frac{\beta}{M_s} M \times [(u \cdot \nabla) M] \quad (1.38)$$

There is still a lot of confusion on the second mechanism; it is generally believed that it originates from the spatial mistracking of the conduction electron spins and the local moments. The spin-polarized conduction electron can be scattered (reflected) if it cannot follow the local moments. Linear momentum transfer from the reflected conduction electrons to the local moments can also result in DW motion. This mechanism is generally called as the non-adiabatic spin transfer process, where the non-adiabaticity represents the mistracking of the conduction electron spins and the local moments. β is the non-adiabatic parameter, which quantifies the relative contribution of non-adiabatic STT to the adiabatic term.

1.6 Domain wall resistance

When current is applied to a ferromagnetic nanowire with a DW, the conduction electron spin scattering occurs at the DW due to a change in the local magnetization [61-63]. In general, the conduction electrons reflect from the local moments due to the scattering which results in a change of resistance. The presence and absence of a DW in the nanowire can be detected by this change in resistance, called DW resistance. The DW resistance can be understood from the anisotropic magnetoresistance effect (AMR) [64-68]. AMR is the change in the resistance of the magnetic material due to change in the relative orientation between the current and local magnetization. The origin of the AMR effect lies in the interaction between conduction s-electrons and localized 3d electrons. In the absence of a magnetic field, s-electrons scatter by the 3d electrons. In the presence of magnetic field, the cloud of the 3d-electrons deforms which affects the s-electron scattering, changing the resistance. The change in resistance can be either positive or negative depending on the material.

AMR effect can be explained by a simplified equation

$$R(\Phi) = R(0) - \Delta R \cos^2(\Phi) \quad (1.39)$$

where $R(0)$ is the resistance at zero applied field and Φ is the relative orientation between the current and the applied magnetic field (local magnetization). Thus, the resistance is lower when the magnetization is perpendicular to the current. The DW has a component perpendicular to the nanowire length and the current leading to a drop in the resistance. The drop in resistance due to the DW's presence is very small compared to the AMR typically $\sim 0.2 \Omega$.

1.7 Domain walls in cylindrical nanowires

It was predicted that two kinds of reversal modes can be observed in cylindrical nanowires namely transverse reversal mode and vortex reversal mode [69]. The transverse reversal mode occurs by the nucleation of transverse DW in the lower diameter nanowires whereas the vortex reversal mode occurs due to the nucleation of a vortex DW in higher diameter nanowires [70]. The boundary between these two kinds of DWs is predicted to be 50 nm. A transverse DW which exists in cylindrical nanowires of diameter below 50 nm has the transverse component perpendicular to the nanowire's long axis [71]. When the nanowire diameter is more than 50 nm, the demagnetization energy allows the spins to follow the cylindrical surface to form a vortex spin structure at the cross-section of the DW [72]. Though the structures of the DWs are similar to the planar nanowire, the geometrical symmetry in the cylindrical nanowire leads to the different properties of dynamics when they are driven by magnetic field or spin-polarized current.

Figure 1.10 The transverse (top) and vortex (bottom) DWs that are found in cylindrical nanowires and the respective cross-sectional images

A transverse DW follows a spiral like motion around the nanowire's long axis along with the translational motion when driven by magnetic field [71]. The additional degree of motion around the nanowire's long axis comes from the torque acted on the perpendicular spins in the transverse DW. In case of vortex DW, the vortex rotates around its own axis during the lateral motion along the long axis. For a particular field, mobility of the vortex DW is higher compared to the transverse DW in cylindrical nanowires. An opposite behavior was reported when these two DWs are driven by current [73]. The spiral motion of the DW during translational motion prevents the structural breakdown of the fast moving DWs while driven by a magnetic field or current. Absence of structural breakdown allows the transverse DW in sub-50 nm cylindrical nanowires to beat the Walker breakdown limit [74]. This in turn makes the speed of the DWs in cylindrical nanowires to reach higher speeds compared to the DWs in planar nanowires. When the DW reaches its saturation speed, the energy dissipates *via* spin wave emission.

1.8 Objectives of the thesis

The focus of this thesis revolves around DW structures and dynamics in permalloy cylindrical and planar nanostructures. Specific objectives of this thesis are given below:

- i. To study the spin configurations and DW structures in permalloy based cylindrical nanostructures of various dimensions.
- ii. To study the domain pinning and depinning mechanisms at geometrical modulations in cylindrical and planar nanowires.
- iii. To propose and demonstrate methods to inject and detect a transverse DW with a specific chirality.
- iv. To propose and demonstrate magnetic logic devices by exploiting DW dynamics in planar nanostructures.

1.9 Organization of the thesis

Chapter 1 presents the background and motivation of the work carried out in this thesis. Brief introduction on various theoretical aspects of ferromagnetism, DW formation, DW motion and DW properties in ferromagnetic nanowires is given.

In chapter 2, various experimental and characterization techniques employed in this work are discussed.

Chapter 3 presents the spin configurations and DW formations in relatively large diameter cylindrical NiFe nanostructures

In Chapter 4, magnetic field induced DW oscillations and self-sustained (intrinsic) DW oscillations observed in a single and coupled NiFe nanowire systems are discussed.

Chapter 5 focuses on DW dynamics driven by magnetic field and spin-polarized current at the geometrical modulations in ferromagnetic planar and cylindrical nanowires.

In chapter 6, the DW injection method by magnetization reversal is demonstrated. Transverse DW chirality selection and detection processes are presented. A structure which can perform DW rectification is demonstrated. A novel DW-based reconfigurable logic device which can perform all basic logic operations is demonstrated.

Chapter 7 summarizes the overall work presented on the DW dynamics in ferromagnetic nanowires in this thesis. Insights for possible future work are discussed.

Appendix A presents the micromagnetic calculations on a novel GMR sensor, differential dual spin valve (DDSV). The interlayer exchange coupling effect on the sensitivity of DDSV is discussed.

Appendix B presents a detailed study on the STT noise in multilayer DDSV. The effects of the interlayer coupling, thickness of the various layers and the orientation of the external field on the critical current density for the onset of the STT noise are discussed.

Appendices C and D present the DW injection into nanowires by current and oblique magnetic fields, respectively.

References

1. A V Khvalkovskiy *et al.*, *J. Phys. D: Appl. Phys.* **46** 074001 (2013).
2. R. Sbiaa *et al.*, *Appl. Phys. Lett.* **99**, 092506 (2011).
3. S. S. P. Parkin, M. Hayashi and L. Thomas, *Science* **320**, 190 (2008).
4. X. Jiang, L. Thomas, R. Moriya, M. Hayashi, B. Bergman, C. Rettner and S. S. P. Parkin, *Nature Commun.* **1**, 25 (2010).
5. A. J. Annunziata *et al.*, *Symp. On. IEDM* PP. 24 (2011).
6. J. H. Franken, H. J. M. Swagten and B. Koopmans, *Nature Nanotech.* **7**, 499 (2012).
7. D. A. Allwood, Gang Xiong, M. D. Cooke, C. C. Faulkner, D. Atkinson, N. Vernier, R. P. Cowburn *Science* **296**, 2003 (2002).
8. D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit and R. P. Cowburn, *Science* **309**, 1688 (2005).
9. P. Weiss, *Bulletin de la Societe Francaise de Physique* **1**, 95 (1907).
10. W. Heisenber, *Zeitschrift fur Physik* **49** 619 (1928).
11. W. F. Brown, Jr.: *Micromagnetics* (Wiley, New York, 1963).
12. L. Landau and E. Lifshitz *Physikalische Zeitschrift der Sowjetunion.*, **8**, 153 (1935).
13. T.L. Gilbert, *IEEE Trans. Mag.*, **40**(6), 3443 (2004).
14. C.H. Marrows, *Advances in Physics*, **54**(8), 585 (2005).
15. B. N. Filippov, *Physics of Solid state* **54** 2407 (2012).
16. M. Redjda, J. Giusti, M. F. Ruane, and F. B. Humphrey, *J. Appl. Phys.* **91**, 7547 (2002).

17. M. Kläui, *J. of Phys.: Condensed Matter*, **20**(31), 313001(2008).
18. G. Catalan, J. Seidel, R. Ramesh, and J. F. Scott, *Rev.Mod. Phys.* **84**, 119 (2012).
19. R. D. McMichael, and M. J. Donahue, *IEEE Trans. Magn.* **33**, 4167 (1997).
20. Y. Nakatani, A. Thiaville, and J. Miltat, *J. Magn. Magn. Mater.* **290**, 750 (2005).
21. G.S.D. Beach, M. Tsoi, J.L. Erskine, *J. Magn. Magn. Mater.* **320** 1272 (2008).
22. H. T. Zeng, D. Petit, L. O'Brien, D. Read, E. R. Lewis, and R. P. Cowburn, *J. Magn. Magn. Mater.* **322**, 2010 (2010).
23. M. Vázquez, G. A. Basheed, G. Infante, and R. P. Del Real, *Phys. Rev. Lett.* **108**, 037201 (2012).
24. A. Jiménez, R. P. Real, and M. Vázquez, *Eur. Phys. J. B* **86**, 113 (2013).
25. L. O'Brien, D. Petit, H. T. Zeng, E. R. Lewis, J. Sampaio, A. V. Jausovec, D. E. Read, and R. P. Cowburn, *Phys. Rev. Lett.* **103**, 077206 (2009).
26. L. O'Brien, A. Beguivin, A. Fernandez-Pacheco, D. Petit, D. E. Read, and R. P. Cowburn, *Appl. Phys. Lett.* **101**, 062415 (2012).
27. I. Purnama, M. Chandra Sekhar, S. Goolaup, and W. S. Lew, *Appl. Phys. Lett.* **99**, 152501 (2011).
28. T. J. Hayward, M. T. Bryan, P. W. Fry, P. M. Fundil, M. R. J. Gibbs, D. A. Allwood, M.-Y. Im, and P. Fischer, *Phys. Rev. B* **81**, 020410(R) (2010).
29. M. Laufenberg *et al.*, *Appl. Phys. Lett.* **88**, 212510 (2006).
30. L. O'Brien, E. R. Lewis, A. Fernández-Pacheco, D. Petit, and R. P. Cowburn, *Phys. Rev. Lett.* **108**, 187202 (2012).
31. I. Purnama, M. Chandra Sekhar, S. Goolaup, and W. S. Lew, *IEEE Tans. Mag.* **47** 3081 (2011).

32. D. Petit, *et al.*, *J. Appl. Phys.* **103**, 114307(2008).
33. M. Chandra Sekhar, S. Goolaup, I. Purnama and W. S. Lew, *J. Phys. D: Appl. Phys.* **44**, 235002 (2001).
34. D. Petit, *et al.*, *Phys. Rev. B* **79**, 214405 (2009).
35. M. Hara, *et al.*, *Appl. Phys. Lett.* **89**, 192504 (2006).
36. D. Petit, *et al.*, *Appl. Phys. Lett.* **93**, 163108 (2008).
37. L. O'Brien *et al.*, *Phys. Rev. Lett.* **106**, 087204 (2011).
38. O. Tchernyshyov, and G. W. Chern, *Phys. Rev. Lett.* **95**, 197204 (2005).
39. Y. Shen, O. Petrova, P. Mellado, S. Daunheimer, J. Cumings, and O. Tchernyshyov, *New J. of Phys.* **14** 035022 (2012).
40. K. Zeissler, S. K. Walton, S. Ladak, D. E. Read, T. Tyliczszak, L. F. Cohen, and W. R. Branford, *Sci. Rep.* **3**, 1252 (2013).
41. A. Pushp, T. Phung, C. Rettner, B. P. Hughes, S.-H. Yang, L. Thomas, and S. S. P. Parkin, *Nat. Phys.* **9**, 505 (2013).
42. L. Thomas, M. Hayashi, R. Moriya, C. Rettner, C. and S. S. P. Parkin, *Nature Comm.* **3**, 810 (2012).
43. A. Kunz, *Appl. Phys. Lett.* **94**, 132502 (2009).
44. S. Zhang *et al.*, *J. Magn. Magn. Mater.* **347**, 123 (2010).
45. L. Berger, *J. Appl. Phys.* **3**, 2156 (1978).
46. L. Berger, *J. Appl. Phys.* **3**, 2137 (1979).
47. L. Berger, *J. Appl. Phys.* **55**, 1954 (1984).
48. L. B. P.P. Freitas, *J. Appl. Phys.* **57**, 1266 (1985).
49. L. B. C.-Y. Hung, *J. Appl. Phys.* **63**, 4276 (1988).

50. J. C. Slonczewski, *J. Magn. Magn. Mater.* **159**, L1 (1996).
51. L. Berger, *Phys. Rev. B* **54**, 9353 (1996).
52. J. C. Slonczewski, United States Patent #5,695,864, December 9 (1997).
53. M. Tsoi, A. G. M. Jansen, J. Bass, W. C. Chiang, M. Seck, V. Tsoi, and P. Wyder, *Phys. Rev. Lett.* **80**, 4281 (1998).
54. G. Tatara, and H. Kohno, *Phys. Rev. Lett.* **92**, 086601 (2004).
55. G. Tatara, H. Kohno, and J. Shibata, *J. Phys. Soc. Jap.* **77** (2008).
56. X. Waintal, and M. Viret, *Euro phys. Lett.* **65**, 427 (2004).
57. A. Vanhaverbeke, and M. Viret, *Phys. Rev. B* **75**, 024411 (2007).
58. S. Zhang, and Z. Li, *Phys. Rev. Lett* **93**, 127204 (2004).
59. Junya Shibata, Gen Tatara and Hiroshi Kohno, *J. Phys. D: Appl. Phys.* **44**, 384004 (2011).
60. A. Thiaville, Y. Nakatani, J. Miltat and Y. Suzuki, *Euro phys. Lett.* **69**, 990 (2005).
61. G. Tatara and H. Fukuyama, *Phys. Rev. Lett.* **78**, 3773 (1997).
62. E. Simanek, *Phys. Rev. B* **63**, 224412 (2001).
63. U. Ruediger, J.Yu, S. Zhang, A. D. Kent and S.S.P. Parkin, *Phys. Rev. Lett.* **80**, 5639 (1998).
64. L. Bocklage, F.U. Stein, M. Martens, T. Matsuyama and G. Meier, *Appl. Phys. Lett.* **103**, 092406 (2013).
65. M. Munoz and J. L. Prieto, *Nature Comm.* **2** (562) 1 (2011).
66. J. H. Franken, M. Hoeijmakers, H. J. M. Swagten, and B. Koopmans, *Phys. Rev. Lett.* **108**, 037205 (2012).

- 67. Z. Yuan, Y. Liu, A. A. Starikov, Paul J. Kelly, and A. Brataas, *Phys. Rev. Lett.* **109**, 267201 (2012).
- 68. M. Hayashi, *et al.* *Nature Phys.*, **3**(1) 21-25 (2007).
- 69. R. Hertel, *J. Magn. Magn. Mater.* **249**, 251(2002).
- 70. R. Hertel and J. Kirschner, *Physica B* **343**, 206 (2004).
- 71. R. Wieser, U. Nowak and K. D. Usadel, *Phys. Rev. B* **69**, 064401 (2004).
- 72. N. Biziere *et al.*, *Nano Lett.* **13**, 2053 (2013).
- 73. R. Wieser, E. Y. Vedmedenko, P. Weinberger and R. Weisendanger, *Phys. Rev. B* **82**, 144430 (2010).
- 74. M. Yan, A. Kakay, S. Gliga, and R. Hertel, *Phys. Rev. Lett.* **104**, 057201 (2010).

Chapter 2

Experimental Techniques

2.1 Introduction

This chapter presents the details of fabrication and characterization techniques employed in this work to study the DW dynamics. For the fabrication of NiFe nanowires, both top-down and bottom-up approaches are employed in this work. The cylindrical nanowires were grown by template assisted electrodeposition method and the planar nanowires were patterned using electron beam lithography and ion-milling techniques. These two fabrication procedures are discussed in detail. Magnetron sputtering and vacuum evaporation techniques were used for the growth of NiFe thin films and the metal contact depositions. Scanning electron microscopy was used for the structural characterization of the NiFe nanostructures. Electron diffraction (EDX) was used to find the composition of the NiFe nanowire. Magnetic Force Microscopy was employed for the magnetic imaging of the nanostructures to understand the DW dynamics behavior. The measurement set-up for current injection through the stripe line to generate the local Oersted field and the electromagnet to generate the magnetic field to drive the DW are presented.

2.2 Electrodeposition

Electrodeposition is a chemical process in which an electric current is used to reduce the metal cations from an electrolyte. The cations deposit as a film of metallic

material onto a conductive substrate, fixed to the cathode of the electrical circuit [1]. Electrodeposition is one of the most efficient techniques used to grow magnetic nanowires. This method is attractive because of cost effectiveness with minimal environmental requirements compared to the lithography techniques. Electrodeposition allows the fabrication of nanowires with different materials (multilayer) and also with different compositions [2-7]. In this fabrication process, pulsed electrodeposition was used to grow compositionally modulated cylindrical nanowires. The pulsed-electrodeposition setup can be seen in Figure 2.1.

Figure 2.1 The Electrodeposition setup used for cylindrical permalloy nanostructure growth.

Figure 2.1 illustrates various components and their functions in the nanowire growth. The sample which was attached to a metallic clip acts as a cathode. A platinum mesh electrode of 99.9% purity was used as an anode and a saturated calomel electrode (SCE) as the reference electrode. To achieve different compositions along the NiFe nanowires, a pulsed potential is applied similar to the pulse shown in Figure 2.2. The

potential was supplied via a potentiostat (VersaSTAT 3 from Princeton Applied Research[®]) and controlled using the included VersaStudio software.

Figure 2.2 The pulse applied by Verastat 3 system during the electrodeposition

Commercial porous Anodic Aluminum Oxide (AAO) membrane from Whatman (AnodiscTM) [8] was used as a template for the nanowire's growth. The pores are uniform to allow the growth of cylindrical nanowires. It is an established method that the AAO template can be dissolved in sodium hydroxide (NaOH) of 2M molarity. A conductive layer was grown on the backside of the AAO template as a seed layer for the nanowire growth. Often, a thick (400 nm) Al is coated using thermal evaporation at a high vacuum. Once the AAO template was prepared, it was attached to a conducting substrate. The substrate used was a copper tape. Non-conducting Kapton[®] tape was used to seal the sides of the AAO template to prevent NiFe growth outside of the template.

The chemical bath prepared was of nickel sulfate (NiSO_4), iron sulfate (FeSO_4) and boric acid (H_3BO_3) of 40ml in volume. This bath was used as an electrolyte. Boric

acid catalyzes electrodeposition by either forming a complex with Ni^{2+} or by adsorptive interactions at the electrode surface to improve deposition efficiency. It also acts as a buffer to maintain the pH of the electrolyte [9]. Each compound was prepared by weighing the mass for the required molarity.

The AAO template with the substrate was attached to the metallic clip at the cathode in the electrodeposition setup. A pulsed potential was then applied to initiate the growth of the nanowires. In the successful fabrication of nanowires, the solution consisted of NiSO_4 (0.5M), FeSO_4 (0.02M) and boric acid (0.5M) at pH 4.19 and temperature at 40°C . After the growth of nanowires, the sample was immersed in NaOH of molarity 2M for approximately five hours to ensure that AAO is removed completely. The Al grown as a seed layer was also removed to release the nanowires as single strands. The released nanowires were stored in isopropyl alcohol before etching in HNO_3 . Figure 2.3 shows the scanning electron microscopy (SEM) image of the grown nanowires dispersed on a Si substrate. The diameter of the NiFe nanowires is around 350 nm. The nanowires are uniformly grown. The uniformity is found to be 90 %.

Figure 2.3 Scanning electron micrograph of the NiFe nanowires of 350 nm diameter grown by electrodeposition technique.

2.3 Electron beam lithography

Electron beam lithography (EBL) is a very high resolution nano-patterning technique. It is analogous to photolithography in which the substrate with resist is exposed to highly accelerated electrons instead of light. Due to its small spot size, EBL is one of the best techniques for creating extremely fine patterns down to sub-10 nm. The prime advantage is that due to the electron wavelength, it beats the diffraction limit of the light to create features in nanometer range. Lithography is a two step process; first, the surface of the substrate coated with a resist is exposed to light or electron beam and then the resist is developed in which selective areas exposed are removed (positive resist) or the unexposed areas are removed (negative resist). Unlike photolithography, EBL does not need any mask; the patterns drawn using software are directly written on the resist. However, the throughput is very small in this process due to the line (raster) scanning.

In this work, two kinds of resists were used. Primarily, MAN 2403 was used for the nanowire patterning and PMMA was used for patterning of contact pads. MAN 2403 is a high resolution negative resist and it is easy to strip after ion-milling. A step by step working procedure is shown in the Figure 2.4

1. The sample was cleaned in acetone and IPA for 20 mins each by ultrasonication. Ta/NiFe/Ta thin film layers were deposited using magnetron sputtering.
2. MAN 2403 was spin-coated at 6000 rpm for 60 sec. The expected film thickness is around 200 nm. The resist coated substrate was baked at 100°C for 1 min on a hot plate. The sample was loaded to the EBL machine via load lock.

Figure 2.4 A step by step process for e-beam patterning with negative resist

3. Elionix ELS 7000 EBL system was used to pattern the samples. The beam is accelerated at 100 keV. The current is fixed at 30 pA. The beam was focused on Au nanoparticles several times to ensure that the current is stable and the beam is well focused. The nanowire patterns were drawn in the Autocad software [10] and were

transferred to the EBL software. The drawings decomposed into the small lines were written on the resist by e-beam exposure [11].

4. MAD 525 developer was used to develop the resist. The substrate was dipped in developer for 90 sec and thoroughly rinsed in DI water for 5 mins.

5. The metal layer which was exposed after development was removed by Ar-ion beam milling.

6. The residue of the resist left on the substrate after ion-milling was removed by dipping the substrate in PG remover for two hours in ultrasonication. The sample was cleaned in IPA and dried with N₂ gas.

The metal contact pads were made using PMMA resist which is a positive e-beam resist. The method for positive resist differs from the negative resist. The detailed steps of patterning using positive resist are given as shown in Figure 2.5

1. The sample was cleaned using acetone and IPA.
2. PMMA was coated using spin-coater with 4000 rpm for 45 sec. The expected resist thickness is 140 nm. The substrate was pre-baked at 180°C for 5 mins.
3. The sample was loaded into EBL chamber and the patterns were written by e-beam.
4. PMMA was developed in a solution prepared with 1:3 of MIBK:IPA for 30 sec and cleaned in IPA for 1 min followed by blow drying under N₂ gas.
5. Cr/Au film was deposited as a contact layer on the resist using vacuum evaporation.
6. The metal lift-off was done by dipping the substrate in acetone.

Figure 2.5 A step by step process for e-beam patterning with positive resist

2.3.1 Ar-ion milling

Patterns made by the EBL with negative resist needs ion-beam etching to remove the unexposed area of metal film deep down to the substrate to float the patterns covered by the resist. In this work, Veeco ion beam etching system was used for milling. Samples were loaded via load lock. The base pressure of the system was 10^{-8} Torr. The schematic

in Figure 2.6 shows ion-source and sample holder in the main chamber. The fast moving Ar ions bombard with the substrate to release the metal atoms from the film. To avoid redeposition onto the substrate with resist, the ion-milling was always performed at an oblique angle of 10° rotation instead of orthogonal position.

Figure 2.6 A schematic drawing of the ion-beam etching system

The power applied during ion-beam etching was 300 Watt and the working pressure was 2×10^{-4} Torr. The substrate holder was cooled by water flow to avoid burning of the resist due to the high temperature generated by the ion-beam. The substrate holder was rotated at 10 revolutions/min to ensure uniform etching.

2.3.2 Lift-off

Lift-off is a process of removing the residue resist on the substrate after the metal deposition. The sample was dipped into warm (60°C) acetone to etch away the resist. The resist gets dissolved in the acetone and the metal layer on top is removed from the substrate. The metal with no resist at the bottom stands on the substrate as the patterned area.

2.4 Metal deposition

In this work, the metallic layer was deposited on pre-cleaned Si with 300 nm thick SiO₂ for nanostructure fabrication. Substrates were cleaned in Acetone and IPA for 20 mins in ultrasonic bath. The samples were blown with N₂ gas. Ta/NiFe/Ta (5 nm/10 nm/5 nm) multilayer was grown using magnetron sputtering technique. Bottom Ta layer acts as a seed layer for NiFe growth and the top Ta layer acts as a capping layer to avoid oxidation. For contact pads, Cr/Au (5 nm/120 nm) metallic contact layer was deposited using vacuum evaporation. Thin Cr layer was used to enhance the adhesion between SiO₂ and Au. It avoids the Au peel-off during the lift-off process. The following two subsections describe the underlying principle and the system configurations used for metal depositions using magnetron sputtering and vacuum evaporation methods.

2.4.1 Magnetron sputtering

Sputter deposition is a method of depositing thin films by releasing the atoms from target by bombarding with accelerated Ar-ions, which then deposit onto a substrate. A schematic is shown in Figure 2.7 to describe the key components of the sputtering deposition system. Ar-plasma plays a crucial role in the sputtering process. The incident argon ion sets off collision cascade in the target. When such cascades recoil and reach the target surface with energy above the surface binding energy, an atom can be ejected. The average number of ejected atoms from the target per incident ion can be defined as sputtering yield. The sputtering yield depends on the incident angle, energy, mass of the ion and target atoms, and the surface binding energy of atoms of the target. Sputtered

atoms ejected from the target are not in their thermodynamically equilibrium state due to their high energy in gas phase.

Figure 2.7 A schematic diagram of the sputtering process

The atoms tend to deposit on all surfaces in the vacuum chamber. The wafer placed on the substrate holder is coated with the atoms which forms a thin film of the respective target material.

The magnetic poles fitted on the target holder as shown in Figure 2.8 play a vital role in the sputtering deposition. The magnetic flux generated near the target enhances the sputtering rate by increasing the electron path length by making the electrons move in a spiral motion.

Figure 2.8 Magnetic flux generated at the target surface to enhance the collision between the electrons and Ar atoms which increases the deposition rate.

The sputtering deposition was carried out using an in-house built sputter system. This system consists of a main chamber interconnected with a load-lock to transfer samples into the deposition chamber without breaking the vacuum. The chamber has the capability of holding six different target materials. The base pressure in the chamber is always maintained at 2×10^{-8} Torr. The system is capable of DC, RF and co-sputtering. The deposition pressure is controlled by a baratron valve. DC sputtering was used to deposit Ta and NiFe. The sample holder is at the center of the chamber with a self rotation to ensure uniformity in the film deposition.

The deposition rate is mostly determined by the power and the uniformity is determined by the deposition pressure. The deposition rate can be increased by increasing the power. To get a uniform film, it is advisable to grow at a lower deposition pressure. However, a minimum pressure needs to be maintained to ensure stable plasma formation. Ar-gas flow rate affects the film deposition, but in a minor way. Unless the flow rate is too low to maintain the deposition, it does not play an important role.

2.4.2 Vacuum evaporation

An Edwards 306 system was used for the deposition using evaporation. In our system, two thermal boats and one e-beam crucible are allowed. Both thermal and focused electron beam evaporation processes can be used for deposition of different materials without breaking the vacuum condition. Figure 2.9 shows a schematic of the evaporation system.

Figure 2.9 Schematic of the vacuum evaporation system.

The samples for coating are attached to the sample holder. The sample holder can rotate around the central axis to ensure a uniform thin film deposition. The main chamber is pumped by turbo molecular pump and the base pressure for the evaporation is better than 5×10^{-7} Torr. Cr coated Tungsten rods were used for thermal evaporation. The current passed through the rod was increased up to 2 A to heat the rod. Due to low vapor pressure, Cr melts at a lower temperature and transforms into vapor state which directly gets deposited onto the substrate. The sample holder was rotated at 20 revolutions/min for improving uniformity. A Quartz crystal monitor was installed inside the chamber to estimate the thickness. Au layer was deposited by e-beam evaporation. Pure Au pellets were placed in ceramic boat. The e-beam from the filament was collimated directly into the crucible by the magnetic lenses. The current was set at 17 mA. Accelerated e-beam heat the Au and melts it to evaporate onto the substrate.

2.5 Scanning electron microscopy

Scanning electron microscopy (SEM) is a powerful characterization technique in which a high energy focused electron beam scans on the surface of the material or thin film to extract the information about structural and chemical information of the system from micro to nanometers scales. Low wavelength of the electrons allows the SEM to resolve the features down to nanometer regime. When an accelerated electron hits the surface of a thin film, a few types of electrons and light rays are emitted as shown in Figure 2.10. The emitted electrons and X-rays carry the information about the material. Auger electrons and X-rays carry the characteristic energy which helps in elemental

identification. Secondary electrons which are emitted from few tens of nanometer depth of the material carry the information regarding the topology of the surface.

Figure 2.10 The different kinds of electrons and light rays of different wavelength emitted from different layer when an electron incident on a thin film surface.

A JEOL SEM system was used to image the nanostructures grown by electrodeposition and patterned by e-beam lithography. The chamber vacuum was maintained at 10^{-7} Torr to avoid any ion bombardment and electron scattering. The electron beam emitted from a coil is focused by the magnetic lens and acts as a probe to measure the topography. The secondary electrons are collected into a detector consisting of scintillator and photomultiplier to form the topographic image of the sample.

2.6 Transmission electron microscopy

Transmission electron microscopy (TEM) operates on the same basic principles as the scanning electron microscopy. TEMs use highly accelerated electrons and their much lower wavelength making it possible to get a better resolution compared to SEM. Electrons are generated by thermionic discharge process. The discharged electrons are accelerated by an electric field and focused by electrical and magnetic field lenses onto the sample. A photographic film or a fluorescent screen can be employed as electron detector. Achievable information from TEM is particle size, morphology and crystallographic structure.

2.7 Energy dispersive X-ray spectroscopy

Energy dispersive X-ray spectroscopy (EDX) makes use of the X-rays emitted by a solid sample to obtain a localized chemical analysis when a focused beam of electrons is bombarded with the sample surface. EDX is a common feature embedded in SEM or TEM systems. By raster scanning the beam on the sample, EDX displays the intensity of a selected X-ray line and elemental distribution maps are produced.

2.8 Scanning probe microscopy

Scanning probe microscopy (SPM) is a measurement technique, which involves raster scanning of a specific tip on the surface of the sample and interaction between the tip and surface atoms, gives the information about the sample. Several kinds of SPM techniques are atomic force microscopy, scanning tunneling microscopy, magnetic force microscopy, lateral force microscopy, force modulation microscopy, electrical force microscopy etc. The physical movement of the tip on the surface makes it a slow process

compared to the electron and X-ray microscopy techniques. A sharp tip (few nanometers) beats the wavelength of the light and electrons. SPM is fundamentally divided into Scanning tunneling microscopy and Atomic force microscopy.

2.8.1 Atomic Force Microscopy

Atomic Force Microscopy (AFM) is a type of scanning probe microscopy with very high-resolution. The AFM consists of a cantilever with a sharp tip at its end which scans the surface of the specimen as shown in Figure 2.11. The cantilever tip is made of few of atoms of SiN and the radius of curvature of tip is in the order of nm. When the tip is brought into a close proximity of the surface of the sample, Vanderwall's force between them deflects the cantilever. A laser spot reflected from the top of the cantilever is captured by the array of photodiodes to measure the deflection.

Figure 2.11 Schematic shows the working mechanism of the atomic force microscopy.

AFM operates by measuring the force between a tip and the sample that is either attractive or repulsive as shown in Figure 2.12. In the repulsive region, the AFM works in contact mode, where the tip directly touches the surface slightly at the end of a cantilever. The instrument drags the tip over the sample which is called raster scanning. The vertical deflection of the cantilever is measured by detection apparatus which indicates the local sample height. Thus, the repulsive forces between the tip and sample are measured in contact mode AFM. Non-contact mode works in the attractive region and the topographic images from AFM measurements are produced by the attractive forces. The tip scans few nm above the sample without touching the surface. This mode is called as tapping mode.

Figure 2.12 (left) The schematic shows the interaction between the tip atoms and substrate atoms during the scanning. (right) Interatomic force as a function of distance between the tip and sample which showed the two different modes of scanning, contact mode(repulsive force) and tapping mode (attractive force).

2.8.2 Magnetic Force Microscopy

In magnetic force microscopy (MFM) imaging, a tip coated with magnetic material is used to scan the surface to acquire the spatial variation of magnetic field instead of topographic information. MFM detects the force gradient between the tip magnetization and local magnetization on the surface of the sample [12-15]. Due to the magnetic coating, the spatial resolution of the MFM tip is lower compared to the AFM tip. Atomic forces are short range forces and magnetostatic forces are long range. So, MFM can work at a higher distance between the tip and the sample.

The force gradient acting on the cantilever tip due to the stray field from the sample is given by

$$\frac{\delta F}{\delta Z} = \int_{tip} \left(m_x \frac{\partial^2 H_x}{\partial^2 Z^2} + m_y \frac{\partial^2 H_y}{\partial^2 Z^2} + m_z \frac{\partial^2 H_z}{\partial^2 Z^2} \right) \quad (2.1)$$

where F is the magnetic force, Z is the coordinate perpendicular to the surface, m_x , m_y , m_z , H_x , H_y and H_z are magnetization component and field components at a particular point within the tip respectively.

Due to this force gradient, the tip vibrating at its resonance frequency suffers a shift in the frequency. The measured shift can be related to the force gradient by

$$\frac{\delta F}{\delta Z} = -2K \frac{\delta f}{f} \quad (2.2)$$

where K is the spring constant of the tip material, f is the resonance frequency of the tip. The frequency shift δf causes the phase difference which is used for mapping the MFM

image. The major problem with MFM imaging is the separation between the topological and magnetic data. To ignore the atomic forces, MFM scanning is performed in the Lift mode. The tip was lifted 50 nm above the sample during the scanning. Figure 2.13 shows two kinds of interactions between the tip and sample for in-plane and out of plane nanowires with DWs. For out of plane structures the repulsion and the attraction between the tip magnetization and the local magnetization of the sample leads to dark contrast. For in-plane structures, the stray field comes only from the DW and the contrast differentiates whether the DW is a head to head or a tail to tail DW. Figure 2.14 shows an MFM image of a hard disk, where bright and dark contrasts represent two bits of opposite magnetization orientations.

Figure 2.13 The interaction of the tip with local magnetization of out of plane and in-plane nanostructures and the expected the MFM image.

Figure 2.14 The MFM image of the hard disk platter. The bright and dark contrasts show two opposite local magnetizations of the islands which store the two different bits.

2. 9 Current injection and domain wall resistance measurements

To generate DW by local Oersted field [16] around the current carrying Au strip line, voltage pulses were injected into strip line as shown in Figure 2.15. One end of the strip line is connected to a pulse generator (picosecond pulse lab 10300B) and the other end is grounded. To confirm the DW generation, the resistance across the nanowire was measured during the pulse injection using Kethley 2400 voltmeter.

Figure2.15: The optical microscopy image of the nanowire for DW injection with connections. A schematic illustration of DW injection and the DW resistance measurement setup is overlaid on the image.

Figure2.16: Snapshot image of the setup for current injection and the DW driving by magnetic field

Figure 2.16 shows the current injection for local field generation (black arrows) and the DW driving by external magnetic field generated by the in-built electromagnet (red dotted arrows) are synchronized together on the probe station to experimentally verify the reconfigurable logic presented in the chapter 6.

2. 10 Summary

To summarize, electrodeposition for the fabrication of cylindrical nanostructures and e-beam lithography for patterning planar nanostructures are presented. The working principles of vacuum deposition techniques such as magnetron sputtering for NiFe deposition and physical evaporation for Au deposition are discussed. The key physics behind structural characterization by SEM and TEM systems are presented. The AFM and MFM techniques and the difference between the tapping, contact and lift mode are discussed in detail. The principle of the magnetic imaging using MFM is discussed. The probe station setup for current injection into the nanowire for DW injection and driving is presented.

References

1. D. Pletcher. A first course in electrode processes. *RSC Publishing*. pp 140 (2009).
2. H. F. Liew, S. C. Low and W. S. Lew, *J. Physics: Conference Series* **266**, 012058 (2011).
3. H. P. Liang, Y. G. Guo, J. S. Hu, C. F. Zhu, L. J. Wan and C. L. Bai, *Inorg. Chem.* **44**, 3013 (2005).
4. F. Beron, L. P. Carignan, D. Menard and A. Yelon, *IEEE Trans. Magn.* **44**, 2745 (2008).
5. F. V. Belle, J. J. Palfreyman, W. S. Lew, T. Mitrelias, and J. A. C. Bland, *AIP Conference Proceedings* **1025** (1), 34 (2008).
6. J. Choi, S. J. Oh, J. Cheon, *Nano Lett.* **5**, 2179 (2005).
7. P. Yong, T. Cullis, G. Mobus, X. Xu and B. Inkson, *Nanotechnology* **18**, 485704 (2007).
8. Whatman. *Anopore Inorganic Membranes (Anodisc)* 2009; Availablefrom: <http://www.whatman.com/PRODAnoporeInorganicMembraes.aspx>.
9. S. Shivakumara, *et al.*, *Bull. Material. Science* **30**(5), 455 (2007).
10. Auto-cad user guide is available at http://docs.autodesk.com/ACDMAC/2013/ENU/PDFs/acdmac_2013_users_guide.pdf
11. Electron beam lithography Elionix ELS 7000 Manual (2009).
12. A. Hubert, W. Rave, and S. L. Tomlinson, *phys. stat. sol. (b)* **204**, 817 (1997).
13. W. Rave, L. Belliard, M. Labrune, A. Thiaville and J. Miltat, *IEEE Trans. Mag.* **30**, 4473 (1994).
14. J. M. Gracia, A. Thiaville, J. Miltat, *J. Mag. Mag. Mat.* **249**, 163 (2002).

15. P. Grutter, D. Rugar, H. J. Mamin, *Ultramicroscopy*, **47**, 393 (1992).
16. M. Hayashi, *et al.*, *Phys. Rev. Lett.* **98**, 037204 (2007).

Chapter 3

Spin configurations of domain walls in cylindrical nanostructures

3.1 Introduction

In this chapter, the intuition of a new kind of three dimensional vortex domain wall (DW) that is formed in cylindrical nanowires is presented when the aspect ratio is reduced. The DW connects between the two vortices of opposite chirality and is twisted at the centre in helical fashion which is named as “Helical Domain Wall”. The controlled formation of the domain wall is discussed using micromagnetic simulations. The properties of the helical DWs are discussed using magnetic charge calculations. A method to fabricate the constricted NiFe nanowires using a combination of template assisted electrodeposition and differential etching in acid is described. The prediction of helical domain walls is verified by MFM imaging. The formation of complex helical DW structures is found in magnetic nanodiscs of various dimensions. The switching between the double to single vortex states is observed during reversal process. A novel method to fabricate the magnetic nanodiscs using chemical slicing of nanowires is proposed and experimentally shown in this chapter.

3.2 Motivation

Magnetization reversal in ferromagnetic cylindrical nanowires has drawn tremendous interest due to the geometrical symmetry and dramatic behavior of the DWs that are formed in the nanowires[1-3]. At high aspect ratio (long nanowire), the transverse DWs are stable configurations when the nanowire diameter is less than 50 nm above which the

vortex domain walls are stable micromagnetic structures [4]. These DWs are similar to their counter parts in planar nanowires where the transverse DWs are stable in narrow nanowires and vortex DWs are stable in wider nanowires [5]. In the case of planar nanowires, when the aspect ratio decreases, Néel walls in which magnetization rotates in plane gradually transform into Bloch walls where the magnetization rotates out of plane. However, in the case of the cylindrical nanowires there is no such definition of out of plane due to the cylindrical symmetry around the long axis [4-7]. At low aspect ratio (short nanowires), the DWs in cylindrical nanowires are expected to be different compared to the DWs in planar nanowires as the shape anisotropy can play an important role in changing the magnetization configuration. If a soft magnetic material is chosen for study, *e.g.* permalloy, the magnetization configuration is then predominantly decided by the interplay between the shape anisotropy and the exchange energies [8-11]. To date, very little is known about the DWs that are formed in the low aspect ratio cylindrical nanowires. Using micromagnetic simulations, such kind of novel DWs that exists in cylindrical nanowires are predicted and the results are validated experimentally.

3.3 Magnetization configurations of cylindrical nanowire at low aspect ratio

Three-dimensional micromagnetic simulations were carried out by using the OOMMF program [12]. The chosen unit cell size for all simulations is 10 nm × 5 nm × 5 nm in all the simulations. Permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) based cylindrical nanowires are considered. The material parameters were: saturation magnetization (M_s) = 860×10^3 A/m, exchange stiffness constant (A_{ex}) = 1.3×10^{-11} J/m and magnetocrystalline anisotropy $k = 0$. The nanowires are saturated with 1000 Oe field along the long axis and relaxed to zero field. The magnetization configurations shown are at the remanence (zero fields and zero

current). (Gilbert) damping torque, parameterized by Gilbert damping constant (α) which is fixed as 0.1 in our simulations for faster calculations. The magnetization states are converted to *.vtk* files to visualize in 3D using Mayavi software [13].

Shown in Figure 3.1 is the simulated magnetization configuration of 3- μm -long NiFe nanowires at remanence with diameter 150 nm. For nanowire with 150 nm diameter, the magnetization at the center region of the nanowire is aligned along the long axis because of the dominant shape anisotropy. However, at the two ends of the nanowire, the long axis shape anisotropy influence is reduced and the magnetization is allowed to curl following the cylindrical shape of the nanowire. The magnetization curls in clockwise or anti-clockwise orientation at each end.

Figure 3.1 Simulated magnetization configurations of non-constricted cylindrical NiFe nanowires with diameters 150 nm at remanent state.

As the nanowire diameter is increased to 250 nm, the long axis anisotropy is further reduced and the magnetization curling is extended towards the center of the nanowire, forming two distinct vortices as shown in Figure 3.2. When the diameter is further increased to 350 nm, the shape anisotropy energy completely dominates over the exchange energy, further extending the two vortices towards the center of the nanowire. Connection between these two vortices is complete *via* a gradual rotation of the magnetization at the center of the nanowire thus the transition regions forms a helical DW.

Figure 3.2 Simulated magnetization configurations of non-constricted cylindrical NiFe nanowires with diameters 250 nm and 350 nm at remanent state. When the diameter of the cylindrical nanowire increases, the two vortices gradually extended towards the center of the nanowire and eventually they are connected via a helical domain wall.

3.4 Controlled formation of the Helical DW

Introducing geometrical constrictions to the nanowire can lead to changes to the magnetization configuration. Shown in Figure 3.3 are the simulated magnetizations

configurations of a 2- μm -long constricted cylindrical NiFe nanowire of 350 nm diameter, with a constriction at the center. When the constriction diameter is 250 nm, the simulated magnetization configuration is almost identical to that of the non-constricted nanowire. However, when the constriction diameter is decreased to 150 nm, additional DWs are found to be created within the structure. This is due to the interaction between the axial magnetization in the constriction segment and the transverse vortex magnetization in the larger diameter segment. For every n constriction created in the nanowire, $(n + 1)$ DWs are present in the nanowire structure. The number of the DWs is directly related to the number of the constrictions in the nanowire, while the distance between the DWs can be controlled by varying the length of the nanowire and the constriction segment.

Figure 3.3 Simulated magnetization configuration of constricted cylindrical NiFe nanowires with a diameter of 350 nm at remanent state; the constriction dimensions are 250 nm and 150 nm.

3.5 Magnetic Charge at the Helical DW

Shown in Figure 3.4 is the calculated magnetic volume pole (Q) of a nanowire of 350 nm diameter along the long axis. The magnetic volume pole is calculated by finding the divergence of the magnetization in the nanowire ($Q = -\nabla \cdot \vec{M}$) [14]. The plot shows two different magnetic poles present along the nanowire and crossover from negative polarity to the positive occurs at the centre of the nanowire.

Figure 3.4 The variation of the magnetic volume pole as a function of the position of the nanowire along the long axis. Shown below are the snap shot images of the magnetization of the nanowire of 350 nm diameter along with cross-sectional view of magnetization at the two ends and the centre.

The magnetic volume pole resembles the magnetic charge which is analogous to the electric charge. The magnetic charge along the nanowire reveals that the two vortices of different chirality present in the nanowire possess different polarity. As can be seen from the vortices at the two edges of the nanowire, it is clear that the clockwise vortex core at the left edge is not at the centre but offset along the $+z$ direction and the counter-clockwise vortex at the right edge is offset along $-z$ direction. The slight offset of vortex core causes the imbalance of magnetization equilibrium generating a magnetic charge at that position. The clockwise vortex possess the negative magnetic charge whereas the anti-clockwise vortex posses the positive magnetic charge as the core offset direction is opposite in the two vortices, the transition region between the two vortices is the helical domain which can be seen as a crossover from the negative charge to the positive charge. The magnetic charge at the vortices is found to be increased abruptly at the centre which shows that there is a domain wall connecting the two vortices. The position of the vortex core varies until the centre of the nanowire and disappears close to the centre due to annihilation of vortex state. An S-shape magnetization along the Z-direction is formed close to the centre and magnetization rotates in opposite direction at the other side to reach the minimum energy state at the centre. The S-shape magnetization at both sides of centre causes the spikes in the charge. The region between the two peaks of maximum charge in vortices is the helical domain wall separating them.

3.6 Fabrication of the constricted cylindrical nanowires

To fabricate the constricted cylindrical NiFe nanowire, a combination of template-assisted electrodeposition and differential etching techniques has been employed [15-20]. By applying electrical potential to a three-electrode cell, metal ions are driven into

nanoporous template and material is deposited to form the desired metal nanowires. The applied potential strength and electrodeposition conditions are the key factors in determining the composition of the metal nanowires. The process flow of the fabrication is shown in the Figure 3.5. The chosen nanoporous template was the anodized aluminum oxide (AAO) (Anodisc 13, Whatman) and its backside was deposited with a 400 nm aluminium layer for electrical contact.

Figure 3.6 Schematic images to show the various steps in the fabrication of constricted cylindrical NiFe nanowires using pulse electrodeposition method

The template was immersed in a 40 ml electrolyte bath. To optimize the composition of NiFe, the relative concentrations of the $NiSO_4$ and $FeSO_4$ are varied while preparing the electrolyte bath. The NiFe nanowires were grown at potential $V = -1.4 V$. The ratio between the $NiSO_4$ and $FeSO_4$ are varied in the deposition bath. The electrolyte bath was prepared with three different concentrations [(0.5 M $NiSO_4$ & 0.03 M $FeSO_4$), (0.5 M $NiSO_4$ & 0.2 M $FeSO_4$) and (0.5 M $NiSO_4$ & 0.3 M $FeSO_4$)]. Shown in the Figure

3.6 are the Energy dispersive x-ray spectra of three nanowires with three compositions with the Fe concentration of 0.86, 0.56 and 0.36 corresponding to 0.03 M, 0.2M and 0.3M concentration of NiSO_4 , respectively. It shows that composition of the NiFe nanowire depends on the ratio of Nickel sulfate and Iron sulfate in the electrolyte bath. It makes the process attractive as tailoring composition of the NiFe nanowire may exhibit different properties

Figure 3.6 Energy dispersive X-ray spectrums of NiFe nanowires of various compositions grown by electrodeposition.

To achieve a NiFe composition close to permalloy in both the segments the electrolyte bath was prepared with 0.5 M nickel sulfate, 0.01 M iron sulphate, and 0.5 M boric acid ($\text{pH} = 4$). During the $\text{Ni}_x\text{Fe}_{1-x}$ nanowires growth at bath temperature 40°C , the deposition potential was alternately switched between a high potential ($V_H = -1.4\text{ V}$) and a low potential ($V_L = -1.0\text{ V}$) in a square waveform. The layer deposited at V_H showed different composition than that deposited at V_L , with the thickness of each layer being

directly proportional to the electrodeposition growth time. After the growth, the nanowires were released from the AAO template by dissolving them into 3M NaOH, assisted by ultrasonic agitation. The multilayered $\text{Ni}_x\text{Fe}_{1-x}$ nanowires were then thoroughly cleaned with deionized water before selectively etched by 1% HNO_3 .

3.6.1. Structural Characterization

SEM images of the etched nanowires are shown in Figure 3.7, which has a modulation of diameter due to the different etching rate between the layers.

Figure 3.7 SEM image of constricted $\text{Ni}_{95}\text{Fe}_5$ ($l = 125 \text{ nm}$, $\Phi = 350 \text{ nm}$) / $\text{Ni}_{87}\text{Fe}_{13}$ ($l = 50 \text{ nm}$, $\Phi = 250 \text{ nm}$) nanowires.

The etch rate for the layer deposited at V_L is about 5 nm/s while that of the V_H is negligibly small. Shown in Figure 3.8 are Energy dispersive x-ray (EDX) scanning measurements performed to confirm the $\text{Ni}_x\text{Fe}_{1-x}$ composition of the layers. The measurements reveal that the $\text{Ni}_x\text{Fe}_{1-x}$ composition is $\text{Ni}_{95}\text{Fe}_5$ and $\text{Ni}_{87}\text{Fe}_{13}$ in the segments deposited at V_H and V_L , respectively.

Figure 3.8 EDX measurements of the Ni_xFe_{1-x} nanowire deposited at applied potentials of -1.4 V and -1.0 V. The composition is determined to be $Ni_{95}Fe_5$ and $Ni_{87}Fe_{13}$. Inset shows EDX elemental line scanning of Ni and Fe elements (Ni red, Fe blue) along the multilayered $Ni_{95}Fe_5$ and $Ni_{87}Fe_{13}$ nanowires.

During the nanowires deposition, the reduction process is in favor of Ni^{2+} as the potential difference is increased, giving Ni-rich layers when V_H is applied. EDX line scanning was performed across the nanowires (inset of Figure 3.8) and the analysis shows an obvious decrease of Ni concentration at the $Ni_{87}Fe_{13}$ segment while the fluctuations of the Fe element at both segments are negligibly small. The reduced diameter $Ni_{87}Fe_{13}$ structure is considered the constriction region of the nanowire and its shape and size along the nanowires are well defined and uniform. The growth rates of the two different segments $Ni_{95}Fe_5$ and $Ni_{87}Fe_{13}$ are plotted in Figure 3.9. The growth rate is found to be linear for both the segments grown at low and high potentials. The deposition rate for $Ni_{95}Fe_5$ segment which is grown at a $V_H = -1.4$ V is found to be 30 nm/s approximately.

The deposition rate for $\text{Ni}_{87}\text{Fe}_{13}$ which is grown at a lower potential $V_L = -1.0$ V is found to be 2 nm/s.

Figure 3.9 (a) The growth rate of the $\text{Ni}_{95}\text{Fe}_5$ segment (b) The growth rate of $\text{Ni}_{87}\text{Fe}_{13}$ segment

Figure 3.10 shows the constricted structure of the $\text{Ni}_{95}\text{Fe}_5/\text{Ni}_{87}\text{Fe}_{13}$ cylindrical nanowires that can be well modulated by changing the deposition rate of the $\text{Ni}_{95}\text{Fe}_5$ and $\text{Ni}_{87}\text{Fe}_{13}$ segments. Three different length of modulated region are presented. This is achieved by controlling the pulse width during the electrodeposition.

Figure 3.10 A free standing individual strand of constricted $\text{Ni}_{95}\text{Fe}_5/\text{Ni}_{87}\text{Fe}_{13}$ nanowire with different dimension of constriction.

Crystallographic analysis was performed by transmission electron microscope (TEM) to visualize the nanowire surface morphology. The surface morphology imaging was carried out at the tip of the $\text{Ni}_x\text{Fe}_{1-x}$ nanowire and the results indicate that the nanowire is polycrystalline with domains of ordered structures, as shown in Figure 3.11 (b).

Figure 3.11 (a) TEM image of a constricted $\text{Ni}_{95}\text{Fe}_5/\text{Ni}_{87}\text{Fe}_{13}$ nanowire. Inset shows the selective area electron diffraction pattern. The dotted white rectangle is the tip of the nanowire (b) Surface analysis morphology at the tip of the nanowire.

3.6.2. Magnetic Characterization

For magnetic property measurement, the released $\text{Ni}_{95}\text{Fe}_5$ ($\text{Ø}=350$ nm)/ $\text{Ni}_{87}\text{Fe}_{13}$ ($\text{Ø}=150$ nm) nanowires were dispersed on silicon wafer and aligned by a large magnetic field. Figure 3.12 shows the hysteresis behaviors of the constricted cylindrical nanowires with fields applied parallel or perpendicular to the nanowire long axis, that measured by alternating gradient magnetometer (AGFM). For the field applied along the long axis, the hysteresis loop gives a remanence-to-saturation ratio $(M_r/M_s)(//)$ of 0.27. The obtained loop shape is relatively rectangular, which indicates that the easy axis is aligned along the long axis of the nanowires. When the field is applied perpendicularly to the nanowire axis, a sheared loop with a $M_r/M_s(\perp)$ ratio of 0.10 is obtained, which is a characteristic of hard-axis switching in the nanowires.

Figure 3.12 Hysteresis loop measurements of the constricted $\text{Ni}_{95}\text{Fe}_5/\text{Ni}_{87}\text{Fe}_{13}$ nanowires with a magnetic field applied parallel, $H_c(//)$ and perpendicular, $H_c(\perp)$ to the nanowire axis.

Magnetic force microscopy (MFM) scanning (Veeco Dimension 3100) was carried out on the constricted and non-constricted NiFe nanowires. A lift-scan-height of 50 nm [21] was chosen to optimize the magnetic signal. The nanowire samples were first magnetically saturated with a large external field along the nanowire long axis. The field was then removed so that the magnetization of the nanowire relaxed to its remanent state.

Figure 3.13 MFM image of the non-constricted cylindrical NiFe nanowire. Dark and bright magnetic contrasts shown at the two ends of the nanowire indicate the presence of two magnetic vortices with different chiralities. Also shown is the magnetic charge calculation along a non-constricted cylindrical nanowire.

Figure 3.13 shows the MFM image of the non-constricted cylindrical NiFe nanowire of diameter 250 nm. Dark and bright magnetic contrasts are observed separately at the two ends of the nanowire, indicating the presence of opposite magnetic charges. Also shown is the calculated magnetic charge along the 250 nm diameter cylindrical nanowire. From the plot, the magnetic charges can be ascribed to the curling of magnetization in vortex configuration with opposite chirality. The stray magnetic fields generated by clockwise or anticlockwise vortex magnetization are directly detected by the magnetic cantilever to produce the magnetic contrast. The image also reveals that the inner part of the nanowire between the two vortices has homogenous neutral contrast, and zero magnetic charge is found at the center of the nanowire which is an indication of a single-domain state. In principle, there should be no contrast at the single domain state but the shown weak neutral contrast is attributed to the residual topographic interactions between the tip and the nanowire. Therefore, the observed MFM scanning is in good agreement with the simulated magnetization configuration and the calculated the magnetic charge along the non-constricted nanowire, that the nanowire is composed of two vortices of opposite chirality separated by single domain state at the center.

Shown in Figure 3.14 is the MFM image of a constricted cylindrical NiFe nanowire. The image shows a series of alternate bright and dark contrast spots that are present along the nanowire, which is markedly different from the magnetic image of the non-constricted nanowire. The dark and bright magnetic contrasts present in the nanowire are due to the attractive and repulsive interaction between the tip and local magnetization of the nanowire. It reveals that clockwise and anti-clockwise vortices are present throughout the nanowire when the constrictions are introduced. Shown below the MFM

image is the calculated magnetic charge of a constricted cylindrical nanowire with a single constriction.

Figure 3.14 MFM image of the constricted cylindrical NiFe nanowire. The periodical bright and dark contrast spots represent the two different chirality vortices formed along the nanowire. A close-up view of the MFM image and a simulated magnetization configuration are shown for comparison. The boundary between the dark and bright spots indicates the helical DWs present in the constricted cylindrical nanowire. Shown below is the plot of magnetic charge variation along the constricted cylindrical nanowire.

The magnetic charge is found to be positive and turns into negative via the helical domain wall. The variation of the magnetic charge along the constricted cylindrical nanowire shows that two helical domain walls (1 and 2) present in the nanowire. The MFM image clearly supports the simulation results of formation of vortices throughout the constricted nanowires. The boundary between the dark and bright contrasts is the helical DW that connects the magnetization rotation from the clock-wise vortex to the anti-clockwise vortex. Similar spin structures are observed in Ni cylinders [22].

3.7 NiFe nanoparticles synthesis by chemical slicing

This section demonstrates an alternative method to fabricate disc shaped NiFe nanoparticles. The method of interest is by chemical slicing the compositionally modulated nanowires grown by pulsed electrodeposition. Magnetic nanoparticles (MNPs) have steadily gained traction in clinical applications due to their unique magnetic properties and the ability to function at the cellular and molecular level of biological interactions [23]. In this light, investigations into MNP applications such as magnetic resonance imaging, magnetic targeted drug delivery and magnetic hyperthermia [24,25] have been undertaken. Most notably, magnetic hyperthermia has been shown to improve survival rates when used to cure cancer [26,27]. In magnetic hyperthermia, an experimental cancer therapy, a high frequency alternating magnetic field of >100 kHz is applied to the MNPs to rapidly switch the chirality of the single magnetic vortex found in the disk-shaped MNPs [28]. In this process, heat is generated by the damping forces resisting the change in magnetization states. Therefore, the advantage of magnetic hyperthermia over the conventional cancer therapy is the localization of treatment to the cancerous tumor, which minimizes the harmful side effects to the patient. Nanoparticles with superparamagnetic nature have received a lot of attention due to zero magnetic moment at remanence [29]. However, the magnetic field required for manipulation is quite high due to low saturation magnetization [30]. The spin vortex states in NiFe nanodiscs are alternative with very small stray field at the remanence and the low field required for switching. Recently it was demonstrated that a slower alternating field of ~10Hz applied to NiFe magnetic disk of 1 μ m diameter has been shown to initiate programmed cell death by mechanically weakening the cell membrane integrity [31].

However, the traditional method to fabricate the NiFe MNPs is by lithography which suffers from low throughput and less control over the dimensions and composition. Here a novel MNP fabrication method with the aim of achieving a high throughput and control over the MNP profile such as material composition and dimensions is demonstrated.

3.7.1 Fabrication process

The MNP fabrication is similar to the fabrication of the constricted cylindrical nanowires discussed above. The fabrication steps are shown in Figure 3.15. Using pulsed electrodeposition, the compositionally modulated NiFe nanowires are grown. Alternating pulses of high potential ($V_H = -1.45\text{V}$) and low potential ($V_L = -0.95\text{V}$) were applied during the growth.

Figure 3.15 Key steps involved in the fabrication of NiFe magnetic nanoparticles using pulsed electrodeposition and differential etching.

The compositionally-modulated nanowires were released by dissolving the AAO template and aluminum coating in sodium hydroxide solution. The nanowires were etched with 0.67% dilute nitric acid. The etching occurs faster at the Fe rich layer as compared to the Fe deficient layer as discussed previously. It results in the formation of the

constrictions in the nanowire. For the constricted nanowire fabrication, the chemical etching was allowed to take place for a measured duration before the resulting solution is rinsed again to remove the excess acid. However, for the nanoparticle fabrication, the Fe rich layers are allowed to be etched completely. The disappearance of the Fe rich layers leave the Fe deficient layers remain as NiFe nanodiscs formed by chemical slicing as shown in Figure 3.16. In the last step, the solution is filtered through an 800nm Acrodisc syringe filter and the MNPs are recovered as the filtrate.

Figure 3.16 SEM image of the NiFe nanoparticles fabricated by electrodepositing and differential etching method.

3.7.2 Structural characterization of the nanoparticles

An advantage of this fabrication method is the easy control over the thickness of the MNPs via altering the duration of the high potential pulses V_H . The MNPs samples studied with SEM were prepared by placing one drop of MNPs diluted in Isopropyl

alcohol onto a gold substrate and then drying in vacuum for several minutes. MNPs with thickness of 70nm were fabricated with V_H pulse duration of 2s as shown in Figure 3.17(a). The increase in V_H pulse duration is proportional to the increase in MNPs thickness. Hence, other MNPs with thicknesses of 100nm, 250nm and 600nm have been obtained with V_H pulse duration of 3.2s, 8s and 50s respectively as shown in Figure 3.17(b-d).

Figure 3.17 (a-d) NiFe magnetic nanoparticles of various thickness fabricated

EDX mapping of the Ni and Fe elements of an isolated MNP (inset) shown in the Figure 3.18. The results showed that the composition of Ni has a higher percentage as

compared to Fe in the NiFe, with a 98 % atomic concentration of Ni and 2 % atomic concentration of Fe. The increase in the Ni concentration is due to the higher potential. EDX line scanning confirms that Fe rich layers are completely etched to leave the Ni rich layer as the magnetic nanoparticles.

Figure 3.18 EDX mapping on the nanoparticle for Fe (left) and Ni (right) atoms on top of the atom shown in the inset. EDX line scanning on the nanoparticle is shown below.

3.8 Magnetization configuration of the nanoparticles

As the fabrication method is capable of producing nanoparticles of various thickness and diameter, it is imperative that we perform a systematic study on cylindrical

nanostructures. The spin configurations and magnetization dynamics in MNPs with various diameters under various applied magnetic fields using micromagnetic simulations. The simulations are performed using object oriented micromagnetic framework (OOMMF) software. The material parameters are used for Permalloy; saturation magnetization (M_s) = 800×10^3 A/m, exchange stiffness constant (A_{ex}) = 1.3×10^{-11} J/m and magnetocrystalline anisotropy $k = 0$. The damping constant (α) is fixed to be 0.01. To aid the visualization of the magnetization dynamics in MNP of different aspect ratios (nanodiscs and nano-cylinders), 3D glyph maps representing the magnetization vectors are taken. The nanoparticle thickness is along the Z-direction.

3.8.1 Single vortex state

For a nanoparticle of 70 nm thickness, the magnetization reversal with out of plane field is shown in Figure 3.19.

Figure 3.19 Simulated hysteresis loop for 70 nm thick nanoparticle when the out of plane field is applied

In flat nanodiscs below the thickness of 85nm, the magnetization relaxes by pointing radially outwards and retaining a nearly zero net curl along the disc axis. When a critical H_{app} is reached, the magnetization abruptly curls around the cylinder axis, forming a single vortex. The transition from the magnetization pointing radially outwards to curling leads to the small plateau in the hysteresis loop. When the thickness of the nanoparticle increased to 190 nm, the reversal process shows a different behavior as shown in Figure 3.20.

3.8.2 Double vortex state

Magnetization in taller nano-cylinders between the intermediate thicknesses of 85 to 200 nm will relax by gradually curling in opposite chirality at each end. This results in a double vortex structure where the magnetization at each end has opposite chirality with the vortices uncurling towards the center to align with the cylinder axis. The double vortex configuration represents a higher energy state as the aligned magnetization in the center produces a much higher net magnetic moment as compared to the single vortex state. When H_{app} is lowered to below a threshold field, the magnetization rapidly jumps into a single vortex state.

Figure 3.18 Simulated hysteresis loop for 190 nm thick nanoparticle when the out of plane field is applied. Snapshots along the cross-section at the top and bottom corresponding to the two states in the inset.

From the hysteresis curve of these nano-cylinders in Figure 3.20, it is apparent that the abrupt switch between single and double vortex configuration results in a plateau along the curve. Although the magnetization in MNP of different heights evolves very differently, they both experience a sudden change when a critical H_{app} is reached. As expected, flat nanodiscs saturate at a much higher H_{app} than the higher aspect ratio nano-cylinders due to the effect of shape anisotropy.

3.8.3 Quadrupole vortex state

In-plane magnetization behavior was also studied by first saturating the MNP with a 1 kOe applied in-plane magnetic field and subsequently relaxing. While the in-plane magnetization of thinner nanodiscs have been well studied, the magnetization dynamics in thicker nano-cylinders did not receive much attention. In particular, we discovered that the abrupt removal of applied magnetic field results in nano-cylinders thicker than 300 nm forming a complex yet elegant quadrupole metastable state as shown in Figure 3.21.

Figure 3.21 The magnetization configuration of the nanodisc with a quadrupole vortex.

At first glance, the quadrupole state appears strikingly similar to a double vortex state. However, closer inspection reveals that a magnetic vortex resides on the curved surface of the nano-cylinder. The additional magnetic vortex permeates through the diameter of the nano-cylinder and exits on the other side, resulting in stray fields radiated perpendicularly to the cylinder axis. Consequently, the stability of the quadrupoles was studied by subjecting nano-cylinders of different height in the quadrupole state to a gradually increasing applied magnetic field until the quadrupole configuration is deformed irreversibly. Under an external field, the quadrupole state will become

increasing distorted but still reversible only if the field does not exceed a certain threshold amount. For this purpose, a quadrupole is defined to have a pair of anti-chiral vortices residing on the flat faces of the nano-cylinder and another pair vortex across the diameter. The threshold magnetic field (in-plane and out of plane) below which the quadrupole state is reversible is plotted below in Figure 3.20.

Figure 3.22 Threshold field below which quadrupole state is stable as a function of nanodisc thickness

The plot shows that MNP height scales linearly with the applied in plane field and reciprocally with the out of plane field. From shape anisotropy arguments, the quadrupoles in taller nano-cylinders have a higher tolerance to applied in plane magnetic field while being more susceptible to out of plane fields. At the threshold in-plane field, one of the anti-chiral vortices is annihilated while the other remaining vortex typically requires another 100mT to annihilate, resulting in a saturated state for the MNP. In the case of out of plane applied field, the vortex across the diameter of the quadrupole is annihilated as the magnetization gradually aligns with the applied field.

3.9 Summary

Helical DWs are predicted as the stable configurations in cylindrical nanowires with low aspect ratios. The helical DWs exist to connect the clockwise vortex and the anti-clockwise vortex. A method of using constrictions to control the presence of helical DWs in cylindrical nanowire is proposed. Introducing constrictions with diameter less than 150 nm will promote the creation of additional DWs within the structure. The distance between each DW can be controlled by changing the length of the constrictions or the nanowire segments. The micromagnetic simulation results are confirmed by the MFM measurements on the fabricated nanowires, with and without constrictions. From applications viewpoints, the controlled formation of the DWs may lead to a new kind of magnetic memory devices such as DW nanobarcodes. In the second part, a novel method to fabricate the NiFe nanoparticles is demonstrated in which constrictions in the nanowire are completely sliced during the chemical etching. The method is found to be versatile in the formation of NiFe nanoparticles of various dimensions. As the thickness of the MNP is varied, complex magnetization configurations such as double vortex and quadrupole states are formed within the structure.

References

1. X. Jiang, L. Thomas, R. Moriya, M. Hayashi, B. Bergman, C. Rettner and S. S. P. Parkin, *Nature Comm.* **1**, 25 (2010).
2. D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit and R. P. Cowburn, *Science* **309**, 1688 (2005).
3. S. S. P. Parkin, M. Hayashi and L. Thomas, *Science* **320**, 190 (2008).
4. R. Wieser, U. Nowak and K. D. Usadel, *Phys. Rev. B* **69**, 064401 (2004).
5. R. Wieser, E. Y. Vedmedenko, P. Weinberger and R. Weisendanger, *Phys. Rev. B* **82**, 144430 (2010).
6. M. Yan, A. Kakay, S. Gliga, and R. Hertel, *Phys. Rev. Lett.* **104**, 057201 (2010).
7. M. Franchin, A. Knittel, M. Albert, D. S. Chernyshenko, T. Fischbacher, A. Prabhakar and H. Fangohr, *Phys. Rev. B* **84**, 094409 (2011).
8. G. P. Heydon, S. R. Hoon, A. N. Farely, S. L. Tomlinson, M. S. Valera, K. Attenborough and W. Schwarzache, *J. Phys. D: Appl. Phys.* **30**, 1083 (1997).
9. R. Ferre, K. Ounadjela, J. M. Goerge, L. Piraux and S. Dubois, *Phys. Rev. B* **56**, 21(1997).
10. I. L. Prejbeanu, L. D. Buda, U. Ebles, M. Viret, C. Fermon and K. Ounadjela, *IEEE Trans. Mag.* **37**, 2108 (2001).
11. L. Vila, M. Darques, A. Encinas, U. Ebels, J. –M. George, G. Faini, A. Thiaville and L. Piraux, *Phys. Rev. B* **79**, 172410 (2009).
12. 3D OOMMF code is available at <http://math.nist.gov/oommf>.
13. Mayavi software for 3D magnetization images available at <http://code.enthought.com/projects/mayavi/>

14. H. T. Zeng, D. Petit, L. O'Brien, D. Read, E. R. Lewis, and R. P. Cowburn, *J. Magn. Magn. Mater.* **322**, 2010 (2010).
15. H. F. Liew, S. C. Low and W. S. Lew, *J Physics: Conference Series* **266**, 012058 (2011).
16. H. P. Liang, Y. G. Guo, J. S. Hu, C. F. Zhu, L. J. Wan and C. L. Bai, *Inorg. Chem.* **44**, 3013 (2005).
17. F. Beron, L. P. Carignan, D. Menard and A. Yelon, *IEEE Trans. Mag.* **44**, 2745 (2008).
18. F. V. Belle, J. J. Palfreyman, W. S. Lew, T. Mitrelias, and J. A. C. Bland, *AIP Conf. Proc.* **1025**, 34 (2008).
19. J. Choi, S. J. Oh, J. Cheon, *Nano Lett.* **5**, 2179 (2005).
20. P. Yong, T. Cullis, G. Mobus, X. Xu and B. Inkson, *Nanotechnology* **18**, 485704 (2007).
21. S. P. Li, W. S. Lew, J. A. C. Bland, L. Lopez-Diaz, M. Natali, C. A. F. Vaz and Y. Chen, *Nature* **415**, 600 (2002).
22. N. Biziere *et al.*, *Nano Lett.* **13(5)** 2053 (2013).
23. S. Laurent, D. Forge, M. Port, A. Roch, C. Robic, L. Vander Elst and R. N. Muller, *Chemical reviews*, **108**, 2064 (2008).
24. O. Veisoh, J. W. Gunn and M. Zhang, *Adv. drug deliv. Rev.*, **62**, 284 (2010).
25. B. Thiesen, and A. Jordan, *International Journal of Hyperthermia*, **24**, 467 (2008).
26. M. Johannsen, B. Thiesen, P. Wust, and A. Jordan, *International Journal of Hyperthermia*, **26**, 790 (2010).

27. M. T. Basel, S. Balivada, H. Wang, T. B. Shrestha, G. M. Seo, M. Pyle and D.L. Troyer, *International journal of nanomedicine*, **7**, 297(2012).
28. R. Müller, S. Dutz, A. Neeb, A. C. B Cato, and M. Zeisberger, *J. Magn. Magn. Mater.* **328**, 80 (2013).
29. S. Laurent, S. Dutz, U. O Häfeli, and M. Mahmoudi, *Advances in Colloid and Interface Science*, **166**, 8 (2011).
30. R. Hergt, S. Dutz, R. Muller, and M. Zeisberger, *J. Phys. Condens. Matter.* **18**, S2919 (2006).
31. D. H. Kim, E. A. Rozhkova, I. V. Ulasov, S. D. Bader, T. Rajh, M. S. Lesniak and V. Novo., *Nature Mater.* **9**, 165 (2009).

Chapter 4

Domain wall oscillations in single and coupled cylindrical nanowires

4.1 Introduction

This chapter presents the first observation of intrinsic oscillatory behavior in the translational motion of the domain wall (DW) in sub-50nm cylindrical nanowire. The analysis leads to finite mass associated with DW in cylindrical nanowires. Previous understanding of DW motion in cylindrical nanowire gives us a linear propagation under the application of magnetic field or current. The results reveal that in the absence of external energies, the amplitude of the translational oscillation is governed by the change in the rotational frequency of the transverse component of the DW. In addition, the effective displacement of the translational motion is determined by the chirality of the rotational component of the DW. In a system comprised of two closely spaced nanowires, a confined state is created whereby an infinite DW oscillatory and rotational motion can be sustained by balancing the magnetostatic coupling with spin polarized current. The DW undergoes a cyclic shape change, oscillating between a relaxed and a compressed state resembling the simple harmonic oscillatory motion (SHO). There is a confusion concerning the specific mass that is possessed by the DW, whether it is zero or finite [1]. From the oscillatory behavior, it is uncovered that DW in cylindrical nanowire indeed possesses a finite mass. By solving the SHO equation, we have computed that the DW in the cylindrical nanowire has a mass in the order of 10^{-23} kg.

4.2 Motivation

The understanding of domain wall (DW) dynamics is crucial for the realization of next generation non-volatile magnetic solid state memory and logic devices [2-4]. The DW dynamics behavior in planar ferromagnetic nanowires has been relatively well studied, either in in-plane or perpendicular anisotropy materials [5-10]. A prevailing obstacle that limits fast DW dynamics in the in-plane structures is the Walker breakdown phenomenon [11-13], at which complex DW transformations cause a drastic drop in the DW speed. Such a limitation, however, is not present for DW dynamics in sub-50 nm magnetic cylindrical nanowires, where the DW speed can be ten times higher than that in the planar nanowires [1,14]. It is generally accepted that the motion of a transverse DW in cylindrical nanowire is always linear and accompanied by rotation of the transverse component of the DW around the long axis of the nanowire[15-20]. The rotation has been shown to occur without any structural collapse and shape change when driven by external magnetic field or spin-polarized current. Additionally, the critical current density required to initiate and depin the DWs in cylindrical nanowire is much lower compared to that in the planar structures [1,14,15]. These remarkable DW dynamics properties are attributed to the ability of the DW to propagate (linear) by precessing (rotation) around the long axis of the cylindrical nanowire. In this work, the relation between the DW translational and rotational motion is studied in a single nanowire system in the presence of magnetic field. To get a deep understanding of the internal features of the DW dynamics, the external perturbations have to be avoided within the system. In this work, the DW driving field is generated from the magnetostatic interaction between two DWs by setting up a coupled DW system [21-24].

4.3 Intrinsic domain wall oscillation in a cylindrical nanowire

To study the DW dynamics in a single cylindrical nanowire, a transverse DW is relaxed at the center of a 1- μm -long nanowire of 10 nm diameter. The DW dynamics behavior in the $\text{Ni}_{80}\text{Fe}_{20}$ cylindrical nanowires are investigated by using the object oriented micromagnetic framework code (OOMMF) [25,26]. The material parameters were set corresponding to permalloy: the saturation magnetization, M_s is 8.6×10^5 A/m, and the exchange constant, A is 1.3×10^{-11} J/m. The damping coefficient, α was fixed at 0.005 and the non-adiabatic constant, β was chosen as 0.04. The unit cell size for all simulations was set to be $5 \text{ nm} \times 1 \text{ nm} \times 1 \text{ nm}$ in the x , y and z axis respectively. To move the DW along the nanowire, a magnetic field of 10 Oe is applied along the wire (x -) axis. The position of the DW with respect to the nanowire center, and the transverse magnetization component of the DW (m_z) are plotted in Figure 4.1. The DW translational motion along the wire long axis is not simply linear but oscillatory, *i.e.* the DW effectively moves in the field direction (as shown by black the arrow) but with a back-and-forth motion. The oscillation amplitude is calculated to be a constant value of 0.4 nm and the frequency is 0.2 GHz. The DW transverse component rotates continuously at a frequency of 0.05 GHz. The rotation and oscillation are shown to be related to each other: the DW oscillates 4 times for every single rotation.

Figure 4.1 DW motion along the long axis (bottom panel) and around the long axis (top panel) when an external magnetic field of 10 Oe is applied to drive the DW in a cylindrical nanowire.

The correlation between the DW rotation and oscillation can be understood from the breathing motion of the DW in the presence of magnetic field [27,28]. The DW is found to expand and contract in the width two times each during one complete rotation. The variations in the DW width can be seen in the oscillatory translational motion. This ratio between the two motions is maintained even when the applied field is increased up to 100 Oe. For applied fields larger than 100 Oe, the oscillatory motion is no longer distinguishable. This is attributed to the high DW speed resulting in large translational displacement as compared to the oscillation amplitude, thereby rendering the oscillation negligible.

When the orientation of the applied magnetic field is switched to the perpendicular direction ($\pm z$) of the nanowire, the field induces a DW rotation around the long axis, as shown in Figure 4.2. Interestingly, a translational motion via oscillation is still present though there is no field applied along the long axis. As the DW moves towards the end of the nanowire, the DW rotational frequency increases whereas the DW oscillation amplitude drops. The increase in the rotational frequency and the drop in the oscillation amplitude show that the DW acts as a closed system, in which the energy released during the drop in the oscillation amplitude is converted to the increase of the rotational frequency.

Figure 4.2 The DW translational and rotational motion as a function of simulation time when a magnetic field of 10 Oe is applied in the perpendicular direction to the nanowire long axis.

The perpendicular applied field direction ($\pm z$) is found to have influence on the chirality of the DW rotational motion, *i.e.* the DW rotates in clockwise or anti-clockwise orientation when the field is applied along the $+z$ - or $-z$ -direction, respectively. For a clockwise rotation, the oscillation is accompanied by a translational motion along the $+x$ -direction. Conversely, for an anti-clockwise rotation, the effective displacement is in the $-x$ -direction. The rotation chirality-dependent DW translational motion is analogous to the classical Ampere's law following a "right hand grip rule". The presence of the oscillation even under no field along the longitudinal axis suggests that the oscillation is an intrinsic DW behavior and it is self-sustained.

4.4 Domain wall oscillation in coupled nanowire system

The magnetostatic coupling between the transverse DWs is exploited as the local driving force to avoid external influence on the system. It is well known that in planar nanowire, a transverse DW possesses magnetic charge and is considered as a magnetic monopole. A head to head DW is considered as positive charge and a tail to tail DW is considered as a negative magnetic charge according to the convergence of the magnetization within the DW. The charge distribution along the transverse component shows that the two ends have opposite charge with one polarity dominating. However, the geometrical symmetry of the cylindrical nanowire may influence the charge distribution along the transverse component.

To gain an insight on the charge distribution in the transverse DW in cylindrical nanowire, the magnetic volume pole is calculated at the top and bottom surface of a tail to tail (TT) DW in cylindrical nanowire along the transverse component which is plotted in Figure 4.3. The magnetic volume pole is calculated by the taking the divergence of the

magnetization of the DW [29]. Interestingly, the top and bottom surface of the DW possess the opposite magnetic charges. The top surface of the TT DW possesses the positive magnetic charge whereas the bottom surface possesses the negative magnetic charge. However, the negative magnetic charge is found to be one order higher compared to the positive charge which shows that the net magnetic charge possessed by the DW is negative for TT DW. The HH DW shows the similar characteristics with opposite polarities having a positive net magnetic charge.

Figure 4.3 Magnetic volume pole along the top and bottom edge of the transverse component of the DW in cylindrical nanowire. The magnetic volume pole represents the magnetic charge possessed by the DW.

To further ascertain the intrinsic nature of the DW oscillation, we have investigated the behavior of the DW under the influence of magnetostatic coupling between the DWs in closely spaced cylindrical nanowires. Two DWs with the same magnetization configuration (TT DWs) are relaxed in two closely-spaced cylindrical nanowires with diameter, 10 nm and separation of 10 nm. A snapshot image of the coupled DW model is shown in Figure 4.4

Figure 4.4 Schematic of the coupled DW system model. A Tail-to-Tail DW is relaxed in each nanowire.

The translational motion of the DW along the nanowire long axis is plotted as a function of simulation time, as shown in Figure 4.5. As the two DWs possess similar magnetic charges, magnetostatic repulsion causes them to move away from each other, towards the ends of the nanowires. Similar to the single nanowire case, the repulsive translational motion of each DW displays oscillatory behavior with an effective displacement in one direction, *i.e.* one DW in the $+x$ -direction and the other DW in the $-x$ -direction. The oscillation amplitude changes as a function of the simulation time,

displaying two distinct characteristics. In region I, from $t = 0$ when the two DWs are relaxed at the center of the respective nanowire, the oscillation amplitude gradually decreases to reach a minimum amplitude at $t \approx 180$ ns, corresponding to a separation of 60 nm between the DWs. After $t = 180$ ns, the oscillation amplitude increases as a function of time. The occurrence of the minimum oscillation amplitude can be explained by the superposition of two types of oscillations.

Figure 4.5 The position of the DWs along the long axis in both nanowires showing oscillatory translational motion. Region I and II represents the strongly coupled DW oscillation and weakly coupled (self-sustained) DW oscillation, respectively.

The first DW oscillation is due to the translational oscillation induced by the stray fields from the neighbor DW. The second one is due to the DW natural oscillation. These

two oscillations are out of phase with each other. The amplitude of the natural oscillation gradually increases while the amplitude of the translational oscillation drops as the two DWs move away from each other. When $t > 180$ ns, the effect of the magnetostatic coupling becomes negligible and only the natural DW oscillation is sustainable with increasing amplitude. Inset of Figure 4.5 shows the superposition of the two types of oscillations that are present in the system. Dotted red line indicates the amplitude of the stray field-induced oscillation that is damped due to the weakening of the magnetostatic coupling, while solid blue line indicates the self-sustained DW oscillation.

4.5 Domain wall oscillation governed by the rotation

Though, not being subjected to any external energies, in region II, the oscillation amplitude increases as a function of time. The DW being a closed system, the total energy of the DW should be a combination of both the energies from the oscillation and rotational motions.

Figure 4.6 The DW rotational frequency and oscillation amplitude as a function of the simulation time for the DW motion in region II.

In Figure 4.6, the DW rotational frequency and the oscillation amplitude for the natural oscillation is plotted as a function of time. The rotational frequency decreases linearly whereas the amplitude of the DW oscillation increases, as the two DWs move away from each other. The increase in the oscillation amplitude with no influx of external energy can be attributed to the drop in the rotational frequency of the transverse component. The energy dissipated while the DW rotational frequency is decreasing, is transferred as the source energy for the increase in the DW oscillation amplitude. The DW rotation continues until each DW reaches the end point of the nanowire where the DW annihilates. We have modeled the DW transverse component as a rotating disk. The total kinetic energy of the rotating component is given by $K_{DWT} = \frac{1}{2} I (2\pi f_T)^2$, I is the moment of inertia of the rotating spins around the axis of the nanowire, and is given by $\sum_{i=1}^n m_i R_i^2$, where m_i is the mass of each spin and R_i is the radial distance from the axis of rotation; f_T is the frequency of the rotating spins. Modeling the oscillatory motion of the DW as two particles connected by a spring, the energy of the oscillating body, E_{os} is given by $\frac{1}{2} kx^2$, where k is the spring constant and x is the displacement. Assuming the DW to be a closed system, the loss in the rotational energy should give rise to an increase in oscillatory energy; $\Delta K_{DWT} = \Delta E_{os}$. Simplifying the equation, we end up with the relation, $\Delta x = \sqrt{\frac{I}{K}} 2\pi (\Delta f)$, which results in a linear relationship between the change in rotational frequency and increase in amplitude of oscillation, as can be clearly seen in Figure 4.6.

4.6 Effect of Spin transfer torque on the system

When an external energy is supplied to the system, it can be used to balance the magnetostatic repulsion. Spin-polarized current is then applied in the opposite directions to both the nanowires. At a critical current density of 2×10^5 A/cm², the magnetostatic interaction is found to be balanced by the spin-transfer torque. As a consequence, the two DWs are held close to the centers of the nanowires while still moving in an oscillatory manner, as shown in the schematic of Figure 4.7. FFT spectra in Figure 4.7 reveal that the DW oscillations occur at a constant frequency of 0.16 GHz.

Figure 4.7 FFT spectra of the DW translational oscillation along the long axis shows that the frequency for maximum power occurs at 0.16 GHz when the coupling is balanced by the STT effect. Inset shows the DW oscillatory translational motion. Shown above is the schematic of the coupled DW oscillation along the long axis.

Figure 4.8 FFT spectra show periodical frequency modes occurs in the DW rotation.

Inset of Figure 4.8 shows the DW rotation of the transverse component (m_y+m_z) around the long axis in the cylindrical nanowires. The corresponding FFT spectra show that the DW rotation occurs with periodic frequency modes with decreasing power. The maximum power is found to occur at 0.16 GHz in synchronization with the DW oscillation. To study the effect of STT in generation, the DW rotational frequency and the critical current density at various separations between the nanowires are plotted in Figure 4.9.

Figure 4.9: Critical current density to sustain the oscillation and the DW rotation frequency as a function of nanowire spacing.

The critical current density to sustain the DW rotations is found to drop non-linearly with nanowire separation. This can be attributed to the non-linear drop of the magnetostatic force between the magnetic charges when they are moved far apart. This clearly shows that the current has no affect on the DW rotations that are generated in the nanowires. The only role of the current is to balance the magnetostatic repulsion to prevent the coupling breaking which sustains the DW rotations. The DW rotational frequency is found to drop linearly with the spacing. The repulsion force between the DW is reduced as the nanowires are placed far apart.

4.7 Domain wall shape change and Domain wall mass

When the magnetostatic repulsion is balanced by the STT effect, the DW oscillatory translational motion follows the simple harmonic motion unlike the damped harmonic motion of the DW observed in the planar nanostructures [5,21]. To understand the mechanism behind the sustained oscillation, the transverse component of the DW in

the top nanowire and the exchange energy of the system are extracted as a function of simulation time as shown in Figure 4.10.

Figure 4.10 Transverse component of the DW and the exchange energy of the system as a function of simulation time when the DW oscillation is sustained by spin-polarized current.

Both of these parameters represent the shape of the DW. The transverse component and the exchange energy are shown to change continuously in a cyclic manner, which suggests that the DW shape is not constant during the oscillation. During the sustained oscillation, the DW changes its shape continuously between two distinct configurations *i.e.* a compressed state and a relaxed state. The variance of the shape can be attributed to the finite mass possessed by the transverse DW in the cylindrical nanowire [5,6,21,30].

The mass of the DW can be calculated by solving the equation of the simple harmonic motion (SHM) of two masses connected by a spring. The demagnetization energy of the system shown in the Figure 4.11 can be approximated as the potential energy of the spring system [4,20].

Figure 4.11 The demagnetization energy as a function of the simulation time when the confined DW oscillation is infinitely sustained. The position of the two DWs during the sustained oscillation as a function of the simulation time. A and B are two extreme positions of the DW oscillation as shown by the magnetization configurations of the two nanowires.

The potential energy of the system when the two DWs are far from each other is

$$E_A = \frac{1}{2} K X_A^2 \quad (4.1)$$

The potential energy of the system when the two DWs are close to each other is

$$E_B = \frac{1}{2} K X_B^2 \quad (4.2)$$

where K is the spring constant, X_A and X_B are the separation between the two DWs.

The spring constant can be extracted by solving the equation of SHM 4.1 and 4.2 at two extreme points of separation (“A” and “B” in Figure 4.11) between the two DWs.

Solving the above two equations, the spring constant (K) is found to be $3.54 \times 10^{-5} \text{ J/m}^2$. From SHM, the expression for the mass (m) can be written as

$$m = \frac{T^2 K}{4\pi^2} \quad (4.3)$$

The time period, T is $1/f$ where f is oscillation frequency. The mass is found to be $2.95 \times 10^{-23} \text{ kg}$. However, the mass of the coupled DW system represents the reduced mass of the two DWs. As the two DWs are of same type (TT) and equal size, the mass of a single DW is double the reduced mass, $m_{DW} = 5.9 \times 10^{-23} \text{ kg}$. This mass is in the same order as calculated for DWs in planar nanostructures [6,21].

To further ascertain that the DWs in the cylindrical nanowires possess a finite mass, simulations were repeated with different nanowire diameters (10 to 30 nm), while keeping the interwire spacing constant at 10 nm. Figure 4.12 shows the mass of the DW

increases linearly with larger nanowire diameter and it confirms that the DW mass increases with its size.

Figure 4.12 The DW mass as a function of the nanowire diameter.

4.8 Summary

In summary, an intrinsic oscillation present in the translational motion of DW in sub-50 nm cylindrical nanowires is investigated. The direction of the translational motion is found to be related to the chirality of the rotational component of the DW. The amplitude of the oscillation is in turn governed by the loss of the energy of the rotational component. In a coupled DW system, by balancing the repulsive magnetostatic interaction with spin-polarized current, the oscillation and rotation of the DW can be infinitely sustained. Modeling the oscillation as a simple harmonic motion, the mass of the DW is calculated to be in the order of 10^{-23} kg. This work suggests an application of the magnetic microwave generator that is based on the sustained DW oscillation and rotation which can operate at smaller current density.

References

1. M. Yan, A. Kakay, S. Gliga and R. Hertel, *Phys. Rev. Lett.* **104**, 057201 (2010).
2. S. S. P. Parkin, M. Hayashi, and L. Thomas, *Science* **320**, 190 (2008).
3. J. H. Franken, H. J. M. Swagten and B. Koopmans, *Nature Nanotech.* **7**, 499 (2012).
4. D. A. Allwood, G. Xiong, M. D. Cooke, C. C. Faulkner, D. Atkinson, N. Vernier, and R. P. Cowburn, *Science* **296**, 2003 (2002).
5. L. O'Brien, E. R. Lewis, A. Ferná'ndez-Pacheco, D. Petit, and R. P. Cowburn, *Phys. Rev. Lett.* **108**, 187202 (2012).
6. E. Saitoh, H. Miyajima, T. Yamaoka, and G. Tatara, *Nature* **432**, 203 (2004).
7. L. Thomas, R. Moriya, C. Rettner, and S. S. P. Parkin, *Science* **330**, 1810 (2010).
8. T. Koyama, D. Chiba, K. Ueda, K. Kondou, H. Tanigawa, S. Fukami, T. Suzuki, N. Ohshima, N. Ishiwata, Y. Nakatani, K. Kobayashi and T. Ono, *Nature Mater.* **10**, 194 (2011).
9. S. Emori, U. Bauer, S.M. Ahn, E. Martinez and G. S. D. Beach, *Nature Mater.* **12**, 611 (2013).
10. K. S. Ryu, L. Thomas, s. H. Yang and S. S. P. Parkin, *Nature Nanotech.* **8**, 527 (2013).
11. N. L. Schryer and L. R. Walker, *J. Appl. Phys.* **45**, 5406 (1974).
12. M. Hayashi, L. Thomas, C. Rettner, R. Moriya and S. S. P. Parkin, *Nature Phys.* **3**, 21 (2007).

13. G. S. D. Beach, C. Nistor, C. Knutson, M Tsoi and J. L. Erskine, *Nature Mater.* **4**, 741744 (2005).
14. R. Wieser, E. Y. Vedmedenko, P. Weinberger and R. Weisendanger, *Phys. Rev. B* **82**, 144430 (2010).
15. M. Franchin, A. Knittel, M. Albert, D. S. Chernyshenko, T. Fischbacher, A. Prabhakar and H. Fangohr, *Phys. Rev. B* **84**, 094409 (2011).
16. R. Wieser, U. Nowak and K. D. Usadel, *Phys. Rev. B* **69**, 064401 (2004).
17. H. Forster, T. Schrefl, W. Scholz, D. Suess, V. Tsiantos and J. Fidler. *J. Magn. Magn. Mater.* **249**, 181(2002).
18. R. Hertel, *J. Magn. Magn. Mater.* **249**, 251(2002).
19. R. Hertel and J . Kirschner, *Physica B* **343**, 206 (2004).
20. M. Franchin T. Fischbacher, G. Bordinon, P. de Groot, and H. Fangohr, *Phys. Rev. B* **78**, 054447 (2008).
21. I. Purnama, M. Chandra Sekhar, S. Goolaup, and W. S. Lew, *Appl. Phys. Lett.* **99**, 152501 (2011).
22. I. Purnama, M. Chandra Sekhar, S. Goolaup, and W. S. Lew, *IEEE Tans. Mag.* **47** 3081 (2011).
23. L. O'Brien, E. R. Lewis, A. Ferná'ndez-Pacheco, D. Petit, and R. P. Cowburn, *Phys. Rev. Lett.* **108**, 187202 (2012).
24. L. O'Brien, D. Petit, H. T. Zeng, E. R. Lewis, J. Sampaio, A. V. Jausovec, D. E. Read, and R. P. Cowburn, *Phys. Rev. Lett.* **103**, 077206 (2009).

25. M. Donahue and D. G. Porter, OOMMF User's guide, Version 1.0, Interagency Report NISTIR 6376, National Institute of Standard and Technology, Gaithersburg, MD. 1999.
26. OOMMF Extension for Current-induced Domain Wall Motion developed by IBM Research, Zurich; see <http://www.zurich.ibm.com/st/magnetism/spintevolve.html>.
27. X.R. Wang, P. Yan, J. Lu, C. He, *Ann. Phys.* **324**, 1815 (2009).
28. X.R. Wang, P. Yan, J. Lu, *Euro Phys. Lett.* **86**, 67001 (2009).
29. H. T. Zeng, D. Petit, L. O'Brien, D. Read, E. R. Lewis, and R. P. Cowburn, *J. Magn. Magn. Mater.* **322**, 2010 (2010).
30. W. Döring, *Z. Naturforsch. A* **3**, 373 (1948).

Chapter 5

Domain wall pinning and depinning in planar and cylindrical nanowires

5.1 Introduction

This chapter presents a systematic study on the domain wall (DW) pinning and depinning mechanism at geometrical modulation (notch/anti-notch) in planar and cylindrical nanowires using micromagnetic simulations. The chapter is broadly divided into two parts. The first part discusses about the shape and height of the pinning potential in planar nanowires with an anti-notch as a pinning site. The effect of the chirality on the polarity of the potential is calculated. The effect of the relative orientation between the spins in the anti-notch and the transverse component of the DW on the shape of the potential is discussed. The second part reports on the field-driven and current-driven transverse DW depinning mechanisms in sub-50 nm diameter NiFe cylindrical nanowires. The shape of the pinning potential for notch and anti-notch is presented. The effect of the notch depth and the anti-notch height on the depinning field and depinning current density are studied in detail.

5.2 Motivation

The DW pinning at a specific position is essential to allow the DW to be manipulated, much like in the racetrack memory where the DWs need to be pinned in order for the data to be ‘read’ or ‘modified’. The DW energy not only depends on the material of the nanostructure but also on the dimensions. The geometrical variations along

the nanostructures can change the potential energy landscape for the DW [1-6]. Thus the geometrical variations act as pinning sites for the DW. Moving the DW out of pinning site by supplying an external energy is called depinning. The application of magnetic field or current can modify the DW energy landscape to assist the DW to depin from the pinning site. As the DW energy depends on the DW dimensions, so one can predict that, reducing the DW size can create a pinning for it. The DW also possess a magnetic charge, the stray field from a nanomagnet can also introduce pinning due to the magnetostatic coupling. The understanding and characterization of domain wall pinning in ferromagnetic nanowires will be essential to the advancement of its application in spintronic devices. In narrow nanowires, transverse DWs are stable configurations [7,8] which are characterized by the chirality, the direction of the transverse component of the DW. The relative orientation between the DW chirality and the magnetization of the pinning site may affect the strength of the pinning. In the first part of this chapter, some light is shed on this. The transverse DWs in sub-50 nm cylindrical nanowire show unique properties due to the geometrical symmetry of the nanowire [9,10] compared to their counter parts in planar nanowires. For instance, these DWs are predicted to be free from the Walker breakdown, a feature due to the breaking of DW internal structure when the movement is driven by high magnetic field or current [11]. The spin configuration in the cylindrical nanowires allows a combination of rotational and translational motions and that prevents the DW from suffering the structural breakdown [12]. Beating the Walker breakdown allows the DW in the cylindrical nanowire to move with higher speeds compared to that in the planar nanowire. The existence of the unique properties, such as the fast DW motion and the combined rotational and translational motions, should influence the depinning mechanism

in the cylindrical nanowire when compared that to the planar nanowires. For cylindrical nanowires, the pinning sites can be realized by introducing a modulation in the diameter of the nanowire in the form of a notch or anti-notch. The second part of the chapter presents a systematic study of DW depinning mechanism in cylindrical nanowires at geometrical modulations.

5.3 Domain pinning potential as function of anti-notch geometry in planar nanowires

In this study, a $\text{Ni}_{80}\text{Fe}_{20}$ nanowire of length $10\mu\text{m}$ and thickness 10 nm was considered. The width of the nanowire was chosen as 160 nm to ensure that the transverse DWs are the only stable configurations relaxed in the nanowire. To study the DW pinning, an anti-notch of a rectangular shape was introduced at the centre of the nanowire along the length as shown in the schematic of Figure 5.1. The anti-notch width is defined W_{AN} and the height is defined as H_{AN} . The material parameters used in the simulation were saturation magnetization (M_s) = $800 \times 10^3\text{ A/m}$, exchange stiffness constant (A_{ex}) = $1.3 \times 10^{-11}\text{ J/m}$ and magnetocrystalline anisotropy $k = 0$. We used the Object Oriented Micromagnetic Framework code (OOMMF) [13] extended by incorporating the spin transfer torque term [14] to the Landau–Lifshitz–Gilbert (LLG) equation to simulate the DW motion. The unit cell size for all simulations was set to be $5\text{ nm} \times 5\text{ nm} \times 5\text{ nm}$.

5.3.1 Current distribution in the nanowire with an anti-notch

The current density distribution through the nanowire with anti-notch is estimated by modeling the structure with COMSOL multiphysics modeling software [15]. Shown in Figure 5.1 is the current density distribution in a nanowire with an anti-notch, $W_{\text{AN}} = 160\text{ nm}$ and height, $H_{\text{AN}} = 200\text{ nm}$. The current flows along the $+x$ direction (left to right) with a current density of $J = 10^{12}\text{ A/m}^2$. Similar modeling was carried out for different anti-

notch dimensions and current densities. Modeling results reveal that current only flows through the nanowire with a negligible amount into the anti-notch as can be seen in the difference in the contrast in the along the nanowire with anti-notch. Similar current density distribution is utilized in the micromagnetic simulations throughout the study.

Figure 5.1 Schematic diagram of the nanowire with an anti-notch at the centre and the simulated current distribution through the nanowire with an anti-notch when applied current density is $10^{12}\ \text{A/m}^2$.

5.3.2 Effect of Anti-notch width on the DW pinning potential

In this section, the effect of the anti-notch width on the type of pinning potential experienced by the head to head DW (HHDW) with both the chiralities i.e. up chirality (HH-U) and down chirality (HH-D) is investigated. The anti-notch width, W_{AN} was varied

from 40 nm to 200 nm, while the anti-notch height, H_{AN} , was kept at 200 nm. The DWs were driven from left to right along the $+x$ direction in the nanowire. From the simulation on a planar nanowire, the Walker breakdown was observed at a current density $J = 1.6 \times 10^{12}$ A/m². All simulations are performed at a current density $J = 1.48 \times 10^{12}$ A/m² for our wire geometry.

Figure 5.2 (a) Snap shot image of DW configuration of HH-U when it approaches the anti-notch of width $W_{AN} = 40$ nm and height $H_{AN} = 200$ nm. (b) Snap shot image of DW configuration of HH-D when it approaches the anti-notch of width $W_{AN} = 40$ nm and height $H_{AN} = 200$ nm.

The equilibrium DW positions for HH-U and HH-D at an anti-notch geometry with $W_{AN} = 40$ nm. For HH-U, the DW is stable beneath the anti-notch structure as shown in Figure 5.2 (a). For HH-D, the DW is stopped away at a distance E_P from the centre of the anti-notch structure, as seen in Figure 5.2 (b). This difference in equilibrium

position is due to the potential seen by the DW with different chirality at the anti-notch. For HH-U, the anti-notch acts a potential well, whereas for HH-D the anti-notch is seen as a potential barrier. It reveals that the potential at the anti-notch as experienced by the DW is chirality dependent. Interestingly, a completely different behavior is observed when $W_{AN} = 120\text{nm}$. The equilibrium positions of the DWs are shown in Figure 5.3. There is a change in the type of the potential disruption seen by the DW at the anti-notch. The anti-notch acts as a potential barrier for HH-U and a potential well for HH-D. This implies a change in the potential landscape of the anti-notch with varying width.

Figure 5.3 Snap shot image of DW configuration of HH-U when it approaches the anti-notch of width $W_{AN} = 120\text{ nm}$ and height $H_{AN} = 200\text{ nm}$. (b) Snap shot image of DW configuration of HH-D when it approaches the anti-notch of width $W_{AN} = 120\text{ nm}$ and height $H_{AN} = 200\text{ nm}$.

Anti notch width W_{AN}
80 nm
100 nm
120 nm

Table 5.1 Table representing the equilibrium positions of HH-U and HH-D at the anti-notch of different widths from $W_{AN} = 80$ nm to 140 nm at a fixed height of $H_{AN} = 200$ nm.

To gain a better understanding of the DW interaction with the anti-notch, the equilibrium positions of the DW at various anti-notch widths are shown in table 1. The transformation in the potential landscape occurs when the anti-notch width is $W_{AN} = 100$ nm. The change in the potential polarity of the anti-notch can be explained by the transformation in the orientation of the spins along the anti-notch. For the anti-notch width of $W_{AN} \leq 100$ nm, the magnetization state within the anti-notch prefers to align parallel to the y -direction to minimize the demagnetization energy as induced by shape anisotropy. This magnetic configuration within the anti-notch leads to the formation of magnetic charges oriented in the y -direction, as depicted in the inset of Figure 5.2 (a). These magnetic charges explain the different potential as seen by the HHDW with different transverse components. From Figure 5.2(a), it can be clearly observed that when the HH-U reaches the anti-notch, the transverse spins within the DW are aligned in the same direction as the spins in the anti-notch. The magnetic charges are of opposite polarity, as seen in the inset of Figure 5.2(a), which leads to the attraction of the domain wall beneath the anti-notch to minimize the demagnetization energy. Conversely, for the HH-D, the transverse spins of the DW are aligned in the opposite direction with the spins of the anti-notch, leading to the magnetic charges being in the same polarity, as seen in the inset of Figure 5.2(b). This results in the repulsion between the same magnetic charges giving rise to the formation of a potential barrier for HH-D.

For $W_{AN} > 100$ nm, we observed a change in the polarity of the potential as seen by the DWs at the anti-notch. This is due to the decrease in the demagnetisation factor along the x -direction in the anti-notch. The magnetisation direction is no longer constrained to the y -direction. The spins within the anti-notch have a preferential

alignment along the x -direction, adopting the magnetisation direction of the nanowire. The transverse components of the DW are now aligned orthogonally to the magnetisation in the anti-notch. This leads to the repulsion of the HH-U, due to the interaction of the positive charges from both the DW and the anti-notch. The DW is pushed to a distance E_P away from the centre of the anti-notch. For HH-D, the opposite charge leads to the attraction of the DW within the notch, trapping the DW at the left edge of the anti-notch. Additionally, when the anti-notch acts as a barrier, the domain wall undergoes a damped oscillation prior to reaching the equilibrium position.

Figure 5.4 shows the variation of the equilibrium position of the HH-U from the centre of the anti-notch ($W_{AN} > 100$ nm) with increasing anti-notch width.

Figure 5.4 The equilibrium position of HH-U from the centre of the anti-notch as a function of the width of the anti-notch at a fixed height of 200 nm.

The equilibrium position is moving far from the anti-notch with increasing anti-notch width. The increase in the distance between the anti-notch and the HH-U is attributed to the increase in the potential of the anti-notch with the increasing width. When the anti-notch acts as potential barrier for the HH-D ($W_{AN} \leq 100$ nm), the equilibrium position is almost stable at all widths, which is around 70 nm away from the left edge of the anti-notch. This shows that there is no significant change in the potential of the anti-notch with the variation of the width when $W_{AN} \leq 100$ nm.

5.3.3. Effect of anti-notch height on the DW pinning potential

In this section, the effect of the anti-notch height on the motion of the current driven transverse DW in $Ni_{80}Fe_{20}$ nanowire has been investigated. The anti-notch height was varied from $H_{AN} = 100$ nm to 300 nm at different widths ranging from $W_{AN} = 40$ nm to $W_{AN} = 160$ nm. The results obtained from the micromagnetic simulations are summarized in Table 10.1 in appendix. The results reveal that the anti-notch of all heights from $H_{AN} = 100$ nm to 300 nm acts as a potential well for HH-U and a potential barrier for HH-D at anti-notch width $W_{AN} = 40$ nm. Conversely, it acts as a potential barrier for HH-U and a potential well for HH-D when anti-notch width $W_{AN} = 160$ nm. However, as the height of the anti-notch changes from $H_{AN} = 100$ nm to 300 nm, a transition in the polarity of the potential is observed at increasing widths from $W_{AN} = 60$ nm to 140 nm. Careful observation of the potential disruption variation with the dimensions of the anti-notch, the transition in the potential polarity is observed at the anti-notch H_{AN}/W_{AN} ratio of 2.

The transition in the potential behavior of the anti-notch is due to the change in the relative orientation between the spins in the anti-notch and the nanowire. For $H_{AN}/W_{AN} <$

2, the spins in the anti-notch and the wire are almost runs parallel to each other. However, in the case of $H_{AN}/W_{AN} \geq 2$, the spins in the anti-notch and the wire are orthogonal to each other. When $H_{AN}/W_{AN} < 2$, the magnetic charges at the HH-U and the anti-notch are of same polarity causes repulsion resulting a potential barrier at the anti-notch. When $H_{AN}/W_{AN} \geq 2$, the magnetic charges at the HH-U and the anti-notch are of opposite polarity causes attraction between them resulting a potential well at the anti-notch. Similar but opposite behaviour is observed in the case of HH-D.

The equilibrium positions from the centre of the anti-notch have been calculated when anti-notch acts as a barrier for HH-U and HH-D. The variation of the equilibrium position of HH-U with the anti-notch height is presented in Figure 5.5.

Figure 5.5 The equilibrium position of HH-U from the centre of the anti-notch as a function of the height of the anti-notch at a fixed width of 160 nm.

The plot shows that the equilibrium position of HH-U moves away from the centre of the anti-notch as the height of the anti-notch increases. This is attributed to the increase in the potential with the height of the anti-notch for HH-U when $H_{AN}/W_{AN} < 2$. However, in the case of HH-D, the equilibrium position of the DW is almost stable with varying height. This stable behavior shows that the potential barrier is constant with varying height of the anti-notch for HH-D when $H_{AN}/W_{AN} \geq 2$.

5.3.4 Effect of current density on the pinning potential

The equilibrium position of the DW from anti-notch has been calculated by varying the current density J is varied from 0.4 to $1.5 \times 10^{12} \text{ A/m}^2$. When the anti-notch acts as a potential barrier for HH-U ($H_{AN}/W_{AN} < 2$) and HH-D ($H_{AN}/W_{AN} \geq 2$). The variation of the equilibrium positions of HH-U and HH-D with increasing current density have been plotted in Figure 5.6.

Figure 5.6 The equilibrium position of HH-U and HH-D from the centre of the anti-notch as a function of the current density.

For the anti-notch with $H_{AN}/W_{AN} < 2$, the equilibrium position of HH-U moving closer to the centre of the anti-notch as the current density is increased. However, for the anti-notch with $H_{AN}/W_{AN} \geq 2$, the equilibrium position of HH-D is almost constant with increasing current density. The DW undergoes damped oscillation prior to come to an equilibrium position when the anti-notch acts as a barrier.

Figure 5.7(a) DW damped oscillations in magnetisation as a function of simulation time for HH-U at various current densities. (b) DW damped oscillations in magnetisation as a function of simulation time for HH-D at various current densities.

Shown in Figure 5.7(a) and (b) are the variation of the total magnetisation of the structure with the simulation time at various current densities for HH-U and HH-D, respectively. The oscillation in the magnetisation is due to the oscillation of the DW displacement. The time period of the damped oscillation decreases with increasing current density in case of the anti-notch with $H_{AN}/W_{AN} < 2$ acts as a barrier, whereas it is constant in case of $H_{AN}/W_{AN} \geq 2$. The decrease in the equilibrium position and the oscillation period with the increasing current density is attributed to the smooth and gradual potential

barrier at the anti-notch of $H_{AN}/W_{AN} < 2$. Constant equilibrium position and the oscillation period with increasing current density show that the potential barrier is steep with an abrupt increase at the anti-notch of $H_{AN}/W_{AN} \geq 2$. It can be broadly understood as the potential barrier is smooth and gradual if the transverse spins of the wall are orthogonal to the notch configuration, whereas the barrier is abrupt and steep when the spins in the notch are anti-parallel to the transverse component.

5.3.5 Summary of DW pinning at an anti-notch in planar nanowire

To summarize the first part, the variation of the potential disruption observed by the DW at the anti-notch has been studied as a function of the DW chirality and the anti-notch dimensions. The potential disruption experienced at the anti-notch is a function of DW chirality. The potential observed by the DW strongly depends on the anti-notch dimensions. A transition in the potential disruption at the anti-notch is observed at the anti-notch height to width ratio is 2. Increase in the DW equilibrium position for $H_{AN}/W_{AN} < 2$ shows the increase in the potential barrier with the height and width of the anti-notch. The constant equilibrium position of the DW for $H_{AN}/W_{AN} \geq 2$ shows that the potential barrier does not vary with the anti-notch dimensions. The variation of the equilibrium position and the damped oscillation time period with the current density reveals that the potential barrier is smooth and gradual when spins in the anti-notch are orthogonal to the transverse component of the DW. The potential barrier is steep and abrupt when the spins in the anti-notch are aligned with the transverse component of the DW.

5.4. Domain Wall pinning and depinning in cylindrical nanowires

In this section, a detailed study on the field-driven and current-driven depinning mechanisms of transverse DW in cylindrical NiFe nanowires is presented by means of micromagnetic simulation. A cylindrical NiFe nanowire of 30 nm diameter was chosen to ensure that the transverse DW is energetically stable within the system. The notch and anti-notch are cylindrically symmetric and concentric regions with respect to the nanowire, as schematically shown in Figure 5.8.

Figure 5.8 Schematic diagram of the cylindrical nanowire simulation model with symmetrical geometrical modulations, i.e. notch (left) and anti-notch (right) pinning sites.

The length of the modulated regions (*i.e.* notch, anti-notch) was kept constant at 100 nm while the diameter was varied. The depth of the notch (N_d) or the height of the anti-notch (AN_h) is defined as the difference in the diameter between the nanowire and the notch/anti-notch. The length of the nanowire is 2 μm , and the notch/anti-notch was positioned at the center of the nanowire and designated as the center of coordinate ($x = 0$). A DW was initially relaxed at $x = -700$ nm with respect to the center of the nanowire.

5.4.1 Shape of the potential energy landscape at geometrical modulations

To investigate the energy landscape that is present at the notch and anti-notch in the cylindrical nanowire, we have analyzed the DW energy as a function of position while it is driven by a magnetic field of 1 kOe. The depth of the notch N_d , (or the height of the anti-notch AN_h) is fixed at 5 nm. With applied magnetic field, the potential energy landscape can be obtained by subtracting the Zeeman energy from the total energy of the system [16]. The potential energy along the nanowire is plotted in Figure 5.9

Figure 5.9 DW potential energy as a function of the position along the nanowire for (a) notch, and (b) anti-notch.

For the notch structure, the potential energy drops when the DW is within the notch structure, as seen in Figure 5.9 (a), whereas for the anti-notch, the potential energy increases when the DW is within the anti-notch as seen in Figure 5.9 (b). This implies that the two pinning sites have different energy properties – the notch acts as a potential well while the anti-notch acts as a potential barrier. The pinning strength for the notch is

relatively higher as compared to that of the anti-notch, as revealed by the magnitude of the potential well (0.43×10^{-17} J) as compared to the potential barrier (0.32×10^{-17} J) for the same magnitude of the N_d and AN_h .

5.4.2 Field-induced transverse DW depinning at the notch

The dynamic behavior of the field-driven DW in a nanowire with a notch depth (N_d) of 20 nm is shown in Figure 5.10. The magnetic field was increased in steps of 5 Oe to estimate the depinning field.

Figure 5.10 Field-driven DW motion in cylindrical nanowire with a notch ($N_d = 20$ nm). The magnetization along the long axis (m_x) and around the long axis (m_z) corresponds to the DW translational and rotational motion in the cylindrical nanowire, respectively.

The magnetization component along the nanowire long axis (x -axis), m_x indicates the translational motion of the DW; while the magnetization component along the z -axis, m_z can be interpreted to indicate the DW rotation around the longitudinal axis. The DW dynamics plot is analyzed into three regions: region I is the DW dynamics before the DW enters the notch, region II is when the DW is within the notch, and region III is after the

DW has left the notch. In region I, the oscillating m_z component and the linearly increasing m_x component indicate that the DW rotates and moves linearly along the nanowire before it reaches the modulated region. The DW is not immediately pinned when it enters the notch region, instead its size reduces to accommodate the smaller diameter of the notch structure. The DW is pinned at the right edge of the notch as shown in the magnetization configuration in Figure 5.11.

Figure 5.11 The magnetization configuration of the nanowire while the DW is pinned at the notch

The DW pinning can be seen from the constant m_x with respect to simulation time in region II. The DW rotational motion also changes from sustained rotations to discontinuous rotations as shown by the m_z plot. The DW pinning in the notch structure can be understood from the dependence of DW energy on the DW size. From the DW theory, DW energy (E_{DW}) is defined as [17]

$$E_{DW} = \frac{\pi^2 A}{\delta} + K\delta \quad (5.1)$$

where A is the exchange stiffness constant, K is the anisotropy energy density and δ is the DW width (lateral size). Due to the dominance of the second term, the DW energy

is almost proportional to the DW width. The DW energy is lower within the notch due to the reduced size. The DW is pinned at the notch as it is unable to restore the energy and structure to move forward from the notch. As the DW gradually gains sufficient energy from the Zeeman energy, it depins and enters the nanowire as shown in Figure 5.12. The field required for depinning is found to be 1.8 KOe. In region III, the m_z component starts to oscillate again indicating that the DW has regained its rotational motion after it has depinned from the notch.

Figure 5.12 The variation in the DW potential energy as a function of the external magnetic field.

To study the effect of notch depth on the depinning field, the notch depth (N_d) was varied from 20 nm to 5 nm (corresponding to the diameter 10 nm to 25 nm). The depinning field as a function of notch depth is plotted in Figure 5.13

Figure 5.13 DW depinning field as a function of the notch depth.

The depinning field increases as the notch depth is increased. This implies that the depth of the potential well increases with deeper notch. The DW size within the notch is directly related to the notch diameter. When the diameter of the modulated region is reduced, the size of the DW is also scaled down and the DW energy decreases correspondingly. Hence, the field that is required to restore the DW energy via Zeeman contribution increases. Such results are in agreement with the conventional field-induced transverse DW depinning process in planar nanowire structures, where a notch with deeper profile produces a stronger pinning potential.

5.4.3 Field-induced transverse DW depinning at the anti-notch

In the case of anti-notch, the DW follows two distinct depinning mechanisms as shown in Figure 5.14 (region P and Q) in accordance to the anti-notch height. When the anti-notch height (AN_h) ≤ 15 nm, the depinning field increases linearly with the anti-notch height. For anti-notch height $AN_h > 15$ nm, a reverse trend is seen where the depinning field starts to drop.

Figure 5.14 Domain wall depinning field as a function of the height of anti-notch.

To analyze the two depinning mechanisms, the field-dependent demagnetization energy values and the magnetization configurations were extracted. When $AN_h \leq 15$ nm, the transverse DW maintains its transverse configuration when it is trapped inside the anti-notch, as shown in the inset of Figure 5.15. When the applied field is increased, the transverse DW starts to acquire additional energy from the Zeeman contribution to break free from the anti-notch. However, when the height of the anti-notch is greater than 15 nm, a different behavior is observed as the transverse DW transforms into a vortex configuration.

Figure 5.15 Demagnetization energy of the field-induced DW motion in the anti-notch ($AN_h = 10$ nm) corresponding to region P. Inset shows the magnetization configuration of the DW within the anti-notch.

For $AN_h > 20$ nm, the overall diameter of the pinning segment becomes larger than 50 nm, which changes the stable configuration of the DW from transverse to vortex state. The rapid drop of the demagnetization energy as shown in Figure 5.16 confirms the DW transformation. The drop of the demagnetization energy lowers the potential barrier height. In addition, mobility of the vortex DWs is higher compared to the transverse DW when driven by magnetic field [9]. The higher mobility of the vortex DW, along with the drop in the barrier height, allows the DW to depin at a lower field. The vortex DW transforms back into the transverse configuration after leaving the anti-notch structure.

Figure 5.16 Demagnetization energy of the field-induced DW motion in the anti-notch ($AN_h = 25$ nm) corresponding to region Q . Inset shows the magnetization configuration of the DW within the anti-notch.

5.4.4 Current-induced transverse DW depinning at the notch

When under the influence of spin polarized current, the transverse DW moves due to the localized momentum transfer from the spin transfer torque (STT). The modulated regions of the nanowire causes a change in the the current density distribution as it flows within the nanowire. In our simulations, though we do consider the variation of the current density at the modulated region, the critical current density for the DW depinning is taken as the current density that is applied to the nanowire (non-modulated regions). The dynamic behavior of a current-driven DW in a nanowire with a notch, $N_d = 20$ nm is shown in Figure 5.17

Figure 5.17 Current-driven DW motion in cylindrical nanowire with a notch ($N_d = 20$ nm). The magnetization of nanowire along the long axis (m_x) and around the long axis (m_z) represents the DW translational and rotational motion in the nanowire, respectively.

Similar to the field-driven DW analysis, the plot is analyzed in three distinct regions. In region I, where the DW moves towards the notch structure, the DW translational motion (m_x) is not linear but follows an oscillatory behavior. The oscillation is analogous to a damped harmonic motion of a particle that is under the influence of two oppositely-directed forces. In this case, the DW is influenced by the spin-transfer torque from the current and the magnetic stray fields. The origin of the stray fields is the spins that exist at the boundary of the modulation region, as shown by the simulated spin configuration in Figure 5.18

Figure 5.18 The magnetization configuration of the nanowire with a DW pinned at the notch. Dotted red circles indicate spins present at the boundary of the notch structure, which generate stray fields and affect the DW motion.

The m_z plot also shows an oscillatory behavior which indicates that the DW rotates around the longitudinal axis. In region II, where the DW is within the notch structure, the constant m_x value indicates the ceased DW translational motion along the long axis as the DW is trapped at the right edge of the notch. However, unlike the field-driven case, the m_z component continues to oscillate, even though the DW is pinned at the notch. The STT effect provides the energy required to sustain the DW rotation so as to reach an equilibrium condition [18,19]. In the field-driven case the DW rotational motion is not sustained as the torque exerted by the magnetic field decreases in time due to the damping term. However, in the current driven case, the STT effect compensates the damping term and the system achieves an equilibrium condition where the magnetization dynamics can be sustained [20-24].

Two types of DW rotational motions take place at the pinning site depending on the applied current density, as shown in Figure 5.19.

Figure 5.19 The DW rotation (m_z) at the pinning site as a function of the simulation time for two different current densities. At lower current density ($0.4 \times 10^{11} \text{ A/m}^2$), the m_z oscillation is near symmetric and the amplitude is lower, indicating a stable DW rotation at the pinning site. At higher current density ($2.5 \times 10^{11} \text{ A/m}^2$), the m_z oscillation is asymmetric and the amplitude is larger, indicating the DW depinning process.

At a current density, $J = 0.4 \times 10^{11} \text{ A/m}^2$, the rotational m_z component has a near symmetric amplitude, which indicates that the system is at a relatively stable state (lower energy), thus the DW cannot depin from the notch. At a current density $J = 2.5 \times 10^{11} \text{ A/m}^2$, the m_z component has a higher but rather asymmetric amplitude. The asymmetric DW rotational motion maintains a higher energy state and that enables the DW to depin

from the notch. For 20 nm-deep notch, the critical current density is $2.5 \times 10^{11} \text{ A/m}^2$, which is one order smaller as compared to the typical depinning current density in the planar nanowires. In region III, after the DW leaves the notch structure, the DW continues the oscillatory behavior.

Different notch dimensions were investigated to understand the effect of notch depth on the depinning current density. Simulation results show that when the notch depth, N_d is varied from 5 nm to 20 nm, the depinning current density decreases, as shown in Figure 5.20. Such behavior is opposite to that of the field-driven case, where the depinning field increases with the notch depth. The magnetization configurations of the transverse DW when it is pinned at the notch of different depth are shown in Figure 5.21.

Figure 5.20 DW depinning current density as a function of notch depth.

Figure 5.21 Snapshot images of the magnetization configuration of the DW pinned at the notch of two different depths 5 nm and 20 nm.

For the 5-nm-deep notch, the transverse DW is shown to retain its transverse configuration, albeit with a smaller DW width. For the 20-nm-deep notch, the DW width is larger because of shape deformation. The transverse DW shape variation corresponds to energy difference between two systems, which affect the depinning process consequently. Figure 5.22 shows the total energy of the system as a function of simulation time for the two notches (5 nm and 20 nm deep), with an applied current density of $J = 2.5 \times 10^{11} \text{ A/m}^2$. The plot shows that the DW total energy drops significantly when the transverse DW enters the notch. If the applied current density is less than the critical value, the transverse DW is pinned next to the notch with its profile and energy partially restored.

Figure 5.22 Total energy of the system as a function of time for two different notch depths when the DW is driven through the notch by same current density ($J = 2.5 \times 10^{11} \text{ A/m}^2$).

For the 5-nm-deep notch, the DW is able to restore its transverse shape, however it only yields approximately 50% of its initial energy because of the smaller DW width. Hence, it is unable to depin from the notch even with the assistance of the STT effect. For the 20-nm-deep notch, the DW is able to restore approximately 70% of the initial energy because it gains additional energy from the shape deformation. The contribution from the STT effect increases the shape deformation of the transverse DW. The high energy state of the system coupled with the DW deformation eventually leads to a complete depinning process. As the applied current density is increased further, the DW shape deformation occurs faster, resulting in a shorter depinning time.

5.4.5 Current-induced transverse DW depinning at the anti-notch

The translational motion of the current-driven DW along the nanowire axis (m_x component) as it propagates across an anti-notch of $AN_h = 5$ nm is shown in Figure 5.23. The DW reaches an equilibrium position at the left edge of the anti-notch as shown in the inset.

Figure 5.23 Current-driven DW motion in the cylindrical nanowire with an anti-notch.

Inset shows the DW pinned at anti-notch

The depinning current density is plotted as a function of the anti-notch height in Figure 5.24. The plot shows that two DW depinning mechanisms are involved as the anti-notch height is increased. In region A ($AN_h \leq 15$ nm), the depinning current density drops when the anti-notch height is increased from 5 nm to 15 nm. The simulated magnetization configuration (inset of Figure 5.23) reveals that the pinned DW retains its transverse

configuration but is deformed at the boundary of the anti-notch. The degree of the DW deformation at the 15-nm-high anti-notch is higher than that at the 5-nm-high anti-notch, which leads to a lower depinning current density. In region B ($AN_h > 15$ nm), however, the depinning current density increases with increasing anti-notch height, therefore a different depinning mechanism is expected. When the anti-notch height is increased beyond 15 nm (which gives us a modulated region with a total diameter more than 45 nm), the spins within the anti-notch start to follow the cylindrical shape to reduce the demagnetization energy. The current-driven transverse DW is then transformed into a vortex DW inside the anti-notch to follow the spins orientations.

Figure 5.24 Depinning current density as a function of the anti-notch height.

Shown in Figure 5.25 are the cross-sectional magnetization configurations of the DW within an anti-notch with a height of $AN_h = 30$ nm at four different stages. Initially at $t = 0$ ns, the spins of the anti-notch at remanence is found to be rotating in a clock-wise direction. When the transverse DW enters the anti-notch ($t = 86$ ns), the DW is then transformed into a vortex DW with clock-wise chirality. However, due to the spin-

polarized current [11], the DW changes its chirality from clock-wise to counter clock-wise orientation at $t = 158$ ns. Finally, the DW is depinned at $t = 175$ ns.

Figure 5.25 The evolution of the vortex magnetization at the boundary of the anti-notch ($AN_h = 30$ nm) at four different stages during the DW depinning through the anti-notch. The chirality of the vortex configuration switches from clock-wise to counter clock-wise during the DW depinning.

The forward torque ($+x$ direction) from the spin-polarized current is enhanced when the vortex DW has a counter clock-wise chirality [11], which allows it to be depinned from the anti-notch. As the anti-notch height is increased beyond 15 nm, the vortex configuration of the DW inside the anti-notch becomes more pronounced, and thus it requires higher current density to switch its chirality from clockwise to anti-clockwise in order to be depinned from the anti-notch.

5.4.6 Summary of transverse DW pinning in cylindrical nanowires

When a DW propagates in a nanowire with modulated regions, it perceives a notch structure as a potential well and an anti-notch structure acts a potential barrier. In their motions, the transverse DWs are pinned at these modulated structures. The pinning potential is found to increase with notch depth when the motion is field-driven, but an opposite behavior is observed when it is driven by current. Such observation is attributed to the DW deformation and rotational behavior within the notch, which contributes to the depinning process. The degree of the DW deformation is larger at a deeper notch, and it assists to lower the depinning current density. In the case of anti-notch, the DW transforms from transverse to vortex configuration as the anti-notch diameter increases. Such DW transformations induce a change in the height of the DW pinning potential. Anti-notch acts as a weak pinning site compared to the notch irrespective of the driving mechanism.

References

1. D. Atkinson, D. S. Eastwood, L. K. Bogart, *Appl. Phys. Lett.* **92**, 022510 (2008).
2. M. Klaui et al., *Appl. Phys. Lett.* **87**, 102509 (2005).
3. S Goolaup, S C Low, M Chandra Sekhar and W S Lew, *J. Phys.: Conf. Ser.* **266**, 012079 (2011).
4. D. Petit, A-V. Jausovec, H.T. Zeng, E. Lewis, L. O' Brien, D. Read, and R.P. Cowburn, *Phys. Rev. B* **79**, 214405 (2009).
5. M. Chandra Sekhar, S. Goolaup, I. Purnama, and W. S. Lew, *J. Phys. D: Appl. Phys.*, **44**, 235002 (2011).
6. Sheng-Huang Huang, Chih-Huang Lai, *Appl. Phys. Lett.* **95**, 032505 (2009).
7. R. D. McMichael, and M. J. Donahue, *IEEE Trans. Magn.* **33**, 4167 (1997).
8. Y. Nakatani, A. Thiaville, and J. Miltat, *J. Magn. Magn. Mater.* **290**, 750 (2005).
9. R. Wieser, U. Nowak and K. D. Usadel, *Phys. Rev. B* **69**, 064401 (2004).
10. R. Hertel, *J. Magn. Magn. Mater.* **249**, 251 (2002).
11. R. Wieser, E. Y. Vedmedenko, P. Weinberger and R. Weisendanger, *Phys. Rev. B* **82**, 144430 (2010).
12. M. Yan, A. Kakay, S. Gliga and R. Hertel, *Phys. Rev. Lett.* **104**, 057201 (2010).
13. M. Donahue and D. G. Porter, OOMMF User's guide, Version 1.0, Interagency Report NISTIR 6376, National Institute of Standard and Technology, Gaithersburg, MD. 1999.
14. OOMMF Extension for Current-induced Domain Wall Motion developed by IBM Research, Zurich; see <http://www.zurich.ibm.com/st/magnetism/spintevolve.html>.
15. COMSOL Multiphysics modelling Manual

16. M. Hayashi, L. Thomas, C. Rettner, R. Moriya, X. Jiang and S. S. P. Parkin, *Phys. Rev. Lett.* **97**, 207205 (2006).
17. C. H. Marrows, *Advances in Physics* **54**, 585 (2005).
18. M. Franchin T. Fischbacher, G. Bordignon, P. de Groot, and H. Fangohr, *Phys. Rev. B* **78**, 054447 (2008).
19. M. Franchin, A. Knittel, M. Albert, D. S. Chernyshenko, T. Fischbacher, A. Prabhakar, and H. Fangohr, *Phys. Rev. B* **84**, 094409 (2011).
20. S. I. Kiselev, J. C. Sankey, I. N. Krivorotov, N. C. Emley, R. J. Schoelkopf, R. A. Buhrman, and D. C. Ralph, *Nature* **425**, 380(2003).
21. E. Martinez, L. Torres and L. Lopez-Diaz, *Phys. Rev. B* **83**, 174444 (2011).
22. T. Ono and Y. Nakatani, *Appl. Phys. Exp.* **1**, 061301 (2008).
23. K. Matsushita, J. Sato and H. Imamura, *J. Appl. Phys.* **105**, 07D525 (2009).
24. F. Giovanni *et al.*, *IEEE Trans. Mag.* **46**, 1519 (2010).

Chapter 6

Domain wall manipulation in patterned nanostructures for magnetic logic applications

6. 1 Introduction

In this chapter, domain wall (DW) dynamics driven by magnetic field are studied and novel DW based spin-logic applications are presented. This chapter is divided into two sections. The key focus of the first part is devoted to the creation and manipulation of transverse DWs in patterned planar nanowires. A method for DW injection into a nanowire by magnetic field is presented. A technique to select and detect the DW chirality is proposed and tested. A simple structure which can perform DW chirality rectification is demonstrated. In the second part, a DW based reconfigurable magnetic logic is presented. The underlying principal is discussed and two universal logic gate operations (NAND and NOR) are demonstrated experimentally by using MFM imaging technique.

6.2 Motivation

Traditional microelectronic circuits (ICs) work on the concept of controlling electron flow through transistors. The digital signals are processed as the accumulation and dissipation of electronic charge. The device miniaturization leads to a current leakage which imposes major drawback for these devices. Besides charge, electron offers more, intrinsic quantum mechanical dimension “spin”. Unlike charge, spin has two directions. The two directions of a spin can represent two Boolean states. Spintronics which exploits the spin property of electrons along with the charge offers new type of devices with high

performance which can replace the traditional electronics devices. The magnetization direction has been utilized to store the information in magnetic recording from long time *e.g.* hard disc drive. The advantages of spintronic based devices often include low power dissipation, non-volatile data retention, radiation hardness, reduced heating issues and high integration densities. Digital microelectronics is a combination of both memory and logic units. Currently, memory is spin-based (ferromagnetic) whereas the logic is still charge-based (semi-conductor) process. Data from the memory is being converted into charge signal through a combination of CMOS transistors for arithmetic calculations. However, study in to spin based logic is more interesting as it will be compatible with memory which can potentially increase the data processing efficiency.

6.3 Domain wall injection

DW injection into ferromagnetic nanowire is the first step for the DW based memory or logic device applications. Particularly for memory applications, a DW separates two bits of opposite magnetization and motion of the DW leads to the reading or manipulation of the data bits [1-4]. For logic applications [5-7], the DW acts as a medium for functioning of the logic operation. So, it is of great interest to study the DW injection methods in ferromagnetic nanowires. In this study, three kinds of DW injection methods are demonstrated. First, the DW injection by a local magnetic field generation using current carrying stripe line [8-11]. Second, an oblique field is applied at the curvature of an L-structure nanowire to create a DW at the curvature of the nanowire [12-15]. The results corresponding to these two methods are presented in Appendix C and D. The DW injection by magnetization reversal by the application of external magnetic field is presented here. This method of DW injection is employed for all the devices in this

chapter. Throughout this work, ferromagnetic nanowires are fabricated by using electron beam lithography and ion-milling techniques. The nanowires are patterned on the Ta/Ni₈₀Fe₂₀/Ta (5 nm/10 nm/5 nm) thin films deposited using magnetron sputtering. The contact layers are fabricated by electron beam lithography and lift-off techniques. Cr/ Au (3 nm/ 100 nm) is deposited as the contact layer.

6.3.1 Domain wall injection by nucleation pad

In permalloy, due to zero crystalline anisotropy, the magnetization is always constrained to follow the shape of the nanostructure. So in a permalloy nanowire, the spins always align along the long axis direction due to the shape anisotropy. A DW can be injected by reversing the magnetization from one end of the nanowire by the application of external magnetic field. But a large nucleation magnetic field of around 400 Oe is required to switch magnetization from the edge of the nanowire of dimensions 2 μm × 100 nm × 10 nm (length, width and thickness) dimensions. In order to reduce this nucleation field, a diamond shaped pad is attached to the left edge of the nanowire as shown in the SEM image in Figure 6.1. The dimensions of the nucleation pad are 2 μm × 2 μm × 10 nm.

Figure 6.1 SEM image of the permalloy nanowire with a diamond shaped nucleation pad for DW injection

Figure 6.2 (a-c) The evolution of the magnetization dynamics in the nucleation pad when the magnetic field is reversed to inject the DW in to the nanowire.

The magnetization configuration of the structure during the reversal process is studied using micromagnetic simulations and MFM imaging. Initially, the structure is saturated with -300 G magnetic field along $-x$ (nanowire long axis) direction and relaxed. The magnetization relaxation is followed by field reversal. The magnetic field is reversed and slowly increased along $+x$ - direction. Shown in Figure 6.2 are the MFM images and the corresponding micromagnetic configuration of the structure to understand the magnetization evolution during DW nucleation. As the shape anisotropy of the pad is smaller compared to the nanowire, the magnetization follows the diamond shape at remnence as shown in Figure 6.2(a). When the magnetic field is increased to +30 G, the magnetic contrast in the MFM image in Figure 6.2 (b) clearly shows that magnetization within the diamond structure switches first by forming a vortex magnetization configuration [16-19]. When the magnetic field is increased further, the vortex core travels transverse to the magnetic field direction (perpendicular to the nanowire long axis). When the magnetic field is increased to 70 G, the vortex core completely moves towards the bottom of the diamond pad and a DW is pushed in to the nanowire as shown in Figure 6.2(c). A small additional magnetic field can move the DW through the nanowire. This method has an advantage of injection of multiple DWs into the nanowire which is crucial for the memory applications [20]. However, the DW chirality cannot be controlled using the DW nucleation method unless a transverse magnetic field is applied to select the DW chirality. Depending on the initial saturation magnetization direction, the injected DW can be of either Head to Head (HH) or Tail to Tail (TT). When the magnetization is saturated in $-x$ - direction and field is applied in $+x$ - direction, a HH DW is injected where the spins point towards each other. When the magnetization is saturated

in $+X$ - direction and field is applied in $-X$ - direction, a TT DW is injected where the spins point away from each other.

6.4 Domain wall chirality selection

A Transverse DW besides being HH or TT, it possesses one more degree of freedom defined by the direction of the transverse magnetization ($\pm y$) of the DW. The transverse magnetization direction is represented by the DW chirality. As shown by the magnetization configurations in Figure 6.3 four types of transverse DW configurations are possible within a permalloy nanowire.

Figure 6.3 (a&b) Head to Head DW with up chirality and down chirality (c&d) Tail to Tail DW with up and down chirality.

If the transverse DW pointing along the $+y$ -direction (spins within the DW rotates in clockwise direction) the DW is said to possess an “Up” chirality. When the DW

transverse component points along the $-y$ - direction (spins within the DW rotates in anti-clock wise direction), the DW is said to possess a “Down” chirality. The key focus of this work is devoted to select, detect and manipulate the chirality of the transverse DW. In the rest of the chapter, Head to Head DW with “Up” chirality is represented as HH-U and “Down” chirality is represented by HH-D. Tail to Tail DW with “Up” and “Down” chirality are represented by TT-U and TT-D, respectively.

The DW chirality plays a vital role in the DW dynamics for the memory and logic applications. For instance, the pinning potential of an artificial pinning site is influenced by the chirality of the DW [21-25]. In two nanowire systems, the magnetostatic coupling between two DWs is a function of chirality of the DWs. The coupling strength can be tuned by varying the combinations of DWs with different chirality [26-30]. So it is of paramount interest to inject the DW with a specific chirality in to the nanowire. To control the chirality of the DW injected into the nanowire, a chirality selector is added between the nucleation pad and the magnetic nanowire as shown in the SEM image in Figure 6.4.

Figure 6.4 SEM image of the nanowire connected to a nucleation pad and a chirality selector at the junction.

The dimensions of the chirality selector are 200 nm wide (along x -axis) and 5 μm long (along y -axis). The chirality selector which has an easy axis along $\pm y$ direction is placed at the junction between the nucleation pad and the nanowire. The chirality selector is saturated either in $+y$ or $-y$ direction prior to the DW injection. Due to the strong shape anisotropy, the magnetization of the chirality selector is not affected by the lateral magnetic field which is applied to saturate the structure and nucleate the DW. The chirality selector induces the injected DW to align in the same direction as the magnetization of the selector. As shown by the magnetization configuration in Figure 6.5 when the chirality selector is fixed in $+y$ - direction and the structure is saturated in $+x$ -direction, the transverse component of the DW nucleated aligns with the magnetization direction of the chirality selector. This results in to an injection of TT-U in the nanowire as shown in the Figure 6.5 (a). When the magnetization of the chirality selector is reversed to $(-y\text{-direction})$, a TT-D is injected as shown in 6.5 (b) and the DW.

Figure 6.5 (a) A TT-U injected when the chirality selector is saturated in $+Y$ -direction (b) A TT-D injected when the chirality selector is saturated in $-Y$ -direction.

When the chirality selector is saturated in $+y$ -direction and the structure is saturated in $-x$ -direction, a HH-U is injected as shown in the magnetization configuration in 6.6. The Transverse DW always assumes a triangular shape [21]. As seen in Figure 6.3, for HH-U and TT-D, the base of the triangle faces the top edge of the nanowire whereas for HH-D and TT-U, the base of the triangle faces the lower edge of the nanowire. The dark magnetic contrast in the MFM image represents a HH DW that is injected in to the nanowire from the nucleation pad. The triangular shape facing the top edge supports the simulation result showing that a HH-U is injected in to the nanowire. The chirality is selected by the transverse magnetization direction of the chirality selector.

Figure 6.6 A HH-U injected into the nanowire when the chirality selector is saturated in $+Y$ -direction. Corresponding MFM image clearly shows the triangular shape of the HH-U.

The relative angle between the nanowire and the transverse nanowire is critical for reliable DW injection. To estimate the tolerance, micromagnetic simulations are performed with tilted transverse nanowire by varying the angle between the nanowire and chirality selector. The snap shot images for three different angles $\pm 5^\circ$ are presented the

Figure 6.7 and 6.8. It is observed that a variation $\pm 5^\circ$ does not affect the final result. It nucleates the DW with the intended chirality.

Figure 6.7: The snap shot images of magnetization configuration for Up and Down chirality injections when the chirality selector is 95° with respect to the longitudinal nanowire.

Figure 6.8: The snap shot images of magnetization configuration for Up and Down chirality injections when the chirality selector is 85° with respect to the longitudinal nanowire.

Shown in Figure 6.7 and 6.8 are the simulation results when the chirality selector is tilted with an angle $\alpha = 95^\circ$ and 85° , respectively. It is clear from the images that a small tilting does not affect the chirality selection for the injected DW. However, the magnetic field required to saturate the chirality selector along its long axis direction is found to be increasing with increasing α . With the current lithography techniques, the angle between the chirality selector and longitudinal nanowire can be controlled precisely.

6.4.1 Domain wall chirality detection

Transverse DW can be driven by very small magnetic field (of few Gauss). Once the DW is injected into the nanowire, a small increment in the field drives the DW through the nanowire which makes it difficult to probe its chirality. The Transverse DW chirality can be detected by DW anisotropic magnetoresistance (AMR) measurements [8-11], but the difference in the AMR between the “Up” chirality and “Down” chirality is very small [10,11] which makes the AMR method unreliable. An artificial pinning site can be introduced to pin the DW to detect the chirality [11]. However, the DW pinning is stochastic and pinning strength of the notch depends on the shape of the DW [21]. When the magnetic field is applied to depin the DW, the DW may lose its fidelity (structure) due to the interaction with the magnetization configuration of the pinning sites [31]. However, preserving the DW fidelity is important as it plays a key role in the logic operations [32,33]. To keep the DW fidelity unaffected, a reference device can be fabricated which can probe the DW chirality without disturbing the DW structure in the actual device. Such a reference device can act as a DW chirality detector. In this work, a magnetic nanostructure is presented which can act as a transverse DW chirality detector. Shown in Figure 6.9 is the SEM image of the DW chirality detector.

Figure 6.9 SEM image of the nanostructure with a branch structure which acts as a DW chirality detector.

The device consists of a branch structure that is connected to the right edge of the magnetic nanowire. Each branch is tilted 70° away from the nanowire long axis (x -axis). The widths of the nanowire and branch structure are 140 nm and 200 nm respectively. When the DW is injected and driven through the nanowire into the branch structure. The branch structure detects the chirality of the DW due to the selective switching of the DW into one of the two branches. Underlying principle behind the selective switching for DW detection is explained by micromagnetic simulations. As shown in Figure 6.10 (a) the structure and the chirality selector are saturated in $+x$ and $+y$ - directions respectively.

Figure 6.10 (a-b) Initial and final magnetization states of the structure when a TT-U is injected and driven through the branch.

It leads to an injection of TT-U into the nanowire during the magnetic field reversal. The DW is driven through the branch structure by the magnetic field of 100 Gauss. As shown in MFM image of Figure 6. 10 (b), the magnetic contrast is changed from dark to bright in the lower branch. It reveals that the DW switches the magnetization of the lower branch. The magnetization switching of the lower branch can be seen clearly in the simulated magnetization. The magnetization configuration of the upper branch is unchanged.

Figure 6.11 (a-b) Initial and final magnetization states of the structure when a TT-D is injected and driven through the branch.

As shown in Figure 6.11 (a) when the magnetization direction of the chirality selector is flipped to $-y$ -direction and the structure is saturated in $+X$ -direction. A TT-D is injected into the nanowire. With the increase in the magnetic field, the DW moves along the upper branch. The change in magnetic contrast at the upper branch can be clearly seen in Figure 6.11 (b). It reveals that the DW selectively switches the magnetization of the branch depending on its chirality.

To understand this interesting phenomenon of chirality dependent DW selective switching, the magnetization configuration of the DW at the junction between the nanowire and the branch structure is analyzed. When the DW reaches the junction, change in the dimension from the nanowire (140 nm) to branch structure (200 nm) leads to a transformation of DW from transverse to vortex configuration. When TT-U reaches the junction it turns into a vortex DW with a clockwise orientation as shown in Figure 6.12

Figure 6.12: Clockwise vortex DW formed at the junction as the TT-U moves to the junction.

A vortex DW can be characterized by the orientation of the rotation and the direction of the core. The vortex core always moves perpendicular to the direction of the magnetic field. In the vortex DW with clockwise orientation, the DW core moves towards the lower branch. Subsequently the DW switches the magnetization of the lower branch. For TT-D, the vortex formed at the junction has an anti-clockwise orientation contrary to TT-U as shown in Figure 6.13.

Figure 6.13: Clockwise vortex DW formed at the junction as the TT-U moves to the junction.

The vortex core of the anti-clockwise orientation moves towards the upper branch leading to the switching of the upper branch. The magnetization switching in the branch structure is easy to probe using magnetoresistance measurements at each branch. So this structure can be used as reference device for DW chirality detection.

6.4.2 Domain wall chirality rectification

For fast DW injection, it is a common practice to reverse the magnetization locally by generating Oersted field at the nanowire by current carrying strip line [8-11]. The chirality of the injected DW is random [16] could either be “Up” or “Down”. The DW chirality plays an important role in many phenomena such as DW pinning and DW coupling [34-36]. So it requires a DW chirality rectifier to manipulate the injected DW to output a DW with a fixed chirality. The DW transverse magnetization has to be rectified to a specific direction either “Up” or “Down” irrespective of the chirality of the injected DW. A unique structure, which can rectify the chirality of the injected DW by the application

of linear magnetic field, is presented in this section. Shown in Figure 6.14 is the SEM image of the DW rectifier structure.

Figure 6.14 SEM image of the DW rectifier structure and the schematic of the slanted rectangle placed at the center of the nanowire.

The width of the NiFe nanowire is 120 nm. A slanted rectangular structure of width 240 nm and length 480 nm is placed at the centre of the structure. The rectangle is slanted with an angle $\alpha = 10^\circ$. The chirality selector and the branch structure are employed to select and detect the chirality of the DW.

Figure 6.15 (a) The magnetization configuration of the nanowire with rectifier structure before the DW injection. (b) The magnetization configuration of the structure after the *TT-U* pass through the rectifier structure.

When a TT-U is injected in to the nanowire and the DW is driven by linear magnetic field to pass through the rectifier structure as shown in Figure 6.15, the output shows that the DW pass through the lower branch which means there is no chirality reversal occur within the structure as TT-U generally moves in to the lower branch as discussed in the previous section 6.4.1.

Figure 6.16 (a) The magnetization configuration of the nanowire with rectifier structure before the DW injection. (b) The magnetization configuration of the structure after the TT-D pass-through the rectifier structure.

When a TT-D is injected in to the nanowire and the DW is driven by linear magnetic field to pass through the rectifier structure as shown in Figure 6.16, the output shows that the DW pass through the lower branch switching its magnetization. As discussed in section 6.4.2, a TT-D generally switches the upper branch. The magnetization switching of the lower branch shows that TT-U is received at the branch structure from the rectifier structure. It reveals that DW chirality flipping took place within the rectifier structure and a TT-U is injected into the nanowire. A TT-U pass-through the rectifier comes out as a TT-U whereas TT-D flips into TT-U while coming out from the same structure. These two observations imply that the output of the rectifier structure is always TT-U irrespective of the chirality of the input. The rectifier structure can be employed to inject a single chirality DW. Though, in this experiment a DW is injected via a nucleation pad, the chirality rectification works irrespective of the injection method.

To understand the opposite behaviors of TT-U and TT-D within the rectifier structure, the magnetization configurations at various stages are captured when the DW is driven through the rectifier structure. It is found that the magnetization dynamics of the TT-U and TT-D undergoes two different mechanisms while passing through the rectifier structure. The magnetization dynamics for TT-U are shown in Figure 6.17. As shown in Figure 6.17 (a), when the TT-U reaches the slanted rectangular structure, the variation in the geometry leads to the pinning of the DW at the left corner of the structure. However the pinning potential is not strong as the base of the DW faces the smooth variation of the geometry whereas the apex of the DW faces an abrupt variation [21,22]. The DW pinning is strong when the base of the triangle faces the pinning site. Due to lower pinning

strength, the DW can be depinned at a lower magnetic field of 120 Gauss. The DW depins from the base part which switches the rectifier and the spins at the apex follows. Though the transverse configuration is not stable at these dimensions, the transformation to vortex state does not take place as the DW moves out of the structure quickly. The output has no change as shown in the Figure 6.17 (f).

Figure 6.17 (a-f) Magnetization configuration of the rectifier structure while TT-U is moving through the rectifier.

Shown in Figure 6.18 (a-f) are the magnetization configurations of TT-D while passing through the rectifier structure. The DW evolution reveals that the magnetization switching is completely different as compared to TT-U. When TT-D reaches the rectifier structure, the base of the DW (triangular shape) points towards abrupt change in the geometry and the apex of the DW encounter the smooth change. As the base of the triangle points to the pinning site, the pinning strength is higher compared to the previous case. The magnetic field required to depin the DW is found to be 200 Gauss almost twice the depinning field for TT-U.

Figure 6.18 (a-f) Magnetization configuration of the rectifier structure while TT-D is moving through the rectifier.

When the DW depins from the left edge of the rectifier structure, the base part depins first and the strong magnetic field causes it to move faster compared to the apex of the DW. The imbalance in the DW motion along the transverse direction causes the DW transformation from transverse to vortex configuration as shown in Figure 6.18 (c). The TT-D turns into a vortex state with anti-clockwise chirality. The core of the vortex DW gets pinned at the left edge and the DW is pushed towards the right edge of the rectifier structure. An anti-clockwise vortex turns out to be a TT-U as the spins in TT-U also rotate in the similar fashion. Thus the DW transformation from transverse to vortex and back to transverse performs the rectification of the DW chirality from TT-D to TT-U.

The micromagnetic simulations are performed with various titled angles (α) of the slanted rectangle. It was observed that the angle of the slanted rectangle α is critical and the DW chirality rectification occurs only when $\alpha > 8^\circ$ and $\alpha < 14^\circ$. Shown in Figure 6.19 (a-d) are the snap shots of magnetization configurations during the DW motion through the slanted rectangle when $\alpha = 15^\circ$.

Figure 6.19 (a-d) Magnetization configurations of the DW evolution through the slanted rectangle with $\alpha = 15^\circ$, when TT-U is injected (e-f) Magnetization configuration of the DW evolution through the slanted rectangle with $\alpha = 15^\circ$, when TT-D is injected

As shown from the micromagnetic configurations, when a TT-U is injected and driven through the slanted rectangular structure, the magnetization evolution is similar to the previous case when $\alpha = 10^\circ$. It results a TT-U at the output. When a TT-D is injected and driven to the slanted rectangle, a different behavior is observed. As the base of the TT-D points towards the upper edge, TT-D gets pinned at the barrier. The pinning potential is higher compared to the case $\alpha = 10^\circ$ as the barrier became steep. The magnetic field required for the DW depinning field also increases. When the magnetic field is increased to 230 Oe, the DW still pinned at the left edge of the rectangle but the magnetization within the structure starts to switch its magnetization as seen in Figure 6.19 (f). The local magnetization reversal within the structure nucleates two DWs of same chirality. The HH DW nucleated at the left edge travels towards the pinned TT-D and annihilates. The TT DW nucleated at the right edge is pushed out of the structure which is found to possess a Down chirality as shown in Figure 6.19 (h). It means that a TT-D is the output of the operation same as the injected DW. The results reveal that the output is same as the input irrespective of the injected chirality when $\alpha = 15^\circ$.

When the simulation are run with $\alpha = 5^\circ$, completely different results are observed as shown in Figure 6.10 (a-d). For TT-U, the DW does not see any pinning at the left edge of the slanted rectangle. However, it gets pinned at the right edge of the structure which causes the TDW to transform into vortex configuration with clockwise orientation as seen in Figure 6.20 (c). With the increase in the magnetic field, the vortex core moves towards the upper edge and is annihilated. A TT-D is pushed out of the structure as shown in Figure 6.20 (d). Figure 6.20 (e-h) show the magnetization evolution within the rectangle when TT-D is injected is driven. In case of TT-D, the DW gets pinned at the left edge of

structure similar to the previous cases ($\alpha = 10^\circ$ & 15°). The pinning strength is relatively lower and increase in the magnetic field transforms the TT-D to vortex DW with an anti-clockwise orientation as shown Figure 6.20 (g). Further increase in the magnetic field drives the vortex core towards the bottom edge and a TT-U is pushed out of the structure as shown in Figure 6.20 (h). It reveals that the DW with an opposite chirality is always comes out of the structure. Thus the structure acts as an inverter circuit by flipping the chirality of the DW inside the slanted rectangle.

Figure 6.20 (a-d): Magnetization configuration of the DW evolution through the slanted rectangle with $\alpha = 15^\circ$, when a TT-U is injected (e-h) Magnetization configuration of the DW evolution through the slanted rectangle with $\alpha = 15^\circ$, when a TT-U is injected

6.5 Reconfigurable magnetic logic

In the current microelectronics technology, the data storage is non-volatile (spin-based) whereas the data processing is volatile (charge based). The data is transferred to MRAM designed by the combination of the CMOS transistors to perform the logic operation. Spintronics [37,38], an alternative to the microelectronics has the potential to change the basic principle of the logic operations in the devices. The aim is to store and process the data solely in ferromagnetic materials makes the complete device non-volatile which increases the speed of the device and reduce the power consumption. Many attempts were made towards the realization of spin-logic or magnetic logic [39-46]. Imre *et al.*[41]demonstrated the magnetic logic based on the network called magnetic quantum cellular automata. Magnetostatically coupled ferromagnetic islands performs the logic operations by summing up the stray fields at the nodal dots which have different threshold switching fields. The main disadvantage of this device is that the magnetostatic coupling is weaker compared to the demagnetizing fields. A small change in the structure during the fabrication results in completely different results. Magnetic tunnel junction [43-46] based logic devices are proposed which can be even programmable but the high current density required for the operation is the main disadvantage. Allwood *et al.* [5,6] have proposed magnetic logic operation based on DW motion using a rotating magnetic field. Four different operations were demonstrated on different structures. However, if a device can perform all the basic logic operations in a single structure, it shall benefit us greatly by reducing the production cost of the devices. Such device is called reconfigurable logic. Semiconductor based reconfigurable logic devices were proposed [47,48]. Different combinations of InSb based p-n junction diodes perform different logic operations by the

application of large out of plane magnetic fields [47]. In this section, a unique non-volatile device is presented which can perform all the basic logic operation and is purely magnetic, and therefore shall be named as a reconfigurable magnetic logic. In this magnetic logic we nucleate a domain wall (DW) by using the diamond pad and drive it into the nanowire using a linear magnetic field. The logic function to be performed by the structure is determined by the dynamics of the field-driven DW. The magnetic structure is made of $\text{Ni}_{80}\text{Fe}_{20}$. The thickness of the structure is 10 nm. Shown in Figure 6.21(a) is a schematic of the reconfigurable logic circuit.

Figure 6.21(a) A schematic depiction of the reconfigurable magnetic logic device.(dimensions are not scaled) (b) SEM image of the fabricated reconfigurable logic structure.

Figure 6.21 (b) shows the SEM image of the device fabricated using e-beam lithography. The nanostructure is made of Ta (3 nm)/ The device consists of five parts: (1) DW generator, (2) a chirality selector, (3) a nanowire, (4) an orthogonal U- shape structure with two branches (5) a metal strip at the junction between the nanowire and the U-shape which acts as a gate to control the logic operation. *DW generator*: A diamond shaped pad which is connected to the left edge of the nanowire acts as a DW generator. The dimensions of the pad are $2\text{ }\mu\text{m} \times 2\text{ }\mu\text{m}$. The magnetization reversal mechanism leads to the nucleation of a DW in to the nanowire structure as described previously. A HH DW is injected when the magnetization is saturated in $-x$ - direction and a TT DW is injected when the magnetization is saturated in $+x$ -direction.

(1) *DW chirality selector*: A long strip transverse to the nanowire at the junction between DW generator and the nanowire acts as a DW chirality selector. The strip is $5\text{ }\mu\text{m}$ long in the y - direction and 100 nm wide in the x -direction. Due to the large shape anisotropy, the magnetization in the nanowire is not affected by the field applied along x - axis. The magnetization of the DW chirality selector can be saturated along the $+y$ - or $-y$ - direction by a transverse magnetic field of 300 Gauss . The DW acquires the same transverse component as the chirality selector magnetization. When the chirality selector is saturated in $+y$ - direction, the DW injected into the nanowire has the transverse component along the $+y$ - direction, which is the “Up” chirality DW. When the magnetization of the chirality selector is reversed ($-y$ - direction), a “Down” chirality DW is injected. The magnetization of the chirality selector is taken as the “Input 1” for the logic operation. The

magnetization saturated in $+y$ - direction is defined as the logic “1” whereas the magnetization saturated along the $-y$ - direction is defined as the logic “0”.

(2) *Nanowire*: A nanowire of 2 μm long (x - direction) and 160 nm width (y -direction) is the medium for the DW motion from input to output for the logic operation. The transverse DWs are the only possible DW configurations at these dimensions. The magnetization direction of the nanowire is defined as the “Input 2” *i.e.* the magnetization along the $+x$ -direction is defined as logic “1” and the magnetization along the $-x$ -direction is defined as logic “0”.

(3) *Orthogonal U-shaped structure*: The Output of the logic operation can be taken at the one of the two branches of the orthogonal U- shape structure. Definitions of logic states are same as the Input 2 (the magnetization of the nanowire). The magnetization along the $+x$ - direction is defined as logic “1” whereas the magnetization along the $-x$ -direction is defined as logic “0”.

(4) *The metal strip*: A rectangular metal strip is placed at the junction between the nanowire and the orthogonal U-shaped structure. The strip is of 200 nm wide and 400 nm long. The material for the strip is made up of Cr(5 nm)/Au(100 nm). The metal strip is placed just above the junction between the Input 2 (nanowire) and Output (orthogonal U-shape). The metal strip is overlapped only 25 % on top of the NiFe nanowire. The purpose of the metal strip is to generate local Oersted field in the nanowire when current is flown through it. The local magnetic field generated at the junction plays a vital role both in the logic operation and the

selection of the logic function (programmability). The metal strip is named as the “gate” as it can control all logic operations performed within this unique structure

The two binary inputs to perform the logic operations are chosen from the magnetization directions of the chirality selector (Input 1) and the magnetization direction of the nanowire (Input 2). Two outputs can be obtained in each operation which are the magnetization directions of the upper half ring (UHR) or the lower half ring (LHR). The two outputs always complement each other.

Input 1		Input 2		Output	
Input 1 M_y	Bit	Input 2 M_x	Bit	Output M	Bit
1		1		1
0		0		0

Table 6.1: In this work, the logic “1” is defined as the magnetization pointing in the positive direction along the co-ordinate axis (+x or +y) and logic “0” as the magnetization pointing in the negative direction (-x or -y).

The two inputs give rise to four combinations for two bit logic operation. The four combinations are defined with type of transverse DW (HH or TT) and with a specific chirality (Up or Down). The type of the DW can be controlled by the initial magnetization direction of the nanowire (Input 2) whereas the chirality can be controlled by the direction of chirality selector (Input 1). The controlled motion of the DW through the nanostructure performs all basic logic operations. To understand the working mechanism, two essential features of the transverse DWs which play a crucial role in realizing the reconfigurable magnetic logic device are discussed below in 6.5.1 and 6.5.2.

6.5.1 DW selective switching

When a Transverse DW is driven through a nanowire connected to the orthogonal half-ring shown in Figure 6.22. The DW motion through one of the two half ring switches the magnetization of the structure. Unlike the DW detector presented in section 6.4.1, the DW cannot transform to vortex configuration at the junction as the dimensions of the nanowire (160 nm) and the half-ring (100 nm) are narrow. At these dimensions, the transverse DW is still a stable configuration at the junction. However, the DW still follows the same trend of selective switching as the chirality detector. The transverse energy distribution of the DW controls the DW motion into either of the branch. The transverse DW adopts a triangular shape as shown in the inset of Figure 6.20. The energy of the transverse DW is a function of its lateral width. The transverse energy distribution of the DW is calculated and plotted against the DW lateral size. The DW energy increases from apex to base of the triangular shape as shown in Figure 6.20. The higher width at the base of the triangular shape of the DW makes it to store higher energy compared to the apex. The DW selective switching in the half ring into one of the branch depends on its transverse energy distribution.

Figure 6.22: Transverse energy distribution of the DW [49].

When a TT-U is injected into the nanowire as shown in Figure 6.23 (a), the base of the TT-U is facing the lower edge of the nanowire so the DW has higher energy at the bottom. When the external magnetic field to drive the DW is increased to 250 Gauss, the higher energy at the lower edge leads the DWs to pass through the LHR. The DW selectively switches magnetization of the LHR which can be seen from the magnetization configuration in Figure 6.23(b). The magnetic contrast in the MFM image at the UHR is unchanged but the change in the magnetic contrast at the edge of the LHR from dark to bright clearly shows that the DW motion leads to the switching of LHR.

Figure 6.23: (a) Snap shot image of the simulation and the corresponding MFM image of a TT-U injected into the nanowire connected to the orthogonal half-ring. (b) Snap shot image of the simulation and the corresponding MFM image of the structure after TT-U selectively switches the lower half-ring.

When the magnetization direction of the chirality selector is flipped to $-y$ -direction, a TT-D is injected into the nanowire as shown in the simulated magnetization in the Figure 6.24(a). When the DW is driven with an external magnetic field, the DW switches the magnetization of the UHR. Contrary to the previous case of TT-U, the base of the DW is at the upper edge of the nanowire for TT-D. The higher energy at the top edge leads to switching of UHR leaving LHR unchanged. The change in the magnetic contrast from dark to bright in UHR can be clearly seen in the MFM image shown in 6.24(b).

Figure 6.24(a) Snap shot image of the simulation and the corresponding MFM image of a TT-D injected into the nanowire connected to the orthogonal half-ring. (b) Snap shot image of the simulation and the corresponding MFM image of the structure after TT-D selectively switches the upper half-ring.

6.5.2. DW charge distribution and the effect of transverse magnetic field

TDWs are characterized by a magnetostatic charge, Positive for head-to-head (HH) DWs where the two domains are pointing towards each other, and negative for tail to tail (TT) DWs where they are pointing away [50]. Due to the opposite magnetic charges, the two DWs move in opposite directions in the presence of magnetic field. The charge distribution of the DW along the nanowire can be calculated by taking the divergence of the magnetization. Shown in Figure 6.23 is the magnetic volume pole of a

HH DW is plotted against the position on the nanowire. The magnetic volume pole is analogous to the magnetic charge [50]. The DW charge distribution shows that for HH DW, the base of the triangle possesses a positive magnetic charge whereas the apex possesses a negative magnetic charge. However, the magnitude of the positive charge is 30 times higher than the negative charge.

Figure 6.25 Magnetic volume pole along the length of the nanowire with A HH DW.

Interestingly, the positive magnetic charge is concentrated at the 30 % of the DW size of the nanowire along the transverse direction. When the DW is at the junction between the nanowire and half ring, application of magnetic field transverse to the nanowire ($\pm y$) direction may affect the motion. However, the effect depends on the strength and distribution of the magnetic field along the DW. The effect of the local transverse magnetic field on the DW motion is tested in device. To generate the transverse magnetic field locally, current is applied through the gate (metallic stripe line) which

induces Oersted field. The metallic gate provides a second degree of control on the intrinsic selective switching of TDW at the bifurcation. The application of a current through the gate produces a local Oersted field, which influences the motion the TDW in the logic device due to the interaction between the field and the magnetic charge of the TDW. By overlapping the gate with the upper edge of the longitudinal nanowire, the locally generated field influences the motion of TDW having the higher charge concentration along the upper edge. The metal strip overlaps only 25 % with the nanowire so that the strength of the Oersted field is higher at the top edge of the nanowire compared to the bottom edge. For the logic operation to takes place, only top edge of the nanowire at the junction should be affected by the strong local Oersted field (200 Gauss). So the stripe line is placed on the top of the nanowire with a small (25%) overlap onto the nanowire as shown in 6.19.

Figure 6.26 The magnetic field distribution along the transverse direction (+Y) and schematic to show NiFe with Au stripe line (top view).

The magnetic field distribution in the NiFe nanowire due to the current carrying Au stripe line is estimated by COMSOL multiphysics software. The cross-sectional image of the nanowire with Au stripe line is shown in Figure 6.24. It shows the transverse (y-

direction, along the width) field distribution along direction of NiFe nanowire. When a current of 2 mA is passed through the Au stripe line, the Oersted field distribution generated along the nanowire reveals that field is higher (200 Gauss) at the top edge of the nanowire due to the overlap and lower (50 Gauss) at the bottom edge of the nanowire. The minimum field required to affect the DW motion at the junction is 200 Gauss. The DWs with base pointing towards the top edge of the nanowire will only be affected by the transverse field due to stripe line. The DWs with base pointing towards the lower edge of the nanowire won't be affected as the field (50 Gauss) is not strong enough.

6.5.3 NAND and AND gate operations

To describe the logic operation performed by this device, current direction through the copper stripe line has to be fixed in one direction. When current is flowing from B to A *i.e.* in clockwise orientation through the magnetic gate, the local Oersted field generated repels the positive magnetic charges (HH DW) and attracts the negative magnetic charges (TT DW). The MFM images of initial and final configurations of the logical operations are shown in Figure 6.27 (a-d) for all combinations.

Inputs “0” and “0”: The initial configuration with both input bits in logical “0” state is captured with MFM as seen in Figure 6.27(a). The magnetization orientations of Input 1 and Input 2 are both aligned along $-y$ and $-x$ directions, respectively. Initially, the output states of both the UHR and LHR are logical bit “0” as defined by a bright contrast initially. Following the application of a linear external field, a HH DW is injected into the nanowire. The transverse component of the HH DW points to the $-y$ direction (HH-D) as dictated by the Input 1 nanowire, which results in the base of the TDW triangular shape to be located at the lower edge of the nanowire. MFM image after the application of a linear

magnetic field shows a change in magnetic contrast of the LHR from bright to dark, which indicates that the injected HH-D has entered the LHR which eventually switches it. The effect of magnetic field from the gate is negligible as here the HH-D has the higher charge concentration at the lower edge of the nanowire. This leads to the TDW to move into the LHR which results in the switching of the LHR from $-x$ to $+x$ direction, *i.e.* from binary “0” to output binary of “1”.

Inputs “0” and “1”: In this particular logic combination, the magnetisation orientation of the horizontal nanowire (Input 2) is aligned along the $+x$ direction. This initial configuration for Input 2 preset the outputs of the logical structure to logical “1”. Following the application of a linear magnetic field along the $-x$ direction, a TT-DW travels through the horizontal nanowire (Input 2). MFM imaging after the field application shows a change in the magnetic contrast at the UHR from dark to bright, as seen in Figure 6.27(b). The transverse component of the injected TT-DW points to the $-y$ direction (down chirality) as dictated by the vertical nanowire (Input 1) magnetic configuration. For a TT-DW with down chirality (TT-D), the higher charge concentration is at the upper edge of the horizontal nanowire. The Oersted field from the magnetic gate attracts and guides the TT-D into the UHR. Consequently, the UHR magnetisation is switched from logical bit “1” to “0”. The magnetisation of the LHR remained unchanged, *i.e.*, logical bit “1”. Without the Oersted field from the magnetic gate, the TT-D would still moved into the UHR as the higher energy component is also along the upper edge.

Inputs “1” and “0”: In this configuration, the magnetisation orientation of Input 1 is aligned along $+y$ direction (“1”) and the magnetisation orientation of Input 2 is aligned along the $-x$ direction (“0”). The MFM image of the final state, following the application

of the driving magnetic field, is shown in Figure 6.72(c). The magnetic contrast at the LHR indicates the switching of magnetisation orientation of the LHR. A HH-DW with an up chirality (HH-U) is injected into the horizontal nanowire as the magnetisation orientation in Input 1 is aligned along +y direction. The HH-U has a higher energy component and charge concentration along the upper edge of the nanowire. Though intrinsically the DW should move into the UHR, the local Oersted field from the magnetic gate strongly repels the HH-U and pushed into the LHR. Consequently, this results in the reversal in the magnetisation of the LHR to +x direction, which corresponds to an output bit of “1”.

Inputs “1” and “1”: When the magnetisation orientations of the vertical and horizontal nanowire are aligned along the +y and +x directions, respectively, both logical input bits (Input 1 and Input 2) are “1”. Under the external magnetic field, a TT-DW with an up chirality (TT-D) is injected into the structure. For this DW, the higher charge concentration is along the lower edge of the nanowire. MFM image of the output after the field application shows that the magnetisation orientation of LHR has been switched as seen in Figure 6.27(d). Similar to the case of HH-D with the down chirality, this TT-D is not affected by the local Oersted field from the magnetic gate, as the DW charge is concentrated at the lower edge of the nanowire. The movement of the DW from the horizontal nanowire into the LHR switches the magnetisation orientation corresponds to the output bit of “0”.

Figure 6.27 (a-d) The MFM images of the structure before and after the logic operation for all four possible combinations when the current of 2 mA flown in clockwise orientation.

NAND			AND		
My (Input 1)	Mx (Input 2)	M (LHR) (Output 2)	My (Input 1)	Mx (Input 2)	M (UHR) (Output 1)
↓ 0	← 0	→ 1	↓ 0	← 0	← 0
↓ 0	→ 1	→ 1	↓ 0	→ 1	← 0
↑ 1	← 0	→ 1	↑ 1	← 0	← 0
↑ 1	→ 1	← 0	↑ 1	→ 1	→ 1

Table 6.2 Truth table of the DW logic performing NAND and AND gate operation at the LHR and UHR respectively when the current in the stripe line is flowing in clockwise orientation.

The truth table is formed for all 4 combinations in table 6.2, which shows that for LHR the structure acts as a NAND gate. Interestingly, if the output is read at the UHR, in all four possible combinations of the logic operation, the UHR is found to complement with LHR. It results in an AND gate operation at the UHR.

6.5.4 NOR and OR gate operations

By reversing the direction of the current flow to anti-clockwise orientation (B to A), the polarity of the local Oersted field is switched, The same structure can then be made to perform the NOR universal logic operation. In this case, the local Oersted field attracts the DW with a positive charge but it repels the DW with a negative charge. From our previous NAND operation discussion, the magnetic gate has no effect on configuration I (“0” and “0”) and configuration IV (“1” and “1”) as the magnetic charge is concentrated along the lower edge of the nanowire. As such, the logic operation for these

configurations is not affected by the polarity of the field from the magnetic gate. As shown in Figure 6.28 (a), when Input 1 is logic bit “0” and Input 2 is logic bit “1”, a TT-DW with a down chirality (TT-D) is injected. As TT-D has a higher charge concentration along the upper edge of the nanowire, it is strongly influenced by the field from the magnetic gate. Consequently, the DW is pushed into the LHR. The TDW motion leads to the magnetisation switching of the LHR giving rise to an output bit “0”, as revealed by the MFM magnetic contrast change at the LHR from dark to bright..

When Input 1 is set to logical bit “1” and Input 2 is set to bit “0”, respectively, a HH-DW with an up chirality (HH-U) in which the higher charge concentration is along the upper edge of the nanowire is injected. Shown in Figure 6.28(b) is the MFM image of the logical output after the application of the field indicates that the magnetic contrast of the UHR has switched from dark to bright. The results are summarised in the truth table in Figure 6.3 (c). The obtained logical output at the LHR indicates a logical NOR gate operation. Naturally, a logical OR gate operation is obtained at the UHR. The experimental results clearly shows that the device can be programmed to perform both the universal logic operations (NAND and NOR) by changing the current direction through the magnetic gate. For applied current in clockwise orientation the device acts as NAND (AND) gate whereas that for anti-clockwise orientation it acts as a NOR (OR) at the LHR (UHR), respectively.

Figure 6.28 (a-b) The MFM images of the device before and after the logic operation for the combinations of (0&1) and (1&0) when the current of 2 mA is flown in anti-clockwise orientation.

OR				NOR			
My (Input 1)		Mx (Input 2)	M (UHR) (Output 1)	My (Input 1)		Mx (Input 2)	M (LHR) (Output 2)
↓	0	←	0	0	↓	0	←
↓	0	→	1	0	↓	1	→
↑	1	←	0	1	↑	0	←
↑	1	→	1	1	↑	1	→

Table 6.3 Truth neither table of the DW logic performing NOR gate operation at the LHR and the OR gate operation when the current in the stripe line is flowing from A to B. Summarizing the results in a truth table 6.3 shows that at LHR, the logic operation results

in NOR gate functioning whereas at the UHR it results in OR gate operation complementing the other. It proves that a single structure can perform NAND gate operation when the current is +5 mA and NOR gate operation when the current is -5 mA. Moreover in each operation, the device provides two results which always complement each other.

6.5.5 XNOR, XOR and NOT gate operations

By adding an additional gate at the bottom edge of the longitudinal nanowire similar to the top gate, we can even perform XOR and XNOR operations using this device. The current direction along the gate has to be constrained according to the initial magnetization direction of the Input 1 (transverse nanowire). When the Input 1 is “0” that is the transverse nanowire is saturated in $-y$ direction, the current should flow in clockwise orientation through the top gate. When the Input 1 is “1”, the current should flow in anti-clockwise orientation through the bottom gate. In this case the output at the UHR shows a XOR operation and the output at the LHR shows a XNOR operation as shown in the table 6.4.

		XOR XNOR	
My (Input 1)	Mx (Input 2)	M (UHR) (Output 1)	M (LHR) (Output 2)
↓ 0	← 0	← 0	→ 1
↓ 0	→ 1	→ 1	← 0
↑ 1	← 0	→ 1	← 0
↑ 1	→ 1	← 0	→ 1

Table 6.4 Truth table of the DW logic performing XNOR gate operation at the LHR and the XOR gate operation.

The device is also capable of performing logic operation on a single Boolean logic bit. Keeping the chirality selector (Input 1) unchanged along +y direction and the current flows from along B to A along -x direction, the output of the structure acts as an inverter circuit at the LHR for the magnetization of the longitudinal nanowire. This results in NOT gate operation. The same operation also results in COPY function at the UHR as shown by Boolean logic output in table 6.4

		COPY		NOT	
My	Mx (Input)	M (UHR) (Output)	M (LHR) (Output)
1	0	1	0
1	1	0	1		

Table 6.4 Truth table of the NOT and COPY gate operation.

6.6 Summary

In summary, transverse DW dynamics in NiFe nanostructures are studied for logic applications. An approach to control the chirality of the DW injected by employing a chirality selector at the junction between the nucleation pad and the naowire is demonstrated. A branch structure at the right edge of the nanowire can act as a reference device to detect the chirality of the DW. The DW detection is possible by the transformation of transverse to vortex at the junction of branch structure. The orthogonal motion of vortex core leads the clockwise and anti-clockwise vortex DWs to selectively switch the branch. A simple slanted rectangular structure is used to rectify the DW chirality. The DW triangular shape helps the rectification process by complex DW transformations within the rectifier structure. Finally, a single structure with a current carrying stripe line is shown to perform all basic logic operations. The direction of the current passing through the stripe line controls the specific logic function. Such device is

the first DW based reconfigurable magnetic logic. The underlying principles are the transverse DW selective switching due to transverse energy distribution and the effect of transverse local field on DW dynamics. The key concepts of the device are verified by micromagnetic simulations and MFM imaging.

References

1. S. S. P. Parkin, M. Hayashi and L. Thomas, *Science* **320**, 190 (2008).
2. J. H. Franken, H. J. M. Swagten and B. Koopmans *Nature Nanotech.* **7** 499 (2012).
3. M. Hayashi, L. Thomas, R. Moriya, C. Rettner, and S.S.P. Parkin, *Science*. **320**, 209 (2008).
4. X. Jiang, L. Thomas, R. Moriya, M. Hayashi, B. Bergman, C. Rettner and S. S. P. Parkin, *Nature Comm.* **1**, 25 (2010).
5. D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit and R. P. Cowburn, *Science* **309**, 1688 (2005).
6. D. A. Allwood, Gang Xiong, M. D. Cooke, C. C. Faulkner, D. Atkinson, N. Vernier, R. P. Cowburn, *Science* **296**, 2003 (2002).
7. P. Xu, K Xia, C. Gu, L. Tang, H. Yang and J. Li, *Nature Nanotech.* **3** 97 (2008).
8. M. Munoz and J. L. Prieto, *Nature Comm.* **2**, 1 (2011).
9. L. Bocklage, F. U. Stein, M. Martens, T. Matsuyama, and G. Meier, *App. Phys. Lett.* **103**, 092406 (2013).
10. M. Hayashi, L. Thomas, C. Rettner, R. Moriya, and S.S.P. Parkin, *Nature Phys.* **3**, 21 (2007).
11. M. Hayashi, L. Thomas, C. Rettner, R. Moriya, X. Jiang and S. S. P. Parkin, *Phys. Rev. Lett.* **97**, 207205 (2006).
12. E. R. Lewis, D. Petit, A.-V. Jausovec, L. O'Brien, D. E. Read, H. T. Zeng, and R. P. Cowburn, *Phys. Rev. Lett.* **102**, 057209 (2009).

13. E. R. Lewis, D. Petit, L. O'Brien, A. Fernandez-Pacheco, J. Sampaio, A-V. Jausovec, H. T. Zeng, D. E. Read and R. P. Cowburn, *Nature Mater.* **9**, 980 (2010).
14. E. R. Lewis, D. Petit, L. O'Brien, A.-V. Jausovec, H. T. Zeng, D. E. Read, and R. P. Cowburn, *Appl. Phys. Lett.* **98**, 042502 (2011).
15. D. Petit, A-V. Jausovec, H.T. Zeng, E. Lewis, L. O' Brien, D. Read, and R.P. Cowburn, *Phys. Rev. B* **79**, 214405 (2009).
16. A. Kunz and S. C. Reiff, *Appl. Phys. Lett.* **94**, 192504 (2009).
17. K. He, D. J. Smith, and M. R. McCartney, *Appl. Phys. Lett.* **95**, 182507 (2009).
18. S.-M. Ahn and K.-W. Moon, *Nanotechnology* **24**, 105304 (2013).
19. A. Vogel *et al.*, *IEEE Trans. Mag.* **46**, 1708 (2010).
20. A. Kunz, J. D. Priem, S. C. Reiff, *Proc of SPIE*, **7760**, 776005 (2010).
21. D. Atkinson, D. S. Eastwood, and L. K. Bogart, *Appl. Phys. Lett.* **92**, 022510 (2008).
22. S Goolaup, S C Low, M Chandra Sekhar and W S Lew, *J. Phys.: Conf. Ser.* **266** 012079 (2011).
23. M. Chandra Sekhar, S. Goolaup, I. Purnama, and W. S. Lew, *J. Phys. D: Appl. Phys.*, **44**, 235002 (2011).
24. M. T. Bryan, T. Schrefl, and D. A. Allwood, *Appl. Phys. Lett.* **91**, 142502 (2007).
25. D. Petit, A.-V. Jausovec, D. Read, and R. P. Cowburn, *J. Appl. Phys.* **103**, 114307 (2008).
26. L. O'Brien, E. R. Lewis, A. Ferna'ndez-Pacheco, D. Petit, and R. P. Cowburn, *Phys. Rev. Lett.* **108**, 187202 (2012).

27. I. Purnama, M. Chandra Sekhar, S. Goolaup, and W. S. Lew, *IEEE Tans. Mag.* **47**, 3081 (2011).
28. L. O'Brien, D. Petit, H. T. Zeng, E. R. Lewis, J. Sampaio, A. V. Jausovec, D. E. Read, and R. P. Cowburn, *Phys. Rev. Lett.* **103**, 077206 (2009).
29. I. Purnama, M. Chandra Sekhar, S. Goolaup, and W. S. Lew, *Appl. Phys. Lett.* **99**, 152501 (2011).
30. T. J. Hayward, M. T. Bryan, P. W. Fry, P. M. Fundil, M. R. J. Gibbs, D. A. Allwood, M.-Y. Im, and P. Fischer, *Phys. Rev. B* **81**, 020410(R) (2010).
31. L. J. Chang, Y. D. Yao , Pang Lin , and S. F. Lee, *IEEE Trans. Mag.* **47**, 2519 (2011)
32. Huang T. Zeng, D. Read, L. O'Brien, J. Sampaio, E. R. Lewis, D. Petit, and R. P. Cowburn, *Appl. Phys. Lett.* **96**, 262510 (2010).
33. E. R. Lewis, D. Petit, L. O'Brien, H. T. Zeng, D. E. Read, and R. P. Cowburn, *J. Appl. Phys.* **109**, 053904 (2011).
34. A. Beguivin, L. A. O'Brien, A. V. Jausovec, D. Petit, and R. P. Cowburn, *Appl. Phys. Lett.* **99**, 142506 (2011).
35. A. Kunz and J. V. Wunsch, *Appl. Phys. Lett.* **101**, 192402 (2012).
36. S. Glathe, U. H. Ubner, R. Mattheis, and P. Seidel, *J. Appl. Phys.* **112**, 023911 (2012).
37. G. A. Prinz, *Science* **282**, 1660 (1998).
38. S. A. Wolf *et al.*, *Science* **294**, 1488 (2001).
39. R. P. Cowburn and M. E. Welland, *Science* **287**, 1466 (2000).

40. A. Imre, G. Csaba, V. Metlushko, G. H. Bernstein and W. Porod, *Physica E* **19**, 240 (2003).
41. A. Imre *et al.*, *Science*, **311**, 205 (2006)
42. I. Amlani *et al.*, *Science* **284**, 289 (1999).
43. G. Reiss *et al.*, *Phys. Status Solidi* **201**, 1628 (2004).
44. A. Ney, C. Pampuch, R. Koch and K. H. Ploog, *Nature* **425**, 485 (2003).
45. R. Richter *et al.*, *Solid State Electron.* **46**, 639 (2002).
46. S. Patil *et al.*, *Proc. IEEE Int. Conf. Computer Design*, 125-131 (2010).
47. S. Joo, T. Kim, S. H. Shin, J. Y. Lim, J. Hong, J. D. Song, J. Chang, H.-W. Lee, K. Rhie, S. H. Han, K.-H. Shin, and M. Johnson, *Nature* **494**, 72 (2013).
48. H. Dery, P. Dalal, L. Cywinski¹ and L. J. Sham, *Nature* **447**, 573 (2007).
49. C.H. Marrows, *Advances in Physics*, **54**, 585 (2005).
50. H. T. Zeng, D. Petit, L. O'Brien, D. Read, E. R. Lewis, and R. P. Cowburn, *J. Magn. Magn. Mater.* **322**, 2010 (2010).

Chapter 7

Conclusion

This chapter concludes the work presented in this thesis. In the course of this work, a comprehensive study on the DW formation and the DW dynamics in the NiFe cylindrical and planar nanostructures has been carried out. The DW dynamics are studied under the presence of magnetic field and the spin polarized current. Micromagnetic simulations were carried out to understand the novel phenomenon in DW dynamics and also to conclusively support the experimental results.

7.1 Conclusion

In the first part of this thesis, the spin configurations of NiFe cylindrical nanowire of various aspect ratios were studied using micromagnetic simulations. At relatively aspect ratio, the vortices of opposite chirality are formed at the two edges of the nanowire. Further reduction in the aspect ratio leads to the formation of a helical DW which separates these two vortices. Magnetic charge calculations along the helical DW show that the helical DW is a transition between a positive to negative magnetic charge. Introduction of constrictions is found to control the formation of the DWs within the nanowire. For n constrictions, $n+1$ DWs can be formed in the non-constriction regions. To verify these results experimentally, constricted NiFe nanowires are grown using template assisted pulsed electrodeposition and differential etching techniques. The potential variation during the growth results in compositionally modulated NiFe nanowires. Fe rich layers are formed at the lower potential and Fe deficient layers are formed at higher potential. The etching rate of the NiFe in nitric acid is found to strongly depend on the

composition. The etching rate of Fe rich layer is 5 times faster than Fe deficient layer. The difference in the etching rate made the Fe rich layers as constrictions along the nanowire. The depth and length of the constriction can be well controlled by the electrodeposition pulse duration and the etching time. MFM imaging on the non-constricted nanowire supports the formation of two vortices at the two edges of the nanowire. MFM imaging on the constricted cylindrical nanowire shows the series of dark and bright contrasts throughout the nanowire. The boundary between the two contrasts is the helical DW predicted by the simulations. When the etching in the nanowire is done for a longer time, the Fe rich layers dissolve leaving the Fe deficient layers as disc shape NiFe nanoparticles. It is an alternative and novel method for NiFe nanoparticle fabrication for biomedical applications. The method is capable of producing the particles of various dimensions. Micromagnetic simulations reveal that nanoparticle undergoes complex reversal process as the thickness is varied. Nanoparticle of thickness above 200 nm is found to possess a quadrupole magnetic vortex state. The external in-plane field required to distort the quadrupole state is higher for a longer nanowire.

Secondly, the DW dynamics in higher aspect ratio cylindrical nanowires are studied under the influence of the magnetic field. Transverse DWs are stable configurations in sub-50 nm diameter NiFe cylindrical nanowires. The transverse DW possesses a combined translational and rotational motion. The DW motion is found to be intrinsically oscillatory irrespective of direction of the external magnetic field. In the absence of external force, the DW translational motion is found to be governed by the energy transfer from the DW rotational motion. The DW translational oscillations and rotations are in sync with each other. In two closely spaced coupled nanowire system, the

magnetostatic coupling can be balanced by the application of spin polarized current. The balance between the two torques results in a sustained oscillatory and rotational motion of the DW in a confined state analogous to simple harmonic motion. During the sustained oscillations, the DW shape is found varied between compressed and relaxed states. The DW shape change is attributed to the finite mass possessed by the DW. Solving the equation of simple harmonic motion, the mass of the DW in 10 nm diameter cylindrical nanowire is calculated to be in the order of 10^{-23} Kg. It is in the same order of the DW mass in planar nanowire.

Thirdly, the DW pinning and depinning mechanisms are studied in planar and cylindrical nanowires at the geometrical modulations. In planar nanowires, the DW is driven by current through a nanowire with an anti-notch. As the dimensions of the anti-notch are varied, the pinning potential is found to change from the well to barrier. The pinning potential of the anti-notch is observed to be a strong function of the chirality. The transition in the potential occurs at critical dimension of the anti-notch when the height is twice the width. The change in the magnetization configuration within the anti-notch structure due to the change in the shape anisotropy plays an important role in different potential shapes. The current driven DW at an anti-notch reveals that a crossover from a smooth and gradual barrier to an abrupt and steep potential when the relative orientation between the spins in the DW and anti-notch is changed from orthogonal to parallel.

In sub-50 nm diameter cylindrical nanowires, the DW pinning and depinning mechanisms are investigated in the presence of magnetic field and the spin-polarized current. With notch as a pinning site, the DW pinning follows opposite trends when driven by magnetic field and current. The pinning strength of the notch is lowered with

increasing the notch depth in current driven case. This interesting behavior is explained by the DW deformation and the DW rotation at the notch structure. The degree of the DW deformation depends on the notch depth and it assists the spin-polarized current in depinning the DW. With anti-notch as a pinning site, two pinning behaviors are observed as the height of the anti-notch is varied. The DW pinning and depinning mechanisms are similar for notch and anti-notch, when the anti-notch height is less than 20 nm. Different pinning and depinning behaviors of the anti-notch of height above 20 nm is attributed to the DW transformation from the transverse to vortex. The DW transformation is found to reduce the potential in the field driven case and increases the barrier for current driven case. An intrinsic pinning within the anti-notch due to the DW chirality change from clockwise to anti-clockwise orientation leads to the increase in the barrier potential.

Finally, DW dynamics in patterned structure as studied for DW based logic applications. The key focus is devoted to the transverse DWs that are formed in narrow nanowires. Three different methods are demonstrated to inject the DWs in the nanowires are proposed. The methods include local field generation by current carrying stripe line, application of large oblique field at the junction of an L-shaped nanowire and the DW nucleation and injection due to magnetization reversal in a diamond shaped pad connected to the nanowire. An approach to control the chirality of the transverse DW is proposed and verified by MFM imaging. The design includes a chirality selector in which magnetization can be fixed in the transverse direction to the nanowire by employing strong shape anisotropy. A reference device is proposed which can detect the DW chirality by selective switching of the DW into one the branch structure. The selective switching occurs due to the DW transformation from transverse to vortex configuration of

either clockwise or anti-clockwise orientation. A DW rectifier network is demonstrated in which the output DW is of unique chirality irrespective of the chirality of the injected DW. Two different switching mechanisms by two DWs of opposite chirality lead to the rectifying operation. Employing all these concepts a novel device is proposed and tested in which a single magnetic nanostructure can perform all basic logic operations. By changing the direction of the current through the stripe line placed at the junction, different logic functions can be realized such as NAND, NOR, XNOR and NOT gate operations. The stripe line acts a gate. Interestingly in each operation, the device results two output at the two half rings which always complement each other. Such a device is the first DW based magnetic reconfigurable logic.

7.2 Future work

In this thesis, a helical DW structure in cylindrical nanowires has been reported. Unlike the transverse or vortex DWs found in ferromagnetic nanowires, helical DW is a transition region between two vortices of opposite chirality. The transition at the DW leads to an abrupt change in the stray field emanated at the DW due to opposite charges possessed by the two vortices. The change in the stray field can be detected by GMR/TMR sensors. It gives an advantage that two vortices of opposite chirality can be read as binary “1” and “0” and the nanowire can be used as medium for race track memory. Fabrication of these cylindrical nanowires is easier compared to the smaller diameter (<100 nm) nanowire. Moreover, the cylindrical nanowires may open the avenue for 3D storage as they can stand vertically which improves the density by many folds. However, fundamental investigation on helical DW dynamics is the first step towards the application as memory device. The helical DW dynamics under the external field can be

studied by reversal process of the constricted nanowires by anisotropic magnetoresistance measurements (AMR) as shown in the schematic image in Figure 7.1. Comparison between AMR measurements on constricted nanowires with various depths of the constrictions help in digging the physics underlying in the helical DWs dynamics.

Figure 7.1 Schematic image of the contact pads on the on the constricted cylindrical nanowires for anisotropic magnetoresistance measurements.

Appendix A

Interlayer exchange coupling effect on the reversal process of Differential dual spin valves

A.1 Introduction

This chapter presents the systematic study on the reversal process of a novel Giant Magneto Resistance (GMR) sensor so called Differential dual spin valve (DDSV). DDSV sensor stack consists of two mirror imaged spin valves separated by a conductive gap layer. The effect of the interlayer coupling due to gap layer between the two free layers on the reversal process of a self-biased DDSV has been studied under the uniform and differential magnetic field. The competition between magnetostatic coupling, interlayer coupling and the shape anisotropy of are presented. By looking into detailed magnetization states of the DDSV an interesting evolution of states as a function of interlayer coupling was extracted to elucidate competition of the energy terms. The role of the interlayer coupling on the down track response of the DDSV is also presented.

A.2 Motivation

Today's digital age with popular internet, social network sites and besiege of consumer electronics, global data storage limits are increasing the global data storage limits to its pinnacle. From 2008 onwards, the amount of data produced surpassed the available data storage. Data storage leader, Hard disc drive (HDD) has dominated over the other technologies with low price while catching up with the higher density requirements. However, there is a stiff competition from solid state drives. To survive in the competition

with other data storage technologies, HDD has to reach an areal density of 10 Tb/in² by 2015. This high density requires the bit length (BL) of the media to shrink down to 4-8 nm. This small BL poses a strong challenge to the hard disk (HDD) read sensor, as the shield-to-shield spacing (SSS), which is determined by the sensor stack thickness, has to scale accordingly to maintain the linear resolution. In a conventional spin-valve-type of reader, the overall thickness of the multilayer composed of seed layer, anti-ferromagnetic (AFM) layer, pinned layer (PL) reference layer (RL), spacer layer (SL), free layer (FL) and capping layer will hit a wall at 20 nm, which limits the detectable BL to be more than 10 nm [1]. It is thus crucial to develop new sensor designs. Differential dual spin valves (DDSV) were proposed as potential read sensors for 10 Tb/in² and beyond [2-4]. A DDSV sensor stack consists of two mirror imaged spin valves (SV) separated by a conductive gap layer (GL) as shown in Figure A.1.

Figure A.1 A schematic of the DDSV stack layers (with two mirror imaged spin valves. FL1 and FL2 are the free layers of two spin valves separated by the GL (gap layer). SL (spacer layer), RL (reference layer) PL (pinned layer) of the two spin valves respectively.

The magnetization of the reference layers (RLs) in the two SVs are aligned opposite to each other for differential effect to takes place. Self-biased DDSVs in which the two free layers (FLs) align in flux closure configuration could potentially remove permanent hard bias which is a common feature in conventional SV read sensors. This unique attribute enables the possible implementation of side shields to diminish the inter-track interference further enhancing the performance of DDSV. The stiffness of the self-bias can be tuned by varying the interlayer coupling strength between the two FLs mediated through the conductive gap layer. Towards this end, the effect of interlayer coupling on the reversal process of the DDSV is studied in this chapter.

A.3 Methodology

In this study, the active potion of a DDSV consisting of two identical FLs separated by a GL as shown in Figure A.2 is considered as the model for micromagnetic simulations. For FLs, a rectangular geometry has been considered with stripe height (SH) = 10 nm and reader width (RW) = 12 nm with thickness = 2 nm. FLs are separated by a GL of 1 nm thickness.

Figure A.2 Simulation model for the study of reversal process

The Object Oriented Micromagnetic Framework code [8] was used to simulate the quasi-static reversal process of the structure. The material parameters used in the simulation were saturation magnetisation (M_s) = 800×10^3 A/m, exchange stiffness constant (A_{ex}) = 30×10^{-12} J/m. Gilbert damping constant (α) which is fixed to 0.5 with a stopping criterion of $dm/dt < 0.001$. The mesh size for all simulations was set to be $1 \times 1 \times 1$ nm³. The reversal process is characterized by the GMR effect using cosine dependence for the respective SV. For simplicity, the resistance of individual SV in quiescent state is assumed to be 3Ω , and an MR% of 100% is defined as $(R_{\max} - R_{\min})/R_{\min}$. The total MR response of the DDSV is simply the arithmetic sum of the two GMR responses. The initial magnetization of the FLs is fixed as anti-parallel to each other to form flux closure configuration. The interlayer coupling is introduced through an exchange coupling constant between two FLs due to the Ruderman-Kittel-Kasuya-Yosida (RKKY) effect [5-7]. The bilinear exchange constant (σ) is only considered, as its contribution is prominent in common ferromagnetic-metal-ferromagnetic sandwich structures. The exchange coupling energy as a function of bilinear coupling constant (σ) can be expressed as

$$E_{ex} = -\sigma \cos(\Delta\theta) \quad (\text{A.1})$$

Where $\Delta\theta$ is the angle between the magnetization of the two FLs. A negative σ promotes an anti-parallel magnetization configuration. The reversal process is simulated in all major magnetic field configurations experienced by DDSV *i.e.* uniform magnetic field, differential magnetic field and the field at the down track at bit transition

A.4 DDSV response to uniform magnetic field

The uniform field MR response of a DDSV where the external field is applied along the SH is plotted in Figure A.3 (b) with zero interlayer coupling. The DDSV scissors the magnetic moments in the FLs with almost identical spin rotation resulting in a constant net-response due to the cancellation of GMR effect in the respective SV. For this reversal process, the Zeeman energy due to the external magnetic field needs to conquer both the demagnetization energy of the individual SV and the magnetostatic coupling between them, which prefers to have their magnetic moments in an anti-parallel state along the RW direction. As we vary the bilinear coupling constant from -0.1 to 0.1 erg/cm², the symmetry and linearity of the MR response in the respective SV remain the same as the case with no interlayer exchange coupling interaction. However, the sensitivity of the SV, which is signified by the saturation field in the respective SV, is increased almost linearly as σ becomes more negative, as shown in Figure A.3 (c).

Figure A.3 Schematic of the DDSV with uniform field applied (b) The normalized MR response of the DDSV with interlayer coupling and (c) the variation of the saturation magnetic field as a function of the interlayer coupling (σ). Below are the snapshots of the magnetization of the FLs at different stages during reversal process when the strength of the interlayer coupling $\sigma = -0.1$ erg/cm² and $\sigma = 0.1$ erg/cm².

The increase can be attributed to the fact that the negative exchange coupling promoting the anti-parallel alignment between the two FLs reinforces the magnetostatic coupling, heightening the energy barrier between anti-parallel alignment along the RW direction and the final parallel alignment along the SH direction. Interestingly a different behavior can be seen when the two FLs coupled via ferromagnetic coupling. When σ is in between 0.01 to 0.04 erg/cm², the saturation magnetic field decreases linearly and saturates at 400 Oe beyond that. When $0 < \sigma < 0.04$ erg/cm², the ferromagnetic coupling

introduced by the interlayer coupling counteracts the magnetostatic coupling, and the anti-parallel aligned state is less stable with higher σ . As σ further increases, the ferromagnetic exchange coupling dominates, and it was observed that when $\sigma \geq 0.04 \text{ erg/cm}^2$, the magnetization of the two FLs acting as a single giant spin are always parallel to each other during the reversal process as shown by the snapshots of the magnetization state in Figure A.3(c). Further increase in σ does not change the ferromagnetic coupling state, and the energy cost of varying the magnetization state of a single-giant-spin-like DDSV as a whole is invariant. This results in the same reversal response observed for a uniform field, and hence a constant saturation field. As shown above, the MR curve is not an effective way to characterize the relative alignment of the FLs, as the shape of the MR curves for all σ is quite similar. This issue can be complemented in a quantitative manner by looking into the interlayer exchange energy profile, plotted the in Figure A.4

Figure A.4 Exchange energy profile during the reversal process of the DDSV when the two FLs coupled via ferromagnetic and anti-ferromagnetic coupling in the uniform field test.

As can be seen, the MR curve does not reflect the relative alignment of the FLs, as the shape of the MR curves for all σ is quite similar. This issue can be complemented in a quantitative manner by looking into the interlayer exchange energy profile, plotted in the Figure A.4. For clarity, we have normalized the exchange energy by dividing it with σ . According to the equation (A.1), the normalized exchange energy is -1 when the magnetization in two FLs is parallel to each other and 1 when the magnetization in the two FLs is anti-parallel to each other. From Figure A.4, it can be seen that for $\sigma < 0.04$ erg/cm², it is characterized by a bell shape curve which clearly shows an anti-ferromagnetic configuration at zero field and parallel alignment beyond saturation field. The lower is σ , the more gradually the magnetic moments are oriented parallel to each other. For $\sigma > 0.04$ erg/cm², the energy profile lies flat at -1 showing the two FLs are always coupled in parallel manner.

It is interesting to note that the interlayer coupling cannot perfectly compensate the effect of magnetostatic coupling, so that the DDSV behaves as two independently operating SVs. This can be seen from the saturation field as a function of σ terminates at 400 Oe, in contrast with the saturation of a single free layer or decoupled FLs which has a saturation field of 300 Oe. This is attributed to the fact that the interlayer coupling energy is only dependent on the angle between the two ferromagnetic layers ($\Delta\theta$), not the absolute orientation of the individual ferromagnetic layer. In another word, once $\Delta\theta$ is fixed, the interlayer coupling energy is isotropic regardless of the magnetization orientation. The magnetostatic coupling energy, though commonly understood to favour anti-parallel magnetization state, is anisotropic in an elongated DDSV, as it can be seen from the energy profile for a perfectly anti-parallel aligned DDSV as a function of the free

layer magnetization orientation in Figure A.5. From the figure, we can see that, the magnetostatic coupling energy is highest along the RW direction and lowest when the magnetization along the SH direction, while the exchange energy is constant. This anisotropy will gradually disappear as the geometry of the DDSV becomes more circular. The elongated DDSV is however necessary for the reader application, as the FLs need shape anisotropy to bias the sensor at the most sensitive operating point (90° apart from the reference layer).

Figure A.5 The profile of the interlayer exchange energy and the magnetostatic coupling energy during the rotation of the spins of the two FLs from RW direction to SH direction in flux closure configuration.

A.5 DDSV response to differential magnetic field

To obtain the transfer curves of the DDSV in differential fields, the two FLs are subjected to equal and opposite magnetic fields along the SH direction. Shown in Figure A.6(b) is the normalized MR curve for the DDSV with zero interlayer coupling.

Figure A.6 (a) A schematic of the DDSV with differential media field (b) The normalized MR response of a DDSV in the differential field test at zero interlayer coupling. Equal and opposite fields are applied to the two FLs during the differential field test (c) Saturation magnetic field as a function of the interlayer coupling (σ). Below are the snapshot images of the magnetization of the FLs at different stages during reversal process when the strength of the interlayer coupling $\sigma < 0.04$ erg/cm² and $\sigma \geq 0.04$ erg/cm².

The MR curves for the two FLs follow each other with the overall output as the double of the individual MR of FLs. Shown in figure A.6 (c) is the variation of the saturation magnetic field as a function of the interlayer coupling constant from $\sigma = -0.1$ to 0.1 erg/cm^2 . An opposite trend is observed for the saturation field variation, as we observe a constant plateau for the saturation field at 400 Oe for $\sigma < 0.04 \text{ erg/cm}^2$, and a linear increase for σ greater than that. From the uniform field response, the constant plateau occurs at the region where the antiferromagnetic coupling due to net effect of interlayer and magnetostatic coupling dominates. The two FLs behave like a single entity, rotating their magnetization in the same fashion with a favorable 180° phase shift, as shown by the magnetization states. When the two FLs are coupled ferromagnetically at $\sigma \geq 0.04 \text{ erg/cm}^2$, the ferromagnetic coupling aligns the two FLs parallel to each other. The coupling between the two FLs opposes the differential field which tries to align them anti-parallel to each other along the SH direction, as illustrated in the magnetization evolution. Higher the ferromagnetic coupling, stronger the field needed to rotate the spins along the SH. Shown in Figure A.7 is the normalized exchange energy (E/σ) profile during the reversal process.

Figure A.7 Exchange energy profile during the reversal process of the DDSV when the two FLs coupled via ferromagnetic and anti-ferromagnetic coupling in differential field test.

As expected, the exchange energy is constant at 1 during the entire field sweeping when $\sigma < 0.04 \text{ erg/cm}^2$, showing the two FLs are always following each other in flux closure configuration during the reversal process making the normalized exchange energy to be higher and constant. When $\sigma \geq 0.04 \text{ erg/cm}^2$, the exchange energy is -1 without field as ferromagnetic coupling keeps the two FLs parallel to each other. The exchange energy cost gradually rises with the field as the differential fields force the magnetization of the FLs to move away from each other and saturates at 1 when the two FLs are aligned anti-parallel to each other along the SH direction.

A.6 Down track response of DDSV

The dependence of the reading performance of a DDSV on the interlayer coupling is evaluated in the down track response.

Figure A.8: The down track response of the ideal DDSV (The two FLs are independent of each other) and the magnetic field profile along with the snapshots of the magnetization states of the FLs at various positions on the down track.

We have modeled the reader response from the bit transition in a 1-D perpendicular recording media with a thickness of 20 nm [9]. The saturation magnetization of media is taken to be 200×10^3 A/m and the magnetic spacing is considered to be 5 nm above the media. Shown in Figure A.8 is the MR response of an ideal DDSV (the two FLs are not coupled) for comparison study and the magnetic field profile is superimposed at the background. The signal of the DDSV output is higher when the DDSV is at the centre of the transition, with an opposite field of the same magnitude sensed by the two FLs. When DDSV is at point A, both the SVs experience a magnetic

field higher than 300 Oe from the media which drives the spins to saturate along the SH direction so that the GMR response of the two SVs is same. The overall response of the DDSV is low at this point due to the cancellation of the individual GMR effect of the respective SV. When DDSV is at point B, SV1 experiences higher field as compared to SV2. The GMR response is higher for SV1 as compared to SV2 which results in an increase in the overall response as compared with point A. When DDSV is at point C, the two SVs experience the same and opposite fields from the media. The response is highest due to the large differential field. The response of the DDSV at D and E points can be explained by the same and opposite effects at B and A respectively. When the two FLs are coupled by anti-ferromagnetic coupling, the sensitivity of the DDSV is improved as signified by the higher dynamic range as shown in Figure A.9. The sensitivity however is nearly σ -independent, as shown by the largely overlapped curves for different σ . If we look into the detailed magnetization state, a distinctive mode of operation as compared to ideal DDSV can be identified near the bit transition when the sensed fields have the same polarity, e.g. at point B and D. At point B, The FL of SV2 of the anti-ferromagnetically coupled DDSV, which senses smaller negative field, instead of following the media field pointing downwards, rotates its magnetization away from media trying to respond to the antiferromagnetic coupling due to the FL of SV1, as shown in the magnetization state B.

Figure A.9 The down track response of the DDSV when the two FLs are coupled via anti-ferromagnetic coupling along with the magnetization states of the FLs at various positions on the down track.

In this sensing mode, only one of the two FLs experiencing higher magnitude is driven by the media field and the anti-ferromagnetic coupling spontaneously drives the other. In order for this mode to be observed clearly, a few parameters, such as the absolute field magnitude sensed by the two SVs, and the anti-ferromagnetic coupling strength, need to be fine tuned. A detailed study on this will be reported somewhere else.

When the two FLs are coupled via ferromagnetic coupling for $\sigma \geq 0.04 \text{ erg/cm}^2$, the sensitivity of the DDSV is deteriorated with the increase in the strength of the coupling as shown in Figure A.10 When DDSV is at point A and E, the field from the media is above the saturation field of the two SVs resulting the overall output to be minimum. At point B and D, the magnetization states of the two FLs respond swiftly to

the uniform field as can be seen from the tilting of the magnetization states compared with anti-ferromagnetic coupled DDSV in Figure A.9. However, due to the net effect of the SVs being compensated, the net output from the DDSV is low for ferromagnetic coupling. When the differential field with the same polarity emerges, the magnetization of the two FLs prefers to stay aligned due to the ferromagnetic coupling energy.

Figure A.10 the down track response of the DDSV when the two FLs are under the ferromagnetic coupling. Below are the snapshots of the magnetization states of the FLs at various positions on the down track.

It is expected that higher the strength of the ferromagnetic coupling, smaller is the angle between the FLs for the same differential field. The similar argument is valid at the bit transition (C), where the magnetization symmetrically aligned close to the RW direction. Therefore, a drop in DDSV sensitivity is expected with σ . It clearly suggests

that DDSV needs to operate in the anti-ferromagnetic coupled region to ensure a good performance in sensitivity.

A.7 Effect of gap layer thickness on the DDSV sensitivity

To improve the responsivity of the DDSV, the GL thickness is varied. The differential field experienced by the DDSV depends on the GL thickness. DDSV experiences a higher field at a higher GL thickness. Shown 8.11 is the magnetic field experienced by the FLs from the down track at two different GL thicknesses.

Figure A.11 DDSV with two different GL thickness overlapped with the down track magnetic field. The GL thickness chosen are arbitrary for illustration purpose.

From the above Figure A.11, it is clear that FLs of DDSV with a lower GL thickness experience a magnetic field of around 180 Oe, whereas the DDSV with a higher GL thickness experience a magnetic field of 300 Oe. One would expect a higher differential field should result in a better response. To ascertain the guess, the GL

thickness varied from 2 nm to 22 nm to calculate the response of the DDSV which is plotted in Figure A.12. Surprisingly, it is found that the signal output from the DDSV decreases as the GL thickness increases from 2nm to 22nm. As the differential field between the two free layers is expected to increase with GL thickness till 10nm at which the maximum differential field is reached, the observed decrease in the signal output is ascribed to fast reduction in the sensitivity of free layers to the magnetic field due to weak magnetostatic coupling at large GLs.

Figure A.12 DDSV response as a function of GL thickness.

The essential aspect of magnetostatic Coupling is that it favors a flux closure configuration in order to reduce the magnetostatic energy. This flux closure configuration corresponds to the anti-parallel alignment of the two free layers. In flux closure configuration, the DDSV follows a scissor switching in which one of the FL which experiences a higher field leads the other to follow in anti-parallel fashion. The scissor

switching mechanism provides a low-energy mechanism to facilitate the switching of orientation of the FLs of the DDSV [10]. When the GL thickness increases, the magnetostatic coupling drops and the effect of scissor switching too drops and hence the stiffness of the FLs will increase. Therefore, the total MR response of the DDSV reader will drop as magnetostatic coupling drops. From our results, we can conclude that the increase in the differential field is greatly outweighed by the decrease in magnetostatic coupling. Thus a DDSV reader will be expected to have a larger MR response at a lower Gap Layer, despite the smaller differential field experienced.

A.8 Summary

In summary, the effect of the interlayer coupling on the reversal process of the DDSV has been systematically studied. DDSV shows different reversal mechanism depending on the sign and the magnitude of the interlayer coupling due to the gap layer. It is observed that interlayer coupling along with the magnetostatic coupling and the shape anisotropy strongly influence the overall response of the DDSV. The differential field test shows that the sensitivity of the DDSV is observed to be constant when $\sigma < 0.04 \text{ erg/cm}^2$ and drops with the increase in the coupling strength above 0.04 erg/cm^2 . The one dimensional down track response reveals that the sensitivity of the DDSV is improved when the two FLs are coupled anti-ferromagnetically as compared to the decoupled DDSV. With increases in GL thickness, the sensitivity of the DDSV drops, though the differential field experienced by the FLs is higher. The results show that magnetostatic coupling and interlayer coupling are vital parameters to tune the performance of the DDSV reader.

References

1. Y. Chen, et al., *IEEE Trans. Mag.* **46**, 697 (2010).
2. G. C. Han, J. J. Qiu, L. Wang, W. K. Yeo and C. C. Wang, *IEEE Trans. Mag.* **46**, 709 (2010).
3. G. C. Han, J. J. Qiu, C. C. Wang, V. Ko and Z. B. Guo, *Appl. Phys. Lett.* **96**, 212506 (2010).
4. G. C. Han, C. C. Wang, J. J. Qiu and P. Luo, *IEEE Transactions on Magnetism*, **48** (5)1770 (2012).
5. S. S. P. Parkin, N. More, K. P. Roche, *Phys. Rev. Lett.* **64**, 2304 (1990).
6. J. Fassbender, F. C. Nortemann, R. L. Stamps, R. E. Camley, B. Hillebrands, G. Guntherodt, and S. S. P. Parkin, *J. Magn. Magn. Mater.* **121**, 270 (1993).
7. K. Ounajela, A. Arbaoui, A. Herr, R. Poinso, A. Dinia, D. Muller and P. Panissod, *J. Magn. Magn. Mater* **104**, 1896 (1992).
8. M.J. Donahue and D.G. Porter, OOMMF User's Guide, Version 1.0 Interagency Report NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD, 1999.
9. H. Neal Bertram, *Theory of Magnetic Recording*, 1st ed., Cambridge, 1994, pp.96.
10. C. C. Wang and G. Han, *J. Appl. Phys.*, **109**, 043905 (2011).

Appendix B

Spin Transfer Torque noise in differential dual spin valves

B.1 Introduction

When current is applied to a ferromagnetic material, the spins of electrons polarize due to the angular momentum transfer from the local spins of the material. Due to conservation of angular momentum, the conduction electrons exert a torque on the local electrons which is called as spin transfer torque. The spin transfer torque (STT) phenomenon has been attractive in switching the magnetization of ferromagnetic layer by electrical current instead of magnetic field which is used STT-RAM. The STT effect has also induced lot of attention for the realization of race-track memory which is discussed in first chapter. Beside, the promising advantages, STT can also cause the noise due to the magnetization fluctuation a fundamental issue in all read sensors of hard disc drives. This chapter presents a detailed study of spin-transfer torque induced noise in self-biased Differential Dual Spin Valves (DDSV).

B.2 Motivation

With hard-disk drives industries setting the areal density milestone for magnetic data storage at more than 10 Tb/in² in the next decade [1], new challenges arise from the shrinking dimensions of the media bits' size. New read- and write-heads paradigms have to be developed in order to meet the required physical specifications [2]. The inherent differential nature allows, DDSV read-heads are expected to overcome the Shield to

Shield Spacing limitation of current Magnetic Tunnel Junction based single spin-valves read-heads [3]. Nevertheless, more studies, both theoretical and experimental, are required to prove their viability. One fundamental issue of DDSV, and more generally of all magnetic read-heads, is the decrease of the signal to noise ratio due to spin torque noise as sensor dimensions are reduced. Contrary to MRAM devices, STT is detrimental to read-heads as it induces magnetic instabilities, therefore noise [4]. It is expected to be the major limiting factor of read-heads [5] towards 10Tb/in^2 . So it is of paramount interest to perform a systematic study on the STT noise in DDSV in all magnetic field configurations it experiences with in the media.

B.3 Micromagnetic methodology

A typical DDSV is composed of 2 spin valves in series, separated by a non-magnetic conducting gap layer. Each spin valve is made of a free layer, a non-magnetic conducting separating layer and a reference layer as depicted in Figure B.1.

Figure B.1 Geometry of the simulated DDSV. The arrows represent the magnetic field direction. Also indicated are the electrons direction for positive current and a typical media.

The magnetizations of the 2 reference layers are oriented anti-parallel intrinsically due to the interlayer dipolar coupling. We have used OOMMF [6] to model a simplified $26 \times 32 \text{ nm}^2$ section (aspect ratio $AR \sim 1.2$) DDSV consisting in 2 $\text{Co}_{90}\text{Fe}_{10}$ free layers (3 nm thickness each) separated by a Ru gap layer (2nm), unless specified. The free layers magnetizations point along $\pm y$ (Track width TW), which is the easy axis, while the reference layers are pinned along $\pm z$ (Stripe height SH)

The use of synthetic antiferromagnets reference layers ensures that the magnetic flux closes within the synthetic antiferromagnet structure, hence the simplified trilayer model [7]. We do not consider noise stemming from these synthetic antiferromagnets structures as they are similar in both single spin valves and DDSV [8,9]. Since CoFe/Ru interfaces have a weak (negative) interfacial spin asymmetry and high interfacial spin memory loss, we consider the 2 spin valves to be independent from a transport point of view in first approximation [10,11]. Only a quantitative analysis of the magnetoresistance of a DDSV would require a full drift-diffusion description, since Ru can either lead to an increase or decrease of the magnetoresistance [12]. Additionally, the antisymmetry of the reference layers magnetizations allows us to use a single spin polarization constant, because for a given current, the spin torque has the same direction in both free layers, only different amplitudes. We thus model the spin-torque effect after Slonczewski [13]

$$\frac{\partial \vec{m}}{\partial t} = -|\gamma| \vec{m} \times \vec{H}_{eff} + \frac{\alpha}{M_s} (\vec{m} \times \frac{\partial \vec{m}}{\partial t}) + \frac{J}{e} p_i g \mu_B (\vec{m} \times (\vec{m}_s \times \vec{m})) \quad (\text{B.1})$$

where J is the charge current density, $\vec{m}_s$ the unit spin polarization vector, $p_i = J_s/J$ the ratio of spin polarized over charge current entering the free layer, $\vec{m}$ the magnetization

vector, γ the gyromagnetic factor, α resp. g the damping resp. Lande factor of each free layer. In our definition, a positive current is defined as the direction of electrons flow from the SV1 to SV2.

A modification to the OOMMF code was made in order to account for the difference in amplitude at the 2nd spin valve due to electron backscattering [14]. While the dynamics of the spin accumulation have to be evaluated in specific cases such as wavy structures [15,16], most of the physics of our device regarding STT noise can be captured by considering 2 spin valves independent from the transport point of view but coupled by dipolar interaction and exchange bias. Given the small section of the sensor, the Oersted field was neglected throughout this study. In order to determine STT-induced noise, we let the system relax between $t=0$ ns and t_0 before saving the magnetization data until t_1 and then calculate the sensor output $s(t)$ using a phenomenological Current Perpendicular to the Plane Giant Magnetoresistance (CPP-GMR) model:

$$s(t) = \frac{\Delta RA}{RA} \times RA \times [\cos \theta_1(t) + \cos \theta_2(t)] \quad (\text{B.2})$$

where ΔR is the magnetoresistance of an individual spin valve and $\theta_1(t)$ and $\theta_2(t)$ are the angles between each free layer and their respective reference layer magnetization. The power spectral density (PSD) is calculated accordingly:

$$PSD(f) = \lim_{t_0 \rightarrow t_1} \frac{1}{t} E \left[|s(f)|^2 \right] \quad (\text{B.3})$$

where E is the expectation value and $s(f)$ the FFT of $s(t)$. We choose $t_0 = 25$ ns which is a high value (it corresponds to a data rate upper cut-off frequency of 40MHz) but accommodates the artificial increase of the initial simulation-related relaxation time. $t_1 =$

50ns yields reasonably clean FFT spectra while keeping the computation time low enough. The root mean square value of the noise N is then given by integrating the power spectral density over the available frequency range and taking its root value:

$$N = \sqrt{\sum_{f>0} 2 \times PSD(f) \Delta f} \quad (\text{B.4})$$

where Δf is the frequency resolution of the FFT.

B.4 Spin torque noise of DDSV for uniform and differential field

Shown in Figure B.2 is a plot of the simulated absolute noise of a DDSV for a 50mT uniform (black squares) and differential ($H_{FL1} = \pm 50\text{mT}$ and $H_{FL2} = \mp 50\text{mT}$ in open triangles and red circles respectively) magnetic fields. We did not consider the case of a uniform -50mT field, as it would give the same results with opposite current sign.

Figure B.3 STT induced noise as a function of the applied current in three different possible configurations in DDSV. The magnetic field amplitude is 50mT along the SH direction.

As expected for a uniform field, STT is only observed for one current direction [17]. This corresponds to the worst case regarding STT noise for a DDSV, because the torque tends to destabilize both free layers' magnetizations, whereas for differential fields, STT only destabilizes one free layer at a time, yielding lower noise levels. The notable difference in noise levels between the 2 differential fields configurations is due to the asymmetry of effective spin polarization $P_i(J > 0) \neq P_i(J < 0)$ for each spin valve [14]. For (+,-) configuration, The FLs in both the SVs align parallel to their respective RLs. When the electrons flow from SV1 to SV2, FL1 feels the forward torque in parallel state which results in no noise at the SV1. However, FL2 feels the torque towards anti-parallel state due to reflected electrons which results in noise at SV2. For (-,+) configuration, the FLs in both the SVs align anti-parallel to their respective RLs. When the electrons flow from SV1 to SV2, FL1 feels forward torque in parallel state results in noise at SV1 and FL2 feels reverse torque in anti-parallel state which results in no noise at SV2. The STT noise is higher in (-,+) configuration compared to (+,-) as the noise due to forward torque is always higher compared to the reverse torque. The argument is valid for DDSV irrespective of the current direction as the two SVs are mirroring each other.

B.5 STT noise: DDSV vs. Single spin valve

A comparison between similar Single Spin Valve (SSV) and DDSV is made on Figure B.3 for a uniform 50mT field. In a self-biased DDSV, the two FLs experience an additional dipolar field which aligns their magnetizations anti-parallel to each other. The average dipolar field is found to be ~70mT, at a GL thickness of 2nm. To make a reasonable comparison between the SSV and the DDSV, an additional hard bias field of 70mT is therefore applied along the easy axis (TW) direction to the SSV. We find a

critical current density for the onset of STT noise in SV is $2.6 \times 10^7 \text{ A/cm}^2$ which is lower than the critical current density ($4 \times 10^7 \text{ A/cm}^2$) of the DDSV. This implies that DDSV are more stable against STT noise compared to the SSV.

Figure B.3 STT induced noise as a function of the applied current with a uniform field for a typical single spin valve with hard bias field as explained in the text and a DDSV. The magnetic field amplitude is 50mT along the SH direction.

The higher critical current density in case of DDSV can be attributed to differences in bias field distributions between the 2 types of sensors. Self-biased DDSV indeed possess a more inhomogeneous field along the TW direction with higher values at the edges which help stabilize them.

B.6 Effect of interlayer dipolar coupling on the onset of STT-noise

In order to further confirm the influence of the interlayer dipolar coupling, we have modeled additional DDSV with varying gap layer thicknesses ranging between 2nm and 10nm.

Figure B.4 Critical current density as a function of the gap layer thickness in red open circles (the line is a $1/d$ fit to the data). Error bars express the uncertainty due to reading errors.

Increasing the thickness of the gap layer should indeed lead to a decrease of the dipolar coupling strength while keeping other parameters of the simulation constant. The results are presented on Figure B.4. The results unambiguously demonstrate the importance of H_d as J_c decreases as $\sim 1/d$ (d the gap layer thickness), as expected from the dipole-dipole interaction between 2 thin magnetic films. A strong interlayer dipolar coupling is thus highly desirable to prevent STT noise.

B.7 Effect of interlayer exchange coupling on the onset of STT-noise

Ru being a transition metal across which a strong exchange bias is observed due to the RKKY mechanism [18], we have also assessed its influence on the dynamics of the free layers magnetizations. The exchange constant lies around $\sigma = 10^{-5} \text{ J/m}^2$ for a 2 nm thick Ru layer [19,20] and we have run simulations for both positive and negative values to take into account the oscillating behavior of the coupling as a function of Ru thickness.

Figure B.5 Critical current density as a function of the exchange bias constant σ in black squares (the line is only a guide for the eyes).

The results, also shown on Figure B.5 are straightforward: $\sigma > 0$ ($\sigma < 0$) results in a decrease (increase) of J_c as a positive (negative) value of σ stabilizes a parallel (antiparallel) alignment of magnetizations. $\sigma < 0$ reduces the sensitivity to STT-noise because it adds an effective field which stabilizes the antiparallel alignment of both free layers, concurrently with the dipolar field. It is therefore highly desirable when designing a self-biased DDSV sensor.

B.8 Effect of shape anisotropy on the onset of STT-noise

To get an insight into the effect of shape anisotropy on the critical current density, we have varied the aspect ratio (TW/SH) of the FL from 1.2 to 3. The critical current density (J_c) is calculated at different homogenous media fields ranging from 25mT to 120mT as shown in Figure B.6

Figure B.6 Critical current density as a function of the aspect ratio (AR) at various media fields.

As expected, the critical current density (J_c) is found to increase with aspect ratio since a higher anisotropy field along the TW direction stabilizes the two FLs against STT noise. However, the relative sensitivity of the reader also drops dramatically as shown in Figure B.7. For a comparison between AR=1.2 and 3 at a media field of 50mT, the critical current density rises ~ 3 times, but the sensitivity of the DDSV reader drops 4 times. We therefore need to consider these two aspects while tuning the dimensions of the reader.

Figure B.7 The relative sensitivity of DDSV as a function of differential media field.

B.9 Effect of relative orientation between FLs on the onset of STT-noise

In order to study the effect of the relative orientation of the FLs on the critical current density, we have varied the uniform media field from 25mT to 120mT. The critical current density is found to drop with increasing media field, which indicates that STT noise is low when the FLs are aligned in the quiescent state. In a self-biased DDSV, the two FLs always form a flux-closure in the ground state (no external field and no current). The uniform media field acts against the dipolar coupling to break the anti-parallel alignment between the FLs, therefore rendering the device more sensitive to STT-noise. From Figure B.5, it is worth noting that the drop in critical current density is not so significant when the media field changes from 75mT to 120mT. This is due to fact that the both FLs are almost saturated at 75mT along SH direction above which the effect of the media field on the critical current density becomes negligible.

B.10 Maximum signal output of the DDSV

A typical magnetic field distribution above a 10nm-bit length media at a media-head distance of 2 nm is shown in Figure B.8 and points out that the overlap of magnetic fields generated by each nearby bit leads to variable media field values, depending on the magnetic bits Sequence.

Figure B.8 Typical distribution of transverse magnetic fields experience by the FL at a media-head distance of 2nm.

The maximum signal output of DDSV readers below the threshold of STT-noise for various dimensions is calculated for both MTJ and CPP-GMR based DDSV read-heads according to the following formula:

$$\Delta V = \frac{\Delta RA}{RA} \times RA \times J_{\max} \times v \quad (B.5)$$

where v is the sensitivity of the read-head, J_{max} is the current density applied to the reader is considered as 80% of the critical current density ($J_{max} = 0.8 J_c$), RA and $\Delta RA/RA$ are assumed to be $50 \text{ m}\Omega\cdot\mu\text{m}^2$ and 10% for CPP-GMR based DDSV and $1 \text{ }\Omega\cdot\mu\text{m}^2$ and 100% for MTJ based DDSV respectively. Here A is the cross sectional area of the FL and R is the resistance across the DDSV.

Figure B.9 The maximum signal output of the DDSV reader as a function of differential media field at different dimensions of the FL. The voltage has been calculated for both the MTJ and CPP-GMR based DDSV.

In order to obtain realistic output values, J_{max} is then calculated for the worst case of STT (corresponding to uniform fields) while v is determined at the corresponding differential field. For differential fields of resp. 25mT, 50mT and 75mT, we find uniform fields of resp. 39mT, 78mT and 118mT. The maximum output voltage is then plotted against the media differential field in Figure B.9. The maximum allowed output voltage

is found be highest at low aspect ratio and low media differential field, because the gain in sensitivity is offset by the drop in critical current density when these parameters are increased.

B.11 Summary

Micromagnetic simulations of self-biased DDSV and single spin valve sensors have been performed taking into account Slonczewski's spin transfer torque model. We have found that DDSV sensors possess an intrinsic increased stability against STT-induced noise compared to single spin valves which is mainly due to dipole-dipole coupling between the 2 free layers' magnetizations. We have shown that the exchange bias should be set with a negative σ in order to also favour an anti-parallel alignment. These findings set one design rule that the gap layer thickness must be minimized in order to maximize the dipolar interlayer coupling and the exchange bias, but it must be carefully controlled to avoid a positive RKKY coupling. Shape anisotropy was also found to increase the stability against STT, due to an increase in anisotropy field (but this also applies to a single spin valve) at the cost of a reduced sensitivity to the differential media field. Higher the uniform media field, DDSV are less stable against STT and maximum signal output is obtained at lower aspect ratio and lower media field. The results presented here are useful for the optimisation of DDSVs for ultrahigh density hard disk recording.

References

1. Seagate Reaches 1 Terabit Per Square Inch Milestone In Hard Drive Storage With New Technology Demonstration, Press release (2012).
2. Y. Shiroishi, K. Fukuda, I. Tagawa, H. Iwasaki, S. Takenoiri, H. Tanaka, H. Mutoh, and N. Yoshikawa, *IEEE Trans. Mag.* **45**, 3816 (2009).
3. G. C. Han, C. C. Wang, J. J. Qiu, P. Luo, V. Ko, Z. B. Guo, B. Y. Zong, and L. H. An, *J. Appl. Phys.* **109**, 07B707 (2011).
4. G. C. Han, J. Qiu, L. Wang, W. Yeo, and C. C. Wang, *IEEE Trans. Mag.* **46**, 709 (2010).
5. N. Smith, J. Katine, J. Childress, and M. Carey, *IEEE Trans. Mag.* **41**, 2935 (2005).
6. M. Donahue, and D. Porter: Interagency Report NISTIR 6376 NIST (1999) <http://math.nist.gov/oommf>.
7. G. C. Han, J. J. Qiu, C. C. Wang, V. Ko, and Z. B. Guo, *Appl. Phys. Lett.* **96**, 212506 (2010).
8. G. C. Han, Y. K. Zheng, Z. Y. Liu, B. Liu, and S. N. Mao, *J. Appl. Phys.* **100**, 063912 (2006).
9. L. Chen, F. Liu, K. Stoev, S. Li, M. Ho, and S. Mao, *J. Appl. Phys* **105**, 07B730 (2009).

10. K. Eid, R. Fonck, M. A. Darwish, J. W. P. Pratt, and J. Bass, *J. Appl. Phys.* **91**, 8102 (2002).
11. A. Manchon, N. Strelkov, A. Deac, A. Vedyayev, and B. Dieny, *Phys. Rev. B* **73**, 184418 (2006).
12. T. Valet, and A. Fert, *Phys. Rev. B* **48**, 7099 (1993).
13. J. Slonczewski, *J. Magn. Magn. Mater.* **159**, L1 (1996).
14. A. Fert, V. Cros, J.-M. George, J. Grollier, H. Jaffres, A. Hamzic, A. Vaures, G. Faini, J. Ben Youssef, and H. Le Gall, *J. Magn. Magn. Mater.* **272**, 1706 (2004).
15. J. Barnas, A. Fert, M. Gmitra, I. Weymann, and V. K. Dugaev, *Phys. Rev. B* **72**, 024426 (2005).
16. O. Boulle, V. Cros, J. Grollier, L. G. Pereira, C. Deranlot, F. Petroff, G. Faini, J. Barnas, and A. Fert, *Nature Phys.* **3**, 492 (2007).
17. J.-G. Zhu, and X. Zhu, *IEEE Trans. Mag.* **40**, 182 (2004).
18. S. S. P. Parkin, N. More, and K. P. Roche, *Phys. Rev. Lett.* **64**, 2304 (1990).
19. S. S. P. Parkin and D. Mauri, *Phys. Rev. B* **44**, 7131 (1991).
20. B. Negulescu, D. Lacour, M. Hehn, A. Gerken, J. Paul, and C. Duret: *J. Appl. Phys.* **109**, 103911 (2011).

Appendix C

C.1 Domain wall generation by local Oersted field

The DW creation by magnetic field generated by the current carrying stripe line placed on the magnetic nanowire is attractive as the effect is local. To generate the local magnetic field, a stripe line is placed perpendicular to the magnetic nanowire as shown by the SEM image in Figure C.1

Figure C.1 SEM image of the nanowire with DW injection stripe line and the contacts for resistance measurements.

The stripe line is made of Cr/Au (5 nm/100 nm) with width of 500 nm. Using pulse generator, a voltage pulse of 2.5 V is passed through the stripe line. The pulse width of 50 ns is injected in to stripe line. Due to low resistance of the stripe line, the current only passes through the stripe line but not through the magnetic nanowire. The generation

of the DW is detected by AMR measurement. A small current ($10\ \mu\text{A}$) flows through the nanowire from A to B. A drop in the resistance shows the generation of pair of DWs formed in the nanowire. Shown in the Figure C.2 is the resistance variation of the nanowire.

Figure C.2 The resistance of the nanowire during the DW injection by current pulse.

The drop in the resistance is around $0.5\ \Omega$ which shows that two vortex DWs are formed on either side of the stripe line. The DW formation is confirmed by the MFM imaging. Shown in Figure C.3 is the MFM image of the nanowire after the current pulse injection. A Tail to tail DW (left) and a head to head DW (right) can be clearly seen in the MFM image. The DW injection by local field generation method is fast but stochastic. The chirality of the DW cannot be controlled in this DW injection method.

Figure C.3 MFM image of the nanowire with two DW generated by passing current pulse through the stripe line.

Appendix D

D.1 Domain wall creation by oblique field

An alternative technique to create a DW is to use an L-shaped nanowire and applying an oblique magnetic field with reference to the curved nanowire. The magnetization of the L-shaped nanowire is saturated in one direction and a field applied perpendicular to the curvature as shown in Figure D.1 to generate a DW. The width of the nanowire is 150 nm.

Figure D.1 Schematic of the direction of magnetic field applied overlapped with AFM image of the curved nanowire.

Figure D.2 MFM image and the corresponding simulated magnetization for vortex wall and the transverse DW respectively.

In the L-shaped nanowire, the curvature in the nanowire has the lowest energy state. A transverse DW is formed as shown in Figure D.2. The magnetic field required for the transverse DW generation is 1.2 KOe much higher than the vortex DW generation. The increased shape anisotropy of the narrow nanowire causes the surge in the field required for the DW generation. To move the DW from the curvature, a large magnetic field needs to be applied to depin the DW from the lowest energy stable state.

Height Width	Chirality	100 nm	150 nm	200 nm	250 nm	300 nm
40 nm		Well	Well	Well	Well	Well
	Barrier	Barrier	Barrier	Barrier	Barrier
60 nm		Barrier	Well	Well	Well	Well
	Well	Barrier	Barrier	Barrier	Barrier
100		Barrier	Barrier	Well	Well	Well
	Well	Well	Barrier	Barrier	Barrier
120 nm		Barrier	Barrier	Barrier	Well	Well
	Well	Well	Well	Barrier	Barrier
140 nm		Barrier	Barrier	Barrier	Barrier	Well
	Well	Well	Well	Well	Barrier
160 nm		Barrier	Barrier	Barrier	Barrier	Barrier
	Well	Well	Well	Well	Well

Table A.1 Table representing the type of potential disruption observed by the DW at the anti-notch of different heights and widths. All the heights and widths are in nm. DW chiralities shown in table are HH-U and HH-D.

Publications in International Refereed Journals

1. **M. Chandra Sekhar**, S. Goolaup, I. Purnama and W. S. Lew, “Crossover in the domain wall potential polarity as function of anti-notch geometry”, J. Phys. D: Appl. Physics., **44**, 235002 (2011).
2. **M. Chandra Sekhar**, H. F. Liew, I. Purnama, W. S. Lew, M. Tran and G. C. Han, “Helical domain walls in constricted cylindrical NiFe nanowires”, Appl. Phys. Lett. **101**, 242404 (2012).
3. **M. Chandra Sekhar**, C. C. Wang, G. C. Han and W. S. Lew, “Effect of interlayer coupling on the reversal process of differential dual spin valves”, J. Appl. Phys. **111**, 07B723 (2012).
4. **M. Chandra Sekhar**, M. Tran, L. Wang, G. C. Han and W. S. Lew, “Increased stability against spin torque noise in current perpendicular to the plane self-biased differential dual spin valves”, J. Magn. Magn. Mat. **374**, 740 (2015).
5. **M. Chandra Sekhar**, P. Sethi, S. Goolaup, M. Ramu, Y. J. Chen, S. H. Leong, and W.S. Lew*, "Direct observation of domain wall evolution at a bifurcation in magnetic network structures", Appl. Phys. Exp. **7**, 113003 (2014).

6. **M. Chandra Sekhar**, S. Goolaup, I. Purnama and W. S. Lew, “Depinning assisted by domain wall deformation in cylindrical nanowires”, J. Appl. Phys. **115**, 083913 (2014).

7. **M. Chandra Sekhar**, S. Goolaup, I. Purnama and W. S. Lew, “Coupled domain wall oscillations in magnetic cylindrical nanowires”, (accepted J. Appl. Phys. 2014).

8. I. Purnama, **M. Chandrasekhar**, W. S. Lew and T. Ono, “Remote driving of multiple magnetic domain walls due to topological interaction” Appl. Phys. Lett. **104**, 092414 (2014).

9. W.L. Gan, **M. Chandra Sekhar**, D.W. Wong, I. Purnama, S.Y. Chiam, N. Wong and W.S. Lew*, "Multi-vortex states in magnetic nanoparticles", Appl. Phys. Lett. **105**, 152405 (2014).

10. I. Purnama, **M. Chandrasekhar**, S. Goolaup and W. S. Lew, “Current-induced coupled domain wall motions in two nanowire system”, Applied Physics Letters **99**, 152501 (2011). (Appeared in Virtual Journal of Nanoscience and Nanotechnology).

11. X. H. Wang, **M. Chandra Sekhar**, I. Purnama, W. S. Lew, S. Goolaup and C. X. Cong, “Magnetization reversal in nano triangles fabricated by nanosphere lithography”, Thin Solid Films **520** (2012) 6980.

12. D. W. Wong, **M. Chandra Sekhar**, W. L. Gan, I. Purnama and W. S. Lew*,
"Dynamics of three-dimensional helical domain wall in cylindrical NiFe
nanowires", (accepted J. Appl. Phys. 2014).

13. I. Purnama, **M. Chandra Sekhar**, S. Goolaup and W. S. Lew, "Collective
motions assisted by magnetostatic interactions in coupled domain wall system",
IEEE Trans. Mag. **47**, 3081 (2011).

14. C. Guite, I. S. Kerk, **M. Chandra Sekhar**, R. Maddu, S. Goolaup, and W.S. Lew,
"All-electrical single domain wall generation for on-chip applications", Scientific
Reports, **7**, 7459 (2014).

15. Y. P. Liu, S. Goolaup, **M. Chandra Sekhar**, W. S. Lew and S. K. Wong, "Effect
of magnetic field on the electronic transport in trilayer grapheme", ACS Nano, **4**,
7087 (2010). (Highlighted by Nature Publishing Group).

16. X. H. wang, I. Purnama, **M. Chandra Sekhar** and W. S. Lew, "Highly Stable
Vortex State in Sub-100nm Nanomagnets", Appl. Phys. Exp. **5** (2012) 053001.

17. S. Goolaup, S. C. Low, **M. Chandra Sekhar** and W. S. Lew, "Dependence of
pinning on domain wall spin structure and notch geometry", J. Phys. Conf. Ser.
266, 012079 (2011).

18. G. C. Han, Q. Jinjun, Q. J. Yap, L. Ping, **M. Chandra Sekhar**, Z. Baoyu, K. C. Weng, “ Gap layer effect on performances of differential dual spin valve”, IEEE Trans. Mag. **49**, 3714 (2013).
19. R. Maddu, I. Purnama, S. Goolaup, **M.Chandra Sekhar**, and W.S. Lew*, "Investigation of dominant spin wave modes by domain walls collision", J. Appl. Phys. **115**, 243908 (2014).
20. Y. P. Liu, S. Goolaup, W. S. Lew, I. Purnama, **M. Chandra Sekhar**, S. Goolaup, T. Zhou and S. K. Wong, “Excitonic bandgap dependence on stacking configuration in four layer graphene”, Appl. Phys. Lett. **103**, 163108 (2013).

Patents

1. **“Non-Volatile Logic Device”**, W.S. Lew, **M. Chandra Sekhar**, I. Purnama, S. Goolaup, P. Sethi and C. Guite, US patent 61/824,738 (2014); Patent Cooperation Treaty (PCT) Application No: PCT/SG2014/000218.
2. **“A memory device”**, W.S. Lew, I. Purnama and **M. Chandra Sekhar**, US patent 61/747/316 (2014); Patent Cooperation Treaty (PCT) Application No: PCT/SG2014/000002.
3. **“Logic operation based on magnetic domain wall profile”**, W.S. Lew, **M. Chandra Sekhar**, and I. Purnama, US Provisional Patent 61/748, 337 (2012).
4. **“Coupled domain wall oscillator as microwave generator”**, W.S. Lew, **M. Chandra Sekhar**, and I. Purnama, US Provisional Patent 61/845,097 (2013).
5. **“Deterministic generation of domain wall in zero external magnetic field”**, Chinkhanlun Guite, I.S. Kerk, **M. Chandra Sekhar** and W. S. Lew, Singapore Provisional patent Application No: 10201405402X (2014).

Conference Presentations

1. “Striped Cylindrical Nanowire as a Magnetic Domain Wall Nanobarcode”, **M. Chandra Sekhar**, H. F. Liew, I. Purnama and W. S. Lew (Oral presentation, Intermag 2012, Vancouver, Canada).
2. “Crossover in Domain Wall Potential Polarity as a Function of Anti-notch Geometry”, **M. Chandra Sekhar**, S. Goolaup, I. Purnama and W. S. Lew (Poster presentation, ICMAT 2011, Singapore).
3. “Effect of interlayer coupling on the reversal process of differential dual spin valves”, **M. Chandra Sekhar**, C. C. Wang, G. C. Han and W. S. Lew (Poster presentation MMM 2011, Scottsdale, Arizona).
4. “Coupled Domain Wall Oscillations in closely spaced Cylindrical Nanowires”, **M. Chandra Sekhar**, I. Purnama and W. S. Lew (Poster presentation, Intermag 2012, Vancouver, Canada).
5. “Field and current driven domain wall depinning at the notch and anti-notch in cylindrical nanowires” **M. Chandra Sekhar**, I. Purnama and W. S. Lew (Poster presentation Intermag 2012, Vancouver, Canada).
6. “Helical Domain Walls in constricted cylindrical NiFe nanowires” **M. Chandra Sekhar**, H. F. Liew, I. Purnama, W. S. Lew, M. Tran and W. S. Lew (Poster

presentation, IEEE magnetic Summer School 2012, SRM University Chennai, India).

7. “Spin Transfer induced Noise in Permalloy- Based Differential Dual Spin Valves”
M. Chandra Sekhar, M. Tran, C. C. Wang, G. C. Han and W. S. Lew (Poster presentation, ICYRAM 2012, Singapore).
8. “Low current domain-wall oscillators”, **M. Chandra Sekhar** I. Purnama and W. S. Lew (Oral presentation, ISAMMA 2013 Taichung, Taiwan).
9. “Fabrication of NiFe Nanoparticles by Chemically Slicing NiFe Nanowires” G. Weiliang, **M. Chandra Sekhar**, I. Purnama and W. S. Lew (Oral presentation, ISAMMA 2013 Taichung, Taiwan).
10. “Coupled vortex domain wall transformation and selective motion” I. Purnama, R. Shiina, **M. Chandra Sekhar**, T. Taniyama and W. S. Lew (Oral Presentation, ISAMMA 2013 Taichung, Taiwan).
11. “Spin wave generation due to domain wall collision” M. Ramu, I. Purnama, **M. Chandra Sekhar** and W. S. Lew (Poster presentation, ISAMMA 2013 Taichung, Taiwan).

12. “Multiple remote domain wall motion due to exchange interaction” I. Purnama, **M. Chandra Sekhar** and W. S. Lew (Poster presentation, ISAMMA 2013 Taichung, Taiwan).
13. “Remote Barrier and Trap Induced by Neighboring Domain Walls” I. Purnama, **M. Chandra Sekhar** and W. S. Lew (Oral Presentation, Intermag 2012, Vancouver, Canada).
14. “Vortex-to-transverse coupled domain-wall transformation in two-nanowire Systems” I. Purnama, **M. Chandra Sekhar** and W. S. Lew (Poster presentation, Intermag 2012, Vancouver, Canada).
15. “Colletive motions in coupled domain wall system”, I. Purnama, **M. Chandra Sekhar**, S. Goolaup and W. S. Lew (Poster presentation, ICMAT 2011, Singapore).
16. “Natural domain wall oscillator”, **M. Chandra Sekhar**, I. Purnama and W. S. Lew (Oral presentation, Joint European Magnetic Symposia 2013).
17. “Anomalous domain wall depinning behavior in cylindrical nanowires”, **M. Chandra Sekhar**, I. Purnama and W. S. Lew (Poster presentation, Joint European Magnetic Symposia 2013).

18. “Magnetic nanoparticles synthesized by chemical slicing method”, G. Weiliang, **M. Chandra Sekhar**, I. Purnama and W. S. Lew (Oral presentation, Joint European Magnetic Symposia 2013).
19. “Polarity dependant vortex domain wall coupling”, I. Purnama, **M. Chandra Sekhar**, and W. S. Lew (Poster presentation, Joint European Magnetic Symposia 2013).
20. “Dependence of pinning on domain wall spin structure and notch geometry”, S. Goolaup, S. C. Low, **M. Chandra Sekhar** and W. Lew (Poster presentation, ISAMMA 2010, Singapore).