Nanowire spintronics for storage class memories and logic

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Patterned magnetic nanowires are extremely well suited for data storage and logic devices. They offer non-volatile storage, fast switching times, efficient operation and a bistable magnetic configuration that are convenient for representing digital information. Key to this is the high level of control that is possible over the position and behaviour of domain walls (DWs) in magnetic nanowires. Magnetic random access memory based on the propagation of DWs in nanowires has been released commercially, while more dynamic shift register memory and logic circuits have been demonstrated. Here, we discuss the present standing of this technology as well as reviewing some of the basic DW effects that have been observed and the underlying physics of DW motion. We also discuss the future direction of magnetic nanowire technology to look at possible developments, hurdles to overcome and what nanowire devices may appear in the future, both in classical information technology and beyond into quantum computation and biology.

Keywords: magnetic nanowire; domain-wall propagation; domain-wall memory; domain-wall logic

1. Introduction

The motion of domain walls (DWs) in magnetic nanowires offers an interesting and potentially useful approach within spintronics. The interest in this stems from the high degree of control that nanowire systems offer over the position, structure and dynamic behaviour of DWs. The ability to modify the functionality of a nanowire system simply by changing local geometry or anisotropy using standard lithographic techniques gives the technology a great deal of flexibility. There has been particular focus on information storage [1–3] and logic [4,5] devices operated by magnetic DWs in nanowires. This is partly because the nanowires generally have a twofold degeneracy resulting from a single magnetic easy axis, which is ideal for representing digital information. DWs move relatively quickly in nanowires, often over 1 km s$^{-1}$ [6], which allows fast device switching, and the ferromagnetic nature of most materials chosen leads to non-volatile retention.
of the magnetic configuration. We choose to consider both magnetic field- and electric current-induced motion of DWs owing to the similarity of the physics required to describe the interactions and of the proposed applications.

Here, we review DW-based information technology applications in a manner that is hopefully useful both to the newcomer to the subject and to those with more previous knowledge of the area. After considering the basic phenomenology of DWs in magnetic nanowires, we look at some of the underlying physics of DW motion and the current status of magnetic DW-based memory and logic devices. Finally, we look at future trends in the area and to what alternative nanowire technologies may also emerge.

2. Basic observations

Here, we review the general behaviour and features of DWs in magnetic nanowires that underpin the operation of devices.

The relevant structures are generally fabricated from magnetic thin films to have dimensions of thickness 1–30 nm (soft materials usually greater than 3 nm), width from 50 to 1000 nm and lengths of many micrometres. Nanowires fabricated from soft magnetic materials, such as permalloy (Ni81Fe19), exhibit in-plane magnetization and head-to-head-type DWs [7]. The structure of these walls is often described as either ‘transverse’ (figure 1a), with magnetization rotating in an identical direction through any line across the wall, or ‘vortex’ (figure 1b), in which the DW magnetization circulates internally through 360°. DWs can alternate between these two structures during propagation [8] and there are many variations from these broad categories [9,10]. A detailed review of the behaviour of DWs can be found elsewhere [11]. Nanowires of hard magnetic materials have strong perpendicular magnetocrystalline anisotropy (PMA; e.g. FePt [12]), which results in confined Neél or Bloch-type DW structures (figure 1c). These various DW structures can also vary in their direction of magnetization rotation or ‘chirality’.

Early demonstrations with DWs in soft magnetic nanowires were relatively simple, showing how DWs could be injected into a nanowire under relatively low magnetic fields by modifying the local shape of one end of a wire to create a large magnetic pad [13,14]. While useful for testing, this method generally results in DW nucleation on every half-cycle of the field. More sophisticated methods of introducing DWs selectively have since been introduced, including heat-assisted nucleation [15] and using the Oersted field from an overlaid current-carrying wire [2,3,16]. DWs propagated under applied magnetic fields could then be positioned at deliberate edge defects [16–19], wire junctions [20,21], 90° wire corners [4,5,22] or regions of changing wire width [23]. The use of geometrical features to control the DW position is complicated by the magnetic interactions, often depending on the DW structure and its propagation direction [9,19,20,24,25]. Furthermore, the depinning of nominally identical DWs from wire defects or junctions is subject to thermally driven stochastic processes that broaden the range of switching fields compared with simple propagation in the wire [10,12,26].

The original reports [27–29] of DW propagation by electrical currents through nanowires have led to enormous subsequent interest in the process. This approach offers highly efficient, unidirectional DW motion independent of the adjacent...
Figure 1. Simulated magnetization configurations of domain walls (DWs) in a 200 nm wide soft magnetic nanowire having (a) transverse and (b) vortex structures, and (c) in a 100 nm wide, 5 nm thick nanowire with large perpendicular magnetic anisotropy. The arrows represent local averages of magnetization.

magnetic domain configuration. While DW motion under applied fields is relatively slow in nanowires with PMA, current-induced motion in these materials can be relatively fast and efficient [30]. Controlling DW position under spin-polarized currents and/or with PMA materials can be achieved using pinning from geometric features [2,12,31,32]. Recent experiments [33,34] of DW dynamics including relaxation and transformational behaviour with spin-polarized currents have also shown interesting inertial-like propagation of DWs.

A useful feature of ferromagnetic nanowire systems used to study DWs is their accessibility by magnetoresistance (MR) measurements. Although a wide range of analytical techniques have been used, MR is consistent with schemes to produce fully integrated nanowire devices and allows spatially resolved measurements dictated by the contact positions. Anisotropic MR (AMR) of DWs in single-layer nanowires has been widespread in studying DW behaviour [8,17,35]. In multi-layer nanowires, giant MR (GMR) [13,36] or tunnelling MR (TMR) [1] measurements have switched the ‘free’ layer using DW motion while leaving the ‘pinned’ layer in a fixed and a uniform magnetic configuration.
3. Underlying theory

Numerical micromagnetics is one of many techniques that are used to describe and predict field- and current-driven DW propagation in magnetic nanodevices. It is unique in the sense that it takes into account the nanoscale structure of the magnet for the calculation of its magnetic properties. The theory of micromagnetism is a continuum theory and describes magnetization processes of ferromagnets on a characteristic length of a few nanometres by meeting the following two criteria:

— The length scale is large enough to replace the atomistic magnetic moments by a continuous function in space. Instead of a discrete representation of a magnetic state of the ferromagnet by the set of magnetic moments at the atomic lattice sites, the magnetic state is represented by the magnetization, \( \mathbf{M}(\mathbf{r}) \). The magnetization is the magnetic moment per unit volume.

— The length scale is small enough to describe DWs. The term ‘DW’ denotes the transition of the magnetization between magnetic domains.

Within a magnetic domain, the magnetization is uniform and points in the same direction. Domains are formed to reduce the magnetostatic energy of a magnet. However, energy is required to form the DWs that separate adjacent domains. The wall energy per unit area is given (in SI units) by

\[
E_{\text{wall}} = 4\sqrt{AK},
\]

where \( A \) is the exchange constant and \( K \) the anisotropy constant of the magnetic material. The interplay between the exchange energy and the anisotropy energy determines the DW width. In equilibrium, the DW configuration minimizes the sum of the exchange energy and the anisotropy energy. The smaller the transition region, the smaller is the region where the magnetization deviates from the easy axis. Therefore, we see that thinner walls reduce the integrated anisotropy energy for the particular material system in question. On the other hand, the exchange energy will reach a minimum when the magnetization changes slowly as a function of position, which favours a wide DW. In hard magnetic materials, the wall width is given by

\[
\delta = \pi\sqrt{\frac{A}{K}},
\]

the width of a so-called Bloch wall. The factor \( \delta_0 = \sqrt{A/K} \) is the characteristic length in hard magnetic materials and is called the Bloch parameter. In thin soft magnetic films, the magnetocrystalline anisotropy energy is small when compared with the other energy contributions, and magnetostatic interactions keep the magnetization in the plane of the film. Indeed, in soft magnetic thin films, the magnetostatic energy plays the role of the anisotropy in hard magnets: the narrower the DW, the smaller the magnetostatic energy. Thus, the interplay between the exchange and the magnetostatic energy determines the DW width. To obtain the wall width, we replace the anisotropy constant in equation (3.2) with \( (1/2)\mu_0 M_s^2 \), where \( M_s \) is the spontaneous magnetization.
In soft magnetic materials, the characteristic length is the exchange length

\[ l_{\text{ex}} = \sqrt{\frac{2A}{\mu_0 M_s^2}}. \] (3.3)

This characteristic length is strongly material dependent, ranging from approximately 1 nm for hard magnetic materials to more than 100 nm for soft magnetic materials. In numerical studies, the discretization length scale must be lower than the exchange length or Bloch parameter of the material under investigation in order to obtain a realistic representation of the magnetization structure. The transverse and vortex structures of DWs in soft magnetic nanowires arise from further consideration of the exchange and magnetostatic energies arising from their configurations [7]. This detailed structure plays a crucial role in determining their motion under an applied magnetic field or a spin transfer torque [37].

Within micromagnetics, field-induced DW motion is described by the Landau–Lifshitz–Gilbert equation [38] and Maxwell’s equations, but the magnetization dynamics of spin-polarized current-induced DW motion requires the inclusion of the interaction of the electron charge density and the magnetic moments of the magnetic material [39–42].

A simple approximation [41–44] to understand and describe current-induced DW motion is to assume that the electron spins follow the magnetization direction adiabatically. The resulting evolution of the spin current \( s \) is given by

\[ \frac{\partial s}{\partial t} = -\gamma_0 \left[ \frac{A}{2\mu_0 M_s^2} \right] s \times \nabla^2 M - \gamma_0 s \times H, \] (3.4)

where \( \gamma_0 \) is the gyromagnetic ratio, and \( H \) is the effective field given by the various magnetic energy terms. This gives a momentum transfer on the magnetization of \( -(p_0 \cdot \nabla)M(r) \), with \( p_0 \) being a vector in the current direction with the magnitude \( P|j|\mu_B/eM_s \) (\( P \) is the polarization of the current, \( j \) the current density and \( \mu_B \) the Bohr magneton). For a uniform current, the torque density translates the DW in the direction of the electron flow with a speed equal to the magnitude of the current vector [45–47]. The degree to which the spins adiabatically follow the magnetization has been computed in several models [44,48,49]. The results show that the deviations are small except for narrow DWs. For the case, where the deviations are non-negligible an additional torque is introduced in the \( M \times (p_0 \cdot \nabla)M \) direction, which is referred to as the non-adiabatic torque. The narrow (few nanometres wide) DWs in nanowires with very large PMA are the reason for their high sensitivity to spin-polarized currents [30].

But there is still a debate in the theoretical description of current-induced DW motion on how to describe the damping and whether there is an additional torque in the direction of the non-adiabatic torque [44,48], which arises from the same processes that contribute to magnetic damping. Such a torque, while it is not related to a true non-adiabatic torque, is still sometimes called a non-adiabatic torque. Sometimes it is referred to as ‘the beta term’ \( \beta \) [43,45–47], a dimensionless parameter that is frequently used to characterize the strength of the non-adiabatic torque.

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Many experiments and simulations have shown the sometimes complex magnetization dynamics during DW motion. The structure of a DW can distort due to the non-adiabatic spin torque, damping and the presence of non-uniformities in the nanowire. The dynamics of DW motion also differ with the different wall structures and the details within them. Under an applied field, the linear response to low-strength fields is halted by the onset of ‘Walker breakdown’ [50,51], during which the (often local) rotation of DW magnetization about the magnetic easy axis leads to periods of a DW stopping and even undergoing retrograde motion. This effect is very sensitive to the nanowire conditions, e.g. edge roughness [50] and wire dimensions [52,53] in soft magnetic systems. Recent work [54] has shown how the phase of the DW rotation affects strongly the interaction of the wall with local imperfections in the nanowire, giving the DW propagation chaotic properties. DWs moving under the action of spin-polarized currents can also undergo highly complex dynamics, for example, oscillating between transverse and vortex structures on a nanosecond time scale [8].

4. Current applications

There has been great interest over many years in developing magnetic random access memory (MRAM) that combines non-volatile storage, fast switching speeds (less than 10 ns) and low-power operation. The stable nature of magnetization in MRAM offers an immediate benefit over semiconductor dynamic random access memory cells, which require refreshing constantly.

The use of single-domain magnetic tunnel junctions as MRAM cells operated by field or spin-polarized current is well developed and described elsewhere [55]. For nanowire-based MRAM devices, the required bistable operation is achieved by moving a DW between two pinning positions along a wire (figure 2a). These pinning sites are generally asymmetric in nature, with lower fields or currents required to move a DW back across an MRAM cell to switch the element than to remove the DW from the element altogether [24,56]. This has even been extended using DW-chirality-dependent switching to create multi-bit memories [56].

The reduced currents required for DW motion in perpendicular anisotropy nanowires [30] have been exploited to create highly efficient MRAM chips. In 2009, the NEC Corporation announced the development of a 32 Mbit (4 MByte) MRAM chip based on nanowires with perpendicular anisotropy [1]. Switching currents of 0.1 mA and switching times of 2 ns have been demonstrated, which compare well with semiconductor equivalents. The nanowire containing a DW is included as the free layer in a magnetic tunnel junction (e.g. figure 2b) to provide a high-impedance, high-dynamic-range read-out mechanism. Similar devices are currently under development by other companies, with larger-scale memory chips promised in the near future.

DW-based data storage can be extended further by not constraining DWs to a bistable element. A conceptually simple concept known as ‘racetrack memory’ uses a magnetic nanowire that contains a series of DWs to represent a data stream (figure 2c) [2,3]. Crucially, DWs are propagated using spin-polarized currents to ensure that they move in the same direction. This shift register memory has straightforward integration requirements, and so a potentially high memory density, and switching speeds measured in nanoseconds. A three-dimensional
Figure 2. Schematic views of various magnetic nanowire memories, with magnetization shown by the white arrows. (a) A bistable element for magnetic random access memory (MRAM) showing the configurations to represent ‘1’ and ‘0’ and (b) inclusion of a magnetic tunnel junction for read-out. Magnetization is shown as in-plane for convenience but devices with perpendicular magnetic anisotropy can be represented by rotating all magnetizations shown by $90^\circ$. (c) Magnetic ‘racetrack’ memory [2,3] to form a shift register device.

architecture has even been proposed for an ultra-high-density memory [2]. Data writing is achieved by creating a magnetic domain within a wire using the magnetic fringe field of a nearby current-carrying wire. For the shift register to operate correctly, successive DWs must be kept separated to avoid their annihilation and the accompanying loss of data. One approach considered has been to use a periodic array of notches in a wire edge to pin DWs at regular intervals. However, this is difficult to use in practice owing to the stochastic nature of DW depinning and large variations in observed cycle-to-cycle switching properties [10,12,26]. Alternatively, racetrack memory operation using wires with near-perfect edges has been demonstrated [3], with the distance travelled by co-propagating DWs defined by the current density and pulse length. While overcoming the stochastic depinning problems, this approach will be very sensitive to wire edge features, which may cause a succession of DWs to pin and annihilate at a defect.

More complex magnetic nanowire networks containing wire junctions can be used to perform logic operations [4,5]. In these structures, DWs are driven by a global rotating in-plane magnetic field that moves DWs around corners of the same handedness as the field rotation direction. This defines the direction of information flow, which is a central requirement for a logic system. Various Boolean logic operations can be performed by propagation of DWs through the various junctions. Logical NOT is achieved using a two- or three-terminal junction consisting of a single input wire and one or two outputs (figure 3a). Logical AND and OR gates are created using identical three-terminal junctions (figure 3b) with the type of operation selected by the sense of a DC magnetic field bias. These are complemented with signal fan-out junctions (figure 3c) for creating additional copies of an incident DW [57] and signal cross-over junctions (figure 3d) to allow
Figure 3. Schematic showing design of magnetic nanowire junctions for performing (a) logical NOT operations, (b) logical AND/OR operations, (c) signal fan-out and (d) signal cross-over using DWs propagating through the wires. (e) Example magnetization configuration in a shift register formed by concatenating NOT-gate junctions. As the applied field vector $H_{\text{app}}$ is rotated anti-clockwise, the DWs move in the direction shown to create (f) the resulting magnetization configuration [4].

DWs to cross perpendicular wires without interference. Additional features may be used for writing arbitrary streams of DWs to represent information, while DW pinning at junctions under low fields can be exploited to selectively remove DW pairs, effectively erasing data [4]. The most straightforward expression of this architecture is the use of a chain of NOT-gate junctions to form a shift register (figure 3e). Each NOT gate may be considered as an individual memory cell and each half cycle of applied field moves DWs to an adjacent cell (figure 3f). In this field-driven system, wire corners limit the extent of DW propagation in any particular direction, and a turn of 180° between memory cells guarantees the separation of adjacent DWs. The power consumption of this system is dominated by the magnetic field generation. However, the global rotating field gives the opportunity for significant efficiencies. High-speed operation is a challenge for this architecture, particularly owing to the usual stochastic nature of overcoming DW pinning at wire junctions. A high-frequency magnetic field could, in principle, be generated from crossed microstrips to avoid inductive losses.
Recently, Xu et al. [58] presented an alternative magnetic logic NOT-gate circuit design where two magnetic domains were trapped in two identical 50 nm wide Fe$_{64}$Ni$_{36}$ (Invar) contacts connected by two 400 nm wide Invar wires. They showed that, by applying current through the contacts, the DW can be displaced, resulting in a change in resistance. By coupling two such contacts together, logical 0 can be transformed into logical 1 and vice versa. The operational speed of such a NOT-gate circuit depends on the width of the wire, ranging from about 4.5 MHz for 250 nm to 7.5 MHz for 50 nm. The operational speed and the all-metallic design of the circuit make it a promising candidate for a future complementary metal–oxide–semiconductor compatible device.

5. Future developments

The future of DW MRAM looks likely to be dominated by various commercially developed systems using PMA nanowires and current-induced switching. Although NEC has made the first announcement in this area, this will be followed by several other companies over the next 2 years. The intrinsically high magnetic anisotropy of PMA materials makes miniaturization relatively straightforward, since altering the lateral dimension of the nanowires should not affect their overall magnetic character significantly. The near future is likely also to see improvements in the capacity of DW MRAM chips and their integration as ‘system-on-chip’ elements with processors, particularly in mobile devices to make use of their low power consumption.

Technologies that use mobile DWs in nanowires with in-plane magnetic anisotropy need to overcome the serious thermal effects that lead to stochastic depinning, which is a problem for both reliable switching and long-term data stability. There is also the need for a reliable and sensitive read-out mechanism. AMR works well in the research laboratory but offers insufficient MR for a high-speed device. Alternative approaches may be to integrate the soft nanowire into a GMR or TMR device, as has been achieved with PMA nanowires. Miniaturization of soft magnetic nanowire systems will have to consider geometric effects on DW structure and properties, but there is still much to be studied at wire widths less than 50 nm. Recent studies of DWs in closely spaced nanowires [59–61] suggest that the separation of nanowires in dense memories should not be lower than the wire width. Where this is the case, there is the risk that the magnetic charge-carrying head-to-head walls will interact either attractively or repulsively and disrupt the expected operation of a device. The three-dimensional architectures proposed by Parkin [2] and Cowburn [4] offer another approach to increased storage density. This is now being pursued in research laboratories and would be of great interest commercially were the ultra-high densities promised by this route to be realized.

However, the future may lead to fresh approaches to the control and detection of DWs. For example, we have recently proposed the artificial multiferroic structure of a soft magnetostrictive nanowire (e.g. Fe–Ga) on a piezoelectric layer (e.g. lead zirconate titanate) to control the position of DWs by electric fields (figure 4a) [62]. Potentials applied to patterned contacts cause local stress gradients in the piezoelectric layer that couple with the magnetostrictive nanowire. A DW in the magnetostrictive nanowire experiences an energy gradient...
in this region that can pin or move the DW (figure 4b). The pinning is thermally stable and could be used to prevent a DW from propagating against an applied field or current. The switchable nature of the potentials means that stochastic depinning would be avoided by removing the pinning potential completely. However, the ability to propagate a DW in a nanowire removes the need for applied magnetic fields or electric currents altogether. The system is further simplified by the possibility of a simple DW detection mechanism, by which the presence of a DW causes a local stress in the nanowire, which couples

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with the piezoelectric layer and creates a potential between contacts. Switching configurations can be arranged to allow for either bistable MRAM operation or a continuous, bi-directional shift register, although control over individual DWs would always be possible. Although we have made no effort to optimize this system yet, our initial calculations show switching times of the order of 6 ns and switching energies less than 100 keV (10 fJ), which is dominated by the work done in straining the piezoelectric layer. This architecture would appear to be robust to unforeseen changes in DW structure, with the stress-induced pinning and motion being largely unaffected by DW chirality or structure. Although an experimental demonstration is very much required for this technology to be developed further, control over DW position has already been observed in a thin-film system using a similar layer structure [63].

The future is likely to see more complex ‘hybrid’ devices in which the motion of a DW is only a part of the overall system operation. These could include DW-assisted recording devices that use either the stray field or the magnetization structure of a DW to initiate highly efficient, current-assisted magnetization reversal. Although not in nanowires, DWs could be introduced into what have previously been single-domain MRAM elements in order to reduce the switching power requirements, and will perhaps lead to multiple electrical contacts for each memory cell [64]. There are other exciting developments in ferromagnetic semiconductor elements, with control of DW behaviour being demonstrated using magnetic fields and spin-polarized currents [65].

Although we have discussed nanowire-based spintronic information technology developments, it is germane to mention that nanowires have other potential uses. Magnetic field sensors [66] are in the later stages of development for automotive applications. The magnetic field from the head-to-head DWs found in soft magnetic nanowires is being developed to control secondary systems such as nerve cells [67] and paramagnetic beads [68,69] in biology, and laser-cooled (less than 100 μK) paramagnetic atoms in atomic physics. This could lead to novel developments in tissue engineering, proteomics and quantum computation.

6. Conclusion

In this paper, we have tried to highlight some of the open questions in the study of field- and current-driven DW magneto-logic and memory.

There have been major developments in our understanding and ability to control DWs in magnetic nanowires over the past decade. Magnetic field- and spin-polarized current-driven DW motions have been demonstrated and a large amount of detail is now understood about the physical processes taking place. Commercial DW MRAM has been released and there is every prospect of improved devices becoming available over the next few years. DW shift register and logic-based systems in isolation or as hybrid magneto-spintronics devices should start to have commercial impact in the near future, but there are still important scientific issues to work through. New directions may be provided in data storage by the development of efficient (artificial) multiferroic systems and of three-dimensional recording methodologies, and beyond this to use DWs in magnetic nanowires to control secondary systems, for example, in biology or atomic physics.

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Field- and current-induced DW motions in nanowires and their developments are more recent than those in magnetic multi-layers and single-domain MRAMs, so the final form of applications is still more uncertain. However, the experiments are becoming rapidly more sophisticated and more meaningful results are appearing. New theories of spin-transfer torques are being developed but it is likely that experimental progress will challenge these theories and more work will be required.

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