Magnetic properties of materials

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Part 3. Measurements and applications

We've looked at a wide variety of magnetic phenomena, and will now examine the methods for measuring the magnetic properties of materials, and how they can be exploited in technological applications.

3.1 Measuring magnetisation by force

If the potential energy of a magnetic moment in a magnetic field is $U = -m \cdot B$, then the force, which is the derivative of energy with respect to distance is:

(3.1)

In other words, a moment in a field *gradient* feels a force. If we treat a specimen as a *point sample* in a magnetic field gradient, its overall moment is the magnetisation M times the volume V, and M can be expressed in terms of the susceptibility and applied field.

(3.2)

So, if we place the sample in a region of constant $\frac{dB}{dz}$ and non-zero overall B, it will experience a force. If this gradient is in the vertical direction, this will serve to change the weight of the sample (note — with large enough field gradients this has been shown to levitate objects with negative χ, such as water-based objects like frogs!).

By measuring the apparent weight of the sample with the field gradient on, and off, we can measure the force on the sample resulting from its net magnetisation, and thus the susceptibility. This technique is known as the *Faraday method*, and works for small samples.

An alternative is to use a rod of material (or fill a liquid/powder into a rod-shaped container), and suspend it vertically so that one end is between the pole-pieces of a magnet. Taking some element δz of the rod, the force on the element is:

$$\delta F_z = \frac{\chi A \delta z B}{\mu_0} \frac{dB}{dz} \tag{3.3}$$

This can be rearranged to give:

$$dF_z = \frac{\chi A}{2\mu_0} \frac{d(B^2)}{dz} dz \tag{3.4}$$

Integrating along the length of rod we have:

(3.5)

Where B_1 and B_2 are the magnetic field values at each end of the rod. If one end is far from field centre ($B_1 \gg B_2$), this is approximated to

$$F_z = \frac{\chi A}{2\mu_0} B_1^2 \tag{3.6}$$

This force can be measured through the change in weight of the sample, as above. This rod technique is known as the *Gouy method*.

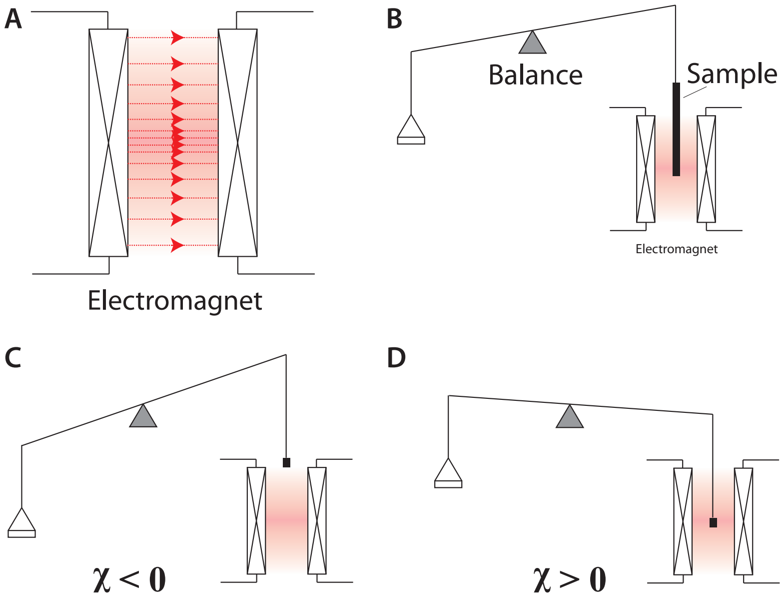

Figure 3.1: A) An electromagnet produces a horizontal magnetic field, which gets weaker with distance from the centre, providing a vertical field gradient. B) A long rod of sample can be placed within the field gradient, following the Gouy method, or (C,D) a small piece of sample, following the Faraday method. C) A negative susceptibility gives a repulsive force away from increasing field, pushing the sample up while D) a positive susceptibility gives an attractive force, drawing the sample towards the field maximum (centre).

3.2 Measuring magnetisation by induction

It is also possible to use the relationship between magnetisation and induction: $I = \Phi/L$. The current I induced in a circuit is proportional to the inductance of the circuit L and the flux Φ through it. If we vibrate a magnetised sample placed between two coils, this leads to an oscillating magnetic field at the point of the coil, which in turn induces an alternating current. The sample can be magnetised by placing the whole assembly within the pole-pieces of an electromagnet. This technique is known as *vibrating sample magnetometry.*

3.3 SQUID magnetometers

The most sensitive way to measure small magnetic fields employs a SQUID, or Superconducting Quantum Interference Device. This is based on flux quantisation within a superconducting loop, which we discussed in the previous course. The phase difference of two current paths around a loop is based on the flux through the loop:

$$\Delta\phi = \frac{q\Phi}{\hbar} \tag{3.7}$$

In order to avoid scattering of these two paths, this phase difference must be a multiple of 2π, thus limiting the flux allowed within the superconducting loop to multiples of Φ_0:

$$\Phi = \frac{nh}{q} = \frac{nh}{2e} = n\Phi_0 = 2 \times 10^{-15} \text{ Weber} \tag{3.8}$$

Let's say a magnetic field B is applied such that given the area of the loop A, the flux contained should be $\Phi = BA$. For a general B, this would not be a multiple of Φ_0, but rather we could write it as $n\Phi_0 + \delta\Phi$. Therefore, a screening current I_s is induced in the superconductor to cancel out this additional $\delta\Phi$ component of flux, keeping the flux in the loop strictly to $n\Phi_0$.

If we pass a current I through the loop, this would split equally between the two arms in the absence of a field, as shown in Figure 3.2. When a magnetic field is applied, the screening current I_s adds/subtracts to the two arms, such that the current in one arm is enhanced, and in the other, decreased. If $\delta\Phi$ is sufficiently large such that the enhanced current exceeds the critical current, the material will go normal and a voltage can be measured across the device. Once $\delta\Phi$ exceeds $\Phi_0/2$, the screening current is reversed as it now becomes more favourable to generate an additional flux to bring the flux enclosed to $(n+1)\Phi_0$. As the applied field increases further, the screening current now falls back towards zero, as would any measured voltage caused by driving the material into the normal state. Thus, oscillations

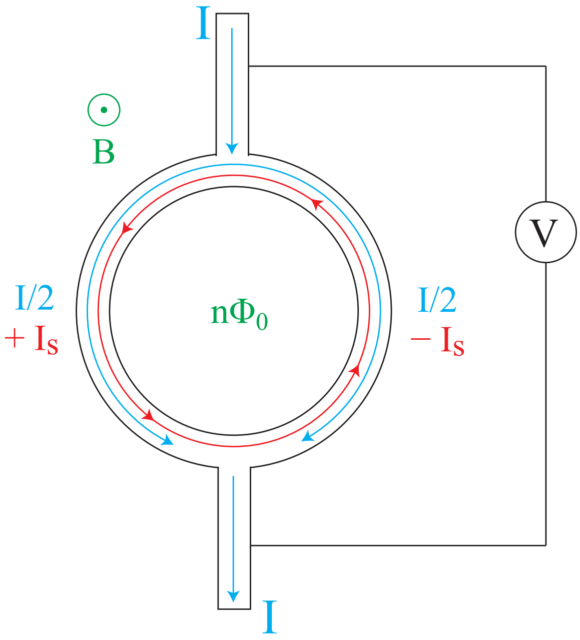

Figure 3.2: A SQUID, or Superconducting Quantum Interference Device.

in the measured voltage are seen for each multiple of Φ_0. It is worth pointing out that the flux quantum Φ_0 is tiny! — performing this measurement with a loop of 1 mm radius would yield voltage oscillations for every nanotesla or so (10^{-9} T) of applied B field. Consider also that it is possible to measure voltage on a much finer scale than one complete oscillation: typical measurements give a sensitivity of 1:10^4 of an oscillation, or 10^{-13} T = 100 femtotesla (fT). Further techniques (such as employing multiple turns of a SQUID coil) can take this to the 1 fT limit. For comparison, the magnetic field generated by the heart is 50,000 fT, while that of the brain is on the order of fT.

3.4 Imaging magnetic domains

There are wide variety of techniques for imaging the magnetic domains which form within a material, a few of these are summarised in Table 3.1:

a. Lorentz Transmission Electron Microscopy (L-TEM)

b. Scanning electron microscopy with polarisation analysis (SEMPA)

c. Magneto-optic Kerr Effect (MOKE) / Magneto-optic Faraday Effect

d. Magnetic Force Microscopy (MFM)

Method	**Probe**	**Interaction**	**Resolution**	**Adv.**	**Disadv.**
L-TEM	Electrons	Lorentz Force	$\leq$10 nm	Resolution Quantitative	Sample prep. Cost
SEMPA	Electrons	Polarised electrons emitted	$\leq$ 20 nm	Resolution Quantitative	Surface only
MOKE	Photons	Polarised light Kerr/Faraday Effect	Optical (sub-μm)	External applied field	Semi-quantitative
MFM	Mechanical tip	Force from magnetic stray fields	$\leq$ 20 nm	Resolution Sample prep.	Probe-sample interaction

Table 3.1: Summary of methods for imaging magnetic domains

3.4.1 Lorentz TEM

The electrons passing through a magnetic field experience a Lorentz force perpendicular to their velocity and to the magnetisation:

(3.9)

For a thin sample with in-plane magnetisation, as shown in Figure 3.3, the deflection of the electron beam as a result of the Lorentz force varies depending on the magnetisation of the domain. If we over- or under- focus the image, we see the increase or decrease of electron flux at the domain walls (the *Fresnel image*). Alternatively, we can focus the image correctly, but use an aperture to cut out the contribution of one type of domain to the image, so that that region appears black — the *Foucault* image).

3.4.2 Scanning electron microscopy with polarisation analysis

A scanning electron microscope (SEM) works by scanning a surface with a high-energy beam of electrons producing a variety of effects: back-scattered and transmitted electrons, X-rays, light, current etc.. In this technique we focus on the secondary electrons ejected from the surface atoms by the incident electron beam. In magnetic materials, these secondary electrons are spin-polarised (i.e. have their spin aligned with the magnetisation of the domain). By detecting the spin polarisation of the secondary electrons, an image of the magnetic domain structure can be obtained.

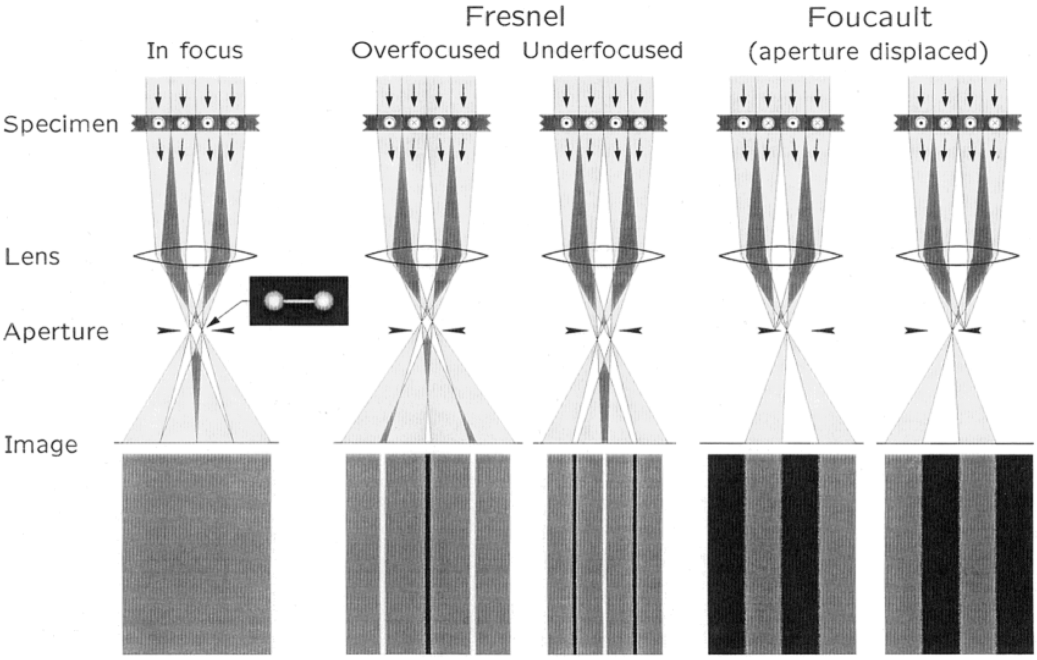

Figure 3.3: Lorentz TEM for imaging magnetic domains [image from X. Portier and A.K. Petford-Long, J. Phys. D: Appl. Phys. 32 (1999) R89–R108]

3.4.3 Magneto-optic Kerr/Faraday effect

Michael Faraday discovered in 1845 that when polarised light passes through a magnetised material, the polarisation rotates by some angle given by the magnetic field in the material B and the distance travelled through the material. Thus, by measuring the transmission of light with the use of appropriately aligned polarisers, contrast from the different magnetic domains is visible. This is known as the magneto-optic *Faraday effect.*

Often it is more convenient to use reflection of light from a material, rather than transmission. The same rotation of the polarisation light is observed, through a related phenomenon known as the magneto-optic *Kerr effect.*

This effect is used to read magneto-optic discs (such as audio Mini-Discs which were popular in the 1990s). For writing, the laser heats region it wishes to write to beyond the Curie-Weiss temperature and an electromagnet re-magnetises the domain.

3.4.4 Magnetic force microscopy

The techniques of scanning probe microscopy allow the surface of materials to be imaged with great precision. By applying a ferrmomagnetic coating to an atomic force microscope (AFM) tip, or using a ferromagnetic tip, it is possible to scan over a surface and measure the attractive and repulsive forces arising from the interaction with magnetised regions of the material. A limitation of the technique is that it is somewhat invasive: the presence of the scanning magnetised tip can affect the sample magnetisation.

3.5 Applications of magnetic materials

As we have discussed above, magnetic materials can be classified in terms of the difficulty in reversing their magnetisation, i.e. as magnetically *hard* or *soft* materials, each with their own important practical applications. Another very important application of magnetic materials is in information storage which requires some of the characteristics of both hard and soft materials. Each of these is characterised by different shapes of hysteresis loop, shown in Figure 3.4.

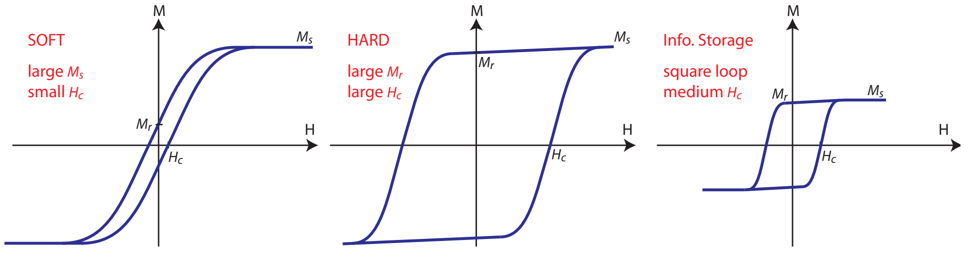

Figure 3.4: Typical hysteresis loops for standard soft magnetic materials, hard magnetic materials, and materials for information storage.

3.5.1 Soft magnetic materials

Soft magnetic materials have applications in electromagnet cores and transformer cores, where the aim is to enhance the magnetic field from a current-carrying core. The current will change (at some frequency for transformers), so we need a material whose magnetisation can be readily changed. The magnetic field enhancement provided by the core is maximised by a large saturation magnetisation M_s, but as the energy dissipated in one switching cycle is proportional to the area of the hysteresis loop, a small coercivity H_c is desirable, leading to a narrow hysteresis loop. A large susceptibility χ, or in other words permeability ($\mu_r = 1 + \chi$) ensures the hysteresis curve is steep.

In transformer cores in particular, it is important to avoid eddy currents being induced in the magnetic material (a result of Lenz's law), as these will also dissipate energy. Eddy currents can be minimised by using a magnetic material with a high electrical resistivity.

In short, for DC applications, a large M_s is the most important materials property, while for high-frequency applications, a small H_c and large μ_r are most important to avoid energy loss. For intermediate frequency applications, a compromise is reached.

Electromagnets (DC)

The classic material for an electromagnet core is soft (pure) iron. It is the element with the highest saturation magnetisation $M_s = 1.7 \times 10^6$ Am^{-1} (expressing this as a magnetic field $B_s = \mu_0 M_s = 2.1$ T). It is difficult to purify completely, leading to a coercivity between 4–80 Am^{-1} (or $B_c = \mu_0 H_c \sim 25\ \mu$T), limiting the use of pure iron in higher frequency applications.

Iron can be alloyed with cobalt yielding the largest M_s in the [35% Co, 65% Fe] composition ($M_s = 2.0 \times 10^6$ Am^{-1}, $B_s = 2.5$ T). Such alloys suffer from being brittle. This can be overcome by adding small quantities of vanadium, but this requires greater cobalt content [49% Fe, 49% Co, 2% V], giving $M_s = 1.9 \times 10^6$ Am^{-1}, $B_s = 2.4$ T.

Transformers (AC)

The most important material in transformer cores (especially at 50/60 Hz mains frequencies) is iron with a few percent silicon content. The silicon serves a number of important purposes: i) it reduces the magnetic anisotropy and the magnetostriction which minimises H_c, ii) while at the same time it increases the electrical resistivity thus suppressing eddy currents. Other properties such as the saturation magnetisation and the Curie-Weiss temperature θ_W are adversely affected, but not too severely. The major limitation with increasing silicon content is the reduction in ductility of the material.

For higher frequency applications, e.g. in audio applications, materials based on nickel-iron alloys (*permalloys*) are most common, with trade names such as *Mumetal*. These allows have high permeabilities ($\mu_r =$ several 10^5) and low coercivities ($H_c = 0.2$ Am^{-1}, $B_c = 0.25\ \mu$T).

Magnetic shields

To make a magnetic shield we require materials with as large a permeability as possible to trap the magnetic field lines within the material, as shown in Figure 3.5. Amorphous materials must have no magnetic anisotropy, and are used in achieving the maximum permeabilities. An example is MetGlas (trade name), a cobalt-based alloy (also containing Ni, Fe, Si and B) with the record DC permeability 10^6, making it ideal for magnetic shielding.

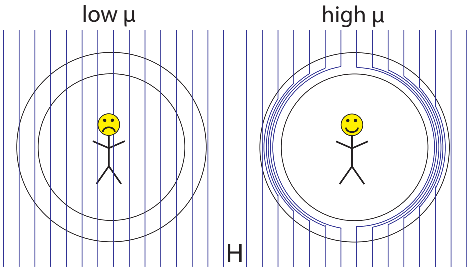

Figure 3.5: Materials for magnetic shields require high relative permeabilities.

3.5.2 Hard magnetic materials

Hard magnetic materials, i.e. permanent magnets, must have a large remnant magnetisation M_r (or remnant field $B_r = \mu_0 M_r$). In order to avoid losing this magnetisation, the coercivity H_c should also be large, such that in contrast to the soft magnetic materials, there is a large energy cost in traversing the hysteresis loop: $(BH)_{\text{max}}$.

Carbon steels were popular for permanent magnets in the late nineteenth century with remnant fields about 1 T. Newer alloys such as Alnico (aluminium, nickel, cobalt, plus iron), and rare-earth alloys (e.g. neodymium-based) have more or less the same remnant field, but offer major increases in the coercivity: $H_c = 4$ kAm^{-1} ($B_c = 5$ mT) for carbon-steel, 100 kAm^{-1} ($B_c = 120$ mT) for the best Alnico material, and 900 kAm^{-1} ($B_c = 1.13$ T) for $Nd_2Fe_{14}B$.

The Stoner-Wohlfahrt theory for how single-grain domains rotate as the applied magnetic field varies provided guidance in designing polycrystalline magnetic materials such as ferrite powders: $(MO)(Fe_2O_3)_6$, where $M =$ Ba, Sr, Pb, or a mixture. These powders are first magnetically aligned, then cast into resins or even plastics.

Important applications for permanent magnets include:

- Compass needles [Steel or Alnico]

- Magnetic catches on doors [Alnico] or fridges, toys [ferrites]
- Magnetic chucks [Alnico or ferrites]
- Frictionless bearings, such as in turbo-molecular pumps [Alnico or ferrites]
- Loudspeakers [Ferrites]
- Motors, generators [Rare-earth alloys increasingly used for size/weight reduction]

3.5.3 Magnetic materials for information storage

Permanent magnets can possess two orientations of magnetisation (M_r or $-M_r$) in the absence of an applied field, and these two states can be used to represent digital information. Therefore, there is a class of magnetic material which has some of the properties of a hard magnet (box-shaped hysteresis loop), and some of soft magnet (small-medium switching energy).

Magnetic tapes

Magnetic tape, such as (was) found in cassettes etc., consists of anisotropic magnetic particles bonded to a non-magnetic tape, preferentially aligned to the direction of the tape (along which the magnetic field is applied when recording). A typical material is Ferric oxide γ-Fe_2O_3, with elongated particles a few hundred nanometres in length. The coercivity is about $H_c = 20\ \text{kAm}^{-1}$ ($B_c = 25$ mT), while the saturation magnetisation is $M_s = 400\ \text{kAm}^{-1}$ ($B_s = 0.5$ T).

Magnetic disks

A typical magnetic hard disk consists of several platters of non-magnetic material (e.g. glass) coated with a thin layer of magnetic material. They are spun a speeds up to 15,000 rpm, while the write head sits a matter of nanometers above the surface of the disk. Typical storage capacities are 100 GB to 2 TB and read rates are around 0.5 Gbit/s.

Since about 2006, the magnetic orientation of the domains in the highest-density disks is perpendicular to the thin film. This serves two major advantages: i) it increases the information density and ii) makes the write head more efficient allowing for higher coercivity materials to be used. Small single-domain grains only a few 10s of nm in size are used — originally many hundreds would be used to represent each bit of information, but latest technologies are moving towards the single-domain limit. CoCr-based alloys are very common as the main recording medium, but the actual disk structure is a complex, multi-layered device.

Disk read/write heads

Crucial elements of the magnetic disk are the head which reads/writes information. The write head is a small electromagnet consisting of a soft magnetic core (e.g. Ni-Fe alloy, due to the high frequencies involved) with a coil wrapped around. The direction of the current dictates the orientation of the magnetic field produced, and thus the bit being written (0 or 1).

The read head needs to offer a measure of the magnetic field arising from the magnetisation of the cell of domains used to represent one bit of information. The materials used are *magneto-resistive*, which means the electrical resistance of the head can be changed as a function of the local magnetic field. The bigger this effect the better, and the so-called *giant-magnetoresistance* or *GMR* effect has been revolutionary in making read heads sensitive enough to read a tiny magnetised domain on the disk. The actual device is a rich structure with a combination of magnetic alloys based on Co and NiFe, metal conductors combined with ceramic and polymer insulators.

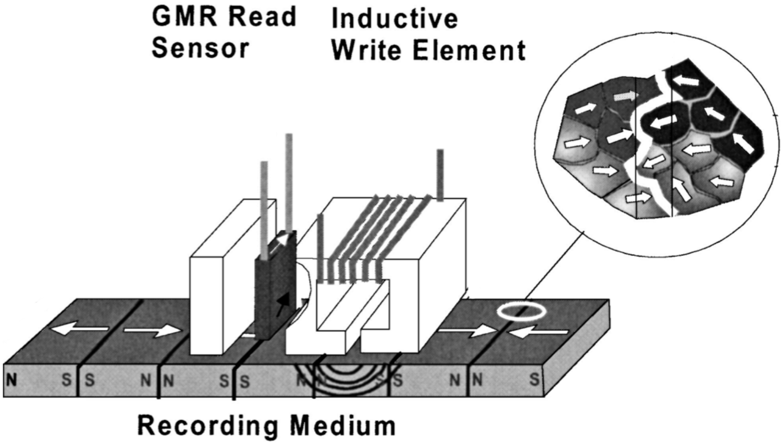

Figure 3.6: A read/write head for a magnetic disk with domains orientated parallel to the disk surface (pre-2005 design). [From D. Weller and M.F. Doerner, Annu. Rev. Mater. Sci. **30** 611 (2000)]

Racetrack memories

As a taste of what future magnetic disks might look like, we'll end by taking a look at the proposal for *Magnetic domain-wall racetrack memory* from IBM. The main goal is to overcome the limitation of conventional hard disks to two dimensions (although many platters are stacked on top of each other, the volume efficiency is very poor when you consider the active part of the disk is on the scale of 100 nm). Another goal is to remove the need for disks to rotate at high speeds in order to access data — in other words, why not move the magnetic domains themselves within the material rather than moving the whole disk?

The key idea is that a current composed of spin-polarised electrons can move a domain wall boundary by transferring their spin orientation to the underlying magnetic moments of the atoms in the material. When a current is passed through a region of magnetised material, the spin of the electrons becomes aligned with the magnetisation of the domain. When these electrons reach a domain wall, they transfer their angular moment to the wall, applying a torque to the moments in the wall which can move it forward. By reversing the current, the wall can be moved back. The information is therefore stored in a pattern of domains along a magnetic nanowire, through which current can be passed in either direction. The read/write is then fixed at some point near the middle of the nanowire.

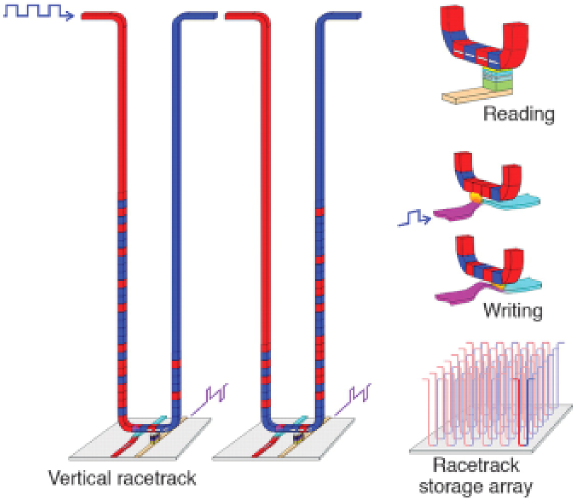

Figure 3.7: A magnetic racetrack memory is a magnetic nanowire, with data encoded as a pattern of magnetic domains along a portion of the wire. The pattern of domains can be moved by applying an electrical current. [From S.S.P. Parkin *et al.*, Science **320** 190 (2008)]