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Ultrafast nanomagnets: seeing data storage in a new light

By R. J. Hicken

School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK

Magnetic materials provide the most important form of erasable data storage for information technology today. The demand for increased storage capacity has caused bit sizes and features of the read–write transducers to be reduced to the nanoscale. However, increased storage capacity is only useful if there is a commensurate reduction in the time taken to read and write the data. In this article, the basic principles that determine the behaviour of nanomagnetic materials are introduced and their use in data-storage systems is described. Particular attention is paid to processes that limit the speed of operation of the data-storage system. It is shown that optical pump-probe experiments may be used to characterize dynamic magnetic processes with femtosecond temporal resolution. The macroscopic magnetization of a ferromagnet can be made to precess in response to an optically triggered magnetic field pulse, leading to reduced switching times. Alternatively, an ultrashort laser pulse may be used to manipulate the magnitude of the magnetization on femtosecond time-scales, leading to an ultrafast demagnetization in certain ferromagnets, and providing new insight into magnetotransport phenomena. Finally, the outlook for increased record and replay rates is assessed and the prospect of further use of optical techniques within magnetic data-storage technology is discussed.

Keywords: magnetism; data storage; ultrafast; nanomagnetism; optics

1. Introduction

The field of nanotechnology has caused excitement within many of the traditional scientific disciplines. By manipulating structure on atomic and nanometre length-scales new properties may emerge. Nanoscale building blocks may then be used to construct larger structures that perform multiple functions with increased speed. The latest generation of magnetic materials provides an example of this process of development. Nanostructuring has allowed researchers to enhance the properties of bulk materials, providing stronger magnets that remain magnetized for longer, and discover new phenomena, such as 'giant magnetoresistance' (GMR), which has led to a new generation of improved magnetic field sensors. Today magnetic materials are used in a multitude of devices from electric motors and actuators to the devices that store data in our computers. Indeed, let us consider the hard disk drive in a

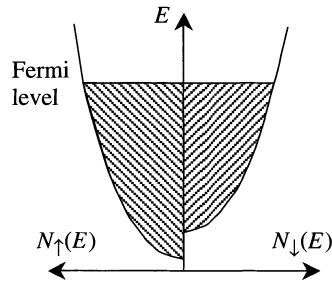*Phil. Trans. R. Soc. Lond.* A (2003) **361**, 2827–2841

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Figure 1. The number of spin-up $N_\uparrow(E)$ and spin-down $N_\downarrow(E)$ electrons in
an idealized ferromagnetic metal in schematic form.

desktop or laptop computer. The storage capacity doubles approximately every year. This has been possible because the size of the region used to store each '1' or '0' of binary data has continued to decrease deep into the nanoscale regime. Since we expect the stored information to be almost instantly available, reduced bit sizes have been accompanied by reduced record and replay times.

In this paper the speed limits that constrain the development of magnetics-based technology will be considered. We will consider why familiar materials such as iron are magnetic, and how manipulation of atomic and nanoscale structure may alter their magnetic properties. Some common formats used in magnetic data storage will be examined and their speed of operation discussed. It will become apparent that many important processes have characteristic time-scales shorter than 1 ns and so call for specialized measurement techniques. In particular it will be shown that ultrashort optical pulses can be used to probe and perhaps manipulate the magnetic state. We will see that magnets may be made to reorient or have their magnetism temporarily suppressed. Finally, we will explore how these processes might be exploited in future technologies and used to extend our existing understanding of magnetic materials.

2. What makes a magnet?

Before attempting to understand the properties of nanomagnetic materials, we must first understand the origin of magnetism in familiar materials such as iron. Our first experience of magnetism is gained from permanent bar magnets and loops of wire that carry a current. It is tempting to believe that the magnetism has a common source. We know that the atoms of a magnetic material contain shells of orbiting electrons, each of which can be considered as a tiny current loop. Each electron has orbital angular momentum and an associated magnetic moment. We might obtain a macroscopic magnetic moment if the electrons could be persuaded to orbit in the same sense. However this is not the dominant source of magnetism in iron. Electrons are identical particles that satisfy the Pauli exclusion principle. They fill the available energy states within metallic iron, so that those in the highest energy states, near the Fermi level, have a large kinetic energy. This corresponds to a velocity of *ca.* 1% of the speed of light, and suggests that relativistic effects must be considered.

The quantum mechanics of relativistic electrons is described by the Dirac equation, from which it is found that electrons have an additional degree of freedom known as 'spin'. Spin is a form of angular momentum, which is sometimes visualized as the electron rotating about an axis through its centre. Each electron has a
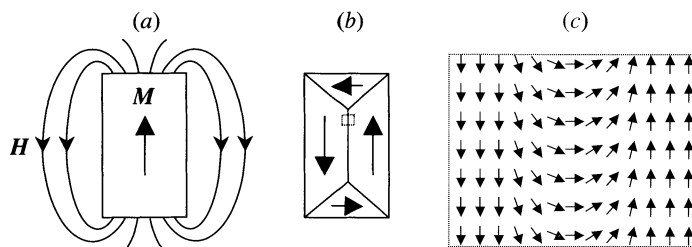
Figure 2. (*a*) The stray field **H** generated by the magnetization **M** of a uniformly magnetized thin film element. (*b*) A typical closure domain structure formed in the absence of an applied field. No external field is generated in this case. (*c*) A Néel-type domain wall separating two anti-parallel domains.

magnetic moment associated with its spin. In most metals the electron spins are randomly oriented and no macroscopic magnet moment is observed. For the Pauli exclusion principle to be satisfied, the many-body wave function of the electrons must change sign (be antisymmetric) when the coordinates of any pair of electrons are interchanged. The overall symmetry is the product of that of the spatial and spin parts of the wave function. In a ferromagnetic metal, due to the electrostatic 'exchange' interaction between electrons, an antisymmetric spatial wave function has the lowest energy. The spin wave function of the lowest energy state must therefore be symmetric, requiring the spins of different electrons to be aligned, and leading to the magnetization observed in Fe, Ni and Co, the ferromagnetic transition metals. The situation in a real metal is complicated by the fact that electrons fill a number of different energy bands. These may experience a different exchange interaction, and the number of available states $N(E)$ at a particular energy E may contain many fine features. However, we may consider an idealized case, shown in figure 1, where electrons occupy a single band. Spins may occupy either up or down states and the exchange interaction leads to an excess of up spins.

Many objects formed from magnetic metals exhibit no net magnetization unless they are subject to an external magnetic field. Let us consider a thin rectangular element of magnetic material. When fully magnetized the element generates a magnetic field, as shown in figure 2*a*, in which energy is stored. This energy depends upon the orientation of the magnetization and gives rise to 'shape anisotropy'. The energy is a minimum when the magnetization lies parallel to the long side of the element, and a maximum when the magnetization lies perpendicular to the plane of the element. However, a lower-energy state may be obtained by the formation of 'domains' that generate no external field. The transitions between domains are not abrupt because the exchange interaction favours parallel alignment of neighbouring spins. Instead a domain wall forms across which the spins rotate gradually. The width of the wall is limited by magnetocrystalline anisotropy. This means that it is energetically favourable to align the magnetization in certain directions relative to the crystallographic axes of the element. This anisotropy arises because the spin and orbital angular momentum of an individual electron interact. In this way the spin senses the anisotropy of the orbital angular momentum that occurs because the spatial wave function must have the symmetry of the crystal lattice. The structure of a wall in a real material can be complicated. However, if the element in figure 2 is made sufficiently thin, then the spins in the domain wall rotate within the plane

of the element to form a Néel wall. When a magnetic field is applied to the element in figure 2b the domain walls move so that the domain in which the magnetization is parallel to the applied field grows until the element is magnetized as in figure 2a.

3. How are nanomagnets different?

Let us define a nanomagnet as an object with at least one nanoscale dimension. Continuous films of nanometre thickness may be fabricated by vapour deposition. Electron-beam lithography and focused-ion-beam etching can then be used to define nanoparticles or nanowires of a chosen size and shape. These techniques are rather slow and unsuitable for fabricating the large quantities of material needed for data storage. However, through careful control of the vapour deposition process alloys may be fabricated that self-segregate into a monolayer of weakly interacting nanoparticles. This is the method used to fabricate the coatings on magnetic hard disk drives. Much effort is made to control the distribution of grain sizes and the strength of intergranular interactions, and new methods such as chemical and biological self-assembly have recently attracted interest as a new means by which to achieve this aim.

Nanomagnets may behave very differently to their bulk counterparts. This may be because new crystallographic structures can be stabilized in a nanomagnet, or because the atoms at its surfaces and edges represent a larger fraction of the total volume. These atoms have fewer nearest neighbours and experience electric and magnetic fields of different symmetry to those within the interior of the crystal. They may possess a different magnetic moment and magnetocrystalline anisotropy that significantly modifies the overall behaviour of the nanoparticle. Finally, as the size of the particle becomes comparable with the domain-wall width, it is no longer possible to accommodate a domain structure. The response of the magnetization to an external field is then qualitatively different. The magnetization remains nearly uniform and rotates towards an applied field as its strength is increased.

Completely new properties may be obtained when composition is modulated at the nanoscale. The spin-split band structure of a ferromagnetic metal, shown schematically in figure 1, underlies a class of GMR effects. Electrons close to the Fermi level are responsible for electrical conduction. The resistance increases with the rate of electronic scattering and hence with the number of vacant states available. Assuming that the electron spin is unaffected when the electron is scattered, electrons with spin parallel (spin up) or anti-parallel (spin down) to the majority spin direction will experience different resistance due to the different density of states at the Fermi level. When an ultrathin layer of non-magnetic metal is used to separate two ferromagnetic metals, forming a 'spin-valve' structure, electrons passing through the structure experience a resistance that depends upon the local orientation of the magnetization. Conduction can be thought to occur through two parallel spin channels and the total resistance depends upon whether the layer magnetizations are parallel or anti-parallel, as shown in figure 3. Changes in resistance of tens of per cent may be observed when a magnetic field causes the relative alignment of the magnetizations to change. However, the size of the GMR effect depends upon the spin-dependent scattering time and also the longer spin relaxation time. These quantities are poorly known and difficult to measure.
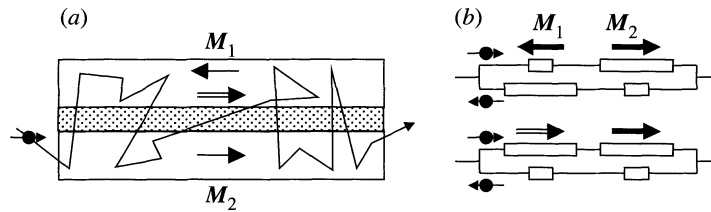
Figure 3. (a) The trajectory of an electron within a spin-valve device. (b) The effective resistances seen by the two spin types for parallel and anti-parallel alignment of the magnetization of the two layers. The parallel arrangement has lower resistance.
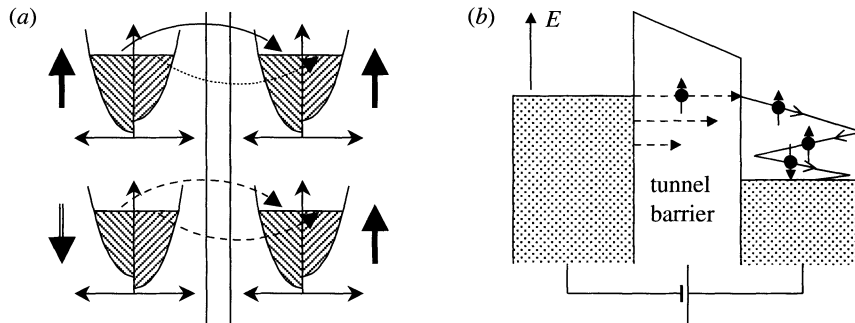

Figure 4. (a) Schematic of the tunnel process for parallel and anti-parallel alignment of the magnetizations of the magnetic layers. Since the spin is unchanged during tunnelling, the process indicated by the solid arrow has greatest probability and so resistance is smallest for the parallel case where the magnetizations are parallel. (b) Injection and scattering of hot electrons within the second layer.

Let us now assume that the ferromagnetic layers are instead separated by an insulator. A potential-energy barrier prevents the flow of current between the layers. However, electrons may pass through a sufficiently thin barrier by quantum tunnelling. The probability of tunnelling is proportional to the number of electrons in the left-hand electrode and the number of vacant states in the right-hand electrode. Assuming that spin is unchanged during tunnelling, electrons of up and down spin tunnel in parallel. Changing the relative alignment of the layer magnetizations results in a 'tunnel magnetoresistance' (TMR), as shown in figure 4. The use of tunnel injection greatly extends the parameter space available to conduction electrons and may be of great utility in 'spintronic' devices. A larger bias voltage allows electrons to be injected into the right-hand electrode at energies far above the Fermi level. These 'hot' electrons are strongly scattered and lose their excess energy within tens of femtoseconds. The spin dependence of the energy relaxation and the time taken for the spin of the hot electron to relax are not well known.

4. Recording technology and speed bottlenecks

The use of nanomagnets in data-storage technology has been reviewed by Cowburn (2000) and Kirk (2000). In this section we focus on the factors that limit speed of operation. Let us return to the magnetic hard disk drive (Weller & Moser 1999). It consists of the storage medium and a recording head containing a miniature electromagnet and a spin-valve sensor, as shown in figure 5a. Fabrication of the recording
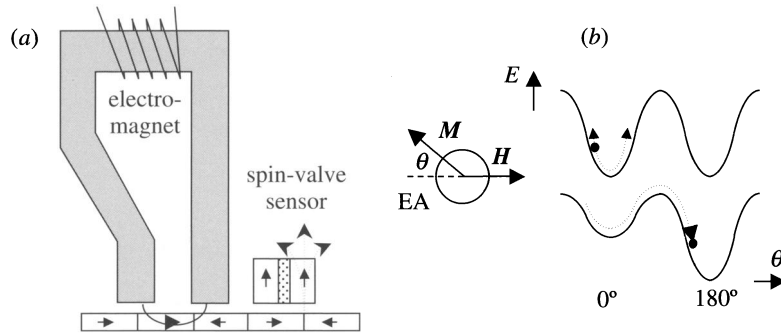
Figure 5. (*a*) Schematic of the essential components of a hard disk drive system. (*b*) A single grain from the storage medium. The dependence of the magnetic free energy upon the orientation of the magnetization both with (bottom) and without (top) an applied magnetic field is shown.

head requires multiple stages of thin-film deposition and photolithography. The pole pieces of the electromagnet generate the magnetic field that realigns the magnetization of the storage medium. The magnetization of the pole pieces switches by a domain-wall process. Since wall velocities are of the order of $100 \mathrm{~m~s}^{-1}$, tens of nanoseconds may be required for a wall to propagate across a pole piece that extends tens of micrometres from the surface of the storage medium. Data are read out from the storage medium by using the stray field from the bit transitions to reorient the magnetization in one of the layers of a spin-valve sensor. The sensor normally has a built-in biasing magnetic field so that the magnetization rotates in response to the stray field from the medium. The uniformity of this reorientation is highly important if the maximum GMR response is to be obtained.

Each 'bit' of stored data is less than 100 nm long and is comprised of a large number of grains, with diameters of the order of 10 nm, that behave as single-domain particles. These particles possess a strong uniaxial anisotropy, so that the magnetization occupies one of two stable states, parallel or anti-parallel to the easy axis (EA), as shown in figure 5*b*. The energy barrier between these two states must be sufficiently high that the magnetic moment remains in the desired state in spite of thermal energy fluctuations of the order of $k_{\mathrm{B}}T$, where k_{B} is Boltzmann's constant and T is the temperature. The average time taken for the magnetization to move between the two states is roughly equal to $\tau_0 \exp(\Delta E / k_{\mathrm{B}}T)$, where ΔE is the height of the energy barrier. Here τ_0 is the characteristic time with which the system oscillates about the minimum-energy position. Its value is proportional to the anisotropy and is typically tens of picoseconds. For data to be stable for 10 years, ΔE must be greater than *ca.* $40 k_{\mathrm{B}}T$. During the write process an applied field reduces the height of the barrier so that the system may cross to the other minimum with the assistance of the thermal fluctuations. The height of the barrier is proportional to both the anisotropy and the particle volume. Although τ values of just a few nanoseconds are commonly achieved, these values still greatly exceed τ_0. On shorter time-scales problems are encountered due to the distribution of grain sizes present, and because the nature of the oscillatory motion of the magnetization must be more carefully considered. As the grain size is reduced, the anisotropy must be made stronger if thermal stability is to be maintained. Larger anisotropy then requires larger fields to be applied during writing. Hard-disk technology now faces a major difficulty because the write field is limited by the finite magnetization of the pole piece material. Despite
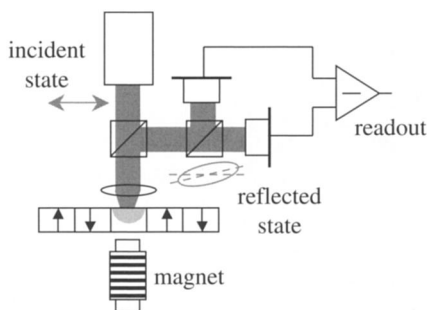
Figure 6. The essential components of a magneto-optical recording system are shown. The same laser is used to heat the surface of the storage layer during writing and then to read the written data.

extensive efforts, little progress has been made in developing materials with higher magnetization than the standard Fe–Co alloys.

Magneto-optical (MO) recording uses a different approach to read and write data (Tsunashima 2001), as shown in figure 6. Again data are stored on a disk that is moved beneath a stationary recording head. The disk coating consists of an amorphous rare earth–transition metal (RETM) alloy that has magnetization perpendicular to the plane. Bits are written by heating the coating with a focused laser beam in the presence of a reversed magnetic field. Heating causes the magnitude of the magnetization to be reduced and allows it to reverse more easily in the applied field. Data may be recorded by modulating either the laser beam or the magnetic field. The speed of writing is limited by the time taken to demagnetize the storage medium. This is achieved within a few nanoseconds using a low-power semiconductor laser. Further time may be required to modulate the applied magnetic field, as in a hard disk drive, and for motion of the domain wall that marks the edge of the bit. The latter effect is not yet a limiting factor for sub-micrometre bit sizes. Data are read out with the same laser by means of the magneto-optical Kerr effect (MOKE). Here the optical electric field transfers momentum to electrons in the surface of the metal film, which are then deflected due to the spin–orbit interaction before re-radiating light of modified polarization. If the incident light is plane polarized, the reflected light generally has a small ellipticity and has its principal plane of polarization rotated slightly relative to that of the incident beam. This Kerr rotation is proportional to the magnetization of the storage medium, and changes by *ca.* 1° as the orientation of the magnetization changes between in and out of the plane of the disk. Rotations of this magnitude are readily measured using an optical bridge arrangement, as shown in figure 6. The reflected beam is passed through a beam-splitting polarizer so that near-equal intensity falls on the two photodiode detectors. The difference of their outputs is then proportional to the Kerr rotation. The time of interaction of the light with the storage medium is extremely short, a few femtoseconds only, and so the speed of the readout process is limited by other factors such as the bandwidth of the detector electronics.

Much effort has recently been devoted to the development of magnetic random access memory (MRAM) chips. Spin-valves and magnetic tunnel junctions (MTJs) may possess the property of bistability, whereby parallel and anti-parallel alignment of the magnetizations give two stable states. Arrays of these devices may be used to store large quantities of binary data that remain present when the power to the
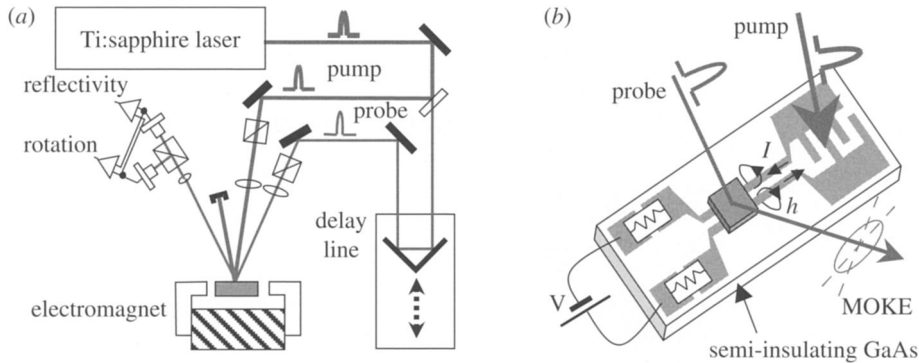
Figure 7. (*a*) The optical pump-probe apparatus in schematic format. (*b*) A device used to supply an optically triggered magnetic field pulse to the sample.

device is switched off. A matrix of address lines is used to read out the state of a selected element. These lines may also be used to propagate large current pulses that generate the magnetic field that switches the storage element between its stable states. Consequently, the speed of operation of MRAM is constrained by similar principles to those affecting the spin-valve sensor in a hard-disk system.

5. Observing ultrafast magnetization dynamics

The study of magnetic processes in microscopic samples on sub-nanosecond time-scales has required the development of new experimental techniques (Hicken *et al.* 2002). Optical 'pump-probe' techniques are strongly favoured because a focused laser beam can provide sub-micrometre spatial resolution, while the recent development of commercial ultrafast laser systems provides unrivalled temporal resolution. A pump-probe apparatus is shown in schematic form in figure 7*a*. A Ti:sapphire laser produces 100 fs pulses at a repetition rate of 82 MHz. Each pulse is split into an intense pump and a weaker probe part. The pump is used to stimulate the sample while the probe is delayed in time and used to determine the instantaneous state of the sample at a later time. A retro-reflector on a translation stage is used to delay the probe pulse with a time resolution of *ca.* 1 fs. By measuring the response of the system at a series of different time delays, the dynamic behaviour can be mapped out. The magnetic state of the sample is determined with an MOKE measurement using an optical bridge similar to that employed in an MO recording drive.

The pump pulse may be used to directly excite electrons within the surface of the sample. However, another way to excite a magnetic sample is to apply a magnetic field pulse generated by a device such as that shown in figure 7*b*. A transmission line is deposited upon a semi-insulating GaAs substrate and a bias voltage applied. When the pump pulse is directed onto a region of interlocking fingers at one end of the device, electrons are excited to the conduction band of the GaAs, causing it to conduct. A current pulse then propagates along the transmission line, generating a magnetic field that interacts with the sample (Freeman *et al.* 1991). The pulsed field has a rise time of tens of picoseconds, and a nanosecond decay time that is related to the time taken for carriers to recombine within the GaAs. Fields of tens of gauss may be generated when the width of the tracks is reduced to a few tens of micrometres.
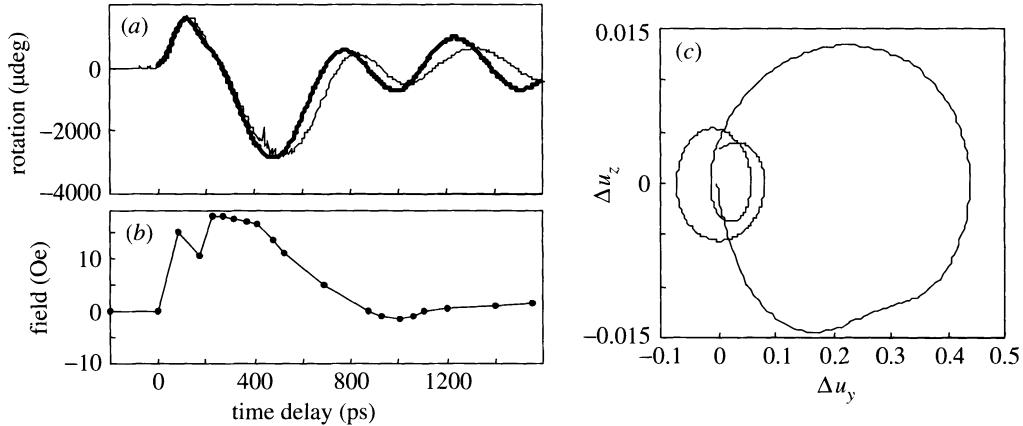
Figure 8. (a) The measured (fine) and calculated (bold) time-dependent Kerr rotation from a $Ni_{81}Fe_{19}$ dot of 30 µm diameter. (b) The form of the pulsed field. (c) The calculated trajectory of the normalized magnetization vector $u = M/M$.

6. Harnessing precession

From the previous discussion it was found that domain-wall motion in micrometre-scale elements and thermally activated switching of single-domain particles are essentially nanosecond processes. Let us now consider now what may happen when a magnetic moment is stimulated by a magnetic field pulse with sub-nanosecond rise time. The response of the magnetization vector M is described by the Landau–Lifshitz–Gilbert (LLG) equation,

$$\frac{\partial M}{\partial t} = -|\gamma| M \times H_{\mathrm{eff}} + \frac{\alpha}{M}\left(M \times \frac{\partial M}{\partial t}\right), \tag{6.1}$$

in which γ and α are the gyromagnetic ratio and Gilbert damping parameter. An effective field H_{eff} is used to describe the effect of the applied field and other contributions to the free energy of the system. When H_{eff} is independent of time, the first term in equation (6.1) causes the magnetization vector to sweep out a cone with axis parallel to H_{eff}. This is referred to as magnetization 'precession'. The second term damps the motion and causes the angle of the cone to decrease with time.

Figure 8 shows the result of a measurement (Wu *et al.* 2002) made upon a circular element of $Ni_{81}Fe_{19}$ with a diameter of 30 µm and a thickness of 50 nm. The element was placed upon a track of a transmission line, similar to that in figure 7, so that the pulsed field lay in the plane of the element, 140° from a static field of 54 Oe. A focused probe spot with a diameter of *ca.* 15 µm was placed at the centre of the element. The time variation of the pulsed field was determined by a magneto-optical sampling technique and is shown in figure 8b. The magnetization initially lies close to the static field but is then deflected by the pulsed field, as shown in figure 8c. The trajectory is very flat because the shape anisotropy of the element prevents the magnetization tipping very far out of the film plane. A maximum in-plane deflection of *ca.* 30° occurs after 350 ps, demonstrating that large-angle reorientation is possible on sub-nanosecond time-scales. However, the precession is lightly damped and continues for a number of nanoseconds afterwards.
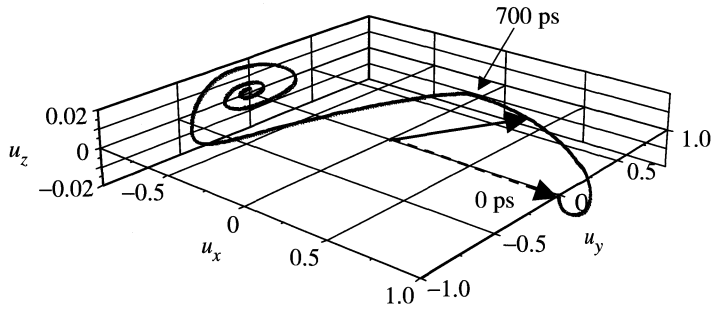
Figure 9. A simulation of magnetization reversal of the element in figure 7. There is no static field and the trajectory is plotted over a period of 4000 ps.
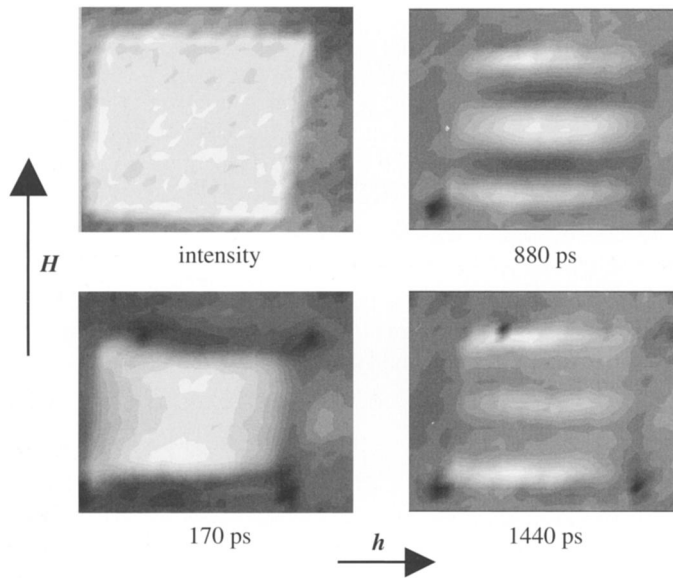

Figure 10. Images of the static reflectivity, and the out-of-plane component of magnetization, at different time delays for a 10 μm × 10 μm element.

A static field was applied in the experiment to reset the magnetization to its initial value before the arrival of the next pump pulse. However, the LLG equation can be used to predict the trajectory in the absence of a static field, as in figure 9. The magnetization, M, initially lies parallel to the in-plane uniaxial anisotropy axis. The anisotropy field is equal to 12 Oe (as in figure 8). When a pulsed field of 10 Oe is applied along the y-axis for 700 ps, the magnetization begins by moving out of the film plane. Due to the shape anisotropy of the thin film, a large out-of-plane contribution to H_{eff} develops that deflects M towards the y-axis. The angular deflection of M exceeds 90° after *ca.* 570 ps and then spirals down towards the anisotropy axis in the reverse direction. The first observations of full precessional switching were recently reported (Gerrits *et al.* 2002; Schumacher *et al.* 2003). The reversal time can be further reduced, by increasing the anisotropy field of the element and the magnitude of the pulsed field. So far we have assumed that the magnetization of the element rotates uniformly. By focusing the probe to a sub-micrometre spot we can check
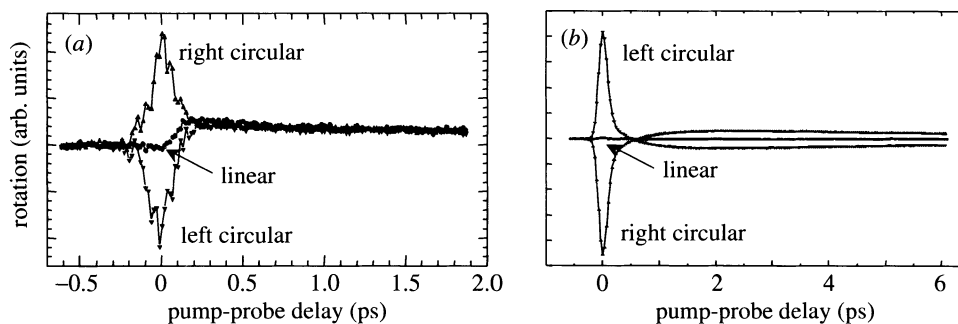
Figure 11. The transient Kerr rotation obtained from (*a*) a Ni thin film and (*b*) an intrinsic GaAs wafer. The curves are labelled according to the helicity of the pump pulse.

the validity of this assumption. The time delay between pump and probe is fixed and the sample moved under the stationary probe spot, using a computer-controlled piezoelectric stage, to acquire a dynamic image. Images of the out-of-plane component of the magnetization within a 10 μm × 10 μm element of $Ni_{81}Fe_{19}$, of 150 nm thickness, are shown in figure 10 (Hicken *et al.* 2003). The static field of 288 Oe and the pulsed field, with a peak value of 27 Oe, were applied in the plane of the element at right angles to one another. The magnetization quickly becomes non-uniform and the images suggest that standing waves are generated with wave vector parallel to the static field. These spin wave excitations exhibit a rich phenomenology that is only just beginning to be explored.

7. Optical modification of the spontaneous magnetization

While a pulsed field may modify the orientation of the local magnetization, it has negligible effect upon its magnitude. However, the writing in MO recording requires a reduction of the magnetization. The pulses from an ultrafast laser have modest energy, of the order of 10 nJ, yet very high peak intensity, of the order of 100 kW. When the laser pulse is incident upon a metallic surface, it transfers a large amount of energy to the conduction electrons in a very short time. These electrons become very hot while the lattice temperature is almost unchanged. The effect of pumping a nickel thin film with ultrashort pulses of different helicity is shown in figure 11*a*. The *change* in the Kerr rotation of the probe pulse is plotted, so that the step observed with a linearly polarized pump beam corresponds to a *reduction* of the magnetization of *ca.* 10%. The peak demagnetization signal is obtained after *ca.* 200 fs. Experiments with 20 fs laser pulses have shown that demagnetization may be achieved in less than 50 fs (Guidoni *et al.* 2002) in a $CoPt_3$ alloy, while theoretical investigations (Zhang & Hübner 1999) suggest an intrinsic time-scale as short as 10 fs.

When the pump beam is circularly polarized, a peak is observed at zero time delay with width limited by the laser pulse width. The circularly polarized light transfers angular momentum to the electrons in the metal, inducing a net orbital angular momentum and hence a magnetic moment. The electrons are scattered on time-scales of the order of 1 fs so that the orbital moment is soon destroyed. However, in some circumstances, spin–orbit coupling can cause the conduction electrons to obtain a net spin polarization that is much longer lived. This may be seen in the measurements made upon GaAs in figure 11*b* (Wilks *et al.* 2003), where a long tail
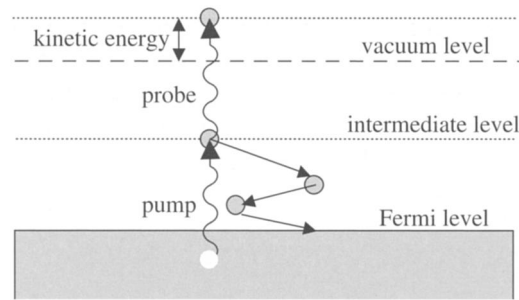
Figure 12. The principle of the TRTPPE technique is illustrated.

in the Kerr signal is observed. The decay of this tail allows the spin relaxation time of electrons in the conduction band to be deduced. Having created a non-equilibrium spin polarization it is then possible to manipulate its orientation through precession in an applied magnetic field, or, with the electric field from a second intense optical pulse, by means of the optical Stark effect (Gupta *et al.* 2001).

Optical experiments may potentially give access to a variety of other electronic relaxation times. The time-resolved two-photon photoemission (TRTPPE) technique is shown schematically in figure 12. The pump pulse is used to excite electrons to vacant states above the Fermi level, after which the excited electrons cascade back towards the Fermi level within a few hundred femtoseconds. The probe pulse may be used to promote some of the hot electrons to above the vacuum level before they relax. They are then emitted from the sample surface where an electric field is used to select electrons of a specific energy. Using a spin-sensitive electron detector the spin dependence of the energy relaxation process may be deduced. Measurements made on Co (Aeschlimann *et al.* 1997) have shown that at 1 eV above the Fermi level, minority spin electrons relax at about twice the rate of those with majority spin.

8. Future trends

The examples given in the previous two sections suggest that we are some way from the fundamental speed limits relevant to magnetic data-storage technology. Magnetic switching of the transducers in a hard disk drive can clearly be pushed into the picosecond regime if precessional motion is used instead of domain-wall motion. However, this may require some redesign of existing heads since precession is most easily stimulated when the pulsed field is applied perpendicular rather than anti-parallel to the magnetic moment that is to be switched. It is also important to curtail precession after switching has been achieved. Otherwise the moment might continue to rotate through a full 360° and so regain its initial orientation. Such control may be achieved by tailoring the pulse duration to the period of precession (Bauer *et al.* 2000; Crawford *et al.* 2000). Further increases in switching speeds require the frequency of precession to increase through the use of larger anisotropies and stronger pulsed fields.

There is certainly scope for further reduction of the time, τ, taken for thermally activated switching of storage media. Media with larger anisotropy are needed to maintain thermal stability at higher storage densities and so the value of τ_0, the

period of precession, will continue to decrease. Tighter control of grain-size distributions may also allow τ to be reduced to a smaller fraction of τ_0. Ultimately, the precessional character of the motion will have to be taken into account, with further implications for the design of recording transducers. Since generation of the necessary write fields may be difficult to achieve, serious consideration is being given to heating the storage medium during the write process in order to enhance thermal activation. A further possibility might be to dispense with the traditional writer structure altogether. The transmission-line structure used in pump-probe experiments has a bandwidth of tens of gigahertz, but so far the maximum field has been limited to *ca.* 1 kOe. The field is inversely proportional to the linear dimensions of the transmission line, and so much larger fields might be generated by a much smaller structure designed to switch a single nanoscale bit.

It is now clear that intense laser pulses can be used to change the spin polarization of certain materials on femtosecond time-scales. Laser technology continues to evolve rapidly and battery-powered femtosecond lasers have been demonstrated (Agate *et al.* 2002). We can even imagine ultrafast lasers being used in future recording systems. Studies of ultrafast demagnetization have already shown that erasure times in MO recording could be reduced to tens of femtoseconds. More serious constraints are introduced by the attendant electronics and the need to switch an applied magnetic field on comparable time-scales. Consequently, for speed of operation, an all-optical technology will always be favoured. If circularly polarized light could be used to reset the spin polarization of the demagnetized medium, then the entire write process might be completed within a single picosecond. There is also no reason why such a process should be confined to rotating-disk systems. Future architectures might involve steerable beam access, or the incorporation of magnetic materials into photonic chips where they could provide on-board memory function. Indeed, all-optical magnetic recording would be an important step towards the further integration of computer and telecommunications technology.

Ultrafast optical techniques will continue to be used to increase our understanding of the processes that underlie electronic device operation, and magneto-optical probes are of particular relevance to spintronics. While spin relaxation times have been determined in semiconductors, there is a pressing need to apply similar techniques to the metals from which existing GMR devices are constructed. It will also be necessary to determine the characteristic time-scales for spin-dependent momentum and energy relaxation, which may range from 1 to 100 fs. Optical techniques seem like the most viable candidate for such studies as laser pulse widths are reduced to the attosecond regime. The TRTPPE technique has provided an indication of what may be possible. The challenge now is to develop methods that allow the important relaxation processes to be investigated within more complicated structures as spin valves. Recent developments in laser technology promise to make this possible. Ultrafast lasers are now available that allow the photon wavelength to be tuned through the entire visible spectrum. By tuning to optical resonances in the electronic band structure of the constituent materials it may be possible to characterize spin-dependent processes within different regions of a heterogeneous nanoscale structure.

In conclusion, there is an urgent need to reduce read and write times within magnetic data-storage technology in line with increased storage densities. Existing systems operate on nanometre length-scales, where new phenomena such as single-domain switching and GMR have emerged, and on nanosecond time-scales. The

fundamental limits on speed of operation have been assessed and we have seen that optical measurement techniques allow dynamic magnetic processes to be investigated with femtosecond temporal resolution. While the speed of recording systems will undoubtedly increase, the nanosecond barrier represents a watershed beyond which the precessional nature of magnetization reversal must be taken into account. Ultimately, magneto-optical technology may offer the highest possible record and replay rates. Indeed, magnetic data storage is far from the limits of what may be achieved with this new light.

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AUTHOR PROFILE

R. J. Hicken

Robert Hicken was born in Nantwich, Cheshire, in 1965. He read Physics at Brasenose College, University of Oxford, graduating in 1986, and obtained his PhD in Physics from the Johns Hopkins University in 1991. Following a postdoctoral appointment at the University of Cambridge, he became a Lecturer at Exeter University in 1996 and was awarded an Engineering and Physical Sciences Research Council (EPSRC) fellowship in 1999. Current research interests include magnetism, photonics and data-storage technology.