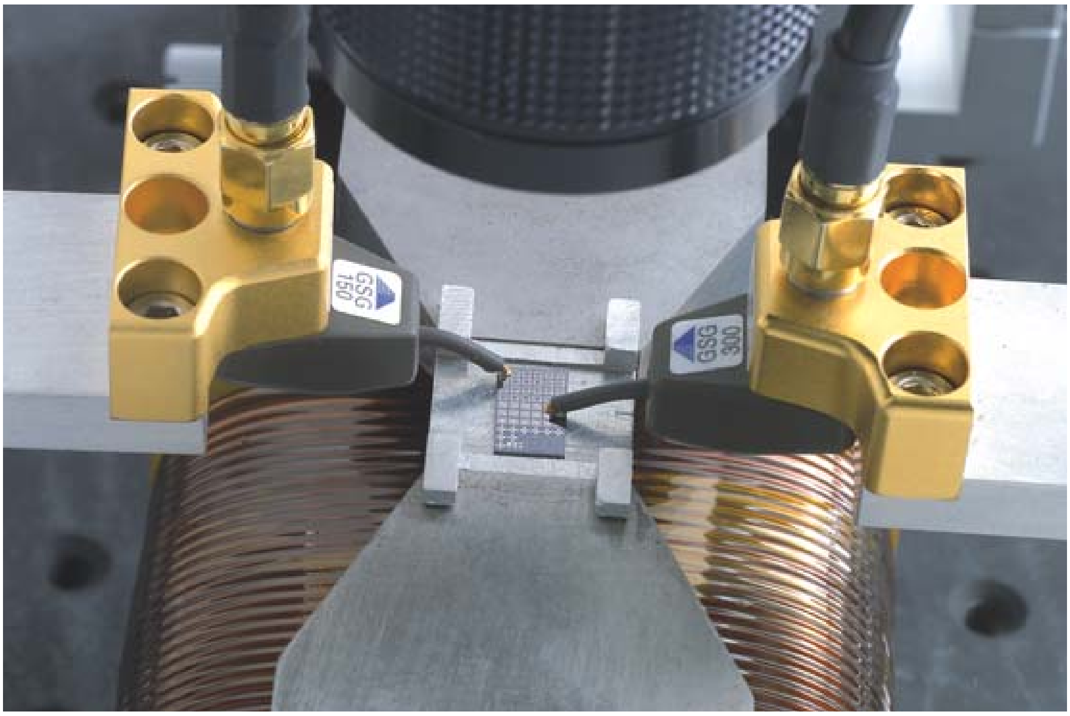
Data storage: achievements and promises of nanomagnetism and spintronics

Ever since the beginnings of electronic data processing, new discoveries made by basic science in the field of magnetism have continued to drive spectacular advances in the performance of data storage systems. Progress in nanomagnetism and spintronics promises to take these advances even further.

Artechnique/CEA

Instrumentation for broadband electrical spectral measurement (0–26 GHz) dedicated to the study of spin-polarised current magnetic nanostructures at CEA Grenoble.

Data storage has been one of the major applications of magnetism for more than a century. In a magnetic material, an item of information can be recorded by locally orienting the **magnetisation** in either of its two possible directions to form a binary storage system. Recording is the area of applied magnetism in which technological progress has been most spectacular over the last 50 years. This is especially true since the first computer hard drive arrived in 1956. Since then the storage capacity of hard drives has continued growing at an average rate of 45% a year, in half a century producing an increase in storage density of 8 orders of magnitude (300 **bits**/cm^2 in 1956, 50 billion bits/cm^2 in 2007). Correspondingly, the size of each data bit has continued to fall, from 0.3 mm × 1.2 mm in 1956 to 25 **nm** × 80 nm in 2007. Thus magnetism, like many other areas of physics, has come down to the **nanometre** scale. Several factors have made this progress possible. First, at the pure science level, a more thorough understanding of certain magnetic phenomena specific to this scale, *e.g.* instabilities in magnetisation linked to thermal fluctuations, and the evolution of magnetic properties when the lateral dimension of the system becomes comparable to or less than certain lengths characteristic of magnetism. Enormous progress has also been made in the development of magnetic materials for both writing and reading data. New data storage support media have been devised, and others are under development. Thus in a few years, instead of storing information on continuous magnetic layers, we shall be using media composed of arrays of nanometric-scale magnetic dots, each of which will carry one or more data bits. **Magnetoresistive** materials have been designed to read data. These materials use properties associated with the **spin** of **electrons**, *i.e.* their intrinsic **magnetic moment**, and make it possible to produce ultrasensitive **magnetic field** sensors able to read the magnetic field on the surface of a hard disk and extract the information written there. Other areas of R&D connected with hard drive applications have emerged in the last fifteen years,



Artechnique/CEA

Instrumentation at CEA Grenoble used to characterise the variation in the electrical resistance of spintronic components subjected to current pulses lasting between 70 picoseconds and 100 nanoseconds in a magnetic field.

in particular with the rise of **spin electronics** or **spintronics**. This area of study allies electronics and magnetism. It uses the spin of electrons to obtain new properties or functions. These developments concern new types of non-volatile memories, *i.e.* systems that can conserve data without a power supply, and also **radiofrequency** components for telecommunications, data processing devices and hypersensitive magnetic field sensors that can be used in biology, for example, to measure the magnetic field generated by electric currents in the brain (see Chapter II).

The CEA is active in these different domains at its research centres in Grenoble (Isère), Saclay (Essonne) and Le Ripault (Indre-et-Loire). The Spintec department (Spintronics and Component Technology) was purposely set up at the Institute for Nanoscience and Cryogenics (Inac, ex-DRFMC) in Grenoble to facilitate the application of upstream research efforts, in the framework of a joint organisation bringing together the **CNRS**, Joseph Fourier University and the National Polytechnic Institute of Grenoble.

An alliance of electronics and magnetism

Electrons possess several elementary characteristics, the best known of which are *mass* and *electric charge*. The whole of 'conventional' electronics was based on using electric fields to act on the charge of electrons. However, electrons also possess an intrinsic magnetic moment, called spin, classically represented by a movement of rotation about a diametrical axis. All electrons have spin. This is a **quantum** property and so can take one of only two values, commonly notated ↑ or ↓. In non-magnetic materials, electrons with spins ↑ and ↓ are equal in number, but in magnetic materials there is an imbalance between these two populations, and the electrons with spin ↑ predominate (Focus A, ***The different forms of magnetism***, p. 10). The result is that the electric current circulating in a magnetic material displays spin polarisation. If this polarised current then flows from a magnetic material into a non-magnetic one, such as copper, this spin polarisation gradually diminishes owing to spin relaxation processes, but over relatively large distances of up to several hundred nanometres. The magnetic materials can then act as **polarisers** or analysers(1) of spin-polarised electrons. Spintronic components thus combine magnetic and non-magnetic materials, which can be metals, insulators or **semi-conductors**. They often have a sandwich structure – **ferromagnetic** layer (F1) / non-magnetic layer (NM) / ferromagnetic layer (F2) – in which the relative orientation of the magnetisation of layers F1 and F2 can be changed. This structure resembles a polariser/analyser pair in optics, a science where we know that by acting on the angle between the polarising directions of the polariser and the analyser, the light transmission through the pair can be changed. In spin electronics, when an electric current flows through the F1/NM/F2 structure perpendicular to the interfaces, the first layer (F1) spin-polarises the electrons parallel to its magnetisation. This polarisation is transmitted through the non-magnetic layer, provided it is sufficiently thin (typically a few nanometres). The ability of electrons to penetrate layer F2 then depends on the angle between the F1 and F2 magnetisations. This is demonstrated by a change in the electrical **resistance** of the structure according to the magnetisation angle.

(1) analyser: device used to measure the rotation of the plane of **polarised** radiation caused by travelling through a material.


CNRS/C. Lebedinski

Albert Fert, co-winner of the 2007 Nobel Prize in physics.

From giant magnetoresistance to spin valves

This effect was first demonstrated at Orsay in 1988 in multilayers made up of alternating layers of iron (2 nm) and chromium (1 nm). It was dubbed **giant magnetoresistance** because the relative change in resistance observed in a magnetic field, about 50% at room temperature, was much greater than in any other magnetoresistance effects known to date in metals. This discovery, which earned Frenchman Albert Fert and the German scientist Peter Gründberg the 2007 Nobel Prize in physics, is considered as the foundation stone of spin electronics. It stimulated abundant research into these interactions between magnetism and charge transport. In 1990, materials exhibiting giant magnetoresistance at low fields, **spin valves**, were developed to make ultrasensitive magnetic field sensors. They came into use in computer hard drive read heads in 1998 thus marking the first industrial application of spintronic components. By 1991 the CEA was very active in the development, optimisation and study of the electrical transport properties of these materials.

The rise of magnetic tunnel junctions

Another milestone in spin electronics was the observation of **tunnel magnetoresistance** effects in magnetic **tunnel junctions** at room temperature. Magnetic tunnel junctions can also take the form of F1/NM/F2 sandwiches, but unlike spin valves, in which the NM spacer is a metal (typically copper), they have a thin layer of an insulating material (*e.g.* a 1.5-nm thick layer of alumina). This layer forms an energy barrier for **conduction electrons**. However, electrons can still cross it by a pure quantum effect, the **tunnel effect**. When **electrodes** on each side of the barrier are magnetic, the probability of electrons tunnelling through the barrier depends on the angle between the spin of the electrons and the magnetisation of the electrode that receives the electrons on the other side. This means that when an electrical potential is applied between the two electrodes, the electron current across the junction depends on the angle between the magnetisations of the two electrodes. This effect was first observed in 1975 by a French scientist, Michel Jullière, at low temperature in semiconducting magnetic junctions based on germanium. However, interest in tunnel junctions really took off only after 1995 when tunnel magnetoresistance was observed at room temperature in alumina-based **amorphous** junctions, which displayed magnetoresistance amplitudes of 30-70%. Since then, enormous progress has been made in the materials used to make tunnel barriers. In particular, crystallised magnetic junctions based on magnesium oxide (MgO) have been developed, with magnetoresistance amplitudes greater than 400% at room temperature (Figure 1). This considerable increase in the amplitude of the magnetoresistance of MgO-based junctions relative to alumina-based amorphous junctions stems from the **crystallised** nature of the MgO barriers. In amorphous barrier junctions, the magnetoresistance comes only from the difference in the ↑ and ↓ spin populations along the interface between the magnetic electrode and the tunnel barrier. In crystallised tunnel junctions, an additional effect occurs, namely a filtering of the electrons tunnelling through the barrier according to the symmetry of their electronic **wave functions**. Only electrons that have wave functions with symmetry compatible with that of the crystal lattice of the MgO are allowed through the tunnel barrier. If the electrodes are made of cobalt-iron based alloys with *body-centred cubic structures*(2) like MgO, only the electrons with spin ↑ have the right symmetry to get through the tunnel barrier. This results in a near-perfect filtering of the ↑ electrons, *i.e.* a polarisation of the tunnel electrons close to 100%, and therefore very high magnetoresistance amplitudes.

Besides the purely scientific importance of their effects, these tunnel junctions have drawn considerable interest for various types of applications. First they make it possible to produce magnetic field sensors that are even more sensitive than spin valves, owing to their greater magnetoresistance amplitudes. These sensors are already used in the latest generation of hard drive read heads. They may also find use in position and angle coders for robotics, automobile applications and electronic compasses.

Another major area of application of tunnel junctions is that of non-volatile magnetic storage (see *Data storage: the hard disk's pre-eminence challenged*, p. 67). In this application, each storage point is a magnetic tunnel junction. A data bit is stored by switching the magnetic configuration of the tunnel junction to either parallel (low resistance state representing a binary '0') or antiparallel (high resistance state representing a binary '1'). This binary

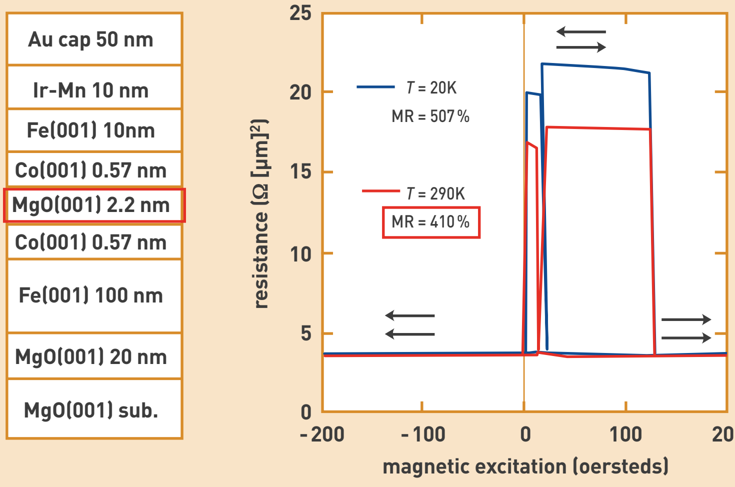


Figure 1.
Magnetoresistance of MgO-based tunnel junctions, taken from Yuasa *et al*, Appl. Phys. Lett. 89, 042505 (2006). The resistance of the sample ranges from 4 kΩ to 17 kΩ when the magnetisations of the two magnetic electrodes change from a parallel to an antiparallel alignment.

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(2) Body-centred cubic structure: crystal structure in which atoms occupy the eight corners and the centre of a cube.

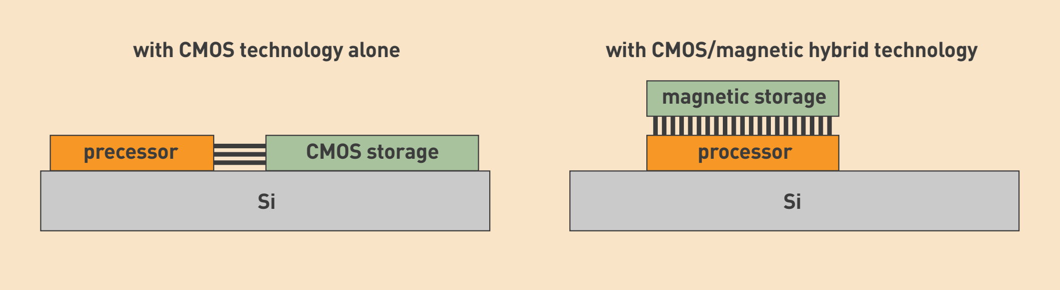


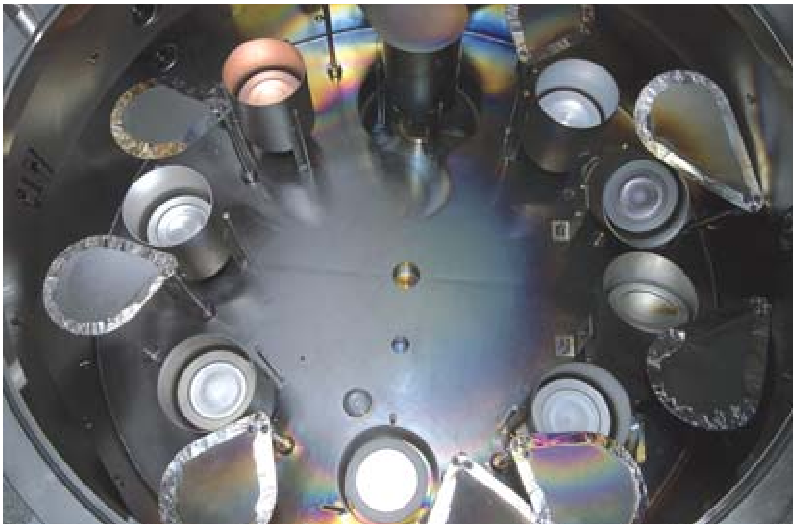
Figure 2.
Imbrication of processing and storage functions in silicon (Si) substrate circuits.
Left: all-semiconductor.
Right: hybrid semiconductor / magnetic.

information is read by measuring the level of resistance of the tunnel junction. The CEA is strongly involved in the development of these magnetic random access memories (MRAMs), and a new company, **Crocus Technology**, was created in 2006 to develop novel MRAM technology using thermally assisted data writing (see also p. 67). Besides storage applications, magnetic tunnel junctions can be used in logic circuits to process data and perform calculations, etc. They can act as variable resistors whose value can be set by changing their magnetic configuration. The CEA is working on reprogrammable processing components that combine semiconductor components and magnetic tunnel junctions. The resistance of the tunnel junctions determines the switching thresholds of the semiconductors. This makes it possible to construct **logic gates** whose function is changed by modifying the magnetic configuration of the tunnel junctions (*e.g.* a **NOR gate** can be turned into a **NAND** gate just by changing the magnetic configuration of a magnetic tunnel junction). Reprogrammable components of this type already exist in semiconductor form as field programmable gate arrays (FPGAs). The advantages offered by the semi-conductor / magnetic tunnel junction combination are (i) a much smaller component surface area, (ii) a significantly higher reprogramming speed and (iii) non-volatility provided by the magnetic tunnel junctions.

Semiconductor and magnetic components can also be combined to design novel complex electronic circuitry associating storage and processing functions and capable of much higher performance. This novel circuit architecture exploits the fact that the magnetic components, such as magnetic tunnel junctions, can be laid down on practically any support provided it is not too rough to allow the growth of a very thin tunnel barrier. In ‘'conventional' circuits, all the semiconductor circuits use the properties of silicon and are therefore built on a silicon substrate. Thus, the processing components and storage systems are located side by side on the **silicon** chip, where they are linked by a small number of often long interconnections, which limits the speed of communication between processors and stored data. This architecture currently sets an upper limit to computer processing speeds, partly overcome by increasing the number of processors. However, by combining semiconductor and magnetic materials the magnetic storage systems can be distributed much more efficiently on top of semiconductor logic circuits, and so processors and data storage can communicate through large numbers of short vertical conductors (Figure 2). This significantly speeds up the communication, which is particularly useful for multimedia applications in which relatively simple processing tasks have to be carried out on large amounts of stored data.

Spin transfer

The spin electronic effects described above are magnetoresistance effects (giant or tunnel), *i.e.* variations of electrical resistance in a magnetic field. These effects enable us to act on a spin-polarised electric current through the magnetisation of a magnetic nanostructure. However, the inverse effect also exists. It was predicted in 1996 by two theoreticians, J.-C. Slonczewski and L. Berger, and observed experimentally soon afterwards. This effect, called ‘spin transfer’, is an action of spin-polarised current on the magnetisation of a nanostructure. This is how it works: when spin-polarised electrons are injected into a magnetic nanostructure whose magnetisation direction forms an angle with the electron spin polarisation axis, this spin is very rapidly re-aligned parallel to the local magnetisation in the first nanometre following the penetration of the electrons in the nanostructure. This realignment of the spin polarisation is equivalent to a transfer of angular momentum, which results in a magnetic torque acting on the magnetisation of the nanostructure. If the density of the polarised current penetrating into the magnetic nanostructure is high enough, the torque can cause the magnetisation of the nanostructure to switch, or in certain geometries, to generate and sustain exci-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Interior of a device for depositing thin magnetic layers by cathodic sputtering, showing the targets for the materials being deposited.

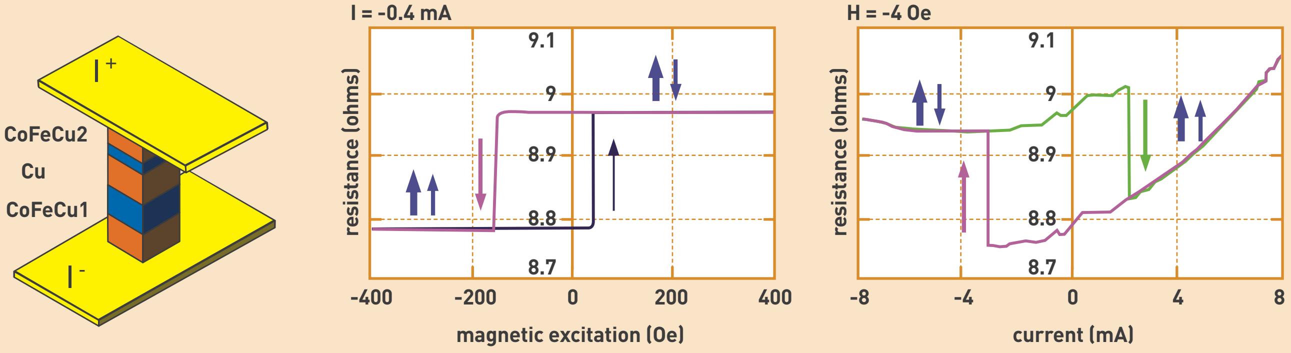

Figure 3.
Examples of magnetic switching in a spin valve structure through which a current flows perpendicular to the plane of the layers. Left: switching caused by applying a magnetic field. Right: switching caused by the spin-polarised current flowing through the structure.

tation of the magnetisation. This effect has drawn considerable interest because it opens up a whole new area of study in the dynamics of magnetisation induced by spin-polarised currents. It also opens a new route for manipulating the magnetisation of magnetic nanostructures, and in particular for writing data in MRAM cells. In structures of the spin valve type, for example (Figure 3), the magnetic configuration can be switched from parallel to antiparallel by either the ‘'conventional' method (by applying a magnetic field) or by spin transfer from current flowing through the structure. For MRAMs, this method of writing offers significant advantages over writing with a magnetic field in terms of energy consumption and memory point selectivity.
The CEA is also actively studying the spin transfer effect for use in radiofrequency oscillators. Spintec has patented an RF oscillator concept based on the injection of electrons spin-polarised out of the plane into a magnetic layer with planar magnetisation. It has been shown that in this geometry, the magnetisation of the magnetic layer **precesses** sustainably in a cone with an axis perpendicular to the plane (Figure 4). If the structure is extended by a magnetic tunnel junction comprising a fixed magnetisation reference layer, the continuous variation of the angle between the excited and fixed magnetisations causes a sinusoidal variation in resistance, which in turn results in an oscillation of the potential at the terminals of the device. The frequency of these oscillations is in the 2-30 **GHz** range and can be adjusted by the **current density** flowing through the structure.
This type of tunable-frequency device is very useful for telecommunications applications. The existing voltage-controlled oscillators (VCO), based on LC circuits (made up of an inductor and a condenser), typically offer frequency-tunability over ranges of the order of 200 **MHz** and take up a large area of silicon, of the order of 100 μm^2 per oscillator. In comparison, the spintronic oscillators described above have a much greater frequency agility (several GHz) and are of much smaller size (sub-micron). Current efforts are being made to increase the emission power of these oscillators.

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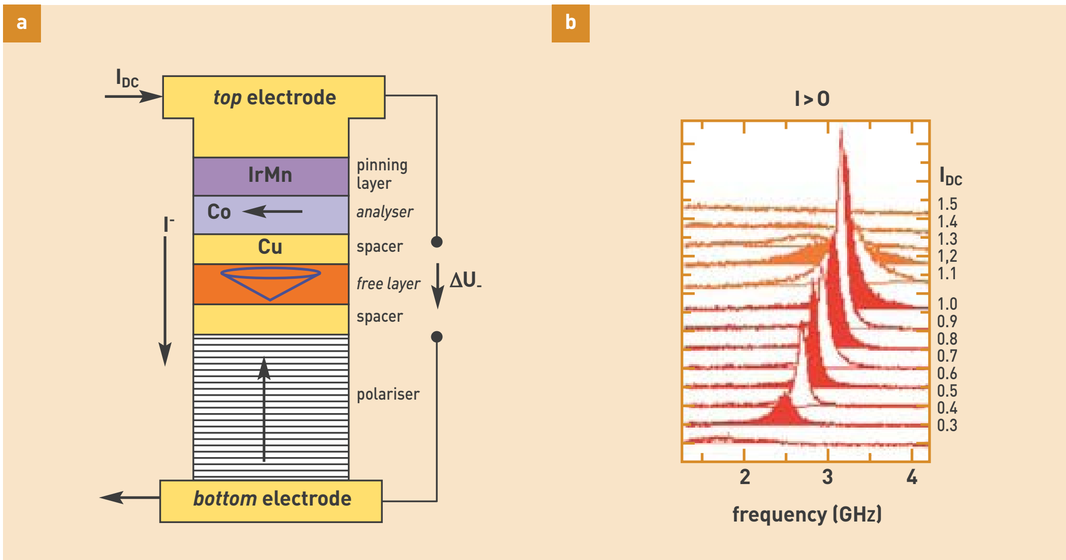
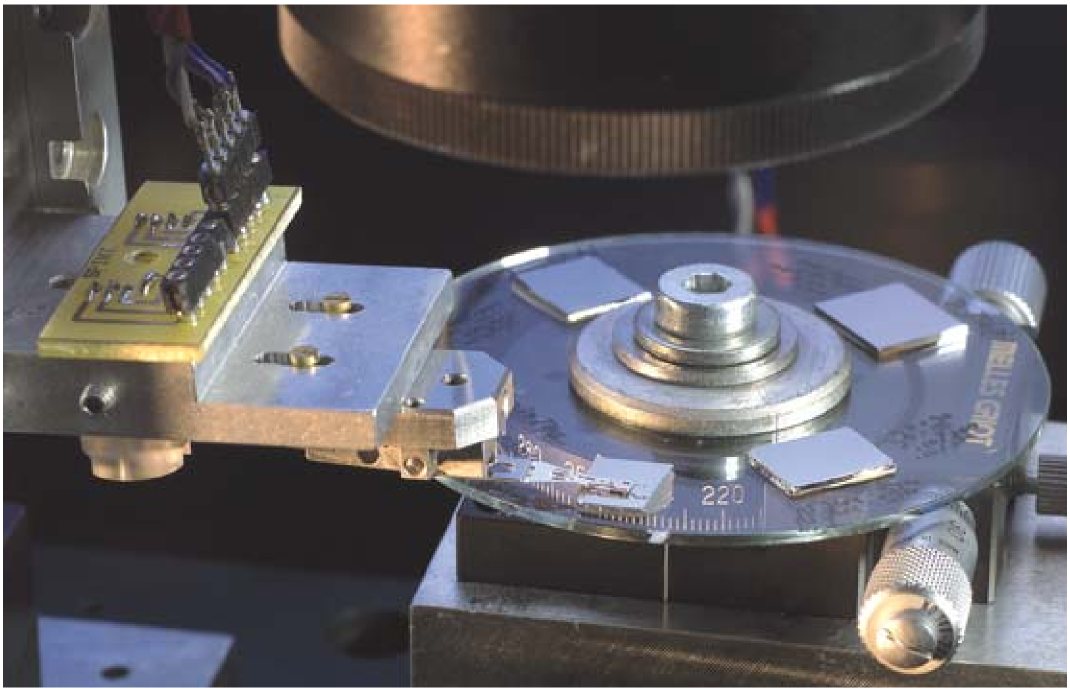


Figure 4.
(a) Diagram of a spintronic oscillator with a polariser perpendicular to the plane of the layers. The direct current flowing through the structure sustains the precession of the magnetisation of the 'free' layer. Through the magnetoresistance effect arising from the variation of the angle between the magnetisation of the free layer and of the reference layer (analyser), an alternating potential ΔU appears between the two electrodes of the device.
(b) Experimental spectra of the spectral density of the output potential ΔU for different currents ranging between 0.3 and 1.5 mA. The oscillation frequency increases with the current.

Data storage: The hard disk's pre-eminence challenged

While the hard disk drive continues to develop its capacity and read/write performance, solid-state magnetic memories and spin-polarised current devices are opening up new perspectives.



Artechnique/CEA

Quasi-static test bed at CEA Grenoble, used to read and write on magnetic dot arrays.

In 2006 the computer hard disk drive (HDD) celebrated its 50th birthday. The very first hard disk drive, the RAMAC, for 'random access method of accounting and control', was introduced in 1956 by IBM. It had a capacity of 5 **megabytes**. The hard disk drive owes its remarkably long life to continual innovations and technological breakthroughs in both the support medium and the read/write heads. In comparison, the Compact Disc, another storage support for the general public, is already practically obsolete after only 25 years, because it has failed to stand up to the inexorable rise of solid-state memories (i.e. ones with no moving parts) that have flooded the market for nomad devices. In 50 years the capacity of HDDs has increased by more than five orders of magnitude, now reaching the **terabyte** in the best parallel-architecture systems. This growth rate, which outpaces even *Moore's law*(1) has enabled the HDD to hold its own against solid-state memories. Even so, these are serious challengers in many applications. The first laptop computers with solid-state memory drives came on the market in 2006, and are enjoying growing popularity due to their higher speeds, lower energy consumption, greater robustness and lower weight. In the medium term the HDD is liable to find itself confined to the applications that require the most storage capacity, such as high-definition video or massive archive storage. Although solid-state flash-type drives certainly have a future alongside HDDs, competition from emerging technology based on phase-change materials or magnetic materials that offer better performance, mainly in transfer speeds, has to be allowed for. Ironically, the flash memory could be outmatched on its home ground by a magnetic memory using the same technology as today's hard disks!

Magnetic storage in hard disks

The two essential parts of an *HDD are the magnetic medium*, which is the support for the information, and the head, which reads and writes data bits on the medium. Both parts have evolved substantially in the last 50 years, and have taken advantage of technological breakthroughs to increase storage density, sensitivity and data transfer speeds.

Spin transfer

At the present time the medium, which is laid down on aluminium or glass substrates selected for their high smoothness, consists of one or two magnetic layers, a hard carbon-based protective layer and a thin layer of lubricant to prevent wear of the head/medium interface. The magnetic layers, generally based on cobalt, chromium and platinum alloys, are made up of tiny independent magnetic

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(1) Moore's law, named after the co-founder of Intel Corp., stated – originally – that the number of transistors per unit surface area of an integrated circuit doubled every 18 months for the same cost.

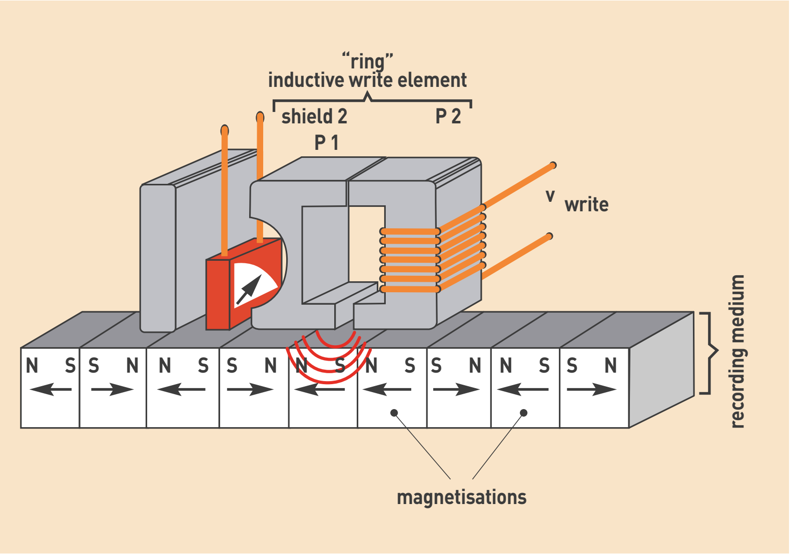


Figure 1.
Principle of longitudinal recording. The data bits are recorded in the plane of the layers by a write head consisting of a tiny electromagnet of submicron dimensions made up of a magnetic ring with a gap that lets out the magnetic field generated by the writing coil. Reading is done by measuring the magnetic field radiated by the medium at the transition between adjacent bits at a few nanometres above the surface. This measurement is made using a magnetoresistive element that converts the variations in the magnetic field into variations in an electric potential at the terminals of the read head. A variation in potential appears when the magnetisation of the sensitive layer is oriented in a transition. This is because the resistance of the head is proportional to the relative orientation between the magnetisation of the sensitive layer and that of the reference layer (Source: Hitachi Global Storage Technology).

grains. To write data, the magnetic field produced by the head orients the magnetisation of a set of grains corresponding to one binary digit in either of its two possible directions (Figure 1).

At the interface between two digits there is a transition zone over which the magnetisation is reversed. This transition zone displays a degree of irregularity directly linked to the size of the grains in the medium (typically 10 nm).

Uneven transition causes magnetic noise, which impairs data recognition. To limit this noise the number of grains per bit must be above a threshold (typically 50-100 grains).

To increase the density of data stored in these media, we can try to reduce the size of each data bit or, better, the width of the transition zone between adjacent data bits. This necessarily implies reducing the grain size of the medium. However, when the grains become very small, their magnetic stability, which is the product of their **anisotropy** K_u and their volume V, decreases rapidly, and they will no longer store data indefinitely: this is the **superparamagnetic** limit. Data tends to get wiped off simply by the effect of **thermal agitation**. We can compensate for this reduction in volume by increasing anisotropy. However, the field required to write data will then exceed the fields we can produce with a write head.

To reach storage densities greater than a terabit per square inch (6.45 cm^2) without being limited by grain size, discrete rather than continuous media have been proposed. These discrete media are made up of an array of nanometric-scale magnetic dots, physically separated and mutually independent. Each dot carries one binary digit: its magnetisation can be oriented in one of two stable directions. Here the transition widths between data bits are set by the physical process by which the medium is patterned, and are no longer linked to the size of the grains that make up the magnetic layers. Thus the dots can be composed of larger grains than continuous media, and yet the data bits take up less space. Using these discrete media, it is estimated that storage densities can be increased by two orders of magnitude. However, there is an obstacle: to industrialise this technology these discrete media have to be produced rapidly and cheaply (a ''conventional' hard disk costs about $2 to make).

The technology currently favoured by the sector's major industrial players (Seagate, Hitachi and Western Digital) was initially proposed by the Spintec laboratory jointly with LETI and the microelectronics technology laboratory (LTM) of the

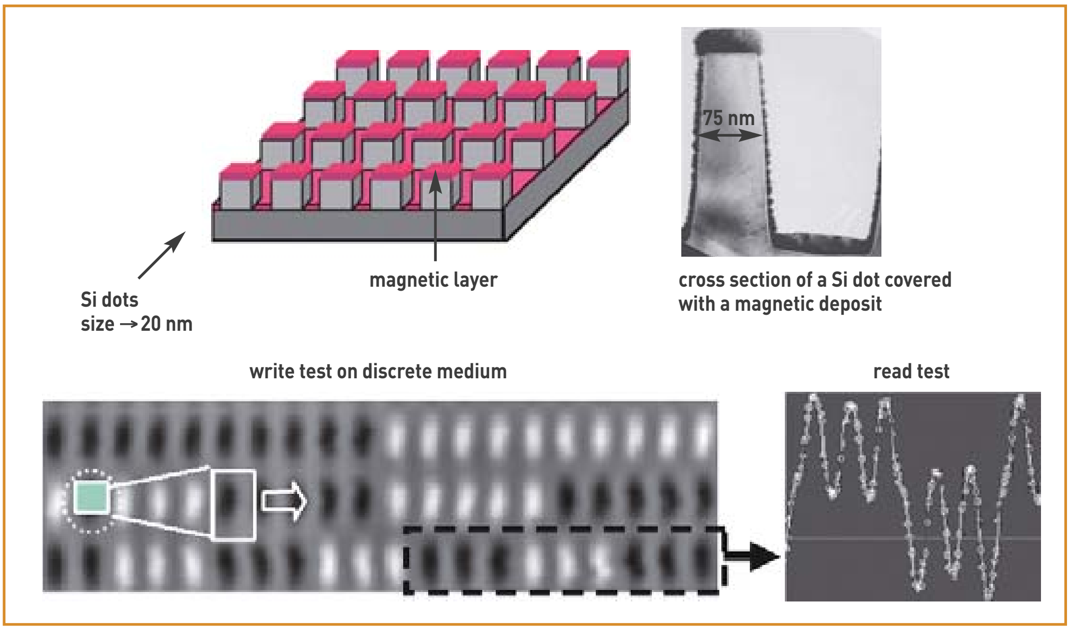
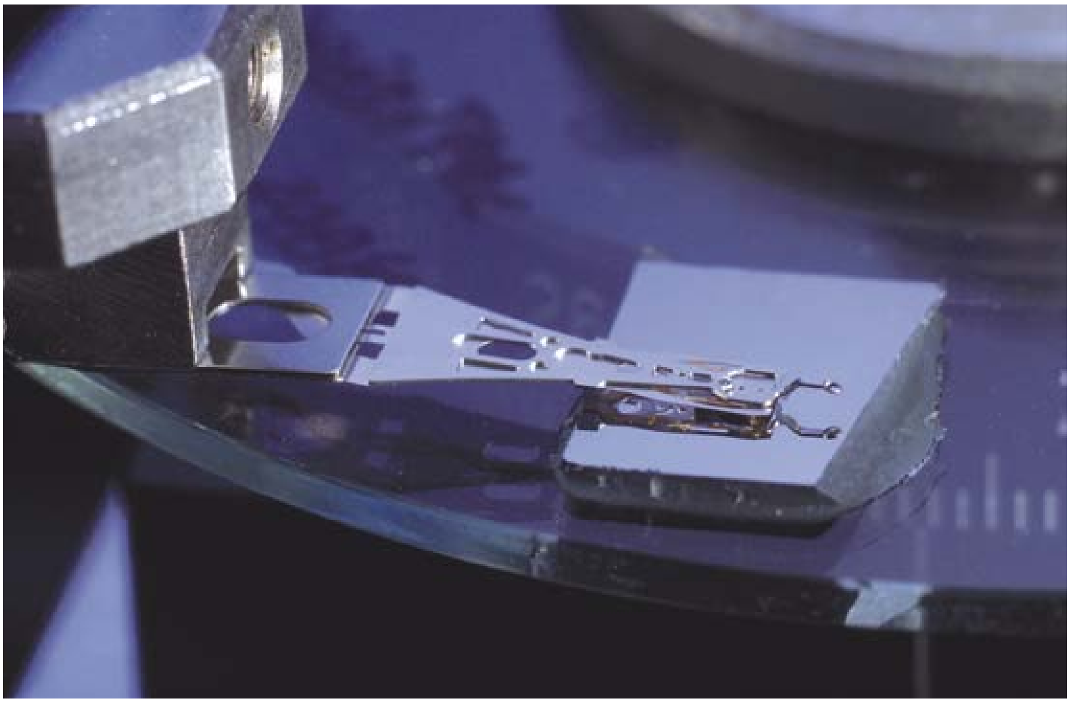


Figure 2.
Discrete media developed at CEA Grenoble. Configuration of the magnetic layer (top left) and cross section of a silicon dot covered with a magnetic deposit (top right). Bottom: write test (left) and read test (right) on discrete medium with dots 100 nm × 200 nm. The signal is delivered by the magnetoresistive read head by scanning the track which contains 3 '0' bits alternating with 3 '1' bits.


Artechnique/CEA

Read/write head
of quasi-static test bed.

CNRS. This technology first consists in patterning a silicon, glass or aluminium substrate with an array of nanometric dots. This patterning can be carried out by a rapid, low-cost technique called nanoprinting. This consists in imprinting a resin resist using a mould presenting a dot array.

The resin resist is then used as a mask to etch the substrate. A magnetic storage layer, which covers the tops of the dots and the bases of the troughs between the dots, is deposited on the etched substrate (Figure 2, top). The deposit on the tops of the dots then supports data bits via the up or down orientation of the magnetisation of the material. Write/read tests on this type of medium carried out by Spintec are convincing (Figure 2 bottom).

In the longer term, researchers at Spintec are planning to store several data bits on each dot by depositing on them a multilayer made up of several magnetically decoupled layers with different write fields. By applying a sequence of diminishing write fields, the magnetisation of each layer can be oriented in turn, starting with the hardest to write and ending with the easiest(2). With this approach the density of information can be increased without having to reduce the size of the data bits.

Every medium, even **discrete** media, will inevitably come up against the superparamagnetic limit when the data bits fall below a certain size(~10 nm, corresponding to an information density of 5 terabits per square inch). The only solution is to increase the magnetic anisotropy of the data bits to compensate for the smaller volume. To obviate increasing the write field, researchers have proposed heat-assisted magnetic recording (HAMR). Here the data bit is heated individually by a near-field optical approach to reduce the magnetic anisotropy just as it is being read. Another approach is also being studied, using assistance not by heat but by a radiofrequency wave applied at the spatial scale of a bit.

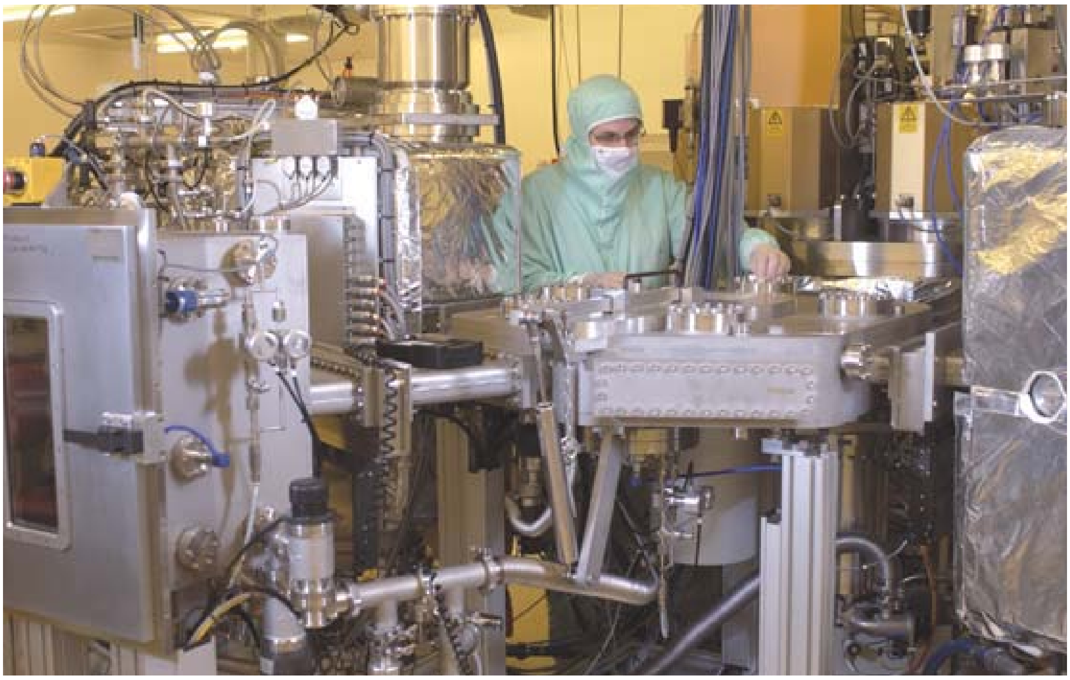
Trends in read/write heads

In the last 50 years read/write heads have evolved considerably, in both miniaturisation and the technology used. In only the last 30 years the weight of the head and air bearing slider assembly has been reduced by a factor of 100, falling from 55 mg to 0.6 mg. Five generations of heads, derived from major technological breakthroughs, have raised the areal recording density growth rate (ARDGR) from 25% per year to more than 100% per year!

From the fifties to the seventies, *inductive technology* was dominant, with a coil wound on a micromachined **ferrite** pole piece. The read/write gap was formed simply by assembling the pole pieces. With this technology, the **coil** served as a source of a magnetic field for writing and reading, by measuring the electromotive potential induced in the coil during a read flight. During the eighties the first *thin layer* technology arrived. Inductive heads were then made collectively on substrates using microelectronic processes. Size and alignment control was improved using online characterisation tools. **Permalloy** superseded ferrite for pole pieces, as it allowed higher write fields to be produced.

During the next decade there was a technological breakthrough for read heads. *Anisotropic magnetoresistance* (AMR) technology superseded inductive technology. This more sensitive technology increased ARDGR to 60% per year. Now read and write heads were dissociated and stacked one on top of the other, making manufacture considera-

(2) That is, first write on the layer with the highest reversal field (hardest layer, magnetically speaking), and then the other layers in decreasing order of reversal field strength. Otherwise, the information stored in the softest magnetic layers (those with the lowest reversal fields) would be automatically erased.



Magnetic thin layer deposition machine for the manufacture of MRAMs at CEA Grenoble.

P.Stroppa/CEA

bly more complicated. AMR technology, proposed for flow sensors in 1971 by R. Hunt took less than 20 years to find use in a product designed for the general public. But this application was to be short lived as in 1997 it was unseated by **spin valve** technology (low-field giant magnetoresistance) introduced in 1990 by Bernard Diény, then at **IBM**.

This new read/write head, which was more sensitive than the AMR head, led to an ARDGR of more than 100% per year. It is still used in many hard drives despite the emergence of *tunnel magnetoresistance* (TMR) heads, derived from GMR heads. In both types of heads, the variations in the potential at the detector terminals are proportional to the relative orientation of the magnetisations of the two magnetic layers. One layer is fixed, and acts as an analyser, while the other layer, the sensitive one, is mobile. When there is no field, these two magnetisations are oriented at 90° to 'linearise' the response of the detector. When the detector flies over a transition the magnetisation of the sensitive layer lines up with the direction of its magnetic field. This modifies the relative orientation of the sensitive and reference layers. If the relative angle diminishes, so does the potential, and *vice versa.* The only difference between a GMR head and a TMR head is the direction of the current feeding the detector. It is parallel to the plane of the magnetic layers in the GMR head and perpendicular in the TMR head. In a TMR head, the spacing layer between the magnetic layers is a very thin insulator (~1 nm thick) that the electrons tunnel through. The variation in the resistance in a TMR detector can reach more than 400% with insulators of the MgO type, against no more than about 20% in the best GMR heads.

Another aspect that researchers in this area are studying closely is the *electronic noise* generated by the spin-polarised current. As explained in the previous article, a spin-polarised current of sufficient density can generate a spin transfer torque on the local magnetisation able to cause an excitation of the magnetisation, or even reverse it. In the currently available heads, the dimensions of the detector are such that these critical current densities are approached (typically 10^7 A/cm^2). These magnetic excitations generated in the sensitive layer of the read head are a source of noise in the signal delivered by the head. Spintec is studying the noise dynamics in the heads made by a partner in order to evaluate the criticality of this interference and propose structures to overcome it, or use the spin transfer effect to reduce the noise to below its natural level at the working temperature of the head.

Toshiba

Figure 3.
Disk made by Toshiba measuring 2 cm in diameter with a capacity of 4 GB and weighing a mere 8.5 g!

Hard disks and solid-state memories

Besides the evolution of the two main parts of the hard drive, another aspect linked to the use of space has to be considered: the *form factor.* IBM's RAMAC used 50 disks 60 cm in diameter to store 5 MB of data, and weighed no less than a ton! Today, thanks to technological progress in miniaturisation, the form factor has dropped to less than 2.5 cm with Toshiba's record-breaking 2-cm disk that can store 4 GB in a device weighing only 8.5 g (Figure 3). In driving technology to achieve such small form factors, hard disk manufacturers are aiming at the market for nomad components.

Competition between HDDs and solid-state flash memories

The HDDs in our office computers use a form factor of 9 cm, which readily allows capacities of 400 GB with several disks. Laptops use HDDs with a format of 6.3 cm or even 4.5 cm, which are lighter, but have a slightly lower capacity. The lightest HDDs have a single disk with a capacity of about 160 GB. The 2.5-cm format was introduced in 1998 for the first nomad applications. In 2004, Apple's mini *iPod* was sold with an HDD with this format and a capacity of 6 GB. But by 2005, this mini-HDD was replaced by a solid-state flash-type drive of lower capacity, but which was faster and consumed less power. Other HDD products with a form factor of 2.5 cm have been introduced by various manufacturers to compete with USB flash drives or memories of the Compact Flash type used for digital photography. However, consumer response has been lukewarm, as their performance is inferior to that of solid-state memories. Solid-state storage is actually taking market share from HDDs in top-end laptop applications. Dell was the first to market a laptop with a solid-state drive (SSD) with a capacity of 32 GBs.

Today's spectacular rise in the consumption of music downloaded onto nomad devices is a godsend for the SSD market. However, music files are very often downloaded from a desktop computer where they are stored on a conventional high-capacity HDD. Similarly, internet providers use servers based on very high-capacity HDDs to store and archive data. Hence the emergence of this new mode of nomad consumption benefits both magnetic technology and flash technology at different segments along the processing chain.

Flash technology: the competitors

Flash memories use either of two types of technology: **NOR memories** allow rapid random access to recorded data, but have limited capacity. They are used mainly to store system programs that have to be executed frequently. By contrast, **NAND memories** offer only sequential access to data, but with higher read/write speeds and much greater capacities. They are used as storage memories in applications of the USB, MP3 or SSD type. With increasing densities, designers are faced with higher and higher technological barriers. Grid oxides have to be increasingly fine, which raises problems not only of reliability but also of data retention and endurance. New non-volatile memories are emerging and may compete in the short term with flash memories.

The most advanced of these is the phase-change random-access memory (PC-RAM). Its storage principle is based on the difference in **electrical conductivity** between the crystalline and amorphous phases of chalcogenide(3) materials (of the GeSbTe type). The phase change is caused by a current of the order of a few hundred microamperes (µA) which heats the memory point to above its melting point (~600-700°C). This random-access memory is much faster than a flash memory (write time less than 100 ns) and needs much lower write potentials (~1-2 V). These PC-RAMs are in their pre-production phase at Samsung, Intel and STM. Since 2007 Intel has been giving samples of 128 MB components with 90-nm technology to potential clients, but these memories will probably not be introduced before the 45-nm node(4) has been reached, *i.e.* in 2009-2010.

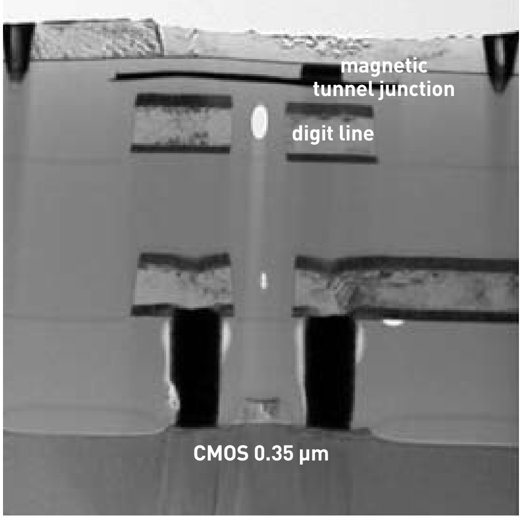
Magnetic random-access memories (**MRAMs**) are another serious competitor for flash systems. At the moment they are less dense but much faster (write/read cycle < 50 ns) and have greater endurance. Their speed enables them to compete with DRAM memories (those most widely used as operating system memories in our computers), while offering non-volatility. **Freescale** is the leader for this technology and commercialises MRAMs with a capacity of 4 MB for micro-controller applications or to replace battery-powered SRAM-type memories for data backup.

Already three types of MRAM technology

The first MRAM components are just being marketed, and there are already three generations of this type of memory (Figure 4) corresponding to three writing strategies: writing by local magnetic field (MRAM), thermally assisted writing (TA-MRAM) and writing by polarised current (STT-RAM for spin transfer torque RAM).

In all three cases the basic units in which the data is stored are magnetic tunnel junctions in which the sensitive magnetic layer can take one of only two different orientations: parallel or antiparallel to the reference layer. This clearly distinguishes between the levels of resistance associated with the binary digits 0 and 1. The conventional writing strategy uses a combination of two orthogonal magnetic fields to ensure selectivity between memory points in the memory plane. However, this approach is ill-suited to achieving greater densities because the writing fields are inversely proportional to the size of the memory point, and the data retention capacity of the memory point is no longer guaranteed below 200 nm.

Accordingly, in 2000 the CEA proposed alternative technology based on thermally assisted writing



CEA/LETI

Scanning electron microscope (SEM) cross section of a TA-MRAM cell on a CMOS circuit etched at 0.35 micrometres.

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(3) Chalcogenide: from Greek *khalkos* (copper), the sulphides, selenides and tellurides.

(4) Node (45 nm): technological generation of microelectronics corresponding to a characteristic dimension of circuit etching of 45 nanometres, according to the ITRS (International Technology Roadmap for Semiconductors).

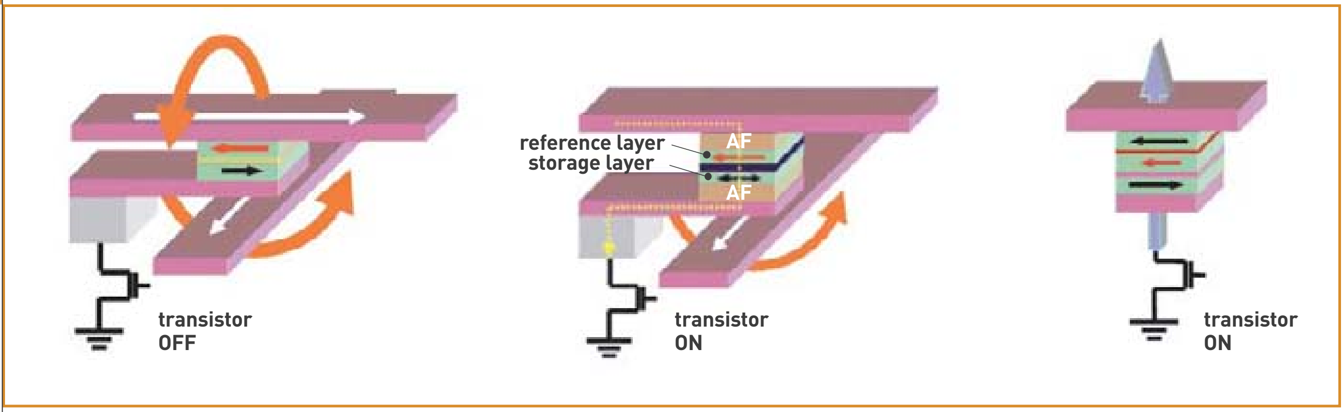
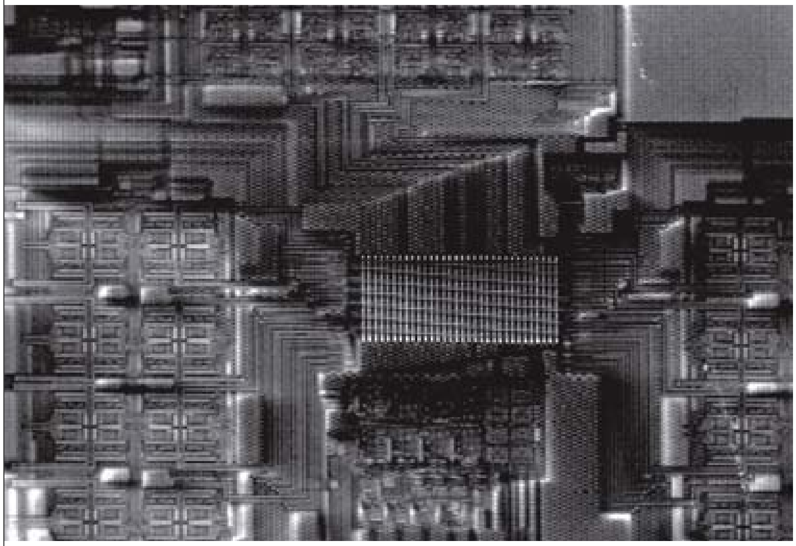


Figure 4.
Three generations of MRAM cells. Left: MRM with writing by orthogonal magnetic fields. Centre: TA-MRAM with a combination of heating current (yellow dotted line) and a single magnetic field. Right: STT-RAM in which the writing is done only by spin-polarised current.


CEA

1 KB TA-MRAM memory.

(TA-MRAM). This concept combines local heating of the memory point to be written on, to ensure both selectivity and a reduced writing field, and a reversal of magnetisation by a single low-amplitude magnetic field. To inhibit the writing of non-addressed memory points (*i.e.* points that we do not want to modify), the magnetisation of the sensitive magnetic layer is stiffened with an **anti-ferromagnetic** material. The temperature rises above the writing temperature (corresponding to the blocking temperature of the anti-ferromagnetic material) only when a current flows in the tunnel junction, freeing the magnetisation of the sensitive layer. This can then be reversed by applying a local writing field. This new approach offers many advantages over the first generation, not only concerning energy consumption and data retention capacity for the smaller sizes but also because it is intrinsically immunised against electromagnetic disturbances. The first integration on 0.35 μm **CMOS** technology was achieved as part of the NEXT European project and was a finalist for the 2006 Descartes Prize. This TA-MRAM approach has already attracted the attention of international investors and led to the creation of the start-up company Crocus Technology, which will make available samples of its first prototypes at the beginning of 2009.

Breaking free from magnetic fields

The next generation of MRAMs will try to break completely free from magnetic fields: the writing will be done only by spin-polarised current. As described above, the torque produced on a magnetisation axis by a spin-polarised current can in certain conditions cause the reversal of the direction of that magnetisation. To date, the current densities necessary to observe this effect are an order of magnitude lower than those required to change the phase in PC-RAM memories. Energy consumption will thus be strongly reduced, and densities should progress rapidly. Hitachi, Renesas and Grandis are the leaders in this technology, and a first demonstration of a 2 MB memory was published in 2006. This third generation is the most promising, but it suffers from the same drawback as the first, namely that its data retention capacity will diminish rapidly with miniaturisation. The coupling of TA-MRAM and STT-RAM technology is therefore a solution that the CEA is exploring in partnership with Crocus Technology.

A new lease of life for magnetic hard disks?

Thanks to its remarkable evolution, magnetic HDD technology has managed to keep pace for more than 50 years. Its future still looks good, with favourable perspectives for growth thanks to the rapid expansion of ‘digital consumption’ with its great need for high storage capacities. The arrival on the market of SSD products has changed the situation somewhat for nomad products and laptop computers, as they offer better performance than HDDs. Thus HDDs with low form factors (< 4.5 cm) will not find many end users, if any, and will remain on the fringe. Flash NAND technology, which underpins SSD, could in the medium term be challenged or even superseded by memory technology with higher performance such as PC-RAMs or MRAMs. An MRAM SSD is more than conceivable. So the magnetic HDD may still get a new lease of life in nomad applications.

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FOCUS A

The different types of magnetism

The origins of magnetism lie in the properties of electrons as explained by the laws of quantum physics. Part of an electron's magnetic properties (*spin magnetism*) results from its quantum-mechanical spin state, while another part results from the orbital motion of electrons around an atom's nucleus (*orbital magnetism*) and from the magnetism of the nucleus itself (nuclear magnetism). This is put to use, in particular, for nuclear magnetic resonance imaging in the medical field. Magnetism is therefore produced by electric charges in motion. The force acting on these charges, called the Lorentz force, demonstrates the presence of a magnetic field.

Electrons have an intrinsic magnetic dipole moment (the magnetic quantum state being the Bohr *magneton*), which can be pictured as an electron's rotational motion of spin around itself in one direction or another, oriented either upwards or downwards. The *spin quantum number* (one of the four numbers that 'quantifies' the properties of an electron) equals 1/2 (+ 1/2 or - 1/2). A pair of electrons can only occupy the same *orbital* if they have opposite magnetic dipole moments.

Each atom acts like a tiny magnet carrying an intrinsic magnetic dipole moment. A nucleus (the neutron and proton individually have a half-integer spin) will have a half-integer spin if it has an odd atomic mass number; zero spin if the atomic mass number and charge are even, and an integer spin if the atomic mass number is even and the charge odd.

On a larger scale, several magnetic moments can together form magnetic domains in which all these moments are aligned in the same direction. These spatial regions are separated by domain walls. When grouped together, these domains can themselves form a macroscopic-scale magnet (Figure E1).

The type of magnetism that comes into play is determined by how these elementary constituents are ordered, and is generally associated with three main categories of material: *ferromagnetic*, *paramagnetic* and *diamagnetic*.

Any material that is not diamagnetic is by definition paramagnetic provided that its magnetic susceptibility is positive. However, ferromagnetic materials have particularly high magnetic susceptibility and therefore form a separate category.

1. Ferromagnetic materials are formed of tiny domains inside which atoms exhibiting parallel magnetisation tend to align themselves in the direction of an external magnetic field like elementary dipoles. In fact, the magnetic moments of each atom can align themselves spontaneously within these domains, even in the absence of an external magnetic field. Applying an external field triggers domain wall movement that tends to strengthen the applied field. If this field exceeds a certain value, the domain most closely oriented with the direction of the applied field will tend to grow at the expense of the other domains, eventually occupying the material's whole volume. If the field diminishes, the domain walls will move, but not symmetrically as the walls cannot fully reverse back to their original positions. This results in remanent magnetisation, which is an important feature of naturally occurring magnetite, or of magnets themselves.

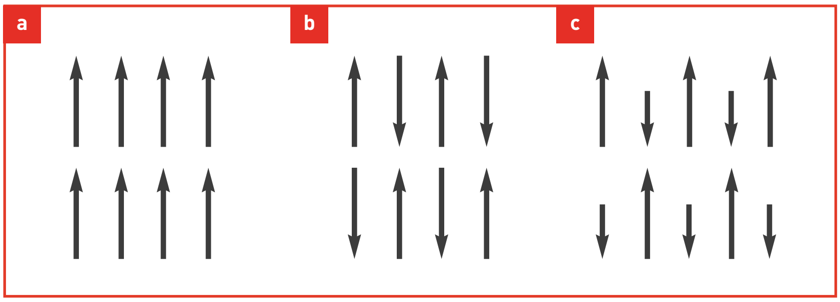


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

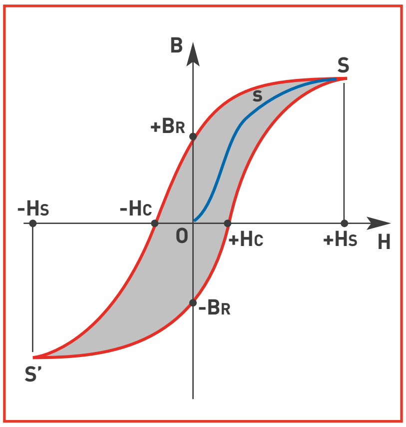


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches zero; this remanent induction can only be cancelled out by reversing the magnetic field to a "coercive" field value. This hysteresis loop illustrates the losses due to "friction" between the magnetic domains shown on the area bounded by the magnetisation and demagnetisation curves.

The whole process forms a hysteresis loop, i.e. when the induced field is plotted against the applied field it traces out a *hysteresis curve* or *loop* where the surface area represents the amount of energy lost during the irreversible part of the process (Figure E2). In order to cancel out the induced field, a coercive field has to be applied: the materials used to make artificial permanent magnets have a high coercivity.

Ferromagnetic materials generally have a zero total magnetic moment as the domains are all oriented in different directions. This ferromagnetism disappears above a certain temperature, which is known as the Curie Temperature or Curie point.

The magnetic properties of a given material stem from the way the electrons in the metallic cores of a material or of a transition metal complex collectively couple their spins as this results in all their spin moments being aligned in the same direction.

Materials whose atoms are widely distributed throughout their crystal structure tend to better align these elementary magnets via a coupling effect. This category of materials, which is characterised by a very high positive magnetic

Stoiber Productions, München

A Transrapid train using magnetic levitation arriving at the Long Yang bus station in Shanghai (China). This German-built high-speed, monorail train was commissioned in 2004 to service the rail link to Pudong international airport.

susceptibility, includes iron, cobalt and nickel and their alloys, steels in particular, and some of their compounds, and, to a lesser extent, some rare earth metals and alloys with large crystal lattices, and certain combinations of elements that do not themselves belong to this category. In ferrimagnetic materials, the magnetic domains group into an anti-parallel alignment but retain a non-zero magnetic moment even in the absence of an external field. Examples include magnetite, ilmenite and iron oxides. Ferrimagnetism is a feature of materials containing two types of atoms that behave as tiny magnets with magnetic moments of unequal magnitude and anti-parallel alignment. Anti-ferromagnetism occurs when the sum of a material's parallel and anti-parallel moments is zero (e.g. chromium or haematite). In fact, when atoms are in a close configuration, the most stable magnetic arrangement is an anti-parallel alignment as each magnet balances out its neighbour so to speak (Figure E1).

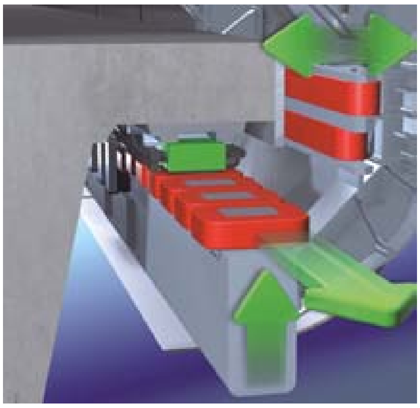
2. Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field, the magnetic moments align up, thus amplifying this field. However, this effect decreases as temperature rises since the thermal agitation disrupts the alignment of the elementary dipoles. Paramagnetic materials lose their magnetisation as soon as they are released from the magnetic field. Most metals, including alloys comprising ferromagnetic elements are paramagnetic, as are certain minerals such as pegmatite.

3. Diamagnetic materials exhibit a negative and an extremely weak magnetic susceptibility of around 10^{-5}. The magnetisation induced by a magnetic field acts in the opposite direction to this field and tends to head away from field lines towards areas of lower field strengths. A perfect diamagnetic material would offer maximum resistance to an external magnetic field and exhibit zero permeability. Metals such as silver, gold, copper, mercury or lead, plus quartz, graphite, the noble gases and the majority of organic compounds are all diamagnetic materials.

In fact, all materials exhibit diamagnetic properties to a greater or lesser extent, resulting from changes in the orbital motion of electrons around atoms in response to an external magnetic field, an effect that disappears once the external field is removed. As Michael Faraday showed all that time ago, all substances can be "magnetised" to a greater or lesser degree provided that they are placed within a sufficiently intense magnetic field.

Electromagnetism

It was the Danish physicist Hans Christian Ørsted, professor at the University of Copenhagen, who, in 1820, was first to discover the relationship between the hitherto separate fields of electricity and magnetism. Ørsted showed that a compass needle was deflected when an electric current passed through a wire, before Faraday had formulated the physical law that carries his name: the magnetic field produced is proportional to the intensity of the current. Magnetostatics is the study of static magnetic fields, i.e. fields which do not vary with time.



Close-up of the magnets used to guide and power the train.

Magnetic and electric fields together form the two components of electromagnetism. Electromagnetic waves can move freely through space, and also through most materials at pretty much every frequency band (radio waves, microwaves, infrared, visible light, ultraviolet light, X-rays and gamma rays). Electromagnetic fields therefore combine electric and magnetic force fields that may be natural (the Earth's magnetic field) or man-made (low frequencies such as electric power transmission lines and cables, or higher frequencies such as radio waves (including cell phones) or television.

Mathematically speaking, the basic laws of electromagnetism can be summarised in the four Maxwell equations (or Maxwell-Lorentz equations) which can be used to provide a coherent description of all electromagnetic phenomena from electrostatics and magnetostatics to electromagnetic wave propagation. James Clerk Maxwell set out these laws in 1873, thirty-two years before Albert Einstein incorporated the theory of electromagnetism in his *special theory of relativity*, which explained the incompatibilities with the laws of classical physics.