The **environmental** sensitivity of **soft magnetic materials**

The environment surrounding 'soft' magnetic materials can interfere with their properties, but it can also be exploited to create new functions. Researchers are therefore working on both these aspects of the relationship these materials hold with their environment.

When they are exposed to even the weakest **magnetic field**, **soft magnetic materials**, which trace out a narrow **hysteresis loop**, react. This makes them attractive candidate materials for creating applications like inductive functions useable at high frequencies. This area has generated much research into increasing the performance of microelectronic inductors by pairing them with soft magnetic materials. Objective number 1: to scale down the size of these components and take advantage of the high **magnetic permeability** of the soft magnetic inclusion.

Although these soft magnetic materials tend to be extremely sensitive to magnetic field, they also tend to react equally easily to a certain number of other environment-related factors, such as temperature or mechanical stress. This sensitivity therefore has to be identified, understood and characterised in order to predict the final performance levels of the devices incorporating these soft magnetic materials.

Magnetic field effect

What essentially characterises a magnetic material is that it houses local **magnetic moments** that work together in a given direction to generate what is commonly known as a **magnetisation**. This magnetisation may or may not be spontaneous. If the magnetic moments within the body are not organised but oriented in every spatial direction, then the material's magnetisation is zero. If however the magnetic moments are organised, such as preferentially in a given direction, then the material's magnetisation is non-zero.

When a magnetic material is subjected to an external magnetic field, its magnetic moments tend to align themselves in the direction of this external field. This implies a change in the material's **anisotropy**, which increases in the direction of the magnetic field applied. Refocusing on the high-frequency properties of these materials, they can be characterised under a magnetic field as a means of investigating their intrinsic properties.

On one hand, this sensitivity is that it can be exploited to voluntarily modify the material's properties. If the crude material tends to display its properties at low frequencies, then a field applied in the right direction would increase its high-frequency properties. On the other hand, if the Earth's magnetic field manages to modify the properties of a filter in a mobile phone due to the fact that it features a magnetic inclusion, the effect would be detrimental.


CEA/DAM

Coil-turn interference measurement cell for determining the permeability spectra of magnetic thin layers at temperatures from -180°C up to 300°C. The cell forms part of the facilities installed at the CEA's Le Ripault centre (Indre-et-Loire).

At the Materials Science Department of the CEA's Military Applications Division ('DAM') at the Le Ripault centre (in the Indre-et-Loire), research led on engineering high-frequency properties now makes it possible to design devices with high-frequency magnetic and even electrical properties that are dependent on the magnetic field applied. The researchers have for example demonstrated that a network of magnetic wires can be employed to control the high-frequency electric field by working with a low-frequency magnetic field (see *Microwave-magnetic materials*).

Temperature effect

If a magnet is heated strongly enough, it no longer attracts iron. The temperature at which the material spontaneously loses its magnetisation is called the **Curie temperature**. However, this effect does not happen as sharply as it would appear. The increase in temperature results in a decrease in the **saturation magnetisation** of magnetic materials. The material becomes progressively less magnetic as temperature increases.

Saturation magnetisation is a static magnetic characteristic – it is a parameter that among other things is dependent on the composition and structure of the magnetic material. It also directly affects the material's frequency response. The *magnetic permeability spectrum* is also dependent on this parameter, both in form and level. Clearly, temperature is more than

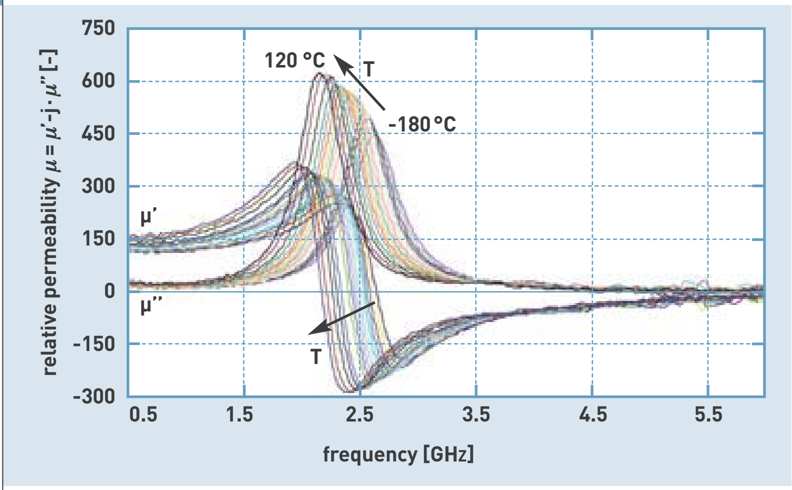

Figure 1.
The pattern of development of the permeability spectrum of a magnetic thin layer against temperatures measured at −180°C to 120°C using facilities installed at the CEA/DAM Materials Science Department.
j is the pure imaginary number [j^2=-1] normally written '*i*' but replaced with a '*j*' in predominantly electronics or magnetics-based research to avoid any confusion with the value for electric current [A] which is normally written '*i*'.

capable of 'gate-crashing' the properties of a **radio-frequency** filter under the action of heat.

The CEA has developed a specific set of instruments able to characterise the properties of magnetic spectra from -180°C up to 300°C (Figures 1 and 2). The data acquired are inserted directly as input data into the computational tools calculating the characteristics of devices integrating magnetic materials. The same instrumentation is able to assess the effects of high temperatures, but this time in the longer term. This takes us into *magnetic* ***annealing***, which is designed to definitively modify the material's properties by subjecting it to optimised thermal cycling. The temperatures generated during these cycles can be well below the temperature at which the material is formed. The phenomena involved have an effect similar to a local reorganisation in the material, and the extent of this reorganisation can be amplified by applying a strong magnetic field during the annealing phase.

When the annealing temperature approaches the temperature at which the material is produced, it becomes possible to change the material microstructure. Hence, an **amorphous** material can become **nanocrystallised**. Recent results from Le Ripault show that this kind of procedure can enhance the temperature stability of magnetic materials, which offers obvious advantages for applications.

Mechanical stress effects

Magnetostrictive effects cover all the possible couplings between a material's magnetic properties and its mechanical properties. The volume of the material changes when the magnetic properties are activated, such as when the temperature drops and falls below the Curie temperature. Similarly, when a magnetic field is applied to a magnetic material, it causes deformation.

Conversely, a mechanical stress applied to a magnetic material will cause a deformation that can in turn modify the magnetism of the material. On a scalar level, a change is observed in the material's magnetisation, which will tend to either align towards or away from the direction in which the stress force is applied. Figure 2 provides an illustration of the influence of a stress on the free energy of a magnetic **crystal**. The vectorial distribution of this stress will dictate the direction of magnetisation within the material. This directional orientation in response to the stress depends on the sign of the magnetostriction coefficient of the material. In crude terms, this coefficient gives an expression of how sensitive the material's magnetism is to stress.

Research is currently focused on pairing magnetic materials with **piezoelectric** materials. Piezoelectric materials are deformed when subjected to an electric field. This deformation can, when transferred to the magnetic material, modify its properties. Recent research led by a University of Western Brittany (**Université de Bretagne occidentale**) team from the Laboratory of Electronics and Telecommunications Systems (UMR 6165) in tandem with the CEA/DAM Materials Science Department has clearly highlighted the potential for this kind of pairing. Applications-wise, the aim is to produce 'frequency-agile' components, i.e. components whose properties can be made 'controllable', in order for example to adapt them to the telephone signal receiving frequency. For magnetic materials, this control has traditionally been operated using a magnetic field. The advantage of using an electric field on a piezoelectric material is that it becomes possible to cut down on electricity consumption while eliminating the footprint area needed when using coils to generate a magnetic field.

High-frequency magnetism shows great promise

Hence, although the environment surrounding magnetic materials can strongly disrupt their properties, it can also spawn new innovations, and there is often only a short step between the two. Current research is therefore working towards stabilising the environmental sensitivity of the properties of the materials while at the same time capitalising on this environment in order to create new functional applications. The magnetic field is no longer the sole source of control over these properties. Work is currently aimed at developing and integrating these principles so that high-frequency magnetism can become an even more high-tech industrial reality.

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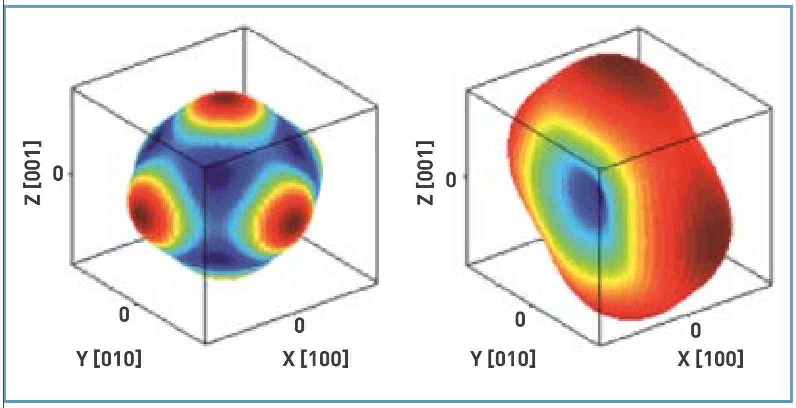

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Figure 2.
Free-energy-surface deformation in a magnetic crystal under stress, which in this example follows the x-axis (on the left, without stress; on the right, with stress). The blue surface areas correspond to the directions of easy magnetisation.
When a stress is exerted, the magnetisation will tend to align to the x direction.

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.

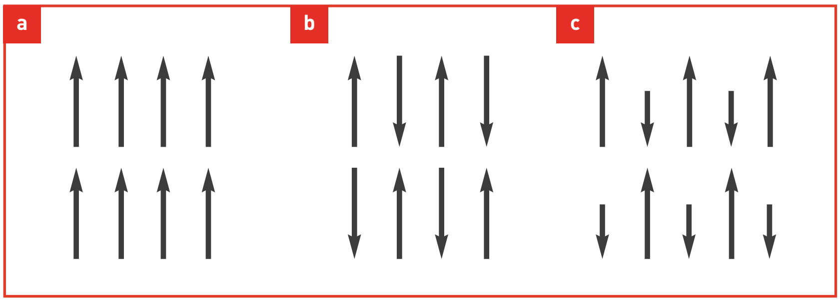


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

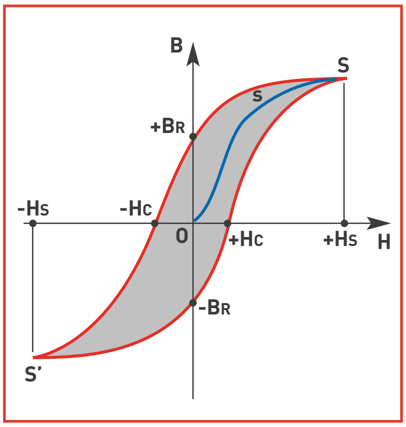


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches 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).

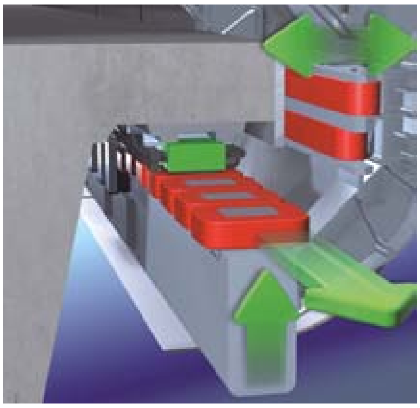
2. Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field, 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.