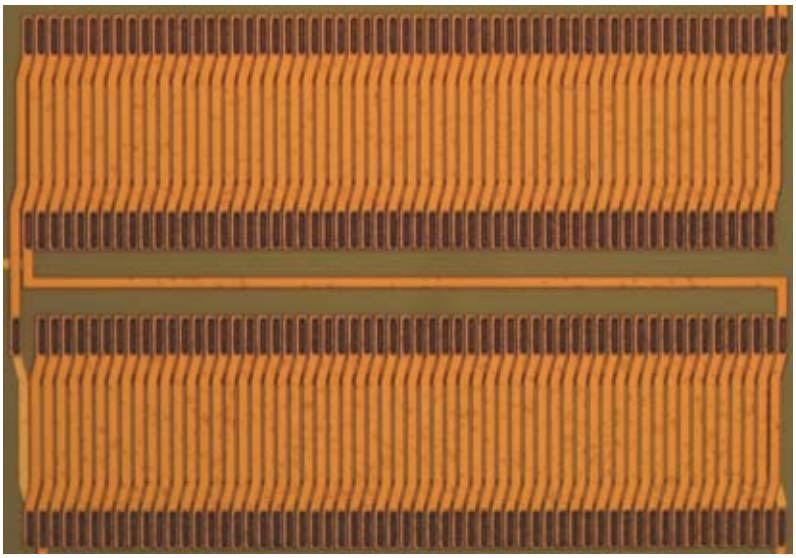
The **micro-fluxgate**, or how to combine **precision** and **economy** in a **magnetometer**

Armed with the latest miniaturised "fluxgate" magnetometers, physicists at the CEA-LETI are now able to offer high-precision, low-consumption magnetic sensors set to open up a host of novel 3D nomad applications.

One of the biggest challenges facing researchers in the micro-sensor domain is to engineer integrated 3D magnetic sensors that combine high performance with low power consumption. The high demand for such applications is fuelling a thriving research agenda in this domain. The systems presently on the market are not equipped to capture high-dynamics motion and, as yet, there is no large-scale production of low cost but high-performance solutions. Nonetheless, there is a wealth of diverse applications to aim for including spatial orientation and positioning functions incorporated in a mobile phone or a wrist watch, position detection and recognition instruments that improve how subjects under medical supervision are monitored, systems that couple magnetic sensors with accelerometers to facilitate the capture of dynamic motion, man-machine interfaces for virtual reality and video game applications, to name just a few.
The CEA-LETI's (Laboratory of Electronics and Information Technologies) DIHS (Heterogeneous Integration of Silicon) and DCIS (Design and Systems Integration) Departments have joined forces to design and develop a **magnetometer**, comprising a micro-fluxgate sensor and a new-generation **ASIC**, capable of mastering miniaturisation, performance and low power consumption constraints.



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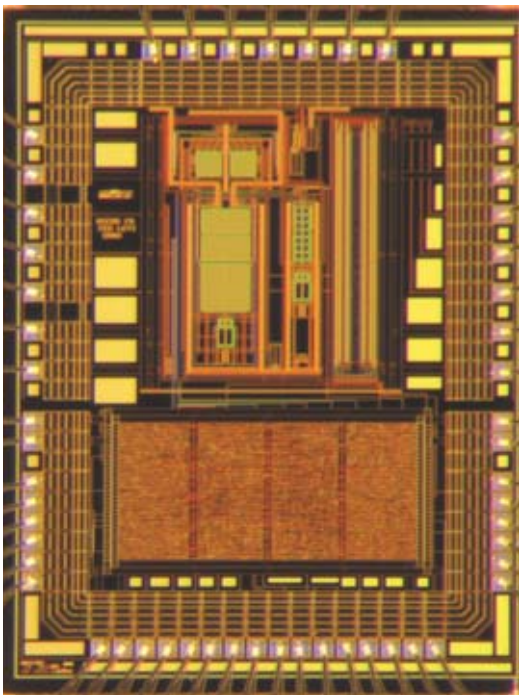
Micro-fluxgate sensor with a surface area of less than 1 mm². The sensor component consisting of two identical cores around which are wound excitation and detection coils covers a surface area of 800 µm x 500 µm. The final surface area including the electrical connection pads covers 800 µm x 700 µm.

A high-precision magnetic sensor

Fluxgate micro-sensors exploit the **hysteresis** of **soft magnetic materials** (Focus A, ***The different types of magnetism***, p. 10). The system sensor component, comprising copper **coils** wound around **Permalloy ferromagnetic** cores, is overlaid onto **silicon** substrates using jointly-developed manufacturing techniques. A first series of coils excites these cores via a known **magnetic field**, which is superimposed on the ambient magnetic field; a second series of coils is used to observe the cores' response to this excitation and thus arrive at a measurement of the ambient magnetic field along the coil-core axis. The sensor function is fully optimised using an electronic ASIC-type control developed by microelectronic integrated circuit manufacturers. This control operates and slaves the sensor, and shapes the output signal.
Micro-fluxgates have an inherently high metrologic performance characterised by exceptionally low noise levels and high stability, particularly in response to temperature variations. They are therefore able to measure magnetic fields to an extremely high level of precision. For example, a compass using micro-fluxgate technology would be able to achieve an angular accuracy of well under 1°, while the products currently on the market in this sector only guarantee an angular accuracy of 5° at most. These characteristics make it a potential rival for today's most widely used sensor technologies, such as **Hall effect** sensors or **magnetoresistive** sensors, provided that it can further cut down on power consumption and final cost. At equivalent performance levels, improving the system makes it possible to reduce the surface area of the two chips, thus lowering the power input. Engineers are now on the threshold of successfully demonstrating the performance-cost fit that will open up the mass market sector to micro-fluxgate



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Electronic control for the micro-fluxgate sensor based on the novel excitation and detection principle. The large surface area (9 mm²) of this first ASIC illustrating method feasibility is significantly reduced once the test and evaluation pads and modules for each sub-unit have been removed.

magnetometers, even for three-axis requirements (magnetic field measurements taken along the three axes of a spatial referential).

A novel low consumption electronic architecture

The main concern here was to find a way of reducing power consumption, which meant the designers had to completely rethink the sensor's basic operating architecture. While a fluxgate is typically based on a synchronous detection method - a periodic signal with frequency *f* is injected into the excitation coils of ferromagnetic cores; the ambient field is then measured by detecting the harmonic (*2f*) that appears in the detection coils -, a novel detection principle that exploits transient and high frequency effects has now been developed and patented. Instead of a periodic signal, the magnetic circuit is now excited via short, low-voltage pulses that nevertheless have extremely steep edges. The ambient magnetic field is measured by simply integrating the response of these cores with a suitable short time interval. This method naturally uses less power than a system based on synchronous detection. Another advantage is that, as the electronics are configurable, the magnetometer's power consumption can be regulated to fit the desired **resolution**, by modifying the pulse repeat pitch for example. A prototype demonstrator of this electronic architecture made it possible to validate the concept and establish that this new technique will provide equivalent metrologic performance.

Miniaturising to increase performance levels

This new excitation method exploits the high-frequency performance of thin-layer magnetic materials. Micro-fluxgates are able to operate at excitations of several hundred **MHz**, which correspond to voltage pulse rise times of a few nanoseconds (1 ns = 10^{-9} s). This makes it possible to reduce the size of the sensor, and thereby further enhance its frequency response. It is also necessary to push back the conventional frequency limits due in particular to the creation of **eddy currents**, to the motion of the **walls**, and to the configuration of the **magnetisation domains** in ferromagnetic cores. The transposition of magnetic core "lamination" techniques to the microtechnologies domain has now been developed and validated. These cores resemble a *mille-feuille* of alternately stacked ferromagnetic material layers and thin insulating layers. This technological breakthrough will improve sensor performance by enhancing its response to rising edges generated in the range of 2 to 20 ns. This novel approach combined with a sensor surface area of about 1 mm² makes it possible to achieve a power consumption of about 1 mW per measurement axis, thus opening up possibilities for a broad range of mainstream applications. Engineers have also been working upstream to develop and integrate a three-axis **monolithic** sensor. A number of patents have been filed aimed at further reducing the size of the cores and improving certain parameters such as noise levels, residual offset voltage(1), sensor with common mode rejection(2), etc.

Opening up to mainstream markets

The LETI-developed micro-fluxgate sensor is finally able to meet the specifications of a broad range of applications for which the combined constraints of cost, performance, power consumption and footprint have so far never been met. This development specifically targeted the fast-growing market for nomad applications requiring this type of sensor. It will therefore come as no surprise to find micro-fluxgates in your next mobile phone, built to help you find your way around the streets of a strange town, or improve your tennis serve or your golf swing via integrated mechanisms that capture and analyse your sports technique, and yet no bigger than a pinhead.

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(1) Residual offset voltage: residual voltage measured when the sensor is placed in a zero magnetic field.

(2) Common mode rejection (by analogy with electronics): method of deleting unwanted contributions that are not part of the signal to be measured, in particular the excitation signals injected in the two sensor channels. In electronics, the Common Mode Rejection Ratio (CMRR) is a numerical value that quantifies how well a differential amplifier rejects input signals common to both input leads.

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.

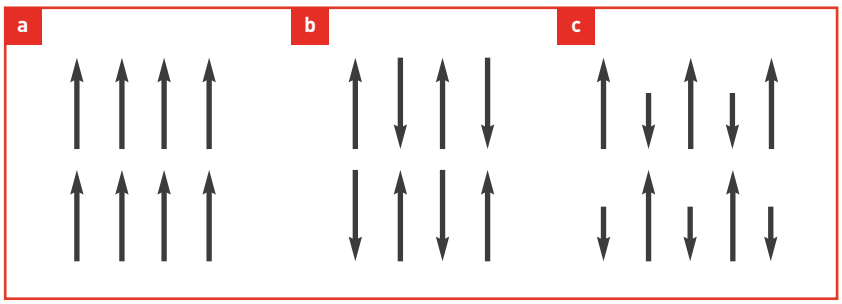


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

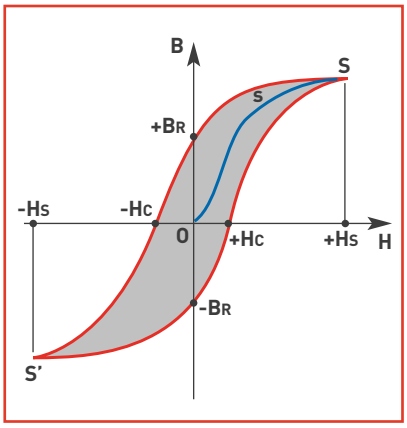


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches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

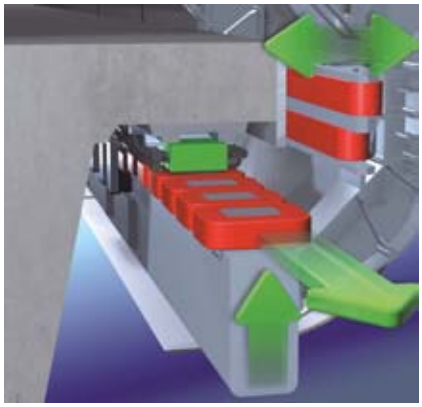
2. Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field,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