Fluxgate Magnetic Sensor System for
Electronic Compass

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A Laurie...
e a tutta la mia famiglia...
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Chapter 1: Introduction
1 Introduction

High demand of today’s market stimulates the development of high resolution, small and low power magnetic sensors. New applications, such as electronic compass, magnetic ink reading, vehicle detection, non-destructive testing of metals and detection of markers in medicine, are emerging everyday.

The goal of this thesis is the development, fabrication, with standard CMOS technology, and characterization of an integrated micro-fluxgate. The objective is to design a magnetic sensor for portable compass application, operating at 5 V voltage supply provided by batteries, and with a power consumption of few milliwatt. The goal is accomplished using a magnetic core 1 µm thick, realized with the DC-magnetron sputtering technique.

1.1 Applications

The applications areas of magnetic sensors can be divided in two main categories [1-4]: direct and indirect measurements.

In direct measurements the desired information are the magnetic field strength and its direction. Examples for such applications are:

- readout of magnetic data storage media such as tapes, credit cards or hard disk [5];
- measurement of Earth magnetic field for navigation purposes [6-7];
- measurement of biomagnetic fields, i.e. to map the function of heart or brain [8];
- control of magnetic apparatus [3, 4].

In indirect application, non magnetic signals are detected by using the magnetic field as intermediary carrier. In this case the non magnetic information is transferred into the magnetic domain and then measured using a magnetic sensor. Examples are the measurement of:

- electric current carried by a conductor evaluated measuring the generated magnetic filed [9];
- mechanical quantities, such as linear and angular positions, or displacement and velocity of moving parts evaluated by monitoring the change in a magnetic field imposed with a
permanent magnet [3, 4].

Each of the above mentioned application comes with specific requirements on sensor performance. The most important specifications includes [3, 4]: magnetic field resolution, sensitivity, linearity, offset, power consumption, size, spatial resolution, noise and temperature coefficients.

It is possible to distinguish two distinct application areas. The first one demands accurate and high resolution sensing techniques, while cost is not the main factor. The second one is the area of large scale applications where inexpensive, batch fabricated magnetic field sensors are requested.

Modern magnetic sensors are expected to be small, sensitive, low noise and stable. Trends in consumer products drive the demand for low power consumption, as well as operation from low voltage batteries.

### 1.2 Magnetic field sensors technologies

The available magnetic sensor technologies are summarized in Fig. 1-1 together with a comparison of their sensitivity ranges.

<table>
<thead>
<tr>
<th>Magnetic Sensor Technology</th>
<th>Detectable Field (Tesla)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>Search-Coil Magnetometer</td>
<td>[ ]</td>
</tr>
<tr>
<td>Fluxgate Magnetometer</td>
<td>[ ]</td>
</tr>
<tr>
<td>Optically Pumped Magnetometer</td>
<td>[ ]</td>
</tr>
<tr>
<td>Nuclear Precession Magnetometer</td>
<td>[ ]</td>
</tr>
<tr>
<td>SQUID Magnetometer</td>
<td>[ ]</td>
</tr>
<tr>
<td>Hall Effect Sensor</td>
<td>[ ]</td>
</tr>
<tr>
<td>Magnetoresistive Magnetometer</td>
<td>[ ]</td>
</tr>
<tr>
<td>Magnetodiode</td>
<td>[ ]</td>
</tr>
<tr>
<td>Magnetotransistor</td>
<td>[ ]</td>
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<tr>
<td>Fiber Optic Magnetometer</td>
<td>[ ]</td>
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<tr>
<td>Magneto Optical Sensor</td>
<td>[ ]</td>
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<tr>
<td>Magnetoimpedance Magnetometer</td>
<td>[ ]</td>
</tr>
</tbody>
</table>

**Fig. 1-1.** Comparison between available magnetic sensor technologies.
A possible classification in term of sensitivity and class of applications is shown in Table 1.

Table 1. Categorization of magnetic sensor application

<table>
<thead>
<tr>
<th>High Sensitivity</th>
<th>Medium Sensitivity</th>
<th>Low Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition:</strong></td>
<td><strong>Definition:</strong></td>
<td><strong>Definition:</strong></td>
</tr>
<tr>
<td>• Measuring field gradient or differences due to induced (in Earth magnetic field) or permanent dipole moments.</td>
<td>• Measuring perturbations in the magnitudes and/or direction of Earth magnetic field due to induced or permanent dipole moments.</td>
<td>• Measuring fields stronger than the Earth magnetic field.</td>
</tr>
<tr>
<td><strong>Major application:</strong></td>
<td><strong>Major application:</strong></td>
<td><strong>Major application:</strong></td>
</tr>
<tr>
<td>• Brain function mapping;</td>
<td>• Magnetic compass;</td>
<td>• Noncontact switching;</td>
</tr>
<tr>
<td>• Magnetic anomaly detection.</td>
<td>• Mineral prospecting.</td>
<td>• Current measurement.</td>
</tr>
<tr>
<td><strong>Most common sensor:</strong></td>
<td><strong>Most common sensor:</strong></td>
<td><strong>Most common sensor:</strong></td>
</tr>
<tr>
<td>• SQUID;</td>
<td>• Search coil;</td>
<td>• Search coil;</td>
</tr>
<tr>
<td>• Optically pumped magnetometer.</td>
<td>• Fluxgate;</td>
<td>• Hall sensor.</td>
</tr>
<tr>
<td></td>
<td>• Magnetoresistance.</td>
<td></td>
</tr>
</tbody>
</table>

The solutions suitable for the measurement with high sensitivity and accuracy of low magnetic fields, in the microtesla or tens of microtesla range (such as the Earth's magnetic field, which has a maximum intensity of about 50 µT), are [10-13]:

- Search-coil magnetometer;
- SQUID (Superconducting Quantum Interference Devices) magnetometer;
- Magnetoresistive magnetometer;
- (Giant) Magnetoresistance magnetometer;
- Fluxgate magnetometer.

### 1.3 Search-coil Magnetometer

The operating principle of search-coil magnetometer is based upon Faraday’s law of induction:
Introduction

\[ V_{IND} = -\frac{d}{dt}\Phi_c \]  

[1]

The voltage induced in the coil, \( V_{IND} \), is proportional to the time rate of change of the flux linked with the same coil (\( \Phi_c \)). It is possible to use the search coil with two different operating modes:

1. Sensing AC magnetic field with a stationary coil.
2. Sensing DC magnetic field with a moving coil.

In the evaluation of DC magnetic fields the driving mechanism is the core of the sensor. Moreover, taking into account the possible application of this sensor in low field measurement and very compact system (like an integrated solution) the driving mechanism is an hard task. For this reason nowadays no integrated solution exists.

1.4 SQUID Magnetometer

The principle of measuring magnetic field using superconducting materials is based on the Meissner effect (the expulsion of magnetic flux) and flux quantisation which result in the constancy of the magnetic flux through a superconducting closed loop. If such a superconducting loop is placed in an external field \( H_{ex} \), a shielding current, know as the supercurrent \( I_S \), will circulate around the inner surface of the ring such that the total magnetic flux, \( \Phi_I \), inside the ring is quantised and composed of the flux \( LI_S \) (\( L \) is self inductance around which the supercurrent flows) and the flux \( \Phi_{EX} \) of the external field:

\[ LI_S + \Phi_{EX} = \Phi_I = m\Phi_0 \]  

[2]

where \( \Phi_0 = 2.07 \times 10^{-15} \) Wb is the flux quantum and \( m \) an integer. Thus the superconducting ring responds to any change in external flux by setting up an equal but opposite flux. Provided that the supercurrent value does not exceeds the critical current density, \( I_c \), for as long as the superconducting specimen remains superconducting, \( \Phi_I \) will remain constant, and quantised, at the same value. This behaviour, coupled with the Josephson effects, provides the operational basis of the SQUID [13]. A Josephson junction, as named after Brian D. Josephson who discovered the structure in 1962, is effectively a weak link between two
superconductors that is capable of carrying supercurrents below a critical value $I_c$. The ‘weak link’ can be either a thin layer of insulator, an area where the superconductor itself narrows to a very small cross-section, or a superconducting bridge between two superconducting sections. When a superconducting ring interrupted by a weak link is exposed to an external magnetic field, a shielding supercurrent flows around the inner surface of the ring via the weak link. However, in this case the supercurrent will be an oscillating function of the magnetic field intensity, such that it first rises to a peak as the field increases, then falls to zero then increases again and so on. In a SQUID, these periodic variations are exploited to measure the current in the superconducting ring and, hence, the applied magnetic field. There are two types of SQUIDs: rf and dc. In both types, the device consists of a superconducting ring interrupted by one Josephson junction, in the case of the former, or two Josephson junctions in the case of the latter, as depicted in Fig. 1-2. The difference between the two is in the nature of the biasing current being an rf or a dc. In either type, the special properties of the Josephson junction cause the impedance of the SQUID to be a periodic function of the magnetic flux threading the ring.

In terms of performance, SQUIDs have excellent characteristics that comprise true dc response, wide band-width, zero phase distortion and, for the DC SQUID type, energy sensitivity better than $10^{-32} \text{ J/Hz}$ (equivalent to a magnetic flux noise of $10^{-6} \Phi_0 \text{ Hz}^{-1/2}$ at frequencies down to few Hz), as well as high degree of linearity and dynamic range.
Since their commercialisation few decades ago, SQUIDs have evolved from a mere specialised laboratory measurement instrument that operates in the sub-nano/pico range of magnetic field, to systems routinely used in such diverse applications as neuromagnetism (where signal levels of $10^{-12}$ T or lower are involved), magnetic resonance and geology. Recent progress in high-$T_c$ superconductors (HTS) technology has increased the operating temperatures of SQUID devices. On the other hand, the steady progress in HTS thin film technology has enhanced the sensitivity of these devices [14]. This has renewed various efforts to produce more commercial acceptance of these devices.

1.5 Magnetoresistive Magnetometer

1.5.1 Anisotropic Magneto-Resistance (AMR)

The magnetoresistive effect was first observed by William Thomson in ferromagnetic metals in 1856 [3, 4]. The discovery had to wait more than 100 years before its utilization. In fact, up to the development of the thin film technology the magnetoresistance effect didn’t find a commercial application.

Materials such as Permalloy (NiFe) can be given a preferred magnetic orientation such that a current passed through a ribbon of the material magnetizes it in a direction parallel to the direction of the current. If a magnetic field is then applied, perpendicular to the current, the direction of magnetization will rotate toward the direction of the magnetic field. Finally, resulting in a variation of the thin film resistance [12, 13]. Basic principle of operation of the anisotropic magnetoresistance (AMR) sensors is shown in Fig. 1-3.

![Diagram](image)

**Fig. 1-3. Basic configuration of the magnetoresistance sensor.**
Introduction

The resistance change roughly as the square of the cosine of the angle through which the direction of the magnetization is rotated:

\[ R = R_0 + \Delta R_0 \cos^2 \theta \]  \hspace{1cm} [3]

\( R_0 \) and \( \Delta R_0 \) are material parameters. It is obvious from this quadratic equation that the relation between the resistance of the thin film and the magnetic field is non-linear (Fig. 1-4) and in addition, each value of \( R \) is not necessarily associated with a unique value of \( H \). In this basic form, the magnetoresistance effect can be used effectively for rotational speed measurements, which do not require linearization of the sensor characteristic.

\[ \text{Resistance} \]
\[ \text{Magnetic field} \]
\[ R_0 \]
\[ \Delta R_0 \]

**Fig. 1-4. Characteristic Resistance-Magnetic field of a thin film magnetoresistance.**

On the other hand, when the direction of the magnetic field has to be evaluated the linearization of the sensor output is necessary. The magnetoresistive effect can be linearized by depositing aluminium stripes (Barber poles), on top of the permalloy strip at an angle of

\[ \text{Permalloy} \quad \text{Barber pole} \]
\[ \text{Magnetization} \]

**Fig. 1-5. Barber pole configuration for magnetoresistance sensor.**
45° to the strip axis (see Fig. 1-5). As aluminium has a much higher conductivity than permalloy, the effect of the Barber poles is to rotate the current direction by 45° [15]. Barber-poles inclined in the opposite direction will result in the opposite sign for the R-H characteristic, making it extremely simple to realize a Wheatstone bridge set-up. In the case of the Barber pole configuration the characteristic resistance versus magnetic field is plotted in Fig. 1-6.

![Graph showing the resistance vs magnetic field characteristic for the barber pole configuration](image)

The AMR are suitable for the magnetic sensors that require a good sensitivity, typically 10 V/VT (sensitivity normalized to the excitation voltage), in the range up to 200 µT [16]. They have a bridge resistance of around 2 kΩ, noise lower than 10 nT/√Hz at 1 Hz, wide operating temperature range and an offset which is more stable than thus of the Hall sensors. The AMR properties are well defined if the magnetization of the material is in the correct direction. Therefore, if a high magnetic field is applied to the sensor it can exhibit a hysteresis. In fact, if the field is strong enough to flip the magnetization, for the same external magnetic field, we get an output of different sign. To prevent that and to improve the performance of the AMR, the sensors have built in flipping coils, as well as feedback coils to extend the linear working range. Flipping field, created by a short current pulse of up to 2.8 A, and a bias voltage of ±10 V is needed to reduce the hysteresis to a value of 100 nT and a noise of 2 nT/√Hz. For the low voltage application the limiting factor will be the resistance of the flipping coils which will leads to a current pulse of 1 A, hysteresis of 2 µT and the noise level of about 4 nT/√Hz [17].
1.5.2 Giant Magneto-Resistance (GMR)

The giant magnetoresistance effect was first observed in the 1988 in metallic thin films of magnetic layers, of few nanometers thick, separated by an equally thin non-magnetic layer [4]. The net effect observed is a large decrease in the resistance when an external magnetic field is applied to the thin films.

The giant magnetoresistance phenomenon is partially due to the increased resistivity of conductors of a few atomic layers thick. In bulk material form, conduction electrons can travel a long distance before they scatter or change their direction, because of a collision with another atomic particle. The average length that the electron travels before being scattered is called the mean free path length. In the case of very thin material the electrons cannot travel the maximum mean free path length. It is more likely that the electron will reach the boundary of the material and scatter there. This result in a lower mean free path length for a very thin material, therefore in a higher electrical resistivity. In order to take advantage of this effect, GMR films are manufactured with very thin layers of alternating magnetic and non-magnetic materials. This is done to allow magnetic modulation of the electron spin in the materials. The spin dependence of conduction electrons in magnetic materials, along with the increasing resistivity at very small material thicknesses, combines to make the GMR effect possible.

In Fig. 1-7 the basic configuration of the giant magnetoresistance is shown. The figure shows two magnetic material layers, sandwiching a non-magnetic interlayer. The magnetic layers are designed to have anti-ferromagnetic coupling. This means that the magnetization of these layers is opposite to each other when there is no external magnetic field applied to the material.

![Fig. 1-7 Giant magnetoresistance configurations: without external magnetic field applied.](image)

The conduction electrons in magnetic materials have a spin characteristic. The electrons are normally referred to as spin up electrons when the material is magnetized in one direction,
and spin down electrons when the material is magnetized in the opposite direction. In Fig. 1-8 two electrons free path length are indicates. Notice that the electrons tend to scatter off at the two GMR material interfaces. This is because the electrons from the spin up layer are trying to enter the spin down layer, and vice versa.

Fig. 1-8 Cross section of a GMR configuration with the indication of the mean free path length: no external field is applied.

Because of the differences in the electron spins, it is more likely that the electrons will scatter at these interfaces. In this case the mean free path length of the conduction electron is fairly short, resulting in a relatively high electrical resistance.

If an external magnetic field of sufficient magnitude is applied to this GMR material, it will overcome the antiferromagnet coupling of the magnetizations between the two magnetic

Fig. 1-9 Cross section of a GMR configuration with the indication of the mean free path length: in presence of the external magnetic field.
layers. At this point all the electrons in both films will have the same spin. It will then become easier for the electrons move between the two layers (Fig. 1-9). Note that the mean free path length of the electrons has now increased. This results in an overall lower electrical resistance for the GMR material. Nowadays sensors are of micron dimensions and can produce >10%/Oe resistance change at room temperatures. The solution with the better sensitivity, referred to a Wheatstone bridge configuration with resistance of 5 kΩ, is that gives a sensitivity of about 47 V/VT [13].

1.6 Giant Magnetoimpedance Magnetometer

The giant magneto-impedance (GMI) effect includes a large and sensitive change in an ac voltage measured across a soft magnetic specimen subjected to a high frequency current under the effect of a dc (or lower frequency) magnetic field [13]. A typical circuit is shown in Fig. 1-10. Two conditions are important to get a large change in impedance, the first one is the frequency of the excitation current that must be such to insure a strong skin effect, and the second is the magnetic structure that has to provide an ac transverse permeability sensitive to the external field. At frequency of few MHz, these conditions are realised in 30 µm diameter CoFeSiB amorphous wires having circular domain structure, showing the impedance change as much as 40–100%/Oe [18, 19].

Fig. 1-10 Simplified circuit of GMI configuration.

Because of its high sensitivity in combination with other advantageous properties, the GMI effect has received much attention as a candidate to develop new generation micro-magnetic sensors. Magnetic sensors based on GMI in amorphous wires were recently developed, which
demonstrate the field detection resolution of 100 pT for the full scale of ±150–200 µT with a sensor head length of less than 1 mm, and power consumption of less than 10mW. Taking into consideration a configuration compatible with the standard CMOS technology, the sputtered Co-rich amorphous films typically exhibit a lower GMI sensitivity of 4–10%/Oe because of a higher anisotropy field induced during the fabrication process and annealing. To realise high frequency operation and avoid microwave problems, such as impedance mismatching, the GMI elements have to be assessed for use with self-oscillation circuits, such as Colpitts oscillator or multivibrator. To obtain good linearity and stability, the GMI circuits have to be completed with a detector (de-modulator), a differential amplifier and a negative feedback loop. In the Colpitts oscillator configuration, having a frequency of 50–100MHz, the typical field sensing resolution is 1 nT.

Using GMI elements, new sensitive and quick response micro magnetic sensors are being developed for advanced intelligent measurement and control system [20], including non-destructive testing, highly accurate rotary encoder heads, medical electronics, and automobile control.

1.7 Objectives of the research activity

The scope of this research activity is the development of a small, high sensitivity and low power consumption magnetometer. The sensor to be realized needs to have two axes sensitivity and its fabrication process has to be compatible with the standard CMOS technology. This sensor should to be able to detect the Earth magnetic field for compass application, therefore with good sensitivity and linearity in the range up to 50 µT. At present, resolution and offset stability of AMR sensors is hardly sufficient for the detection of the Earth magnetic field. They could be applied for this purpose only using a complicate assembling arrangement. Moreover, the GMR sensors still suffer from significant hysteresis error, important factor for the DC magnetic field measurement. According with the results of the world research activity the most promising are expected form the fluxgate technology. The most important performance are actually given by [40] with a complex CMOS post-process for the core realization and with a minimum power consumption of 8.5 mW. Improvements in this kind are expected with a better post-process material deposition, able to realize magnetic core with smaller thickness, like magnetron sputtering technology.
Chapter 2, starting with the physical principle of the fluxgate magnetic sensor, shows the different existing configuration.

Chapter 3 presents the printed circuit board realization to evaluate the sensor performance when the commercial available amorphous core is utilized. In this chapter the performance of different configuration of planar fluxgate, realized using the commercial available materials, are evaluated.

Chapter 4 takes into consideration the possible industrial technology that could be used for the core deposition. Therefore polishing and chemical etching, electroplating and DC-magnetron sputtering technique were analyzed in detail.

In Chapter 5 a possible integrated planar micro-fluxgate configuration is analyzed. The performance of the realized DC-magnetron sputtering core was evaluated with an suitable set-up.
Chapter 2: Fluxgate principle
2. **Fluxgate Principle**

A Fluxgate magnetometer is a device for measuring magnetic fields by utilizing the non-linear magnetic characteristic of ferromagnetic core material as the sensing element \[3, 4\]. It is a directional device, measuring the component of the field parallel to the magnetic core.

Fluxgate magnetometers were first introduced in the 1930’s \[41\]. Some development was for airborne magnetic surveys and for submarine detection during the World War II. They were further developed for geomagnetic studies, for mineral prospecting and for magnetic measurements in outer space. They have also been adapted and developed for various detection and surveillance devices, both for civilian and military use. Despite the advent of newer technologies for magnetic field measurement, fluxgate magnetometers continue to be used successfully in all of these areas, because of their reliability, relative simplicity, and economy.

With the beginning of the space age in the late 1950’s, the fluxgate was adapted to space magnetometry application. Even as early as 1948, a three-axis fluxgate was flown in an Aerobee sounding rocket to a peak altitude of 112 km. The first satellite to carry a magnetometer of any type was Sputnik 3 which was launched in 1958 and carried a servo oriented fluxgate. Luniks 1 and 2 (Russian lunar probe), both launched in 1958, carried triaxial fluxgate. The USSR Venus probe launched in 1961 carried two single-axis fluxgate. The first American satellite to carry a fluxgate was earth orbiting Explorer 6 launched in 1959. Some satellites or space probes carrying fluxgate have included USSR mars probe, Nasa Explorer 12, 14 and 18, Mariner 2 (Venus) the USSR earth-orbit Electron 2 and Apollo 12, 14, 15 and 16.

Nowadays, developments for this sensor are expected in the solution based on CMOS technology for the coils and CMOS compatible post-process technology (i.e. sputtering) for the core deposition. All that for the possibility to realize micro-fluxgate with very low power consumption (few milliWatt) over a least spatial occupation.

### 2.1 Operating Principle

The basic structure of a Fluxgate sensor, shown in Fig. 2-1, consists of two coils: a primary (excitation) and a secondary (sensing) coil, wrapped around a common high permeability ferromagnetic core. The excitation current \(I_{\text{exc}}\) flowing through the excitation coil produces a field that periodically saturates the soft magnetic material core (in both directions). In
saturation (Fig. 2-1b), the permeability of the core drops and the DC flux associated with the DC magnetic field $B_0$ to be measured decreases. The name of the device derives from this “gating” of the flux that occurs when the core is saturated. When the field to be measured is present the 2\textsuperscript{nd} harmonic, and also higher order even harmonics, appear in the voltage $V_{\text{ind}}$ induced in the sensing coil. This behaviour is strictly related to the transfer function of the system that is the hysteresis loop of the magnetic field. Without an external magnetic field, exciting the excitation coil with a current at frequency $f$, the induced voltage will be due to the sum of different harmonic at frequency $f$, $3f$, $5f$, $7f$ ecc., in according with the odd transfer function. When an external magnetic field is applied, the different working point involves no symmetry in the transfer function and therefore, together with the odd harmonics, the even harmonics will appear. The amplitude of this even harmonics, that represents the sensor output, will be proportional to the intensity of the external magnetic field [42-45].

The amplitude of the induced voltage is described by the Faraday’s law:

$$V_{\text{ind}} = -N_{\text{sens}} \cdot S \cdot \frac{d}{dt} \left[ \bar{B}(t) \right] = -N_{\text{sens}} \cdot S \cdot \frac{d}{dt} \left( \bar{\mu} \cdot N_{\text{exc}} \cdot I_0 \cdot \sin(2\pi f_{\text{exc}} \cdot t) \right)$$

[Eq.1]

where $N_{\text{sens}}$ is the number of turns of the sensing coil, $N_{\text{exc}}$ is the number of turns of the excitation coil, $S$ is the cross section of the sensing coil, $l$ is the length of the excitation coil, $\mu$ is the magnetic permeability and $I_0 \cdot \sin(2\pi f_{\text{exc}} \cdot t)$ is the sinusoidal excitation current at
Fluxgate principle

frequency \( f_{\text{exc}} \). The sensor sensitivity can be improved by maximizing the induced voltage, and this can be done using the following solutions:

- increasing the excitation frequency \( (f_{\text{exc}}) \); however, an upper limitation to \( f_{\text{exc}} \) is given by the cut-off frequency of the ferromagnetic material relative permeability;
- increasing the number of turn of the sensing coil \( (N_{\text{sens}}) \);
- increasing the cross section of the ferromagnetic material \( (S) \), considering that a larger cross-section requires a larger current to saturate the ferromagnetic material and hence the power consumption increases.

The main drawback of Fluxgate magnetic sensors realized with the schematic shown in Fig. 2-1 is the complex construction of the core and of the coils when they have to be realized within planar technologies (CMOS-IC or Printed Circuit Board), in which it would be desirable to fabricate the ferromagnetic core with a technological step on-top of the planar process. In these cases the solution shown in Fig. 2-1 can be difficult to implement. For this reason, new topologies of planar integrated micro-Fluxgate [26, 27, 32-34] were recently presented. For instance, a structure for a differential single axis planar Fluxgate magnetic sensor is shown in Fig. 2-2. The ferromagnetic core is placed over the diagonal of the excitation coil. Supplying the excitation coil with a suitable current, each half of the core periodically saturates in opposite directions, as illustrated in Fig. 2-3. When no external magnetic field is applied, the two sensing coils, connected in antseries, show an output voltage that ideally is zero.

![Fig. 2-2. Schematic of a double axis planar Fluxgate magnetic sensor in single axis configuration.](image-url)
By contrast, when an external magnetic field component is present and parallel to the core, the magnetization in one half of the core is in the same direction as the external magnetic field, while the magnetization of the other half of the core is in the opposite direction (Fig. 2-3). Therefore, the voltage induced in the two sensing coils is not the same and the differential output voltage increases its value, resulting in an amplitude modulation. In Fig. 2-4 three different cases are shown, when the external magnetic field was not applied and applied with two different values.

Fig. 2-3. Core magnetization and external magnetic field direction: because of excitation magnetic field each half of the core is magnetized in opposite direction.

Fig. 2-4. Fluxgate principle explained with the waveform of the magnetic field and of the voltage induced.
With a suitable core shape, e. g. cross shape, and with four sensing coils the structure proposed in Fig. 2-3 can be used as a double axis magnetic sensor [27]. Moreover, it can be observed that the same structure can be realized on the top of an IC (achieving small dimensions and low power consumption) or in PCB technology [46-50]. The PCB solution is not affected by the main disadvantages of integrated Fluxgate, where the ferromagnetic material has to be deposited during the integration process, or PCB Fluxgate with coils wrapped around the core, where the ferromagnetic material is introduced as a layer of a multilayer PCB.

On the other hand a drawback of the planar Fluxgate is that the coupled magnetic field is much smaller than the magnetic field produced inside the coils (as in the structure of Fig. 2-1).

### 2.2 Fluxgate magnetic sensors: state of the art

Compared with the presented solutions the best trade-off between cost and performance, for the sensing of low magnetic field, is given by the fluxgate magnetometer [10-13]. It is capable of measuring static or slowly variable magnetic fields [21] with amplitude between 100 nT and 1 mT achieving a resolution of about 0.1 nT. The absolute precision of presently available fluxgates is about 100 nT and can reach 1 nT for the best devices. These sensors exhibit an offset whose temperature coefficient is below 0.1 nT/°C, while the sensitivity temperature coefficient is usually between 30 and 50 ppm/°C. In terms of dynamic range and resolution fluxgate magnetometers perform better than the Hall effect sensors and are preferable with respect to SQUIDs because of their lower cost and size.

Fluxgate magnetometers exploit a soft magnetic material (i.e. with a low coercitive field $H_c$) that should have the following characteristics [22]:

- low losses at the excitation frequency, which is usually in the tens of kilohertz range;
- a low saturation induction value, which implies a low power consumption;
- a minimal magnetostriction effect;
- a low magnetic noise, due to easy reversibility of the magnetization, and a minimum number of structural imperfections;
- uniformity of the cross section.
Fluxgate principle

The most commonly used materials are permalloy 80 (NiFe con 80% Ni) and amorphous alloys (e.g. those based on cobalt).

The most widely used fluxgate magnetometer for low noise applications is the "parallel" type with ring core [23]. "Parallel" means that the excitation field and the field to be measured have the same direction. This type of sensor has an high sensitivity, 16.7 V/T, and a low power consumption thanks to the closed magnetic core and the minimum cross section. The main disadvantage of this solution is the size of the sensor. In the recent years the dimension of the sensors were continuously reduced to allow their use in reading magnetic heads, safety sensors, electronic compass and sensor arrays. Because of this the technology is evolving towards integrated magnetometers. A CMOS integrated fluxgate sensor, with coil wrapped around the core, is presented in [24]. The operating temperature range goes from -40°C to +125°C with a sensitivity temperature coefficient of 100 ppm/K and a sensibility as high as 30 mV/µT. This device has a good performance for its dimensions of 15 mm x 15.24 mm x 3 mm and a power consumption of 165 mW (33 mA, 5 V). While this value is relatively low, it is still to high for portable applications supplied by batteries. An alternative structure, that uses planar coils and magnetic material deposited over and below the excitation and sensing coils, is presented in [25]. In this case the sensor has a sensitivity of 28 V/T.

Since the deposition of the magnetic material, using electroplating or sputtering, in an intermediate step of the integration process is troublesome, a number of structures were proposed in which the material is deposed after the integration is completed [26]. In this case the sensor is realized in CMOS technology but the magnetic material is deposed over the coils when the integration process is over. The device proposed in [26] has a good sensitivity, 90 V/T, and an area of 25 mm².

In spite of the achievable performance, so far the quality of sputtered or electrodeposited permalloy is not sufficient for low-noise fluxgate applications, therefore etched patterns of thin tape of amorphous material commercially available are often used for the core of miniaturized sensors. Anyway, in recent years new technique was developed for deposition of soft magnetic material, e.g. RF-magnetron sputtering, in this sense improvement are expected [27-31].

For the commercially available solution, Vacuumschmelze (Germany) and Metglas (USA) produce amorphous Co-based alloy materials, called Vitrovac 6025 and Metglas 2714AZ [Appendix 1], respectively, with a thickness of about 20 µm, which is to thick for the application. Metglas 2714AZ was used in integrated fluxgate sensors [32]. In this case the magnetic material was further thinned with a mechanical-chemical process and finally glued.
Fluxgate principle

over the coils. The device shows a sensitivity of 3670 V/T, a low power consumption of 12.5 mW (17 mA peak current, 5 V), an area of 5.3 mm\(^2\) and has the capability of measuring two coplanar components of the magnetic field with the same structure. This sensor was recently improved as described in [33, 34].

The most commonly used readout technique is based on the second harmonic detection. The second harmonic component of the voltage induced in the sensing coil, which is proportional to the external field, is extracted by exploiting a synchronous demodulator.

Other readout strategies were developed recently. In [35] the sensing coil is short-circuited and a current-output fluxgate is obtained. In this case the quantity that is proportional to the external magnetic field is the current in the sensing coil. In both second harmonic and current-output fluxgate systems a capacitor is often connected to the sensing coil. This capacitor, together with the sensing coil inductance, forms a highly selective filter, giving rise to a tuned-output fluxgate.

Other readout techniques are described in [36, 37]. Until now, they were not fully proved to bring substantial advantages except simplification of the circuitry [38, 39].
Chapter 3: Printed Circuit Board Planar Fluxgate
3. **PCB Planar Fluxgate**

In this chapter the development and the comparison of different planar Fluxgate magnetic sensor structures realized in printed circuitry board (PCB) technology are presented. This work allowed us to define a design approach for the development of planar magnetic sensor and to verify the simulated performance with experimental results in order to validate the entire procedure. This is a key issue, due to the intrinsic critical sensitivity of the planar Fluxgate sensors. The choice of a PCB technology derived primarily from its reduced cost and easy prototyping. The proposed Fluxgate magnetic sensor structure does not require electroplating or sputtering processes for ferromagnetic material deposition because very thin amorphous metal is commercially available (25 μm for Vitrovac 6025X, 20 μm for Vitrovac 6025Z and 16 μm for Metglas 2714A) with very good magnetic characteristics [Appendix 1]. In this way it is possible to have quickly prototypes to be analyzed and compared with the simulation results. The design methodology can be naturally extended to the case of IC realization to achieve the development of a fully-integrated electronic compass. The first activity of this research was choosing a suitable model to develop and analyze the sensor. In literature several models to analyze Fluxgate magnetic sensors (i.e. [51, 52]) were reported. However, when the coils are not wrapped around the core [26, 27, 32-34] the typical formulation cannot be used and in this case the only option is to use correction factors or to perform simulations with appropriate software. For this reason a software tool based on the finite element method (FEM) was used to analyze the magnetic characteristics of the different PCB structures, with single and double axis of sensitivity. The developed structures were prototyped and tested (using a dedicated front-end circuitry, based on second harmonic detection, specifically realized to drive and read the sensor signals). The procedure was applied in the development of several prototypes with different shapes and design parameters. For all of them a good matching between simulation results and experimental data was demonstrated and this validates the proposed approach.
3.1 Single Axis PCB Fluxgate

3.1.1 The developed architecture

A single-axis planar Fluxgate magnetic sensor can be realized using an excitation coil and two sensing coils, placed in differential configuration. The layout of such a sensor is shown in Fig. 3-1. The excitation and sensing coils are placed on two different metal layers in a multilayer PCB structure. The ferromagnetic sheet core is a special amorphous alloy known under the trade name of Vitrovac 6025. This material was chosen primarily because of its extremely high relative permeability ($\mu_r \approx 10^5$). Its magnetic induction at saturation is 0.55 T. Two types of Vitrovac 6025 (6025X, with a thickness of 25 µm, and 6025Z with a thickness of 20 µm) were glued on the top of the PCB structure. Their difference is essentially in the shape of hysteresis loop, in fact, with a suitable heat treatment in presence of magnetic field, the hysteresis loop can be adjusted in a particular shape (i.e. Z). This property influences the peak of excitation current needed to obtain the ferromagnetic material saturation.

In the design of the above mentioned sensor structure, the following parameters are fixed by the technology used:

- excitation metal layers thickness: 30 µm;
- sensing metal layer thickness: 17 µm;
- metal lines pitch: 400 µm;
- Vitrovac thickness: 25 µm (6025 X) and 20µm (6025 Z).

In consideration of these technology parameters and of the maximum size of the sensor, we have to optimize the number of turns in the excitation coils and in the sensing coils and the shape of the coils themselves. The design of the sensor was carried out with a successive approximation optimization obtaining the following final parameter values:

- excitation coil: 30 turns with the total shape of 25.12 x 31.3 mm;
- sensing coils: 30 turns with the total shape of 31.3 x 31.3 mm.

In order to minimize the size of the sensor and considering that the excitation coil does not magnetize the ferromagnetic material positioned in its center (due to the distribution of the
magnetic field lines generated by the excitation current), the hole in the center of the excitation coil was set the minimum possible (Fig. 3-1).

The sensing coils were realized in a separate layer of the PCB structure, with a distance of 50 µm with respect to the layer of the excitation coil. The metal line of the sensing coils were overlapped with that of a side of the excitation coil, this for the correct magnetic coupling between excitation and sensing coil.

The geometrical dimensions of the ferromagnetic material were selected with a tradeoff with the current peak. A larger ferromagnetic material allows a better sensitivity to be achieved, but requires larger current. The dimensions were finally set to be 17000 x 7000 x 25 µm (for the Vitrovac 6025X) using different magnestostatic analysis, that will be reported in detail in Section 3.1.2. Then the center of the sensing coils were designed with the necessary hole to guarantee the maximum magnetic linkage.

A photograph of the final structure of the prototype realized is shown in Fig. 3-2.
3.1.2 Sensor development and simulation results

The software “Flux3D®” [53] that was used for the simulations is based on the finite element method. Several simulations were performed to find the best geometrical configuration of the ferromagnetic material on top of the device. After an iterative process of design optimization, the ferromagnetic material shape selected is a rectangular sheet with dimensions 17000 x 7000 x 25 μm (for Vitrovac 6025X). The main issue in this iterative optimization process is the creation of a good mesh for the model of the structure. The critical dimension of the device is the thickness of only 25 μm, which leads to a large number of elements in the mesh (288259 volume elements). To generate the finite element mesh, the user of “Flux3D®” has the following mesh generators available:

- The automatic (free) mesh generator: this is the default mesh generator. It generates tetrahedral volume elements (4 facets) and triangular surfaces.
- The extrusive mesh generator: it allows us to obtain by translation, rotation or affinity, a volume mesh arranged in layers, of a domain that can be obtained by extrusion. The meshes can be anisotropic and the obtained volume elements are prisms or bricks depending on the mesh type of the faces of the base (triangles or rectangles).
- The mapped mesh generator: it generates hexahedral volume elements (6 facets) and rectangular surfaces. A surface mapped mesh generator is often combined with an extrusive volume mesh generator.
- The linked mesh generator: it allows you to impose the same mesh over two or n patterns.
- The mixed mesh: it consists of combining different of the previous mesh generators for the same problem. The pyramidal elements ensure the mesh conformity.

In the mesh generation, the most convenient way of setting the size of elements is the use of mesh-point entities and the mesh-line entities. The principle of using the mesh-point entities requires the user to set the lengths to points. “Flux3D®” then meshes the lines, faces and volumes by observing as much as possible the lengths assigned to the points. The mesh-line command allows us to create nodes on lines, by observing the mesh-point entities assigned to points (geometric progression on the lines).
In the geometrical configuration realized, a combination of two mesh generators was used: the automatic mesh generator for the air volume and the mapped mesh generator for the ferromagnetic material volume. In addition, the mesh-point and mesh-line command were used to adjust the mesh generation. Particular attention was devoted to realize the mesh in the ferromagnetic material volume. This volume was divided in different pieces (as shown in Fig. 3-3 and also in Fig. 3-5) in order to create the best condition for the mesh generation. After this the mapped mesh generator was used for each sub-volume. Without this subdivision the mapped mesh generator does not operate properly, due to the very small thickness of the ferromagnetic material compared with the other geometrical parameter. Using the above mentioned procedure, we obtained the mesh shown in Fig. 3-4.

![Fig. 3-3. Indication of the ferromagnetic material volume subdivision.](image)

![Fig. 3-4. Mesh view near one ferromagnetic sheet core.](image)

The first analysis step is to evaluate the minimum peak excitation current value that guarantees the ferromagnetic material to saturate, for a given geometrical dimension of the excitation coils. Using different magnetostatic analyses a peak current of about 700 mA turned out to be sufficient to saturate the Vitrovac with the chosen geometrical dimension of 17000 x 7000 x 25 µm. Fig. 3-5 shows the magnetization of the material under these operating conditions.
The second analysis regards the induced voltage across the sensor, under the following operating condition (a sinusoidal excitation current of 700 mA of peak amplitude and at frequency of 10 kHz, and the geometrical model proposed in Fig. 3-5). An external magnetic field of 150 μT coplanar to the PCB and parallel to the ferromagnetic material is assumed to be applied to the device. The results of this transient magnetic simulation are shown in Fig. 3-6. The simulation shows a differential output voltage in accordance with the Fluxgate principle. The voltage at the output of the sensor (i.e. without the additional gain of the readout electronics) has an amplitude of 0.11 V.
3.1.3 Experimental results

The model of Fig. 3-2 was realized and analyzed in detail. To characterize the Fluxgate sensor, a pair of the Helmholtz coils were used to create a constant and uniform magnetic field and the Earth magnetic field was utilized to evaluate the sensor like a compass. In addition a front-end circuit, whose block diagram is shown in Fig. 3-7, was developed to excite the sensor and read the output signal, for both the single-axis and the double-axis sensors (described in the next section). In this circuit, the voltage induced on the sensing coil is read with a synchronous demodulation at the frequency of the 2\textsuperscript{nd} harmonic of the excitation signal.

![Electronic Front-End](image)

**Fig. 3-7.** Schematic of the front-end electronic circuitry based on second harmonic detection.

The excitation signal of the Fluxgate sensor with a frequency of 10 kHz is derived from an on-board 20 kHz square-wave reference clock by means of a frequency divider. In addition the excitation signal is filtered by a 2\textsuperscript{nd}-order Sallen-Key low-pass filter to remove the harmonics and produce a sinewave. This 10 kHz sinusoidal signal acts as the reference signal for the class-AB output stage which, through a current feedback, forces a sinusoidal current
into the excitation coil. In the detection chain the reference clock is converted to a 20 kHz sinusoid by a 2\textsuperscript{nd}-order Sallen-Key low-pass filter, which is then multiplied, by an analog multiplier, with an amplified replica of the voltage induced in the pick-up coils. In this way the 2\textsuperscript{nd}-harmonic content of the induced voltage, that is the fundamental harmonic content of the differential output voltage, is down-converted to dc. The output of the sensor, proportional to the external magnetic field, is obtained by averaging the multiplier through a low-pass filter with 10 Hz cut-off frequency. Both the excitation and the detection chains include a phase shifter to optimize the demodulation gain.

The differential output voltage of the Fluxgate sensor was measured in the presence of the Earth’s magnetic field (25 µT) coplanar to the PCB and parallel to the ferromagnetic material using a sinusoidal current excitation at 10 kHz with a peak value of 700 mA (Fig. 3-8). The differential voltage output has a value of about 80 mV\textsubscript{pp}.

The differential output voltage with the Earth’s magnetic field coplanar to the PCB surface and orthogonal to the ferromagnetic material is shown in Fig. 3-9. As expected, the output voltage is significantly lower than in the previous case although not zero because of the misalignment in the excitation and sensing coils overlay, due to the imprecision in the PCB realization, in the experimental set-up and in the manual realization of the core.
To verify the simulation result, a magnetic field of 150 μT coplanar to the PCB and parallel to the ferromagnetic material was imposed on the device using the Helmholtz coils. The differential output voltage in this case reaches 0.2 V$_{pp}$, as shown in Fig. 3-10, in a good agreement with the simulated value reported in Fig. 3-6 (0.22 V$_{pp}$).

The linearity and the sensitivity of the sensor in the range of ±400 μT were evaluated using a 10 kHz sinusoidal excitation current with a peak value of 700 mA. The differential output
voltage of the pick-up coils was analyzed with a 3562A Hewlett Packard Dynamic Signal Analyzer to extract the value of the fundamental harmonic. In this case only the excitation chain of the front-end circuitry was used. The differential voltage is plotted in Fig. 3-11 against the external magnetic field. The sensor exhibits a maximum linearity error of 2.8% in the range of \( \pm 60 \ \mu T \), and a sensitivity of 0.456 mV/\( \mu T \).

![Graph showing differential output voltage as a function of magnetic field](image)

**Fig. 3-11.** Single axis Fluxgate differential output voltage as a function of the external magnetic field measured with a spectrum analyser.

The dependence of the sensor performance on the peak excitation current has then been studied. The sensitivity of a Fluxgate sensor, indeed, does not increase monotonically with the excitation current, but above a given current level it starts to decrease. To understand this, a comparison between the sensors outputs with two different values of the excitation current were reported in Fig. 3-12 (solid line for the higher excitation current). This figure shows two different flux linkages (\( \Phi \)) with the sensing coil, relative to the two different values of the excitation current.

The peak of the voltage induced in each sensing coil is proportional to the derivate of the corresponding flux linkage and, therefore, the differential output voltage exhibits in the two case a different peak value and a different area. Due to the second harmonic detection principle, which produces an output voltage proportional to the average value of the differential voltage, the sensor output is larger when the excitation current value is the lower one, as shown in Fig. 3-13. This means that for a given geometrical configuration of the magnetic core there is a value of the excitation current that maximizes the sensitivity, as also
reported in [1]. By contrast, a larger value of the excitation current leads to a larger dynamic range for the sensor. The analysis was carried out for excitation currents with peak value between 500 mA and 800 mA. A lower current would not saturate the material, while for larger current levels the sensitivity is already decreasing. Fig. 3-14 shows the sensor

Fig. 3-12. Characteristics of the Fluxgate magnetic sensor with two different values of the excitation current.

Fig. 3-13. Comparison between the voltage outputs of the low-pass filter of the front-end circuit with two different peak values of the excitation current.
characteristics for four values of the excitation current. The different slopes of the curves over the ±100 µT range indicate different sensitivity values of the device, whose values are reported in Table 2. It can be seen from both Fig. 3-14 and Table 2 that the highest sensitivity is obtained with 700 mA of peak excitation current. These measurements demonstrate that a power reduction can be obtained (by operating the sensor with 500mA current peak) at the cost of a lower sensitivity.

Table 2. Sensitivity in the range of ±100 µT of a single axis Fluxgate with different excitation current peak values at 10 kHz.

<table>
<thead>
<tr>
<th></th>
<th>500mA</th>
<th>600mA</th>
<th>700mA</th>
<th>800mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity [mV/µT]</td>
<td>0.36</td>
<td>0.4</td>
<td>0.46</td>
<td>0.37</td>
</tr>
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</table>

The same design and fabrication procedure was applied in the realization of other sensors based on the same structure, but with different coils sizes (as shown in Fig. 3-15). Fig. 3-16 shows the fundamental harmonic component of the differential output voltage of these sensors covered with the Vitrovac 6025X ferromagnetic material core. Maintaining the fixed pitch for
the coil’s metal lines at 400 µm, the lower possible value with the PCB technology available, the reduction of the coil dimensions implies the reduction of the number of turns and of the area of the sensing coils. Therefore, the maximum induced voltage, according to [Eq.1], is obtained with the structure featuring the maximum size (Fig. 3-15 a) and hence the maximum number of turns (N) and the maximum section (S) of the sensing coils.

![Fig. 3-15. Different sensor’s sizes that were investigated; a) 30 turns; b) 25 turns; c) 20 turns.](image)

For this structure (Fig. 3-15 a), which appears to be the most promising, we performed additional measurements using the detection chain of the front-end circuitry. In particular, Fig. 3-17 shows the comparison between the sensor outputs, as a function of the magnetic field amplitude, with the two ferromagnetic materials (Vitrovac 6025X and 6025Z). Due to the different shape of the hysteresis loop and to the different thickness of the two materials, the excitation current necessary to saturate the material is 450 mA for...
Vitrovac 6025Z (20 µm thick) and 700 mA for Vitrovac 6025X (25 µm thick). This means that by using the Vitrovac 6025Z the power consumption can be reduced. To further improve the power consumption it is possible to increase the number of turns per unit of area of the coils, actual pitch is 400 µm, reduce the core thickness and perform a periodical measurement of the external magnetic field, switching off the sensor when not used.

The Fluxgate magnetic sensor with Vitrovac 6025Z shows, in the range of ±60 µT and with a sinusoidal excitation current at 10 kHz with a peak value of 450 mA, a linearity error of 0.47% full scale and a sensitivity of 2 mV/µT. On the other hand, the Fluxgate magnetic sensor with Vitrovac 6025X shows, in the range of ±60 µT and with a sinusoidal excitation current at 10 kHz with a peak value of 700 mA peak, a linearity error of 0.64% full scale and a sensitivity of 1.745 mV/µT.
### 3.2 Double Axis Fluxgate

With the same technology and design procedure was also developed a double-axis Fluxgate sensor. In literature the two most promising structures for implementing a double axis planar Fluxgate magnetic sensor were proposed in [27] and [54]. The two solutions were developed using the PCB technology and compared. As a first consideration, the best choice, in term of power dissipation and response time, appears to be the structure with ferromagnetic material core in cross shape presented in [27]. In fact, in this case the two components of the external magnetic field can be evaluated with a single measurement (like explained and demonstrated in the next paragraph). For this reason this structure was analyzed in deeper detail.

#### 3.2.1 The developed architecture

The structure of the double axis planar Fluxgate magnetic sensor proposed in [27] is shown in Fig. 3-18. This structure consists of an excitation coil and four sensing coils. Using the iterative optimization procedure already adopted for the single axis device, we designed the planar excitation coil with 30 $\mu$m thickness, 30 turns and 400 $\mu$m pitch. For each component of the magnetic field the output voltage is obtained from two sensing coils, with 17 $\mu$m thickness, 21 turns and 400 $\mu$m pitch, placed in differential configuration. The excitation and sensing coils are realized on two different metal layers of the multilayer PCB structure, at a distance of 50 $\mu$m from each other. The total device size is 57.3 x 58.1 mm.

![Fig. 3-18. Schematic of the double axis planar Fluxgate magnetic sensor realized.](image-url)
For this double axis sensor the ferromagnetic material core used was the Vitrovac 6025 and the Metglas 2714A. The latter features magnetic properties comparable with that of the Vitrovac: 0.57 T of magnetic induction at saturation and relative permeability $\mu_r = 80 \times 10^3$. The fundamental difference is that the thickness of Metglas is about 16 μm, i.e. lower than the Vitrovac.

The core was modeled in cross shape using a scissor, therefore the orthogonality between the two axis of sensitivity will be tightly correlated to the precision of manual approach.

### 3.2.2 Simulation results

Firstly, the peak of excitation current necessary to saturate the ferromagnetic material was evaluated. Also in this case the critical point was to realize a good mesh after taking into account the geometrical configuration of the ferromagnetic material, which is a cross sheet with dimensions of about 37000 x 3400 x 25 μm, for Vitrovac 6025X, on the diagonal (Fig. 3-19). The critical dimension is again the thickness of only 25 μm, which leads to a large number of elements in the mesh (285985 volume elements).

![Diagram](image.png)

Fig. 3-19. Schematic of the geometrical configuration realized in the magnetostatic problem analysed with Flux3D.
For this geometrical configuration the mesh was realized using the automatic mesh generator setting suitable mesh-point and mesh-line values. A detail of the mesh obtained is shown in Fig. 3-20.

With different magnetostatic simulation we evaluated the excitation current peak necessary to saturate the ferromagnetic material. In the case of Vitrovac 6025X a current of 600 mA required. Fig. 3-21 shows that this current value saturates the ferromagnetic core.

**Fig. 3-20. Mesh view near the ferromagnetic core.**

**Fig. 3-21. Simulated magnetic induction in the structure with a 600 mA excitation current (saturation condition).**
After the saturation current peak evaluation, was estimated the induced voltage (under the above mentioned conditions, i.e. a sinusoidal excitation current of 600 mA of peak amplitude and at frequency of 10 kHz, the geometrical model proposed in Fig. 3-21 and an external magnetic field of 20 \( \mu \)T coplanar to the PCB and parallel to the ferromagnetic material). The results of this transient magnetic simulation are shown in Fig. 3-22. The simulation shows a differential output voltage in accordance with the Fluxgate principle. The voltage at the output of the sensor has an amplitude of 15 mV.

![Graph showing differential output voltage](image)

**Fig. 3-22. Differential output voltage obtained in simulation with a dc external field imposed of 20 \( \mu \)T.**

### 3.2.3 Experimental results

The optimized device was realized in PCB technology and its photo is shown in Fig. 3-23. The first measurement performed was the evaluation of the voltage output of the front-end circuitry when an external magnetic field was imposed. Fig. 3-24 shows the voltage output as a function of the external magnetic field when an excitation current of 600 mA at 10 kHz was imposed and using the Vitrovac 6025X as magnetic core. The sensor shows a linearity error of about 1.55% full scale in the range of ±60 \( \mu \)T and a maximum sensitivity of about 1.68 mV/\( \mu \)T.
Fig. 3-23. Photograph of the double axis planar Fluxgate magnetic sensor proposed. The ferromagnetic material core was glued over the excitation coil with an adhesive.

Fig. 3-24. Voltage output from the front-end circuitry. The ferromagnetic material core is the Vitrovac 6025X. The external magnetic field was imposed with a pair of Helmholtz coils.

The differential output voltage of the Fluxgate sensor was measured with the Earth’s magnetic field coplanar to the PCB and parallel to the ferromagnetic material with a sinusoidal excitation current of 600 mA at 10 kHz (Fig. 3-25). The differential voltage output has a value of about 30 mVpeak-peak.
When the Vitrovac 6025Z is glued over the sensors instead of 6025X, the peak of excitation current necessary to saturate the core is reduced to 450 mA. The lower current required is due to the different shape of the hysteresis loop and to the lower thickness of ferromagnetic material, (20 µm with 6025Z instead of 25µm for the 6025X). A comparison between the voltage outputs obtained using the two ferromagnetic material cores is shown in Fig. 3.26. In
the range of ±60 µT (Fig. 3.27) the sensor with the Vitrovac 6025Z shows a linearity error of about 1.5% full scale and a maximum sensitivity of about 1.27 mV/µT.

When the ferromagnetic material core glued over the PCB is the Metglas 2714A the current necessary to saturate the core is 450 mA, as for the Vitrovac 6025 Z. The two cores have different thickness, 16 µm Metglas and 20 µm 6025Z, but the same magnetic flux is needed to saturate them. In this condition the flux linkage from the sensing coils will be smaller in the
case of Metglas core if compared with the Vitrovac 6025Z. Therefore, as expected, due to its lower thickness, the voltage induced in the sensing coils is lower in the case of Metglas (Fig. 3-28). In the range of ±60 μT the sensor shows a linearity error of about 3.9% full scale and a maximum sensitivity of about 1.02 mV/μT.

As an alternative to the device described so far, was implemented and tested also a PCB version of the double axis Fluxgate sensor presented in [54]. The magnetic core in this case is the Vitrovac 6025X glued over the coil with a simple adhesive. The schematic of the structure realized is shown in Fig. 3-29. This structure consists of four coils, two for excitation and two for sensing alternatively. Each component of an external magnetic field, coplanar with the PCB structure, is evaluated by alternatively exciting two coils and sensing the voltage induced in the other two coils. Each coil consists of 33 turns with a thickness of 30 μm and 400 μm pitch. The actual realization, in PCB technology, of the above structure is shown in Fig. 3-30.

The magnetization of the core and the effect of the external magnetic field, when the horizontal component of the external magnetic field is being measurement, are shown in Fig. 3-31. In this case, the external applied field decreases the effective field in one sensing coil and increases it in the other. Therefore the differential output voltage is not zero and its amplitude is proportional to the external magnetic field. Using a pair of coils to excite and the other pair of coils to sense it is possible to evaluate the two components of a magnetic field coplanar with the sensor plane.
The performance of this structure was investigated using the excitation chain of the front-end circuitry and analyzing the differential output voltage with the DSA. Fig. 3-32 shows the sensor output as a function of the external magnetic field when an excitation current of 700 mA at 10 kHz was imposed using the Vitrovac 6025X as magnetic core. The sensor shows a linearity error of about 3.2% full scale in the range of ±60 μT and a maximum sensitivity of about 0.49 mV/μT. This structure was not investigated further because of the higher power dissipation and the larger measurement time with respect to the structure presented in Fig. 3-18.
3.3 Discussion

The good agreement between simulation results and experimental data validate the adopted design approach. Under the same operating conditions, the error between the differential output voltage obtained in the simulations and in the measurements is close to 15% (Fig. 3-33). The major drawback of this simulation approach is the relatively long computation time, which for transient analysis was about 120 hours on a P4 2.4 GHz processor.
b) Double axis (core: Vitrovac 6025X)

Fig. 3-33. Simulation compared to experimental results for single axis and double axis Fluxgate sensors.

A much shorter times was obtained when the simulator was used to investigate the minimum value of excitation current necessary to saturate the ferromagnetic material. In this case the static analysis time is reduced to 1 hour (for both single and double axis Fluxgate sensors).

Fig. 3-34. Single axis Fluxgate at various excitation current frequencies.

Fig. 3-34 reports the sensor output for single axis Fluxgate at various frequencies (from 1 kHz to 130 kHz) with 700 mA of excitation current and 50 μT of external field. As expected from
Eq. [1], increasing the excitation frequency the sensor output amplitude increases. However, beyond a certain frequency the output voltage amplitude is expected to reduce, due to parasitic capacitive coupling and to the magnetic permeability frequency dependence. This has not been observed due to practical limitation of the available set-up.

In view of the results obtained, the presented PCB magnetic sensor system (sensor and front-end circuitry) appears a promising solution for the realization of a 2D electronic compass. This is demonstrated by the measurement of the voltage output from the double axis Fluxgate while rotating the sensor in a horizontal plane. Fig. 3-35 indeed shows the output voltage for each axis of sensitivity using the Vitrovac 6025Z as ferromagnetic core. The angle error is smaller than 6° and includes signal non-linearity, hysteresis and noise. This value of angle error is mainly due to the manual imprecision in cutting the ferromagnetic material in cross shape.

Finally, Fig. 3-36 shows the measured output noise power spectral density (PSD) of the double axis sensor with the cross shaped core, evaluated by using the HP 3562A dynamic signal analyzer. Considering a sensitivity of about 1.25 mV/µT, an overall gain in the read-out circuit of 3.5 and a measured noise PSD of $2.6 \times 10^{-6}$ Vrms/√Hz at 1 Hz, the noise PSD referred to the input magnetic field is equal to 7.4 nT/√Hz, thus leading to a signal-to-noise ratio of about 68 dB with the full scale Earth’s magnetic field considering a 10 Hz bandwidth.
Compared with the existing PCB implementations of fluxgate sensors [54-56], the proposed device exhibits:

1. a lower sensitivity with respect to the solution reported in [54, 55], due to the magnetic circuit configuration of the proposed sensor, coils not wrapped around the core and not in toroid shape, and to the readout circuitry, i.e. the sensing is not tuned (by tuning the sensing coil the sensitivity could be increased);
2. a power consumption comparable to the device reported in [55];
3. a larger noise with respect to [55];
4. a much simpler realization of the ferromagnetic core with respect to [54-56], not particular processing steps are required for the fabrication of the device.

Therefore, considering the possibility to increase the performance of the readout circuitry, the proposed sensor is preferable because of its reduced cost and efficient fabrication.

The PCB Fluxgate show a very good solution when large dimensions (typically few centimeter) are not a fundamental aspect, but when small dimensions and low power consumption are the crucial point the PCB solution must be replaced with the integrate micro-Fluxgate. The most important aspect in the integrated Fluxgate is the deposition of the magnetic core. In the next chapter this aspect will be discussed in detail.
Chapter 4: Industrial technology for magnetic material integration
4 Industrial technology for magnetic material integration

Technology of integrating a soft ferromagnetic material with coils is the fundamental necessity for a development of the micro-Fluxgate magnetometers. The process usually consists in the deposition and structuring of a ferromagnetic material on the sensor substrate. The mostly used material is the permalloy, fundamentally due to the large commercialization of the magnetoresistive heads for hard disks. The most diffused technology for the deposition of this material is the electroplating process, which is CMOS compatible. Based on this technology the permalloy was utilized in the realization of micro-Fluxgate magnetometer with good results [24-26, 57].

Anyway, considering the ferromagnetic properties, especially the relative magnetic permeability, the best performances are actually given from the amorphous Co-based alloy [Appendix 1]. For this material good results were obtained form Drljaca [32-34], which has utilized a CMOS compatible post-process, based on the polishing and chemical etching, to place an amorphous core (Metglas 2714A) over a planar micro-Fluxgate. The most important difference between the two aforesaid procedures (electroplating and polishing and chemical etching) is the different thickness that is possible to obtain for the core. About a micron for the electroplating and few microns (typically: 6 µm) for the polishing and chemical etching.

Actually, improvements are expected and the most promising technology is the magnetron sputtering process, which has demonstrated that it is possible to create a core with a thickness of about 1 µm, typical of an electrodeposited core, and with the good magnetic properties of the amorphous magnetic materials which usually are thicker [58].

In this chapter the electroplating and the polishing and chemical etching will be presented. Moreover, in this section a new solution, the DC-magnetron sputtering technology, applied in the field of micro-Fluxgate sensor will be presented and the more important experimental results obtained will be reported.
4.1 Magnetic material for micro-Fluxgate magnetometer

Fluxgate magnetometers require soft magnetic materials to be used. This material have a small coercitivity field (typical $H_c < 20$ A/m), small saturation (typical $B_{sat} < 1$ T) and high relative permeability ($\mu_r > 10^3$). All these parameters lead to a low overall material power loss and less excitation field necessary to saturate the material. Fig. 4-1 reports the most common group of soft magnetic materials.

![Diagram of magnetic materials classification](image)

**Fig. 4-1 Classification of soft magnetic material considering the coercitivity field.**

Since they were invented, fluxgate magnetometers changed the core material along with the progress of the metallurgy. Various types of electrical steels were used at the beginning. They were replaced with the invention of NiFe, alloys such as Permalloy, in 1940s. Each of these materials have improved over the years and have other roles in the electrical engineering. The 1970s and 1980s witnessed remarkable advances with the development of totally new soft magnetic materials with distinctly improved properties. The invention of rapid solidification technology had provided a way to produce novel compositions and microstructures. This technology, also known as rapid quenching, gave a birth to amorphous
Industrial technology for magnetic material integration

metals, also known as metallic glasses. A composition is heated to a melting temperature to form an alloy. It is ejected, under pressure, through the nozzle to a cool rotating wheel (see Fig. 4-2). The melt solidified with a cooling rates of $10^4$-10$^7$ K/s or more, avoiding the crystallization. The material is cast out from the wheel in form of ribbon with the thickness in the order of 20-40 µm. The upper limit is set by the need to achieve critical quench rate. Compositions obtained in this way expresses extraordinary soft magnetic properties. Magnetic properties could be additionally tailored using various thermal and mechanical processing.

There are several amorphous ferromagnetic materials on the market that are good candidates for our application. The two most prominent, are Vitrovac 6025 (Vacuumschmeltze GmbH, Germany) and Metglas 2714A (Hitachi Metals America Ltd., USA) of composition Co$_{66}$Fe$_4$Mo$_2$B$_{13.5}$Si$_{15}$ and Co$_{66}$Fe$_4$Ni$_{14}$B$_{14}$Si$_{15}$ respectively.

![Fig. 4-2 Rapid quenching process for the obtaining of the soft amorphous ferromagnetic metal ribbons.](image)

Today, for the integrated fluxgate magnetometers, we can see a comeback of NiFe based materials. This comes from the extensive research in the domain of the magnetoresistors for the reading heads, and developed electroplating process. The electroplating process allows the realization of magnetic cores with a small thickness, about one micron, but with poor
magnetic properties if compared with the amorphous cores. On the other hand, the thickness of the amorphous cores is not so small if compared with the electroplated NiFe, but in this sense a new prospective derives from the polishing and chemical etching process [32-34].

### 4.2 Electroplating of NiFe

Electroplating is the deposition of a metal on a conducting substrate by an electrochemical reaction. The reaction occurs by application of an electrical current on the surface of an electrode immersed into an electrolytic solution. The plating solution contains cations of the metals $M_i^{n+}$ to be deposited and additional agents for wetting, brightening, surface finishing and stress reduction in the plated films. A possible electroplating set-up is schematically shown in Fig. 4-3. A glass beaker contains the plating solution. The rectangular anode is realized with a nickel foil. The anode and the cathode to be plated are in contact with the solution and connected to a power supply. As an option, the setup reports the application of a static magnetic induction of several milliTesla at the location of the cathode by a bar magnet in order to optimize magnetic film properties. Plating is always carried out under d.c. conditions at room temperature without stirring. In advanced plating setups for production, homogeneity and stability of the deposition process is often optimized by, e.g., a continuous flow of solution and by monitoring of pH value and bath composition with appropriate adjustment. To achieve specific film properties, a.c. pulse plating can be applied.

![Diagram of electroplating set-up](image)

**Fig. 4-3.** Set-up for electroplating of alloys with optimized magnetic properties.

The basic electroplating process consists of two parts: the first is the transport of molecules to the electrodes and the second is the electrochemical reaction at the cathode surface. The motion of molecules in the plating solution is governed by drift of ions under the influence of
an electrical field, by diffusion of molecules due to a concentration gradient, and by free or forced convection. In a boundary layer close to the surface of anode and cathode, no convection is possible and only diffusion or drift occurs. For high electrolytic concentrations, drift can be neglected. In the static case under d.c. plating conditions, the molecule motion is described by Nernst-Planck's equation. The electrochemical reaction consists of several intermediate steps which take place at different rates and influence each other. The total reaction rate is dominated by the slowest process in the reaction sequence. The situation is further complicated, if two or more metals are deposited at the same time.

Electrodeposition of permalloy exhibits the phenomenon of anomalous codeposition, where the less noble iron preferentially deposits relative to nickel. Therefore, plating parameters such as, bath composition, total current density, ion concentration, and temperature strongly influence the final alloy composition in this system. Moreover, the plating parameters determine the mechanical film properties like stress, strain, grain size and grain shape. Finally, the magnetic film properties like permeability, coercivity, domain size and domain orientation are influenced by the above film properties and by thickness. An additional influence comes from a magnetic field present at the location of deposition. This can be the earth's magnetic field or an additionally applied magnetic field. Different models exist for description of the electroplating of nickel-iron alloys, but predictions of final film properties based on these models are difficult. Hence, an experimental optimization of the plating process is indispensable.

Electroplating techniques can be used for deposition of permalloy films with thickness of several micron. The permalloy films can be structured by standard technologies, such as etching or lift-off.

The following requirements must be fulfilled in order to ensure compatibility of integrated ferromagnetic microstructures with IC fabrication, i.e. to maintain circuit reliability. First, possible annealing must be carried out under controlled atmosphere, e.g. of hydrogen at temperatures well below the temperature of the final alloying step in the CMOS process which is usually carried out at a temperature of about 400°C. Second, the contamination of standard process equipment and circuitry parts with non standard ions, e.g., nickel or iron must be avoided. This can be achieved, if the ferromagnetic material is separated by a layer of Cr, Ti, TiW or Ta from all other materials [59, 60]. This layer acts as a barrier for interdiffusion of metal atoms into, e.g., aluminium, silicon oxide or silicon nitride and can improve adhesion. Hence, intermediate processing of ferromagnetic materials during IC fabrication must be done in dedicated equipment and finished completely before finishing the
IC process. In contrast, post-processing enables the use of standard IC processes. No equipment contamination can occur and circuit protection by overall wafer coverage with an interdiffusion barrier is sufficient.

4.3 Polishing and chemical etching

The magnetic cores derived from the electroplating process give very thin thickness but magnetic properties that are not suitable for very low power application. Considering this kind of applications, a solution was developed in [40]. In that case the commercially available material [Appendix 1] was thinned with two different steps, based on polishing and chemical etching.

The polishing is a procedure that results in the middle between lapping and polishing used for micro-finishing of surfaces. The machine utilized for the purpose uses belt rotating abrasive paper in the presence of vibration and lubricant. The technology presented in [40] uses 3 different grades of paper to achieve desired finish on the both faces of the ribbon of material. During the process the thickness, at the beginning of 18 µm, is reduced to a value of 11 µm. The result of the polishing is still a thick material, which does not give improvements in term of power dissipation if utilized as a magnetic core in a micro-Fluxgate. Therefore a chemical etching is realized. The speed of the chemical thinning process is about 1 µm per minute. This gives a sufficient control over the final thickness of the core. The final result is a material with a thickness of about 5 µm. Lower value is not applicable because of the limits of the chemical thinning. The material roughness is good locally but on the overall size of the 6" wafers it differs slightly. For the thickness around and below 5 µm holes inside the material becomes evident. The minimal thickness must be above this value to ensure a good yield of the cores. Moreover, with a thickness lower than 5 µm the ribbon of material becomes extremely fragile and then the procedure to place it over the micro-Fluxgate structures becomes very hard.

The final step consists in the annealing of the material to reduce the induced stress. Heat treatment (annealing) of the ferromagnetic materials is known and usually employed in order to tailor the hysteresis [61]. The idea is to heat the material around Curie temperature and increase its atoms mobility. At the same time magnetic anisotropy energy is reduced [62]. In this state, material is prone to external influence and reduces the internal stress [63]. Process is usually done in the presence of the external magnetic field [64, 65] or stress [66; 67] to induce desired characteristics. Slow cooling of the material will freeze new domain structure.
resulting in a material with changed characteristics. The amount of change depends on the material structure and differs in soft magnetic materials.

4.4 DC-magnetron sputtering of soft magnetic material

The polishing and chemical etching presented in the previous section has demonstrated the possibility to realize a magnetic core with very good magnetic properties and, despite the obtained thickness, with low power consumption for the sensor. Anyway in the recent application, i.e. portable system, lower power consumption is required. In this way, the goal could be obtained using a magnetic core with the magnetic properties of the amorphous magnetic material but with a thickness of 1 µm or lower. For this purpose the sputtering technology is actually the most promising solution [58].

4.4.1 The principle

Within the sputtering process gas ions out of a plasma are accelerated towards a target consisting of the material to be deposited. Material is detached ("sputtered") from the target and afterwards deposited on a substrate in the vicinity. The process is realized in a closed recipient, which is pumped down to a vacuum base pressure before deposition starts (see Fig. 4-4).

![Fig. 4-4. Typical set-up of the DC-magnetron sputtering process.](image)
To enable the ignition of a plasma usually argon is fed into the chamber up to a pressure between 0.5-12 Pa. By natural cosmic radiation there are always some ionized Ar$^+$-ions available. In the dc-sputtering a negative potential $U$, up to some hundred Volts, is applied to the target. As a result, the Ar-ions are accelerated towards the target and set material free, on the other hand they produce secondary electrons. These electrons cause a further ionization of the gas. The gas pressure $p$ and the electrode distance $d$ determine a break-through voltage $U_D$, from which on a self sustaining glow discharge starts, following the equation:

$$U_D = A \cdot \frac{pd}{\ln(pd) + B}$$  \hspace{1cm} \text{Eq.[4]}

with materials constants $A$ and $B$. The ionization probability rises with an increase in pressure and hence the number of ions and the conductivity of the gas also increase. The break-through voltage drops. For a sufficient ionization rate a stable burning plasma results, wherefrom a sufficient amount of ions is available for sputtering of the material.

To increase the ionization rate by emitted secondary electrons even further, a ring magnet below the target is used in the magnetron sputtering. The electrons in its field are trapped in cycloids and circulate over the targets surface. By the longer dwell time in the gas they cause a higher ionization probability and hence form a plasma ignition at pressures, which can be up to one hundred times smaller than for conventional sputtering. On the one hand, higher deposition rates can be realized thereby. On the other hand, less collisions occur for the sputtered material on the way to the substrate because of the lower pressure and hence the kinetic energy at the impact on the substrate is higher. The electron density and hence the number of generated ions is highest, where the B-field is parallel to the substrate surface. The highest sputter yield happens on the target area right below this region. An erosion zone is formed which follows the form of the magnetic field. The bombardment of a non-conducting target with positive ions would lead to a charging of the surface and subsequently to a shielding of the electrical field. The ion current would die off. Therefore the dc-sputtering is restricted to conducting materials like metals or doped semiconductors. There are now two ways to produce dielectric films: In RF-magnetron sputtering (radio frequency) an ac-voltage is applied to the target. In one phase ions are accelerated towards the target surface and sputter material. In the other phase charge neutrality is achieved. Hereby sputtering of non-conducting materials is possible as well.
Alternatively, for reactive sputtering other gases like oxygen or nitrogen are fed into the sputter chamber additionally to the argon, to produce oxidic or nitridic films.

4.4.2 Sputtering parameters

The resulting film properties can be controlled by adjusting the following sputter parameters:

The *sputter current* \(I_{sp}\) determines mainly the rate of the deposition process and hence the time which remains for the arriving particles during the growth process for either surface diffusion and agglomeration on existing growth centers or nucleation with other adatoms.

The *applied voltage* \(U\) determines the maximum energy, with which sputtered particles can escape from the target (reduced by the binding energy). Energies of the sputtered particles show a broad distribution with a maximum of the distribution between 1 eV and 10 eV. The applied voltage determines also the sputter yield, which is the number of sputtered particles per incoming ion.

The *pressure* \(p\) in the sputter chamber determines the mean free path for the sputtered material, which is proportional to \(1/p\). Together with the *target-substrate* distance (TS) the pressure controls, how many collisions occur for the particles on their way from the target to the substrate. This can influence the porosity of the films. But also the crystallinity and texture can be effected.

Via the *gasmixture* it is possible to control the stoichiometry of films, which are sputtered from a metallic target.

The *oxygen flow* \(q(O_2)\) is the parameter varied, whereas the desired total pressure is kept constant by regulation of the Ar-flow \(q(Ar)\).

The *substrate temperature* can have a strong impact on the growth behaviour with respect to crystallinity or density of the samples. It can be adjusted between room temperature and 500 °C. But even during sputtering without external heating the substrate temperature may rise considerably, especially during long sputtering times for the deposition of thick films.

In principle a bias-voltage can be applied to the substrate up to \(±100V\), which has the effect of accelerating electrons or ions towards the substrate or keeping them away. Both may have an influence on the layer growth as reported in the literature [68, 69].

Usually substrate and target surface are parallel to each other. A variation of the deposition angle (also: sputtering under oblique incidence) can be achieved by tilting the substrate. Thereby a new preferential direction for the film growth and potentially anisotropic films can be produced.
4.5 Vitrovac deposition with DC-magnetron sputtering

In this section the procedure utilized for the core deposition will be presented. Different sample with dimensions of 2 x 4 cm and with a thickness of about 1 µm was realized. The goal of 1 µm of thickness was obtained iterating different step of deposition.

4.5.1 Target and substrate preparation

The Vitrovac is commercially available in ribbon of 57 mm width and 25 µm thick. This disposability of shape for the material, which is the only possible due to the process fabrication, conduce to the necessity to use different layers of Vitrovac over the backing plate to prevent the creation of pinholes. Therefore, two layers of Vitrovac were utilized to produce a film of 1 µm thick, like reported in Fig. 4-5.

![Target and substrate preparation diagram](image)

Fig. 4-5 Utilized set-up for the DC-magnetron sputtering deposition.

The target of circular form with a diameter of 10 cm was obtained adapting two strips, of 10 cm in length, over the target support. These strips was cleaned in acetone and isopropanol and dried with nitrogen gas. Moreover the target was clean with 5 minutes pre-sputtering at the begin of process to remove any surface contamination. The target was utilized free from any contact fix method to avoid stress due to heating during the deposition and stress from mechanical fixing. The positioning was guaranteed with the utilization of the magnetron magnets situated below the backing plate. Magnetron is a permanent magnet put under backing plate with the purpose of increasing the sputtering yield acting on condensation of the electrons on the target surface.
In a typical sputter system the target is normally situated at 10 cm distance from the substrate holder, to obtain good film uniformity usually as an area of 3 in². In this case the aforesaid distance appears too much, because of the small volume of the material placed over the target. Therefore, to obtain a significant rate of material deposition on the substrate, without increasing the power dissipated in the sputtering process, the distance between the target and the substrate was set at 4 cm. The sputtering process was realized setting a power of 45 W, resulting in a 1.4 Å/sec rates of deposition and a maximum temperature, for the substrate, of 55 °C.

4.5.2 The deposition procedure

All the films were grown with the IONVAC SPS RF/DC-magnetron sputtering equipment. The system was configured to operate in the sputter-up mode, where the substrate was mounted directly above the target electrode. After target and substrates cleaning procedures, the substrate was fixed to the holder with a kapton tape. This fixing method masks part of the substrate but gives many advantages in consideration of the mechanical stress with a rigid fixing solution. A small silicon layer was placed under the substrate. This is to measure the thickness that in this case was measured with a stylus profilometer.

Due to the necessity to preventing the magnetic core degradation it was necessary to bring the system to atmospheric pressure with Nitrogen after any deposition and before to removing the substrate. Moreover, based on the well know effect of the pressure on the magnetic characteristic of the realized films, after different tests, it was established that a pressure of about 4 mTorr was the good condition for the deposition. This working point was imposed starting from a pressure of 10⁻⁶ Torr, reached with the vacuum system constituted by mechanical pump and turbomolecular pump with baffle valve, then reducing the pressure at 30% of its value and putting 41 sccm¹ of Argon gas in the chamber.

Settled the working condition, the deposition can start switching on the DC generator and slowly increasing the power up to 46 W. At this value the glow discharge starts and with the shutter (substrate shield) closed it was possible to sputter the target, for a time of about 5 min, to clean the same target. After the cleaning procedure, the shutter was opened to depose the target over the substrate. The deposition took place at steps of about 15 minutes each and with 5 minutes for cooling between each step, this to avoid the target crystallization due to the

¹ Standard Cubic Centimeters per Minute
temperature reached by the substrate. At the desired thickness, monitored by a microbalance thickness controller, the glow discharge was stopped. The latest procedures, before to open the vacuum chamber, were:

1. take 30 minutes of exposure of the Argon gas also with the controlled pressure in the vacuum chamber;
2. then the baffle valve was opened, the vacuum procedure stopped and the Nitrogen was inserted in the chamber to return to atmospheric pressure;
3. the substrates was removed with Teflon tweezers;
4. to validate the procedure, optical inspection and thickness measurements was realized.

4.5.3 Calibration of the deposition rate

The thickness of Vitrovac film was monitored by quartz microbalance which measures also the rate of the material growth (about 1.4 Å/s). It is not exactly calculated because in the controller microbalance program it is necessary to input the density and z-ratio (material answer to mismatch 6 MHz quartz frequency) of this material, but it’s a metallic alloy with Co, Si, Mo, Fe, Nb, B therefore we decide to put the values of the more weighty element present (Co 78%) 8.2 gm/cc e 0.343. Anyway the thickness measurement is performed at the end of process with a Contact stylus profilometer Alpha Step IQ by KLA-Tencor that measures the width (1 µm) between film and substrate Kapton shielded. Dividing by time (120 min) we obtain the approx rate of 1.38 Å/sec.

In the next chapter the principal method to evaluate the magnetic properties, in term of B-H hysteresis loop, will be presented with the performance obtained for the sputtered material.
Chapter 5: Magnetic properties of sputtered Vitrovac® 6025X
5 Magnetic properties of sputtered Vitrovac 6025X

In literature it is possible to find different techniques to evaluate the hysteresis loop of a deposited magnetic material. The most popular are:

1. Vibrating sample magnetometer.
3. Inductive magnetometer (IM).

5.1 Vibrating sample magnetometer

The vibrating sample magnetometer is a system used for measurement of d.c. magnetic material properties, such as B-H characteristics. The applied magnetic field $H$ is generated by Helmholtz coils, by an electromagnet or by a superconducting magnet depending on the required field range and measured by an appropriate gaussmeter, e.g. a Hall probe. The complete setup is computer-controlled. The measurement principle of the VSM is based on the periodic movement of the sample which is fixed at the end of a vibrating rod as shown in Fig. 5-1.

![Fig. 5-1. Schematic of a possible Vibrating sample magnetometer system.](image-url)
The sample is magnetized in the applied homogeneous magnetic field and can be seen as a magnetic dipole with magnetic moment $m$. The movement of the magnetic dipole corresponds to a stationary quadrupole which fluctuates with time, and thus, induces a voltage in the pick-up coils which is proportional to the magnitude of the magnetic moment $m$. The induced voltage is measured by a lock-in amplifier which is locked to the vibration frequency of the rod. Assuming homogeneous magnetization parallel to the applied magnetic field $H$, the magnetization $M(H)$ of the sample material can be calculated from the magnetic moment $m(H)$ according to:

$$M = \frac{m}{V}$$  \hspace{1cm} \text{Eq.[5]}

where $V$ denotes the total sample volume. The magnetic induction $B$ in the samples then given by $B = \mu_0(H+M)$. The effective permeability of the sample is $\mu_{\text{eff}} = B / \mu_0 H$ which depends on the relative permeability $\mu_r$ of the sample material and on sample geometry. For precise determination of $\mu_r$ a correction for demagnetization [Appendix 2] must be performed. The most critical procedure for precise determination of permeability and saturation flux density $B_s$ is the measurement of total sample volume.

### 5.2 Magneto optical Kerr effect (MOKE) magnetometer

The MOKE magnetometer characterizes materials by providing magnetic information in the form of a hysteresis loop. It relates the magnetization $M$, to the applied magnetic field, $H$. The principles of the MOKE magnetometer are based on the Kerr effect, which were observed by John Kerr in 1887, and are analogous to the Faraday effect where the polarization of the light is rotated through a transparent material subjected to a magnetic field as observed by Michael Faraday in 1845.

Magneto Optical Kerr effects are generally described macroscopically by dielectric tensor theory [70], or the effects can also be described microscopically, where the coupling between the electric field of the light and the magnetization occurs by the spin-orbit interaction [71]. To understand the magneto optical Kerr effects, it is necessary to understand the terminologies associated with the effect, how the state of polarization of reflected light is
dependent upon the initial polarization and the magneto optical geometry in which it is being used.

Light is a transverse electromagnetic wave which can be manipulated optically into plane, circularly or elliptically polarized light. Generally, the plane of polarization is the plane which contains the electric field E and the direction of propagation. If the electric field is polarized in the plane of incidence, it is referred to as p-polarized light as shown in Fig. 5-2. Conversely, if the electric field is polarized perpendicular to the plane of incidence, then it is referred to as s-polarized light. Plane polarized light which is reflected off a metallic surface, is generally elliptically polarized.

However if the incident light is either p or s-polarized, then the reflected light will still be plane polarized upon reflection (p or s). This is because the reflecting surface is a plane of symmetry for the system. This symmetry is destroyed in the situation where plane polarized light is reflected off a magnetized surface. When p-polarized light is reflected off a magnetic surface, the reflected light has a p-component as in the ordinary metallic reflection but, in addition, a small s-component also appears in the beam. In general, this second electric field component is out of phase with the reflected p-component. This causes the light to become elliptically polarized with its major axis rotated from its initial incident polarization plane. This magneto optic interaction is shown schematically in Fig. 5-3. A similar effect occurs for s-polarized light. The two effects are known as the Kerr ellipticity and the Kerr rotation.

Basically, what MOKE measures directly, is the magneto optic response of the medium, which is a change in the incident polarisation of the light. This magneto optic response...
Magnetic properties of sputtered Vitrovac® 6025X

consists of two parts: a change in the polarisation of the in-phase component of the reflected light which gives rise to the rotation, and a change in the polarisation of the out-of-phase component of the reflected light which gives rise to the ellipticity.

There are principally three Kerr effects which are classified depending upon the magneto optic geometry being employed. These are shown in Fig. 5-4. The effects are dependent on the orientation of the magnetisation with respect to the incident and sample planes. In the longitudinal Kerr effect, the magnetisation is in the plane of the sample and parallel to the incident plane. In the transverse Kerr effect, the magnetisation is also in the plane of the sample, but is perpendicular to the incident plane. In the polar Kerr effect, the magnetisation is perpendicular to the sample plane and is parallel to the plane of incidence. It should be noted the Kerr effect will occur for any arbitrary direction of magnetisation within the sample.

Consideration of these three magneto optic geometries simplifies the understanding of the Kerr effect. The longitudinal and transverse Kerr effects are generally used to study the in-plane magnetic anisotropy, whereas the polar configuration is used to study thin films, which exhibit perpendicular anisotropy.
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Fig. 5-5 shows a possible schematic layout of the MOKE proposed in [58]. This system included the computer automation of the equipment and the writing of the associated software. Light was provided by a 15 mW He-Ne laser ($\lambda=633\text{nm}$) at an incident angle of 45° to the sample plane. The polarization of the light beam before reflection was controlled by a Glan Taylor polarizer to be either $p$ or $s$-polarized, which was then focused onto the sample by a lens of focal length 30 cm. The sampling area was determined by the size of the laser spot. The reflected light beam was passed through an analyzing Glan Taylor polarizer onto a photo-diode, where the reflected intensity was measured. The output signal from the photo-diode was fed into the signal conditioning unit before being read by the computer by means of an analogue to digital converter (ADC - 12 bit). The software was also interfaced to a programmable voltage controlled bipolar current source (KEPCO BOP 36-12M), by means of a digital to analogue converter (DAC - 14 bit). The KEPCO was used to provide the driving current for the Helmholtz coils, which produced the sweeping magnetic field. The software simultaneously swept the magnetic field and recorded the transmitted intensity as a function of the applied magnetic field. All components were mounted onto an optical table which had anti-vibration cushioning and the MOKE magnetometer was placed in a Faraday room to screen the apparatus from electromagnetic noise. The Faraday room also doubled as dark room which eliminated the problem of the fluctuating ambient light. The samples were mounted onto a non-magnetic holder either by a high temperature vacuum grease, wax or by double sided tape. The holder could be traversed, and this moved the sample in the XY plane.

![Fig. 5-5 Schematic of a possible MOKE system.](image-url)
of the magnetic field (Fig. 5-5) by means of two micrometers; it also provided the freedom of rotating the sample through a full 360° in the plane of the magnetic field. Typically, the MOKE system is utilized for very thin material characterization, about few hundreds of nanometers. In the case in analysis the magnetic core has thickness of about 1 µm, therefore the inductive magnetometer system appears preferable.

### 5.3 Inductive Magnetometer (IM)

The Inductive Magnetometer shown in Fig. 5-6 was used to provide the magnetic hysteresis loops (referred to as MH loops) of the core deposited. The magnetometer is based on a similar design to that which is described in [72].

![Schematic diagram of inductive magnetometer](image)

**Fig. 5-6 Schematic diagram of inductive magnetometer used to obtain the magnetic hysteresis loops of Vitrovac deposited.**

It is an induction method which is dependent on Faraday’s law of electromagnetic induction; this states that the voltage $V$ induced in the search coils is equal to the rate of change of flux linking the coil:

\[
V = -\frac{d}{dt}\Phi_c = -\frac{d}{dt}NAB \quad \text{Eq.[5]}
\]
Here, N is the number of coil turns linking the flux, A is the cross-sectional area of the search coil, and B is the flux density which is defined as:

\[ B = \mu_0 M \]

Eq.[6]

From Eq. [5] and [6] it is possible conclude that the magnetisation, M, of the sample is proportional to the integral of the induced voltage:

\[ M = -\frac{1}{NA\mu_0} \int V dt \]

Eq.[7]

and this is the basis of the magnetometer described here.
The system realized is shows in Fig. 5-7. The magnetometer consists of a solenoid one meter in length, with 3,015 turns, in which two identical search coils were positioned 50 cm apart along the central axis of the solenoid. The dimensions of the search coils, which consist of 13,000 turns, allowed sample with maximum dimensions of 4×2×1.5 cm to be measured. The search coils were placed in antiseries to take only the induced voltage due to the magnetic core inserted in one of them (S1). This ensured that when no sample was present within the search coil S1 there was no net signal from the applied field. The signal from the oscilloscope was recorded and stored on the computer for a post-elaboration in Matlab®.

![Fig. 5-7 Photograph of the Inductive Magnetometer realized.](image)

Different samples were realized, with the DC-magnetron sputtering, with dimension of 2 x 4 cm or 1 x 2 cm with the thickness of about 1 µm, like reported in Fig. 5-8. To proceed with
the core characterization the solenoid was excited with a sinusoidal current of 1 A\textsubscript{peak} at frequency of 30 Hz. For a sample with dimensions of 2 x 4 cm and thickness of 1155 nm, the measured hysteresis loop is shown in Fig. 5-9. First consideration, about the measured B-H loop, was that the obtained hysteresis doesn’t show the expected saturation value. In fact, the B-H loop supplied by Vacuumschmelze gives a magnetic induction at saturation of about 0.55 T, like shown in Fig. 5-10. To better understand the difference between the two
saturation values, an evaluation of the B-H loop of the Vitrovac as-cast was realized with the Inductive Magnetometer. The measured loop, in comparison with the sputtered core, is shown

Fig. 5-10 Hysteresis loop of the as-cast Vitrovac 6025X.

Fig. 5-11 Comparison between the hysteresis loops of the Vitrovac sputtered (blue line) and as-cast (red line).
Magnetic properties of sputtered Vitrovac® 6025X

in Fig. 5-11. The red line is referred to the as-cast material and the blue line to the sputtered material. It is evident that the two measured loops are different from the loop given by the supplier (Vacuumschmelze, Fig. 5-10). These differences can be explained as follows:

1. In our system the magnetic circuit is open (the sputtered core is not a toroid) and therefore the demagnetization field must be taken into account [Appendix II].
2. The secondary coils are not strictly wrapped around the sputtered core, therefore a flux leakage exists.

Because of this, only a comparison between the B-H loop of the sputtered material and the as-cast material is possible. From this point of view, the two loops look similar, resulting in nearly equivalent magnetic properties. The fundamental difference is the coercitivity field, that for the deposited core is greater, about 100 A/m. This difference is in agreement with the results described in [58]. The increase of the coercitivity after deposition of the material will result in a slight increase of the current required in the excitation coil to achieve the saturation of the core. The measured magnetic properties of the deposited material are anyway suitable for the correct operation of the Fluxgate sensor with only a slight increase of the power consumption.
Chapter 6: Integrated Planar micro-Fluxgate
6 Integrated Planar micro-Fluxgate

Many applications require low-cost and low-power highly sensitive miniaturized magnetic sensors to locally and accurately measure weak magnetic fields in a plane [4, 12]. For this task integrated devices appear to be the best solution. Unfortunately, none of the existing integrated magnetic sensors, such as magnetoresistive [73] or Hall sensors [3], fulfills simultaneously all the desired requirements due to their poor magnetic field measurement accuracy. Innovations are expected in the integrated sensors based on the Fluxgate principle. There are a few fully integrated magnetometers described in the literature. Gottfried-Gottfried et al. developed a two-chip system, consisting of a sensor part and a separate ASIC for biasing and signal processing electronics [59]. A NiFe magnetic core, sandwiched between two metal layers of the CMOS process, is structured using electron-beam evaporation and a lift off process. Choi et al. developed a sensor using CMOS technology for the electronics and coils with electrodeposited NiFeMo film for the ferromagnetic core [26, 57]. A similar sensor using the sandwich structure was described in [25] and presented in [74], with a delta-sigma modulator and an integrator in the feedback loop. Chiesi et al. introduced the concept of combining a flat CMOS structure and amorphous ferromagnetic material, obtained from a photolithography process, to achieve a parallel fluxgate configuration [27]. The sensor is further developed in [75].

Following the experience with the PCB Fluxgate, the sensors presented in this chapter are micro-Fluxgate, developed in a CMOS process, where the ferromagnetic core is realized as a post processing step with the DC-magnetron sputtering technology, presented in previous chapters. This technique allows us to realize a core with the good magnetic properties of the amorphous ferromagnetic material and with a very small thickness (about 1 µm). At this time, in literature it is possible to find solutions with electrodeposited magnetic core of few microns of thickness [26, 57], but with magnetic properties not so good if compared to the amorphous ferromagnetic material, or devices with amorphous core [27, 75], but with large thickness if compared to the electrodeposited core and therefore characterized by a larger power consumption.
6.1 Exploiting the PCB experience to design and simulate an integrated planar micro-Fluxgate

Using the experience with the PCB prototype an IC version of the double axis Fluxgate sensor for low power applications requiring small dimension was developed [76, 77]. The design features were assumed in agreement with the IC realization of the coils in a 0.5 μm CMOS technology with a post processing for the deposition of the ferromagnetic material. To establish the best geometrical dimensions for the IC structure, it was necessary to evaluate for each sensing coil the influence on the induced voltage of the number of turns and the active area (i.e. the flux linkage) of the coils as well as the frequency of the excitation current. According to the Faraday law, the induced voltage for a coil wrapped around the core is given by:

\[
V_{\text{ind}} = -\frac{d\Phi}{dt} = -N_{\text{sens}} \cdot S \cdot \frac{dB(t)}{dt} = -N_{\text{sens}} \cdot S \cdot \frac{d}{dt} \left( \mu \cdot N_{\text{exc}} \cdot I_0 \sin(2\pi f_{\text{exc}} t) \right)
\]

Eq.[8]

where \( N_{\text{sens}} \) is the number of turns of the sensing coil, \( N_{\text{exc}} \) is the number of turns of the excitation coil, \( S \) is the cross section of the sensing coil, \( l \) is the length of the excitation coil, \( \mu \) is the absolute magnetic permeability and \( I_0 \sin(2\pi f_{\text{exc}} t) \) is the sinusoidal excitation current at frequency \( f_{\text{exc}} \). In the case of a planar coil a scale factor could be introduced to adjust the formulas in the particular case. Since all the parameters related to the area in the IC version are scaled down, the desired sensitivity should be achieved by:

1. increasing the excitation frequency (\( f_{\text{exc}} \));
2. increasing the number of turns of the sensing coil (\( N_{\text{sens}} \));
3. increasing the cross section of the ferromagnetic material (\( S \)).

However, the increase of the excitation frequency is limited by the loss in the relative permeability due to the eddy current effect. The frequency dependence of the relative magnetic permeability for Vitrovac 6025 is shown in Fig. 6-1 where a cut off frequency of 10 kHz is present. The number of turns in the sensing coils can be increased according to the minimum pitch of the used technology but a limit on the overall area exists. Finally, if a larger cross section of the material is used, a higher current is required to saturate the ferromagnetic material and the power consumption increases.
Fig. 6-1 Frequency dependence of the relative magnetic permeability of the Vitrovac 6025.

The model created in Flux3D is shown in Fig. 6-2: it consists of an excitation coil and four sensing coils, a pair for each axis of sensitivity. The planar excitation coil is characterized by 5.5 μm thickness, 95 turns and 9 μm pitch (5 μm width and 4 μm spacing). The total area for the excitation coil is (1760 x 1760) μm².

Fig. 6-2 Simulation model of the integrated version of the PCB structure.

In order to optimize the device area occupation a number of magnetostatic analyses were performed varying the area of the sensing coil. The simulations showed that the component of magnetic induction associated with the ferromagnetic material perpendicular to the plane of
the sensing coil is concentrated in a small area under each of the outer end of the core branches (Fig. 6-3). Therefore the sensing coils were centered in these areas and their size was reduced to the minimum possible. This gives a 75% area saving with respect to the direct scaling of the PCB prototype, without any performance loss. The geometrical parameters of the sensing coils based on the used technology are: 1 μm thickness, 1.3 μm width and 1.6 μm spacing. The total area for the sensing coils, consisting of 75 turns, is 450 x 450 μm². The Vitrovac 6025 was introduced in the simulation in cross shape with the dimensions of 2513 μm x 113 μm on the diagonal (Fig. 6-2).

The first analysis step was to evaluate the minimum thickness for the ferromagnetic material which can be saturated with a peak current of about 5 mA (in order to limit the power consumption). Using different magnetostatic analysis we established that the complete saturation condition is obtained with a thickness of 1 μm, as shown in Fig. 6-4.

![Fig. 6-3 Distribution of the perpendicular component of the magnetic induction in a plane coplanar with the sensing coil.](image)

The second analysis was performed considering the geometrical model proposed in Fig. 6-2 with a 100 kHz, 5 mA peak amplitude sinusoidal excitation current together with a 60 μT magnetic field coplanar to the micro-integrated structure and parallel to the ferromagnetic material. The results of this transient magnetic simulation, for one axis of sensitivity, are shown in Fig. 6-5. The simulation shows a differential output voltage in agreement with the
Integrated Planar micro-Fluxgate

Fluxgate principle. The output voltage obtained has an amplitude of about 1 mV, sufficiently large to be processed by the readout circuit.

Fig. 6-4 Simulated magnetic induction in the structure with a 5 mA peak of excitation current.

$B_{\text{max}} = 0.55 \, \text{T}$

Fig. 6-5 Differential output voltage simulated with Flux3D.
6.2 Models of integrated planar micro-Fluxgate realized

Due to the large size of the wafer of silicon, 4” entirely dedicated to the Fluxgate sensors fabrication, different structures of micro-Fluxgate was designed to be realized. Even if only one of that structures was modelled using the software simulator.

In Fig. 6-6 the twelve structures proposed for realization are shown. The structures are represented by nine basic models (named: model 1, model 2, model 3, etc…). Three of them were also realized using an external ring of metal to avoid the possibility to break the sensor while cutting the wafer. The ring of metal has not been utilized in the entire models because of the possibility to incur in the mutual induction interference.

Like reported in the chapter 4 and chapter 5 the magnetic core was realized with the DC-magnetron sputtering process. This procedure was realized in a post-process with respect the CMOS process utilized for the coils fabrication. This, to prevent the foundry contamination.

Fig. 6-6 Schematic of the integrated planar micro-Fluxgate realized.
Before analyzing the realized sensors, an suitable circuitry was studied in detail and sent for fabrication. At the moment only the simulation can be presented.

### 6.3 Front-end circuitry

To be competitive with the classical magnetometers, the integrated devices must have performance comparable with the systems proposed in the past, but with the main features of standard IC products [78]. The advantages of the proposed solution are essentially related to its low power consumption and small area occupation, without loss in performance. For this reason, it was necessary to develop an integrated CMOS front end circuit which guarantees all the performance required both in terms of noise and power consumption, in order to meet the requirements explained above. The solution proposed will be useful not only for a System on Chip solution (SoC), but also for a System on Package approach (SoP). Indeed, if the magnetic sensors previously mentioned will be realized in a separate die it is quite easy to bond together the dies and attach them on the same substrate. In literature, front-end circuits for fluxgate sensors are typically based on a sinusoidal or pulsed excitation [79].

The approach adopted in the proposed circuit, instead, exploits a triangular current to feed the excitation coil and a synchronous demodulation for reading out the voltage induced in the sensing coils. This solution represents a trade-off between the low-noise performance achieved by the solutions based on sinusoidal excitation and the simple implementation of solutions based on pulsed excitation [80].

![Fig. 6-7 Block diagram of the complete microsystem for magnetic field sensing.](image-url)
The front-end circuit can be divided in three main blocks: the timing block, the excitation block and the read-out unit. The timing block is common to the other two and provides the synchronization of the entire system. The block diagram of the entire microsystem is shown in Fig. 6-7. The circuit was realized in a standard 0.35µm CMOS process, with 2 poly, 4 metals, 5V devices and high resistivity polysilicon.

6.3.1 Timing Block

In order to ensure proper timing for the excitation and read-out blocks, the whole circuit is driven by a clock at 400 kHz. This clock is internally divided, by a cascade of flip-flops. The outputs of the timing block are two signals: a 100 kHz square wave signal which is used to drive the excitation block and a 200 kHz square wave signal which is used to drive the read-out block and realize the second harmonic demodulation, needed to measure the sensor output. By using a 400 kHz master clock we can ensure that both the 100 kHz and the 200 kHz output waveforms feature a 50% duty cycle. A duty cycle different from 50%, indeed, could compromise the demodulation of the signals produced by the sensing coils and therefore has to be avoided.

6.3.2 Excitation Block

To saturate periodically the ferromagnetic material, deposed over the excitation coil of the planar fluxgate sensor, a triangular current waveform was used. This current is generated with an voltage integrator followed by a trans conductance amplifier. The input signal of the this block is a scaled version of the 100 kHz square wave produced by the timing block, as shown in Fig. 6-8. Moreover, in order to guarantee the programmability of the system and hence the possibility to use it with different kind of sensors and magnetic materials, the input of the integrator in not fixed. In this way it is possible to modify the output current, according to the sensor characteristics and the power consumption requirement. Indeed, a higher excitation current improves the saturation of the ferromagnetic materials, thus allowing to achieve better results in terms of noise and sensitivity, but with higher power consumption.

The behavior of the excitation block is the following: for half of the clock period the integrator input is connected to Vin, while in the other half to –Vin, changing the slope of the triangular wave at the output of voltage integrator. This voltage feeds the transconductance amplifier. The peak output current can be regulated by trimming the value of Vin, according
Fig. 6-8 Simplified schematic of the excitation block.

\[ I_{\text{OUT,Max}} = G \cdot \frac{V_{\text{in}} \cdot T}{CR} \]  

Eq. [9]

where \( G \) is the transconductance gain, \( CR \) is the time constant of the integrator and \( T \) is half of the input square wave period. To guaranty the current needed to saturate the core of different fluxgate sensors, the coefficient \( G \) has to be at least 0.01 A/V, and it should be linear over the whole input swing. The high resistance of the integrated coil (estimated around 200 \( \Omega \)) and the possibility to test the sensor with an excitation current higher than ±5 mA (e.g. ±10 mA or higher) could produce 4 V output swing. For this reason the output stage of the transonductance amplifier was realized with high voltage transistors using 5 V power supply (HV). In this way, it is possible to separate the power consumption of two structures, supplying with high voltage only the power stage and hence reducing the power consumption in the integrator and amplifiers. The transconductance gain \( G \) is realized using two matched resistors, made of high resistive polysilicon devices to save area. A common centroid layout was chosen to improve the matching factor. A gain enhancement of 547 A/A is then provided by a current mirror in order to reduce the power consumption. The biasing voltages \( V_{\text{bias1}} \) and...
$V_{bias2}$ were introduced to control the bias current in the class AB output stage. These voltage references are fixed and integrated to reduce the number of pins and hence the area occupation.

### 6.3.3 Read-Out Block

The pick-up coils of the planar fluxgate magnetic sensor detect the signal induced by the rising and falling edges of core magnetizing current. The schematic of the read-out block is shown in Fig. 6-9.

![Fig. 6-9 Schematic of the read-out block.](image)

Without external field

With external field

![Fig. 6-10 Expected waveforms in the read-out block.](image)
As well known, the frequency of the differential voltage produced by the pick-up coils is twice the frequency of the excitation current. Therefore, it is possible to extract the information on the external magnetic field by a synchronous demodulation. Using four switches driven by the 200 kHz clock produced by the timing block, at the output of the first amplifier, we obtain a rectified signal, due to the “timed-difference” of the output coils. Then, a second order Sallen-Key low pass filter is used to remove the high-frequency components from the signal and produce a DC output voltage proportional to the applied external magnetic field. The cut-off frequency of the filter was chosen as low as possible (10 Hz), considering the area occupation. The expected output waveforms of the pick-up coils and of the amplifier, with a triangular excitation current in the sensor, are shown in Fig. 6-10.

6.4 Integrated planar micro-Fluxgate: Model 1

The first model, that was analyzed, is shown in Fig. 6-11.

Fig. 6-11 Photograph of the Model 1 of the integrated planar micro-Fluxgates realized.
The integrated sensor consists of five planar coils. The greater coil is the excitation coil that has the fundamental function of saturating the magnetic cross core, which is the sputtered Vitrovac. The other four coils are the sensing coils, a pair for each axis of sensitivity. Three different metal layers were utilized to create the coils:

1. Metal_3 = upper layer, realized with copper.
2. Metal_2 = middle layer, realized with aluminium.
3. Metal_1 = lower layer, realized with aluminium.

Their geometrical parameters are:

- Metal_3: metal width = 5 µm; spacing = 4 µm; copper thickness= 5.5 µm.
- Metal_2: metal width = 1.3 µm; spacing = 1.6 µm; aluminium thickness= 1 µm.
- Metal_1: metal width = 1.1 µm; spacing = 1.2 µm; aluminium thickness= 0.8 µm.

The total area for the excitation coil, which consists of 95 turns, is $1760 \times 1760 \mu m^2$ and its resistance is about of 277 $\Omega$. The total area for the sensing coils, consisting of 66 turns, is $650 \times 650 \mu m^2$ and their resistance is about of 1.59 k$\Omega$.

Since the integrated front-end circuitry is not still available a suitable set-up was realized to characterize the sensor in term of sensitivity to the magnetic field and to evaluate the possibility to use it like a compass. The schematic of the utilized system is shows in Fig. 6-12, which consists of:

1. a pair of Helmholtz coils to impose the external magnetic field;
2. a function generator to supply the excitation coil of the micro-Fluxgate with a triangular excitation current at 100 kHz;
3. an instrumentation amplifier to cancel the common mode noise and evaluate the differential output voltage from the sensing coils;
4. a stage of amplification with a gain of about 33 dB;
5. a spectrum analyzer (3562A Hewlett Packard Dynamic Signal Analyzer) to evaluate the amplitude of the spectral component at 200 kHz;
To evaluate the performance of the sensor like a compass the Earth magnetic field was used instead the Helmholtz coils. In this last case the measurement was realized rotating the sensor in the horizontal plane with the rotational system reported in Fig. 6-13.
The fundamental component of the differential output voltage was then evaluated, using the spectrum analyzer, imposing a voltage supply of 12 V_{peak-peak} and varying the external magnetic field with the Helmholtz coils. This voltage is plotted in Fig. 6-14 against the external magnetic field. The sensor shows a linearity error of about 1.15% of the full scale in the range of ±50 µT with a sensitivity of about 0.45 mV/µT.

![Graph showing voltage output against flux density](image)

**Fig. 6-14** Voltage output from the sensor imposing different values for the external magnetic field.

To evaluate the possibility of using this integrated micro-Fluxgate sensor as a compass, the voltage output was measured while rotating the sensor in a horizontal plane. Fig. 6-15 shows the output voltage for each axis of sensitivity. The reconstructed angles Φ, obtained with the following relation:

\[
\phi = a \tan \left( \frac{V_y}{V_x} \right) \quad \text{Eq.}[10]
\]

where \( V_y \) and \( V_x \) are the voltage output of the sensor (Fig. 6-15), are reported in Fig. 6-16.
Fig. 6-15 Sensor output, at different angles of evaluation, in the Earth magnetic field.

Fig. 6-16 Reconstructed angle with the voltage output of the sensor.
To establish the maximum angle error the effective angular position and the reconstructed angle were compared, like reported in Table 1.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Angle evaluated</th>
<th>Angle reconstructed</th>
<th>Angular error</th>
</tr>
</thead>
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The maximum angular error is underlined in red colour. This angular error was obtained using an amplitude of the triangular supply voltage of 12 V<sub>peak-peak</sub>, therefore the imposed current excitation was:

\[ I_{EXC} = \frac{V_{EFF}}{R} = \frac{12/\sqrt{2}}{277} \cdot \frac{1}{3} = 12.5mA \]  

Eq.[11]

and the power consumption, due only to the sensor, was:

\[ P_{12V} = (12.5mA)^2 \cdot 277 = 43.28mW \]  

Eq.[12]
6.5 Integrated planar micro-Fluxgate: Model 6

The second model analyzed is shown in Fig. 6-17.

![Fig. 6-17 Photograph of the Model 6 of the integrated planar micro-Fluxgates realized.](image)

Also in this case three different metal layers were used to create the coils. Their geometrical parameters are:

- Metal_3: metal width = 8 µm; spacing = 4 µm; copper thickness= 5.5 µm.
- Metal_2: metal width = 1.3 µm; spacing = 1.6 µm; aluminium thickness= 1 µm.
- Metal_1: metal width = 1.1 µm; spacing = 1.2 µm; aluminium thickness= 0.8 µm.

The total area for the excitation coil, which consists of 71 turns, is 1760 x 1760 µm² and its electrical resistance is about of 123.4 Ω. The total area for the sensing coil, which in this case was modified to linkage a more quantity of flux and consisting of 66 turns, is 850 x 850 µm².
with an electrical resistance of about 1.84 kΩ.

The fundamental component of the differential output voltage has then been evaluated, using the spectrum analyzer, imposing a voltage supply of 4.5 V\text{peak-peak} and varying the external magnetic field with the Helmholtz coils. This voltage is plotted in Fig. 6-18 against the external magnetic field. The sensor shows a linearity error of about 1.4% of the full scale in the range of ±50 µT with a sensitivity of about 0.3 mV/µT.

![Fig. 6-18 Voltage output from the sensor imposing different values for the external magnetic field.](image)

For this second model different supply voltages were set to evaluate the performance of the sensor, in term of angular error, at different current excitation.

**6.5.1 Case of study #1: supply voltage 4.5 V\text{peak-peak}**

The supply voltage imposed to drive the sensor is a triangular wave. Using an amplitude voltage of 4.5 V\text{peak-peak} the effective imposed current excitation was:

\[
I_{\text{exc}} = \frac{V_{\text{eff}}}{R} = \frac{4.5}{\sqrt{3}} \cdot \frac{1}{123.4} = 10.5mA
\]

Eq.[13]
and the power consumption, due only to the sensor, was:

\[ P_{4.5V} = (10.5mA)^2 \cdot 123.4 = 13.67mW \]

Eq.[14]

In this case the sensor output, rotating it in the horizontal plane, is shown in Fig. 6-19 and the evaluated angle, with the foregoing sensor outputs, in Fig. 6-20.

Fig. 6-19 Sensor output, at different angles of evaluation, in the Earth magnetic field.
Fig. 6-20 Evaluated angle for Model 6 with 4.5 V supply voltage.

The evaluated angular error is reported in the following table:

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</tr>
<tr>
<td>345</td>
<td>349.0237</td>
<td>352.467</td>
<td>-3.4433</td>
</tr>
<tr>
<td>360</td>
<td>366.7448</td>
<td>367.47132</td>
<td>-0.72852</td>
</tr>
</tbody>
</table>

The maximum angular error is underlined in red colour.
6.5.2 Case of study #2: supply voltage $6 \, V_{\text{peak-peak}}$

The supply voltage imposed to drive the sensor is a triangular wave. Using an amplitude voltage of $6 \, V_{\text{peak-peak}}$ the effective imposed current excitation was:

$$I_{\text{EXC}} = \frac{V_{\text{EFF}}}{R} = \frac{6}{2\sqrt{3}} \cdot \frac{1}{123.4} = 14mA$$  \hspace{1cm} \text{Eq.[15]}

and the power consumption, due only to the sensor, was:

$$P_{\text{sw}} = (14mA)^2 \cdot 123.4 = 24.31mW$$ \hspace{1cm} \text{Eq.[16]}

In this case the sensor output, rotating it in the horizontal plane, is shown in Fig. 6-21 and the evaluated angle, with the foregoing sensor outputs, in Fig. 6-22.

![Sensor output, at different angles of evaluation, in the Earth magnetic field.](image)

---

**Integrated Planar micro-Fluxgate**

96
The evaluated angular error is reported in the following table:

<table>
<thead>
<tr>
<th>Angle</th>
<th>Angle evaluated</th>
<th>Angle reconstructed</th>
<th>Angular error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-81.7054</td>
<td>-84.2530333</td>
<td>-2.5476336</td>
</tr>
<tr>
<td>15</td>
<td>-66.2956</td>
<td>-69.1994916</td>
<td>-2.9039916</td>
</tr>
<tr>
<td>30</td>
<td>-53.3796</td>
<td>-54.1459494</td>
<td>-0.7663494</td>
</tr>
<tr>
<td>45</td>
<td>-39.1901</td>
<td>-39.0324072</td>
<td>0.0976928</td>
</tr>
<tr>
<td>60</td>
<td>-26.9166</td>
<td>-24.038665</td>
<td>2.077735</td>
</tr>
<tr>
<td>75</td>
<td>-14.2426</td>
<td>-8.9532239</td>
<td><strong>5.287477</strong></td>
</tr>
<tr>
<td>90</td>
<td>4.0626</td>
<td>6.0362194</td>
<td>1.9950194</td>
</tr>
<tr>
<td>105</td>
<td>19.0201</td>
<td>21.1217616</td>
<td>2.1018516</td>
</tr>
<tr>
<td>120</td>
<td>36.0868</td>
<td>36.1753038</td>
<td>0.0895038</td>
</tr>
<tr>
<td>135</td>
<td>52.1491</td>
<td>51.228846</td>
<td>-0.920254</td>
</tr>
<tr>
<td>150</td>
<td>67.4399</td>
<td>66.2923882</td>
<td>-1.1575118</td>
</tr>
<tr>
<td>165</td>
<td>84.8013</td>
<td>81.3359304</td>
<td>-3.4653696</td>
</tr>
<tr>
<td>180</td>
<td>97.6344</td>
<td>96.3994725</td>
<td>-1.2449274</td>
</tr>
<tr>
<td>195</td>
<td>112.2046</td>
<td>111.4430149</td>
<td>-0.7617852</td>
</tr>
<tr>
<td>210</td>
<td>127.1123</td>
<td>126.496557</td>
<td>-0.615743</td>
</tr>
<tr>
<td>225</td>
<td>140.763</td>
<td>141.5500992</td>
<td>0.7870992</td>
</tr>
<tr>
<td>240</td>
<td>157.227</td>
<td>156.6036414</td>
<td>-0.6233586</td>
</tr>
<tr>
<td>255</td>
<td>173.46</td>
<td>171.6571836</td>
<td>-1.6020164</td>
</tr>
<tr>
<td>270</td>
<td>182.8506</td>
<td>186.7107258</td>
<td>3.8599258</td>
</tr>
<tr>
<td>285</td>
<td>200.039</td>
<td>201.764263</td>
<td>1.725269</td>
</tr>
<tr>
<td>300</td>
<td>214.006</td>
<td>216.8178102</td>
<td>2.8128102</td>
</tr>
<tr>
<td>315</td>
<td>230.7621</td>
<td>231.8713524</td>
<td>1.1092524</td>
</tr>
<tr>
<td>330</td>
<td>247.2453</td>
<td>246.9248946</td>
<td>-0.3204954</td>
</tr>
<tr>
<td>345</td>
<td>265.846</td>
<td>261.9784369</td>
<td>-3.8675632</td>
</tr>
<tr>
<td>360</td>
<td>277.9381</td>
<td>277.031979</td>
<td>-0.906121</td>
</tr>
</tbody>
</table>

The maximum angular error is underlined in red colour.
6.5.3 Case of study #3: supply voltage $7 \text{ V}_{\text{peak-peak}}$

The supply voltage imposed to drive the sensor is a triangular wave. Using an amplitude voltage of $7 \text{ V}_{\text{peak-peak}}$ the effective imposed current excitation was:

$$I_{\text{EXC}} = \frac{V_{\text{EFF}}}{R} = \frac{7}{2} \cdot \frac{1}{\sqrt{3}} \text{mA} = 16.37 \text{mA}$$  \hspace{1cm} \text{Eq.[17]}

and the power consumption, due only to the sensor, was:

$$P_{\text{FE}} = (16.37 \text{mA})^2 \cdot 1.234 = 33.1 \text{mW}$$  \hspace{1cm} \text{Eq.[18]}

In this case the sensor output, rotating it in the horizontal plane, is shown in Fig. 6-23 and the evaluated angle, with the foregoing sensor outputs, in Fig. 6-24.

![Figure 6-23](image)

**Fig. 6-23 Sensor output, at different angles of evaluation, in the Earth magnetic field.**
The evaluated angular error is reported in the following table:

**Table 4: Angular error evaluation for Model 6, in the case of 7 V supply voltage.**

<table>
<thead>
<tr>
<th>Angle</th>
<th>Angle evaluated</th>
<th>Angle reconstructed</th>
<th>Angular error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-86.2992</td>
<td>-88.53740769</td>
<td>-2.23620769</td>
</tr>
<tr>
<td>15</td>
<td>-71.8039</td>
<td>-73.51166393</td>
<td>-1.707769385</td>
</tr>
<tr>
<td>30</td>
<td>-58.5068</td>
<td>-59.45393108</td>
<td>0.01988892</td>
</tr>
<tr>
<td>45</td>
<td>-44.2799</td>
<td>-43.48019278</td>
<td>0.819707225</td>
</tr>
<tr>
<td>60</td>
<td>-29.0944</td>
<td>-23.43454547</td>
<td>0.64994553</td>
</tr>
<tr>
<td>75</td>
<td>-14.4313</td>
<td>-13.40871617</td>
<td>1.02506335</td>
</tr>
<tr>
<td>90</td>
<td>-2.1906</td>
<td>1.61702214</td>
<td>-3.64762214</td>
</tr>
<tr>
<td>105</td>
<td>14.0178</td>
<td>16.64276045</td>
<td>2.624960445</td>
</tr>
<tr>
<td>120</td>
<td>29.8134</td>
<td>31.68849975</td>
<td>1.85593975</td>
</tr>
<tr>
<td>135</td>
<td>46.6849</td>
<td>46.6923706</td>
<td>0.00637366</td>
</tr>
<tr>
<td>150</td>
<td>63.1295</td>
<td>61.71997536</td>
<td>-1.40952464</td>
</tr>
<tr>
<td>165</td>
<td>78.4981</td>
<td>75.74571367</td>
<td>-1.75286335</td>
</tr>
<tr>
<td>180</td>
<td>94.2907</td>
<td>91.77145197</td>
<td>-2.5193403</td>
</tr>
<tr>
<td>195</td>
<td>108.169</td>
<td>106.7971903</td>
<td>-1.371809725</td>
</tr>
<tr>
<td>210</td>
<td>122.6536</td>
<td>121.8229266</td>
<td>-0.83067142</td>
</tr>
<tr>
<td>225</td>
<td>137.8924</td>
<td>136.8466669</td>
<td>-1.04373315</td>
</tr>
<tr>
<td>240</td>
<td>152.7214</td>
<td>151.6744055</td>
<td>-0.94699481</td>
</tr>
<tr>
<td>255</td>
<td>166.9443</td>
<td>166.9001435</td>
<td>-0.04416565</td>
</tr>
<tr>
<td>270</td>
<td>183.8421</td>
<td>181.9258818</td>
<td>-1.9162162</td>
</tr>
<tr>
<td>285</td>
<td>193.8669</td>
<td>196.9516201</td>
<td>3.095720105</td>
</tr>
<tr>
<td>300</td>
<td>210.0381</td>
<td>211.9773584</td>
<td>1.93925841</td>
</tr>
<tr>
<td>315</td>
<td>226.1615</td>
<td>227.0030967</td>
<td>0.841596715</td>
</tr>
<tr>
<td>330</td>
<td>242.3835</td>
<td>242.0268335</td>
<td>-0.35466498</td>
</tr>
<tr>
<td>345</td>
<td>258.0055</td>
<td>257.0546733</td>
<td>-0.956926675</td>
</tr>
<tr>
<td>360</td>
<td>271.7698</td>
<td>272.0803116</td>
<td>0.31051163</td>
</tr>
</tbody>
</table>

The maximum angular error is underlined in red colour.
6.5.4 Case of study #4: supply voltage 8.9 V\text{peak-peak}

The supply voltage imposed to drive the sensor is a triangular wave. Using an amplitude voltage of 8.9 V\text{peak-peak} the effective imposed current excitation was:

\[
I_{\text{EXC}} = \frac{V_{\text{EFF}}}{R} = \frac{8.9}{2} \cdot \frac{1}{\sqrt{3}} = 20.82\text{mA}
\]

and the power consumption, due only to the sensor, was:

\[
P_{\text{SFF}} = (20.82\text{mA})^2 \cdot 123.4 = 53.49\text{mW}
\]

In this case the sensor output, rotating it in the horizontal plane, is shown in Fig. 6-25 and the evaluated angle, with the foregoing sensor outputs, in Fig. 6-26.

![Sensor output at different angles of evaluation in the Earth magnetic field](image-url)

Fig. 6-25 Sensor output, at different angles of evaluation, in the Earth magnetic field.
Fig. 6-26 Evaluated angle for Model 6 with 8.9 V supply voltage.

The evaluated angular error is reported in the following table:

Table 5: Angular error evaluation for Model 6, in the case of 8.9 V supply voltage.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Angle evaluated</th>
<th>Angle reconstructed</th>
<th>Angular error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-86.2356</td>
<td>-87.9896</td>
<td>-1.7542</td>
</tr>
<tr>
<td>15</td>
<td>-72.8603</td>
<td>-73.01906</td>
<td>-0.15876</td>
</tr>
<tr>
<td>30</td>
<td>-57.3242</td>
<td>-58.03832</td>
<td>-0.71412</td>
</tr>
<tr>
<td>45</td>
<td>-42.4568</td>
<td>-43.05758</td>
<td>-0.60078</td>
</tr>
<tr>
<td>60</td>
<td>-26.5460</td>
<td>-26.07634</td>
<td>-1.53004</td>
</tr>
<tr>
<td>75</td>
<td>-12.325</td>
<td>-13.0961</td>
<td>-0.7711</td>
</tr>
<tr>
<td>90</td>
<td>-4.762</td>
<td>1.88454</td>
<td>6.64364</td>
</tr>
<tr>
<td>105</td>
<td>14.2444</td>
<td>16.86536</td>
<td>2.62098</td>
</tr>
<tr>
<td>120</td>
<td>29.2461</td>
<td>31.84612</td>
<td>2.60002</td>
</tr>
<tr>
<td>135</td>
<td>46.5773</td>
<td>46.82686</td>
<td>0.24956</td>
</tr>
<tr>
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<td>63.156</td>
<td>61.8076</td>
<td>-1.3484</td>
</tr>
<tr>
<td>165</td>
<td>78.6688</td>
<td>76.78834</td>
<td>-1.88146</td>
</tr>
<tr>
<td>180</td>
<td>93.1962</td>
<td>91.76908</td>
<td>-1.42712</td>
</tr>
<tr>
<td>195</td>
<td>107.9429</td>
<td>106.74962</td>
<td>-1.19306</td>
</tr>
<tr>
<td>210</td>
<td>122.3688</td>
<td>121.73056</td>
<td>-0.63624</td>
</tr>
<tr>
<td>225</td>
<td>136.2999</td>
<td>136.7113</td>
<td>-1.5765</td>
</tr>
<tr>
<td>240</td>
<td>153.3065</td>
<td>151.69204</td>
<td>-1.61546</td>
</tr>
<tr>
<td>255</td>
<td>165.6416</td>
<td>166.67276</td>
<td>1.03110</td>
</tr>
<tr>
<td>270</td>
<td>185.5339</td>
<td>181.66352</td>
<td>-3.88038</td>
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<td>285</td>
<td>193.0046</td>
<td>196.63426</td>
<td>3.62966</td>
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<tr>
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<td>211.615</td>
<td>2.9835</td>
</tr>
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<td>225.3991</td>
<td>226.59574</td>
<td>1.19364</td>
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<td>241.5113</td>
<td>241.57648</td>
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<td>345</td>
<td>257.2041</td>
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<tr>
<td>360</td>
<td>272.8165</td>
<td>271.53796</td>
<td>-1.27354</td>
</tr>
</tbody>
</table>

The maximum angular error is underlined in red colour.
6.6 Discussion

The results obtained for the model 1 shown that the micro-Fluxgate realized is able to detect the Earth magnetic field, therefore validating the adopted DC-magnetron sputtering technique for the core deposition. Moreover, the maximum angular error, 4.5°, underlines the possibility to use the sensor like a compass. On the other hand, the power consumption of about 43.28 mW appears not so low but it isn’t comparable with the solutions presented in literature (because of the absence of the part of power consumption due to the front-end circuitry).

The principal results obtained for the model 6 are summarized in the Table 1.

<table>
<thead>
<tr>
<th>Supply voltage</th>
<th>4.5 V</th>
<th>6 V</th>
<th>7 V</th>
<th>8.9 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>13.67 mW</td>
<td>24.31 mW</td>
<td>33.1 mW</td>
<td>53.49 mW</td>
</tr>
<tr>
<td>Maximum angular error</td>
<td>3.6°</td>
<td>5.26°</td>
<td>3.81°</td>
<td>6.65°</td>
</tr>
</tbody>
</table>

The angular error doesn’t show a monotonic trend with the power consumption and the best performance is obtained with the minimum power consumption (13.67 mW). Like reported in the case of the model 1, also in this case the power consumption is not comparable with the solution presented in literature. Anyway, 3.6° angular error and 13.67 mW appear a good results and a good starting point for a future improvement of the performance of the micro-Fluxgate realized.
Conclusions and outlook

In this research activity a new micro-Fluxgate magnetometer with sputtered magnetic core with a thickness of 1 µm was realized. The sensor is planar, fully integrated, based on CMOS process and the magnetic core was deposited above the coils metallization with a CMOS compatible post-process. The micro-Fluxgate is the result of an intense research activity started with the realization of printed circuit board Fluxgate structures and with the utilization of the commercial available soft magnetic material, which shows very good magnetic properties. The PCB Fluxgates realized show good sensitivity, 1.25 mV/µT, and linearity, 1.5 % of the full scale in the range of about ±60 µT, but the high power consumption limits its possible application in portable system.

The micro-Fluxgate realized shows, in the best case, a sensitivity of about 0.45 mV/µT and a linearity error of about 1.15% of the full scale in the range of ±50 µT. The power consumption of 14 mW, even if at the moment not comparable with the solution presented in literature, is expected to be the actual state of the art in the field of Fluxgate magnetic sensor. Improvements were possible using the DC-magnetron sputtering process, for the magnetic core deposition, which allowed the realization of a core only 1 µm thick.

The good sensitivity and the low power consumption, as well as a possibility to detect the filed along two orthogonal directions makes it suitable for a portable compass application. In addition to the work realized, there are some points that could be further improved:

- measurement of the permings, in term of the variation of the sensitivity and the offset of the sensor after the exposure of an intense external magnetic field;
- measurement of the temperature dependence of the sensor offset;
- measurement of the sensitivity stability with the variation of the temperature;
- evaluation of the possibility to improve the magnetic properties of the magnetic core annealing the sputtered core.

The application areas of the developed micro sensor are wide. Good sensitivity and low power consumption from low power supply voltage makes it interesting for portable application that include:

- Electronic compass;
Conclusions and outlook

- Magnetic field detection for medical applications;
- Current measurement;
- Vehicle recognition and other…
Appendixes

A.1 Vitrovac 6025

The homogeneous and isotropic structure of amorphous metals are ideal for good soft magnetic properties. The characteristic low coercitivity field strengths and high permeabilities outperform the best Crystalline Nickel-Iron (NiFe) alloys.

The magnetostriction-free Amorphous Cobalt-based VITROVAC® alloys achieve peak values. By combining a unique alloy selection with an adapted heat treatment, hysteresis loops can be customized to meet the specific needs of each application.

The production of Amorphous metals requires a manufacturing technology that operates on the basis of the necessary cooling rates, which is known as rapid solidification.

The nature of the production process is the reason why Amorphous alloys are offered only in the form of thin metal foils or circular tape cores made from them. Subsequently, tapes can be made for screening or magnet heads as well as sectioned or punched parts for special electrical engineering applications.

Overview

<table>
<thead>
<tr>
<th>VAC-product</th>
<th>Applications</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>VITROVAC 6025</td>
<td>Magnet heads, Magnetic field sensors, Chokes, Transformer, Electronic article surveillance tags</td>
<td>very high permeability, low losses</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VAC-product</th>
<th>Density</th>
<th>Curie Temperature</th>
<th>Crystallisation Temperature $T_x$</th>
<th>Specific electrical resistance $\mu\Omega\ m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VITROVAC 6025</td>
<td>7.7</td>
<td>200</td>
<td>530</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Appendixes

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation flux density (25 °C), B_s</td>
<td>0.58 T</td>
</tr>
<tr>
<td>Bipolar flux density swing (25 °C)</td>
<td>1.15 T</td>
</tr>
<tr>
<td>Bipolar flux density swing (90 °C)</td>
<td>1.0 T</td>
</tr>
<tr>
<td>Squareness, B_s / B_s (100 kHz), typ.</td>
<td>&gt; 96 %</td>
</tr>
<tr>
<td>Saturation magnetostriction (25 °C)</td>
<td>&lt; 0.2 × 10⁻⁸</td>
</tr>
<tr>
<td>Curie temperature, T_c</td>
<td>240 °C</td>
</tr>
<tr>
<td>Continuous upper operation temperature</td>
<td>90 °C</td>
</tr>
</tbody>
</table>

**Diagram:**

- **VITROVAC 8026 Z**
  - H = 80 A/cm
  - f = 100 kHz
  - B_s = 0.58 T (20°C)
  - B_r = 0.57 T (20°C)
  - B_r/B_s = 98%
  - H_s = 19 A/cm (20°C)

- Temperature effects:
  - T = 20 °C
  - T = 100 °C
A.2 Metglas 2714a

**Applications**

- Switch-mode power supply applications
- High frequency transformers
- High sensitivity matching transformers
- Ultra-sensitive current transformers
- Shielding
- Sensor applications

**Benefits**

- Extremely low core loss
- Ultra-high permeability
- High squareness ratio – low coercive force
- Near-zero magnetostriction
- Excellent corrosion resistance

**Typical DC Hysteresis Loop**

**Typical Impedance Permeability Curves, No-Field Anneal**

**Physical Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>7.59</td>
</tr>
<tr>
<td>Vicker's Hardness (50g load)</td>
<td>960</td>
</tr>
<tr>
<td>Tensil Strength (GPa)</td>
<td>1-2</td>
</tr>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>100-110</td>
</tr>
<tr>
<td>Lamination Factor (%)</td>
<td>&gt;75</td>
</tr>
<tr>
<td>Thermal Expansion (ppm/°C)</td>
<td>12.7</td>
</tr>
<tr>
<td>Crystallization Temperature (°C)</td>
<td>550</td>
</tr>
<tr>
<td>Continuous Service Temp. (°C)</td>
<td>90</td>
</tr>
</tbody>
</table>

**Magnetic Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation Induction (Tesla)</td>
<td>0.57</td>
</tr>
<tr>
<td>Maximum D.C. Permeability (µ)</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Annealed</td>
<td>&gt;80,000</td>
</tr>
<tr>
<td>As Cast</td>
<td>&lt;=1</td>
</tr>
<tr>
<td>Saturation Magnetostriction (ppm)</td>
<td>142</td>
</tr>
<tr>
<td>Electrical Resistivity (µ-cm)</td>
<td>225</td>
</tr>
</tbody>
</table>
Typical Core Loss Curves METGLAS Alloy 2714A
A.3 Demagnetization

The distribution of oriented magnetic dipoles in a magnetized body results in an overall dipole moment $m$ and a corresponding distribution of magnetic field $H_d$ as shown in Fig. A.1. This demagnetization field $H_d$ distribution differs in magnitude and direction from the external magnetic field $H_{\text{ext}}$ and can be calculated from the body magnetization and geometry.

![Fig. A.1 Distribution of demagnetization field $H_d$ of a bar magnetized by the external field $H_{\text{ext}}$. Inside the body, the fields have opposite direction.](image)

Exact analytical solutions can be obtained only in the case of second order shapes such as spheres and ellipsoids, because only then $M$ is homogeneous and parallel to $H_{\text{ext}}$. In this case, the demagnetization field is given by:

$$H_d = -DM$$  \hspace{1cm} \text{Eq.}[A.1]$$

where $D$ denotes the demagnetization factor. The internal magnetic field $H_{\text{int}}$ in the body is reduced with respect to the external field $H_{\text{ext}}$ because $H_d$ and $H_{\text{ext}}$ point in opposite directions. The internal field can be expressed by the relation:

$$H_{\text{int}} = H_{\text{ext}} + H_d = H_{\text{ext}} - DM$$  \hspace{1cm} \text{Eq.}[A.2]$$

The demagnetization factor $D$ is calculated solely from the body geometry. For the general ellipsoid with semi-axes $a$, $b$, and $c$, assuming $a \geq b \geq c$ and magnetic field parallel to the long axis $a$, the calculation of $D$ is still rather complex. For an ellipsoid of revolution, i.e. an oblate
or prolate spheroid, the resulting expressions reduce to simpler forms which are listed below:

if $a = b$ (oblate spheroid),

$$\begin{align*}
D &= \frac{1}{2} \left[ \frac{m^2}{(m^2 - 1)^{3/2}} \arcsin \left( \frac{\sqrt{(m^2 - 1)} - 1}{m - 1} \right) \right] \approx \frac{\pi}{4m} \left( 1 - \frac{4}{\pi m} \right)
\end{align*}$$

if $b = c$ (prolate spheroid),

$$\begin{align*}
D &= \left[ \frac{m^2}{(m^2 - 1)^{3/2}} \ln (m + \sqrt{m^2 - 1}) - \frac{1}{m^2 - 1} \right] \approx \frac{1}{m^2} \left( \ln 2m - 1 \right)
\end{align*}$$

where $m = a / c$. Both relations are plotted in Fig. A.2a. The limiting cases in Eq.[A.3] are valid form $m \gg 1$. The demagnetization factor of an extended brick with thickness $t$, width $w$ and length $l$ can be approximated by the corresponding values of the equivalent ellipsoid. For fields parallel to side $l$, it is found to be:

$$D = \frac{wt}{l^2} \left( \ln \frac{4l}{w + t} - 1 \right) \text{ for } l \gg w, \text{ and } D = \frac{t}{l + t} \text{ for } l \ll w \quad \text{Eq.[A.4]}$$

The demagnetization factor of a quadratic thin film with $l = w$ which is approximated by a very flat oblate spheroid can be derived from Eqn. A.3. It is given by:

$$D = \frac{\pi}{4w} \quad \text{Eq.[A.5]}$$

if the quadratic term is neglected. For spheres, $D = 1/3$. Films and rods of infinite size have $D = 0$ for field parallel and $D = 1$ for field perpendicular to their long axis. Due to the reduction of the internal magnetic field in the body, the effective or apparent material permeability, which can be measured, is reduced as well with respect to the relative material permeability. Substituting the definition of the magnetization $M$ in Eq.[A.2] the effective permeability becomes:
\[ \mu_{\text{eff}} = \frac{\mu_r}{1 + D(\mu_r - 1)} \]  

Eq.[A.6]

\( \mu_{\text{eff}} \) only depends on the relative material permeability \( \mu_r \) and on the body demagnetization factor \( D \). In the case of \( \mu_r \gg D^{-1} \) demagnetization limits \( \mu_{\text{eff}} \) independent of \( \mu_r \) and the effective permeability can be approximated by:

\[ \mu_{\text{eff}} \approx \frac{1}{D} \]  

Eq.[A.7]

This can be clearly seen in Fig. A.2b where the transfer function of Eq.[A.6] is shown for oblate spheroids having different semi-axis ratios \( m \) as an example.

Fig.A. 2 (a) Demagnetization factor \( D \) for oblate and prolate spheroids versus semi-axis ratio \( m = a / c \) and (b) transfer function of relative into effective permeability for oblate spheroids for different values of \( m \).
References


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List of Publications


