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Nanomagnetism

Applications and Perspectives
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Thanks to my wife for her patience with me spending many hours working on the book series through the nights and over weekends. The assistance of my son Marc Philip related to the complex and large computer files with many sophisticated scientific figures is also greatly appreciated.

Marcel Van de Voorde
Series Editor Preface

Since years, nanoscience and nanotechnology have become particularly an important technology areas worldwide. As a result, there are many universities that offer courses as well as degrees in nanotechnology. Many governments including European institutions and research agencies have vast nanotechnology programmes and many companies file nanotechnology-related patents to protect their innovations. In short, nanoscience is a hot topic!

Nanoscience started in the physics field with electronics as a forerunner, quickly followed by the chemical and pharmacy industries. Today, nanotechnology finds interests in all branches of research and industry worldwide. In addition, governments and consumers are also keen to follow the developments, particularly from a safety and security point of view.

This books series fills the gap between books that are available on various specific topics and the encyclopedias on nanoscience. This well-selected series of books consists of volumes that are all edited by experts in the field from all over the world and assemble top-class contributions. The topical scope of the book is broad, ranging from nanoelectronics and nanocatalysis to nanometrology. Common to all the books in the series is that they represent top-notch research and are highly application-oriented, innovative, and relevant for industry. Finally they collect a valuable source of information on safety aspects for governments, consumer agencies and the society.

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The book series appeals to a wide range of readers with backgrounds in physics, chemistry, biology, and medicine, from students at universities to scientists at institutes, in industrial companies and government agencies and ministries.

Ever since nanoscience was introduced many years ago, it has greatly changed our lives – and will continue to do so!

March 2016

Marcel Van de Voorde
About the Series Editor

Marcel Van de Voorde, Prof. Dr. ir. Ing. Dr. h.c., has 40 years’ experience in European Research Organisations, including CERN-Geneva and the European Commission, with 10 years at the Max Planck Institute for Metals Research, Stuttgart. For many years, he was involved in research and research strategies, policy, and management, especially in European research institutions.

He has been a member of many Research Councils and Governing Boards of research institutions across Europe, the United States, and Japan. In addition to his Professorship at the University of Technology in Delft, the Netherlands, he holds multiple visiting professorships in Europe and worldwide. He holds a doctor honoris causa and various honorary professorships.

He is a senator of the European Academy for Sciences and Arts, Salzburg, and Fellow of the World Academy for Sciences. He is a member of the Science Council of the French Senate/National Assembly in Paris. He has also provided executive advisory services to presidents, ministers of science policy, rectors of Universities, and CEOs of technology institutions, for example, to the president and CEO of IMEC, Technology Centre in Leuven, Belgium. He is also a Fellow of various scientific societies. He has been honored by the Belgian King and European authorities, for example, he received an award for European merits in Luxemburg given by the former President of the European Commission. He is author of multiple scientific and technical publications and has coedited multiple books, especially in the field of nanoscience and nanotechnology.
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Part One
Spin Electronics and Magnetic Sensing Applications
1
Introduction on Magnetic Sensing and Spin Electronics

Claude Fermon

DRF/IRAMIS/SPEC/LNO, CEA CNRS Paris Saclay, 91191 Gif sur Yvette Cedex, France

This introductory chapter provides the basic knowledge of magnetism and spin electronics, which will help the reader to understand the contents of the book. Then, after a brief introduction to magnetic fields, some bases of magnetic sensing and spin electronics are proposed. The last part of the chapter provides definitions that are useful for understanding spin electronics applications. More in-depth information can be found [1,2]. A number of books have been published on nanomagnetism [3], spin electronics [4,5], GMR [6], and spin dynamics [7], where each particular topic is discussed in detail.

1.1
Magnetic Fields

1.1.1
Introduction

Magnetism and magnetic field are known since thousands of years. First magnetic sensors were compass made of magnetite stones in China during the Han dynasty rule and later used by sailors to navigate. Today, magnetic objects, such as fridge magnets, are used as ornaments or for health purposes. In parallel, electricity is associated with electrons flowing in conductors and its use in domestic applications. Rotating magnetic fields seen by a coil is today the major source of electricity and, inversely, current in a coil produces magnetic fields like in MRI devices. The fundamental reason is that both are, in fact, identical depending on the reference frame taken. This has been highlighted by the well-known Maxwell equations that link electric fields and magnetic fields, one being the derivative of the other.

In parallel to the enormous importance of electricity in our life, electromagnetism has a fundamental property that justifies the billions of magnetic sensors and antennas produced each year: it is the only long-range interaction that we can create, modify, and detect. This long-range interaction property takes
various forms. Light is an electromagnetic wave. Radiofrequency transmissions used for radio, TV, or mobiles are electromagnetic waves at lower frequencies. Static or low-frequency magnetic fields are the extremely low or zero frequency aspect of the same interaction.

1.1.2
**Magnetic Field, Magnetic Induction, and Units**

Historically, the magnetic field has been described by two different quantities. The first one is the field created by a magnet that has been called \( \vec{B} \), the magnetic field intensity. The second one is the field created by a current that has been called \( \vec{H} \), the magnetic induction.

It took some time to reconcile the two quantities that are proportional in the vacuum.

Magnetic field intensity \( H \) is given in A/m or in Oersted and magnetic field induction is given in Tesla or in Gauss. They are related by the following relation:

\[
\vec{B} = \mu_0 (\vec{H} + \vec{M}),
\]

where \( \vec{M} \) is the magnetization of the material at the point where the field is measured. In the presence of vacuum or in nonmagnetic materials that quantity is 0. \( \mu_0 \) is a constant equal to \( 4\pi \times 10^{-7} \).

\( \text{A/m} \) is not a very useful quantity for a common comparison, and now nearly everybody is using Tesla or Gauss as a unit both for magnetic field intensity and induction. In this book, we will follow the same use knowing that this is just a commodity.

The relationship between these quantities is given in Table 1.1.

1.1.3
**Magnetic Materials**

Materials present various states of magnetism and they are classified into three main classes: diamagnetic materials, paramagnetic materials, and ordered

<table>
<thead>
<tr>
<th>Table 1.1 Main fields units.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>Magnetic field intensity</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Magnetic field induction</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
magnetic materials. The first one, diamagnetic materials, corresponds to the large majority of materials. These materials present a very weak magnetization that is proportional and opposite of the applied magnetic field. This magnetization is due to the reaction of electrons. Their magnetization is then simply:

\[
\vec{M} = \chi \vec{H},
\]

where the magnetic susceptibility \(\chi\) is negative of the order of \(10^{-6}\).

Superconducting materials like Niobium at very low temperature are also diamagnetic, but in that case, the susceptibility is nearly equal to \(-1\).

Other materials, called magnetic materials, present an internal magnetization much higher than diamagnetic materials. That magnetization is created by unpaired electrons.

Magnetic materials are disordered at high temperature and become ordered below a critical temperature. When they are disordered, they are called paramagnetic materials and their magnetization can be written as Eq. (1.2) with \(\chi\) positive and relatively large, typically \(10^{-3}\). Magnetic ordered materials are ferromagnetic, antiferromagnetic, or ferromagnetic. Table 1.2 gives a list of the materials you will encounter in this book with their order type and ordering temperature.

Here, we do not consider pure rare earths that exhibit a larger variety of magnetic ordering. Some of them have a different kind of order as function of the temperature.

### Table 1.2 Main magnetic materials found in this book.

<table>
<thead>
<tr>
<th>Material</th>
<th>Order</th>
<th>Temperature of ordering (K)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>Ferromagnetic</td>
<td>1388 K</td>
<td>3D metal</td>
</tr>
<tr>
<td>Fe</td>
<td>Ferromagnetic</td>
<td>1043 K</td>
<td>3D metal</td>
</tr>
<tr>
<td>Ni</td>
<td>Ferromagnetic</td>
<td>627 K</td>
<td>3D metal</td>
</tr>
<tr>
<td>Ni79Fe21</td>
<td>Ferromagnetic</td>
<td>553–871</td>
<td>Very soft alloy called micrometal. Ordering temperature depends on crystal structure</td>
</tr>
<tr>
<td>CoFe</td>
<td>Ferromagnetic</td>
<td>1360</td>
<td>Used due to its large spin polarization</td>
</tr>
<tr>
<td>CoFeB</td>
<td>Ferromagnetic</td>
<td>1300</td>
<td>Used due to its large spin polarization and very soft material</td>
</tr>
<tr>
<td>PtMn</td>
<td>Antiferromagnetic</td>
<td>1000 K</td>
<td>Used for spin electronics</td>
</tr>
<tr>
<td>IrMn</td>
<td>Antiferromagnetic</td>
<td>700 K</td>
<td>Unsed for spin electronics</td>
</tr>
<tr>
<td>Fe3O4</td>
<td>Ferrimagnetic</td>
<td>948 K</td>
<td>Called magnetite</td>
</tr>
<tr>
<td>YIG</td>
<td>Ferromagnetic</td>
<td>560 K</td>
<td>Soft magnetic insulator used for its dynamic properties</td>
</tr>
<tr>
<td>Nd2FeB</td>
<td>Ferromagnetic</td>
<td>593–673</td>
<td>Rare earth-based hard magnet</td>
</tr>
<tr>
<td>Co2Sm17</td>
<td>Ferromagnetic</td>
<td>720</td>
<td>Rare earth-based hard magnet</td>
</tr>
</tbody>
</table>
1.1.4 Magnetic Field Created by a Magnet

The magnetic field created by a magnet is the sum of the fields created by the individual components of the material. This principle of superposition is very important and is included in the Maxwell equations. This principle applies for both magnetic materials and fields created by electrical currents. However, in the determination of the field created by a magnetic material, one has to take care of the magnetization induced by the field created by the other parts of the magnetic material or by external currents. This field-induced effect is very important when you have magnetic cores inserted in coils.

The field created by a small magnet having a homogeneous magnetization $\vec{m}$ taken, for example, along $z$ at a large distance from it decreases at $1/r^3$ and has a shape given in Figure 1.1. This shape, called dipolar shape, will appear very often in this book. The formula of this field is as follows:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \cdot \left( \frac{3\vec{r} \cdot (\vec{r} \cdot \vec{m})}{|\vec{r}|^6} - \frac{\vec{m}}{|\vec{r}|^5} \right), \quad (1.3)$$

where $\vec{r}$ is the distance from the small magnet considered as a point (Figure 1.1).

The main features to retain are this rapid decrease, the fact that the field created along $\vec{m}$ has the same direction to $\vec{m}$, and the field created perpendicular is opposite to it and for the same value of $r$ equal to $\frac{1}{2}$ of the longitudinal field.

1.1.5 Magnetic Fields Created by Electrical Currents

In 1819, Hans Christian Oersted discovered that an electric current is able to generate a magnetic field. One year later, Jean-Baptiste Biot and Félix Savart
wrote the famous Biot–Savart law that gave the magnetic field intensity as function of the current in an elementary element. This law is always used to calculate the field created by an arbitrary conductor. If we consider an element of length \(dl\) with a current \(I\), the field created at a distance \(r\) is given by

\[
\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \cdot \frac{I\mathbf{dl} \times \mathbf{r}}{|\mathbf{r}|^3}.
\] (1.4)

For having in mind an order of magnitude, useful for understanding the various concepts described in this book, we are giving here two simple examples.

The first one is the field created by a long wire, assumed as infinite in its neighborhood (see Figure 1.2). The integration of the formula (1.3) is then

\[
B_0(r) = \frac{\mu_0}{2\pi} \cdot \frac{I}{r}.
\] (1.5)

\(B_0\) is the orthoradial component of the field. The two other components are 0 due to symmetry.

The field created by a circular loop can also be calculated by the (1.3) formula. Along the axis, the field is perpendicular to the coil plane and varies as follows:

\[
B_2(r) = \frac{\mu_0}{2\pi} \cdot \frac{Ia}{\sqrt{a^2 + r^2}}.
\] (1.6)

Outside of the axis, the field has a dipolar shape, similar to the field created by a small magnet.

1.1.6

**Magnetic Thin Films**

Nearly all devices presently fabricated are composed of thin films deposited on flat surfaces, typically silicon wafers. Industrial tools are now able to deposit these films on surfaces up to 300 mm with accuracy better than 0.1 nm and homogeneity on
the whole surface better than 1 % of the thickness. Properties of these thin films are
in general similar to bulk properties, but thin films may exhibit new features. For
example, some films can be crystallized in a structure impossible to achieve with
bulk materials. The second effect of thin-film geometry is to modify strongly the
magnetic anisotropy of the magnetic materials.
Some films can be crystallized in relation to the wafer underneath, we are
hence speaking about epitaxy. A lot of films are textured, that is, they are par-
tially crystallized with a preferred direction imposed by the thin-film geometry.
Some are nearly amorphous: an assembly of small grains with random direc-
tions. Conditions of deposition (method, temperature, and pressure) and anneal-
ing have a large impact on the final structure.

1.1.6.1 Magnetic Anisotropy
A magnetic material may have preferential axis of magnetization induced either
by the crystalline anisotropy or by its shape. The crystalline anisotropy is due to
the coupling between spin orientation and crystalline electric field. The mini-
imization of the corresponding energy gives in general some preferred orienta-
tion.
That anisotropy may be very strong in crystalline materials. Rare earth-based
materials present usually a very high magnetic anisotropy due to their orbital
shape. It is the reason why the strongest permanent magnets are rare earth
based.
A specific magnetic anisotropy appears also at the surface of the magnetic
material. This is due to the breaking of the crystalline electric field symmetry at
the interface. That anisotropy can be larger than the shape anisotropy and help
to create magnetic thin films with a magnetization perpendicular to the plane.
This is the case of, for example, a thin Co layer on Pt.
The shape anisotropy is simply due to the field created by each individual
atom of the layer to the others. This field, called dipolar field or demagnetizing
field, has a dipolar shape given in Eq. (1.3). This field decreases as $1/r^3$, but as the
number of atoms varies as $r^3$ its impact at long distance is huge for ferromag-
netic or ferrimagnetic materials. The first main effect of this shape anisotropy is
to force magnetization to be in the plane of the film. This can be counteracted
only by using very thin films having an additional surface anisotropy. The second
effect of this shape anisotropy is to create domains, that is, parts of the films,
where the magnetization has the same direction.

1.1.6.2 Magnetic Domains
Dipolar interactions responsible for the shape anisotropy impose an overall mag-
netic configuration of the thin film that tends to minimize the overall energy. If
the film is infinite, a uniform magnetization is the lowest energy state, but as
soon as lateral dimensions are reduced, it costs dipolar energy to have a magne-
tization perpendicular to the edge more than rotating smoothly the magnetiza-
tion inside the layer. For that reason, patterned objects in thin films acquire
specific magnetic configurations that you will encounter in this book. Figure 1.3
gives examples of some classical shapes you will see with their stable state.
1.2 Magnetic Field Sensing

There is a large variety of magnetic sensors and it would take several books to describe all of them. Here, we are just giving some indications that will help the teacher to find more information. Some sensors such as Hall effect or inductive sensors have been developed since decades and now main innovations for these sensors are mainly coming from the integration of sophisticated electronics able to perform in real-time complicated algorithms. Others, such as NV sensors (Chapter 6), are very promising for specific applications and are at the stage of research and development. We decided to focus a part of this book on magneto-resistive sensors because they illustrate the dynamism of research in magnetism and are reaching large-volume applications that were mainly covered by Hall sensors. Table 1.3 provides some characteristic properties of the main magnetic sensors technologies.

1.2.1 Magnetic Sensors for DC and Low-Frequency Applications

The main sensor used for DC and low-frequency applications is the Hall sensor based on the Hall effect. When a field is applied on a material where a current is flowing, a voltage appears perpendicular to the current direction due to Lorentz force. This voltage is proportional to the field and the applied current through a factor $R_H$ called Hall resistance.

$$V = R_H \cdot H_{\text{perp}} \cdot I.$$  \hspace{1cm} (1.7)

Today, Hall sensors represent 85% of the world production of magnetic sensors for DC and low-frequencies applications with a growth of about 3% per year. The main competitors are magneto-resistive sensors (AMR, GMR, and TMR) described in this book that represent only 10% but are growing at an annual rate of about 10%. Magneto-electric sensors also appear in some commercial products. They present the advantage to be passive, but they cannot be integrated. Fluxgates are mainly used for very sensitive applications such as earth field mapping for field monitoring.
### Table 1.3 Main magnetic sensors technologies with some properties.

<table>
<thead>
<tr>
<th>Principle</th>
<th>Scalar/Vectorial</th>
<th>Operating temperature range</th>
<th>Field range</th>
<th>Frequency range</th>
<th>Linearity</th>
<th>Size</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall</td>
<td>Vect.</td>
<td>−200 °C/150 °C</td>
<td>1 µT–10 T</td>
<td>DC-1 MHz</td>
<td>Good</td>
<td>µm–mm</td>
<td>Semiconductor</td>
</tr>
<tr>
<td>AMR</td>
<td>Vect.</td>
<td>−275 °C/200 °C</td>
<td>1 nT–1 mT</td>
<td>DC-10 MHz</td>
<td>Limited</td>
<td>µm–mm</td>
<td>Ferromagnet</td>
</tr>
<tr>
<td>Optical</td>
<td>Vect. or scalar</td>
<td>Room temp.</td>
<td>1 fT–1 µT</td>
<td>DC</td>
<td>Requires feedback</td>
<td>mm–cm</td>
<td>Alkali gas</td>
</tr>
<tr>
<td>GMI</td>
<td>Vect.</td>
<td>−50–150 °C</td>
<td>10 pT–0.1 mT</td>
<td>DC-10 kHz</td>
<td>Requires feedback</td>
<td>mm–cm</td>
<td>Soft ferromagnet</td>
</tr>
<tr>
<td>Magnetoelectric</td>
<td>Vect.</td>
<td>−50–150 °C</td>
<td>100 pT–1 mT</td>
<td>DC-1 kHz</td>
<td>Limited</td>
<td>0.1 mm–cm</td>
<td>Composite</td>
</tr>
<tr>
<td>GMR/TMR</td>
<td>Vect.</td>
<td>−273–180 °C</td>
<td>100 pT–10 mT</td>
<td>DC-GHz</td>
<td>Limited</td>
<td>µm</td>
<td>Multilayer</td>
</tr>
<tr>
<td>Coils</td>
<td>Vect.</td>
<td>−273–600 °C</td>
<td>1 fT–10 T</td>
<td>AC</td>
<td>Excellent</td>
<td>0.1 mm–m</td>
<td>Metal</td>
</tr>
<tr>
<td>Search coil</td>
<td>Vect.</td>
<td>−50–200 °C</td>
<td>1 fT–10 mT</td>
<td>AC</td>
<td>Excellent</td>
<td>0.1 mm–1 m</td>
<td>Ferrite core</td>
</tr>
<tr>
<td>Fluxgate</td>
<td>Vect.</td>
<td>−50–200 °C</td>
<td>5 pT–100 µT</td>
<td>DC-5 kHz</td>
<td>Good</td>
<td>0.1 mm–5 cm</td>
<td>Ferrite core</td>
</tr>
<tr>
<td>SQUID</td>
<td>Vect.</td>
<td>−273–200 °C</td>
<td>1 fT–10 µT</td>
<td>DC-100 kHz</td>
<td>Requires feedback</td>
<td>0.1 mm–1 cm</td>
<td>Metallic</td>
</tr>
</tbody>
</table>