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Magnetic Sensors for Biomedical Applications

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IEEE Press Series on Sensors

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Sensing phenomena and sensing technology is perhaps the most common thread that connects just about all areas of technology, as well as technology with medical and biological sciences. Until the year 2000, IEEE had no journal or transactions or a society or council devoted to the topic of sensors. It is thus no surprise that the IEEE Sensors Journal launched by the newly-minted IEEE Sensors Council in 2000 (with this Series Editor as founding Editor-in-Chief) turned out to be so successful, both in quantity (from 460 to 10,000 pages a year in the span 2001–2016) and quality (today one of the very top in the field). The very existence of the Journal, its owner, IEEE Sensors Council, and its flagship IEEE SENSORS Conference, have stimulated research efforts in the sensing field around the world. The same philosophy that made this happen is brought to bear with the book series.

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Preface

Magnetic field sensors are widely being used for various applications, ranging from navigation to industrial as well as biomedical applications. A large variety of magnetic sensors based on miniaturized and integrated Hall effect and magnetoresistive (MR) sensors to bulky superconducting quantum interference devices (SQUIDs) have been employed in automotive, information storage, and medical marketplaces. Biomedical magnetic sensors which can capture magnetic fields from biological tissues (e.g. brain, muscle, and cardiac) as well as point-of-care diagnostics were in the center of attention in the past couple of decades. In this regard, highly sensitive, low noise, low power, and integrated magnetic sensors are required to be portable, wearable, and implantable. This book presents the progress and state-of-the-art toward this direction.

As one of the most well-known magnetic sensors, Hall sensors are compact and versatile devices, exhibiting a high magnetic moment sensitivity over a wide field range in both low and room temperature conditions. Moreover, they generally offer a highly linear response, without being affected by magnetic saturation. These sensors have been studied and investigated both numerically and experimentally for different medical applications, such as Hall magnetometry on nanostructures and detection of magnetic beads as a label.

Among the magnetic sensors, it has always been to the benefit of MR sensors that thin-film technology and large magnetoresistance were the interested objects of other often better financially supported activities. For fundamental physics, the investigations of phenomena in thin magnetic films were always valuable because it was easier to explain and understand the magnetism in this specific form of magnetic materials. The most significant support for researches of the magnetoresistance in thin film arises from the success of random access memory technology because it is obvious that the next generation of high-density recording heads will be based on large MR effects.

In this book, the physics of magnetic sensors, their fabrication technologies, and applications are presented. For example, the technology of giant magnetoresistive (GMR) sensors is very sophisticated and refined and therefore it is described as an excellent example of the thin-film technology. Thus, this book not only describes some classes of magnetic sensors but also discusses many more universal subjects, such as magnetism, thin-film technology, fabrication techniques, magnetic measurements, and applications. Therefore, it should be useful for various kinds of readers, especially addressed to engineers. For high-quality specialists, it should be interesting as a comprehensive review of all available knowledge to date. For the sensors' working mechanism, the mathematical descriptions are also presented; therefore, the level is also applicable to students and practising engineers. In this book, there is much computational information about magnetic sensor performance because the authors are engineers who have been active for numerous years in the field of designing and computational modeling of different magnetic sensors and also magnetic measurements.

As one of the most important applications for magnetic sensors, biomedical applications have been addressed and discussed comprehensively. For example, Hall sensors for the detection and even counting of individual magnetic nanobeads, which can be used as labels for medical imaging, drug delivery, and manipulation of biological species, have been discussed. MR sensors for detection of bioanalytes, monitoring of magnetic fluids, biomolecular recognition experiments, and neural activity recording as an ultrasensitive magnetic array have been addressed. We have also presented applications of nuclear magnetic resonance (NMR) sensors for magnetic resonance imaging, electron spin resonance (ESR) sensors for direct detection of paramagnetic species and ESR oximetry, as well as SQUIDs for biomagnetism, magnetoencephalography, and magnetocardiography. That is why this book is entitled "magnetic sensors for biomedical applications."

All parts of the book, Hall effect, MR, NMR, and SQUID sensors and their applications, are written as separate chapters (with independent references and independent logical concept). So, it is not necessary to read the book "from the beginning." If, for example, readers are interested in the one specific sensor, it is sufficient to read only the relevant chapter. In all parts, the structure is the same, consisting of overview, sensor structure and working mechanism theory, sensor different classes, and finally applications. Therefore, it is worth reading this book to gain a better understanding of the features of magnetic sensors and hopefully to use them more effectively. In addition, the authors also recommend reading this book as a story that is one of the most fascinating events of advanced technology. The sensors fabricated in nanometric atomic scale exhibit extraordinary and not fully understood phenomena. The expected future applications of magnetic sensors, especially in medical applications and data storage systems, open new perspectives for the whole of science.

Hadi Heidari and Vahid Nabaei

1

Introduction

1.1 Overview

Magnetic field sensors have been born and used for many years in early applications of direction finding or navigation. Today, magnetic sensors are still a primary means of navigation, but many more uses have evolved. The technology for sensing magnetic fields has also evolved driven by the need for improved sensitivity, smaller size, and compatibility with electronic systems. The output of other sensors, such as temperature, pressure, strain, and light sensors, directly reports the desired parameters, while using magnetic sensors to detect direction, presence, rotation, angle, or electrical currents only indirectly detect these parameters. The output signal of a magnetic sensor requires some signal processing to translate it into the desired parameter value. This makes magnetic sensing a little more challenging to apply in most applications, but it allows for reliable and accurate sensing of parameters that are difficult to sense otherwise. One approach to the development of magnetic sensors is the pursuit of an ideal device that meets the demands and limitations of all the possible applications. Such an ideal sensor must have an ultra-high resolution, a wide bandwidth, very low power consumption, as well as being miniature, low cost, which, all together, does not seem realistic. An optimal magnetic sensing device is that which best fits a set of requirements dictated by a specific application.

This book aims to assist the readers in their search for their optimal magnetic sensing system. From the more common and popular Hall effect sensors up to the nuclear magnetic resonance (NMR)-based magnetometers, each chapter describes a specific type of sensor and provides useful information that is necessary to understand the magnetometer behavior, including theoretical background, noise model, materials, electronics, applications, design, and fabrication techniques. In this chapter, we outline the history of magnetic sensors, natural and technical magnetic fields, magnetic terms and units, magnetic microsensors and their properties and classification, magnetic sensor

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terminology, and noise in magnetic sensors. In Chapter 2, we focus on Hall magnetic sensors, and discuss Hall effect, characteristics of Hall effect devices such as geometry and material, horizontal and vertical CMOS Hall devices, and Hall sensor applications. Magnetoresistance (MR) sensors' material and principles, classes, modeling and simulation, design and fabrication technologies, as well as their various biomedical applications have been outlined in Chapter 3. In Chapter 4, we review models, instruments, and biomedical applications of different resonance magnetometers such as NMR, magnetic resonance imaging, and electron spin resonance. Chapter 5 provides an overview of fundamentals, fabrication technologies, and biomagnetism applications of superconducting quantum interference devices. Comparisons of Hall sensors with other galvanomagnetic sensors, NMR with electron spin resonance, and conclusion are presented in Chapter 6.

1.2 History of Magnetism Studies and of Its Use in Magnetic Sensors

The expression "magnet" or "magnetic" originates from the region Magnesia in Thessaly (Greece) where magnetic loadstone (Magnetite, Fe, O) is found as a natural resource [1]. The first reports, in Europe, of the attraction and repulsion forces arising between magnetic loadstones were made by Thales of Miletus around 600 BCE. The expression "sensor" is derived from the Latin "sensus" meaning capable of sensitivity. It is gradually replacing previously used expressions such as "measurement pick-up" and "probe." The directional compass can be regarded as the first magnetic sensor since it reacts to the Earth's magnetic field. Its history stretches back over 4000 years and can be traced to the Chinese who first discovered magnetic loadstone as a natural source of magnetism and used it as a directional aid for orientation [2]. The compass became significantly more important in Europe from about 1200 CE onwards, and in particular, around the time of the great seafaring adventurers and explorers. On his transatlantic voyages, Christopher Columbus observed the behavior of the compass as he sailed westward; famous compass-makers are known to have lived in London and Nurnberg around 1500. In 1820, Oersted discovered that a current-carrying wire deflected a compass needle in its vicinity, and with that the age of electromagnetism had arrived. The first mathematical formula describing the correlation between electric current and magnetism through the deflection of a magnetic needle was Biot–Savart's law. Faraday repeated and extended Oersted's experiments and while doing so discovered the Law of Induction in 1831. The first magnetometer to be constructed was the bifilar magnetometer built in 1831 by Gauss and Weber and the Weber–Bussole compass in 1841, which included a magnetic needle used to measure powerful currents. In 1862, Maxwell created the common theoretical basis for electromagnetism with laws which were named after him, though the expression “permeability” can be traced to Lord Kelvin. Throughout the history of this topic it is evident that the availability of different types of sensors operating on a magnetic basis is very closely linked to the development and availability of special magnetic materials and to the discovery of new physical and magnetic effects. Some of these effects were very soon exploited to make new magnetic sensors, others were not used until much later, and some are yet to be utilized in sensors. Table 1.1 gives a brief history of the use of magnetic effects in sensors, see also [3].

1.3 Natural and Technical Magnetic Fields and Their Order of Magnitude

Both our natural environment and our technical surroundings provide magnetic fields of many different types and orders of magnitude [1]. Many magnetic sensors detect such fields either directly or indirectly using various principles. Hence, it is essential to take a closer look at the types and magnitudes of the various fields.

1.3.1 Natural Magnetic Fields

1.3.1.1 The Earth’s Magnetic Field

The most ubiquitous natural field of all is the magnetic field of the Earth which surrounds us perpetually. It is a dipole field, whose field lines originate at the magnetic poles in the interior of the earth, escaping through the surface and reaching into outer space (Figure 1.1). The Earth’s magnetic field is used every day by people with compasses to determine the direction or at altitudes of several hundred kilometers to stabilize satellites; on the Earth’s surface it can be employed as a constant reference field within certain ranges and times. The precise determination of the parameters of the Earth’s magnetic field, namely its magnitude and direction, was one of the great pioneer acts in the field of magnetism and went back to the works of Gauss and Oersted [1].

1.3.1.2 Magnetic Fields in Outer Space

With the aid of satellites and sensitive magnetic-field sensors, magnetic fields in the vicinity of planets and in outer space can also be determined directly, see Table 1.2 and [4].

1.3.1.3 Biomagnetic Fields

Human beings also produce small magnetic fields, which are primarily caused by microcurrents in cardiac, brain, and muscle tissues [5]. They can nowadays

Table 1.1 History in examples: the magnetic effects in first magnetic sensors [1].

Year	Effect	Explanation	Technical use
1842	Joule effect	Change in the shape of ferromagnetic body with magnetization (magnetostriction)	In combination with piezoelectric elements for magnetometers and potentiometers
1846	AE effect	Change in Young's modulus with magnetization	Acoustic delay line components for magnetic field measurement
1847	Matteucci effect	Torsion of a ferromagnetic rod in a longitudinal field changes magnetization	Magnetoelastic sensors
1856	Magnetoresistance (Thomson effect)	Change in resistance with magnetic field	Magnetoresistive sensors
1858	Wiedemann effect	A torsion is produced in a current-carrying ferromagnetic rod when subjected to a longitudinal field	Torque and force measurement
1865	Villari effect	Effect on magnetization by tensile or compressive strength	Magnetoelastic sensors
1879	Hall effect	A current carrying crystal produces a transverse voltage when subjected to a magnetic field vertical to its surface	Magnetogalvanic sensors
1903	Skin effect	Displacement of current from the interior of material to surface layer due to eddy currents	Distance sensors, proximity sensors
1931	Sixtus–Tonks effect	Pulse magnetization by large Barkhausen jumps	Wiegand and pulse-wire sensors
1962	Josephson effect	Tunnel effect between two superconducting materials with an extremely thin separating layer; quantum effect	SQUID magnetometers

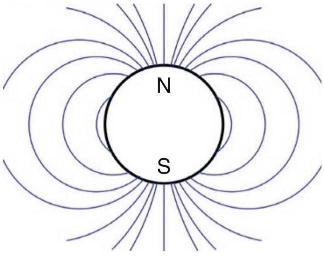

Figure 1.1 Magnetic field formed around the Earth.

Table 1.2 Magnetic field strengths of celestial bodies and objects in outer space [1].

Celestial bodies	Field strength (A/cm)	Flux density (mT)
Galaxies	$\approx 0.15 - 0.25 \times 10^{-6}$	$0.2 - 0.3 \times 10^{-6}$
Mercury (poles)	$\approx 3 \times 10^{-3}$	0.35×10^{-3}
Jupiter (Poles)	Up to 6	Up to 0.8
Mars	0	0
Saturn (equator)	$\approx 2.4 - 16$	$0.3 - 2$
Sun (surface)	$\approx 4 - 8$	$0.5 - 1$
Earth (poles)	≈ 0.5	0.06
A-stars	Up to 28×10^3 A/cm	Up to 3.5 T

be measured with highly sensitive magnetic-field detectors such as flux-gate magnetometers, superconducting quantum interference devices (SQUIDs), and gradiometer coils on the surface of the body, whereas in the past, it had only been possible to measure these currents indirectly by attaching electrodes to the skin and measuring the relevant voltage drops, a technique which forms the basis for the electrocardiogram (ECG). The magnitude of the field strengths and flux densities produced by the heart and brain currents are approximately 50×10^{-3} nT and 1×10^{-3} nT, respectively [6].

1.3.2 Technical Magnetic Fields

1.3.2.1 Magnetic Fields in the Vicinity of Transformers and Electric Motors

Magnetic fields produced in electrotechnical devices, equipment, and plants are usually in the field-strength range of $0.1–10^4$ A/cm [1]. In most cases, these would be AC fields emitted by overhead lines, electrified lines (train or tram lines, etc.), transformers, and electrically powered machinery. Transformers and machinery are mostly operated near the saturation limit of their iron cores, and as such the polarization in the core material attains a level of about 2 T. Similarly, both flux densities in the air gaps of big choke coils or in the gaps between rotors and stators of electric machinery and the stray fields in the vicinity are, as a rule, not much lower.

1.3.2.2 Fields of Permanent Magnets

Except for electromagnets, permanent magnets and magnetic systems are frequently used to produce static magnetic fields, particularly in measurement devices. In such cases, the field is mostly concentrated into a specified volume (e.g. operating air gap) through appropriate design of the magnet and magnetic circuit. The magnitude of the field strengths or flux densities attainable depends on both the remanence and the energy density of the magnetic materials as well as on the geometry of the magnetic circuit. Solenoids with a conventional design, iron-cored coils (electromagnets), and superconducting (solenoid) coils can produce flux densities in the region of 1–100 T depending on their dimensions, their magnitude, and their mode of operation [7–9]. Superconducting coils in medical scanning machines (NMR systems) with a practical diameter of roughly 1 m can produce fields of 1 –2 T, and individual coils with large diameters are used for specified tasks in elementary particle physics and nuclear fusion producing flux densities anywhere from 2 to 10 T.

1.4 Magnetic Terms and Units

The subject of magnetism generates a number of terms and units which are commonly used, the more important ones being included in Table 1.3 [1]. Nowadays, magnetic terms and units are given using the MKSA system, a subsystem of the SI system, and they are based on the four basic units of meter, kilogram, second, and ampere. Although the previously used electromagnetic system of dimensions (CGS electromagnetic units, emu), also known as the Gauss system, is officially no longer acceptable, it is still sometimes found in

Table 1.3 Magnetic terms and units [1].

Term	Quantity	MKSA unit	Subunits	CGS unit	Conversion
Magnetic field strength	H	A/m	1 A/cm = 100 A/m	Oe (Oersted)	1 Oe = 79.58 A/m
Magnetization	M	A/m	See field strength		
Magnetic induction	B	T	1 mT = 10^{-3} T	G (Gauss)	1 G = 10^{-4} T
Magnetic flux	ϕ	Wb	—	Mx (Maxwell)	1 Mx = 10^{-8} Wb
Magnetic polarization	J	T	See induction		
Permeability (absolute)	P	T·m/A	—	G/Oe	
Permeability of vacuum (magnetic constant)	μ_0	$4 \times \pi 10^{-7}$ T·m/A	$0.4 \times \pi 10^{-7}$ T·m/A	1	—

the literature and so a conversion table (Table 1.3) for the CGS units has been included [10].

The most important basic equations are:

$$B = \mu_0 \cdot (H + M) = \mu_0 \cdot H + J \tag{1.1}$$

$$M = \frac{B}{\mu_0} - H \tag{1.2}$$

$$\mu = \mu_0 \cdot \mu_r \qquad \mu_r = \text{Relative permeability} \tag{1.3}$$

$$B = \mu_0 \cdot \mu_r \cdot H \tag{1.4}$$

where, B is magnetic induction, μ_0 is permeability of vacuum, H is magnetic field strength, J is magnetic polarization.

1.5 Magnetic (Micro) Sensors

1.5.1 Definition of Magnetic Sensors

Magnetic materials, i.e. soft and hard magnetic materials and all other materials, which are sensitive to magnetic fields, play a principal role in the nature and operation of magnetic sensors. But at this stage it is not relevant to consider whether metals, metal oxides, or semiconductors are concerned, or which magnetic field is influencing physical properties [11–14]. In textbooks on measurements and control, books on sensors and review articles, sensors have been classified using the following methods [15, 16]: Types of sensors; Physical principles; Properties measured; Sensor applications; Sensor technologies. For example, in [1], a classification system has been selected which is primarily based on physical principles and effects, as follows: Magnetogalvanic sensors; Magnetoelastic sensors; Magnetic-field sensors: saturation-core magnetometers (flux-gate magnetometers) and induction-coil and search-coil magnetometers; Inductive sensors (including eddy-current sensors); Wiegand and pulse-wire sensors; Magnetoresistive sensors; SQUID sensors. Microsensors for a magnetic field are modulating transducers (all semiconductor sensors and all silicon sensors) [17]. They convert the magnetic field, whether it is constant or variable, or even of biological origin, if possible, with a maximal degree of accuracy and reliability, into an output electrical signal (current, voltage, or frequency) with high fidelity. The output energy of the modulating sensors is fed by an external power source through an additional input. More specifically, these microdevices are fabricated using standard semiconductor IC technologies (most frequently, silicon processing technologies). Contemporary microsystems for magnetic fields (hybrid or monolithic) must integrate at least two functions. One of them must be the sensing by an input transducer or sensor of the strength and the direction of this physical measurand; the other can be signal processing (when necessary, including a processor and the corresponding software) and/or an actuator. Elements that locally enhance, compensate, or change the direction of the external magnetic field such as ferrite flux concentrators or coils, can also be installed in the microsystem [1, 18–20]. By using appropriate packages with small dimensions, these MEMS offer a variety of contactless sensing.

1.5.2 Soft and Hard Magnetic Materials for Sensors

Almost all magnetic sensors include magnetic materials in the form of active or passive components, and to a large extent, they determine the concept, construction, and ultimately the sensitivity of the sensors. In view of this, a brief survey of magnetic materials and their most important characteristic is presented in Tables 1.4 and 1.5. These materials are classified according to the IEC system for soft and hard magnetic materials. For textbooks on materials refer to [21, 24]. The magnetic materials listed in Tables 1.4 and 1.5 are closely related to the main classes of magnetic sensors shown in Table 1.6 although some special materials have been added.

1.5.2.1 Shape of the Hysteresis Loop

The most typical characteristic of soft magnetic materials is its hysteresis loop. The shape of the loop can vary greatly and is determined by the type of material and its structure which can be changed by processing and annealing. This is

Table 1.4 Soft magnetic materials [1].

Group	Code	
	A	Irons
	B	Low carbon mild steel
	C	Silicon steel, mainly with 3% Si
Crystal metals	D	Other steels
	E	Nickel–iron alloys (five groups E1 – E5 with 30% – 83% Ni)
	F	Iron–cobalt alloys (three groups F1 – F3 with 23% – 50% Co)
	G	Other alloys as AlSiFe-alloys
Oxides	H	Soft ferrites as NiZn and MnZn oxides
Amorphous metal	I	Amorphous alloys (Fe-based and Co-based alloys)
Powder composite metals	—	Based on Fe and iron alloy powders

Table 1.5 Hard magnetic materials [21–23].

Group	Code	
Crystal metals	R1	Alloys of AlNiCo-type
	R2	Platinum–cobalt alloys
	R3	Iron–cobalt–vanadium (Chromium) alloys
	R6	Chromium–iron–cobalt alloys
	R5	Rare earth cobalt alloys
	R7	Rare earth iron alloys
Amorphous metal	—	Rare earth iron alloys
Oxides	Sl	Hard ferrites as Ba- and Sr-ferrites
	T	Other hard magnetic materials, e.g. magnetically semi hard metals

Table 1.6 Magnetic material for sensors (materials are defined in Tables 1.4 and 1.5).

	Magnetically soft		Magnetically hard	
Sensor class	Material	Useful for	Material	Useful for
Magnetogalvanic	C, E	Slotted cores yokes	R1, R5, R7	Magnetic circuit
Magnetoelastic	D, E1, I, C, E1	Shafts, surface layers for shafts, laminated core packages, pot-cores	—	—
Fluxgate	E1, H, I	Strips and rods, toroidal cores	—	—
Inductive, eddy current	C, E2, E3, H	Rods, yokes, laminated cores, pot core, rods	R1, R5, R7, S1	Parts
Wiegand, pulse-wire	F, special alloys	Wires	R6	Magnets as rods for switching
Magnetoresistive	E1, I, NiCo, NiFeCo	Resistors	R2, R5, CoCr	Permagnetizing layers