Part One
Spin Electronics and Magnetic Sensing Applications

1
Introduction on Magnetic Sensing and Spin Electronics

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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 purpose. 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

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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:

$$\vec{B} = \mu_0\left(\vec{H}+\vec{M}\right), \tag{1.1}$$

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. μ_0 is a constant equal to $4\pi 10^{-7}$.

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 1.1 Main fields units.

Quantity	Designation	Unit	Link
Magnetic field intensity	H	A/m (MKS)	In vacuum $1T = 4\pi 10^{-7}$ A/m.
		Oe: Oersted (CGS)	In vacuum 1Oe = 1G
Magnetic field induction	B	T: Tesla (MKS)	In vacuum $1T = 4\pi 10^{-7}$ A/m.
		G: Gauss (CGS)	$1G = 10^{-4}$ T

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:

$$\vec{M} = \chi\vec{H}, \tag{1.2}$$

where the magnetic susceptibility χ 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 χ 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.

Material	Order	Temperature of ordering (K)	Comment
Co	Ferromagnetic	1388 K	3D metal
Fe	Ferromagnetic	1043 K	3D metal
Ni	Ferromagnetic	627 K	3D metal
Ni79Fe21	Ferromagnetic	553–871	Very soft alloy called micrometal. Ordering temperature depends on crystal structure
CoFe	Ferromagnetic	1360	Used due to its large spin polarization
CoFeB	Ferromagnetic	1300	Used due to its large spin polarization and very soft material
PtMn	Antiferromagnetic	1000 K	Used for spin electronics
IrMn	Antiferromagnetic	700 K	Unsed for spin electronics
Fe3O4	Ferrimagnetic	948 K	Called magnetite
YIG (yttrium garnet)	Ferromagnetic	560 K	Soft magnetic insulator used for its dynamic properties
Nd_2FeB	Ferromagnetic	593–673	Rare earth-based hard magnet
Co_2Sm_{17}	Ferromagnetic	720	Rare earth-based hard magnet

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:

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

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 ½ 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

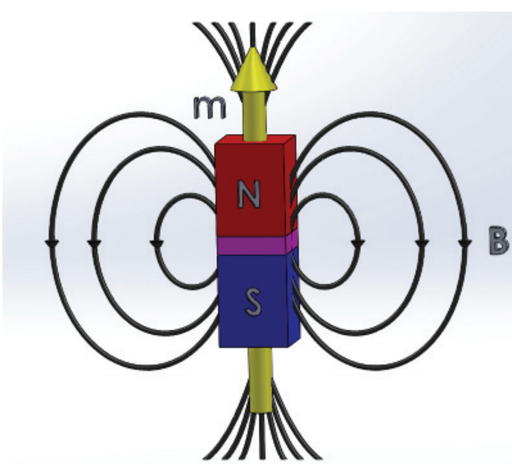

Figure 1.1 Dipolar shape created by a small magnet.

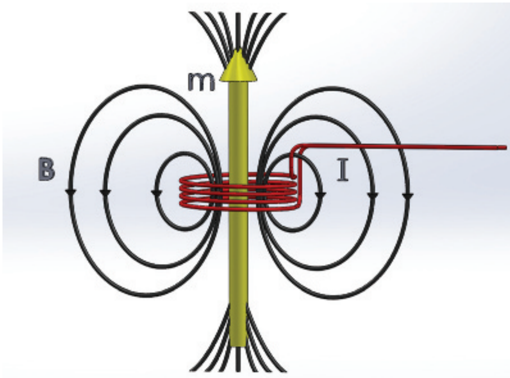

Figure 1.2 Field created by a wire and by a circular coil.

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

$$\vec{B}\,(\vec{r}\,) = \frac{\mu_0}{4\pi} \cdot \frac{I\overrightarrow{\mathrm{d}l} \times \vec{\boldsymbol{r}}}{|\vec{r}\,|^3}. \tag{1.4}$$

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

$$B_\theta(r) = \frac{\mu_0}{2\pi} \cdot \frac{I}{r}. \tag{1.5}$$

B_θ 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:

$$B_Z(r) = \frac{\mu_0}{2\pi} \cdot \frac{Ia}{\sqrt{a^2 + r^2}}. \tag{1.6}$$

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 partially crystallized with a preferred direction imposed by the thin-film geometry. Some are nearly amorphous: an assembly of small grains with random directions. Conditions of deposition (method, temperature, and pressure) and annealing 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 minimization of the corresponding energy gives in general some preferred orientation.

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 ferromagnetic 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 magnetic 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 magnetization perpendicular to the edge more than rotating smoothly the magnetization 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.

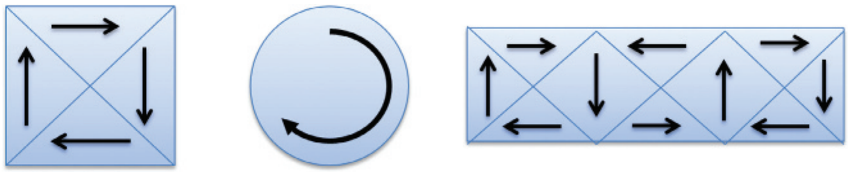

Figure 1.3 Typical magnetic domains observed in small objects. Arrows indicate the direction of magnetization and blue lines domain walls. In the cross of domain walls or in the center of the disk, the magnetization goes out of plane. This is called a vortex.

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 magnetoresistive 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.

$$V = R_{\mathrm{H}} \cdot H_{\mathrm{perp}} \cdot I. \tag{1.7}$$

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 magnetoresistive sensors (AMR, GMR, and TMR) described in this book that represent only 10 % but are growing at an annual rate of about 10 %. Magnetoelectric 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.

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

1.2.2
Magnetic Sensors for High-Frequency Applications

When the frequency is increased, the sensor used universally is the coil or antenna. The radiofrequency field creates a current inside a metallic wire that can be amplified and detected. As this current is proportional to the frequency, higher the frequency, the higher the sensitivity of a coil is. The electromagnetic wave is both an electric field and a magnetic field and antennas are designed to be more sensitive to electric fields, whereas coils are designed to be more sensitive to magnetic fields. There is, however, one specific case where coils/antennas are less competitive than magnetoresistive sensors: when the size becomes so small that it is impossible to build a performing coil. This has created two application cases for magnetoresistive sensors: nondestructive evaluation (see Chapter 5) and integrated position sensors.

1.2.3
Very Sensitive Magnetic Sensors

The development of very sensitive sensors for low-frequency magnetic field detection is a domain where a very active research work is going on across the world. Table 1.4 describes the main sensors technologies for subpicotesla detection. Applications of very sensitive sensors are brain/body imaging like biomagnetism and low-field MRI (Chapter 2), magnetic particles detection (Chapters 8 and 9) and earth field mapping.

Table 1.4 Very sensitive magnetic sensors with their working temperature and field equivalent noise.

Sensor type	Working temperature	Minimal detectivity for 1 cm^2	Comments
SQUIDs	4 K	1 fT/sqrt(Hz)	Extensively developed and used. This is the reference sensor
HTS SQUIDs	77 K	30 fT/sqrt(Hz)	
Atomic magnetometers	150 °C	10 fT/sqrt(Hz)	Absolute magnetometers. Need the suppression of DC fields
Fluxgates	RT	1 pT/sqrt(Hz)	
Superconducting/GMR Mixed sensors	4 K	3 fT/sqrt(Hz)	Large 1/f noise
Superconducting/GMR Mixed sensors	77 K	7 fT/sqrt(Hz)	Large 1/f noise

1.3 Introduction to Spin Electronics

Spin electronics is based on the fact that electrons have not only a charge but also a magnetic moment, called spin, which is quantified. The aim is to use this magnetic moment to filter electrons, to manipulate macroscopic magnetization, and in some cases to transport information. Historically, the first spin electronic effect, called the GMR effect, was discovered by P. Grunberg and A. Fert, who were awarded the Nobel Prize in 2007 [8]. The TMR effect was proposed earlier by Julière in 1975 [9] and observed later. Spin electronics applications are today mainly magnetic sensing with GMR and TMR sensors and magnetic storage with MRAMs and magnetic logics. Both are now in their commercial phase and are still being improved in terms of their performance.

1.3.1 Bases

1.3.1.1 Spin Polarization

The base of spin electronics is the fact that conduction electrons in magnetic materials are polarized, that is, the direction of the spin is not arbitrary but has a preferred direction imposed by the magnetization of the material. That polarization strongly depends on the nature of the material and on its crystalline structure. CoFe is the 3D alloy mainly used in devices as it is easy to deposit and presents a large spin polarization, around 70 %.

1.3.1.2 Spin Diffusion Length

When a polarized electron is sent inside a material, it experiences collisions. A lot of collisions are elastic and the spin is conserved, while some are inelastic and may conduct to a change in its spin orientation. The typical length on which the memory of the spin is lost is few nanometers at room temperature. This implies that in a nonmagnetic material, a spin polarization cannot be maintained beyond that distance. The impact is that all spin electronics devices have to be engineered with at least one dimension at nanometer scale. The thin-film technology and micronanofabrication techniques have hence played an essential role in the development of spin electronics.

1.3.1.3 Spin Currents and Spin Hall Effects

A spin current is the propagation of a net magnetic moment. Two kinds of spin currents can be proposed. The first one is the spin wave that propagates magnetic information by elementary excitations of the magnetic material. This is discussed in Section 1.4.3. The second way is to use polarized electrons. A polarized electron current propagates magnetic information that can be used, for example, to rotate a magnetic layer through a spin torque effect. This effect is described in detail in Chapter 4.

More recently, pure spin currents carried by electrons have been created. These currents are created by two flows of polarized electrons with opposite polarities and opposite directions: there is a net magnetic moment transferred and no charge.

These spin currents can be created by a spin Hall effect where an electrical current can create a transverse spin current through spin–orbit coupling. A very recent review of spin Hall effects has been published [10], which discusses the main aspects of this subfield of spintronics.

1.4 Main Applications of Spin Electronics

1.4.1 GMR and TMR Sensors

1.4.1.1 Principle

The GMR device was the first spin electronics device proposed 25 years ago. The principle is to have magnetic thin layers separated by nonmagnetic layers having a large enough spin diffusion length. Electrons traveling inside the first layer have a spin polarization that depends on the magnetization direction. When they arrive inside the nonmagnetic layer, electrons conserve their polarization to a distance of the order of the spin diffusion length. If there is another magnetic material nearby, electrons enter it. But that entrance will be easier if the magnetization direction of this second magnetic layer is identical to the first one. Hence, electrical resistance of the stack will depend on the relative orientations of the magnetization of each magnetic layer.

1.4.1.2 Spin Valve Devices

The simplest GMR device is called spin valve where there are only two magnetic layers, one with a large coercivity, that is, reasonably blocked in an external field, and another one that can easily rotate in an external field. A typical spin valve is given in Figure 1.4. This device is composed of a blocked magnetic layer. The

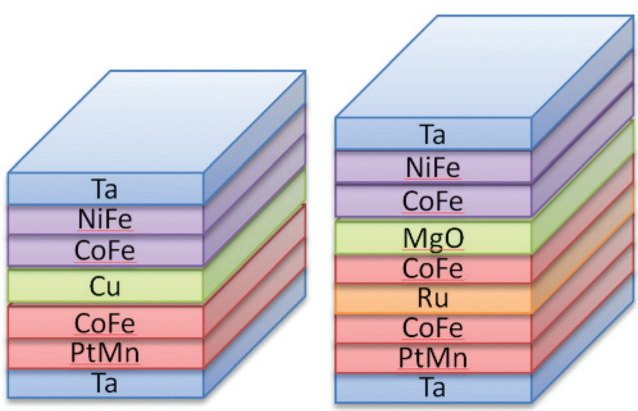

Figure 1.4 GMR simple spin valve (a). TMR spin valve with an SAF configuration (b).

blocking is obtained by using an antiferromagnet, typically PtMn or IrMn, coupled with a CoFe layer. The antiferromagnet has the property of being insensitive to the external magnetic field. Furthermore, it has typically a blocking temperature below its ordering temperature. Below the blocking temperature, it is very hard to move it and above this temperature it becomes easy to move it with a field. The blocking temperature for IrMn is typically 240 °C and for PtMn about 340 °C. For that reason, PtMn is more interesting for high-temperature applications such as in automotive. Often an extra synthetic antiferromagnet (SAF) is added to increase the field stability.

The second magnetic layer is usually a free layer, that is, able to rotate easily in external magnetic fields. It is in general composed of a bilayer of NiFe and CoFe. NiFe, called permalloy, is a very soft material, whereas CoFe ensures a high spin polarization.

The GMR spacer is generally a Cu thin layer. The typical Cu thickness is about 2 nm, and this insures a magnetic decoupling of the two magnetic layers and a low enough spin depolarization.

TMR (tunnel magnetoresistance), also called MTJ (magnetic tunnel junctions), has the same structure as GMR's, but the spacer is a very thin insulating layer called barrier. The transport through this spacer is no longer a diffusive path but requires a tunnel transport, and the TMR ratio mainly depends on the electrode spin polarization at the interface. This has several consequences. The first consequence is that the resistance of the device increases exponentially as the thickness of the barrier increases and hence has to be very well controlled; the second is that the effect can be much higher than the GMR effect; the third is that for practical devices, resistance and size are partly decoupled; and finally the current has to flow through the barrier, so it requires top and down contacts. MgO insulating barriers create a symmetry filtering that increases the TMR ratios and thus are generally used.

1.4.1.3 Electric Response

Response

A spin valve gives an angular response: the resistance varies with the angle between the free layer and the hard layer. This is, for example, very different from a Hall sensor where the response is mainly linear with field. Figure 1.5 gives a typical response of a GMR sensor as function of the external field direction. For that reason, except for angle sensors (Chapter 3) the GMR response is linearized. This can be done either by a closed-loop scheme, in which a coil creates a field on the GMR device that cancels the external field, or by applying a bias field on the GMR along an axis perpendicular to the sensitive axis. The bias field has to be larger than the field range required for the device. This bias field can be created in three different ways: the first one is an external magnet, the second is to play on the shape, and the third is to use a second antiferromagnet to partly pin the free layer perpendicular to the sensitive layer. All these approaches are more thoroughly described in Chapters 3 and 9.

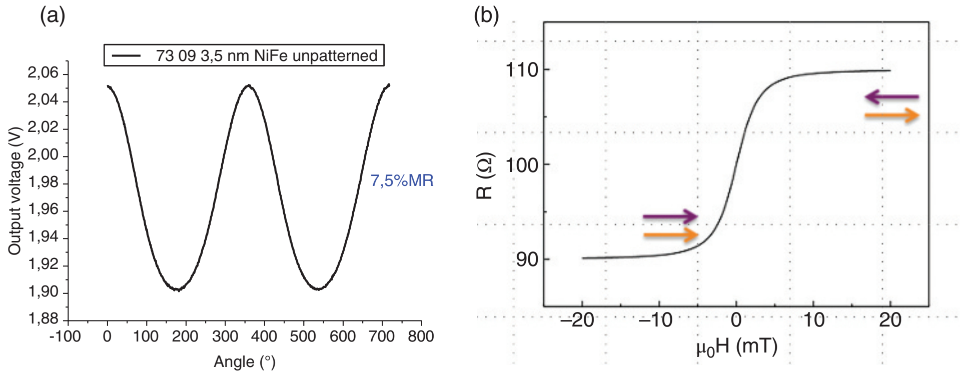

Figure 1.5 (a) Response of a GMR as function of external field and (b) response of a linearized GMR.

The typical variation of magnetoresistance is 6–12 % for GMR and 200 % for MgO based TMR.

Noise

Reig *et al.* [6] give a detailed description of noise of GMR and TMR devices. Here, we give only the main features. Electric noise in GMR and TMR has mainly three sources. The first one is a frequency-independent noise that in GMR is only the thermal noise related to the resistance of the devices. The second source is a 1/f noise that comes from resistance fluctuations in the device. For GMR, the fluctuations are related to defects and 1/f noise is comparable to usual metals and follows the classical Hooge [11] empirical formula. For TMR, the noise is mainly related to conductance fluctuations of the barrier. The 1/f noise in TMR strongly depends on the resistance and materials and is usually much higher than the noise in GMR, and this mitigates the advantages of TMR versus GMR for low-frequency applications. The third source of noise is the magnetic noise that comes mainly from domain fluctuations. This noise can be avoided by giving the device a proper shape that does not allow domain formation in the active region. The C shape, also called yoke shape, is very often used.

Sensitivity and Detectivity

The sensitivity of a device is strongly related to its linearization. In practice, if a device has a magnetoresistance of 10 %, 5 % can be used as a linear range. If you bias your device so that this 5 % variation covers 1 mT, the sensitivity will be 5 %/mT. If you apply a much stronger bias on the spin valve, say 20 mT, the sensitivity decreases to 0.25 %/mT. So, the sensitivity can be tailored as function of the applications. In the various chapters, you will see how sensitivity and field dynamic range have been chosen for the targeted applications.

Table 1.5 Detectivity of spin electronics sensors as function of size and frequency.

Device	Detectivity at 1 Hz	Detectivity at 1 kHz	1/f corner	Detectivity at high frequency
GMR 1 mm^2	30 pT/sqrt(Hz)	10 pT/sqrt(Hz)	10 Hz	10 pT/sqrt(Hz)
GMR 3 μm × 20 μm	1 nT/sqrt(hz)	30 pT/sqrt(hz)	10 khz	10 pT/sqrt(Hz)
Array of TMR 1 mm^2	100 pT/sqrt(Hz)	3 pT/sqrt(Hz)	10 kHz	1 pT/sqrt(hz)
TMR 3 μm × 20 μm	1 nT/sqrt(Hz)	30 pT/sqrt(Hz)	1 MHz	1 pT/sqrt(hz)

Very often, a magnetic sensor is characterized by the detectivity that is the field corresponding to a signal-to-noise ratio of one. It corresponds to the noise divided by the sensitivity given in V/T. The detectivity of GMR and TMR sensors depend on the size because of the 1/f noise . Table 1.5 gives a short summary of classical detectivity achieved today for magnetic sensing.

1.4.2
Spin Electronics Devices for Storage, MRAM, and Magnetic Logics

The basic block of a spin valve is used for magnetic storage. At present, MgO-based magnetic tunnel junctions present a typical magnetoresistance of 150–200 % at room temperature. This large magnetoresistance induces a good separation between the 0 and the 1 level. Contrary to magnetic sensors, magnetic tunnel junctions used for storage are not at all linear but should present a high stability against external field while preserving the writing possibility. This aspect of spin electronics is developed in Chapters 4 and 11.

1.4.3
Spin Dynamics and Magnonics

The dynamics of small magnetic objects has been a field of intense research for the past two decades.

We can separate different main regimes: a low-frequency regime, typically below 1 GHz where the magnetization of the thin magnetic layer in small devices is able to follow the external magnetic field. In this regime, static description works well. It has, in particular, been demonstrated that the GMR effect does not decrease up to 20 GHz. The second regime corresponds to the same domain of frequency, but the size of the device is increased. Then, domains are appearing, and domain propagation, reversal, and creation dominate the dynamics of these objects. This is partly described in Chapters 10 and 11. Nevertheless, if domain propagation has been extensively studied, no devices based on their use are presently commercialized.

The third domain is the high-frequency domain between GHz and THz. In this frequency domain, natural thermal excitations of magnetic ferromagnetic order appear; these excitations, called spin waves or magnons, are the magnetic equivalent of phonons, the vibrations of crystals. They are able to propagate, to be diffused, and could be used for magnetic logic. This aspect of spintronics called magnonics is a fast-growing field, where Europe has conducted a lot a pioneering work.

Spin waves are used for small RF devices in particular circulators and dephasing devices. The two new main applications forecast today are:

- STNO (spin torque nano-oscillators). It has been demonstrated that a DC current is able to induce spontaneous precession of small magnetic pillars through a torque applied by polarized electrons on thin layers. This can be used to generate locally GHz frequency with a large agility.
- Spin wave logics based on the combination of propagating spin waves to perform fast logic computing.

These aspects of spintronics are described in Chapters 11 and 12.

References

1 Kronmüller, H. and Parkin, S. (eds) (2007) *Handbook of Magnetism and Advanced Magnetic Materials*, vol. **5**, John Wiley & Sons, Ltd, Chichester.

2 Coey, J.M.D. (2009) *Magnetism and Magnetic Materials*, Cambridge University Press, Cambridge.

3 Rosa, A. (2015) *Handbook of Nanomagnetism: Applications and Tools*, Pan Standford Publishing, Lukaszew.

4 Ziese, M. and Thornton, M.J. (eds) (2013) *Spin Electronics*, Springer, Berlin.

5 Shinjo, T. (ed.) (2013) *Nanomagnetism and Spintronics*, Elsevier.

6 Reig, C., Cardoso, S., and Mukhopadhyay, S. (eds) (2013) *Giant Magnetoresistance (GMR) Sensors*, Springer, Berlin.

7 Hillebrands, B. and Ounadjela, K. (eds) (2003) *Spin Dynamics in Confined Magnetic Structures*, Springer, Berlin.

8 Baibich, M.N., Broto, J.M., Fert, A., and Van Dau, F.N. (1988) *Phys. Rev. Lett.*, **61** (1), 2472–2475.

9 Julliere, M. (1975) *Phys. Lett.*, **54A**, 225–226.

10 Sinova, J., Valenzuela, S.O., Wunderlich, J., Back, C.H., and Jungwirth, T. (2015) *Rev. Mod. Phys.*, **87**, 1213.

11 Hooge, F.N. (1976) *Physica B*, **83**, 14–23.