Denny D. Tang and Yuan-Jen Lee

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Magnetic Memory

If you are a semiconductor engineer or a magnetics physicist developing magnetic memory, get the information you need with this, the first book on magnetic memory.

From magnetics to the engineering design of memory, this practical book explains key magnetic properties and how they are related to memory performance, characterization methods of magnetic films, and tunneling magnetoresistance effect devices. It also covers memory cell options, array architecture, circuit models, and read-write engineering issues.

You'll understand the soft-fail nature of magnetic memory, which is very different from that of semiconductor memory, as well as methods to deal with the issue. You'll also get invaluable problem-solving insights from real-world memory case studies.

This is an essential book, both for semiconductor engineers who need to understand magnetics, and for magnetics physicists who work with MRAM. It is also a valuable reference for graduate students working in electronic/magnetic device research.

Denny D. Tang is Vice President of MagIC Technologies, Inc., and has over 30 years' experience in the semiconductor industry. After receiving his Ph.D. in Electrical Engineering from the University of Michigan in 1975, he spent 15 years at IBM T. J. Watson Research Center, Yorktown Heights, NY, 11 years at IBM Almaden Research Center at San José, CA, and 6 years at Taiwan Semiconductor Manufacturing Company (TSMC). He is a Fellow of the IEEE, TSMC, and the Industrial Technology Research Institute (ITRI).

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Preface

The advent of semiconductor technology has impacted the lives of many of us since the 1970s. Silicon CMOS (complementary metal-oxide-semiconductor) devices are practically ubiquitous, and by the year 2000, the value of the semiconductor industry exceeded that of the automobile industry. The magnetic industry, on the other hand, is much smaller than the semiconductor industry. Engineering schools of universities rarely cover any courses in this discipline. Nonetheless, a tiny magnetic recording device is in the hard disk of every computer. Like CMOS devices, magnetic recording technology is being scaled down from generation to generation. At the time of writing, the physical size of the magnetic bit remains smaller than a DRAM bit on silicon chips.

Researchers working in these two communities had little in common until the development of the modern magnetic random access memory, or MRAM. A MRAM chip is built by integrating magnetic tunneling junction (MTJ) devices onto the silicon CMOS circuits. The research activity of MTJs in academia and industry, both hard disk and semiconductor, has been very active since it first showed signs of technology implication in the mid 1990s. That effort led to the mass production of the MTJ recording head in hard disk in 2006. In the same year, the semiconductor industry announced the first successful introduction of an MTJ memory product. The viability of MTJ technology is proven. It is expected that research activities will develop further, which will increase cooperation between these two research communities. The purpose of this book is to facilitate the dialog and to bridge the gap. Each simple homework problem and answer is designed to help readers to link the magnetics to the memory performance. Thus, the book is suitable for those with discipline of semiconductor devices and wish to expand their knowledge base into the field of magnetic memory, and for those in magnetics who wish to "fine-tune" magnetics for MRAM chips.

The book is organized into seven chapters. Chapter 1 reviews the electric current, as most electrical engineering students learn, in their sophomore and junior years, that magnetism results from an electric current. This chapter introduces readers to the unit conversion ready for the discussion in Chapter 2, which deals with the origin of magnetism in materials and introduces the concepts of electron spin, magnetic moments and its dynamics. It covers the microscopic view of the magnetic moment of an electron and an atom, and investigates its relationship with the macroscopic properties of magnetic thin film materials. Once the film is patterned to make devices, it behaves very differently from a full film. Chapter 3 covers the properties of the patterned thin magnetic films. This leads to the discussion of magnetization switching properties of many modern magnetic RAM devices. Chapter 4 introduces the magnetoresistance effect in thin film stacks, covering AMR (anisotropy magneto-resistance), GMR (giant magneto-resistance) and TMR (tunnel magneto-resistance) effects. The magneto-resistance effect is the operational principle of all modern non-volatile magnetic memories. A thorough discussion of the magnetic tunnel junction is presented. A detailed description of the properties and the design of field-write modes magnetic memory device are given in Chapter 5 and that of spin-torque transfer mode in Chapter 6. The discussion also covers circuit aspects of the memory cell and memory array, and the circuit model of the magnetic tunnel junction device, so that one can gain a better perspective of the merits in the design of the magnetic tunnel junction for memory. Chapter 7 covers the present memory market and the position of the magnetic memory in this market. New applications of this technology will also be discussed.

This is a very active field. Papers and patent applications of the related subject appear continuously and in large quantities. This book aims to provide the reader with a sufficient understanding of the fundamental physics of magnetics, the properties of magnetic thin film materials, device properties, design, memory operation and many other aspects of engineering. It also aims to give those working with semiconductors a head start so that they may bring in more fruitful results to this relatively new field.

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Contents

1 Basic electromagnetism

1.1 Introduction

Two thousand years ago, the Chinese invented the compass, a special metallic needle with one end always pointing to the North Pole. That was the first recorded human application of magnetism. Important understandings and developments were achieved in the mid 19th century and continue into the present day. Indeed, today, magnetic devices are ubiquitous. For example, to name just two: energy conversion devices provide electricity to our homes and magnetic recording devices store data in our computers. This chapter provides an introduction to basic magnetism. Starting from the simple attractive (or repelling) force between magnets, we define magnetic field, dipole moment, torque, energy and its equivalence to current. Then we will state the Maxwell equations, which describe electromagnetism, or the relationship between electricity and magnetism.

A great tutorial is provided by Kittel [1], which may be used to support students studying Chapters 1–4.

1.2 Magnetic forces, poles and fields

In the early days, magnetic phenomena were described as analogous to electrical phenomena: like an electric charge, a magnetic pole was considered to be the source of magnetic field and force. The magnetic field was defined through the concept of force exerted on one pole by another. In cgs units, the force is proportional to the strength of the magnetic poles, defined as

$$F = \frac{p_1 p_2}{r^2}, \tag{1.1}$$

where r is the distance between two poles (in units of centimeters) and the unit of force F is the dyne. There is no unit for the pole, p. This equation defines the pole strength as one unit, when the force is 1 dyne and the distance between the poles is 1 cm. Analogous to Coulomb's Law of electric charge, one may consider a magnetic pole, say p_1, which generates a magnetic field H, and H exerts a force on the other pole, p_2. Thus,

$$F = \left(\frac{p_1}{r^2}\right) p_2 = H\, p_2, \tag{1.2}$$

where H is given by

$$H = \frac{p_1}{r^2}. \tag{1.3}$$

Thus, a magnetic field H of unit strength exerts a force of 1 dyne onto one unit of magnetic pole. The unit of the magnetic field in cgs units is the oersted (Oe). To get a feel for the strength of the magnetic field, at the end of a magnetic bar on a classroom white board the magnetic field can be as high as 5000 Oe, whereas the earth's magnetic field is smaller than 0.5 Oe.

1.3 Magnetic dipoles

Although a magnetic pole is the counterpart of an electric charge, there is a difference. Magnetic poles always come in pairs: a north pole and a south pole. A monopole has never been found. This pair of positive and negative poles occurs at the same time and forms a dipole. For example, a bar magnet always has a north pole at one end and a south pole at the other. Magnetic field lines emit from one pole, diverge into the surroundings and then converge and return into the other pole of the magnet. Figure 1.1 shows the field lines around a magnet.

If a bar magnet with a north pole and a south pole is dissected into two bars, will these two bars becomes two magnets? The answer is yes, since poles are always in pairs.

In 1820, H. C. Oersted discovered that a compass needle could be deflected when electric current passes through a wire positioned near to the compass. This was the first time electricity was linked to magnetic phenomena. Subsequent work by André-Marie Ampère established the basis of modern electromagnetism. He established the relationship between a magnetic dipole and a circulating current in a conductor loop around an axis. The direction of the dipole is along the axis of the loop, which is orthogonal to the loop plane. Figure 1.2 illustrates

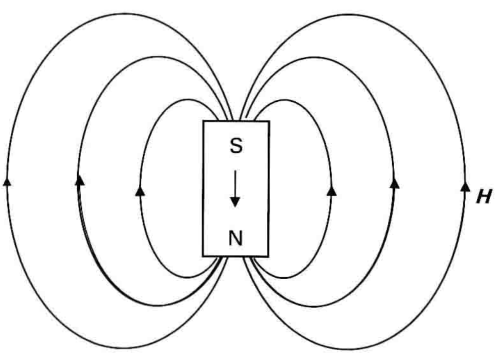

Figure 1.1. Magnetic field lines from a magnet.

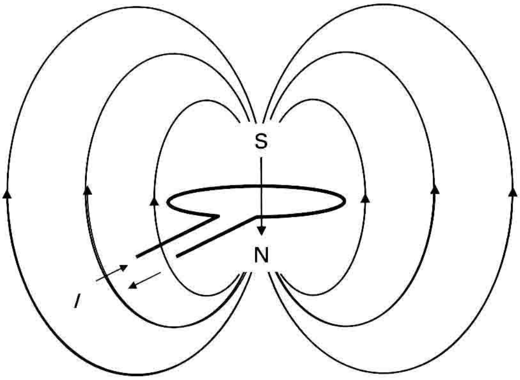

Figure 1.2. Magnetic field from a circular current loop.

the relationship between the dipole and the current loop. The polarity is dictated by the direction of the current, I. Reversing the direction of the electric current changes the polarity of the dipole. Thus, the magnetic dipole is another form of electric current, or moving electric charge.

Although both the electric field and the magnetic field are originated from electric charges, the difference is that the magnetic field must come from moving electric charges or electric current, rather than a stationary electric charge. The moving electric charge concept adequately explained the origin of magnetic poles at the time. The observation was later proven incorrect, however, when electron spin was taken into consideration. We will discuss this topic in a later part of this book.

1.4 Ampère's circuital law

Ampère further established that the relationship between the magnetic field H and the current I is given by

$$\oint \boldsymbol{H} \cdot d\boldsymbol{l} = 4\pi \cdot 10^{-4} I \quad (1.4a)$$

where, in cgs units, $\boldsymbol{H}$ is in oersted, $d\boldsymbol{l}$ is in centimeters and I is in milliamperes, and later one finds that it is more convenient to calculate H in thin films using

$$\oint \boldsymbol{H} \cdot d\boldsymbol{l} = 4\pi I \quad (1.4b)$$

($\boldsymbol{H}$ is in oersted, $d\boldsymbol{l}$ is in micrometers and I is in milliamperes), where $d\boldsymbol{l}$ is the segment length of an arbitrary closed loop where the integration is performed and I is the current within the closed loop. This law is simple in concept and is

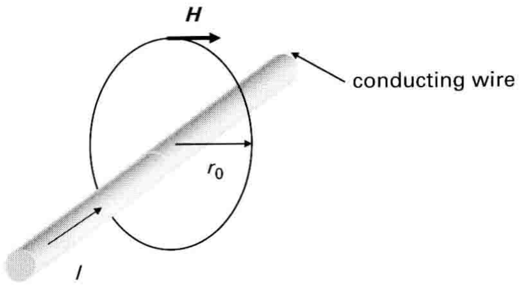

Figure 1.3. Magnetic field around a conducting wire carrying a current I. The magnetic field at a distance r_0 from the wire is $H = I/2\pi r_0$.

particularly useful in computing the field generated by the current in a long conductor and conducting thin film.

Here, we would like to discuss the units. Historically, there have been two complementary ways of developing the theory and definitions of magnetism. As a result, there are two sets of units for magnetic field, and thus for a magnetic pole. The definitions are similar, but not entirely identical. The major difference lies in how the magnetic field is defined inside the material. Centimeter-gram-second (cgs) units are used for studying physics, such as the origin of the magnetic pole and the magnetic properties in a material. The Systéme International d'Unités (SI units) are frequently used for obtaining magnetic field strength from circulating currents. Engineers working on electromagnetic waves, electric motors, etc. like to use SI units. This book will use both sets of units, depending on whichever makes more sense and in line with journal publications.

In SI units, Ampère's law is given as

$$\oint \boldsymbol{H} \cdot dl = I. \tag{1.5}$$

(In SI units, $\boldsymbol{H}$ is given in amperes/meter, dl is in meters and I is in amperes.) From these two equations, one finds that a magnetic field of 1 (Oe) = 1000/4π (A/m) ~ 80 (A/m).

Example 1.1: The magnetic field lines go around a current-carrying wire in closed circles, as illustrated in Fig. 1.3. At a distance r_0 from the conductor, the magnitude of the field $\boldsymbol{H}$ is constant. This makes the line integral of Ampère's law straightforward. It is simply given by

$$\oint \boldsymbol{H} \cdot dl = 2\pi r_0 \boldsymbol{H} = I,$$

and so the field $\boldsymbol{H}$ is given by

$$H = \frac{I}{2\pi r_0}.$$

1.5 Biot–Savart Law

An equivalent statement to Ampère's circuital law (which is sometimes easier to use for certain systems) is given by the Biot–Savart Law. The Biot–Savart Law states that the fraction of a field, $\delta\boldsymbol{H}$, is contributed by a current I flowing in an elemental length, $\delta\boldsymbol{l}$, of a conductor:

$$\delta\boldsymbol{H} = \frac{1}{4\pi r^2} I\ \delta\boldsymbol{l} \times \boldsymbol{n}, \tag{1.6}$$

(in SI units), where r is the radial distance from the current element and $\boldsymbol{n}$ is a unit vector along the radial direction from the current element to the point where the magnetic field is measured. Note that the direction of the vector $\delta\boldsymbol{H}$ is orthogonal to the plane formed by $I\ \boldsymbol{dl}$ and $\boldsymbol{n}$, as a result of the vector operation "×" of two vectors $I\ \boldsymbol{dl}$ and $\boldsymbol{n}$, and the amplitude of $|I\ dl|\sin\theta$, where θ is the angle between vectors $\boldsymbol{dl}$ and $\boldsymbol{n}$.

Example 1.2: Field from a current in a loop wire The magnetic field at the center of the loop plane as shown in Fig. 1.2 is calculated by the Biot–Savart Law as follows.

The radius of the loop is r_0, and H can be in the positive or negative z-direction, depending on the current direction, and only in the z-direction. The vector sum is simplified into a scalar sum. On the loop plane, $z=0$. So, $|\boldsymbol{H}|=H_0$, where H_0 is the integral of the field contributed by each segment $\boldsymbol{dl}$ of the loop, and

$$H_0 = 2\pi r_0 \left[\frac{1}{4\pi r_0^2} I\right] = \frac{1}{2r_0}, \tag{1.7}$$

(in SI units) and

$$\boldsymbol{H} = H_0 \boldsymbol{n}_z,$$

where $\boldsymbol{n}_z$ is the unit vector in the z-direction.

1.6 Magnetic moments

Next we need to introduce the concept of magnetic moment, which is an angular moment exerted on either a bar magnet or a current loop when it is in a magnetic field. The angular moment causes the dipole to rotate.

For a bar magnet positioned at an angle ϕ to a uniform magnetic field, $\boldsymbol{H}$, as shown in Fig. 1.4, the forces on the pair of poles are given by $\boldsymbol{F}_+ = +p\boldsymbol{H}$ and $\boldsymbol{F}_- = -p\boldsymbol{H}$. The two forces are equal but have opposite direction. So, the moment acting on the magnet, which is just the force times the perpendicular distance from the center of the mass, is

$$pH\sin\phi(l/2) + pH\sin\phi(l/2) = pH\ l\sin\phi = mH\sin\phi, \tag{1.8}$$

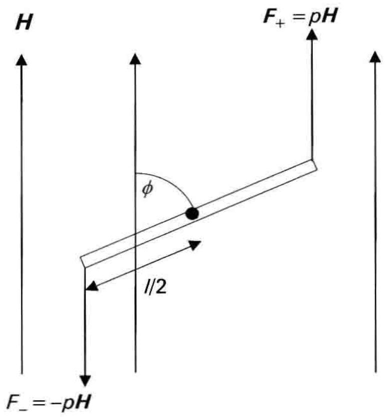

Figure 1.4. Dipole moment of a bar magnet in a uniform magnetic field.

where $m = pl$, the product of the pole strength and the length of the magnet, is the amplitude of the magnetic moment. The magnetic moment is a vector, pointing to a direction normal to the plane formed by the magnet and the magnetic field. One cgs unit of magnetic moment is the angular moment exerted on a magnet when it is perpendicular to a uniform field of 1 Oe. The cgs unit of magnetic moment is the emu (electromagnetic unit).

Since a magnetic dipole is equivalent to a current loop, it can be quantified by loop area A and a current I in the loop, and its magnetic moment is defined as

$$\boldsymbol{m} = IA\boldsymbol{n}, \tag{1.9}$$

where $\boldsymbol{n}$ is a vector normal to the plane of the current loop. In SI units, magnetic moment is measured in amperes times squared meters (A m^2).

1.7 Magnetic dipole energy

A magnetic dipole can be defined in two ways. First, it is the magnetic moment, $\boldsymbol{m}$, of a bar magnet at the limit of very short but finite length. Second, it is the magnetic moment, $\boldsymbol{m}$, of a current loop at the limit of a very small but finite loop area. Either way, there is a finite magnetic moment.

The energy of a magnetic dipole is defined to be zero when the dipole is perpendicular to a magnetic field. So the work done in turning through an angle ϕ against the field is given by

$$\delta E = 2(pH \sin \phi)(l/2)\ d\phi = mH \sin \phi\ d\phi,$$

and the energy of a dipole at an angle ϕ to a magnetic field is given by

$$E = \int_{\pi/2}^{\phi} mH\ \sin\ \phi\ d\phi = -mH \cos \phi = -m \cdot H \tag{1.10}$$

This expression for the energy of a magnetic dipole in a magnetic field is in cgs units. In Eq. (1.10), E is in erg, $\boldsymbol{m}$ is in emu and $\boldsymbol{H}$ is in Oe. Equation (1.10) is also known as the formula for magnetostatic energy. In SI units the energy is $E = -\mu_0 \boldsymbol{m} \cdot \boldsymbol{H}$. When the dipole moment, $\boldsymbol{m}$, is in the same direction as $\boldsymbol{H}$, the magnetostatic energy takes its lowest value.

The torque exerted on a dipole moment is the gradient of the dipole energy with respect to the angle ϕ, or

$$\Gamma = dE/d\phi = mH \sin\phi. \tag{1.11}$$

The torque is exerted in the direction that lowers the dipole energy and the unit is expressed in erg/radian. When $\boldsymbol{m}$ and $\boldsymbol{H}$ are parallel, or $\phi = 0$, the energy is at a minimum, and the torque is zero. The torque is maximum when $\phi = \pi/2$. We will be using the concept of magnetic dipoles, and this expression for its energy in a magnetic field is used extensively throughout this book.

1.8 Magnetic flux

Here, we introduce another parameter: the flux Φ. Flux is defined as the integrated strength of a normal component of magnetic field lines crossing an area, or

$$\Phi = \int (\boldsymbol{H} \cdot \boldsymbol{n}) dA, \tag{1.12}$$

where $\boldsymbol{n}$ is the unit vector normal to the plane of the cross-sectional area, A. In cgs units, the flux is expressed in oersted times squared centimeters (Oe cm^2).

Magnetic flux is an important parameter in electric motor and generator design. The time-varying flux induces an electric current in any conductor which it intersects. Electromotive force ε is equal to the rate of change of the flux linked with the conductor:

$$\varepsilon = -\frac{d\Phi}{dt}. \tag{1.13}$$

This equation is Faraday's Law of electromagnetic induction. The electromotive force provides the potential difference that drives the electric current in a conductor. The minus sign indicates that the induced current sets up a time-varying magnetic field that acts against the change in the magnetic flux. This is known as Lenz's Law. The units in Eq. (1.13) as expressed in SI are: flux in webers (Wb), time in seconds and an electromotive force in volts.

1.9 Magnetic induction

When a magnetic field, $\boldsymbol{H}$, is applied to a material, the response of the material to $\boldsymbol{H}$ is called magnetic induction, $\boldsymbol{B}$. The relationship between $\boldsymbol{B}$ and $\boldsymbol{H}$ is a property