Nanoscale Magnetic Materials and Applications

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Foreword by Peter Grünberg

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Foreword

The appearance of materials with dimensions on the nanoscale has brought new stimulus also to magnetism. The discoveries of giant magnetoresistance and tunnel magnetoresistance can be seen as a result of this development.

Generally, magnetism tends to become weaker or even disappears when the geometrical dimensions of samples are decreased. In thin films used for data storage in magnetic recording, for example, this can lead to instability of stored information.

However, this trend is not always to the disadvantage of possible applications. In small nanoscale particles, for example, the occurrence of superparamagnetism leads to hysteresis-free magnetization curves with vanishing remanence. This is useful when the magnetic response should be given as much as possible by an external field rather than by the "magnetic history" of the material. There are numerous examples for this in medical applications as described in this volume. On the other hand – to dwell a little further on the mentioned problem in data storage – new interactions have also been discovered, which are operative on the nanoscale and can be used to solve a given problem. Such an interaction is the interlayer exchange coupling, which is employed in antiferromagnetically coupled (AFC) media to enhance the stability of stored information.

Magnetic surfaces and interfaces represent further special classes of nanoscale materials. Uncompensated spins at the surface of an antiferromagnet, for instance, give rise to a phenomenon called "exchange bias", which is applied in magnetic field sensors to tailor the response curve.

For magnetic structures on the nanoscale there is also a new possibility to affect their magnetic order by means of electrical currents. This phenomenon called "current-induced magnetization dynamics" is foreseen to be used for writing information. It is currently one of the most active fields of research on nanoscale magnetism and also offers a new method of microwave generation by the current-driven precession of the magnetization.

Hence, a variety of new phenomena operative on the nanoscale is available to render nanomagnetism an interesting research field and to generate the potential for new applications. What are the systems, in which these phenomena can occur? We mentioned already layered magnetic structures and nanoparticles. Other classes of materials are magnetic nanowires and dots, either lithographically defined or

realized by assembling molecules and atoms such as fullerenes filled with magnetic materials.

The field of nanomagnetism is rich indeed both from a fundamental scientific viewpoint and with respect to applications and new devices.

Peter Grünberg
2007 Nobel Prize in Physics

Preface

This book has its genesis in the 2007 Materials Research Society (MRS) Fall Meeting where we organized the symposium "Nanoscale Magnetic Materials and Applications". This symposium, with more than 200 submissions of presentations and 30 invited talks, was one of the most successful meetings in magnetic materials research in recent years. Ms. Elaine Tham from Springer suggested us to edit a book based on the topics presented in this symposium. We invited a number of presenters in the symposium to be the authors of this book which shares the title of the symposium. Moreover, we have extended the scope of the book to other topics as well that were not covered in the symposium.

Magnetic materials have a long history. People have been using compasses for thousands of years. However, new magnetic materials and applications are emerging and are proving indispensable in our daily lives and modern industries. One example is that there are already over a billion giant magnetoresistance sensors produced for information technology and other related applications. Hard and soft magnetic materials are key for efficient energy conversion, especially for converting electric energy to mechanical energy so that they are important to meet the challenges of the depletion of fossil fuels, climate change, and global warming.

Nanotechnology is one of the most important developments in science and technology in our generation, and it has brought revolutionary progress in materials processing and characterization. Current magnetic nanotechnologies have their roots in the development of bulk materials, such as permanent magnets where the functionality is derived from a complex nanoscale multi-phase morphology. Nanotechnology has offered a coupling of synthesis, theory, and characterization of materials at the nanoscale that enables materials design to evolve beyond earlier Edisonian approaches. By its very nature, magnetic materials are a class of nanoscale materials. Although early researchers did not explicitly work on the nanoscale, theoretical research revealed some time ago that nanoscale correlations exist in magnetic materials and control their properties. Several important characteristic dimensions in magnetism are in the nanoscale range such as the magnetic domain wall thickness and the "exchange length" in hard magnetic phases. This highlights why the research and development of new nanoscale magnetic materials are important and will lead to enhanced performance and new functionality. Some recent examples highlighted in this book include patterned magnetic recording

media and exchange-coupled nanocomposite magnets, where intense worldwide efforts are underway to significantly improve the areal density of data storage and the energy product of permanent magnets, respectively.

This book covers many of the exciting areas in nanoscale magnetic materials and applications. Readers will find topics in the book including theoretical work on novel magnetic structures, characterization of magnetic structures, single-phase materials and nanocomposite magnets, spintronic materials, domain structure and domain wall motion, magnetic nanoparticles and patterned magnetic recording media, magnetocaloric effect, and shape memory effect. The book also covers the most important emerging applications of advanced materials. The applications include new devices based on domain wall motion driven by current or fields, new magnetic sensors based on giant magnetoresistance and tunneling magnetoresistance, soft and hard magnetic materials for specific applications, thin-film applications in micro-electro-mechanical systems, and nanoparticle applications in biomedicine. We hope that this new book provides a comprehensive view of recent progress in all the related fields.

While attempting to present the most exciting developments in materials research and device applications, discussions in depth about the novel phenomena and emerging new materials are also presented in the book, such as the controllable exchange bias and inter-phase exchange interactions. Though more work is needed to understand the issues, we hope that this book gives a good introduction to future advancement.

We thank Prof. Peter Grünberg, the 2007 Nobel Laureate in Physics, for giving his insightful and visionary foreword to this book. We thank Ms. Elaine Tham and Ms. Lauren Danahy from Springer who initiated this book and did a great deal of work to bring it to completion. Mrs. Grace Liu has worked hard in collecting all the manuscripts, figures, and related paperwork. Finally, we thank all of our authors who contributed their very informative and in-depth chapters which made this new book a reality.

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Chapter 1
Spin Dynamics: Fast Switching of Macro-spins

X.R. Wang, Z.Z. Sun, and J. Lu

Abstract Recent progress on the theoretical studies of fast magnetization reversal of Stoner particles is reviewed. The following results are discussed: (1) The Stoner–Wohlfarth (SW) limit becomes exact when the damping constant is infinitely large. Under the limit, magnetization moves along the steepest energy descent path. (2) For a given magnetic anisotropy, there is a critical damping constant, above which the minimal switching field is the same as that of the SW-limit. (3) The field of a ballistic magnetization reversal should be along a certain direction window in the presence of energy dissipation. (4) Since a time-dependent magnetic field can be an energy source, two new reversal strategies are possible. One is to use a field following magnetization motion, and the other is to use a circularly polarized microwave near the ferromagnetic resonance frequency. The critical switching fields of both strategies are substantially lower than that of precessional reversal for realistic materials. (5) The theoretical limits for both field-induced and current-induced magnetization reversal are presented for uniaxial Stoner particles.

1.1 Introduction

Spin dynamics is an old and important subject rooted in magnetism and the nuclear/electron-spin/ferromagnetic resonances that have wide applications in physics, information processing, chemistry, biology, and medicine [1–5]. In the field of magnetic data storage [4], magnetization reversal has received a lot of attention because data input and output involve switching the magnetization of magnetic storage cells that are important components of modern computers. The typical switching time with currently used technology is of the order of nanoseconds. If one wants to have a faster computer (modern electronic computers are working at a clock speed

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of the order of GHz) with magnetic random access memory (MRAM), the conventional magnetization reversal method shall be a bottleneck. Thus, fast magnetization switching shall be of great importance for future development of high-speed information industry.

Magnetization reversal is a very complicated problem in bulk material [5] because it can be achieved in many different ways. For example, magnetization reversal can go through bucking and curling modes, coherent rotation, and/or domain nucleation and domain wall propagation. Recent technological advances allow us to fabricate magnetic nano-particles [6] that are believed to be useful for high-density information storage [7–10]. For a magnetic nano-particle, strong exchange interactions keep the magnetic moments of atoms rigid, creating just a single magnetic domain, such that the constituent spins rotate in unison. Such a nano-particle is often called a Stoner–Wohlfarth (SW) or Stoner particle. The understanding of magnetization reversal of a Stoner particle should be relatively simple in comparison with that of a bulk system, yet important in nano-technologies [4] as a consequence of the miniaturization into the nano-meter scale.

Magnetization reversal of macro-spins (of Stoner particles) is known as the SW problem because it was first studied by Stoner and Wohlfarth in 1948 [11]. One current topic in nanomagnetism is the control and manipulation of the magnetization of Stoner particles, and magnetization reversal is one of the basic operations. Magnetization state can be manipulated by a magnetic field [11–22], or by a spin-polarized electric current [23–28] through so-called spin-transfer torque (STT), or by a laser light [30]. In terms of applications, manipulation by a magnetic field and/or a spin-polarized electric current dominates and will continue to dominate the information storage industry. Examples are field-driven and current-driven MRAM. Important issues in applications are scalability, power consumption, and speed. These issues relate to the problems of lowering the critical field/current required to reverse a magnetization [4], as well as to the problems of designing a field/current pulse such that the magnetization can be switched from one state to another extremely quickly [21, 29].

Regarding the issue of minimal switching field, Stoner and Wohlfarth [11] showed that a static field larger than the so-called SW-limit can switch a magnetization from its initial state to the target one. The idea is to make the target state to be the only energy minimum. Thus the system rolls down to the target state. However, the system can only gradually dissipate its energy during a precessional motion so that the magnetization moves around the precession axis many times (ringing phenomenon or ringing mode) [12–16, 21, 22] before reaching the target state. As a result, it takes typically nanoseconds to switch a magnetization at a field of teslas. Subsequent theoretical and experimental studies [14, 15] have shown that the minimal switching field can be smaller than the SW-limit. The energy consideration alone in the SW theory is not adequate, and one has to take into account magnetization dynamics. The magnetization dynamics of a nano-structure is governed by the so-called Landau–Lifshitz–Gilbert (LLG) equation that does not have a general analytical solution. Most theoretical work in the field has relied on numerical calculations, and most reversal schemes [21, 27, 28] have

been proposed on a hunch. Ideas include thermal assistance [27] and sample designs [28].

Regarding the issue of switching time, picoseconds magnetization switching has been observed recently in experiments [14, 15] by using pulsed magnetic fields. This approach has received much theoretical attention [12, 17–19]. Numerical investigations [12] showed that the switching time can be substantially reduced because ringing effect is avoided so that the magnetization moves along a so-called ballistic trajectory [19]. The precessional magnetization reversal provides not only a shorter time but also a lower switching field (well below the SW-limit), as found in the early numerical calculations [12]. In the absence of energy dissipation, precessional magnetization switching can also be investigated analytically. Analytical results for the minimal field were obtained by Porter [20].

There are already many nice reviews and books on the general subject of spin dynamics, and we shall not try to make a thorough review on the subject. Instead, we concentrate on the recent theoretical progress on two issues of the SW problem. One is how to make magnetization reversal fast, and the other is how to lower the switching field/current. For those readers who want to know more about many other aspects of spin dynamics, they may read several nice books [1–4] on the subject. The outline of this chapter is as follows. A brief introduction of spin and its kinetics and dynamics subjected to different interactions are given in Section 1.2. These include the dynamics of an isolated spin (without damping) and the dynamics of a macro-spin in contact with the environments (with damping through spin relaxation and spin decoherence). Spin current as a result of spin kinetics is also discussed. Section 1.3 is about magnetization reversal by a static magnetic field. The existence of a critical damping constant, above which the SW theory predicts correctly the switching field, is discussed, and a direction window for ballistic reversal is explained. Section 1.4 is about the macro-spin reversal by a time-dependent magnetic field. The fundamental difference between a static magnetic field and a time-dependent magnetic field is revealed. Based on the fact that a time-dependent magnetic field can be an energy source, two strategies with substantial lower (than the precessional one) critical switching field are discussed. The theoretical limits of the critical switching field or current out of all possible designs, together with the optimal reversal trajectory, are also given. Section 1.5 is a short summary.

1.2 Spin and Its Kinetics and Dynamics

1.2.1 Basic Concepts of Spin

Like electric charge, spin and the associated magnetic moment are fundamental properties (intrinsic quantum numbers) of elementary particles. The spin quantum number relates to many phenomena in elementary particle physics as well as in nuclear, atomic, solid state, and statistical physics. Spin is one type of angular momentum which does not have a classical analogy, but one may tentatively view

a spin coming from a spinning motion of a particle. From the symmetry transformation viewpoint, spin is one class of generators of spatial rotation transformations, while electric charge is the generator of so-called U(1) gauge symmetry transformations. Spin has three components, s_1, s_2, and s_3 that generate rotations around x-, y-, and z-axis. Unlike electric charge being a scalar, the expectation value of a spin operator $\vec{s}$ is a vector. According to quantum mechanics, spin operators $\vec{s}$ satisfies the following fundamental commutation relations

$$[s_j, s_k] = i\hbar\varepsilon_{jkl}s_l, \tag{1.1}$$

where ε_{jkl} is an antisymmetric tensor on three indices, for which $\varepsilon_{jkl} = 0$ except for $\varepsilon_{123} = \varepsilon_{231} = \varepsilon_{312} = 1$ and $\varepsilon_{321} = \varepsilon_{213} = \varepsilon_{132} = -1$. This symmetry viewpoint explains well why spin is a good quantum number of an elementary particle that has an intrinsic rotational symmetry. From quantum mechanics, it is known that a spin can take only integers or half-integers values of $\hbar$.

Following classical electrodynamics, the magnetic moment of a charged particle moving in a circular orbit is given by

$$\vec{M} = \frac{q}{2m_e}\vec{L}, \qquad \vec{L} = \vec{r} \times \vec{p}, \tag{1.2}$$

where q and m_e are the charge and the mass of the particle, respectively. $\vec{L}$ is the orbital angular momentum of a particle at position $\vec{r}$ with momentum $\vec{p}$. Although the magnetic moments of elementary particles and their spins do not follow exactly the above equation, they are related to each other by

$$\vec{M} = g\frac{q}{2m_e}\vec{s} \tag{1.3}$$

with g a fundamental parameter for a given particle.

1.2.2 Kinetics of Spin: Spin Current

Just as the flow of charge generates electric current, so the flow of spin in space creates a spin current. Different from the electric current density which is a vector, spin current density is a rank-2 tensor because of the vector nature of spin. As mentioned earlier, spin is only one type of angular momenta. All particles can have orbital angular momentums besides spins. An electron can exchange its spin with its orbital angular momentum through spin–orbit interaction or exchange its spin angular momentum with the angular momenta of other electrons and/or particles through particle–particle interactions. As a result, spin current is very fragile, not continuous, and does not even conserve because the spin state of an electron is seldom stationary. To see why the spin current behaves like this, it may be helpful to understand why an electric current reaches easily the continuity condition. The

reason is not only due to the charge conservation (otherwise, the spin current should also be very robust) but also because of both charge quantization and large Coulomb interaction. Each type of particle carries only a fixed number of charges. For example, all electrons have one negative charge. Large Coulomb interaction prevents any real material from either absorbing or releasing excessive charges. In comparison, an electron can be in any innumerable number of possible spin states, and there is no interaction to prevent angular momentum accumulation and transformation from one object to another.

The differences in the electric current and spin current make the study of spin current much more challenging than that of electric current. In fact, even the issue of a proper definition of the spin current has been an active issue of debate recently in the spintronics community [31–33]. Interested readers are referred to the literature [31–33] for a full discussion.

1.2.3 Dynamics of Spin: Bloch Equation, Landau–Lifshitz Equation, and Landau–Lifshitz–Gilbert Equation

Consider a spin $\vec{s}$ under the influence of its Hamiltonian $W(\vec{s})$. The dynamics of $\vec{s}$ is governed by the Heisenberg equation if $\vec{s}$ can be regarded as a closed system

$$\frac{d\vec{s}}{dt} = \frac{1}{i\hbar}\left[\vec{s}, W(\vec{s})\right]. \tag{1.4}$$

It is straightforward to evaluate the commutator, and Eq. (1.4) becomes

$$\frac{d\vec{s}}{dt} = \gamma \vec{s} \times \vec{H}_t, \tag{1.5}$$

where $\gamma = 2.21 \times 10^5 (rad/s)/(A/m)$ is the gyromagnetic ratio, and the effective field $\vec{H}_t = -\nabla_{\vec{s}} W(\vec{s}) \big/ \gamma$ comes from external magnetic fields and from various magnetic anisotropy energies [5]. If one takes the expectation value of the above equation with respect to the spin state, and assumes $\langle -\gamma \vec{s} \times \vec{H}_t \rangle = -\gamma \langle \vec{s} \rangle \times \langle \vec{H}_t \rangle$, then the magnetization of an isolated spin, $\vec{M} \equiv \gamma \langle \vec{s} \rangle$, satisfies the following dynamic equation

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_t. \tag{1.6}$$

Classically, $\vec{H}_t = -\nabla_{\vec{M}} W(\vec{M})/\mu_0$, where $\mu_0 = 4\pi \times 10^{-7} N/A^2$ is the vacuum magnetic permeability, and $W(\vec{M})$ is the classical magnetic energy density.

1.2.3.1 Bloch Equation

Equation (1.6) is called the Bloch equation of an isolated spin by the nuclear magnetic resonance (NMR) and quantum optics scientific community because of the critical contributions of F. Bloch on these subjects. It is also known as the Landau–Lifshitz equation without dissipation in magnetism. Equation (1.6) is correct only for isolated spins, which is not the case for most realistic systems. Spins in a sample made up by condensed matter experience various interactions with other dynamical degree of freedoms of the sample and its environment. These interactions create internal magnetic fields. Due to the dynamical nature of the environments, these internal fields not only contribute an averaged field to the total magnetic field $\vec{H}_t$ but also exert residual fluctuating fields on the spins. These fluctuating fields, originated in the infinite number of degrees of freedom of the environment as well as their thermal and the quantum fluctuations, can lead to both spin relaxation and spin decoherence, meaning that the spin magnetization will approach to a preferred equilibrium value M_{z0} along the z-axis which is selected by either external magnetic field or sample anisotropy. The physics is as what was explicitly demonstrated in Reference [34]: A random field perpendicular to the z-axis, which produces an off-diagonal term in the Hamiltonian, can induce transitions between different spin states. The randomness in the transitions and the spontaneous decay of quantum fluctuations leads the spin magnetization to take an equilibrium statistical value. The fluctuating field along the z-direction makes the spin precession random, which gives rise to spin decoherence.

If one takes into account spin relaxation and spin decoherence in the spin dynamics, the proper way to describe the magnetization dynamics is the so-called Bloch equation with spin relaxation and spin decoherence.

$$\begin{aligned}
\frac{dM_z}{dt} &= -\gamma(M_x H_{ty} - M_y H_{tx}) - \frac{M_z - M_{z0}}{T_1} \\
\frac{dM_x}{dt} &= -\gamma(M_y H_{tz} - M_z H_{ty}) - \frac{M_x}{T_2} \\
\frac{dM_y}{dt} &= -\gamma(M_z H_{tx} - M_x H_{tz}) - \frac{M_y}{T_2}
\end{aligned} \tag{1.7}$$

where T_1 and T_2 are called spin relaxation time and spin decoherence time, respectively. T_1 is the typical time for an initial non-equilibrium M_z to reach the equilibrium value M_{z0}, and T_2 is the typical time for a magnetization to lose the memory of its initial precession position. The above equation is the starting point of usual NMR analysis because the NMR signal is related to the average magnetization $\vec{M}$ of an ensemble of spins.

1.2.3.2 Landau–Lifshitz Equation and Landau–Lifshitz–Gilbert Equation

The Bloch equation describes well the magnetization dynamics of an ensemble of non-interacting or weakly interacting spins, but it does not capture the proper

physics of a strongly interacting spin system such as a piece of magnet. This is because the magnetization magnitude of a magnet shall not change with time, and Eq. (1.7) does not preserve the magnitude of the magnetization. To take into account the dissipative effect of the environment, Landau and Lifshitz [35] introduced a phenomenological term, $\alpha\gamma\vec{m}\times(\vec{M}\times\vec{H}_t)$, where α is a dimensionless phenomenological parameter measuring the damping strength, and $\vec{m}$ is the unit vector of $\vec{M}$. Equation (1.6) with this damping term becomes

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\times\vec{H}_t - \alpha\gamma\vec{m}\times(\vec{M}\times\vec{H}_t). \tag{1.8}$$

Equation (1.8) is called the Landau–Lifshitz (LL) equation.

Later Gilbert [36] proposed an alternative way to include dissipation. Similar to Ohm's law in electron transport, Gilbert assumed a friction field of $-\alpha(d\vec{m}/dt)$ on a moving magnetization due to the dissipation. This friction field generates a torque on the magnetization. Thus Eq. (1.6) should be modified as

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\times\vec{H}_t + \alpha\vec{M}\times\frac{d\vec{m}}{dt}. \tag{1.9}$$

This equation is called the Landau–Lifshitz–Gilbert (LLG) equation that can also be written as

$$(1+\alpha^2)\frac{d\vec{M}}{dt} = -\gamma\vec{M}\times\vec{H}_t - \alpha\gamma\vec{m}\times(\vec{M}\times\vec{H}_t). \tag{1.10}$$

Although Eqs. (1.10) and (1.8) have the same mathematical form, the two approaches to the dissipation are fundamentally different. According to Eq. (1.10), the change rate of the magnetization goes to zero as $\alpha\to\infty$, and the magnetization shall move along the dissipation direction of $-\vec{m}\times(\vec{M}\times\vec{H}_t)$ when $\alpha\to\infty$. However, Eq. (1.8) says that the rate change of the magnetization becomes infinity at infinite damping, and it does not make any sense. Thus LL's approach to dissipation is not physical! It is generally accepted that LLG equation is the right description of magnetization dynamics for a magnet, and it is the starting point in our discussion of magnetization reversal of Stoner particles.

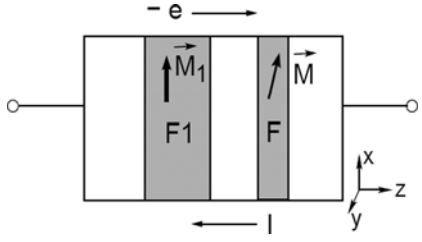

Fig. 1.1 An STT structure. Note that the direction of the electrical current is opposite to that of electron flow