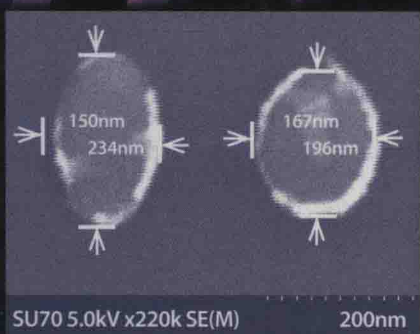
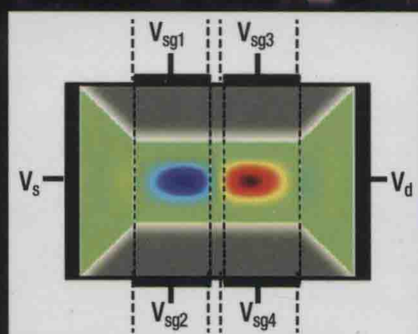
SECOND EDITION

Introduction to SPINTRONICS





Supriyo Bandyopadhyay
Marc Cahay

CRC Press
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The cover artwork shows two figures. On the left is a scanning electron micrograph of two closely spaced nanomagnets—one more shape-anisotropic than the other – which together act as a nanomagnetic inverter or NOT gate because of their mutual dipole interaction. These nanomagnets are made of FeGa alloy and have been delineated on a piezoelectric substrate with electron beam lithography at Virginia Commonwealth University. The magnetizations of both nanomagnets are bistable and can orient along either of the two mutually anti-parallel directions along the ellipses' major axes. These two orientations encode the binary bits 0 and 1. The magnetization of the more shape anisotropic nanomagnet encodes the input bit of the inverter and that of the other encodes the output bit. Because of dipole coupling between them, the magnetizations of the two nanomagnets will be anti-parallel in the ground state, which makes the output bit the logic complement of the input bit, thus realizing a nanomagnetic inverter. Micrograph is provided by Hasnain Ahmad.

On the right is a schematic of an all-electric spin polarizer based on a dual quantum point contact formed in a two-dimensional electron gas. A set of four in-plane side gates is used to control the amount of spin polarization in the narrow portion of the device. The blue and red regions represent accumulations of spin-down and spin-up electrons. The spin polarization configuration can be altered by changing the bias configurations on the four side gates. The onset of spin polarization is accompanied by the presence of anomalies in the conductance of the dual quantum point contact. This figure is the result of simulations and theoretical calculations carried out at University of Cincinnati.

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Introduction to SPINTRONICS

S. B. dedicates this book to Bimalendu, Bela, Anuradha and Saumil Bandyopadhyay.

M. C. dedicates this book to his wife Janie, thanking her for her patience and encouragement, and to the memory of his sister Michèle.

Preface

This is a textbook intended to introduce a student of engineering, materials science and/or applied physics to the field of *spintronics*. While the term "spintronics" may have different connotations for different people, in this textbook it deals primarily with the science and technology of using the spin degree of freedom of a charge carrier to store, encode, access, process and/or transmit information in some way. That role had been traditionally delegated to the "charge" of an electron, not its "spin." Over the last two decades or so, there has been burgeoning interest in augmenting the role of charge with spin, or even replacing charge with spin in information processing devices.

Interest in spintronics was motivated by a longstanding tacit belief that replacing charge with spin may yield some advantages in terms of increased processing speed, lower power consumption, and/or increased device density on a chip. While this may not always be true, there are some scenarios where it *may* become true in the near future. In this textbook, we place particular emphasis on identifying situations where "spin" may have an advantage over "charge" and where it may not (see, in particular, Chapters 13–15).

The advent of quantum computing has added a new dimension to all this. The spin polarization of a single electron can exist in a coherent superposition of two orthogonal spin polarizations (i.e., mutually anti-parallel spin orientations) for a relatively long time without losing phase coherence. The charge degree of freedom, on the other hand, loses phase coherence much faster. Therefore, spin has become the preferred vehicle to host a quantum bit (or "qubit"), which is a coherent superposition of two orthogonal states of a quantum mechanical entity representing classical logic bits 0 and 1. The potential application of spin to scalable quantum logic processors has a short history, but has provided a tremendous boost to spintronics.

This textbook is expected to equip the reader with sufficient knowledge and understanding to conduct research in the field of spintronic devices, particularly semiconductor-based spintronic devices. We assume that readers have first-year graduate-level knowledge of device engineering, solid state physics, and quantum mechanics.

The first edition of this book was organized into fifteen chapters and the second edition contains eighteen chapters. The first chapter provides a historical perspective to those who have had little or no exposure to this field. It traces the early history of spin, the anomalous Zeeman effect, and ends with an account of the accidental discovery of "spin" by Stern and Gerlach in 1922.

Chapter 2 introduces the quantum mechanics machinery needed to understand spin physics, as well as analyze spin transport and general spin dynamics in solid state structures. It also introduces the concept of Pauli spin matrices, the Pauli equation, and finally its relativistic refinement—the Dirac equation. Since, in this textbook, we will never encounter any situation where relativistic corrections become important, we will not have any occasion to use the Dirac equation. The Pauli equation will be sufficient for all scenarios. Nonetheless, it is important to gain an appreciation for the Dirac equation, since the quantum mechanical nuances associated with spin cannot be absorbed without an understanding of Dirac's seminal work.

Chapter 3 introduces the Bloch sphere concept, since it is a very useful tool to visualize the dynamics of a spin-1/2 particle (e.g., an electron), or qubit encoded in the spin of an electron, under the action of external magnetic fields. Applications of the Bloch sphere concept are elucidated with a number of examples. A spinor, representing an electron's spin, is viewed as a radial vector in the Bloch sphere, and this serves as a nice visualization tool for students interested in quantum computing and other applications of spintronics. All coherent motions of the spinor (where spin does not relax) are essentially excursions on the surface of the Bloch sphere.

Chapter 4 deals with an important application of the Bloch sphere concept, namely, the derivation of Rabi oscillation and the Rabi formula for coherent spin rotation or spin flip. These have important applications in many spin-related technologies such as electron spin resonance spectroscopy, nuclear magnetic resonance, and ultimately solid state versions of quantum computing. This chapter is somewhat mathematical and "seasons" the student to deal with the algebra (and recipes) necessary for calculating quantities that are important in spintronics. This chapter can be skipped at first and revisited later.

Chapter 5 introduces the concept of the "density matrix," pure and mixed states, Bloch equations (that describe the temporal relaxation of spin), the Bloch ball concept, and the notion of the longitudinal (T_1) and transverse (T_2) relaxation times. Several numerical examples are also presented to strengthen key concepts. Since here we allow the dynamics of spin to be incoherent, the motion of the spinor is no longer constrained to the Bloch sphere. The "Bloch sphere" actually refers only to the surface of the sphere and excludes the interior. If spin relaxes so that the norm of the sphere's radius is no longer conserved, then we have to allow excursions into the interior of the Bloch sphere. Therefore, we extend the Bloch sphere concept to the "Bloch ball" concept. This chapter contains advanced concepts and may also be skipped at first reading.

Chapter 6 introduces the rather important topic of spin–orbit interaction which is at the heart of many spintronic devices, since it offers a "handle" to manipulate spins. We introduce the general notion of spin–orbit interaction and then focus on the two special types of spin–orbit interactions that are predominant in the conduction band of most direct-gap semiconductors: the Rashba interaction arising from structural inversion asymmetry, and the

Dresselhaus interaction arising from bulk (crystallographic) inversion asymmetry. These two interactions form the basis of spintronic field effect transistors where the current flowing between two of the transistor's terminals is modulated by influencing the spin–orbit interaction in the device via a potential applied to the third terminal. Therefore, it is particularly important for applied physicists, materials scientists, and engineers to understand these interactions.

In Chapter 7, we derive the electron dispersion relations (energy versus wavevector) of electrons in quasi two- and one-dimensional structures (quantum wells and wires) in the presence of Rashba and Dresselhaus spin–orbit interactions, as well as an external magnetic field. We also derive the spin eigenstates, which allows us to deduce the spin polarization of carriers in any band. All this is accomplished by solving the Pauli equation. This is an example of how the Pauli equation is applied to solve a real life problem. We place special emphasis on how the dispersion relations are modified by an external magnetic field. This is important since it ultimately helps the student to appreciate how an external magnetic field can affect the performance of spin-based devices.

Chapter 8 discusses spin relaxation of conduction electrons in metals and semiconductors. We focus on four primary spin relaxation mechanisms: the D'yakonov–Perel, the Elliott–Yafet, the Bir–Aronov–Pikus and hyperfine interactions with nuclear spins, since these are dominant in the conduction band of semiconductors and therefore are most important in device contexts. Because spin relaxation limits the performance of most, if not all, spin-based devices, it is a vital issue. Ultimately, the aim of all device engineers and physicists is to reduce the rate of spin relaxation in spin devices, in order to make them more robust and useful. Spin relaxation also has peculiarities that are completely unexpected and without parallel in solid state physics. We present one example where spin can relax in *time* but not in *space*.

Chapter 9 is a new addition to the second edition and was not included in the first. Since the publication of the first edition in 2008, there has been an explosion in the study of spin-related physical phenomena, particularly those that may have applications in spintronic devices. In this chapter, we also discuss seven important physical phenomena that all have device applications: the extrinsic and intrinsic spin Hall effect along with the inverse spin Hall effect and the giant spin Hall effect, the spin Hanle effect, the spin capacitor effect, the spin-torque effect, the spin Galvanic effect, the spin Seebeck effect, and the inverse spin Seebeck effect or spin Peltier effect.

Chapter 10 introduces the more advanced concepts of exchange and spin–spin interaction. These form the basis of ferromagnetism and also the basis of single-spin computing schemes that are dealt with in Chapters 15 and 16.

Chapter 11 is an introduction to spin transport in solid state structures in the presence of spin relaxation. We focus on two basic models: the drift–diffusion model of spin transport and the semi-classical model that goes beyond the drift–diffusion model. The "spin" drift–diffusion model is very similar to the "charge" drift–diffusion model applied to bipolar transport; the "up-spin" and "down-spin" carriers assume roles analogous to electrons and holes. However, it has limitations. One limitation that we emphasize with specific examples is that it fails to describe essential features of spin transport, even qualitatively, if electrons are traveling "upstream" against the force exerted on them by an electric field. In this chapter, we present many examples of how spin relaxes in time and space in quasi one-dimensional structures in the presence of the D'yakonov–Perel' spin relaxation mechanism, since it is usually the dominant mechanism for spin relaxation in semiconductor structures. These examples are based on the semi-classical model and therefore applicable to both low field transport and high field (hot electron) transport. The semiclassical model is based on combining the Liouville equation for the time evolution of the spin density matrix with the Boltzmann transport equation for time evolution of the carrier momentum in the presence of scattering and external electric fields.

In Chapter 12, we discuss *passive* spintronic devices such as spin valves and devices based on the giant magnetoresistance effect. Most commercial spintronic products that are currently available (magnetic read heads for reading data in computer hard disks or entertainment systems such Apple iPods, and magnetic random access memory) utilize these passive devices. Therefore, an adequate understanding of these devices is vital for engineers. We also discuss the important notions of spin injection efficiency, spin extraction, and the recently discussed spin blockade. This is a long chapter with many topics and it is intended to introduce the reader to important concepts encountered in the modern spintronics literature. We also discuss three very specific devices that are spintronic "sensors"; one is a magnetic field sensor, another is a light sensor (photodetector), and the third is a mechanical strain sensor. These are discussed to show the reader that spintronics has myriad applications in magnetics, mechanics and optics.

Chapter 13 introduces *active* spintronic devices, such as spin field effect transistors and spin bipolar transistors. We explain the physical basis of how these devices operate and what their shortcomings are. We make a simple estimate of their performance figures in order to project a realistic picture of whether they are or are not competitive with traditional electronic devices that are currently extant. Regardless of their actual device potential, these devices are standard-bearers that aroused early interest in the field among engineers and applied physicists. This chapter discusses only the early variants of spin transistors because of their pedagogical importance. New twists to spin transistors appear in the literature frequently and it was not possible to do justice to them within the limited space available. The only way the reader can keep pace with this field is to follow the literature closely.

Chapter 14 discusses the recently discovered field of "spintronics without magnetism," which allows one to manipulate spin currents by purely electrical means. The reader is introduced to lateral spin–orbit interaction, and its many nuances, and the possibility of implementing spin polarizers and analyzers using quantum point contacts. This too is a new addition to the second edition.

Chapter 15 introduces more exotic concepts dealing with single-spin processors. Here, a single electron spin acts as the primitive bistable "switch" with two stable (mutually anti-parallel spin orientation) states that encode classical logic bits 0 and 1. Switching between the bits is accomplished by flipping the electron's spin without moving the electron in space and causing current flow. This chapter addresses fundamental notions like the ultimate limits of dissipation in performing Boolean logic operations and has relevance to the celebrated *Moore's law* scaling. Another distinguishing feature is that this chapter addresses spin-based architectures and not discrete devices like transistors. For example, it describes combinational logic circuits implemented with single-spin-switches that communicate with each other via exchange interaction and not physical wires. This is an area that has remained neglected, but is really no more challenging than spin-based quantum computing, since phase coherence of spin is not required. Being classical, it does not have the promise of quantum speedup of computation, or the ability to solve intractable problems, but it may provide valuable insights into the limits of classical computation.

Chapter 16 is an introduction to the field of spin-based reversible logic gates (that can, in principle, compute without dissipating energy) and spintronic embodiments of quantum computers. This is a rapidly advancing field, extremely popular among many spintronic researchers, and discoveries are made at a fast pace. This chapter is written mostly for engineers and applied physicists (not computer scientists or theoretical physicists), and should provide them with the preliminary knowledge required to delve further into this field. We have also focused on electrical manipulation of spin qubits rather than optical manipulation since this book is almost entirely devoted to electro-spintronics rather than opto-spintronics. Needless to say, because of the rapid advances in this area, it is impossible to address this field comprehensively. The reader is provided with a few examples to whet her/his appetite and is urged to follow the literature closely to keep abreast of the most recent developments.

Chapter 17 introduces the concept of "single-domain-nanomagnet" based computing and is a more practical rendition of the single-spin logic architecture ideas of Chapter 15. This is a new addition to the second edition. In a single domain ferromagnet, all the spins rotate in unison under an external influence because of strong exchange interaction between spins, making the entire ferromagnet behave like a giant classical spin. This chapter is focused primarily on logic architectures and discusses two main variants: dipole coupled nanomagnetic logic (also known as magnetic quantum cellular automata) and magneto-tunneling junction logic. Particular emphasis is placed on various magnet switching methodologies (magnetic field, spin-torque, spin-Hall effect, toplogical insulators, and magneto-elastic switching) since they determine the energy efficiency of nanomagnetic architectures. Much of the material presented in this chapter, dealing with magneto-elastic devices, was the result of collaborative research with Prof. Jayasimha Atulasimha at Virginia Commonwealth University.

Chapter 18 is a stand-alone chapter that can be treated as an appendix. At first sight, it will appear unrelated to spintronics, which it is, but it has been included for a reason. There are many instances in this book when a student will have to recollect or refamiliarize herself/himself with some key results of quantum mechanics. Rather than making a trip to the nearest library, it would be more convenient to have a "quantum mechanics primer" handy where these key results have been re-derived. This chapter is included for completeness and comprehensiveness. The reader can refer to it if and when necessary.

At the time of writing the second edition, this book is still the only known "textbook" in spintronics written in English. By its very nature, it must be incomplete and omit many topics that are both important and interesting. We have focused mostly on electron spin, and, with the sole exception of discussing hyperfine nuclear interactions, we have ignored nuclear spin altogether. Hence, we do not discuss such well-known phenomena as the Overhauser effect, which is more relevant to nuclear spin. Another area that we have intentionally not covered in any detail is *organic spintronics*. We omitted any discussion of this field (it is still in its infancy) and do not discuss it primarily because we feel that this is very much in evolution. Organic semiconductors (mostly hydrocarbons) have weak spin–orbit interactions, so that spin relaxes slowly in these materials compared to inorganic semiconductors. Hence, they have a major advantage over inorganics when it comes to applications where spin relaxation must be suppressed, such as in spin-based classical or quantum computing. Some reviews have appeared in the literature covering organic spintronics and an edited book is available from this publisher.

This textbook also heavily emphasizes transport phenomena as opposed to optical phenomena dealing with the interaction of polarized photons with spin-polarized electrons and holes. Hence, we do not discuss such devices as spin-light-emitting diodes. Delving into "opto-spintronics" would have easily added a couple hundred pages to the 600-odd pages in this textbook. Our own expertise is more in transport phenomena, which has led us to focus more on transport. However, there are many excellent books (although not necessarily "textbooks") available that deal with opto-spintronics, and the interested reader can easily find an assortment of literature in that area.

Table of Universal Constants

Free electron mass (m_0)	9.1×10^{-31} kilograms
Dielectric constant of free space (ϵ_0)	8.854×10^{-12} Farads/meter
Electronic charge (e)	1.61×10^{-19} Coulombs
Reduced Planck constant ($\hbar$)	1.05×10^{-34} Joules-sec
Bohr radius of ground state in H atom (a_0)	0.529 Å$= 5.29 \times 10^{-11}$ meters
Bohr magneton (μ_B)	9.27×10^{-24} Joules/Tesla

Acknowledgments

Some acknowledgments are due. Many of our associates have contributed indirectly to this book. They are our students, laboratory interns and post-doctoral research associates, past and present. They include Prof. Sandipan Pramanik of the University of Alberta, Canada, who was a graduate student and then a post-doctoral researcher at Virginia Commonwealth University (VCU) at the time this book was composed; Dr. Bhargava Kanchibotla, an erstwhile graduate student at VCU who provided the T_2 data in cadmium sulfide nanostructures from his experiments (Figure 8.5); Dr. Sivakumar Ramanathan and Dr. Sridhar Patibandla, two graduate students at VCU working with S. B. who took the first spintronics graduate course offered at VCU by S. B. and provided valuable feedback; Harsh Agarwal, a summer undergraduate intern visiting VCU from the Banaras Hindu University Institute of Technology, Varanasi, India, who computed and generated some of the plots in Chapter 15; and Dr. Amit Trivedi, another summer undergraduate intern from the Indian Institute of Technology, Kanpur, who performed some of the calculations; and Saumil Bandyopadhyay, who performed some of the coherent room temperature spin transport experiments in single subband quantum wires.

At the University of Cincinnati, a former graduate student, Dr. Junjun Wan, and intern Lindsay Ficke, contributed immensely to the generation of data and plots. We also thank graduate student Nishant Vepachedu for proofreading the manuscript. We remain grateful to all of them.

In spite of all our best efforts, quite a few typographical errors made their way into the first edition. We corrected as many of them as we could catch, but some may have still eluded us. Matthew David Mower, a student from the University of Missouri, brought some typographical errors to our notice. We thank him. As always, we will remain grateful to any reader who points out such errors to us. Our e-mails are sbandy@vcu.edu and marc.cahay@uc.edu.

Welcome to the world of spintronics!

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