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Spin Electronics

Springer

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Cover picture: Schematic illustration of the passage of an electron through a spin field. The field was calculated using the OOMMF micromagnetic solver developed by Mike Donahue and Don Porter.

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Foreword

Electrons are tiny magnets as well as elementary charged particles, yet for 50 years conventional electronics has ignored the spin on the electron. Distinguishing the spin up (↑) and spin down (↓) currents, and manipulating the spin as well as the charge information adds a new dimension to the practice of electronics. The first applications are now beginning to make an impact.

'Spin Electronics' provides an introduction for newcomers to the field, whether condensed-matter physicists whose notions of electronics may be hazy, or electronic engineers who know little of magnetism. The book is based on lectures delivered at a Summer School organized by John Gregg in Magdalen College, Oxford during September 1998 in the framework of the Oxide Spin Electronics Network. OXSEN was a group of eight laboratories that formed a network for training and mobility of researchers, funded by the European Commission from 1996–2000. Two of the OXSEN researchers have edited the contributions, many of which have been substantially updated. The material has been divided into three sections. First is an overview of the whole field with an introduction to electronic devices and the way in which magnetism can impact them. The second section presents the basic concepts including transport, theory, metallic and oxide magnetism, semiconductors, giant and colossal magnetoresistance, spin tunnelling, micromagnetism and noise. The third section focuses on materials, methods and spin electronic circuits and devices.

As we have not yet found a magnetic semiconductor that is usable at room temperature, and attempts at spin injection into conventional semiconductors are problematic, the first wave of spin electronics has been concerned with simple magnetoresistors and switches. Exploration of the magnetoresistance in magnetic multilayers, spin valves and tunnel junctions has culminated in the development of ultra-high density magnetic recording and magnetic random-access memory. The direction leading to a new wave of active spin electronic devices and eventually to single-spin devices is signposted. It is expected that the route will lead to closer integration of magnetic with conventional semiconductor technology.

This book is intended to encourage more scientists to make their way into an exciting new field. We are grateful to the European Commission for their support.

Dublin *J. M. D. Coey*
December 2000

Preface

Recent years have seen a rapid development of spin electronics (also called magnetoelectronics or spintronics). This new field of research combines two traditional branches of physics: magnetism and electronics. The aim is to find ways to manipulate the electron spin in transport processes. The approach to spin electronics is very broad and includes the investigation of spin dependent processes in various systems ranging from metallic multilayers via oxide magnets to semiconductors and tunneling junctions. Precise control of the electron spin adds a new degree of freedom for the engineering of electronic devices. In the last decade we have seen the introduction of spin electronic ideas into the first generation of practical devices.

Among the major achievements of spin electronics is the understanding of spin dependent transport processes in various physical systems. These include metallic multilayers showing giant magnetoresistance, ferromagnetic tunnel junctions exhibiting tunneling magnetoresistance and certain ferromagnetic oxides showing colossal magnetoresistance near metal-insulator transitions. The transport of spin polarized currents in semiconductors is barely understood to date, but interesting first results have been achieved.

Evidently there is a need for spin electronic researchers coming from various areas of physics to efficiently grasp the basic concepts of the other fields involved as well as to communicate their results. Moreover, since the understanding of transport processes in magnetic systems has evolved so rapidly in recent years, there exists a large gulf between advanced textbooks and the research front. The aim of this book, the first of its kind on spin electronics, is to bridge this gap as it attempts to describe all the topical themes essential for new researchers entering the field. Most of the chapters include exercises and solutions to help the student become familiar with the material.

The book consists of eighteen chapters, written with a uniform notation, with cross references in each chapter to related subjects in other chapters. The choice of material is intended to provide the basic concepts of the various fields of physics involved in spin electronic research as well as to cover recent developments in spintronics. The book is divided into three parts: the first part consists of a general survey of the field, in the second part basic concepts from magnetism, transport theory and semiconductor physics are introduced and the third part is devoted to an overview of materials, thin film characterization techniques and spin electronic devices.

In the first chapter, J. F. Gregg reviews the field of spin electronics detailing landmark, recent and current experimental devices. Two and three terminal, hybrid and current novel devices are reviewed. Spin injection in semiconductors is discussed and the current difficulties in spin electronics are outlined. He concludes by suggesting possible applications for future spin electronics devices.

The second chapter, written by G. A. Gehring, presents a basic account of magnetic phenomena and transport processes in metals. Starting from Fermi liquid theory, band magnetism and the Stoner theory are discussed. The chapter ends with a brief description of strong coupling theories, including the formation of localized moments, the Kondo–effect and heavy fermion compounds.

Chapter 3 by B. J. Hickey, G. J. Morgan and M. A. Howson is devoted to both theoretical methods for the calculation of metallic conductivity and experimental techniques for resistivity measurements. In the first part the Boltzmann equation and the Kubo–Greenwood formula are introduced, the Fuchs–Sondheimer model for thin metallic films is discussed and a brief account of Lorentz magnetoresistance and quantum interference effects is given. In the second part experimental techniques for the measurement of resistivity, Hall resistivity and thermopower are explained.

In Chap. 4, G. Mathon gives an introduction to the phenomenon of giant magnetoresistance in metallic multilayers such as Fe–Cr or Co–Cu. This chapter presents experimental data on giant magnetoresistance, as well as an analysis of spin dependent scattering processes and quantitative network resistor theory.

Chapter 5 by D. Khomskii gives an overview on the electronic structure, exchange mechanisms and magnetic states in oxides. This theoretical account starts with general properties of transition metal ions in crystals and discusses orbital effects, Jahn–Teller effect, exchange interactions in and classification of insulators, Goodenough–Kanamori–Anderson rules and the double exchange mechanism.

In Chap. 6, M. Viret reviews recent results on the properties of mixed-valence manganites showing colossal magnetoresistance. Starting from an analysis of the electronic structure within an ionic and a band model, the resistivity, magnetotransport and magnetic properties of this class of oxides is characterized from an experimental as well as theoretical viewpoint. Some applications relevant for spin electronics are discussed.

The physics of spin dependent tunneling processes is briefly reviewed by F. Guinea, M. J. Calderón and L. Brey in Chap. 7. Simple models for the tunneling current and the influence of ferromagnetic electrodes are discussed. The significance of magnetic impurities, magnetic excitations and charging effects is studied.

Chapters 8 and 9 cover traditional semiconductor physics. There H. Jenniches gives an overview of the basic properties of semiconductors including band structure, carrier concentration, mobility and p-n junctions and D. I. Pugh briefly reviews metal-semiconductor contacts.

Chapter 10 by R. Skomski is on micromagnetic properties. The intrinsic properties of ferromagnetic materials are defined and extrinsic properties such as domain formation, domain walls, hysteresis and coercivity are discussed within simple models. The chapter concludes with a new model of grain-boundary magnetism that is especially relevant for spin dependent scattering processes in polycrystalline materials.

The second part of the book ends with Chap. 11 which is an extensive review by B. Raquet on electronic noise in magnetic materials and devices. The author starts with a theoretical treatment of the problem and discusses the different types of noise such as thermal, shot, 1/f and telegraph noise. In the second part of this chapter noise measurements on a variety of magnetic and spin electronic systems are reviewed.

The third part of the book starts with Chap. 12 by J. M. D. Coey presenting an overview on materials for spin electronics. Here the properties of Fe-, Ni- and Co- based alloys are reviewed and an account of antiferromagnets, half-metals and ferromagnetic semiconductors is given, as well as an introduction to thin film device structures.

Chapter 13 by E. Steinbeiss covers thin film deposition methods such as thermal evaporation, MBE, pulsed laser deposition and various forms of sputtering. Thin film growth mechanisms are also discussed.

In Chap. 14 A. K. Petford–Long gives an overview on magnetic imaging methods taking into account Bitter patterns, Lorentz microscopy, scanning force microscopy and polarized light microscopy.

In Chapter 15 by K. Ounadjela, I. L. Prejbeanu, L. D. Buda, U. Ebels and M. Hehn the magnetic force microscopy thechnique is introduced and recent results on the magnetic states of nanosized dots, rings and wires are reviewed; furthermore, domain wall scattering in Co wires is discussed.

In Chap. 16 micro– and nanofabrication techniques are described by C. Fermon. This chapter contains a description of basic patterning processes, deposition techniques, lithography processes and etching techniques. It concludes by presenting a couple of novel spin electronic devices.

Chapter 17, written by M. Ziese, is a review of recent developments in the field of spin dependent transport processes in semiconductors. Starting from the basics of spin polarized transport in semiconductors, the author reviews recent experimental results on spin coherent electron transport in semiconductors as well as spin injection and spin detection. The chapter concludes with a brief account of spin electronic semiconductor devices.

In Chap. 18 J. F. Gregg and M. J. Thornton describe the basic principles of circuit theory. The introduction of Norton–Thevenin transforms and transfer functions in ac circuit theory gives the spin electronician a powerful tool for the analysis and design of electronic devices. In the chapter small signal analysis, equivalent circuits, load lines, the Miller effect, Nyquist amplifier stability theory, noise and dc motors are discussed.

Finally, Chap. 19 by P. P. Freitas provides an overview of recent developments of spin valve and spin tunnelling devices. This chapter covers topics such as magnetic data storage, design and fabrication of spin valve sensors, magnetic random access memories and general sensor applications.

We wish to thank all the authors for their cooperation. It is our hope that the book can serve as a textbook for graduate students, for lecturers at universities for preparing course material, for professionals in the electronics industry who need to obtain information on physical concepts and for researchers joining the new field of spin electronics.

Oxford *Martin Thornton*
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December 2000

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