# Preface

This book is intended for readers, who wish to acquire a solid basis for understanding electron transport in spintronics and the fundamental principles of some associated applications. It provides the reader with sufficient knowledge, to be able to invest further in this field of research. To this end, some of the prominent key notions widely used in the field were selected with care, with the aim of providing a simple, concise, and efficient framework. These selected notions are explained, using simple examples and analytical calculations. The technical terms and specialist jargon are explained, and the way subtleties complicate the phenomena, without altering their physical basis, is addressed.

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The text has grown out of lectures, given to MSc and PhD students. Therefore, it is designed for advanced graduates and postgraduates, as well as researchers and engineers, with a background in condensed matter physics and magnetism. Interested readers are encouraged to complement their knowledge by consulting, for example, the following books: N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, Saunders College Philadelphia (1976); C. Kittel, *Introduction to Solid State Physics*, John Wiley & Sons (2004); J. M. D. Coey, *Magnetism and Magnetic Materials*, Cambridge University Press (2010); E. du Tremolet de Lacheisserie *et al.* (eds) *Magnetism I & II*, EDP Sciences (2002).

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The text is structured in seven parts. Each part feeds on the previous one. A careful effort has been made, to indicate how the parts and the physical phenomena, they describe, are related to each other. While the text focuses on the fundamental aspects, the implementation of the fundamental physical effects in typical applications is described in detail. Orders of magnitude of the various parameters and key phenomena are provided in each section, based on experimental data. The references are concise, in order to provide a reasonable initial framework for the interested reader, to explore further. Physical effects, that are more peripheral to current concerns are mentioned wherever relevant, with references. An Index of key concepts allows the reader to navigate from one key area to another. Throughout this textbook, we use SI units. A List of symbols and units, as well as the corresponding formulas, is provided so that the reader can refer to them throughout the reading. When there are several possible definitions in the literature, the definition used in this book is made explicit, and the differences in prefactor depending on the articles and books consulted, are also made explicit.

Chapter 1 gives a concise overview of spintronics and what this discipline contributes to society.

Chapter 2 lays the foundation of spin-dependent electron transport. Based on the two-current and *sd* scattering models, we first show why the electron scattering probability is spin-dependent, and how this effect impacts electron transport, using the example of the current-in-plane (CIP) giant magnetoresistance (GMR) effect. We then show how the addition of spin-orbit interactions mixes the spin states and reshuffles the spin-dependent scattering probabilities, using the anisotropic magnetoresistance (AMR) effect as an example.

In chapter 3, we describe in detail, the effect of spin accumulation, encountered whenever electrons flow across an interface, due to the distinct partial current densities in materials of different types. Here, we detail how the electron dynamics are described in this case, and what kind of spin-flip relaxation mechanisms prevail. We elaborate on the conditions of a key parameter known as the spin-coupled interface resistance, necessary to maintain the spin polarization across an interface, and present how spin accumulation is at the heart of the current perpendicular-to-plane (CPP) GMR effect. How intrinsic interface effects, such as spin memory loss, as well as how non-collinearity and non-uniformity alter spin accumulation, are presented.

Chapter 4 focuses on the process by which spin angular momentum can be transferred from current (spin angular momentum flow) to magnetization, and the type of torque (STT), that this transfer generates. The key parameters involved, including the spin mixing conductance, are discussed in detail. How STT alters electron transport, by providing an additional relaxation channel for the spins, is tackled, as well as how STT can trigger oscillations and magnetization reversal. The spin pumping (SP) reciprocal effect of STT is introduced. Guidance on the morphology of STT in non-uniform magnetic textures, as well as hints on the magnetoelectronic circuit theory widely used in current spintronics, will be given. This chapter ends with a section about spin-orbit torques (SOT), which result from the transfer of angular momentum between lattice and the electron orbitals (crystal field potential), electron orbital and spin (spin-orbit coupling), and spin and magnetization (*sd*-exchange interactions).

In chapter 5, we describe how the intrinsic crystal and spin symmetries, represented by different symmetry groups, are particularly important notions, that have a significant impact on spintronics. With the examples of the different Hall effects, be they unquantized or quantized, we present the Berry formalism, and what it implies for intrinsic physical effects. The importance of breaking spatial or temporal inversion symmetries is detailed and illustrated.

Chapter 6 provides a series of ten comprehensive exercises with solutions. They are specifically designed to illustrate the ideas in the previous chapters and lead to other spintronic effects based on these ideas. The exercises deal with AMR (chapter 2), domain wall AMR (chapter 3), the drift-diffusion equation for spin accumulation (chapters 3–5), spin conductivity mismatch in CPP-GMR (chapter 3), the intrinsic intra-band scattering contribution to damping of magnetization dynamics (chapters 2 and 4), spin pumping and the inverse spin Hall effects (ISHE) (chapters 4 and 5), the extrinsic spin pumping contribution to damping (chapter 6), spin Hall magnetoresistance (SMR) (chapters 2–4), the harmonic analysis of the anomalous Hall voltage and related torques (chapters 4 and 5), and the intrinsic anomalous Hall and Nernst effects (AHE, ANE) (chapter 5).

Finally, chapter 7 concludes the book with a non-exhaustive presentation of some current topics, to which the readers may wish to turn, building on the previous chapters, which now allow them to go further, and understand other related or more elaborate spintronic phenomena.

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