

Preface

This book on Magnetic Nanostructures in the Springer Series on Modern Physics contains seven chapters, highlighting several aspects of this fascinating modern field of condensed matter physics ranging from spin currents and spin torques in magnetic nanostructures to the manipulation of single spins in quantum dots. It complements the Springer book on Magnetic Heterostructures: Advances and Perspectives in Spinstructures and Spintransport published in 2008 [1]. These two books cover much of the scientific progress made possible through the collaborative effort of teams of experimental and theoretical physicists working together in a collaborative research center (SFB 491) for more than 10 years to provide a better understanding of static and dynamic magnetism in novel nanostructures.

The term “nanostructure” is not well defined. Thin films of only a few nanometers thickness are nanostructured in one direction normal to the film. However, by the term nanostructure we usually understand an object which has a size on the nanoscale in at least two directions. Artificial islands, wires, dots, rings, pillars, etc., are nanostructures when their extension is confined to the nanoscale in more than one direction. Nanostructures can be fabricated artificially or may be arranged from nanoparticles via self-assembly. The fabrication of nanostructures from different materials, metals, oxides, and semiconductors is essential for the exploration, and further development of their fascinating properties.

In the late 1990s, the interest in magnetic properties of nanostructured materials has increased dramatically. This interest was fueled for two reasons: technical and scientific. From a technical point-of-view the down-scaling of physical sizes of magnetic data bits and magnetic sensors required investigations of magnetic properties on the submicron scale. From a scientific point-of-view nanostructures—by the choice of their shape or material—offer the possibility to stabilize single magnetic domains or to tailor specific domain structures with well-defined domain walls. An early realization of magnetic nanostructures dates back to Meiklejohn and Bean, who have created magnetic nanoparticles by a bottom-up approach of naturally occurring Co/CoO [2]. The more recent interest was ignited by a publication of Cowburn, showing with magneto-optical hysteresis measurements the vortex state of domains in circular islands [3]. Shortly after, Shinjo and coworkers imaged the

vortex core in circular islands with MFM and demonstrated its stability in external fields at different angles of inclination [4]. Rüdiger and coworkers studied the development of magnetic domains in nanostructures of different shape and aspect ratio [5], and Ono demonstrated how domain walls propagate in narrow wires with a well-defined speed [6]. Katine et al. and Grollier et al. showed that spin currents can produce a torque that switches the magnetization direction in GMR devices, allowing a control via an electric field instead of a magnetic field [7, 8]. All these early experiments inspired many more experiments during the past 10–15 years. The latest twist being the arrangement of magnetic islands with single domain dipole character into two-dimensional arrays with intrinsic geometric frustration for the study of artificial spin ice [9]. In this book, only a few but important aspects of magnetic nanostructures are covered by reviews of developments which took place over the last 15 years or so.

In Chap. 1 by J. Lindner et al. and also partially in Chap. 2 spin torque experiments are discussed. The concept of spin torque was introduced independently by Slonczewski [10] and Berger [11] in the mid-1990s. They pointed out that the spin-polarized current carries an angular momentum that can switch the magnetization of a layer when the torque is absorbed by its magnetization. This leads to a new type of switching mechanism. Instead of switching via an external magnetic field in conventional GMR and TMR devices, in spin torque devices the switching is provided by a change of the direction of the spin current, i.e., by the direction of an electric field. This principle has been demonstrated for the first time by Katine et al. [7] and has inspired many new experiments and device concepts.

In Chap. 2 by M. Farle et al. the spin dynamics in magnetic nanostructures is considered. Experimental detection schemes to analyze the relaxation of the magnetization after microwave excitation are discussed. Modern techniques operating in the time domain, which are able to “visualize” the precession of the magnetization vector are discussed in connection with classical resonance techniques, detecting resonance frequencies of the precessing magnetization as well as more modern magneto-resistive schemes that are based on spin-polarized current driven ferromagnetic resonance. New schemes on how to distinguish different relaxation channels (intrinsic versus extrinsic) are discussed. Examples of how to control such phenomena are presented. For example, by gently structuring the magnetization extrinsic two-magnon scattering can be controlled, offering a bridge to the new field of lithographically patterned magnonic crystals [12] and magnonic electronics [13], possibly called “soft magnonics”.

The Chap. 3 by K. B. Efetov et al. is devoted to proximity effects between superconductors and ferromagnets in nanostructures. These two ground states of the electronic system in solids are antagonistic, since ferromagnetism requires a parallel alignment of the spins, whereas conventional singlet superconductivity requires an antiparallel alignment. The proximity effect in superconductor/ferromagnet nanostructures has raised considerable interest during the last 15 years and has been reviewed at several places [14, 15]. The present review is devoted to recent experimental and theoretical progress in the physics of the proximity effect with special emphasis on the occurrence of odd triplet superconductivity, which

may occur at superconducting/ferromagnetic interfaces in case where the magnetization of the ferromagnetic layer is inhomogeneous. Recent experiments with Josephson tunneling junctions including a ferromagnetic barrier provided evidence for the existence of a long range odd triplet component of the supercurrent [16, 17]. Further topics include experimental progress concerning the realization of superconducting spin valves and experimental evidence for the existence of an inverse proximity effect [18].

Chapter 4 by H. Herper et al. on Heusler alloys includes discussions on their electronic properties and magnetic moment formation, and recognizes the importance of this class of materials for magnetic nanostructures and spintronic devices [19]. The extensive interest in Heusler alloys is due to their unique magnetic properties, such as a predicted 100 % spin polarization at the Fermi level and very high Curie temperatures, which make them suitable for various applications. The present review focusses on nanostructured Heusler alloys as needed for magneto-electronic applications, with special emphasis on the effect of composition, disorder, and structural deformation on the magnetic properties. As the quality of spintronic devices crucially depends on the interfacial properties of Heusler alloys and specific substrates, these aspects are considered in detail.

Chapter 5 on magneto-electric materials by W. Kleemann and Ch. Binek reviews a new development in magnetic nanostructures and spintronics, i.e., the control of the ferromagnetic hysteresis via the polarization of a ferroelectric material in spin valve devices. The classic magneto-electric effect was discovered by a combination of an antiferromagnet Cr_2O_3 with a switchable ferromagnetic surface magnetization in contact with a ferromagnetic layer in a spin valve device [20]. Similarly, in multiferroic materials like BiFeO_3 and BiMnO_3 similar exchange bias was controlled by the application of electric fields [21]. This review provides an overview of these new and exciting developments and shows perspectives for novel multiferroic ordering types including potential applications.

Chapter 6 by O. Hellwig et al. describes in contrast to **Chaps. 1** and **2** the magneto-static properties of different nanomagnetic systems, which are commonly used in spin valve arrays, such as in bit patterns of magnetic storage media or in random access memory devices. In either case, proximity effects via magneto-static interaction are an issue. Vice versa, the magnetostatic interaction can be beneficial in magnetic dipole arrays, which form artificial spin ice structures with various degrees of frustration [9, 22]. This chapter also contains a section which treats self-organized magnetic nanocluster, which are considered as a potential route to new applications in memory devices, immunology, and cancer treatment. At the same time, magnetic nanoclusters provide new aspects for the investigation of magnetic ordering and phase transitions.

Chapter 7 which is the final chapter by A. Ludwig et al. is devoted to the discussion of spins in quantum dots. Several approaches are discussed for spin injection into quantum dots and how the spins can be detected via the circular polarization of the emitted light of quantum dot LED devices. Furthermore, spin injection concepts into single quantum dots are discussed as well as schemes for pulsed spin injection on a sub-nanosecond time scale. Finally, a theoretical

description of the minimal model for spin accumulation and relaxation in metal–semiconductor hybrids is described and extended to the case of coupled spins in distinct quantum dots.

We hope that these reviews are useful for students entering the field of magnetic nanostructures as well as experts working already in this and/or neighboring fields. Clearly, the present volume cannot treat all aspects of magnetic nanostructures because of size restrictions. But it gives an updated perspective on a good fraction of this exciting and fast developing field. For all missing parts, we would like to refer to other reviews, books, and topical monographs published on magnetic nanostructures.

Finally, we would like to thank all authors of the chapters in this book for their time, effort, and dedication to realize this book project in time in spite of all other pressing daily duties. Furthermore, we would like to thank our colleagues, who have critically read and commented selected chapters, thereby providing essential suggestions for the improvement of the content: Prof. M. Albrecht (Universität Chemnitz), Prof. H. J. Elmers (Universität Mainz), Prof. M. Fiebig (ETH Zürich), Prof. B. Hillebrands (Universität Kaiserslautern), Prof. U. Kunze (Ruhr-Universität Bochum), Prof. Strunk (Universität Regensburg). Last but not least, we would like to thank the Deutsche Forschungsgemeinschaft for supporting the collaborative research center on “Magnetic Heterostructures” (SFB 491) for the last 12 years. Without this support, this focussed research and the present book project would not have been possible.

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