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Bekir Aktaş · Faik Mikailzade
Editors

Nanostructured Materials for Magnetoelectronics

Springer

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Preface

The research and development of nanoscale magnetic materials is one of the most promising fields in today's science and is a base for new branches of high-tech industry. In recent decades intensive investigations in this field have promoted great progress in the technological applications of magnetism in various areas. Nanoscale magnetic materials exhibit new and interesting physical properties that cannot be found in the bulk matter. Many of these unique properties have high potential for technical applications in magnetic storage media, magnetic heads of computer hard disk drives, single-electron devices, microwave electronic devices, and magnetic sensors. New terminologies, such as magnetoelectronics and spintronics, have recently been introduced to refer to aspects of the field involving magnetic phenomena at the nanoscale.

The technical progress of recent years involved the preparation of multilayer thin films and nanowires, resulting in the discovery of the giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) phenomena, consisting in an extraordinary change in the resistance/impedance of a material on application of an external magnetic field. GMR and TMR materials have already found applications as sensors of low magnetic fields, computer hard disk read heads, magnetoresistive random access memory (RAM) chips, etc. The most recent investigations in the field of magnetic nanostructured materials introduced the new progressive field of spintronic devices, which utilize not only the electrical charge but also the spin of electrons and optical spin manipulation.

The dynamic behavioral features of magnetic nanostructures, especially the speed of magnetization reversal and the physical limitations, are crucial issues in magnetic data storage and spintronics, as they determine the functionality and frequency response of devices. The need to increase the data transfer rates in magnetic mass storage devices pushes the relevant switching frequencies far into the gigahertz (GHz) regime. The enormous power dissipation in current semiconductor-based microprocessors has resulted in a search for low-power alternatives, for example, magnetic logic circuits, which provide the advantage of an inherent data non-volatility. The successful operation of future "magnetic processors" at GHz frequencies must be based on careful control and tuning of the microscopic mechanisms governing the magnetic switching process.

During the last decade, spin-transfer torque physics has attracted much scientific interest after the transfer of spin momentum by spin-polarized currents was predicted and observed in the wake of the seminal discovery of GMR, which kicked off the fast-paced development of spintronics. Whereas the GMR effect is well suited for sensing and detecting magnetization states, the spin-transfer torque provides a means to act on the magnetization, thus complementing GMR and extending the toolbox for spintronics.

There are two different approaches for realizing spintronic devices. One is metal-based spintronics which uses ferromagnetic metals. The second one is semiconductor-based spintronics consisting of ferromagnetic semiconductors, for which much effort has focused on producing ferromagnetism in semiconductors above room temperature. If successful, this new class of spintronic devices could be integrated much more easily with conventional semiconductor technology. The key requirement in the development of such devices is the efficient injection, transfer, and detection of spin-polarized current from a ferromagnetic material into a semiconductor. Because of the well-known problem of a resistance mismatch at metal/semiconductor interfaces, hindering an effective spin injection, much interest is now concentrated on the development of room-temperature ferromagnetic semiconductors.

In recent years there has been a considerably growing interest in multilayered GMR nanostructures due to their wide magnetoelectronics applications. Obviously, the magnetic anisotropy and interlayer exchange coupling play the most important roles in these structures. Oscillatory interlayer exchange coupling between ferromagnetic layers is an indirect exchange interaction of localized spins in magnetic layers mediated by conducting electrons of nonmagnetic spacers. As the need for ultra high density data recording increases, the size of the films used in spintronic applications must decrease. Therefore, accurate magnetic characterization is one of the major issues related to magnetic multilayer structures.

Another important field is that of interfacial phenomena in perovskite oxide superlattices, which have the potential to provide unique functional properties for a diverse range of applications, including sensing, energy conversion, and information technology. In these systems, the antiferromagnetic and ferromagnetic order parameters display dissimilar dependences on sublayer thickness and temperature due to the competition between different magnetic interactions. For a small range of sublayer thicknesses, a robust spin-flop coupling is observed such that the alignment of the magnetization of the ferromagnetic layer with a magnetic field leads to the reorientation of the magnetic moments in the antiferromagnetic layer to maintain the proper orientation between different moments.

The science and technology of functional nanostructured materials received great impetus by the ability to produce structures on a sub-micrometer scale. Nanofabrication and nanotechnology allowed the manipulation of materials and the engineering of innovative materials and devices, both for fundamental studies and for applications in various fields. One of the major obstacles in the miniaturization of nanoelectronic devices has been the fabrication of interconnects having diameters compatible with the size of the devices they connect. In solid state electronics as well as in nanoelectronics, interconnecting nano or molecular devices has remained a challenge for several decades. Although the search for feasible interconnects in nanoelectronics is continuing, nanosized Si nanowires appear to be an attractive 1D material because of their well-known silicon-based microelectronic fabrication technology and their ability to be used directly on the Si-based chips. Electronic and spintronic devices with conducting interconnects between them can be fabricated on a single Si nanowire at a desired order.

One of the most effective methods of nanotechnology and nanofabrication is the self-assembling of nanoparticles or nanospheres, a low-cost alternative patterning technology particularly well suited to the preparation of arrays of dots or antidots covering a surface area of several square millimeters (mm^2) or larger. While nanoparticles with a sharp size (diameter) distribution can be synthesized by several bottom-up chemical processes, and can even be functionalized for different purposes, their dispersion over large substrates results in well-ordered, short-range periodic templates, with a lack of long-range order and without a precise orientation on the macroscopic scale of the whole sample, of the periodic structure. Self-assembling of polystyrene nanospheres is a powerful technique to prepare large area (several mm^2) nanostructured thin films. Compared to conventional lithographic techniques, which have more resolution and are more versatile, but are limited to very small surface areas, self-assembling of polystyrene nanospheres allows the preparation of large nanostructured samples. This technique limits the shaping to only circular dot and antidot geometries which can be obtained in a hexagonal close-packed configuration.

Another prospective field for research and application of magnetic nanostructures is the fabrication and investigation of magnetic nanoparticles for biomedical applications. Magnetic nanoparticle hyperthermia (MNH) treatment of tumors is at an advanced stage of development; it has been through phase I human clinical trials and is currently being tested in phase II in combination with other therapies. Currently the use of MNH for the treatment of tumors is restricted by the heating performance of the available nanoparticle ferrofluids. Although a massive amount of important biochemical and clinical work is also required to develop this therapy, the heating issue is fundamental and must be solved. Of course, this is just the start of the process, as the magnetic nanoparticles must be made biocompatible, hidden from the immune system, targeted, tested in vivo, etc., but it is clear that MNH will be able to make significant strides towards becoming a stand-alone treatment, and that it is potentially a very low morbidity and generic therapy.

This book is intended to provide a review of the latest developments and the fundamental concepts in the above-mentioned fields of research and application of nanostructured magnetic materials as well as in the emerging fields of magneto-electronics and spintronics. The idea for this book was born at the Fifth International Conference on Nanoscale Magnetism (ICNM-2010) held on September 28–October 2, 2010 in Gebze-Istanbul, Turkey. The meeting was organized by the Department of Physics of the Gebze Institute of Technology (GIT). The scope of the contributions extends from fundamental magnetic properties at the nanometer scale to fabrication and characterization of nanoscale magnetic materials and structures as well as the physics behind the behavior of these structures.

We would like to thank all the authors for their contributions. We also acknowledge the great efforts of our collaborators and research fellows from the Department of Physics and Nanomagnetism and Spintronics Research Center (NASAM) of GIT and others who made major contributions to the organization of the ICNM-2010 Conference and made this publication possible. We are very grateful to Prof. C. Ascheron for his great support, help, and patience during the publishing of this book.

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