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FUNDAMENTALS AND
APPLICATIONS OF
MAGNETIC MATERIALS



KANNAN M. KRISHNAN

Fundamentals and Applications of Magnetic Materials

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FUNDAMENTALS AND APPLICATIONS OF MAGNETIC MATERIALS

To

Appa

Who so much wanted for me to write a book, but did not live long enough to see this one

Amma

Always a source of love, inspiration, and support

The teachers who have influenced me the most

Late Mr. T.B.V. Subhramanyam (HPS)

Professor H.S. Mani (IITK)

Late Professor L. Falicov (UCB)

Late Professor G. Thomas (UCB)

Who, hopefully, see some of themselves in this book

Generations of students at UCB and UW

For keeping me honest

and

M.N.

For simply being the magnet in most of my adult life

Preface

Magnetism is subtle in its manifestations. Driven electronically, it is weak compared with electrostatic interactions. Quantum mechanical in nature, its origin is in the Pauli exclusion principle and the existence of electron spin. However, it is also known for a variety of both classical and quantum mechanical effects, arising from both short- and long-range forces, and is widely associated with “microstructure” or the morphological arrangements of magnetic moments (domains), as well as phases, grains, or individual atoms themselves. These are, in part, the reasons for the richness of structures and properties encountered in magnetic systems from which various useful technological and biomedical applications arise. These are also, in part, the reasons why the magnetic behavior of materials is poorly understood and many fundamental questions remain unanswered.

This book provides a comprehensive discussion of magnetism, magnetic materials, and related applications. The logical train of thought progresses in four parts from physics of magnetism (§1–5), magnetic phenomena in materials (§6–8), size and dimensionality effects (§9–10), and applications (§11–14). Beginning with a description of magnetic phenomena and measurements on a macroscopic scale, this is followed by discussions of intrinsic and phenomenological concepts of magnetism, such as electronic magnetic moments, and classical, quantum, and band theories of magnetic behavior. It then covers ordered magnetic materials, emphasizing their structure-sensitive properties, and magnetic phenomena, including magnetic anisotropy, magnetostriction, and magnetic domain structures and dynamics. There then follows a comprehensive description of imaging methods to resolve magnetic microstructures (domains), along with an introduction to micromagnetic modeling. Size (small particles) and dimensionality (surface and interfaces) effects—the underpinnings of nanoscience and nanotechnology, that magnetism brings into sharp focus—are then explored in some detail. The hallmark of modern science is its interdisciplinarity and hence, after covering the required background material to establish a solid foundation, the second half of the book discusses in substantial depth, with extensive bibliography, information technology, spin electronics—encoding information using the electron spin state—and the future of biomedicine, via recent developments in magnetism. Modern materials, with tailored properties, require careful synthetic and characterization strategies; the book also includes relevant details of the chemical synthesis of small particles and the physical deposition of ultrathin films. In addition, details of state-of-the-art characterization methods and summaries of representative families of materials, including tables of properties, where appropriate, are presented. Finally, CGS equivalents (to SI) are regularly inserted,

in the hope that if one were to be referring to works of a recent antiquity this feature would be useful.

Overall, the text is comprehensive and written with readers of different backgrounds in mind. It is based on more than two decades of teaching this material, and offers a focus that is not easily available elsewhere. The introductory subject matter, covered in the early chapters, does not assume any knowledge of magnetism and is presented carefully with adequate exercises to serve as a useful text, particularly for students of applied magnetism. The target readership is wide, and the text would be a useful addition to lecturers of senior undergraduate courses in physics, engineering, materials science, biology and bioengineering, radiology and medicine, and of graduate courses in these disciplines. In addition, research students, post-doctoral fellows, supervisors, and those crossing over from physics and engineering to biology and medicine, or vice versa, would find this text to be an excellent reference.

This book has grown out of courses taught at the University of California, Berkeley and the University of Washington, Seattle. It began in the early 1990s, at UC, Berkeley, as a set of notes for a one-semester (16 weeks) course, for both undergraduate seniors and graduate students, in various science and engineering disciplines. Lectures over the first 12 weeks covered essential concepts in §1–7, §9, and §11, followed by selective discussions of information storage technologies (§14), spin electronics (§13), and other applications by industry experts and student presentations. Subsequently, I also offered a more advanced one-semester graduate course at UCB emphasizing the second half of the book (§8–14). Such a two-semester course will do proper justice to the subject matter at hand, and the book is ideally suited for it. Since 2001, at the University of Washington, Seattle, I have been teaching a one-quarter (10 weeks) version of this course. This is much more challenging, not only because of the limited time, but also due to the addition of newer topics, such as developments in nanotechnology (§9–10), applications in biology and medicine (§12), and spintronics (§13). The best way to teach this subject in a single quarter is to selectively discuss the important concepts (§1–7), depending on student background, in eight weeks, and in the remaining two weeks give an elementary overview of the biomedical (§12) or physical (§11, §13, and §14) applications of magnetic materials based on student interest. Needless to say, this book encompasses much more than these courses.

In writing this book, in addition to my teachers to whom this book is dedicated with gratitude, I have benefitted immensely from various colleagues who most generously gave of their time in reviewing chapters, particularly in their areas of expertise. I thank them most sincerely. In alphabetical order they are: Dr. Samuel Bader (§10), Professor Yuping Bao (§12), Professor Xavier Batlle (§9), Professor John Chapman (§1–4), Dr. Peter Fischer (§7–8), Dr. R. M. Ferguson (§12), Dr. Emad Girgis (§13), Professor Erol Girt (§14), Dr. Axel Hoffmann (§13), Professor Albrecht Jander (§1), Dr. Samuel Jiang (§11), Professor Laura Henderson-Lewis (§2, §5), Professor Anil Kumar (§6), Professor Amilcar

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Kannan M. Krishnan
Seattle, April 2016

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