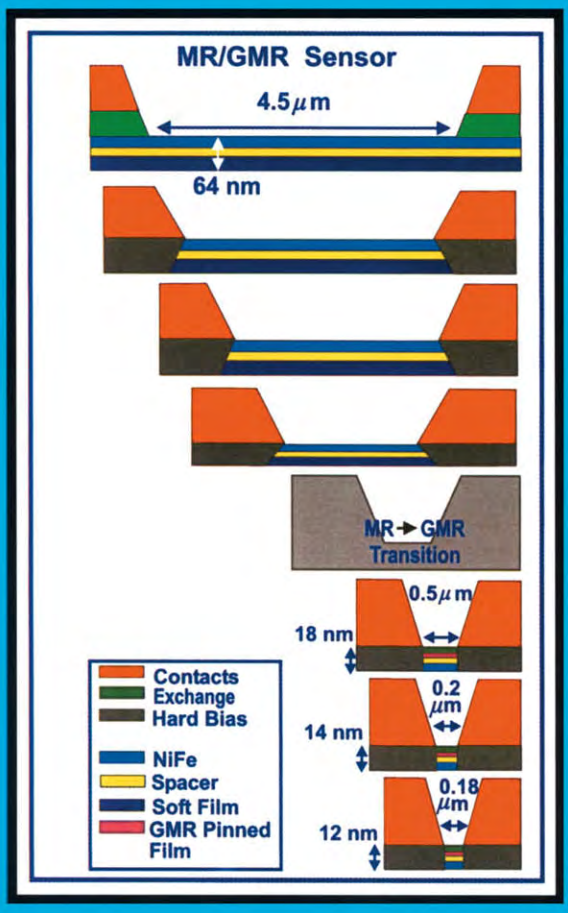
MAGNETO-RESISTIVE and SPIN VALVE HEADS

Fundamentals and Applications

Second Edition



John C. Mallinson

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Second Edition

Academic Press Series in Electromagnetism

Edited by
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COLLEGE PARK, MARYLAND

This volume in the Academic Press Electromagnetism series is the second edition of the book on magneto-resistive heads. This book is written by John C. Mallinson, who is one of the leading experts worldwide in the area of magnetic recording. He is well known and highly regarded in the magnetics community for his many important contributions to the field of magnetic data storage as well, as for his well-written and influential books on magnetic recording.

This second edition of his previous book on magneto-resistive heads reflects the phenomenal and explosive progress in magnetic storage technology where anisotropic magneto-resistive heads were quickly displaced by giant magneto-resistive heads, spin valves. Naturally, this edition contains many newly written chapters related to giant magneto-resistive heads. These chapters cover such new topics as synthetic antiferromagnet and ferrimagnet multilayer technology, magnetization fluctuation noise in small giant magneto-resistive heads, colossal magneto-resistance and spin dependent tunneling phenomena and their relevance to the future development of magnetic recording.

This is a short and concise book that nevertheless covers an extraordinary amount of technical information. The salient features of this book are its clarity, brevity, straightforward and "nonmathematical" manner of presentation with strong emphasis on underlying physics, unique historical perspectives on the field of magnetic recording.

I maintain that this book will be very attractive as a clear and concise exposition of magneto-resistive heads. As such, it will be a valuable reference for beginners and practitioners in the field. Electrical and material engineers, applied physicists, experienced developers of magnetic recording systems and inquiring graduate students will all find this book very informative.

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This book is dedicated to my wife, Phebe,
who once again inspired me to put pencil to paper
and did all the word processing.

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Preface to First Edition

In 1968, the Ampex Corporation Research Department hired a recently graduated doctoral student from the Massachusetts Institute of Technology named Robert P. Hunt. His initial assignment was quite simple: "Find something new and useful in magnetic storage technology." Shortly thereafter, Bob Hunt invented the magneto-resistive head (MRH).

I had the privilege of sharing an office with Bob Hunt and not only witnessed his invention but also provided the first analysis of the output voltage spectrum for both horizontal and vertical unshielded magneto-resistive heads. I have followed MR technology closely in the ensuing 27 years and this book is the result.

Of greater importance is the fact that the office immediately adjacent to mine at Ampex Research was occupied by Irving Wolf, the inventor of the "Wolf" permalloy electroplating bath. When asked by Bob Hunt if he could fabricate a magneto-resistive head, Irving Wolf replied, "Certainly, I'll make it out of evaporated permalloy." This was, indeed, a remarkable piece of serendipity. It is quite possible that, had Bob Hunt and Irv Wolf not been in such close proximity, there would be no MRHs even today. Not only did the first MRHs use permalloy as the sensor, but all MRHs manufactured in large quantities to this day also use permalloy. Moreover, it is likely that most of the advanced MRH designs now being proposed will also use permalloy.

The intent of this book is to introduce the reader to the principal developments in MRH technology that have occurred since Bob Hunt's initial work. To make this book self-contained, Chapter 1 contains a review

of the basics of magnetic materials and magnetism and Chapters 2 and 3 cover the writing process and the usual inductive reading process in magnetic recording, respectively. The anisotropic magneto-resistive effect and the unique properties of permalloy are discussed in Chapter 4.

To achieve linear operation with low harmonic distortion, the MR sensor must be magnetically biased with a vertical bias field. Additionally, a horizontal bias field is usually applied to keep the magnetic state of the MR sensor stable. The principal techniques for producing these biasing fields are the subjects of Chapters 5 and 6.

In Chapter 7, the output voltage spectra and isolated written transition output pulse shapes of Hunt's horizontal and vertical MRHs are reviewed. A similar analysis of the very commonly used "shielded" MRH follows in Chapter 8. Here, the important fact is demonstrated that the output voltage spectral shape and isolated pulse shape of the shielded MRH and an ordinary inductive read head are almost identical.

Alternative designs for MRHs in which the MR element is incorporated into the structure of thin-film ring heads are considered in Chapter 9. These types of MRHs are often called "yoke-type" or "flux-guide" designs.

Considerable interest exists in the performance characteristics of MRHs which have two MR sensors. Depending on the directions of magnetization, the current, and the external voltage sensing connections to these double-element heads, they are called a variety of rather confusing names such as gradiometer, dual-stripe, and dual-magneto-resistive heads. These differences and their relative performance advantages and disadvantages are the topic of Chapter 10.

In Chapter 11, the output voltages of a single-element shielded MRH and an inductive read head are studied in ways that lead to a particularly simple and direct way of comparing their performance.

An entirely new physical phenomenon called the giant magneto-resistive (GMR) effect was discovered in 1987. In Chapter 12, the basic physics of this phenomenon is outlined and, in Chapter 13, a proposed design for some giant magneto-resistive heads (GMRHs) is discussed. It is expected that GMRHs will produce output voltages greater by perhaps a factor of 5 than those of conventional anisotropic MRHs.

The penultimate chapter contains a step-by-step simplified design sequence for a single-element shielded MRH. This material is included because it demonstrates in a straightforward fashion precisely which

physical phenomenon controls each of the principal dimensions of the MR sensor and the MR sensor-shield "half-gaps."

The last chapter is devoted to system considerations such as read amplifier designs and the signal-to-noise ratio of MRHs. Finally, conclusions concerning the significance of MRHs in future high-density digital recorders are offered.

An appendix which contains a listing of the defining equations and a table of conversion factor for cgs–emu and MKS-SI magnetic units is provided. Despite the fact that virtually all physicists and electrical engineers in the world are trained to use MKS-SI, the magnetic storage industries in the United States and Japan continue to use cgs–emu, and this convention is followed in this book. In my opinion, the preference for one convention over another is an unimportant matter of taste.

Most of the material in this book is presented in a nonmathematical manner. Thus there are no mathematical analyses or derivations. On the other hand, the results of such analyses and derivations are used extensively. My belief is that most readers are not interested in detailed mathematical formalism and often find that copious mathematical detail often acts to obscure the intuitive obviousness of the underlying physics. The lack of mathematics should not, however, lead the reader to suppose that this is an elementary exposition. On the contrary, the aim is to lead the reader, in a straightforward fashion, to a high level of scientific understanding of MR materials and heads.

Finally, my hope is that this book will prove enjoyable and fascinating to read. Even after spending the last 35 years in magnetic recording research and theory, I find the seemingly unending inventiveness of my industrial colleagues both amazing and glorious. I hope that this book helps others to share in this rich and fascinating field.

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Preface to Second Edition

When I wrote the first edition of this book in 1994, there was no reason to suppose that anisotropic magneto-resistive heads (AMRHs) would become obsolete in the near future. By 1997, however, giant magnetoresistive heads (GMRHs) were beginning to be installed in hard-disk drives and by 1998 essentially all disk drives used GMRHs. The GMRH was invented, in the early 1990s, at IBM Research and the name "spin valve" was soon adopted, presumably in analogy with the British nomenclature for an electronic or vacuum tube, a valve. Spin valves displaced AMRHs because, with little added complexity, they produce output voltages about 4–5 times greater.

The predominance of GMR spin valves has rendered the first edition of the book out-of-date because it contained but two short chapters on the subject. This second edition redresses that deficiency by including seven chapters of new material devoted exclusively to GMR spin valves. Almost all the AMRH material found in the first edition has been retained, but it has been extensively revised and edited in order to make it relevant to the present-day applications of AMRHs to digital tape recording.

The book commences, as before, with a chapter on the fundamentals of magnetism and magnetic materials. This is followed by a review of the basics of the writing process in Chapter 2 and the inductive reading process in Chapter 3. The anisotropic magneto-resistive effect, first discovered in 1857, is introduced in Chapter 4. The giant magneto-resistive effect, first discovered as recently as 1987, is treated in great detail in Chapter 5.

Chapters 6 and 7 cover all the basic methods that can be used to produce the vertical (transverse) and horizontal (hard) magnetic biasing fields, respectively. Bias fields are necessary for the proper operation of both AMRHs and GMRHs. The original unshielded horizontal and vertical AMRHs invented at Ampex in 1969 are analyzed in Chapter 8.

All magneto-resistive heads are operated today between shields of high-permeability material in order to achieve narrower output pulses. The behavior of shielded single magneto-resistive heads is treated in Chapter 9.

Chapter 10 introduces the basic structure of a simple spin valve and analyzes its giant magneto-resistance versus magnetic field characteristics. All new material is presented in Chapter 11, where many techniques used to enhance the performance of spin valves are discussed. The impressive-sounding synthetic antiferromagnet and ferrimagnet multilayer technology is explained in Chapter 12. This is followed, in Chapter 13, by a review of the phenomenon of antiferromagnet upsets and the strategy employed in a disk drive to recover from an upset. Not only is all the material in Chapters 11, 12, and 13 new, but it also was unknown at the time of the first edition.

The material in Chapter 15, flux-guide and yoke-type MR heads, will be principally of interest to practitioners of digital tape recording and is essentially unchanged from the first edition. Similarly, the subject of double-element MRHs, which can be either AMR or GMR, is covered in Chapter 16. The principal attraction of double-element heads is the suppression of the so-called thermal asperities (TAs) that are due to rapid fluctuations in the magneto-resistive sensor film's temperature caused by magnetic recording media proximity effects.

A comparison of both AMR and GMR shielded and inductive reading heads is undertaken in Chapter 16. Both the small signal sensitivities and the peak digital output pulse voltages are treated.

Simplified design exercises for a shielded AMRH and a shielded GMRH are the subject of Chapters 17 and 18, respectively. These design exercises will be found instructive because they demonstrate how the chosen cgs-emu units used throughout the book work, because they show what physics determines the principal dimensions and performance of the AMR and GMR heads, and finally, because they show that in order to attain optimum performance for an MRH it must be designed optimally to match the transitions written in the recording medium. A forecast of GMR spin valve design from today's 10–20 gigabit/in.^{2} heads to those projected to be suitable for 100 gigabit/in.^{2} is included.

Chapter 19 is devoted to a review of the two types of reading amplifiers that are used and to an analysis of the signal-to-noise ratio of MRHs. In the increasing small GMRHs, thermal fluctuations of the direction of the magnetization cause noise in addition to the familiar Johnson noise due to the conduction electrons' fluctuations. Both of these noise powers are derived from first principles and are then analyzed with the conclusion that the magnetization fluctuation noise will become a serious limitation in spin valves designed to operate at 100 gigabit/in.^{2}.

Colossal magneto-resistive (CMR) and electron spin tunneling heads, two potential candidates to eventually replace GMR spin valves, are considered in Chapter 20. The conclusion is that whereas the outlook for CMR is poor, the electron spin tunneling or magnetic tunneling junction (MTJ) heads appear both feasible and promising.

Finally, in Chapter 21, the extreme sensitivity of MRHs to accidental electrostatic discharges (ESDs) and the standard measures that may be taken to minimize the likelihood of ESD damage are reviewed.

An appendix which contains a listing of the defining equations and a table of conversion factors for cgs-emu and MKS-SI magnetic units is provided. Despite the fact that virtually all physicists and chemical engineers in the world are trained to use MKS-SI, the magnetic storage industries in the United States and Japan continue to use cgs-emu, and this convention is followed in this book. In my opinion, the preference for one convention over another is an unimportant matter of taste.

As in the first edition, the material in this book is presented in a basically nonmathematical manner. Thus there are no mathematical analyses or derivations. On the other hand, the results of such analyses and derivations are used extensively. My belief is that most readers are not interested in detailed mathematical formalism and usually find that copious mathematical detail acts to obscure the intuitive obviousness of the underlying physics. For example, the analysis of magnetization fluctuation noise in Chapter 19 is accomplished directly in only two algebraic operations. Rather than involving the reader in the esoterica of partition functions or the fluctuation-dissipation theorem, I treat the subject as an obvious consequence of the well-known equipartition theorem of thermodynamics. The lack of mathematics should not, however, lead the reader to suppose that this is an elementary exposition. On the contrary, the aim is to lead the reader, in a straightforward fashion, to a high level of scientific understanding of MR materials and heads.