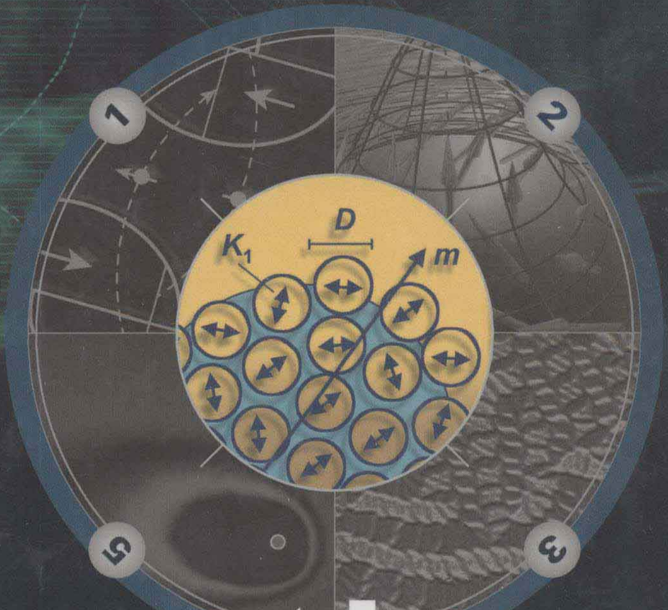
HANDBOOK OF

Magnetism

AND ADVANCED MAGNETIC MATERIALS



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Fundamentals and Theory

Micromagnetism

Novel Techniques for Characterizing and Preparing Samples

Novel Materials

Spintronics and Magnetoelectronics

Editors-in-Chief

HELMUT KRONMÜLLER

STUART PARKIN

WILEY

Handbook of Magnetism and Advanced Magnetic Materials

Volume 4 Novel Materials

Editors-in-Chief

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Magnetism and Advanced Magnetic Materials

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Foreword

Thanks to its fascinating properties in both macroscopic and atomic dimensions magnetism has attracted the attention of philosophers and scientists from ancient times to the present day. Greek philosophers such as Thales and Anaxagoras believed in the divine origin of magnets. Diogenes adopted a materialistic point of view and proposed a materials exchange between magnetite and iron, while the most advanced hypothesis was propagated by Empedokles, Epicurus, and Democritus, who explained the long-range interactions between magnets by an effluvia transporting a form of dynamic field.

It took two millennia until, in the Age of Enlightenment, the discoveries of Coulomb, Oersted, Faraday, and Maxwell gave for the first time a quantitative description of the long-range interactions between magnets on the basis of electromagnetic fields. It was the discovery of the magnetic properties of the electron by Niels Bohr, Uhlenbeck and Goudsmit, which finally gave an explanation of magnetic properties on the atomic scale. These findings may be considered as the starting point of modern research on fundamental magnetic properties and the development of high-quality magnetic materials. The conventional theory of magnetism is mainly based on Weiss's molecular field theory, whereas the modern theory of magnetism, pioneered by Heisenberg and Dirac, uses quantum-mechanical descriptions based on the properties of exchange interactions. It fell to, however, the scientists of the second half of the twentieth century to the present day, to arrive at a quantitative first-principles description of magnetically ordered spin systems and their excited states.

Since the first application of the famous oxide, magnetite, as a compass in ancient times in China, and from the early Middle Ages in Europe, magnetic materials have become an indispensable part of our daily life. In many ways, the modern world is an automated one, which uses ferro- and ferrimagnetic materials in all important technical fields. Magnetic materials are used in all dimensions from the nanoscale for nonvolatile high-density recording and sensor applications to the macroscale for high-voltage transformers, high-energy generators, and levitation mechanisms. This widespread use of magnetic materials has initiated increasing research in academia, national research laboratories, and industry. Despite the fact that development in some areas of magnetic materials research is so rapid that publications can only present the current state of the art, the articles in this handbook present critical, fundamental information, which will guide and inform research efforts across the field.

The *Handbook of Magnetism and Advanced Magnetic Materials*, consisting of five volumes, presents in the form of review articles a broad range of contributions focusing on both fundamental properties and the development of spin-ordered materials with outstanding magnetic properties. The progress made during the last few decades in computational sciences and in advanced materials preparation techniques, has dramatically improved our knowledge of the fundamental properties, and increased our ability to produce materials with tailored properties in nanoscale dimensions. If one considers the most promising new research directions in modern solid-state physics and materials science it becomes clear that phenomena related to the individual electronic spin moment play an increasingly important role. Spintronics, the spin Hall effect, qubits, and spin-torque interactions are fascinating examples of such new research directions. All these new developments are very closely related to low-dimensional electron systems and the progress made in nanosciences, which are among the main topics of the present handbook.

Magnetic materials used so far have, in general, been optimized with respect to only *one* outstanding property, such as, for example, high permeability, high coercivity, or high remanence. For many modern applications, however, it is a prerequisite that a whole spectrum of properties be combined and optimized. Modern technologies in material science allow the realization of multifunctional materials not accessible only a few years ago. Examples of such developments are the combination of ferromagnetic and semiconducting properties with tunable Curie temperatures and high-permeability nanocrystalline alloys with low conductivity and Curie temperatures considerably above room temperature.

Our present knowledge of magnetism is reviewed in the five volumes of this handbook, with over 120 articles written by leading experts in the field, covering the fundamentals of electron theory of spin-ordered materials, the basics and applications of the continuum theory of micromagnetism, and the development of new measuring and sample-preparation techniques. Furthermore numerous novel multifunctional materials such as intermetallic compounds, ferromagnetic semiconductors, Heusler alloys, half-metals, manganites, pnictides, and molecular magnets, as well as bio-magnetic materials are discussed in detail in the handbook. Recent developments in magnetoelectronics and spintronics are also addressed in numerous articles. These two research fields are rapidly growing owing to their high potential for nonvolatile, high-density magnetic recording. The bases for these applications, as outlined in several articles, are the giant magnetoresistance effect, the spin-dependent tunneling effect, the method of spin-injection, and magnetization processes induced by spin-torque interactions.

This handbook summarizes our knowledge of modern magnetism gained during the last few decades, and as such will be a helpful source of new ideas and future developments for physicists, chemists, material scientists, electrical engineers, and applied mathematicians. In particular the development of nanoscale systems including thin films and multilayered systems has led to new phenomena and novel applications which accelerate multidisciplinary cooperation between different groups of scientists. In addition, therefore, this handbook may also be considered as a bridge between basic scientific understanding and important technological developments.

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July 2007

Preface to Volume 4

The *Handbook of Magnetism and Advanced Magnetic Materials* provides an up-to-date review of our present understanding of the fundamental properties of spin-ordered solids and their applications for high-quality magnetic devices. Since the first description of the industrial production of compass needles by the father of magnetism, William Gilbert, in his famous book *De Magnete*, magnetism has penetrated all important technical fields including electrical energy transport, high-power electromotors and generators, telecommunications, micromechanical automation, navigation, aviation and space operations, magnetocaloric refrigeration, nondestructive testing, computer sciences, high-density recording, biomagnetism, and medicine as well as numerous household applications. All these applications have become possible because of the dramatic increase in our knowledge and understanding of the fundamental properties of spin-ordered materials and the discovery of numerous novel materials. The discovery of new effects based on spin ordering has promoted the development of a multitude of new applications. Examples of this are the giant magnetoresistive effect, the spin-dependent tunneling effect, and the spin-torque effect. The development of novel electron theoretical methods for the treatment of spin-dependent multiparticle interactions now allows predictions on the electronic states of spin-ordered alloys, intermetallic compounds, and investigations of the effect of dimensionality. Parallel to the progress in theory, which is also based on the availability of increasing computational facilities, remarkable progress concerning novel magnetic materials has taken place during the last few decades. Whereas in the first half of the twentieth century, iron–carbon steels, iron–silicon alloys, permalloy, and alnico played the major role for hard and soft magnetic materials, the second half of the twentieth century and the beginning of the twenty-first century were characterized by the discovery and development of numerous materials with fascinating electronic and magnetic properties. Well-known examples for this are the intermetallic compounds of rare earth and transition metals, the amorphous alloys, heavy Fermion systems, half-metals, and the tremendous field of thin-film multilayers with their exciting properties of giant magnetoresistances and spin-dependent tunneling phenomena.

Since the middle of the twentieth century, the progress made in the field of magnetism may be attributed to the following developments:

1. Many-body electron theoretical calculations of spin-ordered ground states and their thermally and optically excited states including magnetic phase transitions, spin-dependent transport problems, and the interaction between magnetism and superconductivity.
2. Continuum theoretical micromagnetism of spin structures and the dynamics of magnetization processes on both nano- and micrometer scales.
3. The development of new measuring techniques: X-ray and neutron diffraction methods, X-ray magnetic circular dichroism, spin-polarized photoemission and spin-polarized electron spectroscopy, Lorentz microscopy, electron holography, and magneto-optical methods.
4. Advanced material preparation techniques ranging from the production of multilayers by molecular beam epitaxy and sputtering techniques to patterning and self-assembling techniques as well as the preparation of high-quality single crystals.
5. Discovery and development of novel ferro- and ferrimagnetic materials with extraordinary physical properties. Intermetallic compounds with coercivities from 1 to 5 T and amorphous and nanocrystalline alloys with permeabilities up to 10^6. Diluted ferromagnetic semiconductors and half-metallic Heusler alloys play an increasing role in spintronics and magnetoelectronics. Heavy Fermion systems and magnetocaloric and magnetic shape memory alloys have become highly active research fields.
6. The development of magnetoelectronics and spintronics, which are the most rapidly growing research fields with attractive applications for high-density, nonvolatile magnetic recording systems. The phenomena of spin-torque effects, spin-dependent transport of carriers, and spin-dependent tunneling are the basis for future progress.

In the second half of the twentieth century our knowledge of magnetic materials increased enormously. Conventional ferromagnetic materials, such as iron–carbon steel, permalloy, Fe–Si, and alnico, as well as magnetically soft and hard ferrites, which were the leading magnetic materials up to the 1960s, have to some extent been replaced by novel, more efficient, materials. Even though Fe–Si still retains its importance in the fields of transformers and electrical machines, there now exist amorphous and nanocrystalline alloys with giant permeabilities of 10^5-10^6, which are used in many applications of soft magnetic cores, high-performance electrical machines, and the rapidly expanding field of magnetic sensors. A similar situation has developed in the field of hard magnetic materials, where the discovery of intermetallic compounds of rare earth and transition metals has led to supermagnets with coercive fields from 2 to 8 T and energy products up to $500\,\mathrm{kJ\,m^{-3}}$. The magnitude of these properties exceeds what is observed in alnico by a factor of five.

This progress has been achieved largely by the development of new preparation techniques, for example, the use of rapid quenching methods with quenching rates of $10^6\,\mathrm{K\,s^{-1}}$ has allowed the preparation of amorphous and nanocrystalline magnetic alloys, and the liquid-phase sintering technique has enabled supermagnets to be produced. Thin-film preparation methods based on sputtering and molecular-beam epitaxy have made it possible to generate artificial systems of complex multilayered films. The microstructure and perfection of these layered systems have been continuously improved over recent decades, leading to systems with tailored and reproducible magnetic properties. Remarkable developments have also taken place in the formation of small magnetic clusters and thin wires, and the corresponding formation of self-ordered systems of small particles. In particular, the role of nanocrystalline particles in medicine and biology, and the techniques for their preparation, have become important research fields.

Owing to the rapidly developing fields of magnetoelectronics and spintronics, the demand for ferromagnetic semiconductors and materials with a high degree of polarization of the conduction electrons, such as Heusler alloys, has become very strong. Ferromagnetic oxides and diluted oxides alloyed with magnetic transition metals have, therefore, become an important class of materials. The combination of novel materials and novel, advanced preparation techniques has led to numerous discoveries of outstanding magnetic effects, such as the exchange bias effects which play a role in spin valves, and giant magnetoresistance film systems.

The progress made over recent decades in the development of novel materials, in combination with new preparation techniques, is reviewed in this volume, which is presented in eight parts.

The first part deals with advanced soft magnetic materials based on amorphous nanocrystalline and improved Fe–Si alloys composed of transition metals and metalloid elements. These materials are characterized by giant permeabilities and minimal energy losses. Indeed, the reduction of wasted energy is one of the main aims of the research into such materials.

The second part is devoted to hard magnetic materials based on rare earth–transition metal intermetallic compounds. The leading compounds in this field are the binary SmCo compounds based on $SmCo_5$ and Sm_2Co_{17}, and the ternary REFeB compounds based on $RE_2Fe_{14}B$. One can obtain energy products of $300\,\mathrm{kJ\,m^{-3}}$ for SmCo compounds and of around $500\,\mathrm{kJ\,m^{-3}}$ for REFeB compounds. These alloys exhibit interesting features including hardening mechanisms, which are attributed to the nucleation mechanism in the case of $SmCo_5$ and $Nd_2Fe_{14}B$, and to the domain-wall pinning mechanism in the case of Sm_2Co_{17}. For these magnets the microstructures, which are discussed in detail, play an important role.

The third part reviews semiconducting magnetic ferrites, diluted oxides, and the alloys of half-metals based on Heusler alloys. These materials are becoming increasingly important for the development of high-density recording systems in the field of spintronics. Although materials such as Fe_3O_4 and Heusler alloys are well-known ferromagnets, their electronic structure has been analyzed only recently using the advanced theoretical methods also described in Volume 1. In contrast, many unanswered questions remain with regard to diluted oxides, where the nature of the magnetic coupling mechanism has still to be explained, and possible applications further investigated and developed.

The fourth part deals with ferro- and ferrimagnetic amorphous and nanocrystalline particles. Nanoparticles have many important applications in ferrofluids, catalysts, drug delivery, biotechnology, and magnetic resonance contrast imaging. Another very active area of research into magnetic particles is related to magnetic recording, since the microstructural and magnetic properties may be controlled with remarkable precision. In particular the formation of Fe–C, FePt, and CoPt particles by different methods is described, as is the formation of nanostructures by template-mediated reactions for magnetite and FePt.

The fifth part considers micro- and nanowires produced by rapid quenching from the melt, and by electrochemical deposition on an alumina template. Microwires, which may be considered as one of the magnetically softest materials, reveal bistable behavior for large positive magnetostriction and giant impedance effects for vanishing magnetostriction. These properties make microwires highly suitable for advanced sensor applications. Nanowires produced within the ordered pores of an alumina template may be used as a recording system with recording densities in the terabit range per square inch. Compared with conventional techniques, this latter method has the advantage of being able to produce self-ordered assemblies of magnetic dots over dimensions of centimeters. This part also reviews magnetic carbon nanostructures. For these structures, from a basic research viewpoint, the interesting question is whether s and p electrons may be responsible for magnetic ordering processes.

The sixth part is related to special properties of selected thin-film systems. In a chapter on ultrathin magnetic films the three major deposition techniques are described: thermal deposition, laser pulse deposition, and sputtering. The magnetic properties of ultrathin films are discussed in some detail, and the origin of the magnetocrystalline anisotropy and the role of surface effects are outlined. Of special importance are hard magnetic films of CoPt and FePt because they are considered as a possible basis for ultrahigh-density magnetic recording. The fundamental properties of hard magnetic films are described and their potential applications are discussed.

The seventh part reviews materials with outstanding magnetic properties. Magneto-optical, magnetocaloric, magnetostrictive, and shape memory materials are the main focus of these articles. Magneto-optical effects are used in a wide range of applications from domain observations to magnetic recording. The properties of metallic and semiconducting magneto-optical materials are described in detail. Magnetocaloric materials have become important due to the need to reduce the effects of vapors from chlorofluorocarbons and hydrofluorocarbons, which act as highly active poisons deteriorating the ozone layer and enhancing global warming. The most interesting of today's materials, such as GdSiGe and the chalcogenides and pnictides are discussed in this part. Also included in this part are magnetostrictive and shape memory materials. Two types of magnetostriction are predominantly considered here: the so-called Joule magnetostriction, related to a change in the orientation of the magnetization and based on the spin-orbit interaction, and the large field-induced strains in shape memory alloys such as NiMnGa, which are related to a twin-boundary motion.

The heavy Fermion alloys have some outstanding properties, such as the interplay they exhibit between magnetism and superconductivity. These alloys, which have strong electronic correlations, are characterized by electrons with extremely large effective masses ($1000m_e$). The most important topics discussed here are the relations between magnetism and superconductivity, and the behavior at $T = 0$ at the quantum critical region. In addition, molecular magnets such as the Mn_{12} acetate and the Fe_8 oxo-hydroxo clusters are discussed as materials suitable for the investigation of quantum phenomena of magnetic systems. Thermally activated magnetization processes based on tunneling phenomena are also described.

The eighth part discusses the biomagnetic applications of magnetic materials. There is a strong and growing interest in the detection of biomolecular materials, which is based on the interaction between biomolecules. This part illustrates the advantages of using magnetic biosensors. The applications of magnetic particles in medicine and biology are today becoming more and more widespread due to the development of advanced techniques to produce high-quality ferri- or ferromagnetic particles. A multitude of applications of magnetic particles are described, ranging from the magnetic isolation of proteins and DNA molecules to magnetic drug delivery systems for tumor treatments and diagnostic applications.

This handbook has been compiled with the collaboration of an international advisory board whose distinguished members have invested their time to present a broad and deep spectrum of the most important activities in the field of magnetism, at the beginning of the twenty-first century. The continuous advice and support of the advisory board is highly appreciated. Their active motivation of the authors is one of the reasons for the successful completion of this handbook. Their patience and help in organizing the submission of articles of the highest standard are to be acknowledged. Without doubt too the publication of this handbook is the result of the active cooperation of all the authors. Their contributions should be considered as a solid foundation for further developments in the field of magnetism.

During the preparation of this handbook the cooperation of the editors with the staff of the Chichester offices of John Wiley & Sons over several years has been extremely effective and is appreciated. Questions concerning authors, and the layout of the handbook were discussed intensely to guarantee optimum solutions. Since the first meetings with David Hughes, Publishing Editor, a friendly and productive atmosphere has prevailed which helped in the completion of the handbook. The editors also acknowledge the cooperation of the Publishing Assistants and Project Editor who managed the continuous flow of information between the Chichester offices and the editors.

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Abbreviations and Acronyms

0D	Zero-dimensional
1D	One-dimensional
2D	Two-dimensional
2DBZ	Two-dimensional Brillouin Zone
2DEG	Two-dimensional Electron Gas
2DES	Two-dimensional Electron Systems
2DHG	Two-dimensional Hole Gases
2PPE	Two-photon Photoemission
3D	Three-dimensional
5-FU	5-Fluorouracil
a-MCMB	Activated Mesocarbon Microbead
AA	Asymptotic Analysis
AAF	Artificial Antiferromagnetic
AB	Aharonov–Bohm
ABS	Air Bearing Surface
ABS	Air-lock Braking Systems
AC	Alternating Current
ACP	Air Cushion Press
AD/DA	Analog-to-Digital/Digital-to-Analog
AF or AFM	Antiferromagnetic
AFC	Antiferromagnetically Coupled
AFI	Antiferromagnetic Insulator
AFM	Atomic Force Microscope/Microscopy
AFQ	Antiferroquadrupolar
AGFM	Alternating Gradient Force Magnetometer
AGG	Abnormal Grain Growth
AGM	Alternating Gradient Magnetometer
AHE	Anomalous Hall Effect
AI	Ab Initio
AII	Anisotropic Interion Interactions
AL	Atomic Layers
ALPS	Applications and Libraries For Physics Simulations
ALS	Advanced Light Source
AM	Amplitude Modulation
AM	Angular Momenta
AMMs	Anisotropic Molecular Magnets
AMR	Anisotropic Magnetoresistance
AMR	Anisotropic Magnetoresistive
AMS	Anisotropic Magnetostriction
ANNNH	Axial Next-nearest-neighbor Heisenberg Model
ANNNI	Anisotropic Next-nearest-neighbor Ising Model
AP	Antiparallel
APW	Augmented Plane Wave
AR	Andreev Reflection
AR	Aspect Ratio
ARAES	Angular Resolved Auger Electron Spectroscopies
ARM	Advanced Recording Model
ARPES	Angle-resolved Photoemission Spectroscopy
ARUPS	Angle-resolved Ultraviolet Photoemission Spectroscopy
ASA	Atomic Sphere Approximation
au	Atomic Units
AZC	Akulov–Zener–Callen
BA	Born Approximation
BAP	Bir–Aronov–Pikus
BARC	Bead Array Counter
BC	Boundary Condition
bcc	Body Centered Cubic
BD-BZS	Band Degeneration and Brillouin Zone Symmetry
BDF	Backward Difference
BEC	Bose–Einstein Condensation
BEEL	Ballistic Electron Emission Luminescence
BEEM	Ballistic Electron Emission Microscopy
BEM	Boundary Element Method
BEMM	Ballistic Electron Magnetic Microscopy
BEP	Beam Equivalent Pressure
BETS	Bis(ethylenedithio)tetraselenafulvalene
BFK	Brooks–Fletcher–Katayama
BGAs	Bulk Glassy Alloys
BGRIMM	Beijing General Research Institute of Metallurgy Mining

BHEM	Ballistic Hole Emission Microscopy
BHMM	Ballistic Hole Magnetic Microscopy
BIA	Bulk Inversion Asymmetry
BIG	Bismuth-substituted Iron Garnet
BIS	Bremsstrahlung Isochromat Spectroscopy
BLS	Brillouin Light Scattering
BM	Band Models
BMR	Ballistic Magnetoresistance
BPW	Bethe–Peierls–Weiss
BSE	Back Scattered Electron
BSS	Blankenbecler Scalapino Sugar
BVMSW	Backward Volume Magnetostatic Spin-Wave
BZ	Brillouin Zone
CA	Canted Antiferromagnet
CAICISS	Coaxial Impact Collision Ion Scattering Technique
CB	Coulomb Blockade
CC	Coupled Cluster
CCD	Charge-coupled Device
ccp	Cubic Close-packed
CCSD	Coupled Cluster Expansion With Singles And Doubles
CCT	Continuous Cooling Transformation
CD	Compact Disc
CE	Conduction Band Electron
CEF	Crystal Electric Field
CEF	Crystalline Electric Field
CESR	Conduction Electron Spin Resonance
CF	Correlation Function
CFCs	Chlorofluorocarbons
CFT	Conformal Field Theory
CFTR	Cystic Fibrosis Conductance Regulator
CGO	Conventional Grain-oriented
CI	Configuration Interaction
CIMS	Current-induced Magnetization Switching
CIP	Cold Isostatic Pressing
CIP	Current Flowing in the Plane
CIP	Current-In-Plane
CISP	Current-induced Spin Polarization
CJT	Cooperative Jahn–Teller
CLIO	Cross-linked Iron Oxides
CLM	Constrained Local Moment
CMD	Colossal Magnetodielectric
CMOS	Complementary Metal Oxide Semiconductor
CMP	Chemical–Mechanical Polishing
CMR	Colossal Magnetoresistance
CNR	Contrast-To-Noise Ratio
CNT	Classical Nucleation Theory
COI	Charge Ordered Insulating
COO	Charge/orbital Ordered
CP	Cross Polarization
CPA	Coherent Potential Approximation
CPGE	Circular Photogalvanic Effect
CPM	Classical Preisach Model
CPP	Current Perpendicular To Plane
CPP-GMR	Current Perpendicular To Plane Giant Magnetoresistance
CT	Charge Transfer
CTEM	Conventional Transmission Electron Microscopy
CTF	Contrast Transfer Function
CVD	Chemical Vapor Deposition
CW	Continuous Wave
CZ	Czochralski
DA	Disaccommodation
dc	Direct Current
DCA	Dynamical Cluster Approximation
DCD	Direct Current Demagnetization
DE	Damon and Eshbach
DE	Differential Equations
DE	Double-Exchange
DF	Density-functional
DFA	Density-functional Approximation
DFH	Digital Ferromagnetic Heterostructure
DFT	Density-functional Theory
DHO	Damped Harmonic Oscillator
dHvA	De Haas–Van Alphen
DL	Double Layer
DL	Double Lorentzian
DLD	Delay Line Detector
DM	Dzyaloshinsky–Moriya or Dzyaloshinskii–Moriya
DMFA	Dynamic Mean Field Approximation
DMFT	Dynamical Mean Field Theory
DMR	Density Magnetic Recording
DMRG	Density Matrix Renormalization Group
DMSs	Diluted Magnetic Semiconductors
DNP	Dynamic Nuclear Spin Polarization
DOF	Degrees of Freedom
DOS	Density of States
DP	D'Yakonov–Perel'
DPC	Differential Phase Contrast
DS	Domain State
DSC	Differential Scanning Calorimetry
DTA	Differential Thermal Analysis
DTPA	Diethylenetriaminepentaacetic Acid
DW	Domain Wall

DWBA	Distorted Wave Born Approximation
DWE	Direct Wiedemann Effect
DWMR	Domain Wall Magnetoresistance
DWR	Domain Wall Resistance
DWs	Domain Walls
EA	Edwards–Anderson
EB	Electric Bicycle
EB	Electron Beam
EB	Exchange Bias
EBL	Electron Beam Lithography
EC	Elastic Constant
ECF	Extracellular Fluid
ECV	Electrochemical Capacitance–Voltage
ED	Easy Direction
EDCs	Energy Distribution Curves
EDS	Energy Dispersive Spectroscopy
EDSR	Electric-Dipole Spin Resonance
EDX	Energy Dispersive X-ray
EELS	Electron Energy Loss Spectroscopy
EFA	Envelope Function Approximation
EFAN	Electrical Force-assisted Nil
EL	Electroluminescence
EL	Electron-Lattice
EM	Elastic Moduli
EM	Electromagnetic
EMDs	Easy Magnetization Directions
EMR	Extraordinary Magnetoresistance
EMTO	Exact Muffin-Tin Orbital
EOM	Equation Of Motion
EPMA	Electron Probe-Microanalysis
EPR	Electron Paramagnetic Resonance
EPS	Electronic Phase Separation
ESP	Equal Spin Pairing
ESR	Electron Spin Resonance
ETMs	Early Transition Metals
EV	Electric Vehicle
EW	Elastic Wave
EX-MS	Exchange Magnetostriction
EXAFS	Extended X-ray Absorption Fine Structure
EY	Elliott–Yafet
F	Ferromagnetic
FC	Field Cooling/Cooled
fcc	Face Centered Cubic
FCT	Face Centered Tetragonal
FD	Finite Difference
FDA	U.S. Federal Drug Administration
FDT	Fluctuation-Dissipation Theorem
FE	Ferroelectric
FE	Field Emission
FEA	Finite Element Analysis
FEG	Field Emission Gun
FEL	Free-Electron Laser
FEM	Finite Element Method
FET	Field Effect Transistor
FF	Fourier Filtering
FFLO	Fulde–Ferrell–Larkin–Ovchinnikov
FFT	Fast Fourier Transform
FI	Ferrimagnetic
FI	Ferromagnetic Insulating/Insulator
FIB	Focused Ion Beam
FIF	Ferromagnet-insulator-ferromagnet
FIS	Ferromagnet-insulator-superconductor
FL	Fermi Liquid
FLAPW	Full Potential Linearized Augmented Plane-Wave
FLEX	Fluctuation Exchange
FM	Ferromagnetic
FM	Frequency Modulation
FMM	Fast Multipole Method
FMM	Ferromagnetic Metallic
FMR	Ferromagnetic Resonance
FMS	Forced Magnetostriction
FMSA	Ferromagnetic Shape Memory Alloy
FMSs	Ferromagnetic Semiconductors
FO	Ferro-orbital
FOM	Figure Of Merit
FP	Fokker–Planck
FPE	Fokker–Planck Equation
FS	Fermi Surface
FS	Ferromagnetic Semiconductor
FSMAs	Ferromagnetic Shape Memory Alloys
FSSS	Fisher Sub Sieve Seizer
FT	Force Theorem
FT	Fourier Transform
fu	Formula Unit
FV	Fluctuating Valence
FVMSW	Forward-Volume Magnetostatic Spin-Wave
FWHM	Full Width at Half Maximum
FZ	Floating Zone
g-TMR	*g*-Tensor Modulation Resonance
GB	Grain Boundaries
GDCs	Giant Dielectric Constants
GE	General Electric
GFA	Glass-forming Ability
GGA	Generalized Gradient Approximation
GGG	Ga–Gd–garnet
GIND	Grazing Incidence Neutron Bragg Diffraction

GISANS	Grazing Incidence Small-Angle Scattering of Magnetic In-Plane Structures
GK	Goodenough–Kanamori
GMCE	Giant Magnetocaloric Effect
GMI	Giant Magnetoimpedance
GMR	Giant Magnetoresistance
GMR	Giant Magnetoresistive
GS	Ground-state
HAADF	High-angle Annular Dark-field
HAADF-STEM	High-angle Annular Dark-field Scanning Transmission Electron Microscopy
HAMR	Heat Assisted Magnetic Recording
HAs	Heusler Alloys
HAST	Highly Accelerated Stress Test
HB	Hubbard Band
HCC	Hepatocellular Carcinoma
hCG	Human Chorionic Gonadotropin
HDDR	Hydrogenation-Disproportionation-Desorption-Recombination
HDDs	Hard Disk Drives
HDs	Hard Disks
HEV	Hybrid Electric Vehicle
HF	Hard Ferrite
HF	Hartree–Fock
HF	Heavy Fermion
HF-EPR	High-Frequency Electron Paramagnetic Resonance
HFCs	Heavy-Fermion Compounds
HFCs	Hydrofluorocarbons
HGMS	High-Gradient Magnetic Separator
HGO	High Permeability, Grain-Oriented
HH	Heavy-Hole
HM	Half Metallic
HM	Hubbard Model
HMFs	Half Metallic Ferromagnets
HMM	Half Metallic Materials
HMMs	Hard Magnetic Materials
HMs	Hard Magnetic Materials
HREM	High-resolution Electron Microscopy
HRIR	High-reflectance Infrared Mirror
HRTEM	High-resolution Transmission Electron Microscopy
HRXRD	High-resolution X-ray Diffraction
HS	High Symmetry
HS	Hubbard-Stratonovich
HTI	High-temperature Incommensurate
HV	High Vacuum
HWHM	Half-Width at Half-Maximum
IBMP	Ion Bombardment Induced Magnetic Patterning
ICF	Interconfigurational
IEC	Interlayer Exchange Coupling
IETS	Inelastic Electron Tunneling Spectroscopy
IF	Interface
IHD	Intermediate to High Damping
IL	Interference Lithography
ILD	Isotropic Long-range Dipolar
IMEC	Interuniversitair Micro-Elektronica Centrum
IMERs	Immobilized Magnetic Enzyme Reactors
IMFP	Inelastic Mean Free Path
IMS	Immunomagnetic Separation
INESC–MN	Institute of Engineering of Systems and Computers – Microsystems and Nanotechnologies
INS	Inelastic Neutron Scattering
IPM	Interior Permanent Magnet
IPT	Iterated Perturbation Theory
IR	Irreducible Representation
IRM	Isothermal Remanent Magnetization
IRM	Isothermal Remanent Moment
IS	Irreducible Strain
ISR	Isotropic Short-Range
IWE	Inverse Wiedemann Effect
JASTEC	Japan Superconductor Technology
JT	Jahn–Teller
K	Kondo
KKR	Korringa–Kohn–Rostoker
KKR-CPA	Korringa–Kohn–Rostoker-Coherent Potential Approximation
KLM	Kondo Lattice Model
KR	Kerr Rotation
KTO	Kubic Tensor Operator
LA	Local Ansatz
LAFS	Law of Approach to Ferromagnetic Saturation
LAO	$LaAlO_3$
LBMO	$La_{0.7}Ba_{0.3}MnO_3$
LCCSD	Linearized Coupled-Cluster Expansion with Singles and Doubles
LDA	Local Density Approximation
LDOS	Local Density Of States
LED	Light-emitting Diode
LEED	Low Energy Electron Diffraction

LFL Landau–Fermi Liquid
LGW Landau–Ginzburg–Wilson
LH Left-hand
LH Light-Hole
LHMs Left-handed Materials
LKKR Layer Korringa–Kohn–Rostoker
LL Landau–Lifschitz
LL Layer-by-Layer
LLG Landau–Lifschitz–Gilbert
LLs Landau Levels
LMO $LaMnO_3$
LMTO Linear Muffin-Tin Orbital
LO Longitudinal Optical
LP Lifshitz Point
LPD Laser Pulse Deposition
LSCMO $La_{0.7}(Ca_{0.5}Sr_{0.5})MnO_3$
LSDA Local Spin Density Approximation
LSTP Low Standby Power
LT Low-temperature
LT-MBE Low-temperature Molecular-beam Epitaxy
LTI Low-temperature Incommensurate
LTMs Late Transition Metals
LTM–Met Late Transition Metal–Metalloid
LTT Low-temperature Tetragonal
L–G Landau–Ginzburg

MA Magnetoacoustic
MAD Metalorganic Aerosol Deposition
MAE Magnetic Anisotropy Energy
MAE Magnetoacoustic Emission
MAE Magnetocrystalline Anisotropy Energy
MBE Molecular Beam Epitaxy
MC Magnetoconductance
MC Magnetocurrent
MC Monte Carlo
MCA Magnetocrystalline Anisotropy
MCB Magnetic Circular Birefringence
MCD Magnetic Circular Dichroism
MCE Magnetocaloric Effect
MCL Magnetic Correlation Length
MCP Microchannel Plate
MCRG Monte Carlo Renormalization Group
MCS Monte Carlo Step
MD Multidomain
MDCs Momentum Distribution Curves
ME Magnetoelastic
MEE Migration-enhanced Epitaxy
MEL Magnetoelastic
MEMS Microelectromechanical Systems
MES Magnetic Equation of State
MEXAFS Magnetic Extended Absorption Fine Structures
MExFM Magnetic Exchange Force Microscopy
MF Mean Field
MFA Mean Field Approximation
MFA Mean Field-like Approach
MFM Magnetic Force Microscope/ Microscopy
MI Metal–Insulator
micro-SQUIDs micro-Superconduting Quantum Interference Devices
MIM Metal–Insulator–Metal
MIP Mean Inner Potential
MIS-FET Metal–Insulator–Semiconductor Field-Effect Transistor
MIT Metal–Insulator Transition
ML Monolayer
ML Multilayer
MLB Magnetic Linear Birefringence
MLCs Multiplicative Logarithmic Corrections
MLD Magnetic Linear Dichroism
MMEE Magnetic Multielectron Excitations
MMICs Monolithic Microwave Integrated Circuits
MO Magneto-optical
MOCVD Metalorganic Chemical Vapor Deposition
MOKE Magneto-optical Kerr Effect
MOS Metal Oxide Semiconductor
MOSFET Metal Oxide Semiconductor Field-Effect Transistor
MPCs Magnetic Photonic Crystals
MPH Magnetic Particle Hyperthermia
MPI Magnetic Particle Imaging
MPs Magnetic Particles
MR Magnetoresistance
MR Magnetoresistive
MR Matrix–Recursion
MRAM Magnetic Random Access Memory
MRAM Magnetoresistive Random Access Memory
MRFM Magnetic Resonance Force Microscopy
MRI Magnetic Resonance Imaging
MRM Magnetic Racetrack Memory
MS Magnetostriction
MSBVM Magnetostatic Backward Volume Mode
MSFVM Magnetostatic Forward Volume Mode
MSG Magnetic Symmetry Group
MSH Metal–Semiconductor Hybrids
MSHG Magnetization-induced Second Harmonic Generation