



HANDBOOK OF

# Magnetism

AND ADVANCED MAGNETIC MATERIALS

1

## Fundamentals and Theory

Micromagnetism

Novel Techniques for Characterizing  
and Preparing Samples

Novel Materials

Spintronics and Magnetoelectronics

Editors-in-Chief

HELMUT KRONMÜLLER

STUART PARKIN

# Handbook of Magnetism and Advanced Magnetic Materials

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**Volume 1**      Fundamentals and Theory

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## **Editors-in-Chief**

Helmut Kronmüller

*Max-Planck-Institut für Metallforschung, Stuttgart, Germany*

Stuart Parkin

*IBM Almaden Research Center, San José, CA, USA*



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# EDITORIAL BOARD

## Editors-in-Chief

**Helmut Kronmüller**

*Max-Planck-Institut für Metallforschung, Stuttgart, Germany*

**Stuart Parkin**

*IBM Almaden Research Center, San José, CA, USA*

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*IBM Almaden Research Center, San José, CA, USA*

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# Contributors to Volume 1

**Fakher F. Assaad**

*Universität Würzburg, Würzburg, Germany*

**Tunna Baruah**

*University of Texas at El Paso, El Paso, TX, USA*

**Gustav Bihlmayer**

*Institut für Festkörperforschung, Jülich, Germany*

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**Stefan Blügel**

*Institut für Festkörperforschung, Jülich, Germany*

**Michael S.S. Brooks**

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**Patrick Bruno**

*Max-Planck-Institut für Mikrostrukturphysik, Halle, Germany*

**A. Buzdin**

*Institut Universitaire de France, Paris, France • Université Bordeaux I, Talence, France*

**Piers Coleman**

*Rutgers University, Piscataway, NJ, USA*

**A. del Moral**

*Universidad de Zaragoza and Instituto de Ciencia de Materiales de Aragón (CSIC), Zaragoza, Spain*

**H. Ebert**

*Universität München, München, Germany*

**David M. Edwards**

*Imperial College London, London, UK*

**Axel Enders**

*Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany*

**Manfred Fähnle**

*Max-Planck-Institut für Metallforschung, Stuttgart, Germany*

**J. Flouquet**

*RFMC, SPSMS, CEA-Grenoble, Grenoble, France*

**Pietro Gambardella**

*Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland • Catalan Institute of Research and Advanced Studies (ICREA), Barcelona, Spain*

**Peter Horsch**

*Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany*

**Hiroshi Imamura**

*National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan • Tohoku University, Sendai, Japan*

**Børje Johansson**

*Uppsala University, Uppsala, Sweden*

**Barbara A. Jones**

*IBM Almaden Research Center, San José, CA, USA*

**Mikhail I. Katsnelson**

*Radboud University Nijmegen, Nijmegen, The Netherlands*

**Sharika Nandan Kaul**

*University of Hyderabad, Hyderabad, India*

**Klaus Kern**

*Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany • Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*

**Jürgen Kübler**

*Technische Universität Darmstadt, Darmstadt, Germany*

**David P. Landau**

*The University of Georgia, Athens, GA, USA*

**Alexander I. Lichtenstein**

*Universität Hamburg, Hamburg, Germany*

**S.W. Lovesey**

*Rutherford Appleton Laboratory, Oxfordshire, UK • RIKEN Harima Institute, Hyogo, Japan*

**Sadamichi Maekawa**

*Tohoku University, Sendai, Japan*

**Ingrid Mertig**

*Martin Luther University, Halle, Germany*

**D.L. Mills**

*University of California, Irvine, CA, USA*

**Mark R. Pederson**

*Naval Research Laboratory, Washington, DC, USA*

**Subir Sachdev**

*Harvard University, Cambridge, MA, USA*

**Daniel Steiauf**

*Max-Planck-Institut für Metallforschung, Stuttgart, Germany*

**Gernot Stollhoff**

*Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany*

**Saburo Takahashi**

*Tohoku University, Sendai, Japan*

**Y. Tanaka**

*RIKEN Harima Institute, Hyogo, Japan*

**Matthias Troyer**

*ETH Zürich, Zürich, Switzerland*

**Andrey Umerski**

*Open University, Milton Keynes, UK*

**Ruqian Wu**

*University of California, Irvine, CA, USA*

**A. Peter Young**

*University of California, Santa Cruz, CA, USA*

**Peter Zahn**

*Martin Luther University, Halle, Germany*

# 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 micro-magnetism, 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 biomagnetic 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.

**Klaus von Klitzing**

*Max-Planck-Institut für Festkörperforschung,  
Stuttgart, Germany*

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# Preface to Volume 1

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  $500 \text{ kJ m}^{-3}$ . 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  $10^6 \text{ K s}^{-1}$  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 *Handbook of Magnetism and Advanced Magnetic Materials* reviews in five volumes the aforementioned developments in modern magnetism. The first volume, titled ‘Fundamentals and Theory’, summarizes the present state of our theoretical understanding of physical phenomena in spin-ordered systems. The second volume, is devoted to ‘Micromagnetism’ and its application to the calculation of spin structures and dynamic magnetization processes. The

third volume deals with ‘Novel Techniques for Characterizing and Preparing Samples’ and their application to modern magnetic materials. The fourth volume gives insight into the tremendous field of ‘Novel Materials’ covering soft and hard magnetic materials, oxides, half-metals, magnetocaloric and magneto-optical materials, semiconducting ferromagnets, small particles, and thin wires as well as the recently discovered ferromagnetic oxides doped with transition metals. The fifth volume deals with modern developments in ‘Spintronics and Magnetoelectronics’ where, besides the underlying electronic properties, material properties are also discussed.

The electron theory of spin-ordered solids has always been one of the large challenges of solid-state physics. After the pioneering work of Heisenberg and Dirac the role of itinerant electrons became the subject of consideration by Stoner, Zener, Vonsovsk, Slater, Friedel, Herring, and many others. Major improvements in computational power and methods have enabled the numerical treatment of the band structures of ferromagnetic materials on the basis of new theoretical methods.

In this first volume, the fundamentals of magnetism are treated in 10 parts extending from electron theoretical reviews to the relations between magnetism and superconductivity. In the first part ‘Electron Theory of Magnetism’, the different methods of determining electron structures of spin-ordered solids are presented, namely, the density functional theory, the Hubbard model, the dynamic molecular field theory, and the quantum Monte Carlo method. In the second part, ‘Strongly Correlated Electronic Systems’ are treated in relation to heavy Fermion materials, the Kondo effect, and the interrelations between charge, spin, and orbital degrees of freedom. In the third and fourth parts of Volume 1 the ‘Theory of Magnetic Spectroscopy and Scattering’ and the ‘Spin Dynamics and Relaxation’ are outlined. Here, in particular, the theoretical backgrounds of neutron and X-ray techniques for the analysis of spin structures and the distinction between orbital and spin moments are reviewed.

In the fifth part, several articles discuss the present state of ‘Phase Transitions and Finite Temperature Magnetism’ and deal with statistical mechanics of phase transitions, electron theoretical aspects, disordered and frustrated systems, and quantum phase transitions.

In the following part, theoretical results are compared with experiments and the methods of analysis of experimental results are discussed; three articles deal with the ‘Theory of Magnetocrystalline Anisotropy and Magnetoelasticity’ with special emphasis on 4f and 5f metals. The quantum ‘Theory of Transport and Exchange Phenomena in Thin Film Systems’ is treated in the next part, and the complex field of exchange coupling in multilayers, the tunneling phenomena in metal–insulator systems, and the effect of

enhanced magnetoresistance are presented. 'Magnetism of Low Dimensions' and 'Molecular Magnets' are treated in the following two parts. It is shown that such investigations have become possible by advanced preparation techniques, suitably prepared substrates, and the ion sputtering technique.

The final part of Volume 1 reviews the relations between magnetism and superconductivity, a problem discussed over decades and recently revived by the discovery of novel materials revealing the coexistence of superconductivity and ferromagnetism.

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.

**Helmut Kronmüller**

*Max-Planck-Institut für Metallforschung, Stuttgart,  
Germany*

**Stuart Parkin**

*IBM Almaden Research Center, San José, CA, USA*

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# Abbreviations and Acronyms

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

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

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

GISANS	Grazing Incidence Small-Angle Scattering of Magnetic In-Plane Structures	IBMP	Ion Bombardment Induced Magnetic Patterning
GK	Goodenough–Kanamori	ICF	Interconfigurational
GMCE	Giant Magnetocaloric Effect	IEC	Interlayer Exchange Coupling
GMI	Giant Magnetoimpedance	IETS	Inelastic Electron Tunneling Spectroscopy
GMR	Giant Magnetoresistance	IF	Interface
GMR	Giant Magnetoresistive	IHD	Intermediate to High Damping
GS	Ground-state	IL	Interference Lithography
		ILD	Isotropic Long-range Dipolar
HAADF	High-angle Annular Dark-field	IMEC	Interuniversitair Micro-Elektronica Centrum
HAADF-STEM	High-angle Annular Dark-field Scanning Transmission Electron Microscopy	IMERs	Immobilized Magnetic Enzyme Reactors
HAMR	Heat Assisted Magnetic Recording	IMFP	Inelastic Mean Free Path
HAs	Heusler Alloys	IMS	Immunomagnetic Separation
HAST	Highly Accelerated Stress Test	INESC–MN	Institute of Engineering of Systems and Computers – Microsystems and Nanotechnologies
HB	Hubbard Band		
HCC	Hepatocellular Carcinoma	INS	Inelastic Neutron Scattering
hCG	Human Chorionic Gonadotropin	IPM	Interior Permanent Magnet
HDDR	Hydrogenation-Disproportionation-Desorption-Recombination	IPT	Iterated Perturbation Theory
HDDs	Hard Disk Drives	IR	Irreducible Representation
HDs	Hard Disks	IRM	Isothermal Remanent Magnetization
HEV	Hybrid Electric Vehicle	IRM	Isothermal Remanent Moment
HF	Hard Ferrite	IS	Irreducible Strain
HF	Hartree–Fock	ISR	Isotropic Short-Range
HF	Heavy Fermion	IWE	Inverse Wiedemann Effect
HF-EPR	High-Frequency Electron Paramagnetic Resonance		
HFCs	Heavy-Fermion Compounds	JASTEC	Japan Superconductor Technology
HFCs	Hydrofluorocarbons	JT	Jahn–Teller
HGMS	High-Gradient Magnetic Separator		
HGO	High Permeability, Grain-Oriented	K	Kondo
HH	Heavy-Hole	KKR	Korringa–Kohn–Rostoker
HM	Half Metallic	KKR-CPA	Korringa–Kohn–Rostoker-Coherent Potential Approximation
HM	Hubbard Model		
HMFs	Half Metallic Ferromagnets	KLM	Kondo Lattice Model
HMM	Half Metallic Materials	KR	Kerr Rotation
HMMs	Hard Magnetic Materials	KTO	Kubic Tensor Operator
HMs	Hard Magnetic Materials		
HREM	High-resolution Electron Microscopy	LA	Local Ansatz
		LAFS	Law of Approach to Ferromagnetic Saturation
HRIR	High-reflectance Infrared Mirror	LAO	LaAlO <sub>3</sub>
HRTEM	High-resolution Transmission Electron Microscopy	LBMO	La <sub>0.7</sub> Ba <sub>0.3</sub> MnO <sub>3</sub>
HRXRD	High-resolution X-ray Diffraction	LCCSD	Linearized Coupled-Cluster Expansion with Singles and Doubles
HS	High Symmetry		
HS	Hubbard-Stratonovich	LDA	Local Density Approximation
HTI	High-temperature Incommensurate	LDOS	Local Density Of States
HV	High Vacuum	LED	Light-emitting Diode
HWHM	Half-Width at Half-Maximum	LEED	Low Energy Electron Diffraction



LFL	Landau–Fermi Liquid	MEXAFS	Magnetic Extended Absorption Fine Structures
LGW	Landau–Ginzburg–Wilson	MExFM	Magnetic Exchange Force Microscopy
LH	Left-hand	MF	Mean Field
LH	Light-Hole	MFA	Mean Field Approximation
LHMs	Left-handed Materials	MFA	Mean Field-like Approach
LKKR	Layer Korringa–Kohn–Rostoker	MFM	Magnetic Force Microscope/ Microscopy
LL	Landau–Lifschitz	MI	Metal–Insulator
LL	Layer-by-Layer	micro-SQUIDS	micro-Superconducting Quantum Interference Devices
LLG	Landau–Lifschitz–Gilbert	MIM	Metal–Insulator–Metal
LLs	Landau Levels	MIP	Mean Inner Potential
LMO	LaMnO <sub>3</sub>	MIS-FET	Metal–Insulator–Semiconductor Field-Effect Transistor
LMTO	Linear Muffin-Tin Orbital	MIT	Metal–Insulator Transition
LO	Longitudinal Optical	ML	Monolayer
LP	Lifshitz Point	ML	Multilayer
LPD	Laser Pulse Deposition	MLB	Magnetic Linear Birefringence
LSCMO	La <sub>0.7</sub> (Ca <sub>0.5</sub> Sr <sub>0.5</sub> )MnO <sub>3</sub>	MLCs	Multiplicative Logarithmic Corrections
LSDA	Local Spin Density Approximation	MLD	Magnetic Linear Dichroism
LSTP	Low Standby Power	MMEE	Magnetic Multielectron Excitations
LT	Low-temperature	MMICs	Monolithic Microwave Integrated Circuits
LT-MBE	Low-temperature Molecular-beam Epitaxy	MO	Magneto-optical
LTI	Low-temperature Incommensurate	MOCVD	Metalorganic Chemical Vapor Deposition
LTMs	Late Transition Metals	MOKE	Magneto-optical Kerr Effect
LTM–Met	Late Transition Metal–Metalloid	MOS	Metal Oxide Semiconductor
LTT	Low-temperature Tetragonal	MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
L–G	Landau–Ginzburg	MPCs	Magnetic Photonic Crystals
MA	Magnetoacoustic	MPH	Magnetic Particle Hyperthermia
MAD	Metalorganic Aerosol Deposition	MPI	Magnetic Particle Imaging
MAE	Magnetic Anisotropy Energy	MPs	Magnetic Particles
MAE	Magnetoacoustic Emission	MR	Magnetoresistance
MAE	Magnetocrystalline Anisotropy Energy	MR	Magnetoresistive
MBE	Molecular Beam Epitaxy	MR	Matrix–Recursion
MC	Magnetoconductance	MRAM	Magnetic Random Access Memory
MC	Magnetocurrent	MRAM	Magnetoresistive Random Access Memory
MC	Monte Carlo	MRFM	Magnetic Resonance Force Microscopy
MCA	Magnetocrystalline Anisotropy	MRI	Magnetic Resonance Imaging
MCB	Magnetic Circular Birefringence	MRM	Magnetic Racetrack Memory
MCD	Magnetic Circular Dichroism	MS	Magnetostriction
MCE	Magnetocaloric Effect	MSBVM	Magnetostatic Backward Volume Mode
MCL	Magnetic Correlation Length	MSFVM	Magnetostatic Forward Volume Mode
MCP	Microchannel Plate	MSG	Magnetic Symmetry Group
MCRG	Monte Carlo Renormalization Group	MSH	Metal–Semiconductor Hybrids
MCS	Monte Carlo Step	MSHG	Magnetization-induced Second Harmonic Generation
MD	Multidomain		
MDCs	Momentum Distribution Curves		
ME	Magnetoelastic		
MEE	Migration-enhanced Epitaxy		
MEL	Magnetoelastic		
MEMS	Microelectromechanical Systems		
MES	Magnetic Equation of State		