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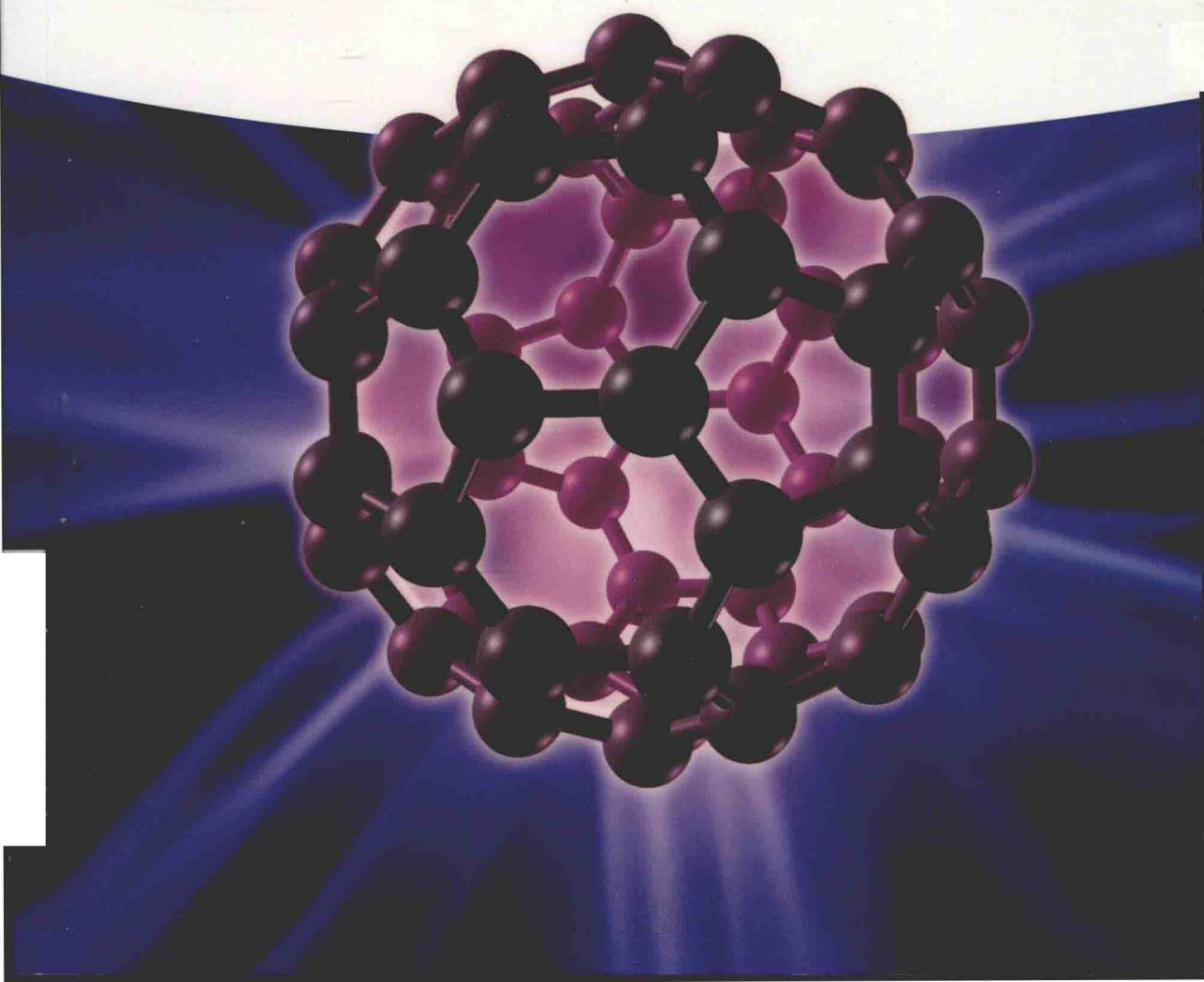
Nanophysics and Nanotechnology

An Introduction to Modern Concepts in Nanoscience

Third Edition



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To
Carol, Doug, Dave, Ben
And
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Preface

Nanophysics, in this nonspecialist textbook, deals with physical effects at the nanometer and subnanometer scales; particularly aspects of importance to the *smallest size scales of any possible technology*.

"Nanophysics" thus includes physical laws applicable from the 100 nm scale down to the subatomic, sub-0.1 nm, scale. This includes "quantum mechanics" as advanced by the theoretical physicist Erwin Schrodinger, about 1925; "mesoscale physics," with more diverse and recent origins; and the physics of the atomic nucleus, on the 10^{-15} m (fm) scale. From a pedagogical point of view, the 1 nm scale requires the concepts of "quantum mechanics" (sometimes here described as "nanophysics"), which, once introduced, are key to understanding behavior down to the femtometer scale of the atomic nucleus.

The third edition includes new material on nanophotonics and nanoplasmonics, and also nanoimprint lithography (Chapter 7), a new section on the quantum annealing computer in Chapter 9, and an entirely new Chapter 10 on graphene. The textbook remains up-to-date also on "nanoelectronics," from magnetic and quantum points of view, and also relating to the possibilities for "quantum computing" as an extension of the existing successful silicon technology. The new Chapter 8 entitled "Quantum technologies based on magnetism, electron spin, superconductivity," is followed by the new Chapter 9 titled "Silicon nanoelectronics and beyond." New electronics-related applications of carbon nanotubes are included. Sections have been added on superconductivity: a concrete example of quantum coherence, and to help understand devices of the "rapid single flux quantum" (RSFQ) computer logic (already mentioned in the original Chapter 7), notable for low power dissipation and fast operation. The original Chapter 8 ("Looking into the Future") becomes the new Chapter 11.

Additional material has been added (in Chapters 4 and 5, primarily), giving concepts needed for the most important new areas, including the absolutely most recent advances in nanotechnology. The basic ideas of ferromagnetic interactions and quantum computing, now included, are central to any quantum- or magnetic-based technology. The new edition is more self-contained, with the addition of a short list of useful constants and a glossary.

A criterion in choice of new material (many astonishing developments have occurred since the 2004 publication of the first edition of this textbook) has been

the author's view of what may be important in the development of nanotechnology. For this reason, nuclear physics is now touched on (briefly), in connection with proposals to use the "nuclear spin $^1/_2$" as the "qubit" of information in a "quantum computer"; and with a recent small-scale experiment demonstrating neutron generation (via a standard "nuclear fusion reaction"), which exploits nanotechnology for its success.

Another essential and relevant aspect of fundamental physics, the "exchange interaction of identical particles," has already been incorporated, as essential to a basic understanding of covalent bonds, ferromagnetism (essential to computer disk drive nanotechnology), and, more recently, to proposals for a "charge qubit" for a quantum computer. This topic (the exchange interaction) is of importance beyond being the basis for covalent bonds in organic chemistry.

From the beginning, this textbook was intended as an introduction to the phenomena and laws of nature applicable on such tiny size scales (without excluding the nuclear, femtometer, size scale) for those who have taken college mathematics and physics, but who have not necessarily studied atomic physics or nuclear physics. Primarily, the reader will need facility with numbers, and an interest in new ideas.

The Exercises have been conceived more as self-learning aids for the interested reader, than as formal problems. Some new material, especially in regard to field ionization by tips, and aspects of the collapse of ultrasonically induced bubbles in dense liquids, appears now in the Exercises, not to clutter the text for the more general reader.

It is hoped that interested readers can find stimulating, even profitable, new ideas in this (still rather slim) textbook. For details, they can use the copious and absolutely current references that are included.

The author is indebted to his colleagues at Wiley-VCH, Ms Ulrike Werner and Stefanie Volk, for their help in preparing the Third Edition. He also thanks his colleagues at New York University Polytechnic School of Engineering, particularly Prof. Lorcan Folan and Ms DeShane Lyew, for their help. He also adds that Mr Malhar Desai and Cornell Anthony have been extremely helpful in preparing the final manuscript. The author thanks his wife Carol for help in many ways in continuous support of the book projects.

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March, 2015

Edward L. Wolf

Glossary of Abbreviations

A	Adenosine; one of the four bases in RNA; one of the four bases in the DNA double helix (joins with T)
ABM	Anti-Ballistic Missile (treaty); suggested as a prototype for limits on robots
ADC	Analog-to-digital converter
AFM	Atomic force microscope
amu	Atomic mass unit (u); defined as 1/12 of mass of carbon-12 (^{12}C): $u = 1.661 \times 10^{-27}$ kg
ATP	Adenosine triphosphate; biological energy source, leading to ADP, adenosine diphosphate
Bar	One atmosphere, 101.3 kPa
BCS	Bardeen, Cooper, Schrieffer (theory); basic accepted theory of superconductivity
BOX	Buried oxide layer; in Si, used to reduce capacitances in FET devices (see SOI)
C	Cytosine; one of the four bases in RNA: one of the four bases in the DNA double helix (joins with G)
CIP	Current in plane; geometry for spin valve type of GMR magnetic field sensor
CMOL	CMOS/nanowire/molecular hybrid; proposed computer logic
CMOS	Complementary metal oxide semiconductor; computer logic
CPP	Current perpendicular to plane; geometry in TMR (tunnel valve) magnetic sensor
CPU	Central processing unit; in computer
CVD	Chemical vapor deposition; a rapid means of depositing layers in semiconductor
D	Debye; unit of electric dipole moment: $1\,\mathrm{D} = 3.3 \times 10^{-30}\,\mathrm{C\,m}$
DMF	Dimethylformamide; a polar molecule
DNA	Deoxyribonucleic acid; polymer, forms single and double helices; latter hydrogen bonded by bases C, G, A, T, encoding information for assembly of proteins
DNT	Dinitrotoluene; an explosive ingredient; a polar molecule, potentially detectable

DOS	Density of states; usually stated per unit energy per unit volume, for electrons
DRAM	Dynamic random access memory
dsDNA	Double-strand DNA
E_F	Fermi energy
E_g	Energy gap of a semiconductor, typically in electron volts
ESR	Electron spin resonance
eV	Electronvolt; $1\,eV = 1.6 \times 10^{-19}\,J$
fcc	Face-centered cubic
FET	Field effect transistor
fm	Femtometer; 10^{-15} m, size scale of the atomic nucleus
FQHE	Fractional quantum Hall effect
G	Guanine; one of the four bases in RNA; one of the four bases in the DNA double helix (joins with C)
GMR	Giant magnetoresistance; basis of "spin valve" CIP hard drive *B*-field sensor
hcp	Hexagonal close packed
HEMT	High-electron-mobility transistor
HTS	High-temperature superconductor
JJ	Josephson tunnel junction
laser	Light amplification by stimulated emission of radiation
maJ	Milliattojoule; possible energy unit for small systems
MBE	Molecular beam epitaxy; a method for depositing atomically perfect crystal layers
MEMS	Micro-electro-mechanical system
meV	Millielectronvolts; thousandth of an electronvolt
MeV	Megaelectronvolts; million electronvolts
MFM	Magnetic force microscope
MOSFET	Metal oxide semiconductor field effect transistor; basic switch in electronics
MRAM	Magnetic random access memory
MRFM	Magnetic resonance force microscope
MRI	Magnetic resonance imaging; use of proton (spin) magnetic resonance to map locations of water molecules in living specimens
MWNT	Multiwall (carbon) nanotube
NEMS	Nano-electro-mechanical system
NMR	Nuclear magnetic resonance
NW	Nanowire
PMMA	Polymethylmethacrylate; used as a photoresist in silicon technology
PN junction	Junction between P (positively doped) and N (negatively doped) semiconductors; rectifier, element of transistor, and voltage-variable capacitor
Py	Permalloy; a high-permeability Ni–Fe ferromagnet

PZT	Lead zirconate titanate; piezoelectric used in sonar, SPM, and SBSL transducers
QCA	Quantum cellular automata
QD	Quantum dot; a three-dimensionally small object, "artificial atom"
QED	Quantum electrodynamics; interaction of radiation with matter, leading, for example, to small change in g-factor of electron spin from 2.0 to 2.0023
QHE	Quantum Hall effect
QPC	Quantum point contact
radar	Radio detection and ranging
RAM	Random access memory
recA	Protein of prototypical bacterium *E. coli* used in DNA assembly of nanostructures
RFSET	Radio frequency single electron transistor
RNA	Ribonucleic acid; polymer, similar to DNA, but uses base U instead of base T; evolutionary precursor of DNA, retains central roles in protein synthesis
RNAP	RNA polymerase; enzyme that transcribes DNA template into messenger RNA
RSFQ	Rapid single flux quantum; form of superconducting computer logic
RTD	Resonant tunneling diode; plus related forms (e.g., TBRTD) of transistor and logic
SBSL	Single-bubble sonoluminescence
SEM	Scanning electron microscope
SET	Single electron transistor
SFQ	Single flux quantum
SHO	Simple harmonic oscillator
SOI	Silicon on insulator; sometimes implemented on single-crystal Si by implanting a deep layer of oxygen, followed by annealing to produce quartz insulator (see BOX)
sonar	Sound navigation and ranging; in modern forms uses piezoelectric transducers for sound generation underwater
SPM	Scanning probe microscope
SQUID	Superconducting quantum interference detector
ssDNA	Single-strand DNA
STM	Scanning tunneling microscope
SWNT	Single-wall (carbon) nanotube
T	Thymine; not present in RNA; one of the four bases in the DNA double helix (joins with A)
TBRTD	Triple-barrier resonant tunneling diode (see RTD)
TEM	Transmission electron microscope
TMR	Tunnel magnetoresistance; basis of "tunnel valve" CPP magnetic field sensor

TPa	Terapascal; 1 TPa = $10^{12}\,\mathrm{N\,m^{-2}}$; possible value of Young's modulus
u	Atomic mass unit (amu); defined as 1/12 of mass of carbon-12 (^{12}C): 1 u = 1.661×10^{-27} kg
U	Uracil; one of the four bases (replacing T) in RNA (joins with A); not present in DNA
2DEG	Two-dimensional electron gas

Contents