

Edward L. Wolf

Nanophysics and Nanotechnology

An Introduction to Modern Concepts in Nanoscience

Third Edition

WILEY-VCH
Verlag GmbH & Co. KGaA

Contents

Preface *XV*

Glossary of abbreviations *XVII*

1	Introduction	<i>1</i>
1.1	Nanometers, Micrometers, and Millimeters	<i>3</i>
1.1.1	Plenty of Room at the Bottom	<i>4</i>
1.1.2	Scaling the Xylophone	<i>4</i>
1.1.3	Reliability of Concepts and Approximate Parameter Values Down to About $L = 10$ nm (100 Atoms)	<i>5</i>
1.1.4	Nanophysics Built into the Properties of Bulk Matter	<i>6</i>
1.2	Moore's Law	<i>7</i>
1.3	Esaki's Quantum Tunneling Diode	<i>9</i>
1.4	QDs of Many Colors	<i>10</i>
1.5	GMR and TMR 100–1000 Gb Hard Drive “Read Heads”	<i>11</i>
1.6	Accelerometers in Your Car	<i>14</i>
1.7	Nanopore Filters	<i>15</i>
1.8	Nanoscale Elements in Traditional Technologies	<i>15</i>
	References	<i>16</i>
2	Systematics of Making Things Smaller, Pre-quantum	<i>17</i>
2.1	Mechanical Frequencies Increase in Small Systems	<i>17</i>
2.2	Scaling Relations Illustrated by a Simple Harmonic Oscillator	<i>20</i>
2.3	Scaling Relations Illustrated by Simple Circuit Elements	<i>21</i>
2.4	Thermal Time Constants and Temperature Differences Decrease	<i>22</i>
2.5	Viscous Forces Become Dominant for Small Particles in Fluid Media	<i>22</i>
2.6	Frictional Forces Can Disappear in Symmetric Molecular Scale Systems	<i>24</i>
	References	<i>26</i>

3	What Are Limits to Smallness?	27
3.1	Particle (Quantum) Nature of Matter: Photons, Electrons, Atoms, and Molecules	27
3.2	Biological Examples of Nanomotors and Nanodevices	28
3.2.1	Linear Spring Motors	29
3.2.2	Linear Engines on Tracks	30
3.2.3	Rotary Motors	33
3.2.4	Ion Channels, the Nanotransistors of Biology	36
3.2.4.1	Ca ⁺⁺ -Gated Potassium Channel	37
3.2.4.2	Voltage-Gated Potassium Channel	37
3.3	How Small Can You Make it?	38
3.3.1	What Are the Methods for Making Small Objects?	39
3.3.2	How Can You See What You Want to Make?	39
3.3.3	How Can You Connect it to the Outside World?	42
3.3.4	If You Cannot See it or Connect to it, Can You Make it Self-Assemble and Work on its Own?	42
3.3.5	Approaches to Assembly of Small Three-Dimensional Objects	42
3.3.5.1	Variable Thickness Electroplating	43
3.3.5.2	Lithography onto Curved Surfaces	43
3.3.5.3	Optical Tweezers	43
3.3.5.4	Arrays of Optical Traps	45
3.3.6	Use of DNA Strands in Guiding Self-Assembly of Nanometer-Sized Structures	46
	References	48
4	Quantum Nature of the Nanoworld	51
4.1	Bohr's Model of Nuclear Atom	52
4.1.1	Quantization of Angular Momentum	52
4.1.2	Extensions of Bohr's Model	53
4.2	Particle–Wave Nature of Light and Matter, DeBroglie Formulas $\lambda = h/p, E = h\nu$	54
4.3	Wavefunction Ψ for Electron, Probability Density $\Psi^*\Psi$, Traveling and Standing Waves	55
4.4	Maxwell's Equations; E and B as Wavefunctions for Photons, Optical Fiber Modes	59
4.5	The Heisenberg Uncertainty Principle	60
4.6	Schrodinger Equation, Quantum States and Energies, Barrier Tunneling	61
4.6.1	Schrodinger Equations in One Dimension	62
4.6.1.1	Time-Dependent Equation	62
4.6.1.2	Time-Independent Equation	63
4.6.2	The Trapped Particle in One Dimension	63
4.6.2.1	Linear Combinations of Solutions	64
4.6.2.2	Expectation Values	64
4.6.2.3	Two-Particle Wavefunction	65

4.6.3	Reflection and Tunneling at a Potential Step	65
4.6.3.1	Case 1: $E > U_0$	66
4.6.3.2	Case 2: $E < U_0$	66
4.6.4	Penetration of a Barrier, Escape Time from a Well, Resonant Tunneling Diode	67
4.6.5	Trapped Particles in Two and Three Dimensions: Quantum Dot	68
4.6.5.1	Electrons Trapped in a 2D Box	69
4.6.5.2	Electrons in a 3D “Quantum Dot”	70
4.6.6	2D Bands and Quantum Wires	71
4.6.6.1	2D Band	71
4.6.6.2	Quantum Wire	71
4.6.7	The Simple Harmonic Oscillator	72
4.6.8	Schrodinger Equation in Spherical Polar Coordinates	73
4.7	The Hydrogen Atom, One-Electron Atoms, Excitons	74
4.7.1	Magnetic Moments	78
4.7.2	Magnetization and Magnetic Susceptibility	79
4.7.3	Positronium and Excitons	80
4.8	Fermions, Bosons, and Occupation Rules	81
	References	81
5	Quantum Consequences for the Macroworld	83
5.1	Chemical Table of the Elements	83
5.2	Nanosymmetry, Diatoms, and Ferromagnets	84
5.2.1	Indistinguishable Particles and Their Exchange	84
5.2.1.1	Fermions	85
5.2.1.2	Bosons	85
5.2.1.3	Orbital and Spin Components of Wavefunctions	85
5.2.2	The Hydrogen Molecule, Dihydrogen: The Covalent Bond	86
5.2.2.1	Covalent Bonding and Covalent AntiBonding, Purely Nanophysical Effects	87
5.2.2.2	Ferromagnetism, a Purely Nanophysical Effect	87
5.3	More Purely Nanophysical Forces: van der Waals, Casimir, and Hydrogen Bonding	88
5.3.1	The Polar and van der Waals Fluctuation Forces	89
5.3.1.1	Electric Polarizability of Neutral Atoms and Molecules	89
5.3.1.2	Dipolar Fluctuations of Neutral and Symmetric Atoms	90
5.3.2	The Casimir Force	92
5.3.3	The Hydrogen Bond	96
5.4	Metals as Boxes of Free Electrons: Fermi Level, DOS, Dimensionality	97
5.4.1	Electronic Conduction, Resistivity, Mean Free Path, Hall Effect, Magnetoresistance	100
5.5	Periodic Structures (e.g., Si, GaAs, InSb, Cu): Kronig–Penney Model for Electron Bands and Gaps	101

5.6	Electron Bands and Conduction in Semiconductors and Insulators; Localization versus Delocalization	107
5.7	Hydrogenic Donors and Acceptors	110
5.7.1	Carrier Concentrations in Semiconductors, Metallic Doping	112
5.7.2	PN Junction, Electrical Diode $I(V)$ Characteristic, Injection Laser	116
5.7.2.1	Radiative Recombination and Emission of Light	117
5.7.2.2	PN Junction Injection Laser	118
5.7.2.3	Increasing Radiative Efficiency η	119
5.7.2.4	Single-Nanowire Electrically Driven Laser	119
5.8	More about Ferromagnetism, the Nanophysical Basis of Disk Memory	121
5.9	Surfaces are Different; Schottky Barrier Thickness $W = [2\epsilon\epsilon_0 V_B / eN_D]^{1/2}$	124
5.10	Ferroelectrics, Piezoelectrics, and Pyroelectrics: Recent Applications to Advancing Nanotechnology	126
5.10.1	Piezoelectric Materials	126
5.10.2	Ultrasonic Initiation of Bubbles, by a Negative Pressure	127
5.10.3	Ferroelectrics and Pyroelectrics	127
5.10.4	A Nanotechnological (Pyroelectric) Compact Source of Neutrons	128
5.10.5	Electric Field Ionization of Deuterium (Hydrogen)	129
5.10.6	An Unexpected High-Temperature Nanoenvironment	131
5.10.7	Collapse of Ultrasonically Produced Bubbles in Dense Liquids	131
	References	134
6	Self-Assembled Nanostructures in Nature and Industry	137
6.1	Carbon Atom $^{12}\text{C } 1s^2 2p^4$ (0.07 nm)	138
6.2	Methane (CH_4), Ethane (C_2H_6), and Octane (C_8H_{18})	139
6.3	Ethylene (C_2H_4), Benzene (C_6H_6), and Acetylene (C_2H_2)	140
6.4	C_{60} Buckyball (~ 0.5 nm)	140
6.5	C_∞ Nanotube (~ 0.5 nm)	141
6.5.1	Si Nanowire (~ 5 nm)	144
6.6	InAs Quantum Dot (~ 5 nm)	145
6.7	AgBr Nanocrystal (0.1–2 μm)	146
6.8	Fe_3O_4 Magnetite and Fe_3S_4 Greigite Nanoparticles in Magnetotactic Bacteria	147
6.9	Self-Assembled Monolayers on Au and Other Smooth Surfaces	149
	References	151
7	Physics-Based Experimental Approaches to Nanofabrication and Nanotechnology	153
7.1	Silicon Technology: The INTEL-IBM Approach to Nanotechnology	154
7.1.1	Patterning, Masks, and Photolithography	154

7.1.1.1	Patterning Deposition Masks	154
7.1.1.2	Masking Layers to Limit Etching	155
7.1.2	Etching Silicon	155
7.1.2.1	Wet Etches	155
7.1.2.2	Dry Etches	156
7.1.3	Defining Highly Conducting Electrode Regions	156
7.1.4	Methods of Deposition of Metal and Insulating Films	156
7.1.4.1	Evaporation	156
7.1.4.2	Sputtering	157
7.1.4.3	Chemical Vapor Deposition	157
7.1.4.4	Laser Ablation	157
7.1.4.5	Molecular Beam Epitaxy	157
7.1.4.6	Ion Implantation	158
7.2	Lateral Resolution (Linewidths) Limited by Wavelength of Light, Now 65 nm	158
7.2.1	Optical and X-Ray Lithography	158
7.2.2	Electron-Beam Lithography	159
7.3	Sacrificial Layers, Suspended Bridges, Single-Electron Transistors	160
7.4	What Is the Future of Silicon Computer Technology?	162
7.5	Heat Dissipation and the RSFQ Technology	163
7.6	Scanning Probe (Machine) Methods: One Atom at a Time	167
7.7	STM as Prototype Molecular Assembler	169
7.7.1	Moving Au Atoms, Making Surface Molecules	169
7.7.2	Assembling Organic Molecules with an STM	172
7.8	Atomic Force Microscope Arrays	173
7.8.1	Cantilever Arrays by Photolithography	173
7.8.2	Nanofabrication with an AFM	174
7.8.3	Imaging a Single Electron Spin by a Magnetic Resonance AFM	175
7.9	Fundamental Questions: Rates, Accuracy, and More	177
7.10	Nanophotonics and Nanoplasmonics	178
	References	181
8	Quantum Technologies Based on Magnetism, Electron and Nuclear Spin, and Superconductivity	183
8.1	Spin as an Element of “Quantum Computing”	183
8.2	The Stern–Gerlach Experiment: Observation of Spin-1/2; Angular Momentum of the Electron	186
8.3	Two Nuclear Spin Effects: MRI (Magnetic Resonance Imaging) and the “21.1 cm Line”	187
8.4	Electron Spin 1/2; as a Qubit for a Quantum Computer: Quantum Superposition, Coherence	190
8.5	Hard and Soft Ferromagnets	193
8.6	The Origins of GMR (Giant Magnetoresistance): Spin-Dependent Scattering of Electrons	194

- 8.7 The GMR Spin Valve, a Nanophysical Magnetoresistance Sensor 197
- 8.8 The Tunnel Valve, a Better (TMR) Nanophysical Magnetic Field Sensor 198
- 8.9 Magnetic Random Access Memory 200
- 8.9.1 Magnetic Tunnel Junction MRAM Arrays 200
- 8.9.2 Hybrid Ferromagnet–Semiconductor Nonvolatile Hall Effect Gate Devices 200
- 8.10 Spin Injection: The Johnson–Silsbee Effect 203
- 8.10.1 Apparent Spin Injection from a Ferromagnet into a Carbon Nanotube 203
- 8.11 Magnetic Logic Devices: A Majority Universal Logic Gate 203
- 8.12 Superconductors and the Superconducting (Magnetic) Flux Quantum 206
- 8.13 Josephson Effect and the Superconducting Quantum Interference Device (SQUID) 211
- 8.14 Superconducting (RSFQ) Logic/Memory Computer Elements 214
- 8.14.1 The Single Flux Quantum Voltage Pulse 215
- 8.14.2 Analog-to-Digital Conversion (ADC) Using RSFQ Logic 217
- References 217

- 9 Silicon Nanoelectronics and Beyond 219**
- 9.1 Electron Interference Devices with Coherent Electrons 220
- 9.1.1 Ballistic Electron Transport in Stubbed Quantum Waveguides: Experiment and Theory 222
- 9.1.2 Well-Defined Quantum Interference Effects in Carbon Nanotubes 223
- 9.2 Carbon Nanotube Sensors and Dense Nonvolatile Random Access Memories 226
- 9.2.1 A Carbon Nanotube Sensor of Polar Molecules, Making Use of the Inherently Large Electric Fields 227
- 9.2.2 Carbon Nanotube Cross-Bar Arrays for Ultradense Ultrafast Nonvolatile Random Access Memory 228
- 9.3 Resonant Tunneling Diodes, Tunneling Hot Electron Transistors 232
- 9.4 Double-Well Potential Charge Qubits 233
- 9.4.1 Silicon-Based Quantum Computer Qubits 238
- 9.5 Single Electron Transistors 239
- 9.5.1 RFSET, a Useful Proven Research Tool 242
- 9.5.2 Readout of the Charge Qubit, with Subelectron Charge Resolution 242
- 9.5.3 A Comparison of SET and RTD Behaviors 244
- 9.6 Experimental Approaches to the Double-Well Charge Qubit 245
- 9.6.1 Coupling of Two-Charge Qubits in a Solid-State (Superconducting) Context 249

9.7	Ion Trap on a GaAs Chip, Pointing to a New Qubit	253
9.8	Quantum Computing by Quantum Annealing with Artificial Spins	254
	References	255
10	Nanophysics and Nanotechnology of Graphene	257
10.1	Graphene: Record-Breaking Physical and Electrical Properties	257
10.2	Consequences of One-Atom Thickness: Softness and Adherence	258
10.3	Impermeability of Single-Layer Graphene	258
10.4	Synthesis by Chemical Vapor Deposition and Direct Reaction	260
10.5	Application to Flexible, Conducting, and Transparent Electrodes	262
10.6	Potential Application to Computer Logic Devices, Extending Moore's Law	264
10.7	Applications of Graphene within Silicon Technology	266
	References	268
11	Looking into the Future	271
11.1	Drexler's Mechanical (Molecular) Axle and Bearing	271
11.1.1	Smalley's Refutation of Machine Assembly	272
11.1.2	van der Waals Forces for Frictionless Bearings?	274
11.2	The Concept of the Molecular Assembler is Flawed	275
11.3	Could Molecular Machines Revolutionize Technology or Even Self-Replicate to Threaten Terrestrial Life?	276
11.4	The Prospect of Radical Abundance by a Breakthrough in Nanoengineering	277
11.5	What about Genetic Engineering and Robotics?	278
11.6	Possible Social and Ethical Implications of Biotechnology and Synthetic Biology	281
11.7	Is there a Posthuman Future as Envisioned by Fukuyama?	282
	References	284
	Some Useful Constants	285
	Exercises	287
	Index	297