Understanding the Nanotechnology Revolution
Contents

Preface  IX

1  Discovery, Invention, and Science in Human Progress  1
  1.1  Origins of Technology, the Need for Human Survival  1
  1.2  The Industrial Revolution: Watt's Steam Engine, Thermodynamics, Energy Sources  2
  1.3  A Short History of Time: Navigation, Longitudes, Clocks  4
  1.4  The Information Revolution: Abacus to Computer Chips and Fiber Optics  5
  1.5  Overlap and Accelerating Cascade of Technologies: GPS, Nuclear Submarines  6
  1.6  Silicon and Biotechnologies: Carbon Dating, Artificial Intelligence  7
  1.7  Nanotechnology: A Leading Edge of Technological Advance, a Bridge to the Future  13
  1.8  How to Use This Book  15
  References  16

2  Smaller Is More, Usually Better, and Sometimes Entirely New!  17
  2.1  Nanometers, Micrometers, Millimeters—Visualizing a Nanometer  18
  2.2  Moore's Law: from 30 Transistors to a Billion Transistors on One Chip and Cloud Computing  19
  2.3  Miniaturization: Esaki's Tunneling Diode, 1-TB Magnetic Disk "Read" Heads  22
  2.4  Accelerometers and Semiconductor Lasers  24
  2.5  Nanophysics-Based Technology: Medical Imaging, Atomic Clock, Sensors, Quantum Computers  26
  References  27
## Contents

3 Systematics ofScaling Things Down: \( L = 1 \, \text{m} \rightarrow 1 \, \text{nm} \) 29  
3.1 One-Dimensional and Three-Dimensional Scaling 29  
3.2 Examples of Scaling: Clocks, Tuning Forks, Quartz Watches, Carbon Nanotubes 31  
3.3 Scaling Relations Illustrated by Simple Circuit Elements 37  
3.4 Viscous Forces for Small Particles in Fluid Media 38  
3.5 What about Scaling Airplanes and Birds to Small Sizes? 39  
References 40  

4 Biology as Successful Nanotechnology 41  
4.1 Molecular Motors in Large Animals: Linear Motors and Rotary Motors 41  
4.2 Information Technology in Biology Based on DNA 46  
4.3 Sensors, Rods, Cones, and Nanoscale Magnets 52  
4.4 Ion Channels: Nanotransistors of Biology 53  
References 53  

5 The End of Scaling: The Lumpiness of All Matter in the Universe 55  
5.1 Lumpiness of Macroscopic Matter below the 10-\( \mu \text{m} \) Scale 55  
5.2 Hydrogen Atom of Bohr: A New Size Scale, Planck’s Constant 57  
5.3 Waves of Water, Light, Electron, and Their Diffractions 60  
5.4 DeBroglie Matter Wavelength 62  
5.5 Schrödinger’s Equation 63  
5.6 The End of Scaling, the Substructure of the Universe 63  
5.7 What Technologies Are Directly Based on These Fundamental Particles and Spin? 64  
Reference 65  

6 Quantum Consequences for the Macroworld 67  
6.1 Quantum Wells and Standing Waves 67  
6.2 Probability Distributions and Uncertainty Principle 69  
6.3 Double Well as Precursor of Molecule 71  
6.4 The Spherical Atom 73  
6.5 Where Did the Nuclei Come From (Atoms Quickly Form around Them)? 75  
6.6 The “Strong Force” Binds Nuclei 75  
6.7 Chemical Elements: Based on Nuclear Stability 76  
6.8 Molecules and Crystals: Metals as Boxes of Free Electrons 77  
References 79
7 Some Natural and Industrial Self-Assembled Nanostructures 81
7.1 Periodic Structures: A Simple Model for Electron Bands and Gaps 81
7.2 Engineering Electrical Conduction in Tetrahedrally Bonded Semiconductors 83
7.3 Quantum Dots 85
7.4 Carbon Nanotubes 86
7.5 C_{60} Buckyball 91
References 92

8 Injection Lasers and Billion-Transistor Chips 93
8.1 Semiconductor P-N Junction Lasers in the Internet 93
8.2 P-N Junction and Emission of Light at 1.24 μm 98
8.3 Field Effect Transistor 101

9 The Scanning Tunneling Microscope and Scanning Tunneling Microscope Revolution 105
9.1 Scanning Tunneling Microscope (STM) as Prototype 105
9.2 Atomic Force Microscope (AFM) and Magnetic Force Microscope (MFM) 110
9.3 SNOM: Scanning Near-Field Optical Microscope 115

10 Magnetic Resonance Imaging (MRI): Nanophysics of Spin ½ 117
10.1 Imaging the Protons in Water: Proton Spin ½, a Two-Level System 117
10.2 Magnetic Moments in a Milligram of Water: Polarization and Detection 118
10.3 Larmor Precession, Level Splitting at 1 T 119
10.4 Magnetic Resonance and Rabi Frequency 120
10.5 Schrodinger’s Cat Realized in Proton Spins 121
10.6 Superconductivity as a Detection Scheme for Magnetic Resonance Imaging 122
10.7 Quantized Magnetic Flux in Closed Superconducting Loops 123
10.8 SQUID Detector of Magnetic Field Strength 124
A SQUID-Based MRI Has Been Demonstrated 125

11 Nanophysics and Nanotechnology of High-Density Data Storage 127
11.1 Approaches to Terabyte Memory: Mechanical and Magnetic 127
11.2 The Nanoelectromechanical “Millipede” Cantilever Array and Its Fabrication 127
11.3 The Magnetic Hard Disk 132
Reference 137

12 Single-Electron Transistors and Molecular Electronics 139
12.1 What Could Possibly Replace the FET at the “End of Moore’s Law”? 139
12.2 The Single-Electron Transistor (SET) 139
12.3 Single-Electron Transistor at Room Temperature Based on a Carbon Nanotube 142
12.4 Random Access Storage Based on Crossbar Arrays of Carbon Nanotubes 143
12.5 A Molecular Computer! 147
References 149

13 Quantum Computers and Superconducting Computers 151
13.1 The Increasing Energy Costs of Silicon Computing 152
13.2 Quantum Computing 152
13.3 Charge Qubit 154
13.4 Silicon-Based Quantum-Computer Qubits 155
13.5 Adiabatic Quantum Computation 157
Analog to Digital Conversion (ADC) Using RSFQ Logic 159
13.6 Opportunity for Innovation in Large-Scale Computation 160
References 161

14 Looking into the Future 163
14.1 Ideas, People, and Technologies 163
14.2 Why the Molecular Assembler of Drexler: One Atom at a Time, Will Not Work 166
14.3 Man-Made Life: The Bacterium Invented by Craig Venter and Hamilton Smith 169
14.4 Future Energy Sources 171
14.5 Exponential Growth in Human Communication 173
14.6 Role of Nanotechnology 175
References 175

Notes 177
Index 199