

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Timetable and Key Achievements	2
1.2	Nobel Prize Winners	12
1.3	General Information	21
 <b>Part I Fundamentals</b>		
<b>2</b>	<b>Bonds</b>	<b>25</b>
2.1	Introduction	25
2.2	Covalent Bonds	25
2.2.1	Electron-Pair Bond	26
2.2.2	$sp^3$ Bonds	26
2.2.3	$sp^2$ Bonds	29
2.3	Ionic Bonds	32
2.4	Mixed Bonds	33
2.5	Metallic Bonding	36
2.6	van-der-Waals Bonds	37
2.7	Hamilton Operator of the Solid	38
<b>3</b>	<b>Crystals</b>	<b>41</b>
3.1	Introduction	41
3.2	Crystal Structure	42
3.3	Lattice	43
3.3.1	Unit Cell	43
3.3.2	Point Group	43
3.3.3	Space Group	45
3.3.4	2D Bravais Lattices	46
3.3.5	3D Bravais Lattices	46
3.3.6	Polycrystalline Semiconductors	51
3.3.7	Amorphous Semiconductors	51

3.4	Important Crystal Structures . . . . .	53
3.4.1	Rocksalt Structure . . . . .	53
3.4.2	CsCl Structure . . . . .	53
3.4.3	Diamond Structure. . . . .	54
3.4.4	Zincblende Structure . . . . .	55
3.4.5	Wurtzite Structure . . . . .	56
3.4.6	Chalcopyrite Structure . . . . .	57
3.4.7	Spinel Structure. . . . .	59
3.4.8	Fluorite Structure. . . . .	61
3.4.9	Delafossite Structure . . . . .	61
3.4.10	Perovskite Structure. . . . .	61
3.4.11	NiAs Structure . . . . .	62
3.4.12	Further Structures . . . . .	63
3.5	Polytypism. . . . .	64
3.6	Reciprocal Lattice . . . . .	66
3.6.1	Reciprocal Lattice Vectors . . . . .	66
3.6.2	Miller Indices . . . . .	67
3.6.3	Brillouin Zone . . . . .	70
3.7	Alloys . . . . .	72
3.7.1	Random Alloys. . . . .	72
3.7.2	Phase Diagram . . . . .	74
3.7.3	Virtual Crystal Approximation . . . . .	77
3.7.4	Lattice Parameter. . . . .	77
3.7.5	Ordering. . . . .	77
<b>4</b>	<b>Defects . . . . .</b>	<b>81</b>
4.1	Introduction . . . . .	81
4.2	Point Defects . . . . .	81
4.2.1	Point Defect Types . . . . .	81
4.2.2	Thermodynamics . . . . .	83
4.2.3	Diffusion . . . . .	85
4.2.4	Dopant Distribution . . . . .	88
4.2.5	Large Concentration Effects . . . . .	92
4.3	Dislocations . . . . .	96
4.3.1	Dislocation Types . . . . .	96
4.3.2	Visualization of Dislocations by Etching . . . . .	100
4.3.3	Impurity Hardening . . . . .	101
4.4	Extended Defects . . . . .	103
4.4.1	Micro-cracks. . . . .	103
4.4.2	Stacking Faults . . . . .	103
4.4.3	Grain Boundaries . . . . .	105
4.4.4	Antiphase and Inversion Domains . . . . .	106
4.5	Disorder. . . . .	110

<b>5</b>	<b>Mechanical Properties</b>	111
5.1	Introduction	111
5.2	Lattice Vibrations	111
5.2.1	Monoatomic Linear Chain	112
5.2.2	Diatomic Linear Chain	115
5.2.3	Lattice Vibrations of a Three-Dimensional Crystal	118
5.2.4	Density of States	121
5.2.5	Phonons	123
5.2.6	Localized Vibrational Modes	124
5.2.7	Phonons in Alloys	127
5.2.8	Disorder	128
5.2.9	Electric Field Created by Optical Phonons	129
5.3	Elasticity	132
5.3.1	Thermal Expansion	132
5.3.2	Stress–Strain Relation	133
5.3.3	Biaxial Strain	137
5.3.4	Three-Dimensional Strain	139
5.3.5	Substrate Bending	141
5.3.6	Scrolling	143
5.4	Plasticity	145
5.4.1	Critical Thickness	145
5.4.2	Cleaving	150
5.4.3	Wafer Breakage	151
<b>6</b>	<b>Band Structure</b>	153
6.1	Introduction	153
6.2	Electrons in a Periodic Potential	154
6.2.1	Bloch’s Theorem	154
6.2.2	Free-Electron Dispersion	155
6.2.3	Non-Vanishing Potential	156
6.2.4	Kramer’s Degeneracy	159
6.2.5	Symmetry Considerations	160
6.3	Band Structures of Selected Semiconductors	162
6.3.1	Silicon	163
6.3.2	Germanium	163
6.3.3	GaAs	163
6.3.4	GaP	163
6.3.5	GaN	163
6.3.6	Lead Salts	163
6.3.7	MgO, ZnO, CdO	164
6.3.8	Chalcopyrites	165
6.3.9	Spinel	166
6.3.10	Delafossites	166
6.3.11	Perovskites	167

6.4	Systematics of Semiconductor Band Gaps . . . . .	168
6.5	Alloy Semiconductors . . . . .	170
6.6	Amorphous Semiconductors . . . . .	173
6.7	Temperature Dependence of the Band Gap . . . . .	174
6.8	Isotope Dependence of the Band Gap . . . . .	176
6.9	Electron Dispersion . . . . .	177
6.9.1	Equation of Electron Motion . . . . .	177
6.9.2	Effective Mass of Electrons . . . . .	178
6.9.3	Nonparabolicity of Electron Mass . . . . .	181
6.10	Holes . . . . .	183
6.10.1	Hole Concept . . . . .	183
6.10.2	Hole Dispersion Relation . . . . .	184
6.10.3	Valence-Band Fine Structure . . . . .	188
6.10.4	Band Inversion . . . . .	189
6.11	Strain Effects on the Band Structure . . . . .	190
6.11.1	Strain Effect on Band Edges . . . . .	191
6.11.2	Strain Effect on Effective Masses . . . . .	193
6.11.3	Interaction with a Localized Level . . . . .	194
6.12	Density of States . . . . .	195
6.12.1	General Band Structure . . . . .	195
6.12.2	Amorphous Semiconductors . . . . .	196
6.12.3	Free-Electron Gas . . . . .	199
<b>7</b>	<b>Electronic Defect States . . . . .</b>	<b>203</b>
7.1	Introduction . . . . .	203
7.2	Carrier Concentration . . . . .	204
7.3	Intrinsic Conduction . . . . .	207
7.4	Doping . . . . .	209
7.4.1	Concept . . . . .	209
7.4.2	Doping Principles . . . . .	210
7.5	Shallow Defects . . . . .	211
7.5.1	Donors . . . . .	211
7.5.2	Acceptors . . . . .	220
7.5.3	Compensation . . . . .	223
7.5.4	Multiple Impurities . . . . .	226
7.5.5	Amphoteric Impurities . . . . .	228
7.5.6	Autodoping . . . . .	229
7.5.7	High Doping . . . . .	230
7.6	Quasi-Fermi Levels . . . . .	234
7.7	Deep Levels . . . . .	235
7.7.1	Charge States . . . . .	236
7.7.2	Double Donors . . . . .	238
7.7.3	Double Acceptors . . . . .	240
7.7.4	Jahn–Teller Effect . . . . .	241
7.7.5	Negative- $U$ Center . . . . .	242

7.7.6	DX Center . . . . .	245
7.7.7	EL2 Defect. . . . .	247
7.7.8	Semi-insulating Semiconductors . . . . .	247
7.7.9	Isoelectronic Impurities . . . . .	249
7.7.10	Surface States . . . . .	251
7.8	Hydrogen in Semiconductors . . . . .	251
<b>8</b>	<b>Transport. . . . .</b>	<b>255</b>
8.1	Introduction . . . . .	255
8.2	Conductivity. . . . .	256
8.3	Low-Field Transport . . . . .	258
8.3.1	Mobility. . . . .	258
8.3.2	Microscopic Scattering Processes. . . . .	259
8.3.3	Ionized Impurity Scattering. . . . .	260
8.3.4	Deformation Potential Scattering . . . . .	261
8.3.5	Piezoelectric Potential Scattering . . . . .	262
8.3.6	Polar Optical Scattering . . . . .	262
8.3.7	Dislocation Scattering . . . . .	263
8.3.8	Grain Boundary Scattering . . . . .	263
8.3.9	Temperature Dependence . . . . .	264
8.3.10	Doping Dependence. . . . .	266
8.3.11	Piezoresistivity . . . . .	267
8.4	High-Field Transport . . . . .	268
8.4.1	Drift-Saturation Velocity . . . . .	269
8.4.2	Negative Differential Resistivity . . . . .	269
8.4.3	Velocity Overshoot . . . . .	270
8.4.4	Impact Ionization. . . . .	271
8.5	High-Frequency Transport . . . . .	275
8.6	Polarons. . . . .	275
8.6.1	Large Polarons . . . . .	275
8.6.2	Small Polarons . . . . .	277
8.7	Hopping Transport . . . . .	278
8.8	Transport in Amorphous Semiconductors . . . . .	280
8.9	Ionic Transport. . . . .	281
8.10	Diffusion . . . . .	282
8.11	Continuity Equation . . . . .	284
8.12	Heat Conduction. . . . .	284
8.13	Coupled Heat and Charge Transport . . . . .	286
8.13.1	Thermopower and Seebeck Effect . . . . .	286
8.13.2	Peltier Effect. . . . .	289
<b>9</b>	<b>Optical Properties. . . . .</b>	<b>291</b>
9.1	Spectral Regions and Overview . . . . .	291
9.2	Complex Dielectric Function . . . . .	292
9.3	Reflection and Diffraction . . . . .	293

9.4	Absorption . . . . .	295
9.5	Electron–Photon Interaction . . . . .	297
9.6	Band–Band Transitions . . . . .	299
9.6.1	Joint Density of States . . . . .	299
9.6.2	Direct Transitions . . . . .	300
9.6.3	Indirect Transitions . . . . .	304
9.6.4	Urbach Tail . . . . .	307
9.6.5	Amorphous Semiconductors . . . . .	308
9.6.6	Excitons . . . . .	309
9.6.7	Phonon Broadening . . . . .	313
9.6.8	Exciton Polariton . . . . .	313
9.6.9	Bound-Exciton Absorption . . . . .	317
9.6.10	Biexcitons . . . . .	319
9.6.11	Trions . . . . .	319
9.6.12	Band Gap Renormalization . . . . .	320
9.6.13	Electron–Hole Droplets . . . . .	321
9.6.14	Two-Photon Absorption . . . . .	322
9.7	Impurity Absorption . . . . .	323
9.7.1	Shallow Levels . . . . .	323
9.7.2	Deep Levels . . . . .	326
9.8	Absorption in the Presence of Free Charge Carriers . . . . .	328
9.8.1	Free-Carrier Absorption . . . . .	328
9.8.2	Burstein–Moss Shift . . . . .	332
9.8.3	Inter-Valenceband Transitions . . . . .	334
9.8.4	Inter-Valley Transitions . . . . .	335
9.8.5	Intra-Band Transitions . . . . .	336
9.9	Lattice Absorption . . . . .	337
9.9.1	Dielectric Constant . . . . .	337
9.9.2	Reststrahlenbande . . . . .	338
9.9.3	Polaritons . . . . .	339
9.9.4	Phonon–Plasmon Coupling . . . . .	340
<b>10</b>	<b>Recombination . . . . .</b>	<b>343</b>
10.1	Introduction . . . . .	343
10.2	Band–Band Recombination . . . . .	344
10.2.1	Spontaneous Emission . . . . .	344
10.2.2	Absorption . . . . .	346
10.2.3	Stimulated Emission . . . . .	347
10.2.4	Net Recombination Rate . . . . .	347
10.2.5	Recombination Dynamics . . . . .	349
10.2.6	Lasing . . . . .	350
10.3	Exciton Recombination . . . . .	351
10.3.1	Free Excitons . . . . .	351
10.3.2	Bound Excitons . . . . .	351
10.3.3	Alloy Broadening . . . . .	358

10.4	Phonon Replica . . . . .	362
10.5	Self-Absorption. . . . .	365
10.6	Donor–Acceptor Pair Transitions. . . . .	366
10.7	Inner-Impurity Recombination . . . . .	367
10.8	Auger Recombination . . . . .	368
10.9	Band–Impurity Recombination . . . . .	370
	10.9.1 Shockley–Read–Hall Kinetics . . . . .	370
	10.9.2 Multilevel Traps . . . . .	374
10.10	ABC Model . . . . .	374
10.11	Field Effect . . . . .	375
	10.11.1 Thermally Activated Emission. . . . .	375
	10.11.2 Direct Tunneling . . . . .	376
	10.11.3 Assisted Tunneling . . . . .	376
10.12	Recombination at Extended Defects. . . . .	377
	10.12.1 Surfaces . . . . .	377
	10.12.2 Grain Boundaries . . . . .	378
	10.12.3 Dislocations . . . . .	378
10.13	Excess-Carrier Profiles. . . . .	379
	10.13.1 Generation at Surface. . . . .	379
	10.13.2 Generation in the Bulk. . . . .	380

## Part II Selected Topics

<b>11</b>	<b>Surfaces . . . . .</b>	<b>385</b>
11.1	Introduction . . . . .	385
11.2	Surface Crystallography . . . . .	386
11.3	Surface Energy . . . . .	387
11.4	Surface Reconstruction . . . . .	388
11.5	Surface Morphology . . . . .	390
11.6	Surface Physical Properties. . . . .	392
	11.6.1 Surface Phonons . . . . .	392
	11.6.2 Surface Plasmons . . . . .	393
	11.6.3 Electronic Surface States . . . . .	395
<b>12</b>	<b>Heterostructures . . . . .</b>	<b>399</b>
12.1	Introduction . . . . .	399
12.2	Heteroepitaxy . . . . .	400
	12.2.1 Growth Methods . . . . .	400
	12.2.2 Substrates. . . . .	400
	12.2.3 Growth Modes . . . . .	403
	12.2.4 Heterosubstrates . . . . .	405
	12.2.5 Patterned Substrates. . . . .	410
	12.2.6 Pseudomorphic Structures. . . . .	412
	12.2.7 Plastic Relaxation . . . . .	413
	12.2.8 Surfactants . . . . .	414

12.3	Energy Levels in Heterostructures . . . . .	415
12.3.1	Band Lineup in Heterostructures . . . . .	415
12.3.2	Quantum Wells . . . . .	417
12.3.3	Superlattices . . . . .	424
12.3.4	Single Heterointerface Between Doped Materials. . .	424
12.4	Recombination in Quantum Wells . . . . .	427
12.4.1	Thickness Dependence . . . . .	427
12.4.2	Broadening Effects . . . . .	428
12.4.3	Quantum Confined Stark Effect. . . . .	431
12.5	Isotope Superlattices . . . . .	433
12.6	Wafer Bonding . . . . .	433
<b>13</b>	<b>External Fields . . . . .</b>	<b>437</b>
13.1	Electric Fields. . . . .	437
13.1.1	Bulk Material . . . . .	437
13.1.2	Quantum Wells . . . . .	439
13.2	Magnetic Fields . . . . .	441
13.2.1	Hall Effect . . . . .	441
13.2.2	Free-Carrier Absorption . . . . .	448
13.2.3	Energy Levels in Bulk Crystals. . . . .	449
13.2.4	Energy Levels in a 2DEG. . . . .	451
13.2.5	Shubnikov–de Haas Oscillations . . . . .	452
13.3	Quantum Hall Effect . . . . .	453
13.3.1	Integral QHE . . . . .	455
13.3.2	Fractional QHE. . . . .	458
13.3.3	Weiss Oscillations . . . . .	460
<b>14</b>	<b>Nanostructures . . . . .</b>	<b>461</b>
14.1	Introduction . . . . .	461
14.2	Quantum Wires. . . . .	462
14.2.1	V-Groove Quantum Wires . . . . .	462
14.2.2	Cleaved-Edge Overgrowth Quantum Wires. . . . .	465
14.2.3	Nanowhiskers . . . . .	465
14.2.4	Nanobelts. . . . .	467
14.2.5	Quantization in Two-Dimensional Potential Wells. . . . .	468
14.3	Quantum Dots . . . . .	471
14.3.1	Quantization in Three-Dimensional Potential Wells. . . . .	471
14.3.2	Electrical and Transport Properties. . . . .	473
14.3.3	Self-Assembled Preparation . . . . .	477
14.3.4	Optical Properties . . . . .	482
<b>15</b>	<b>Polarized Semiconductors . . . . .</b>	<b>489</b>
15.1	Introduction . . . . .	489
15.2	Spontaneous Polarization . . . . .	489



15.3	Ferroelectricity . . . . .	490
15.3.1	Materials . . . . .	492
15.3.2	Soft Phonon Mode . . . . .	492
15.3.3	Phase Transition . . . . .	493
15.3.4	Domains. . . . .	496
15.3.5	Optical Properties . . . . .	497
15.4	Piezoelectricity . . . . .	498
15.4.1	Piezoelectric Effect . . . . .	498
15.4.2	Zincblende Crystals . . . . .	498
15.4.3	Wurtzite Crystals. . . . .	499
15.4.4	Piezoelectric Effects in Nanostructures . . . . .	503
<b>16</b>	<b>Magnetic Semiconductors . . . . .</b>	<b>505</b>
16.1	Introduction . . . . .	505
16.2	Magnetic Semiconductors. . . . .	505
16.3	Diluted Magnetic Semiconductors . . . . .	507
16.4	Spintronics. . . . .	511
16.4.1	Spin Transistor . . . . .	512
16.4.2	Spin LED. . . . .	512
<b>17</b>	<b>Organic Semiconductors . . . . .</b>	<b>515</b>
17.1	Introduction . . . . .	515
17.2	Materials . . . . .	515
17.2.1	Small Organic Molecules, Polymers. . . . .	515
17.2.2	Organic Semiconductor Crystals . . . . .	516
17.3	Electronic Structure. . . . .	519
17.4	Doping . . . . .	520
17.5	Transport Properties . . . . .	521
17.6	Optical Properties . . . . .	522
<b>18</b>	<b>Graphene and Carbon Nanotubes . . . . .</b>	<b>529</b>
18.1	Graphene . . . . .	529
18.1.1	Structure . . . . .	529
18.1.2	Band Structure . . . . .	529
18.1.3	Electrical Properties. . . . .	531
18.1.4	Other Two-Dimensional Crystals. . . . .	536
18.2	Carbon Nanotubes. . . . .	536
18.2.1	Structure . . . . .	536
18.2.2	Band Structure . . . . .	538
18.2.3	Optical Properties . . . . .	541
18.2.4	Other Anorganic Nanotubes . . . . .	541
<b>19</b>	<b>Dielectric Structures . . . . .</b>	<b>545</b>
19.1	Photonic Band Gap Materials . . . . .	545
19.1.1	Introduction . . . . .	545
19.1.2	General 1D Scattering Theory. . . . .	546

19.1.3	Transmission of an $N$ -Period Potential . . . . .	548
19.1.4	The Quarter-Wave Stack . . . . .	550
19.1.5	Formation of a 3D Band Structure. . . . .	552
19.1.6	Disorder. . . . .	558
19.1.7	Defect Modes . . . . .	558
19.1.8	Coupling to an Electronic Resonance. . . . .	562
19.2	Microscopic Resonators . . . . .	565
19.2.1	Microdiscs . . . . .	565
19.2.2	Purcell Effect . . . . .	567
19.2.3	Deformed Resonators. . . . .	568
19.2.4	Hexagonal Cavities . . . . .	571
<b>20</b>	<b>Transparent Conductive Oxide Semiconductors . . . . .</b>	<b>575</b>
20.1	Introduction . . . . .	575
20.2	Materials . . . . .	575
20.3	Properties. . . . .	577
 <b>Part III Applications</b>		
<b>21</b>	<b>Diodes . . . . .</b>	<b>583</b>
21.1	Introduction . . . . .	583
21.2	Metal–Semiconductor Contacts . . . . .	583
21.2.1	Band Diagram in Equilibrium . . . . .	584
21.2.2	Space-Charge Region. . . . .	589
21.2.3	Schottky Effect . . . . .	593
21.2.4	Capacitance . . . . .	594
21.2.5	Current–Voltage Characteristic . . . . .	598
21.2.6	Ohmic Contacts. . . . .	611
21.2.7	Metal Contacts to Organic Semiconductors. . . . .	613
21.3	Metal–Insulator–Semiconductor Diodes . . . . .	615
21.3.1	Band Diagram for Ideal MIS Diode. . . . .	616
21.3.2	Space-Charge Region. . . . .	619
21.3.3	Capacitance . . . . .	623
21.3.4	Nonideal MIS Diode . . . . .	624
21.4	Bipolar Diodes . . . . .	626
21.4.1	Band Diagram. . . . .	626
21.4.2	Space-Charge Region. . . . .	626
21.4.3	Capacitance . . . . .	632
21.4.4	Current–Voltage Characteristics. . . . .	633
21.4.5	Breakdown. . . . .	644
21.4.6	Heterostructure Diodes. . . . .	649
21.4.7	Organic Semiconductor Diodes . . . . .	650
21.5	Applications and Special Diode Devices . . . . .	652
21.5.1	Rectification . . . . .	653
21.5.2	Frequency Mixing . . . . .	655

21.5.3	Voltage Regulator . . . . .	656
21.5.4	Zener Diodes . . . . .	658
21.5.5	Varactors . . . . .	658
21.5.6	Fast-Recovery Diodes . . . . .	660
21.5.7	Step-Recovery Diodes . . . . .	661
21.5.8	Pin-Diodes . . . . .	662
21.5.9	Tunneling Diodes . . . . .	663
21.5.10	Backward Diodes . . . . .	666
21.5.11	Gunn Diodes . . . . .	667
<b>22</b>	<b>Light-to-Electricity Conversion . . . . .</b>	<b>669</b>
22.1	Photocatalysis . . . . .	669
22.2	Photoconductors . . . . .	670
22.2.1	Introduction . . . . .	670
22.2.2	Photoconductivity Detectors . . . . .	671
22.2.3	Electrophotography . . . . .	674
22.2.4	QWIPs . . . . .	675
22.2.5	Blocked Impurity-Band Detectors . . . . .	678
22.3	Photodiodes . . . . .	680
22.3.1	Introduction . . . . .	680
22.3.2	pn Photodiodes . . . . .	681
22.3.3	Pin Photodiodes . . . . .	684
22.3.4	Position-Sensing Detector . . . . .	686
22.3.5	MSM Photodiodes . . . . .	686
22.3.6	Avalanche Photodiodes . . . . .	692
22.3.7	Traveling-Wave Photodetectors . . . . .	695
22.3.8	Charge Coupled Devices . . . . .	698
22.3.9	Photodiode Arrays . . . . .	705
22.4	Solar Cells . . . . .	707
22.4.1	Solar Radiation . . . . .	708
22.4.2	Ideal Solar Cells . . . . .	709
22.4.3	Real Solar Cells . . . . .	714
22.4.4	Design Refinements . . . . .	715
22.4.5	Modules . . . . .	716
22.4.6	Solar-Cell Types . . . . .	718
22.4.7	Commercial Issues . . . . .	721
<b>23</b>	<b>Electricity-to-Light Conversion . . . . .</b>	<b>725</b>
23.1	Radiometric and Photometric Quantities . . . . .	725
23.1.1	Radiometric Quantities . . . . .	725
23.1.2	Photometric Quantities . . . . .	725
23.2	Scintillators . . . . .	727
23.2.1	CIE Chromaticity Diagram . . . . .	727
23.2.2	Display Applications . . . . .	730

23.2.3	Radiation Detection . . . . .	731
23.2.4	Luminescence Mechanisms . . . . .	732
23.3	Light-Emitting Diodes . . . . .	733
23.3.1	Introduction . . . . .	733
23.3.2	Spectral Ranges. . . . .	734
23.3.3	Efficiencies. . . . .	735
23.3.4	Device Design . . . . .	736
23.3.5	White LEDs . . . . .	743
23.3.6	Quantum Dot LEDs . . . . .	746
23.3.7	Organic LEDs . . . . .	747
23.4	Lasers . . . . .	749
23.4.1	Introduction . . . . .	749
23.4.2	Applications . . . . .	750
23.4.3	Gain . . . . .	752
23.4.4	Optical Mode . . . . .	755
23.4.5	Loss Mechanisms . . . . .	762
23.4.6	Threshold. . . . .	763
23.4.7	Spontaneous Emission Factor . . . . .	765
23.4.8	Output Power . . . . .	766
23.4.9	Temperature Dependence . . . . .	768
23.4.10	Mode Spectrum. . . . .	769
23.4.11	Longitudinal Single-Mode Lasers . . . . .	770
23.4.12	Tunability. . . . .	771
23.4.13	Dynamics and Modulation . . . . .	774
23.4.14	Surface-Emitting Lasers . . . . .	778
23.4.15	Optically Pumped Semiconductor Lasers . . . . .	782
23.4.16	Quantum Cascade Lasers . . . . .	783
23.4.17	Hot-Hole Lasers . . . . .	784
23.5	Semiconductor Optical Amplifiers . . . . .	785
<b>24</b>	<b>Transistors . . . . .</b>	<b>787</b>
24.1	Introduction . . . . .	787
24.2	Bipolar Transistors . . . . .	788
24.2.1	Carrier Density and Currents. . . . .	790
24.2.2	Current Amplification . . . . .	792
24.2.3	Ebers–Moll Model. . . . .	794
24.2.4	Current–Voltage Characteristics. . . . .	796
24.2.5	Basic Circuits . . . . .	798
24.2.6	High-Frequency Properties . . . . .	800
24.2.7	Heterojunction Bipolar Transistors . . . . .	800
24.2.8	Light-Emitting Transistors . . . . .	801
24.3	Field-Effect Transistors . . . . .	802
24.4	JFET and MESFET. . . . .	804
24.4.1	General Principle. . . . .	804
24.4.2	Static Characteristics . . . . .	805

24.4.3	Normally on and Normally Off FETs . . . . .	809
24.4.4	Field-Dependent Mobility . . . . .	809
24.4.5	High-Frequency Properties . . . . .	812
24.5	MOSFETs . . . . .	812
24.5.1	Operation Principle . . . . .	812
24.5.2	Current–Voltage Characteristics . . . . .	814
24.5.3	MOSFET Types . . . . .	818
24.5.4	Complementary MOS . . . . .	818
24.5.5	Large-Scale Integration . . . . .	821
24.5.6	Tunneling FETs . . . . .	829
24.5.7	Nonvolatile Memories . . . . .	830
24.5.8	Heterojunction FETs . . . . .	833
24.6	Thin-Film Transistors . . . . .	837
24.6.1	Annealing of Amorphous Silicon . . . . .	837
24.6.2	TFT Devices . . . . .	838
24.6.3	OFETs . . . . .	839
<b>Appendix A: Tensors . . . . .</b>		<b>843</b>
<b>Appendix B: Point and Space Groups . . . . .</b>		<b>847</b>
<b>Appendix C: Kramers–Kronig Relations . . . . .</b>		<b>851</b>
<b>Appendix D: Oscillator Strength . . . . .</b>		<b>853</b>
<b>Appendix E: Quantum Statistics . . . . .</b>		<b>859</b>
<b>Appendix F: Kronig–Penney Model . . . . .</b>		<b>865</b>
<b>Appendix G: The <math>k \cdot p</math> Perturbation Theory . . . . .</b>		<b>869</b>
<b>Appendix H: Effective-Mass Theory . . . . .</b>		<b>873</b>
<b>Appendix I: Boltzmann Transport Theory . . . . .</b>		<b>875</b>
<b>Appendix J: Noise . . . . .</b>		<b>881</b>
<b>References . . . . .</b>		<b>891</b>
<b>Index . . . . .</b>		<b>967</b>

<http://www.springer.com/978-3-319-23879-1>

The Physics of Semiconductors

An Introduction Including Nanophysics and Applications

Grundmann, M.

2016, XXXIX, 989 p. 855 illus., 200 illus. in color.,

Hardcover

ISBN: 978-3-319-23879-1