

Contents

1	Basic characteristics of semiconductors	1
1.1	Qualitative properties	1
1.2	Composition of semiconductors	2
1.3	Structure of solids	2
1.3.1	Crystalline and amorphous forms	2
1.3.2	Lattice and basis	3
1.3.3	Bravais lattices	3
1.3.4	Crystallographic terminology	5
1.3.5	Structures of semiconductors	6
1.4	Chemical bonding in semiconductors	10
1.4.1	Diamond structure semiconductors	10
1.4.2	Zincblende structure semiconductors	11
1.4.3	III–VI layered semiconductors	13
1.4.4	Wurtzite structure semiconductors	14
1.4.5	IV–VI semiconductors	14
1.5	Growth of pure semiconductor crystals	14
	Problems	16
	References	16
2	Electronic energy bands: basic theory	17
2.1	Schrödinger equation	18
2.2	Electrons in a periodic potential	20
2.3	Schrödinger equation for a periodic potential	22
2.4	Expansion of the eigenfunction in plane waves	24
2.5	Bloch's theorem	25
2.6	Electrons in a weak periodic potential	26
2.7	Brillouin zones	28
2.8	Energy bands and energy band gaps	30
2.9	Tight binding method	35
2.9.1	Wannier functions	35
2.9.2	LCAO method	36
	Problems	41
	References	42
3	Electronic energy bands: semiconductors	43
3.1	Spin–orbit interaction	44
3.2	Electron–ion interaction and pseudopotentials	46
3.2.1	Orthogonalized plane wave method	46
3.2.2	Pseudopotential method	47

Contents

3.3	Electron–electron interaction	53
3.3.1	Hartree method	54
3.3.2	Hartree–Fock method	54
3.3.3	Density functional method	55
3.3.4	Excited electronic states	57
3.4	The $k \cdot p$ method	57
3.4.1	Nondegenerate bands	58
3.4.2	Valence bands of Si and Ge	60
3.4.3	Conduction bands of Si and Ge	62
3.4.4	Zincblende structure semiconductors	63
3.4.5	Extended $k \cdot p$ method	64
3.4.6	Nonparabolic bands: the Kane model	65
3.5	Energy band structures for specific semiconductors	66
3.5.1	Elemental semiconductors	66
3.5.2	III–V semiconductors	67
3.5.3	II–VI and IV–VI semiconductors	68
3.6	Modification of energy band gaps	68
3.6.1	Semiconductor alloys	68
3.6.2	Temperature and pressure dependence of band gaps	69
3.7	Amorphous semiconductors	70
	Problems	71
	References	71

4 Kinematics and dynamics of electrons and holes in energy bands **73**

4.1	Group velocity	74
4.2	Inverse effective mass tensor	75
4.3	Force equation	76
4.4	Dynamics of electrons	76
4.5	Dynamics of holes	77
4.6	Experimental determination of effective masses: cyclotron resonance in semiconductors	79
4.6.1	Cyclotron resonance of conduction electrons in Ge and Si	81
4.6.2	Cyclotron resonance of holes in Ge and Si	83
4.6.3	Effective masses of carriers in compound semiconductors	84
4.7	Experimental determination of carrier charge and concentration: Hall effect	85
	Problems	87
	References	87

5 Electronic effects of impurities **89**

5.1	Qualitative aspects of impurities	90
5.2	Effective mass theory	90

Contents

5.3	Donor impurities in Si and Ge	93
5.3.1	Effects of ellipsoidal constant energy surfaces	93
5.3.2	Valley-orbit interaction	93
5.4	Donor impurities in III-V semiconductors	94
5.5	Acceptor impurities	95
5.6	Central cell corrections and deep levels	97
5.7	Impurity bands	98
	Problems	99
	References	99
6	Semiconductor statistics	101
6.1	Intrinsic semiconductors	102
6.1.1	Spherical parabolic energy bands	103
6.1.2	Ellipsoidal energy bands	106
6.1.3	Multiple valence bands	107
6.2	Extrinsic semiconductors	109
6.2.1	Donor impurities	110
6.2.2	Acceptor impurities	113
6.2.3	Compensated semiconductors	115
6.2.4	Majority and minority carriers	116
6.2.5	Contribution of excited impurity states	117
	Problems	119
	References	119
7	Lattice vibrations in semiconductors	121
7.1	Equations of motion	122
7.2	Monatomic linear chain	125
7.3	Diatomic linear chain	126
7.4	Three-dimensional crystals	129
7.4.1	Elastic continuum theory	129
7.4.2	Three-dimensional lattices	131
7.5	Lattice dynamical models for semiconductors	133
7.5.1	Homopolar semiconductors	134
7.5.2	Heteropolar semiconductors	135
7.5.3	First-principles methods	139
7.6	Normal coordinate transformation	140
7.7	Vibrational specific heat	141
7.8	Anharmonic effects	143
7.8.1	Thermal expansion	143
7.8.2	Thermal conductivity	144
7.9	Impurity effects on lattice vibrations	145
7.10	Piezoelectric effects	148
7.11	Effects of stress-induced atomic displacements	149
	Problems	150
	References	151

Contents

8	Charge carrier scattering and transport properties	153
8.1	Simple phenomenological introduction to transport in semiconductors	154
8.1.1	Electric conduction current	154
8.1.2	Conductivity effective mass	157
8.1.3	Diffusion current	159
8.1.4	Displacement current	160
8.2	The Boltzmann equation and its solution	161
8.3	Electrical conductivity and mobility	163
8.4	Energy dependence of the relaxation time	167
8.5	Relaxation times for specific scattering mechanisms	169
8.5.1	Ionized impurity scattering	169
8.5.2	Neutral impurity scattering	174
8.5.3	Lattice vibrational scattering	174
8.6	Magnetotransport properties	186
8.6.1	Magnetoresistance	186
8.6.2	Hall effect	189
8.7	Thermoelectric phenomena	192
8.7.1	Thermoelectric power	192
8.7.2	Thermoelectric devices	194
8.8	Thermal conductivity	195
8.9	Semi-insulating semiconductors	196
8.9.1	Pure GaAs	196
8.9.2	Impure GaAs: shallow impurities	196
8.9.3	Impure GaAs: deep impurities	197
8.10	Hot carrier phenomena	198
8.10.1	Distribution function in high electric fields	198
8.10.2	Gunn effect	199
8.10.3	Field ionization	200
8.10.4	Impact ionization	200
8.11	Variable-range hopping conductivity	203
	Problems	203
	References	204
9	Surface properties of semiconductors	205
9.1	Surface effects on electronic states	206
9.1.1	Nearly free electron approximation	206
9.1.2	Tight binding method	210
9.2	Surface effects on lattice vibrations	215
9.2.1	Surface acoustic modes	215
9.2.2	Surface optical modes	219
9.2.3	Surface vibrational modes in real semiconductors	221
9.2.4	Experimental observation of surface vibrational modes	221
9.3	Surface recombination	223
	Problems	225
	References	225

10	Optical properties of semiconductors	227
10.1	Fundamentals of electromagnetic response	228
10.1.1	Maxwell's equations	228
10.1.2	Propagation of an electromagnetic wave in a conducting medium	230
10.1.3	Optical constants	232
10.1.4	Dielectric function of a crystal	234
10.1.5	Optical spectroscopies	234
10.2	Intrinsic interband absorption	235
10.2.1	Absorption coefficient	235
10.2.2	Transition probability	237
10.2.3	Oscillator strength	240
10.2.4	Excitons	241
10.2.5	Burstein–Moss effect	241
10.2.6	Indirect interband absorption	242
10.2.7	Extrinsic interband absorption	244
10.2.8	Interband absorption in amorphous semiconductors	244
10.3	Optical properties of free carriers	245
10.3.1	Free carrier absorption	245
10.3.2	Free carrier reflectivity	249
10.4	Absorption due to electronic transitions of impurities	250
10.5	Optical properties due to lattice vibrations	251
10.5.1	Dielectric response of polar lattice vibrations	251
10.5.2	Lattice vibration absorption	255
10.6	Radiative recombination	256
10.6.1	Internal quantum efficiency	256
10.6.2	Carrier lifetime limited by band-to-band recombination	258
10.7	Surface polaritons	261
10.7.1	Surface plasmon polaritons	263
10.7.2	Surface optical phonon polaritons	263
10.7.3	Experimental observation of surface polaritons	263
10.8	Light scattering	264
10.8.1	Brillouin scattering	264
10.8.2	Raman scattering	265
10.8.3	Anharmonic effects on Raman spectra	274
10.8.4	Light scattering due to electronic excitations	275
10.9	Photoemission	276
10.9.1	Direct photoemission	276
10.9.2	Inverse photoemission	277
10.9.3	Surface state energies	278
	Problems	278
	References	279
11	Magneto-optical and electro- optical phenomena	281
11.1	Frequency-dependent conductivity tensor	282

Contents

11.2	Propagation of an electromagnetic wave in the presence of a magnetic field	284
11.2.1	Longitudinal propagation, $k \parallel \mathcal{B}_0$	284
11.2.2	Transverse propagation, $k \perp \mathcal{B}_0$	285
11.3	Macroscopic expressions for magnetodispersion and magneto-absorption	286
11.3.1	Longitudinal propagation: Faraday configuration	286
11.3.2	Transverse propagation: Voigt configuration	288
11.4	Faraday rotation due to intraband transitions	289
11.4.1	Classical model for Faraday rotation due to free carriers	289
11.4.2	Conductivity tensor deduced from the Boltzmann equation	290
11.4.3	Analysis of the effective mass obtained by Faraday rotation	291
11.4.4	Cyclotron resonance absorption	292
11.5	Electronic eigenstates in a constant magnetic field	293
11.6	Quantum mechanical theory of cyclotron resonance	295
11.7	Interband magneto-absorption	298
11.8	Electro-optical effects	300
11.8.1	Pockels effect	300
11.8.2	Kerr effect	301
11.8.3	Franz–Keldysh effect	301
11.9	Modulation spectroscopy	303
	Problems	304
	References	304

12 P–N junctions in semiconductors **307**

12.1	Abrupt junction at thermal equilibrium	308
12.1.1	Space charge region	309
12.1.2	Charge density variation	310
12.1.3	Diffusion potential	311
12.1.4	Electric field in the space charge region	313
12.1.5	Electronic energy bands in the space charge region	314
12.1.6	Width of the space charge region	315
12.1.7	Physical interpretation of the Debye length	317
12.2	P–N junction under an applied voltage	318
12.2.1	Qualitative effects of an applied voltage	318
12.2.2	Forward bias: n-type region biased negatively	318
12.2.3	Reverse bias: n-type region biased positively	320
12.2.4	Qualitative description of current flow in a biased junction	320
12.2.5	Quantitative treatment of current flow in a biased junction	321
12.3	Graded p–n junction	329
12.4	P–N junction capacitance	332
12.4.1	Storage capacitance	333
12.4.2	Transition capacitance	333
12.4.3	Applications of p–n junction capacitance	334

12.5	Avalanche breakdown and Zener breakdown	335
12.5.1	Avalanche breakdown	335
12.5.2	Zener breakdown	336
	Problems	336
	References	337
13	Bipolar junction transistor	339
13.1	Fabrication of transistors	340
13.2	Physical basis of the BJT	341
13.3	DC characteristics of the BJT	342
13.3.1	Injected minority carrier concentrations	342
13.3.2	Currents in the BJT	344
13.3.3	Current gain in the BJT	347
13.4	Small-signal characteristics of the BJT	350
	Problems	351
	References	352
14	Semiconductor lasers and photodevices	353
14.1	General features of stimulated emission	354
14.2	Physical basis of semiconductor lasers	355
14.2.1	Qualitative aspects	355
14.2.2	Optical gain in direct gap semiconductors	355
14.2.3	Transparency current density	360
14.2.4	Current density–gain relationship	362
14.2.5	Threshold condition in a Fabry–Perot cavity	363
14.2.6	Light-emitting diodes	364
14.3	Photodetectors	364
14.3.1	Photoconductive gain	364
14.3.2	Responsivity and detectivity	366
14.4	Solar cells	368
	Problems	369
	References	369
15	Heterostructures: electronic states	371
15.1	Heterojunctions	372
15.2	Free charge carrier transfer	373
15.3	Triangular quantum well	373
15.4	Square quantum well	377
15.4.1	Conduction electron energy levels	377
15.4.2	Hole energy levels	380
15.5	Density-of-states of quantum wells	382
15.6	Excitons and shallow impurities in quantum wells	382
15.7	Coupled quantum wells and superlattices	384
15.7.1	Double-well structure	384
15.7.2	Superlattices: periodic coupled quantum wells	385
15.8	Modulation doping of heterostructures	387
15.9	Self-consistent energy-level calculations	388
15.10	N–I–P–I structures	390
	Problems	392
	References	392

16	Phonons in superlattices	393
16.1	Qualitative aspects of phonons in superlattices	394
16.2	Elastic continuum theory of low-frequency modes	394
16.3	Dielectric continuum theory of optical modes	397
16.4	Microscopic theory of optical modes	400
16.4.1	Linear chain model	401
16.4.2	Three-dimensional models	403
	Problems	403
	References	404
17	Optical properties of heterostructures	405
17.1	Optical absorption due to electronic transitions	406
17.1.1	Intrasubband transitions	407
17.1.2	Intersubband transitions in the same band	407
17.1.3	Interband transitions	409
17.1.4	Interband optical transitions in superlattices	414
17.1.5	Optical absorption by excitons in heterostructures	414
17.2	Photoluminescence in two-dimensional systems	417
17.2.1	Experimental techniques	417
17.2.2	Quantum well luminescence	418
	Problems	419
	References	420
18	Transport properties of heterostructures	421
18.1	Effects of a constant electric field	422
18.1.1	Electric field parallel to the interfaces: $\mathcal{E} \parallel \hat{x}$	422
18.1.2	Electric field perpendicular to the interfaces: $\mathcal{E} \parallel \hat{z}$	423
18.2	Effects of a constant magnetic field	425
18.2.1	Energy levels and wave functions	425
18.2.2	Magnetic-field-dependent density-of-states	426
18.2.3	Magnetoconductivity in a 2D heterostructure	427
18.2.4	Cyclotron resonance	431
	Problems	432
	References	432
19	Metal-semiconductor devices	435
19.1	Metal-oxide-semiconductor capacitor	436
19.1.1	Effect of applied bias on energy bands	437
19.1.2	Bias dependence of capacitance	437
19.1.3	Evaluation of capacitance versus voltage curves	440
19.1.4	Applications of the metal-oxide-semiconductor	444
19.2	Metal-semiconductor diode	444
19.2.1	Equilibrium characteristics of the MS diode	444
19.2.2	Current under applied voltage	446
19.3	Metal-oxide-semiconductor field effect transistor	448
19.3.1	Introduction	448
19.3.2	DC characteristics of the MOSFET	450

Problems	455
References	455
20 Applications of semiconductor heterostructures	457
20.1 Devices with transport parallel to the interfaces:	
field effect transistor	458
20.1.1 Analysis of physical processes	458
20.1.2 Analysis of device performance	460
20.1.3 Semiconductor–insulator–semiconductor field effect transistor (SISFET)	461
20.2 Devices with transport perpendicular to the interfaces	461
20.2.1 Heterostructure double-barrier diode	462
20.2.2 Heterojunction bipolar transistor	463
20.3 Quantum well lasers	464
20.3.1 Double-heterostructure lasers	464
20.3.2 Single quantum well (SQW) lasers	465
20.3.3 Multiple quantum well (MQW) lasers	467
20.4 One-dimensional and zero-dimensional quantum structures	468
20.4.1 Theoretical background	469
20.4.2 Fabrication techniques for 1D and 0D structures	470
20.4.3 Electrical applications of 1D and 0D structures	471
20.4.4 Devices based on 1D and 0D structures	473
20.4.5 1D and 0D optical phenomena	473
20.4.6 1D and 0D optical devices	474
20.5 Devices based on electro-optic effects in quantum well structures	475
20.5.1 Quantum-confined Stark effect	475
20.5.2 Quantum well modulators	475
20.5.3 Self-electro-optic-effect devices	476
Problems	477
References	478
Index	479