

Contents

Preface *XIII*

1	Introduction	1
1.1	Preliminary remarks	1
1.2	Mesoscopic transport	2
1.2.1	Ballistic transport	3
1.2.2	The quantum Hall effect and Shubnikov–de Haas oscillations	5
1.2.3	Size quantization	7
1.2.4	Phase coherence	8
1.2.5	Single-electron tunneling and quantum dots	9
1.2.6	Superlattices	10
1.2.7	Spintronics	11
1.2.8	Samples, experimental techniques, and technological relevance	11
2	An update of solid state physics	15
2.1	Crystal structures	16
2.2	Electronic energy bands	18
2.3	Occupation of energy bands	27
2.3.1	The electronic density of states	27
2.3.2	Occupation probability and chemical potential	29
2.3.3	Intrinsic carrier concentration	29
2.3.4	Bloch waves and localized electrons	31
2.4	Envelope wave functions	32
2.5	Doping	36
2.6	Diffusive transport and the Boltzmann equation	40
2.6.1	The Boltzmann equation	41
2.6.2	The conductance predicted by the simplified Boltzmann equation	44
2.6.3	The magneto-resistivity tensor	46
2.6.4	Diffusion currents	47

2.7	Scattering mechanisms	48
2.8	Screening	50
3	Surfaces, interfaces, and layered devices	57
3.1	Electronic surface states	59
3.1.1	Surface states in one dimension	59
3.1.2	Surfaces of three-dimensional crystals	65
3.1.3	Band bending and Fermi level pinning	67
3.2	Semiconductor–metal interfaces	68
3.2.1	Band alignment and Schottky barriers	69
3.2.1.1	The Schottky model	72
3.2.1.2	The Schottky diode	73
3.2.2	Ohmic contacts	73
3.3	Semiconductor heterointerfaces	74
3.4	Field effect transistors and quantum wells	77
3.4.1	The silicon metal–oxide–semiconductor field effect transistor	77
3.4.1.1	The MOSFET and digital electronics	81
3.4.2	The Ga[Al]As high electron mobility transistor	84
3.4.3	Other types of layered devices	87
3.4.3.1	The AlSb–InAs–AlSb quantum well	87
3.4.3.2	Hole gas in Si–Si _{1–x} Ge _x –Si quantum wells	89
3.4.3.3	Organic FETs	89
3.4.4	Quantum confined carriers in comparison to bulk carriers	91
4	Experimental techniques	97
4.1	Sample preparation	97
4.1.1	Single crystal growth	98
4.1.2	Growth of layered structures	100
4.1.2.1	Metal organic chemical vapor deposition (MOCVD)	101
4.1.2.2	Molecular beam epitaxy (MBE)	101
4.1.3	Lateral patterning	107
4.1.3.1	Defining patterns in resists	107
4.1.3.2	Direct writing methods	110
4.1.3.3	Etching	112
4.1.4	Metallization	113
4.1.5	Bonding	115
4.2	Elements of cryogenics	116
4.2.1	Properties of liquid helium	117
4.2.1.1	Some properties of pure ⁴ He	117
4.2.1.2	Some properties of pure ³ He	120
4.2.1.3	The ³ He/ ⁴ He mixture	121
4.2.2	Helium cryostats	122

4.2.2.1	^4He cryostats	122
4.2.2.2	^3He cryostats	125
4.2.2.3	$^3\text{He}/^4\text{He}$ dilution refrigerators	125
4.3	Electronic measurements on nanostructures	127
4.3.1	Sample holders	128
4.3.2	Application and detection of electronic signals	128
4.3.2.1	General considerations	128
4.3.2.2	Voltage and current sources	129
4.3.2.3	Signal detectors	130
4.3.2.4	Some important measurement setups	133
5	Important quantities in mesoscopic transport	139
5.1	Fermi wavelength	139
5.2	Elastic scattering times and lengths	139
5.3	Diffusion constant	140
5.4	Dephasing time and phase coherence length	143
5.5	Electron–electron scattering time	144
5.6	Thermal length	144
5.7	Localization length	145
5.8	Interaction parameter (or gas parameter)	145
5.9	Magnetic length and magnetic time	145
6	Magneto-transport properties of quantum films	147
6.1	Landau quantization	148
6.1.1	Two-dimensional electron gases in perpendicular magnetic fields	148
6.1.2	The chemical potential in strong magnetic fields	151
6.2	The quantum Hall effect	154
6.2.1	Phenomenology	154
6.2.2	Toward an explanation of the integer quantum Hall effect	156
6.2.3	The quantum Hall effect and three dimensions	161
6.3	Elementary analysis of Shubnikov–de Haas oscillations	162
6.4	Some examples of magneto-transport experiments	165
6.4.1	Quasi-two-dimensional electron gases	165
6.4.2	Mapping of the probability density	167
6.4.3	Displacement of the quantum Hall plateaux	167
6.5	Parallel magnetic fields	169
7	Quantum wires and quantum point contacts	177
7.1	Diffusive quantum wires	179
7.1.1	Basic properties	179
7.1.2	Boundary scattering	181

7.2	Ballistic quantum wires	182
7.2.1	Phenomenology	182
7.2.2	Conductance quantization in QPCs	184
7.2.3	Magnetic field effects	191
7.2.4	The “0.7 structure”	195
7.2.5	Four-probe measurements on ballistic quantum wires	195
7.3	The Landauer–Büttiker formalism	198
7.3.1	Edge states	199
7.3.2	Edge channels	202
7.4	Further examples of quantum wires	204
7.4.1	Conductance quantization in conventional metals	204
7.4.2	Molecular wires	206
7.4.2.1	Carbon nanotubes	206
7.5	Quantum point contact circuits	210
7.5.1	Non-Ohmic behavior of QPCs in series	210
7.5.2	QPCs in parallel	212
7.6	Semiclassical limit: conductance of ballistic 2D systems	214
7.7	Concluding remarks	218
8	Electronic phase coherence	223
8.1	The Aharonov–Bohm effect in mesoscopic conductors	223
8.2	Weak localization	226
8.3	Universal conductance fluctuations	229
8.4	Phase coherence in ballistic 2DEGs	234
8.5	Resonant tunneling and s-matrices	236
9	Single-electron tunneling	247
9.1	The principle of Coulomb blockade	247
9.2	Basic single-electron tunneling circuits	250
9.2.1	Coulomb blockade at the double barrier	252
9.2.2	Current–voltage characteristics: The Coulomb staircase	255
9.2.3	The SET transistor	259
9.3	SET circuits with many islands: The single-electron pump	265
10	Quantum dots	273
10.1	Phenomenology of quantum dots	274
10.2	The constant interaction model	279
10.2.1	Quantum dots in intermediate magnetic fields	283
10.2.2	Quantum rings	285
10.3	Beyond the constant interaction model	287
10.3.1	Hund’s rules in quantum dots	287
10.3.2	Quantum dots in strong magnetic fields	287

10.3.3	The distribution of nearest-neighbor spacings	290
10.4	Shape of conductance resonances and I–V characteristics	294
10.5	Other types of quantum dots	297
10.5.1	Metal grains	298
10.5.2	Molecular quantum dots	299
10.6	Quantum dots and quantum computation	301
11	Mesoscopic superlattices	309
11.1	One-dimensional superlattices	310
11.2	Two-dimensional superlattices	312
11.2.1	Semiclassical effects	312
11.2.2	Quantum effects	318
12	Spintronics	323
12.1	Ferromagnetic sandwich structures	324
12.1.1	Tunneling magneto-resistance (TMR) and giant magneto-resistance (GMR)	324
12.1.2	Spin injection into a non-magnetic conductor	328
12.2	The Datta–Das spin field effect transistor	332
12.2.1	Concept of the Datta–Das transistor	332
12.2.2	Spin injection in semiconductors	333
12.2.2.1	Interface tunnel barriers	333
12.2.2.2	Ferromagnetic semiconductors	335
12.2.3	Gate-induced spin rotation: The Rashba effect	336
12.2.4	Spin relaxation and spin dephasing	339
A	SI and cgs units	343
B	Correlation and convolution	345
B.1	Fourier transformation	345
B.2	Convolutions	345
B.3	Correlation functions	347
C	Capacitance matrix and electrostatic energy	349
D	The transfer Hamiltonian	353
E	Solutions to selected exercises	355
	References	383
	Index	393