

Contents

Preface — VII

1 Introduction — 1

2 Low-dimensional semiconductor structures — 7

- 2.1 Overview — 7
- 2.2 Bulk semiconductors — 8
 - 2.2.1 Band structure — 8
 - 2.2.2 Effective mass — 10
 - 2.2.3 Density of states — 12
 - 2.2.4 Intrinsic semiconductors — 14
- 2.3 Doped semiconductors — 16
- 2.4 Transport — 18
 - 2.4.1 Classical diffusive transport — 18
 - 2.4.2 Einstein relation — 19
 - 2.4.3 Mobility — 20
 - 2.4.4 Characteristic length scales — 21
- 2.5 Layer systems — 24
 - 2.5.1 Semiconductor heterostructures — 24
 - 2.5.2 Two-dimensional electron gases — 26
- 2.6 Quantum wires and nanowires — 28
 - 2.6.1 Electron beam lithography — 28
 - 2.6.2 Semiconductor nanowires — 30
 - 2.6.3 Split-gate quantum point contacts — 31
- 2.7 Zero-dimensional structures: quantum dots — 34
 - 2.7.1 Transport at small source-drain bias voltages — 35
 - 2.7.2 Transport as a function of source-drain bias voltage — 37
- 2.8 Transport in a quantizing magnetic field — 39
 - 2.8.1 Landau quantization — 40
 - 2.8.2 Magnetic edge states — 42
- 2.9 Summary — 48

3 Magnetism in solids — 49

- 3.1 Definitions and basics — 49
 - 3.1.1 Definitions — 49
 - 3.1.2 Magnetization — 49
 - 3.1.3 Magnetic moments of electrons in atomic orbitals — 50
 - 3.1.4 The electron spin — 51
- 3.2 Classification — 54

3.3	Paramagnetism — 55
3.3.1	Paramagnetism of localized moments — 55
3.3.2	Hund's rule — 58
3.3.3	Pauli paramagnetism — 59
3.4	Collective magnetism — 60
3.4.1	Exchange interaction — 60
3.4.2	Stoner model — 63
3.5	Summary — 67
4	Diluted magnetic semiconductors — 69
4.1	Overview — 69
4.2	II-VI diluted magnetic semiconductors — 70
4.3	III-V diluted magnetic semiconductors — 75
4.4	Transport properties of III-V diluted magnetic semiconductors — 83
4.5	Summary — 87
5	Magnetic electrodes — 89
5.1	Overview — 89
5.2	Formation of magnetic domains — 90
5.2.1	Magnetic stray field — 90
5.2.2	Crystal anisotropy — 91
5.2.3	Form anisotropy contribution — 92
5.2.4	Exchange energy contribution — 93
5.3	Domain walls — 93
5.4	Ferromagnetic electrodes — 96
5.5	Local Hall effect measurements — 99
5.6	Micromagnetic simulations — 101
5.7	Domain wall motion — 104
5.8	Summary — 107
6	Spin injection — 109
6.1	Overview — 109
6.2	Resistor model — 110
6.3	Local description of spin injection — 114
6.4	Optical detection of spin-polarized carriers — 121
6.5	Experiments on optical detection of spin polarization — 125
6.6	Injection through a barrier — 128
6.6.1	Free electron approximation — 128
6.6.2	Diffusive transport regime — 133
6.7	Experiments on spin injectors with interface barriers — 136
6.8	Nonlocal spin injection — 138

6.9	Optical spin generation —	142
6.9.1	Optical absorption —	142
6.9.2	Optical detection of magnetization —	143
6.9.3	Pump-probe experiments —	144
6.10	Summary —	146
7	Spin transistor —	149
7.1	Overview —	149
7.2	InAs-based two-dimensional electron gases —	150
7.3	The Rashba effect —	152
7.4	Strength of the Rashba spin-orbit coupling —	156
7.4.1	The $k \cdot p$ method —	156
7.4.2	Envelope function approach —	158
7.5	Magnetoresistance measurements —	162
7.5.1	Beating patterns due to the Rashba effect —	162
7.5.2	Gate-control of the Rashba effect —	166
7.6	Bulk inversion asymmetry —	167
7.6.1	Time-reversal symmetry —	168
7.6.2	Spatial inversion symmetry —	169
7.6.3	Dresselhaus term —	170
7.7	Rashba effect in quasi one-dimensional structures —	173
7.7.1	Rashba effect in planar quasi one-dimensional structures —	174
7.7.2	Rashba effect in tubular structures —	178
7.8	Summary —	184
8	Spin interference —	187
8.1	Overview —	187
8.2	Electron interference effects —	188
8.2.1	Electron interference effects —	188
8.2.2	Aharonov–Bohm effect —	189
8.2.3	Altshuler–Aronov–Spivak oscillations —	193
8.2.4	Weak localization —	196
8.3	Spin interference effects —	201
8.3.1	Weak antilocalization —	201
8.3.2	Spin relaxation mechanisms —	203
8.3.3	Weak antilocalization in two-dimensional electron gases —	207
8.3.4	Weak antilocalization in wire structures —	210
8.4	Spin interference effects in ring structures —	215
8.4.1	Berry phase —	215
8.4.2	Spin-interference in a ring with Rashba spin-orbit coupling —	219
8.5	Summary —	225

9 Spin Hall effect — 227

- 9.1 Introductory remarks — 227
- 9.2 Basic phenomena — 228
- 9.3 Boltzmann equation and skew scattering — 229
 - 9.3.1 Boltzmann equation — 229
 - 9.3.2 Intrinsic spin Hall effect — 232
 - 9.3.3 Extrinsic spin Hall effect: skew scattering contribution — 232
 - 9.3.4 Skew scattering in a two-dimensional system — 234
- 9.4 Experiments on spin Hall effect in semiconductor layers — 237
- 9.5 Detection of the spin Hall effect by electroluminescence — 240
- 9.6 Summary — 242

10 Quantum spin Hall effect — 245

- 10.1 Introductory remarks — 245
- 10.2 Inverted quantum well in HgTe/CdTe — 246
- 10.3 Band structure — 250
- 10.4 Helical edge states — 252
- 10.5 Conductance in a normal and inverted HgTe/CdTe quantum well — 255
- 10.6 Edge channel transport — 258
- 10.7 Spin-polarized transport — 259
- 10.8 Summary — 262

11 Topological insulators — 265

- 11.1 Introductory remarks — 265
- 11.2 Material system — 266
- 11.3 Bulk band structure — 266
 - 11.3.1 Level evolution — 268
 - 11.3.2 Effective Hamiltonian — 269
 - 11.3.3 Ab-initio band structure calculations — 270
- 11.4 Surface states — 271
 - 11.4.1 Surface states deduced from the effective Hamiltonian — 272
 - 11.4.2 Surface states obtained from ab initio calculations — 272
 - 11.4.3 Topological protection of surface states — 273
- 11.5 Angle-resolved photo-emission spectroscopy — 275
- 11.6 Transport experiments — 278
 - 11.6.1 Topologically protected surface states in nanowires — 279
 - 11.6.2 Flux-periodic oscillations in nanowire structures — 283
- 11.7 Summary — 285

12	Quantum computation with electron spins — 287
12.1	Introductory remarks — 287
12.2	Basic elements of a quantum computer — 287
12.2.1	Quantum bit — 287
12.2.2	Entangled states — 289
12.3	Basic quantum gates — 290
12.3.1	Single-qubit gate — 290
12.3.2	Controlled-NOT gate — 292
12.3.3	Realization of a quantum computer — 293
12.4	Quantum algorithms — 293
12.4.1	Deutsch–Jozsa quantum algorithm — 294
12.5	Quantum dot spin qubits — 297
12.5.1	General concept — 298
12.5.2	Experimental realization of a quantum dot qubit — 299
12.5.3	Initialization — 300
12.5.4	Read-out — 301
12.5.5	Electron spin resonance — 303
12.5.6	Spin-control in a double dot system — 306
12.5.7	Singlet-triplet qubit — 313
12.5.8	Control of the S - T_0 qubit — 314
12.6	Summary — 317

Solutions — 319

Bibliography — 341

Index — 351