Contents

1 Introduction 1

2 Collisions and cross sections 5
2.1 Introduction 5
2.2 Elastic collisions 6
2.2.1 Cross section 6
2.2.1.1 Cross section and mean free path in kinetic gas theory. 7
2.2.1.2 Cross section and mean free path in plasmas. . 7
2.2.2 Definitions 8
2.3 Elastic collisions between electrons and neutrals 10
2.3.1 The total cross section 10
2.3.2 Differential cross section 11
2.3.3 Modeling 13
2.3.3.1 Cross section for the interaction between a point charge and an induced dipole. 13
2.3.3.2 Ramsauer effect. 16
2.3.4 The frequency of elastic collisions between electrons and neutrals 16
2.3.5 Cross section and rate constant for argon 17
2.4 Elastic collisions between heavy particles 18
2.5 Inelastic collisions 20
2.5.1 Inelastic collisions between electrons and heavy particles 20
2.5.1.1 Experimental methods. 21
2.5.1.2 Cross section. 23
2.5.1.3 Rate constant for ionization. 25
2.5.1.4 Electron attachment. 25
2.5.1.5 Total collision cross section. 27
2.5.2 Inelastic collisions between heavy particles 28
2.5.2.1 Charge transfer. 30
2.5.2.2 Resonant charge transfer. 31
2.5.2.3 Penning ionization. 33

2.5.3 Collisions between photons and molecules 34
2.6 Generation of secondary electrons at surfaces 34
2.6.1 Electrons 34
2.6.2 Ions 36
2.6.3 Photons 39

3 The plasma **41**
3.1 Direct current glow discharge 41
3.1.1 Phenomenology 41
3.1.2 V-I characteristic 44
3.2 Temperature distribution in a plasma 45
3.3 Neutralization of charges in an undisturbed plasma 48
3.4 Potential variation in the plasma 52
3.4.1 The low-voltage plasma sheath 53
3.4.1.1 Approximation of first order. 54
3.4.1.2 Approximation of second order. 54
3.4.1.3 Approximation of third order. 55
3.5 Temperature and density of the electrons 58
3.5.1 Elastic scattering and thermalization 59
3.5.2 Energy loss 60
3.5.3 Electron temperature 61
3.5.4 Electron density 64
3.6 Plasma oscillations 65

4 DC discharges **69**
4.1 Introduction 69
4.2 Gaseous generation of carriers 70
4.2.1 Townsend's equation 70
4.2.2 The primary ionization coefficient 72
4.3 The normal cathode fall 74
4.3.1 The secondary ionization coefficient 74
4.3.2 V-I characteristic 75
4.3.2.1 Matrix sheath. 76
4.3.2.2 Child-Langmuir sheath. 76
4.4 The abnormal cathode fall 81
4.4.1 Discussion of Townsend's approximation 83
4.5 Negative glow and positive column 85
4.6 Ionization 86
4.6.1 Ionization in the negative glow 86
4.7 Loss of carriers 88
4.7.1 Free diffusion 89
4.7.2 Ambipolar diffusion coefficient 90
4.7.3 Modified boundary 93
4.7.4 Diffusion processes in the positive column 94

4.8 Anodic region 95
4.9 Hollow cathode discharge 97
4.10 Similarity laws 98
4.11 Conclusion 101

5 High-frequency discharges I **103**
5.1 Phenomenological introduction 103
5.2 Generation of carriers 105
5.3 Operating frequency and the $\mathcal{EEDF}$ 110
5.4 Loss mechanisms 111
5.4.1 Diffusion 111
5.4.2 Recombination 113
5.4.3 Attachment in electronegative gases 114
5.4.4 Decay 115
5.5 Breakdown 116
5.5.1 Microwave discharges: model for breakdown 120
5.5.1.1 Frequency. 121
5.5.1.2 Pressure. 121
5.5.1.3 Oscillation amplitude. 122
5.5.1.4 Low gas pressure. 123
5.5.1.5 Breakdown. 123
5.5.1.6 Conclusion. 124
5.6 Maintenance 124
5.6.1 EEDF and the electric field 124
5.6.2 Collision frequency 125
5.7 High-frequency coupling: qualitative approach 126
5.8 High-frequency coupling: quantitative approach 130
5.8.1 Absorption circuit 131
5.8.2 Eliminator circuit 132
5.8.3 Coupled parallel circuits 133
5.8.3.1 Transformer coupling. 134
5.8.4 Capacitive and inductive coupling 137
5.8.5 Dual circuit of the capacitively coupled plasma 137
5.8.5.1 First approximation (symmetric discharge). . . 138
5.8.5.2 Second approximation (asymmetric discharge). 138
5.9 Matching networks 139
5.10 Transmission line 141
5.10.1 Coaxial cable 143
5.10.1.1 Characteristic impedance. 144
5.10.2 Waveguide 145
5.10.3 Mode patterns in transmission lines 145
5.10.3.1 Coaxial cable. 145
5.10.3.2 Waveguide. 145
5.10.4 Electrode 146

5.11 Shielding . . . 147

6 High-frequency discharges II **151**
6.1 Introduction . . . 151
6.2 Electric fields across the sheaths . . . 157
6.3 Current-voltage characteristic at one electrode . . . 160
6.4 Sheath potentials . . . 163
6.4.1 Symmetric system . . . 163
6.4.2 Asymmetric system . . . 165
6.4.2.1 Sheath potential theorem. . . . 165
6.4.2.2 Calculation. . . . 166
6.4.3 Resistive Coupling . . . 169
6.5 Power input . . . 172
6.5.1 Sheath heating . . . 175
6.5.1.1 Displacement current heating. . . . 175
6.5.1.2 Ohmic heating. . . . 175
6.5.1.3 Stochastic heating. . . . 176
6.5.2 Two regimes of power transfer . . . 181
6.6 Spatial distribution of charged carriers . . . 182
6.7 Dual-frequency discharges . . . 185
6.7.1 Frequency dependence of plasma density . . . 185
6.7.2 Mutual influence of two electrodes . . . 186
6.7.2.1 Narrow gap. . . . 187
6.7.2.2 Wide gap. . . . 187
6.8 Collisional sheaths . . . 190
6.8.1 Experiments . . . 194
6.8.1.1 Elastic scattering and resonant charge-transfer. 195
6.8.1.2 Elastic scattering. . . . 198
6.8.1.3 Modulation. . . . 198
6.8.2 Computer simulations . . . 201
6.8.3 Hybrid sheath model . . . 205
6.8.3.1 Ions. . . . 206
6.8.4 Measurements and modellings . . . 206
6.8.4.1 IEDF in the sheath. . . . 206
6.8.4.2 IEDF in the sheath of the powered electrode. . 207
6.9 DC discharges and capacitively coupled RF plasmas . . . 209
6.10 Summary . . . 212

7 High-frequency discharges III **215**
7.1 Introduction . . . 215
7.2 Inductively coupled plasma . . . 217
7.2.1 Transformer Model . . . 219
7.2.2 Power input for inductive coupling . . . 222
7.2.2.1 Plasma resistance and plasma impedance. . . . 223

7.2.2.2 Coupling between coil and plasma. . . . 223
7.2.2.3 Primary circuit. . . . 224
7.2.3 Limits of power input . . . 224
7.2.4 Top coil configuration . . . 226
7.2.4.1 E-mode and H-mode. . . . 226
7.2.5 Modeling of ICP discharges . . . 228
7.2.6 Conclusion . . . 232
7.3 Generation of plasmas supported by magnetic fields . . . 232
7.3.1 Résumé of the properties of HF discharges . . . 232
7.3.2 Whistler waves . . . 234
7.3.2.1 Phenomenology. . . . 234
7.3.2.2 Dispersion and absorption. . . . 235
7.4 Helicons in a bounded plasma . . . 237
7.4.1 Introduction . . . 237
7.4.2 Dispersion and wave fields . . . 238
7.4.3 Antenna coupling . . . 238
7.4.4 Operation . . . 243
7.4.5 Experiments . . . 244
7.4.6 Summary . . . 246
7.5 Electron cyclotron resonance . . . 246
7.5.1 The electric field and the diffusion length . . . 246
7.5.2 Coupling of microwaves . . . 253
7.5.3 Electron cyclotron resonance heating . . . 253
7.5.4 Electron cyclotron resonance reactors . . . 256
7.5.4.1 Waveguide applicator. . . . 256
7.5.4.2 Cavity applicator. . . . 260
7.5.4.3 Conclusion. . . . 264
7.6 Comparison of high-density discharges . . . 266

8 Ion beam systems **269**
8.1 Introduction . . . 269
8.2 Plasma sources . . . 271
8.2.1 Kaufman source . . . 271
8.2.2 HF sources . . . 272
8.2.2.1 Design of a grid optics with RF source. . . . 273
8.2.2.2 Boundary voltage. . . . 274
8.3 Grid optics . . . 275
8.3.1 Configuration and potential adjustment . . . 275
8.3.2 Screen grid . . . 277
8.3.2.1 Kaufman source. . . . 277
8.3.2.2 RF source. . . . 277
8.3.3 Accelerator grid . . . 278
8.4 Qualitative treatment of beam extraction . . . 278
8.4.1 Extraction without a grid . . . 279

8.4.2 Extraction with one grid . . . 279
8.4.3 Extraction with two or more grids . . . 280
8.5 Quantitative treatment of beam extraction . . . 280
8.5.1 Current density . . . 280
8.5.1.1 Derivations from Child's law. . . . 280
8.5.1.2 Grid transparency. . . . 282
8.5.2 Focusing and divergence . . . 283
8.5.3 Conclusion . . . 285
8.5.4 Three-grid ion beam source . . . 285
8.5.5 Four-grid ion beam source . . . 288
8.6 Neutralization . . . 288
8.6.1 Principle of operation . . . 288
8.6.2 Neutralization elements . . . 290
8.7 Process optimization . . . 291
8.7.1 Maximum power and substrate damage . . . 291
8.7.2 Discharge voltage and substrate damage . . . 292
8.7.3 Power and grid current . . . 292
8.7.4 Electron backstreaming . . . 293
8.7.5 Current density of the ion beam . . . 294
8.7.6 Uniformity . . . 294

9 Plasma diagnostics 299
9.1 Langmuir probe . . . 300
9.1.1 Introduction . . . 300
9.1.2 Conditions for performance . . . 300
9.1.3 Characteristic of the Langmuir probe . . . 303
9.1.3.1 Principle of the measuring technique. . . . 303
9.1.3.2 Extraction of plasma parameters. . . . 304
9.1.4 Plasma potential . . . 306
9.1.5 Principle of the double probe . . . 307
9.1.6 Principle of the asymmetrical double probe . . . 309
9.1.7 Determination of potentials in high-frequency discharges 310
9.1.8 Details . . . 313
9.1.9 Probe radius . . . 313
9.1.10 Thin sheath: space charge limited current . . . 315
9.1.10.1 Positive ions. . . . 315
9.1.10.2 Electrons. . . . 315
9.1.10.3 Finite electron temperature. . . . 316
9.1.11 Thick sheath: Orbital Motion Theory (OML Theory) . . 318
9.1.11.1 Electron saturation current. . . . 320
9.1.11.2 Electron current in the retarding-field region. . 324
9.1.11.3 Current transition at plasma potential. . . . 324
9.1.11.4 Ion current. . . . 325
9.1.11.5 Summary. . . . 325

9.1.12 Electron temperature and plasma potential . . . 326
9.1.13 Influence of a magnetic field . . . 326
9.1.14 Measurements . . . 327
9.1.14.1 Grounding problems. . . . 327
9.1.14.2 Determination of the characteristic. . . . 327
9.1.14.3 Electron temperature and plasma potential. . . 329
9.1.15 Conclusion . . . 330
9.2 Self-Excited Electron Resonance Spectroscopy . . . 331
9.2.1 Non-linear response between voltage and current . . . 331
9.2.2 Technical realization . . . 336
9.2.3 Inherent properties . . . 337
9.2.3.1 Electronic plasma density. . . . 337
9.2.3.2 Frequency of momentum transfer. . . . 338
9.2.4 Conclusion . . . 340
9.3 Impedance analysis . . . 340
9.4 Optical emission spectroscopy (OES) . . . 343
9.4.1 Electron temperature with OES . . . 344
9.4.1.1 Corona model and its validity. . . . 344
9.4.1.2 Direct electronic excitation. . . . 346
9.4.1.3 Parametrization of the cross section. . . . 347
9.4.1.4 Details of the evaluation. . . . 348
9.4.1.5 Chosing the right electron distribution. . . . 350
9.4.1.6 RF power. . . . 351
9.4.1.7 Corona model: limits of applicability. . . . 351
9.4.2 Plasma gas temperature . . . 353
9.4.2.1 Features in noble and inert gases. . . . 356
9.5 Résumé . . . 358
9.6 Properties of Electronegative Plasmas . . . 359
9.7 Capacitively coupled plasmas . . . 360
9.7.1 Electrical considerations . . . 360
9.7.2 Plasma density . . . 361
9.7.3 Electron temperature . . . 361
9.7.4 Power dissipation . . . 363
9.7.4.1 Effective collision frequency. . . . 363
9.7.4.2 Plasma gas temperature. . . . 363
9.8 Inductively coupled plasmas . . . 366
9.8.1 General remarks . . . 366
9.8.2 Influence of the reactor geometry . . . 367
9.8.3 Electron temperature . . . 367
9.8.4 Plasma density . . . 367
9.8.5 Density of neutrals . . . 368
9.8.6 Plasma gas temperature . . . 369
9.8.7 Modeling . . . 370
9.8.8 Negative Ions . . . 370

9.8.9 Conclusion . . . 373
9.8.10 Interaction between Plasma Bulk and Surfaces . . . 373

10 Plasma deposition processes **375**
10.1 Introduction . . . 375
10.1.1 Sputter deposition systems . . . 376
10.2 Sputtering kinetics . . . 379
10.2.1 Target processes . . . 379
10.2.1.1 Sputtering yield. . . . 379
10.2.1.2 Energy distribution of the sputtered atoms. . . . 384
10.2.2 Transport processes: energy distribution of the atoms . . . 386
10.2.3 Substrate processes: Film formation . . . 387
10.3 Target topography . . . 393
10.3.1 Historical review . . . 394
10.3.1.1 Roughness-induced mechanism. . . . 394
10.3.1.2 Contamination-induced mechanism. . . . 396
10.3.2 Comparison of topographical mechanisms . . . 398
10.4 Sputtering conditions . . . 400
10.4.1 Electrical properties . . . 402
10.4.2 Temperature control of the substrate . . . 402
10.4.2.1 Temperature measurement. . . . 403
10.4.2.2 Temperature control. . . . 404
10.4.3 Contamination . . . 407
10.4.3.1 Target and purity requirements. . . . 407
10.4.3.2 Contamination by argon. . . . 408
10.4.3.3 Contamination by other gases. . . . 409
10.4.3.4 Reactive sputtering. . . . 410
10.4.3.5 Bombardment with other particles. . . . 411
10.5 Sputtering with bias techniques . . . 411
10.5.1 Deposition rate and film composition . . . 412
10.5.2 Further film properties . . . 413
10.5.3 Mechanisms of bias sputtering . . . 413
10.5.4 Homogenity of coating at rectangular steps . . . 414
10.5.5 Mechanical tension and substrate bias . . . 415
10.6 Sputter deposition of multicomponent films . . . 416
10.6.1 Target processes . . . 417
10.6.2 Between target and substrate . . . 417
10.6.3 Substrate processes . . . 418
10.6.4 Preparative aspects . . . 418
10.7 Sputtering systems with increased plasma density . . . 420
10.7.1 Magnetically improved sputtering systems . . . 420
10.7.1.1 Theory. . . . 420
10.7.1.2 Technological issues. . . . 424
10.7.2 Triode systems . . . 427

10.7.3 Ion plating systems . . . 427
10.8 Plasma Enhanced Chemical Vapour Deposition (PECVD) . . . 428
10.8.1 Instantaneous mass spectrometry . . . 431
10.8.2 Diamond-like coatings (DLCs) . . . 432
10.8.2.1 Applications. . . . 434
10.8.2.2 Diamond electronics. . . . 435
10.9 Ion beam deposition (IBD) . . . 436

11 Plasma etch processes **439**
11.1 Introduction . . . 439
11.2 Sputter etching . . . 442
11.3 Reactive etch processes . . . 443
11.4 General dependence on independent properties . . . 446
11.4.1 Substrate temperature . . . 447
11.4.1.1 Introduction. . . . 447
11.4.1.2 Etchrate and its temperature dependence. . . . 448
11.4.2 Gas composition . . . 448
11.4.3 Gas pressure and RF power . . . 449
11.4.4 Electrode geometry . . . 451
11.4.5 Gas flow effects and the loading effect . . . 452
11.4.5.1 Gas flow. . . . 452
11.4.5.2 Loading effect. . . . 455
11.4.6 Transport effects and reactor design . . . 457
11.5 Characteristics of dry etching . . . 464
11.5.1 Anisotropy . . . 465
11.5.2 Selectivity . . . 465
11.5.3 Mask effects . . . 466
11.5.3.1 Erosion. . . . 466
11.5.3.2 Faceting. . . . 466
11.5.3.3 Metal masks and trilevel photoresist. . . . 467
11.5.3.4 LER and CD. . . . 469
11.5.4 Redeposition and sidewall passivation . . . 472
11.5.5 Microfeatures . . . 474
11.5.5.1 Trenching. . . . 474
11.5.5.2 Shadowing. . . . 475
11.5.5.3 Microloading. . . . 476
11.5.5.4 Aspect-Ratio Dependent Etching (ARDE). . . . 478
11.5.6 Charging effects . . . 481
11.5.7 High-end etching processes with high density plasmas . . . 483
11.5.8 Towards nanostructures . . . 488
11.6 Special features of ion beam etching . . . 488
11.6.1 Applications . . . 490
11.6.2 Ion beam assisted etching: IBAE or CAIBE . . . 493
11.7 Damage . . . 494

11.8 Process control . . . 499
11.8.1 Impedance of a discharge . . . 500
11.8.2 Ellipsometry . . . 500
11.8.3 Optical emission spectroscopy . . . 502
11.8.4 Interferometric methods . . . 506
11.8.4.1 Metals and dielectrics. . . . 506
11.8.4.2 Semiconductors. . . . 507
11.8.5 CCD controlled laser interferometry . . . 508
11.8.6 Mass spectrometry . . . 510
11.8.6.1 Conventional mass spectrometry. . . . 511
11.8.6.2 Glow discharge mass spectrometry. . . . 511
11.8.7 Problems during in-situ monitoring . . . 512
11.8.8 Conclusion . . . 514

12 Etch Mechanisms **517**
12.1 Introduction . . . 517
12.2 Quantitative calculation with Langmuir's theory . . . 522
12.3 ...and ion etching? . . . 526
12.3.1 Anisotropy . . . 527
12.4 Etching of Si and its compounds with F-containing gases . . . 529
12.4.1 Experimental observations . . . 530
12.4.2 Model . . . 530
12.4.3 Chemical selectivity . . . 532
12.4.4 PECVD vs. RIE . . . 533
12.4.5 Anisotropy and the so-called Bosch process . . . 535
12.5 Etching of Si and its compounds with Cl-containing gases . . . 536
12.5.1 Thermodynamical selectivity . . . 537
12.5.2 Chemical selectivity . . . 537
12.5.3 Doping effect . . . 538
12.6 Etching of III/V-compounds . . . 539
12.6.1 Why avoid fluorine? . . . 539
12.6.2 Etching with chlorine . . . 541
12.6.2.1 Etchrate and its temperature dependence. . . . 541
12.6.2.2 Chlorine sources. . . . 542
12.6.3 Sidewall passivation . . . 544
12.6.4 Chemical selectivity . . . 547
12.6.5 Kinetics of chlorine etching . . . 548
12.6.6 Methane-hydrogen process . . . 549
12.7 Combination of various etch methods . . . 551
12.8 Hazards associated with chlorine etching . . . 552
12.9 Simulation of dry etching processes . . . 553

13 Outlook **559**

14 Advanced Topics **567**
14.1 Electron Energy Distribution Functions ($\mathcal{EEDF}$s) . . . 567
14.1.1 Boltzmann Equation . . . 567
14.1.2 External field as small disturbance . . . 567
14.1.2.1 Elastic collisions. . . . 568
14.1.2.2 Inelastic collisions. . . . 568
14.1.3 Approximate solutions of the Boltzmann equation . . . 569
14.1.3.1 High frequencies. . . . 569
14.1.3.2 Maxwellian distribution. . . . 570
14.1.3.3 Margenau distribution. . . . 571
14.1.3.4 Druyvesteynian distribution. . . . 571
14.1.4 Frequency effects . . . 575
14.2 Sheath and presheath . . . 576
14.2.1 Conditions . . . 576
14.2.2 Derivation . . . 577
14.2.3 Presheath . . . 579
14.2.4 Charge density across the sheath . . . 580
14.2.5 Approximations . . . 582
14.2.6 Conclusion . . . 583
14.3 Plasma oscillations . . . 583
14.3.1 Dispersion relation . . . 586
14.3.2 Landau damping . . . 589
14.4 Capacitive coupling for collisionless sheaths . . . 591
14.4.1 The symmetric case . . . 591
14.4.1.1 Introduction. . . . 591
14.4.1.2 Assumptions. . . . 592
14.4.1.3 Spatial sheath structure. . . . 593
14.4.1.4 Carrier density and sheath potential. . . . 598
14.4.1.5 Sheath dynamics. . . . 600
14.4.2 The asymmetric case . . . 601
14.5 Motion in a magnetic field . . . 604
14.5.1 The magnetic bottle . . . 604
14.5.2 Modification of diffusion . . . 610
14.6 Dispersion in a HF plasma . . . 613
14.6.1 Cutoff and skin depth . . . 613
14.6.2 Complex properties . . . 617
14.7 Whistler waves . . . 623
14.7.1 Plane waves . . . 623
14.7.1.1 Formula of Appleton and Hartree. . . . 623
14.7.1.2 Cutoff and resonance. . . . 628
14.7.1.3 Dispersion relation. . . . 629
14.7.1.4 R- and L-waves. . . . 631
14.7.1.5 Dispersion relation for arbitrary directions. . . . 633
14.7.2 Bounded plasma . . . 637

14.7.2.1 Introduction. 637
14.7.2.2 Extended Drude equation. 638
14.7.2.3 Wave equation. 639
14.7.2.4 Cylindrical confinement. 642
14.7.2.5 Dispersion relation. 646
14.7.2.6 Azimuthal wave fields. 647
14.7.2.7 Radial modes. 651
14.7.2.8 Conclusion 658

15 Reference list of figures **661**

16 Symbols, abbreviations, acronyms **663**

References **669**

Register **705**