

Yuri P. Raizer

Gas Discharge Physics

With 209 Figures

Springer-Verlag

Berlin Heidelberg New York London Paris
Tokyo Hong Kong Barcelona Budapest

Contents

1. Introduction	1
1.1 What Is the Subject of Gas Discharge Physics	1
1.2 Typical Discharges in a Constant Electric Field	1
1.3 Classification of Discharges	3
1.4 Brief History of Electric Discharge Research	4
1.5 Organization of the Book. Bibliography	6
2. Drift, Energy and Diffusion of Charged Particles in Constant Fields	8
2.1 Drift of Electrons in a Weakly Ionized Gas	8
2.2 Conduction of Ionized Gas	13
2.3 Electron Energy	14
2.4 Diffusion of Electrons	20
2.5 Ions	23
2.6 Ambipolar Diffusion	28
2.7 Electric Current in Plasma in the Presence of Longitudinal Gradients of Charge Density	30
2.8 Hydrodynamic Description of Electrons	33
3. Interaction of Electrons in an Ionized Gas with Oscillating Electric Field and Electromagnetic Waves	35
3.1 The Motion of Electrons in Oscillating Fields	35
3.2 Electron Energy	37
3.3 Basic Equations of Electrodynamics of Continuous Media	41
3.4 High-Frequency Conductivity and Dielectric Permittivity of Plasma	43
3.5 Propagation of Electromagnetic Waves in Plasmas	45
3.6 Total Reflection of Electromagnetic Waves from Plasma and Plasma Oscillations	49
4. Production and Decay of Charged Particles	52
4.1 Electron Impact Ionization in a Constant Field	52
4.2 Other Ionization Mechanisms	57
4.3 Bulk Recombination	60

4.4	Formation and Decay of Negative Ions	63
4.5	Diffusional Loss of Charges	67
4.6	Electron Emission from Solids	68
4.7	Multiplication of Charges in a Gas via Secondary Emission ..	72
5.	Kinetic Equation for Electrons in a Weakly Ionized Gas Placed in an Electric Field	76
5.1	Description of Electron Processes in Terms of the Velocity Distribution Function	76
5.2	Formulation of the Kinetic Equation	77
5.3	Approximation for the Angular Dependence of the Distribution Function	82
5.4	Equation of the Electron Energy Spectrum	85
5.5	Validity Criteria for the Spectrum Equation	90
5.6	Comparison of Some Conclusions Implied by the Kinetic Equation with the Result of Elementary Theory ..	93
5.7	Stationary Spectrum of Electrons in a Field in the Case of only Elastic Losses	95
5.8	Numerical Results for Nitrogen and Air	98
5.9	Spatially Nonuniform Fields of Arbitrary Strength	101
6.	Electric Probes	103
6.1	Introduction. Electric Circuit	103
6.2	Current-Voltage Characteristic of a Single Probe	104
6.3	Theoretical Foundations of Electronic Current Diagnostics of Rarefied Plasmas	106
6.4	Procedure for Measuring the Distribution Function	111
6.5	Ionic Current to a Probe in Rarefied Plasma	113
6.6	Vacuum Diode Current and Space-Charge Layer Close to a Charged Body	115
6.7	Double Probe	119
6.8	Probe in a High-Pressure Plasma	123
7.	Breakdown of Gases in Fields of Various Frequency Ranges	128
7.1	Essential Characteristics of the Phenomenon	128
7.2	Breakdown and Triggering of Self-Sustained Discharge in a Constant Homogeneous Field at Moderately Large Product of Pressure and Discharge Gap Width	130
7.3	Breakdown in Microwave Fields and Interpretation of Experimental Data Using the Elementary Theory	138
7.4	Calculation of Ionization Frequencies and Breakdown Thresholds Using the Kinetic Equation	144

7.5	Optical Breakdown	151
7.6	Methods of Exciting an RF Field in a Discharge Volume	160
7.7	Breakdown in RF and Low-Frequency Ranges	161
8.	Stable Glow Discharge	167
8.1	General Structure and Observable Features	167
8.2	Current-Voltage Characteristic of Discharge Between Electrodes	172
8.3	Dark Discharge and the Role Played by Space Charge in the Formation of the Cathode Layer	175
8.4	Cathode Layer	178
8.5	Transition Region Between the Cathode Layer and the Homogeneous Positive Column	190
8.6	Positive Column	193
8.7	Heating of the Gas and Its Effect on the Current-Voltage Characteristic	199
8.8	Electronegative Gas Plasma	203
8.9	Discharge in Fast Gas Flow	209
8.10	Anode Layer	211
9.	Glow Discharge Instabilities and Their Consequences	214
9.1	Causes and Consequences of Instabilities	214
9.2	Quasisteady Parameters	217
9.3	Field and Electron Temperature Perturbations in the Case of Quasisteady-State T_e	220
9.4	Thermal Instability	222
9.5	Attachment Instability	226
9.6	Some Other Frequently Encountered Destabilizing Mechanisms	228
9.7	Striations	230
9.8	Contraction of the Positive Column	239
10.	Arc Discharge	245
10.1	Definition and Characteristic Features of Arc Discharge	245
10.2	Arc Types	246
10.3	Arc Initiation	248
10.4	Carbon Arc in Free Air	249
10.5	Hot Cathode Arc: Processes near the Cathode	251
10.6	Cathode Spots and Vacuum Arc	259
10.7	Anode Region	266
10.8	Low-Pressure Arc with Externally Heated Cathode	268
10.9	Positive Column of High-Pressure Arc (Experimental Data) .	271
10.10	Plasma Temperature and $V - i$ Characteristic of High-Pressure Arc Columns	275
10.11	The Gap Between Electron and Gas Temperatures in "Equilibrium" Plasma	285

11. Sustainment and Production of Equilibrium Plasma	
by Fields in Various Frequency Ranges	288
11.1 Introduction. Energy Balance in Plasma	288
11.2 Arc Column in a Constant Field	290
11.3 Inductively Coupled Radio-Frequency Discharge	291
11.4 Discharge in Microwave Fields	299
11.5 Continuous Optical Discharges	306
11.6 Plasmatrons: Generators of Dense Low-Temperature Plasma .	315
12. Spark and Corona Discharges	324
12.1 General Concepts	324
12.2 Individual Electron Avalanche	328
12.3 Concept of Streamers	334
12.4 Breakdown and Streamers in Electronegative Gases (Air) in Moderately Wide Gaps with a Uniform Field	338
12.5 Spark Channel	343
12.6 Corona Discharge	345
12.7 Models of Streamer Propagation	352
12.8 Breakdown in Long Air Gaps with Strongly Nonuniform Fields (Experimental Data)	359
12.9 Leader Mechanism of Breakdown of Long Gaps	363
12.10 Return Wave (Return Stroke)	368
12.11 Lightning	370
12.12 Negative Stepped Leader	375
13. Capacitively Coupled Radio-Frequency Discharge	378
13.1 Drift Oscillations of Electron Gas	378
13.2 Idealized Model of the Passage of High-Frequency Current Through a Long Plane Gap at Elevated Pressures	381
13.3 $V - i$ Characteristic of Homogeneous Positive Columns	385
13.4 Two Forms of CCRF Discharge Realization and Constant Positive Potential of Space: Experiment	387
13.5 Electrical Processes in a Nonconducting Electrode Layer and the Mechanism of Closing the Circuit Current	396
13.6 Constant Positive Potential of the Weak-Current Discharge Plasma	400
13.7 High-Current Mode	403
13.8 The Structure of a Medium-Pressure Discharge: Results of Numerical Modeling	408
13.9 Normal Current Density in Weak-Current Mode and Limits on the Existence of this Mode	413

14. Discharges in High-Power CW CO₂ Lasers	415
14.1 Principles of Operation of Electric-Discharge CO ₂ Lasers ...	415
14.2 Two Methods of Heat Removal from Lasers	417
14.3 Methods of Suppressing Instabilities	421
14.4 Organization of Large-Volume Discharges Involving Gas Pumping	425
Appendix	433
References	439
Subject Index	447