

Contents

Foreword	page xxxix
Preface	xli
1 Introduction to Theoretical and Applied Plasma Chemistry	1
1.1. Plasma as the Fourth State of Matter	1
1.2. Plasma in Nature and in the Laboratory	2
1.3. Plasma Temperatures: Thermal and Non-Thermal Plasmas	4
1.4. Plasma Sources for Plasma Chemistry: Gas Discharges	5
1.5. Fundamentals of Plasma Chemistry: Major Components of Chemically Active Plasma and Mechanisms of Plasma-Chemical Processes	8
1.6. Applied Plasma Chemistry	9
1.7. Plasma as a High-Tech Magic Wand of Modern Technology	10
2 Elementary Plasma-Chemical Reactions	12
2.1. Ionization Processes	12
2.1.1. Elementary Charged Particles in Plasma	12
2.1.2. Elastic and Inelastic Collisions and Their Fundamental Parameters	13
2.1.3. Classification of Ionization Processes	14
2.1.4. Elastic Scattering and Energy Transfer in Collisions of Charged Particles: Coulomb Collisions	15
2.1.5. Direct Ionization by Electron Impact: Thomson Formula	16
2.1.6. Specific Features of Ionization of Molecules by Electron Impact: Frank-Condon Principle and Dissociative Ionization	17
2.1.7. Stepwise Ionization by Electron Impact	18
2.1.8. Ionization by High-Energy Electrons and Electron Beams: Bethe-Bloch Formula	20
2.1.9. Photo-Ionization Processes	20
2.1.10. Ionization in Collisions of Heavy Particles: Adiabatic Principle and Massey Parameter	21
2.1.11. Penning Ionization Effect and Associative Ionization	21
2.2. Elementary Plasma-Chemical Reactions of Positive Ions	22
2.2.1. Different Mechanisms of Electron-Ion Recombination in Plasma	22

2.2.2. Dissociative Electron–Ion Recombination and Possible Preliminary Stage of Ion Conversion	23	2.6. Elementary Relaxation Processes of Energy Transfer Involving Vibrationally, Rotationally, and Electronically Excited Molecules	67
2.2.3. Three-Body and Radiative Electron–Ion Recombination Mechanisms	25	2.6.1. Vibrational–Translational (VT) Relaxation: Slow Adiabatic Elementary Process	67
2.2.4. Ion–Molecular Reactions, Ion–Molecular Polarization Collisions, and the Langevin Rate Coefficient	26	2.6.2. Landau–Teller Formula for VT-Relaxation Rate Coefficients	69
2.2.5. Ion–Atomic Charge Transfer Processes and Resonant Charge Transfer	28	2.6.3. Fast Non-Adiabatic Mechanisms of VT Relaxation	71
2.2.6. Non-Resonant Charge Transfer Processes and Ion–Molecular Chemical Reactions of Positive and Negative Ions	29	2.6.4. Vibrational Energy Transfer Between Molecules: Resonant VV Relaxation	72
2.3. Elementary Plasma-Chemical Reactions Involving Negative Ions	31	2.6.5. Non-Resonant VV Exchange: Relaxation of Anharmonic Oscillators and Intermolecular VV Relaxation	74
2.3.1. Dissociative Electron Attachment to Molecules as a Major Mechanism of Negative Ion Formation in Electronegative Molecular Gases	31	2.6.6. Rotational Relaxation Processes: Parker Formula	76
2.3.2. Three-Body Electron Attachment and Other Mechanisms of Formation of Negative Ions	33	2.6.7. Relaxation of Electronically Excited Atoms and Molecules	76
2.3.3. Destruction of Negative Ions: Associative Detachment, Electron Impact Detachment, and Detachment in Collisions with Excited Particles	35	2.7. Elementary Chemical Reactions of Excited Molecules: Fridman-Macheret α -Model	79
2.3.4. Recombination of Negative and Positive Ions	37	2.7.1. Rate Coefficient of Reactions of Excited Molecules	79
2.3.5. Ion–Ion Recombination in Binary Collisions	38	2.7.2. Efficiency α of Vibrational Energy in Overcoming Activation Energy of Chemical Reactions: Numerical Values and Classification Table	81
2.3.6. Three-Body Ion–Ion Recombination: Thomson’s Theory and Langevin Model	39	2.7.3. Fridman-Macheret α -Model	81
2.4. Electron Emission and Heterogeneous Ionization Processes	42	2.7.4. Efficiency of Vibrational Energy in Elementary Reactions Proceeding Through Intermediate Complexes: Synthesis of Lithium Hydride	83
2.4.1. Thermionic Emission: Sommerfeld Formula and Schottky Effect	42	2.7.5. Dissociation of Molecules in Non-Equilibrium Conditions with Essential Contribution of Translational Energy: Non-Equilibrium Dissociation Factor Z	86
2.4.2. Field Emission of Electrons in Strong Electric Fields: Fowler-Nordheim Formula and Thermionic Field Emission	43	2.7.6. Semi-Empirical Models of Non-Equilibrium Dissociation of Molecules Determined by Vibrational and Translational Temperatures	87
2.4.3. Secondary Electron Emission	45	Problems and Concept Questions	89
2.4.4. Photo-Ionization of Aerosols: Monochromatic Radiation	46	3 Plasma-Chemical Kinetics, Thermodynamics, and Electrostatics	92
2.4.5. Photo-Ionization of Aerosols: Continuous-Spectrum Radiation	49	3.1. Plasma Statistics and Thermodynamics, Chemical and Ionization Equilibrium, and the Saha Equation	92
2.4.6. Thermal Ionization of Aerosols: Einbinder Formula	51	3.1.1. Statistical Distributions: Boltzmann Distribution Function	92
2.4.7. Space Distribution of Electrons and Electric Field Around a Thermally Ionized Macro-Particle	52	3.1.2. Equilibrium Statistical Distribution of Diatomic Molecules over Vibrational–Rotational States	93
2.4.8. Electric Conductivity of Thermally Ionized Aerosols	53	3.1.3. Saha Equation for Ionization Equilibrium in Thermal Plasma	94
2.5. Excitation and Dissociation of Neutral Particles in Ionized Gases	54	3.1.4. Dissociation Equilibrium in Molecular Gases	94
2.5.1. Vibrational Excitation of Molecules by Electron Impact	54	3.1.5. Complete Thermodynamic Equilibrium (CTE) and Local Thermodynamic Equilibrium (LTE) in Plasma	95
2.5.2. Rate Coefficients of Vibrational Excitation by Electron Impact: Semi-Empirical Fridman Approximation	56	3.1.6. Thermodynamic Functions of Quasi-Equilibrium Thermal Plasma Systems	95
2.5.3. Rotational Excitation of Molecules by Electron Impact	58	3.1.7. Non-Equilibrium Statistics of Thermal and Non-Thermal Plasmas	97
2.5.4. Electronic Excitation of Atoms and Molecules by Electron Impact	59	3.1.8. Non-Equilibrium Statistics of Vibrationally Excited Molecules: Treanor Distribution	99
2.5.5. Dissociation of Molecules by Direct Electron Impact	61	3.2. Electron Energy Distribution Functions (EEDFs) in Non-Thermal Plasma	100
2.5.6. Distribution of Electron Energy in Non-Thermal Discharges Between Different Channels of Excitation and Ionization	63	3.2.1. Fokker-Planck Kinetic Equation for Determination of EEDF	100

3.2.2. Druyvesteyn Distribution, Margenau Distributions, and Other Specific EEDF	101	3.6.1. Energy Efficiency of Quasi-Equilibrium and Non-Equilibrium Plasma-Chemical Processes	132
3.2.3. Effect of Electron–Molecular and Electron–Electron Collisions on EEDF	103	3.6.2. Energy Efficiency of Plasma-Chemical Processes Stimulated by Vibrational Excitation of Molecules	133
3.2.4. Relation Between Electron Temperature and the Reduced Electric Field	104	3.6.3. Energy Efficiency of Plasma-Chemical Processes Stimulated by Electronic Excitation and Dissociative Attachment	134
3.2.5. Isotropic and Anisotropic Parts of the Electron Distribution Functions: EEDF and Plasma Conductivity	104	3.6.4. Energy Balance and Energy Efficiency of Plasma-Chemical Processes Stimulated by Vibrational Excitation of Molecules	134
3.3. Diffusion, Electric/Thermal Conductivity, and Radiation in Plasma	106	3.6.5. Components of Total Energy Efficiency: Excitation, Relaxation, and Chemical Factors	136
3.3.1. Electron Mobility, Plasma Conductivity, and Joule Heating	106	3.6.6. Energy Efficiency of Quasi-Equilibrium Plasma-Chemical Systems: Absolute, Ideal, and Super-Ideal Quenching	137
3.3.2. Plasma Conductivity in Crossed Electric and Magnetic Fields	107	3.6.7. Mass and Energy Transfer Equations in Multi-Component Quasi-Equilibrium Plasma-Chemical Systems	137
3.3.3. Ion Energy and Ion Drift in Electric Field	109	3.6.8. Transfer Phenomena Influence on Energy Efficiency of Plasma-Chemical Processes	139
3.3.4. Free Diffusion of Electrons and Ions; Continuity Equation; and Einstein Relation Between Diffusion Coefficient, Mobility, and Mean Energy	109	3.7. Elements of Plasma Electrodynamics	140
3.3.5. Ambipolar Diffusion and Debye Radius	110	3.7.1. Ideal and Non-Ideal Plasmas	140
3.3.6. Thermal Conductivity in Plasma	111	3.7.2. Plasma Polarization: Debye Shielding of Electric Field in Plasma	141
3.3.7. Non-Equilibrium Thermal Conductivity and Treanor Effect in Vibrational Energy Transfer	112	3.7.3. Plasmas and Sheaths: Physics of DC Sheaths	142
3.3.8. Plasma Emission and Absorption of Radiation in Continuous Spectrum and Unsold-Kramers Formula	112	3.7.4. High-Voltage Sheaths: Matrix and Child Law Sheath Models	144
3.3.9. Radiation Transfer in Plasma: Optically Thin and Optically Thick Plasmas	113	3.7.5. Electrostatic Plasma Oscillations: Langmuir or Plasma Frequency	145
3.4. Kinetics of Vibrationally and Electronically Excited Molecules in Plasma: Effect of Hot Atoms	114	3.7.6. Penetration of Slow-Changing Fields into Plasma: Skin Effect in Plasma	146
3.4.1. Fokker-Plank Kinetic Equation for Non-Equilibrium Vibrational Distribution Functions	114	3.7.7. Magneto-Hydrodynamics: “Diffusion” of Magnetic Field and Magnetic Field Frozen in Plasma	146
3.4.2. VT and VV Fluxes of Excited Molecules in Energy Space	115	3.7.8. Magnetic Pressure: Plasma Equilibrium in Magnetic Field and Pinch Effect	147
3.4.3. Non-Equilibrium Vibrational Distribution Functions: Regime of Strong Excitation	117	3.7.9. Two-Fluid Magneto-Hydrodynamics: Generalized Ohm’s Law	149
3.4.4. Non-Equilibrium Vibrational Distribution Functions: Regime of Weak Excitation	119	3.7.10. Plasma Diffusion Across Magnetic Field	149
3.4.5. Kinetics of Population of Electronically Excited States in Plasma	120	3.7.11. Magneto-Hydrodynamic Behavior of Plasma: Alfvén Velocity and Magnetic Reynolds Number	150
3.4.6. Non-Equilibrium Translational Energy Distribution Functions of Heavy Neutrals: Effect of “Hot” Atoms in Fast VT-Relaxation Processes	122	3.7.12. High-Frequency Plasma Conductivity and Dielectric Permittivity	151
3.4.7. Generation of “Hot” Atoms in Chemical Reactions	123	3.7.13. Propagation of Electromagnetic Waves in Plasma	153
3.5. Vibrational Kinetics of Gas Mixtures, Chemical Reactions, and Relaxation Processes	124	3.7.14. Plasma Absorption and Reflection of Electromagnetic Waves: Bouguer Law: Critical Electron Density	154
3.5.1. Kinetic Equation and Vibrational Distributions in Gas Mixtures: Treanor Isotopic Effect in Vibrational Kinetics	124	Problems and Concept Questions	155
3.5.2. Reverse Isotopic Effect in Plasma-Chemical Kinetics	126	4 Electric Discharges in Plasma Chemistry	157
3.5.3. Macrokinetics of Chemical Reactions of Vibrationally Excited Molecules	129	4.1. Fundamentals of Electric Breakdown, Streamer Processes, and Steady-State Regimes of Non-Equilibrium Electrical Discharges	157
3.5.4. Vibrational Energy Losses Due to VT Relaxation	131	4.1.1. Townsend Mechanism of Electric Breakdown and Paschen Curves	157
3.5.5. Vibrational Energy Losses Due to Non-Resonance VV Exchange	132	4.1.2. Spark Breakdown Mechanism: Streamer Concept	159
3.6. Energy Balance and Energy Efficiency of Plasma-Chemical Processes	132		

4.1.3. Meek Criterion of Streamer Formation: Streamer Propagation Models	163	4.3.1.1. Special Configurations of Gliding Arc Discharges: Gliding Arc Stabilized in Reverse Vortex (Tornado) Flow	207
4.1.4. Streamers and Microdischarges	164	4.4. Radiofrequency and Microwave Discharges in Plasma Chemistry	209
4.1.5. Interaction of Streamers and Microdischarges	166	4.4.1. Generation of Thermal Plasma in Radiofrequency Discharges	209
4.1.6. Monte Carlo Modeling of Interaction of Streamers and Microdischarges	167	4.4.2. Thermal Plasma Generation in Microwave and Optical Discharges	211
4.1.7. Self-Organized Pattern of DBD Microdischarges due to Streamer Interaction	168	4.4.3. Non-Thermal Radiofrequency Discharges: Capacitive and Inductive Coupling of Plasma	215
4.1.8. Steady-State Regimes of Non-Equilibrium Electric Discharges and General Regimes Controlled by Volume and Surface Recombination Processes	170	4.4.4. Non-Thermal RF-CCP Discharges in Moderate Pressure Regimes	216
4.1.9. Discharge Regime Controlled by Electron-Ion Recombination	171	4.4.5. Low-Pressure Capacitively Coupled RF Discharges	219
4.1.10. Discharge Regime Controlled by Electron Attachment	172	4.4.6. RF Magnetron Discharges	222
4.1.1.1. Non-Thermal Discharge Regime Controlled by Charged-Particle Diffusion to the Walls: The Engel-Steenbeck Relation	172	4.4.7. Non-Thermal Inductively Coupled RF Discharges in Cylindrical Coil	224
4.2. Glow Discharges	175	4.4.8. Planar-Coil and Other Configurations of Non-Thermal Inductively Coupled RF Discharges	226
4.2.1. General Structure and Configurations of Glow Discharges	175	4.4.9. Non-Thermal Low-Pressure Microwave and Other Wave-Heated Discharges	229
4.2.2. Current-Voltage Characteristics of DC Discharges	177	4.4.10. Non-Equilibrium Plasma-Chemical Microwave Discharges of Moderate Pressure	231
4.2.3. Dark Discharge and Transition from Townsend Dark to Glow Discharge	178	4.5. Non-Thermal Atmospheric Pressure Discharges	233
4.2.4. Current-Voltage Characteristics of Cathode Layer: Normal Glow Discharge	179	4.5.1. Corona Discharges	233
4.2.5. Abnormal, Subnormal, and Obstructed Regimes of Glow Discharges	181	4.5.2. Pulsed Corona Discharges	234
4.2.6. Positive Column of Glow Discharge	182	4.5.3. Dielectric Barrier Discharges	237
4.2.7. Hollow Cathode Glow Discharge	183	4.5.4. Special Modifications of DBD: Surface, Packed-Bed, and Ferroelectric Discharges	239
4.2.8. Other Specific Glow Discharge Plasma Sources	184	4.5.5. Spark Discharges	240
4.2.9. Energy Efficiency Peculiarities of Glow Discharge Application for Plasma-Chemical Processes	186	4.5.6. Atmospheric Pressure Glow Mode of DBD	241
4.3. Arc Discharges	187	4.5.7. APGs: Resistive Barrier Discharge	242
4.3.1. Classification and Current-Voltage Characteristics of Arc Discharges	187	4.5.8. One-Atmosphere Uniform Glow Discharge Plasma as Another Modification of APG	243
4.3.2. Cathode and Anode Layers of Arc Discharges	189	4.5.9. Electronically Stabilized APG Discharges	244
4.3.3. Cathode Spots in Arc Discharges	191	4.5.10. Atmospheric-Pressure Plasma Jets	245
4.3.4. Positive Column of High-Pressure Arcs: Elenbaas-Heller Equation	193	4.6. Microdischarges	247
4.3.5. Steenbeck-Raizer "Channel" Model of Positive Column	194	4.6.1. General Features of Microdischarges	247
4.3.6. Steenbeck-Raizer Arc "Channel" Modeling of Plasma Temperature, Specific Power, and Electric Field in Positive Column	196	4.6.2. Micro-Glow Discharge	248
4.3.7. Configurations of Arc Discharges Applied in Plasma Chemistry and Plasma Processing	197	4.6.3. Micro-Hollow-Cathode Discharge	251
4.3.8. Gliding Arc Discharge	200	4.6.4. Arrays of Microdischarges: Microdischarge Self-Organization and Structures	252
4.3.9. Equilibrium Phase of Gliding Arc, Its Critical Parameters, and Fast Equilibrium-to-Non-Equilibrium Transition	204	4.6.5. KiloHertz-Frequency-Range Microdischarges	254
4.3.10. Gliding Arc Stability Analysis and Transitional and Non-Equilibrium Phases of the Discharge	205	4.6.6. RF Microdischarges	255
		4.6.7. Microwave Microdischarges	257
		Problems and Concept Questions	257
		5 Inorganic Gas-Phase Plasma Decomposition Processes	259
		5.1. CO ₂ : Dissociation in Plasma, Thermal, and Non-Thermal Mechanisms	259
		5.1.1. Fundamental and Applied Aspects of the CO ₂ Plasma Chemistry	259

5.1.2. Major Experimental Results on CO ₂ : Dissociation in Different Plasma Systems and Energy Efficiency of the Process	260	5.3.9. Ionization Degree Regimes of the CO ₂ Dissociation Process in Non-Thermal Plasma	285
5.1.3. Mechanisms of CO ₂ Decomposition in Quasi-Equilibrium Thermal Plasma	262	5.3.10. Energy Losses Related to Excitation of CO ₂ Dissociation Products: Hyperbolic Behavior of Energy Efficiency Dependence on Specific Energy Input	286
5.1.4. CO ₂ Dissociation in Plasma, Stimulated by Vibrational Excitation of Molecules	263	5.4. Energy Efficiency of CO ₂ Dissociation in Quasi-Equilibrium Plasma, and Non-Equilibrium Effects of Quenching Products of Thermal Dissociation	288
5.1.5. CO ₂ Dissociation in Plasma by Means of Electronic Excitation of Molecules	265	5.4.1. Ideal and Super-Ideal Modes of Quenching Products of CO ₂ Dissociation in Thermal Plasma	288
5.1.6. CO ₂ Dissociation in Plasma by Means of Dissociative Attachment of Electrons	267	5.4.2. Kinetic Evolution of Thermal CO ₂ Dissociation Products During Quenching Phase	288
5.2. Physical Kinetics of CO ₂ Dissociation, Stimulated by Vibrational Excitation of the Molecules in Non-Equilibrium Plasma	268	5.4.3. Energy Efficiency of CO ₂ Dissociation in Thermal Plasma Under Conditions of Ideal Quenching of Products	289
5.2.1. Asymmetric and Symmetric CO ₂ Vibrational Modes	268	5.4.4. Vibrational–Translational Non-Equilibrium Effects of Quenching Products of Thermal CO ₂ Dissociation in Plasma: Super-Ideal Quenching Mode	290
5.2.2. Contribution of Asymmetric and Symmetric CO ₂ Vibrational Modes into Plasma-Chemical Dissociation Process	269	5.4.5. Maximum Value of Energy Efficiency of CO ₂ Dissociation in Thermal Plasma with Super-Ideal Quenching of the Dissociation Products	291
5.2.3. Transition of Highly Vibrationally Excited CO ₂ Molecules into the Vibrational Quasi Continuum	271	5.4.6. Kinetic Calculations of Energy Efficiency of CO ₂ Dissociation in Thermal Plasma with Super-Ideal Quenching	291
5.2.4. One-Temperature Approximation of CO ₂ Dissociation Kinetics in Non-Thermal Plasma	273	5.4.7. Comparison of Thermal and Non-Thermal Plasma Approaches to CO ₂ Dissociation: Comments on Products (CO–O ₂) Oxidation and Explosion	292
5.2.5. Two-Temperature Approximation of CO ₂ Dissociation Kinetics in Non-Thermal Plasma	274	5.5. Experimental Investigations of CO ₂ Dissociation in Different Discharge Systems	293
5.2.6. Elementary Reaction Rates of CO ₂ Decomposition, Stimulated in Plasma by Vibrational Excitation of the Molecules	275	5.5.1. Experiments with Non-Equilibrium Microwave Discharges of Moderate Pressure, Discharges in Waveguide Perpendicular to Gas Flow Direction, and Microwave Plasma Parameters in CO ₂	293
5.3. Vibrational Kinetics and Energy Balance of Plasma-Chemical CO ₂ Dissociation	276	5.5.2. Plasma-Chemical Experiments with Dissociation of CO ₂ in Non-Equilibrium Microwave Discharges of Moderate Pressure	295
5.3.1. Two-Temperature Approach to Vibrational Kinetics and Energy Balance of CO ₂ Dissociation in Non-Equilibrium Plasma: Major Energy Balance and Dynamic Equations	276	5.5.3. Experimental Diagnostics of Plasma-Chemical Non-Equilibrium Microwave Discharges in Moderate-Pressure CO ₂ : Plasma Measurements	296
5.3.2. Two-Temperature Approach to Vibrational Kinetics and Energy Balance of CO ₂ Dissociation in Non-Equilibrium Plasma: Additional Vibrational Kinetic Relations	277	5.5.4. Experimental Diagnostics of Plasma-Chemical Non-Equilibrium Microwave Discharges in Moderate-Pressure CO ₂ : Temperature Measurements	297
5.3.3. Results of CO ₂ Dissociation Modeling in the Two-Temperature Approach to Vibrational Kinetics	279	5.5.5. CO ₂ Dissociation in Non-Equilibrium Radiofrequency Discharges: Experiments with Inductively Coupled Plasma	299
5.3.4. One-Temperature Approach to Vibrational Kinetics and Energy Balance of CO ₂ Dissociation in Non-Equilibrium Plasma: Major Equations	280	5.5.6. CO ₂ Dissociation in Non-Equilibrium Radiofrequency Discharges: Experiments with Capacitively Coupled Plasma	300
5.3.5. Threshold Values of Vibrational Temperature, Specific Energy Input, and Ionization Degree for Effective Stimulation of CO ₂ Dissociation by Vibrational Excitation of the Molecules	281	5.5.7. CO ₂ Dissociation in Non-Self-Sustained Atmospheric-Pressure Discharges Supported by High-Energy Electron Beams or UV Radiation	302
5.3.6. Characteristic Time Scales of CO ₂ Dissociation in Plasma Stimulated by Vibrational Excitation of the Molecules: VT-Relaxation Time	282	5.5.8. CO ₂ Dissociation in Different Types of Glow Discharges	302
5.3.7. Flow Velocity and Compressibility Effects on Vibrational Relaxation Kinetics During Plasma-Chemical CO ₂ Dissociation: Maximum Linear Preheating Temperature	283		
5.3.8. CO ₂ Dissociation in Active and Passive Discharge Zones: Discharge (τ_{ev}) and After-Glow (τ_p) Residence Time	284		

5.5.9. CO ₂ Dissociation in Other Non-Thermal and Thermal Discharges: Contribution of Vibrational and Electronic Excitation Mechanisms	304	5.8.6. H ₂ O Dissociation in Thermal Plasma and Quenching of the Dissociation Products: Absolute and Ideal Quenching Modes	325
5.6. CO ₂ Dissociation in Special Experimental Systems, Including Supersonic Stimulation and Plasma Radiolysis	304	5.8.7. Cooling Rate Influence on Kinetics of H ₂ O Dissociation Products in Thermal Plasma: Super-Ideal Quenching Effect	326
5.6.1. Dissociation of CO ₂ in Supersonic Non-Equilibrium Discharges: Advantages and Gasdynamic Characteristics	304	5.8.8. Water Dissociation and H ₂ Production in Plasma-Chemical System CO ₂ -H ₂ O	328
5.6.2. Kinetics and Energy Balance of Non-Equilibrium Plasma-Chemical CO ₂ Dissociation in Supersonic Flow	306	5.8.9. CO-to-H ₂ Shift Reaction: Plasma Chemistry of CO-O ₂ -H ₂ O Mixture	330
5.6.3. Limitations of Specific Energy Input and CO ₂ Conversion Degree in Supersonic Plasma Related to Critical Heat Release and Choking the Flow	308	5.9. Experimental Investigations of H ₂ O Dissociation in Different Discharge Systems	331
5.6.4. Experiments with Dissociation of CO ₂ in Non-Equilibrium Supersonic Microwave Discharges	308	5.9.1. Microwave Discharge in Water Vapor	331
5.6.5. Gasdynamic Stimulation of CO ₂ Dissociation in Supersonic Flow: "Plasma Chemistry Without Electricity"	309	5.9.2. Plasma-Chemical Experiments with Microwave Discharge in Water Vapor	332
5.6.6. Plasma Radiolysis of CO ₂ Provided by High-Current Relativistic Electron Beams	310	5.9.3. Dissociation of Water Vapor in Glow Discharges	332
5.6.7. Plasma Radiolysis of CO ₂ in Tracks of Nuclear Fission Fragments	311	5.9.4. Dissociation of H ₂ O with Production of H ₂ and H ₂ O ₂ in Supersonic Microwave Discharges	334
5.6.8. Ionization Degree in Tracks of Nuclear Fission Fragments, Energy Efficiency of Plasma Radiolysis of CO ₂ , and Plasma-Assisted Chemonuclear Reactors	313	5.9.5. Plasma Radiolysis of Water Vapor in Tracks of Nuclear Fission Fragments	335
5.7. Complete CO ₂ Dissociation in Plasma with Production of Carbon and Oxygen	314	5.9.6. Effect of Plasma Radiolysis on Radiation Yield of Hydrogen Production in Tracks of Nuclear Fission Fragments	336
5.7.1. Complete Plasma-Chemical Dissociation of CO ₂ : Specifics of the Process and Elementary Reaction Mechanism	314	5.10. Inorganic Gas-Phase Plasma-Chemical Processes of Decomposition of Triatomic Molecules: NH ₃ , SO ₂ , and N ₂ O	336
5.7.2. Kinetics of CO Disproportioning Stimulated in Non-Equilibrium Plasma by Vibrational Excitation of Molecules	314	5.10.1. Gas-Phase Plasma Decomposition Reactions in Multi-Phase Technologies	336
5.7.3. Experiments with Complete CO ₂ Dissociation in Microwave Discharges Operating in Conditions of Electron Cyclotron Resonance	316	5.10.2. Dissociation of Ammonia in Non-Equilibrium Plasma: Mechanism of the Process in Glow Discharge	337
5.7.4. Experiments with Complete CO ₂ Dissociation in Stationary Plasma-Beam Discharge	317	5.10.3. Mechanism of Formation of Molecular Nitrogen and Hydrogen in Non-Equilibrium Plasma-Chemical Process of Ammonia Dissociation	338
5.8. Dissociation of Water Vapor and Hydrogen Production in Plasma-Chemical Systems	318	5.10.4. Plasma Dissociation of Sulfur Dioxide	338
5.8.1. Fundamental and Applied Aspects of H ₂ O Plasma Chemistry	318	5.10.5. Destruction and Conversion of Nitrous Oxide in Non-Equilibrium Plasma	340
5.8.2. Kinetics of Dissociation of Water Vapor Stimulated in Non-Thermal Plasma by Vibrational Excitation of Water Molecules	319	5.11. Non-Thermal and Thermal Plasma Dissociation of Diatomic Molecules	341
5.8.3. Energy Efficiency of Dissociation of Water Vapor Stimulated in Non-Thermal Plasma by Vibrational Excitation	320	5.11.1. Plasma-Chemical Decomposition of Hydrogen Halides: Example of HBr Dissociation with Formation of Hydrogen and Bromine	341
5.8.4. Contribution of Dissociative Attachment of Electrons into Decomposition of Water Vapor in Non-Thermal Plasma	322	5.11.2. Dissociation of HF, HCl, and HI in Plasma	343
5.8.5. Kinetic Analysis of the Chain Reaction of H ₂ O Dissociation via Dissociative Attachment/Detachment Mechanism	324	5.11.3. Non-Thermal and Thermal Dissociation of Molecular Fluorine	344
		5.11.4. Dissociation of Molecular Hydrogen in Non-Thermal and Thermal Plasma Systems	345
		5.11.5. Dissociation of Molecular Nitrogen in Non-Thermal and Thermal Plasma Systems	347
		5.11.6. Thermal Plasma Dissociation of Other Diatomic Molecules (O ₂ , Cl ₂ , Br ₂)	347
		Problems and Concept Questions	351

6 Gas-Phase Inorganic Synthesis in Plasma	355		
6.1. Plasma-Chemical Synthesis of Nitrogen Oxides from Air and Nitrogen–Oxygen Mixtures: Thermal and Non-Thermal Mechanisms	355		
6.1.1. Fundamental and Applied Aspects of NO Synthesis in Air Plasma	355		
6.1.2. Mechanisms of NO Synthesis Provided in Non-Thermal Plasma by Excitation of Neutral Molecules: Zeldovich Mechanism	356		
6.1.3. Mechanisms of NO Synthesis Provided in Non-Thermal Plasma by Charged Particles	358		
6.1.4. NO Synthesis in Thermal Plasma Systems	358		
6.1.5. Energy Efficiency of Different Mechanisms of NO Synthesis in Thermal and Non-Thermal Discharge Systems	359		
6.2. Elementary Reaction of NO Synthesis Stimulated by Vibrational Excitation of Molecular Nitrogen	361		
6.2.1. Limiting Elementary Reaction of Zeldovich Mechanism: Adiabatic and Non-Adiabatic Channels of NO Synthesis	361		
6.2.2. Electronically Adiabatic Channel of NO Synthesis $O + N_2 \rightarrow NO + N$ Stimulated by Vibrational Excitation of Molecular Nitrogen	361		
6.2.3. Electronically Non-Adiabatic Channel of NO Synthesis ($O + N_2 \rightarrow NO + N$): Stages of the Elementary Process and Method of Vibronic Terms	363		
6.2.4. Transition Probability Between Vibronic Terms Corresponding to Formation of Intermediate $N_2O^*(^1\Sigma^+)$ Complex	364		
6.2.5. Probability of Formation of Intermediate $N_2O^*(^1\Sigma^+)$ Complex in Electronically Non-Adiabatic Channel of NO Synthesis	365		
6.2.6. Decay of Intermediate Complex $N_2O^*(^1\Sigma^+)$: Second Stage of Electronically Non-Adiabatic Channel of NO Synthesis	366		
6.2.7. Total Probability of Electronically Non-Adiabatic Channel of NO Synthesis ($O + N_2 \rightarrow NO + N$)	367		
6.3. Kinetics and Energy Balance of Plasma-Chemical NO Synthesis Stimulated in Air and O_2 – N_2 Mixtures by Vibrational Excitation	367		
6.3.1. Rate Coefficient of Reaction $O + N_2 \rightarrow NO + N$ Stimulated in Non-Equilibrium Plasma by Vibrational Excitation of Nitrogen Molecules	367		
6.3.2. Energy Balance of Plasma-Chemical NO Synthesis: Zeldovich Mechanism Stimulated by Vibrational Excitation	368		
6.3.3. Macro-Kinetics of Plasma-Chemical NO Synthesis: Time Evolution of Vibrational Temperature	369		
6.3.4. Energy Efficiency of Plasma-Chemical NO Synthesis: Excitation and Relaxation Factors	370		
6.3.5. Energy Efficiency of Plasma-Chemical NO Synthesis: Chemical Factor	371		
6.3.6. Stability of Products of Plasma-Chemical Synthesis to Reverse Reactions in Active Zone of Non-Thermal Plasma	371		
		6.3.7. Effect of “Hot Nitrogen Atoms” on Yield of NO Synthesis in Non-Equilibrium Plasma in Air and Nitrogen–Oxygen Mixtures	372
		6.3.8. Stability of Products of Plasma-Chemical NO Synthesis to Reverse Reactions Outside of the Discharge Zone	373
		6.4. Experimental Investigations of NO Synthesis from Air and N_2 – O_2 Mixtures in Different Discharges	374
		6.4.1. Non-Equilibrium Microwave Discharge in Magnetic Field Operating in Conditions of Electron Cyclotron Resonance	374
		6.4.2. Evolution of Vibrational Temperature of Nitrogen Molecules in Non-Equilibrium ECR: Microwave Discharge During Plasma-Chemical NO Synthesis	376
		6.4.3. NO Synthesis in the Non-Equilibrium ECR Microwave Discharge	377
		6.4.4. NO Synthesis in Non-Self-Sustained Discharges Supported by Relativistic Electron Beams	378
		6.4.5. Experiments with NO Synthesis from Air in Stationary Non-Equilibrium Plasma-Beam Discharge	379
		6.4.6. Experiments with NO Synthesis from N_2 and O_2 in Thermal Plasma of Arc Discharges	380
		6.4.7. General Schematic and Parameters of Industrial Plasma-Chemical Technology of NO Synthesis from Air	381
		6.5. Plasma-Chemical Ozone Generation: Mechanisms and Kinetics	382
		6.5.1. Ozone Production as a Large-Scale Industrial Application of Non-Thermal Atmospheric-Pressure Plasma	382
		6.5.2. Energy Cost and Energy Efficiency of Plasma-Chemical Production of Ozone in Some Experimental and Industrial Systems	383
		6.5.3. Plasma-Chemical Ozone Formation in Oxygen	383
		6.5.4. Optimum DBD Microdischarge Strength and Maximization of Energy Efficiency of Ozone Production in Oxygen Plasma	385
		6.5.5. Plasma-Chemical Ozone Generation in Air	386
		6.5.6. Discharge Poisoning Effect During Ozone Generation in Air Plasma	387
		6.5.7. Temperature Effect on Plasma-Chemical Generation and Stability of Ozone	388
		6.5.8. Negative Effect of Water Vapor on Plasma-Chemical Ozone Synthesis	389
		6.5.9. Effect of Hydrogen, Hydrocarbons, and Other Admixtures on Plasma-Chemical Ozone Synthesis	390
		6.6. Experimental and Industrial Plasma-Chemical Ozone Generators	392
		6.6.1. Synthesis of Ozone in Dielectric Barrier Discharges as the Oldest and Still Most Successful Approach to Ozone Generation	392
		6.6.2. Tubular DBD Ozone Generators and Large Ozone Production Installations	392
		6.6.3. Planar and Surface Discharge Configurations of DBD Ozone Generators	394
		6.6.4. Synthesis of Ozone in Pulsed Corona Discharges	395

6.6.5. Peculiarities of Ozone Synthesis in Pulsed Corona with Respect to DBD	396	7.1.4. Thermal Plasma Reduction of Oxides of Aluminum and Other Inorganic Elements	423
6.6.6. Possible Specific Contribution of Vibrational Excitation of Molecules to Ozone Synthesis in Pulsed Corona Discharges	397	7.1.5. Reduction of Metal Oxides and Production of Metals Using Non-Thermal Hydrogen Plasma	425
6.7. Synthesis of KrF ₂ and Other Aggressive Fluorine Oxidizers	399	7.1.6. Non-Equilibrium Surface Heating and Evaporation Effect in Heterogeneous Plasma-Chemical Processes in Non-Thermal Discharges	426
6.7.1. Plasma-Chemical Gas-Phase Synthesis of KrF ₂ and Mechanism of Surface Stabilization of Reaction Products	399	7.1.7. Non-Equilibrium Surface Heating and Evaporation in Plasma Treatment of Thin Layers of Flat Surfaces: Effect of Short Pulses	427
6.7.2. Physical Kinetics of KrF ₂ Synthesis in Krypton Matrix	400	7.2. Production of Metals and Other Elements by Carbothermic Reduction and Direct Decomposition of Their Oxides in Thermal Plasma	429
6.7.3. Synthesis of KrF ₂ in Glow Discharges, Barrier Discharges, and Photo-Chemical Systems	401	7.2.1. Carbothermic Reduction of Elements from Their Oxides	429
6.7.4. Synthesis of KrF ₂ in Non-Equilibrium Microwave Discharge in Magnetic Field	402	7.2.2. Production of Pure Metallic Uranium by Carbothermic Plasma-Chemical Reduction of Uranium Oxides	429
6.7.5. Plasma F ₂ Dissociation as the First Step in Synthesis of Aggressive Fluorine Oxidizers	402	7.2.3. Production of Niobium by Carbothermic Plasma-Chemical Reduction of Niobium Oxides	430
6.7.6. Plasma-Chemical Synthesis of O ₂ F ₂ and Other Oxygen Fluorides	403	7.2.4. Double-Stage Carbothermic Thermal Plasma Reduction of Rare and Refractory Metals from Their Oxides	430
6.7.7. Plasma-Chemical Synthesis of NF ₃ and Other Nitrogen Fluorides	404	7.2.5. Carbothermic Reduction of Iron from Iron Titanium Oxide Concentrates in a Thermal Plasma Fluidized Bed	431
6.7.8. Plasma-Chemical Synthesis of Xenon Fluorides and Other Fluorine Oxidizers	405	7.2.6. Production of Silicon Monoxide by SiO ₂ Decomposition in Thermal Plasma	432
6.8. Plasma-Chemical Synthesis of Hydrazine (N ₂ H ₄), Ammonia (NH ₃), Nitrides of Phosphorus, and Some Other Inorganic Compounds	406	7.2.7. Experiments with SiO ₂ Reduction to Pure Silicon Monoxide in High-Temperature Radiofrequency ICP Discharges	433
6.8.1. Direct Plasma-Chemical Hydrazine (N ₂ H ₄) Synthesis from Nitrogen and Hydrogen in Non-Equilibrium Discharges	406	7.2.8. Reduction of Aluminum by Direct Thermal Plasma Decomposition of Alumina	434
6.8.2. Hydrazine (N ₂ H ₄) Synthesis from N ₂ -H ₂ Mixture in Non-Self-Sustained Stationary Discharge Supported by Electron Beam	407	7.2.9. Reduction of Vanadium by Direct Plasma Decomposition of Its Oxides, V ₂ O ₅ and V ₂ O ₃	436
6.8.3. Kinetics of Hydrazine (N ₂ H ₄) Synthesis from N ₂ -H ₂ Mixture in Non-Thermal Plasma Conditions	407	7.2.10. Reduction of Indium and Germanium by Direct Plasma Decomposition of Their Oxides	439
6.8.4. Synthesis of Ammonia in DBD and Glow Discharges	408	7.3. Hydrogen Plasma Reduction of Metals and Other Elements from Their Halides	440
6.8.5. Plasma-Chemical Synthesis of Nitrides of Phosphorus	409	7.3.1. Using Halides for Production of Metals and Other Elements from Their Compounds	440
6.8.6. Sulfur Gasification by Carbon Dioxide in Non-Thermal and Thermal Plasmas	409	7.3.2. Plasma-Chemical Production of Boron: Thermal Plasma Reduction of BCl ₃ with Hydrogen	441
6.8.7. CN and NO Synthesis in CO-N ₂ Plasma	412	7.3.3. Hydrogen Reduction of Niobium from Its Pentachloride (NiCl ₅) in Thermal Plasma	442
6.8.8. Gas-Phase Synthesis Related to Plasma-Chemical Oxidation of HCl and SO ₂	413	7.3.4. Hydrogen Reduction of Uranium from Its Hexafluoride (UF ₆) in Thermal Plasma	442
Problems and Concept Questions	414	7.3.5. Hydrogen Reduction of Tantalum (Ta), Molybdenum (Mo), Tungsten (W), Zirconium (Zr), and Hafnium (Hf) from Their Chlorides in Thermal Plasma	443
7 Plasma Synthesis, Treatment, and Processing of Inorganic Materials, and Plasma Metallurgy	417	7.3.6. Hydrogen Reduction of Titanium (Ti), Germanium (Ge), and Silicon (Si) from Their Tetrachlorides in Thermal Plasma	445
7.1. Plasma Reduction of Oxides of Metals and Other Elements	417	7.3.7. Thermal Plasma Reduction of Some Other Halides with Hydrogen: Plasma Production of Intermetallic Compounds	446
7.1.1. Thermal Plasma Reduction of Iron Ore, Iron Production from Oxides Using Hydrogen and Hydrocarbons, and Plasma-Chemical Steel Manufacturing	417		
7.1.2. Productivity and Energy Efficiency of Thermal Plasma Reduction of Iron Ore	419		
7.1.3. Hydrogen Reduction of Refractory Metal Oxides in Thermal Plasma and Plasma Metallurgy of Tungsten and Molybdenum	420		

7.3.8. Hydrogen Reduction of Halides in Non-Thermal Plasma	448	7.6.3. Plasma-Chemical Extraction of Nickel from Serpentine Minerals	482
7.4. Direct Decomposition of Halides in Thermal and Non-Thermal Plasma	448	7.6.4. Production of Uranium Oxide (U_3O_8) by Thermal Plasma Decomposition of Uranyl Nitrate ($UO_2(NO_3)_2$) Aqueous Solutions	482
7.4.1. Direct Decomposition of Halides and Production of Metals in Plasma	448	7.6.5. Production of Magnesium Oxide (MgO) by Thermal Plasma Decomposition of Aqueous Solution or Melt of Magnesium Nitrate ($Mg(NO_3)_2$)	483
7.4.2. Direct UF_6 Decomposition in Thermal Plasma: Requirements for Effective Product Quenching	449	7.6.6. Plasma-Chemical Production of Oxide Powders for Synthesis of High-Temperature Superconducting Composites	483
7.4.3. Direct Decomposition of Halides of Some Alkali and Alkaline Earth Metals in Thermal Plasma	451	7.6.7. Production of Uranium Oxide (U_3O_8) by Thermal Plasma Conversion of Uranium Hexafluoride (UF_6) with Water Vapor	484
7.4.4. Direct Thermal Plasma Decomposition of Halides of Aluminum, Silicon, Arsenic, and Some Other Elements of Groups 3, 4, and 5	457	7.6.8. Conversion of Silicon Tetrafluoride (SiF_4) with Water Vapor into Silica (SiO_2) and HF in Thermal Plasma	484
7.4.5. Direct Thermal Plasma Decomposition of Halides of Titanium (Ti), Zirconium (Zr), Hafnium (Hf), Vanadium (V), and Niobium (Nb)	461	7.6.9. Production of Pigment Titanium Dioxide (TiO_2) by Thermal Plasma Conversion of Titanium Tetrachloride ($TiCl_4$) in Oxygen	485
7.4.6. Direct Decomposition of Halides of Iron (Fe), Cobalt (Co), Nickel (Ni), and Other Transition Metals in Thermal Plasma	465	7.6.10. Thermal Plasma Conversion of Halides in Production of Individual and Mixed Oxides of Chromium, Aluminum, and Titanium	486
7.4.7. Direct Decomposition of Halides and Reduction of Metals in Non-Thermal Plasma	469	7.6.11. Thermal Plasma Treatment of Phosphates: Tricalcium Phosphate ($Ca_3(PO_4)_2$) and Fluoroapatite ($Ca_5F(PO_4)_3$)	487
7.4.8. Kinetics of Dissociation of Metal Halides in Non-Thermal Plasma: Distribution of Halides over Oxidation Degrees	470	7.6.12. Oxidation of Phosphorus and Production of Phosphorus Oxides in Air Plasma	488
7.4.9. Heterogeneous Stabilization of Products During Direct Decomposition of Metal Halides in Non-Thermal Plasma: Application of Plasma Centrifuges for Product Quenching	472	7.7. Plasma-Chemical Production of Hydrides, Borides, Carbonyls, and Other Compounds of Inorganic Materials	488
7.5. Plasma-Chemical Synthesis of Nitrides and Carbides of Inorganic Materials	472	7.7.1. Production of Hydrides in Thermal and Non-Thermal Plasma	488
7.5.1. Plasma-Chemical Synthesis of Metal Nitrides from Elements: Gas-Phase and Heterogeneous Reaction Mechanisms	472	7.7.2. Non-Thermal Plasma Mechanisms of Hydride Formation by Hydrogen Gasification of Elements and by Hydrogenation of Thin Films	489
7.5.2. Synthesis of Nitrides of Titanium and Other Elements by Plasma-Chemical Conversion of Their Chlorides	473	7.7.3. Synthesis of Metal Carbonyls in Non-Thermal Plasma: Effect of Vibrational Excitation of CO Molecules on Carbonyl Synthesis	490
7.5.3. Synthesis of Silicon Nitride (Si_3N_4) and Oxynitrides by Non-Thermal Plasma Conversion of Silane (SiH_4)	474	7.7.4. Plasma-Chemical Synthesis of Borides of Inorganic Materials	492
7.5.4. Production of Metal Carbides by Solid-Phase Synthesis in Thermal Plasma of Inert Gases	475	7.7.5. Synthesis of Intermetallic Compounds in Thermal Plasma	493
7.5.5. Synthesis of Metal Carbides by Reaction of Solid Metal Oxides with Gaseous Hydrocarbons in Thermal Plasma	475	7.8. Plasma Cutting, Welding, Melting, and Other High-Temperature Inorganic Material Processing Technologies	493
7.5.6. Gas-Phase Synthesis of Carbides in Plasma-Chemical Reactions of Halides with Hydrocarbons	475	7.8.1. Plasma Cutting Technology	493
7.5.7. Conversion of Solid Oxides into Carbides Using Gaseous Hydrocarbons Inside of RF-ICP Thermal Plasma Discharge and Some Other Plasma Technologies for Carbide Synthesis	477	7.8.2. Plasma Welding Technology	494
7.6. Plasma-Chemical Production of Inorganic Oxides by Thermal Decomposition of Minerals, Aqueous Solutions, and Conversion Processes	477	7.8.3. About Plasma Melting and Remelting of Metals	495
7.6.1. Plasma Production of Zirconia (ZrO_2) by Decomposition of Zircon Sand ($ZrSiO_4$)	477	7.8.4. Plasma Spheroidization and Densification of Powders	495
7.6.2. Plasma Production of Manganese Oxide (MnO) by Decomposition of Rhodonite ($MnSiO_3$)	478	Problems and Concept Questions	496
		8 Plasma-Surface Processing of Inorganic Materials: Micro- and Nano-Technologies	499
		8.1. Thermal Plasma Spraying	499
		8.1.1. Plasma Spraying as a Thermal Spray Technology	499

8.1.2.	DC-Arc Plasma Spray: Air Plasma Spray	500	8.4.1.	In Situ Plasma Cleaning in Micro-Electronics and Related Environmental Issues	531
8.1.3.	DC-Arc Plasma Spray: VPS, LPPS, CAPS, SPS, UPS, and Other Specific Spray Approaches	501	8.4.2.	Remote Plasma Cleaning Technology in Microelectronics: Choice of Cleaning Feedstock Gas	532
8.1.4.	Radiofrequency Plasma Spray	502	8.4.3.	Kinetics of F-Atom Generation from NF_3 , CF_4 , and C_2F_6 in Remote Plasma Sources	533
8.1.5.	Thermal Plasma Spraying of Monolithic Materials	503	8.4.4.	Surface and Volume Recombination of F Atoms in Transport Tube	535
8.1.6.	Thermal Plasma Spraying of Composite Materials	505	8.4.5.	Effectiveness of F Atom Transportation from Remote Plasma Source	538
8.1.7.	Thermal Spray Technologies: Reactive Plasma Spray Forming	507	8.4.6.	Other Plasma Cleaning Processes: Passive Plasma Cleaning	539
8.1.8.	Thermal Plasma Spraying of Functionally Gradient Materials	508	8.4.7.	Other Plasma Cleaning Processes: Active Plasma Cleaning	540
8.1.9.	Thermal Plasma Spray Modeling	510	8.4.8.	Wettability Improvement of Metallic Surfaces by Active and Passive Plasma Cleaning	541
8.2.	Plasma-Chemical Etching: Mechanisms and Kinetics	510	8.5.	Plasma Deposition Processes: Plasma-Enhanced Chemical Vapor Deposition and Sputtering Deposition	541
8.2.1.	Main Principles of Plasma Etching as Part of Integrated Circuit Fabrication Technology	510	8.5.1.	Plasma-Enhanced Chemical Vapor Deposition: General Principles	541
8.2.2.	Etch Rate, Anisotropy, Selectivity, and Other Plasma Etch Requirements	511	8.5.2.	PECVD of Thin Films of Amorphous Silicon	542
8.2.3.	Basic Plasma Etch Processes: Sputtering	514	8.5.3.	Kinetics of Amorphous Silicon Film Deposition in Silane (SiH_4) Discharges	543
8.2.4.	Basic Plasma Etch Processes: Pure Chemical Etching	515	8.5.4.	Plasma Processes of Silicon Oxide (SiO_2) Film Growth: Direct Silicon Oxidation	545
8.2.5.	Basic Plasma Etch Processes: Ion Energy-Driven Etching	516	8.5.5.	Plasma Processes of Silicon Oxide (SiO_2) Film Growth: PECVD from Silane–Oxygen Feedstock Mixtures and Conformal and Non-Conformal Deposition Within Trenches	545
8.2.6.	Basic Plasma Etch Processes: Ion-Enhanced Inhibitor Etching	516	8.5.6.	Plasma Processes of Silicon Oxide (SiO_2) Film Growth: PECVD from TEOS– O_2 Feed-Gas Mixtures	547
8.2.7.	Surface Kinetics of Etching Processes; Kinetics of Ion Energy-Driven Etching	517	8.5.7.	PECVD Process of Silicon Nitride (Si_3N_4)	547
8.2.8.	Discharges Applied for Plasma Etching: RF-CCP Sources, RF Diodes and Triodes, and MERIEs	519	8.5.8.	Sputter Deposition Processes: General Principles	548
8.2.9.	Discharges Applied for Plasma Etching: High-Density Plasma Sources	520	8.5.9.	Physical Sputter Deposition	548
8.2.10.	Discharge Kinetics in Etching Processes: Ion Density and Ion Flux	520	8.5.10.	Reactive Sputter Deposition Processes	549
8.2.11.	Discharge Kinetics in Etching Processes: Density and Flux of Neutral Etchants	521	8.5.11.	Kinetics of Reactive Sputter Deposition: Hysteresis Effect	550
8.3.	Specific Plasma-Chemical Etching Processes	523	8.6.	Ion Implantation Processes: Ion-Beam Implantation and Plasma-Immersion Ion Implantation	551
8.3.1.	Gas Composition in Plasma Etching Processes: Etchants-to-Unsaturates Flux Ratio	523	8.6.1.	Ion-Beam Implantation	551
8.3.2.	Pure Chemical F-Atom Etching of Silicon: Flamm Formulas and Doping Effect	523	8.6.2.	Plasma-Immersion Ion Implantation: General Principles	552
8.3.3.	Ion Energy-Driven F-Atom Etching Process: Main Etching Mechanisms	524	8.6.3.	Dynamics of Sheath Evolution in Plasma-Immersion Ion Implantation: From Matrix Sheath to Child Law Sheath	553
8.3.4.	Plasma Etching of Silicon in CF_4 Discharges: Kinetics of Fluorine Atoms	525	8.6.4.	Time Evolution of Implantation Current in PIII Systems	555
8.3.5.	Plasma Etching of Silicon in CF_4 Discharges: Kinetics of CF_x Radicals and Competition Between Etching and Carbon Deposition	526	8.6.5.	PIII Applications for Processing Semiconductor Materials	556
8.3.6.	Plasma Etching of Silicon by Cl Atoms	528	8.6.6.	PIII Applications for Modifying Metallurgical Surfaces: Plasma Source Ion Implantation	557
8.3.7.	Plasma Etching of SiO_2 by F Atoms and CF_x Radicals	529	8.7.	Microarc (Electrolytic-Spark) Oxidation Coating and Other Microdischarge Surface Processing Systems	557
8.3.8.	Plasma Etching of Silicon Nitride (Si_3N_4)	529	8.7.1.	Microarc (Electrolytic-Spark) Oxidation Coating: General Features	557
8.3.9.	Plasma Etching of Aluminum	529	8.7.2.	Major Characteristics of the Microarc (Electrolytic-Spark) Oxidation Process	558
8.3.10.	Plasma Etching of Photoresist	530			
8.3.11.	Plasma Etching of Refractory Metals and Semiconductors	530			
8.4.	Plasma Cleaning of CVD and Etching Reactors in Micro-Electronics and Other Plasma Cleaning Processes	531			

8.7.3. Mechanism of Microarc (Electrolytic-Spark) Oxidation Coating of Aluminum in Sulfuric Acid	559	9.1.3. Electric Cracking of Natural Gas with Production of Acetylene–Hydrogen or Acetylene–Ethylene–Hydrogen Mixtures	591
8.7.4. Breakdown of Oxide Film and Starting Microarc Discharge	560	9.1.4. Other Processes and Regimes of Hydrocarbon Conversion in Thermal Plasma	592
8.7.5. Microarc Discharge Plasma Chemistry of Oxide Coating Deposition on Aluminum in Concentrated Sulfuric Acid Electrolyte	562	9.1.5. Some Chemical Engineering Aspects of Plasma Pyrolysis of Hydrocarbons	595
8.7.6. Direct Micropatterning and Microfabrication in Atmospheric-Pressure Microdischarges	563	9.1.6. Production of Vinyl Chloride as an Example of Technology Based on Thermal Plasma Pyrolysis of Hydrocarbons	596
8.7.7. Microetching, Microdeposition, and Microsurface Modification by Atmospheric-Pressure Microplasma Discharges	564	9.1.7. Plasma Pyrolysis of Hydrocarbons with Production of Soot and Hydrogen	597
8.8. Plasma Nanotechnologies: Nanoparticles and Dusty Plasmas	566	9.1.8. Thermal Plasma Production of Acetylene by Carbon Vapor Reaction with Hydrogen or Methane	598
8.8.1. Nanoparticles in Plasma: Kinetics of Dusty Plasma Formation in Low-Pressure Silane Discharges	566	9.2. Conversion of Methane into Acetylene and Other Processes of Gas-Phase Conversion of Hydrocarbons in Non-Thermal Plasmas	598
8.8.2. Formation of Nanoparticles in Silane: Plasma Chemistry of Birth and Catastrophic Evolution	567	9.2.1. Energy Efficiency of CH ₄ Conversion into Acetylene in Thermal and Non-Thermal Plasmas	598
8.8.3. Critical Phenomena in Dusty Plasma Kinetics: Nucleation of Nanoparticles, Winchester Mechanism, and Growth of First Generation of Negative Ion Clusters	570	9.2.2. High-Efficiency CH ₄ Conversion into C ₂ H ₂ in Non-Thermal Moderate-Pressure Microwave Discharges	598
8.8.4. Critical Size of Primary Nanoparticles in Silane Plasma	572	9.2.3. Limits of Quasi-Equilibrium Kassel Kinetics for Plasma Conversion of CH ₄ into C ₂ H ₂	600
8.8.5. Critical Phenomenon of Neutral-Particle Trapping in Silane Plasma	573	9.2.4. Contribution of Vibrational Excitation to Methane Conversion into Acetylene in Non-Equilibrium Discharge Conditions	601
8.8.6. Critical Phenomenon of Super-Small Nanoparticle Coagulation	575	9.2.5. Non-Equilibrium Kinetics of Methane Conversion into Acetylene Stimulated by Vibrational Excitation	602
8.8.7. Critical Change of Plasma Parameters due to Formation of Nanoparticles: α – γ Transition	577	9.2.6. Other Processes of Decomposition, Elimination, and Isomerization of Hydrocarbons in Non-Equilibrium Plasma: Plasma Catalysis	603
8.8.8. Other Processes of Plasma Production of Nanoparticles: Synthesis of Aluminum Nanopowder and Luminescent Silicon Quantum Dots	579	9.3. Plasma Synthesis and Conversion of Organic Nitrogen Compounds	604
8.8.9. Plasma Synthesis of Nanocomposite Particles	580	9.3.1. Synthesis of Dicyanogen (C ₂ N ₂) from Carbon and Nitrogen in Thermal Plasma	604
8.9. Plasma Nanotechnologies: Synthesis of Fullerenes and Carbon Nanotubes	581	9.3.2. Co-Production of Hydrogen Cyanide (HCN) and Acetylene (C ₂ H ₂) from Methane and Nitrogen in Thermal Plasma Systems	605
8.9.1. Highly Organized Carbon Nanostructures: Fullerenes and Carbon Nanotubes	581	9.3.3. Hydrogen Cyanide (HCN) Production from Methane and Nitrogen in Non-Thermal Plasma	606
8.9.2. Plasma Synthesis of Fullerenes	583	9.3.4. Production of HCN and H ₂ in CH ₄ –NH ₃ Mixture in Thermal and Non-Thermal Plasmas	608
8.9.3. Plasma Synthesis of Endohedral Fullerenes	583	9.3.5. Thermal and Non-Thermal Plasma Conversion Processes in CO–N ₂ Mixture	609
8.9.4. Plasma Synthesis of Carbon Nanotubes by Dispersion of Thermal Arc Electrodes	584	9.3.6. Other Non-Equilibrium Plasma Processes of Organic Nitrogen Compounds Synthesis	610
8.9.5. Plasma Synthesis of Carbon Nanotubes by Dissociation of Carbon Compounds	584	9.4. Organic Plasma Chemistry of Chlorine and Fluorine Compounds	611
8.9.6. Surface Modification of Carbon Nanotubes by RF Plasma	585	9.4.1. Thermal Plasma Synthesis of Reactive Mixtures for Production of Vinyl Chloride	611
Problems and Concept Questions	586	9.4.2. Thermal Plasma Pyrolysis of Dichloroethane, Butyl Chloride, Hexachlorane, and Other Organic Chlorine Compounds for Further Synthesis of Vinyl Chloride	612
9 Organic and Polymer Plasma Chemistry	589	9.4.3. Thermal Plasma Pyrolysis of Organic Fluorine Compounds	613
9.1. Thermal Plasma Pyrolysis of Methane and Other Hydrocarbons: Production of Acetylene and Ethylene	589		
9.1.1. Kinetics of Thermal Plasma Pyrolysis of Methane and Other Hydrocarbons: The Kassel Mechanism	589		
9.1.2. Kinetics of Double-Step Plasma Pyrolysis of Hydrocarbons	591		

9.4.4. Pyrolysis of Organic Fluorine Compounds in Thermal Plasma of Nitrogen: Synthesis of Nitrogen-Containing Fluorocarbons	614	9.7.3. Kinetics of Formation of Main Chemical Products in Process of Polyethylene Treatment in Pulsed RF Discharges	634
9.4.5. Thermal Plasma Pyrolysis of Chlorofluorocarbons	614	9.7.4. Kinetics of Polyethylene Treatment in Continuous RF Discharge	636
9.4.6. Non-Thermal Plasma Conversion of CFCs and Other Plasma Processes with Halogen-Containing Organic Compounds	616	9.7.5. Non-Thermal Plasma Etching of Polymer Materials	636
9.5. Plasma Synthesis of Aldehydes, Alcohols, Organic Acids, and Other Oxygen-Containing Organic Compounds	617	9.7.6. Contribution of Electrons and Ultraviolet Radiation in the Chemical Effect of Plasma Treatment of Polymer Materials	637
9.5.1. Non-Thermal Plasma Direct Synthesis of Methanol from Methane and Carbon Dioxide	617	9.7.7. Interaction of Atoms, Molecules, and Other Chemically Active Heavy Particles Generated in Non-Thermal Plasma with Polymer Materials: Plasma-Chemical Oxidation of Polymer Surfaces	638
9.5.2. Non-Thermal Plasma Direct Synthesis of Methanol from Methane and Water Vapor	617	9.7.8. Plasma-Chemical Nitrogenation of Polymer Surfaces	639
9.5.3. Production of Formaldehyde (CH ₂ O) by CH ₄ Oxidation in Thermal and Non-Thermal Plasmas	618	9.7.9. Plasma-Chemical Fluorination of Polymer Surfaces	640
9.5.4. Non-Thermal Plasma Oxidation of Methane and Other Hydrocarbons with Production of Methanol and Other Organic Compounds	619	9.7.10. Synergetic Effect of Plasma-Generated Active Atomic/Molecular Particles and UV Radiation During Plasma Interaction with Polymers	640
9.5.5. Non-Thermal Plasma Synthesis of Aldehydes, Alcohols, and Organic Acids in Mixtures of Carbon Oxides with Hydrogen: Organic Synthesis in CO ₂ -H ₂ O Mixture	620	9.7.11. Aging Effect in Plasma-Treated Polymers	641
9.5.6. Non-Thermal Plasma Production of Methane and Acetylene from Syngas (CO-H ₂)	621	9.8. Applications of Plasma Modification of Polymer Surfaces	641
9.6. Plasma-Chemical Polymerization of Hydrocarbons: Formation of Thin Polymer Films	622	9.8.1. Plasma Modification of Wettability of Polymer Surfaces	641
9.6.1. General Features of Plasma Polymerization	622	9.8.2. Plasma Enhancement of Adhesion of Polymer Surfaces: Metallization of Polymer Surfaces	643
9.6.2. General Aspects of Mechanisms and Kinetics of Plasma Polymerization	622	9.8.3. Plasma Modification of Polymer Fibers and Polymer Membranes	645
9.6.3. Initiation of Polymerization by Dissociation of Hydrocarbons in Plasma Volume	623	9.8.4. Plasma Treatment of Textile Fibers: Treatment of Wool	645
9.6.4. Heterogeneous Mechanisms of Plasma-Chemical Polymerization of C ₁ /C ₂ Hydrocarbons	625	9.8.5. Plasma Treatment of Textile Fibers: Treatment of Cotton and Synthetic Textiles and the Lotus Effect	648
9.6.5. Plasma-Initiated Chain Polymerization: Mechanisms of Plasma Polymerization of Methyl Methacrylate	625	9.8.6. Specific Conditions and Results of Non-Thermal Plasma Treatment of Textiles	649
9.6.6. Plasma-Initiated Graft Polymerization	626	9.8.7. Plasma-Chemical Processes for Final Fabric Treatment	649
9.6.7. Formation of Polymer Macroparticles in Volume of Non-Thermal Plasma in Hydrocarbons	627	9.8.8. Plasma-Chemical Treatment of Plastics, Rubber Materials, and Special Polymer Films	654
9.6.8. Plasma-Chemical Reactors for Deposition of Thin Polymer Films	628	9.9. Plasma Modification of Gas-Separating Polymer Membranes	655
9.6.9. Some Specific Properties of Plasma-Polymerized Films	628	9.9.1. Application of Polymer Membranes for Gas Separation: Enhancement of Polymer Membrane Selectivity by Plasma Polymerization and by Plasma Modification of Polymer Surfaces	655
9.6.10. Electric Properties of Plasma-Polymerized Films	630	9.9.2. Microwave Plasma System for Surface Modification of Gas-Separating Polymer Membranes	656
9.6.11. Some Specific Applications of Plasma-Polymerized Film Deposition	631	9.9.3. Influence of Non-Thermal Discharge Treatment Parameters on Permeability of Plasma-Modified Gas-Separating Polymer Membranes	657
9.7. Interaction of Non-Thermal Plasma with Polymer Surfaces: Fundamentals of Plasma Modification of Polymers	632	9.9.4. Plasma Enhancement of Selectivity of Gas-Separating Polymer Membranes	659
9.7.1. Plasma Treatment of Polymer Surfaces	632	9.9.5. Chemical and Structural Modification of Surface Layers of Gas-Separating Polymer Membranes by Microwave Plasma Treatment	661
9.7.2. Major Initial Chemical Products Created on Polymer Surfaces During Their Interaction with Non-Thermal Plasma	633	9.9.6. Theoretical Model of Modification of Polymer Membrane Surfaces in After-Glow of Oxygen-Containing Plasma of Non-Polymerizing Gases: Lame Equation	662

9.9.7. Elasticity/Electrostatics Similarity Approach to Permeability of Plasma-Treated Polymer Membranes	663	10.2. Plasma-Chemical Reforming of Liquid Fuels into Syngas (CO–H ₂): On-Board Generation of Hydrogen-Rich Gases for Internal Combustion Engine Vehicles	692
9.9.8. Effect of Cross-Link's Mobility and Clusterization on Permeability of Plasma-Treated Polymer Membranes	664	10.2.1. Specific Applications of Plasma-Chemical Reforming of Liquid Automotive Fuels: On-Board Generation of Hydrogen-Rich Gases	692
9.9.9. Modeling of Selectivity of Plasma-Treated Gas-Separating Polymer Membranes	666	10.2.2. Plasma-Catalytic Steam Conversion and Partial Oxidation of Kerosene for Syngas Production	693
9.9.10. Effect of Initial Membrane Porosity on Selectivity of Plasma-Treated Gas-Separating Polymer Membranes	667	10.2.3. Plasma-Catalytic Conversion of Ethanol with Production of Syngas	694
9.10. Plasma-Chemical Synthesis of Diamond Films	668	10.2.4. Plasma-Stimulated Reforming of Diesel Fuel and Diesel Oils into Syngas	697
9.10.1. General Features of Diamond-Film Production and Deposition in Plasma	668	10.2.5. Plasma-Stimulated Reforming of Gasoline into Syngas	698
9.10.2. Different Discharge Systems Applied for Synthesis of Diamond Films	669	10.2.6. Plasma-Stimulated Reforming of Aviation Fuels into Syngas	698
9.10.3. Non-Equilibrium Discharge Conditions and Gas-Phase Plasma-Chemical Processes in the Systems Applied for Synthesis of Diamond Films	671	10.2.7. Plasma-Stimulated Partial Oxidation Reforming of Renewable Biomass: Biodiesel	699
9.10.4. Surface Chemical Processes of Diamond-Film Growth in Plasma	672	10.2.8. Plasma-Stimulated Partial Oxidation Reforming of Bio-Oils and Other Renewable Biomass into Syngas	700
9.10.5. Kinetics of Diamond-Film Growth	673	10.3. Combined Plasma–Catalytic Production of Hydrogen by Partial Oxidation of Hydrocarbon Fuels	701
Problems and Concept Questions	674	10.3.1. Combined Plasma–Catalytic Approach Versus Plasma Catalysis in Processes of Hydrogen Production by Partial Oxidation of Hydrocarbons	701
10 Plasma-Chemical Fuel Conversion and Hydrogen Production	676	10.3.2. Pulsed-Corona-Based Combined Plasma–Catalytic System for Reforming of Hydrocarbon Fuel and Production of Hydrogen-Rich Gases	702
10.1. Plasma-Chemical Conversion of Methane, Ethane, Propane, and Natural Gas into Syngas (CO–H ₂) and Other Hydrogen-Rich Mixtures	676	10.3.3. Catalytic Partial Oxidation Reforming of Isooctane	703
10.1.1. General Features of Plasma-Assisted Production of Hydrogen from Hydrocarbons: Plasma Catalysis	676	10.3.4. Partial Oxidation Reforming of Isooctane Stimulated by Non-Equilibrium Atmospheric-Pressure Pulsed Corona Discharge	703
10.1.2. Syngas Production by Partial Oxidation of Methane in Different Non-Equilibrium Plasma Discharges, Application of Gliding Arc Stabilized in Reverse Vortex (Tornado) Flow	678	10.3.5. Reforming of Isooctane and Hydrogen Production in Pulsed-Corona-Based Combined Plasma–Catalytic System	704
10.1.3. Plasma Catalysis for Syngas Production by Partial Oxidation of Methane in Non-Equilibrium Gliding Arc Stabilized in Reverse Vortex (Tornado) Flow	681	10.3.6. Comparison of Isooctane Reforming in Plasma Preprocessing and Plasma Postprocessing Configurations of the Combined Plasma–Catalytic System	706
10.1.4. Non-Equilibrium Plasma-Catalytic Syngas Production from Mixtures of Methane with Water Vapor	683	10.4. Plasma-Chemical Conversion of Coal: Mechanisms, Kinetics, and Thermodynamics	707
10.1.5. Non-Equilibrium Plasma-Chemical Syngas Production from Mixtures of Methane with Carbon Dioxide	685	10.4.1. Coal and Its Composition, Structure, and Conversion to Other Fuels	707
10.1.6. Plasma-Catalytic Direct Decomposition (Pyrolysis) of Ethane in Atmospheric-Pressure Microwave Discharges	687	10.4.2. Thermal Conversion of Coal	708
10.1.7. Plasma Catalysis in the Process of Hydrogen Production by Direct Decomposition (Pyrolysis) of Methane	688	10.4.3. Transformations of Sulfur-Containing Compounds During Thermal Conversion of Coal	710
10.1.8. Mechanism of Plasma Catalysis of Direct CH ₄ Decomposition in Non-Equilibrium Discharges	689	10.4.4. Transformations of Nitrogen-Containing Compounds During Thermal Conversion of Coal	711
10.1.9. Plasma-Chemical Conversion of Propane, Propane–Butane Mixtures, and Other Gaseous Hydrocarbons to Syngas and Other Hydrogen-Rich Mixtures	690	10.4.5. Thermodynamic Analysis of Coal Conversion in Thermal Plasma	711
		10.4.6. Kinetic Phases of Coal Conversion in Thermal Plasma	712

10.4.7. Kinetic Analysis of Thermal Plasma Conversion of Coal: Kinetic Features of the Major Phases of Coal Conversion in Plasma	714	10.7. Hydrogen Sulfide Decomposition in Plasma with Production of Hydrogen and Sulfur: Technological Aspects of Plasma-Chemical Hydrogen Production	738
10.4.8. Coal Conversion in Non-Thermal Plasma	715	10.7.1. H ₂ S Dissociation in Plasma with Production of Hydrogen and Elemental Sulfur and Its Industrial Applications	738
10.5. Thermal and Non-Thermal Plasma-Chemical Systems for Coal Conversion	716	10.7.2. Application of Microwave, Radiofrequency, and Arc Discharges for H ₂ S Dissociation with Production of Hydrogen and Elemental Sulfur	740
10.5.1. General Characteristics of Coal Conversion in Thermal Plasma Jets	716	10.7.3. Technological Aspects of Plasma-Chemical Dissociation of Hydrogen Sulfide with Production of Hydrogen and Elemental Sulfur	741
10.5.2. Thermal Plasma Jet Pyrolysis of Coal in Argon, Hydrogen, and Their Mixtures: Plasma Jet Production of Acetylene from Coal	716	10.7.4. Kinetics of H ₂ S Decomposition in Plasma	744
10.5.3. Heating of Coal Particles and Acetylene Quenching During Pyrolysis of Coal in Argon and Hydrogen Plasma Jets	719	10.7.5. Non-Equilibrium Clusterization in a Centrifugal Field and Its Effect on H ₂ S Decomposition in Plasma with Production of Hydrogen and Condensed-Phase Elemental Sulfur	745
10.5.4. Pyrolysis of Coal in Thermal Nitrogen Plasma Jet with Co-Production of Acetylene and Hydrogen Cyanide	721	10.7.6. Influence of the Centrifugal Field on Average Cluster Sizes: Centrifugal Effect Criterion for Energy Efficiency of H ₂ S Decomposition in Plasma	748
10.5.5. Coal Gasification in a Thermal Plasma Jet of Water Vapor	721	10.7.7. Effect of Additives (CO ₂ , O ₂ , and Hydrocarbons) on Plasma-Chemical Decomposition of H ₂ S	749
10.5.6. Coal Gasification by H ₂ O and Syngas Production in Thermal Plasma Jets: Application of Steam Plasma Jets and Plasma Jets of Other Gases	722	10.7.8. Technological Aspects of H ₂ Production from Water in Double-Step and Multi-Step Plasma-Chemical Cycles	751
10.5.7. Coal Gasification in Steam–Oxygen and Air Plasma Jets	724	Problems and Concept Questions	753
10.5.8. Conversion of Coal Directly in Electric Arcs	724		
10.5.9. Direct Pyrolysis of Coal with Production of Acetylene (C ₂ H ₂) in Arc Plasma of Argon and Hydrogen	724	II Plasma Chemistry in Energy Systems and Environmental Control	755
10.5.10. Direct Gasification of Coal with Production of Syngas (H ₂ –CO) in Electric Arc Plasma of Water Vapor	725	11.1. Plasma Ignition and Stabilization of Flames	755
10.5.11. Coal Conversion in Non-Equilibrium Plasma of Microwave Discharges	726	11.1.1. General Features of Plasma-Assisted Ignition and Combustion	755
10.5.12. Coal Conversion in Non-Equilibrium Microwave Discharges Containing Water Vapor or Nitrogen	728	11.1.2. Experiments with Plasma Ignition of Supersonic Flows	757
10.5.13. Coal Conversion in Low-Pressure Glow and Other Strongly Non-Equilibrium Non-Thermal Discharges	730	11.1.3. Non-Equilibrium Plasma Ignition of Fast and Transonic Flows: Low-Temperature Fuel Oxidation Versus Ignition	758
10.5.14. Plasma-Chemical Coal Conversion in Corona and Dielectric Barrier Discharges	731	11.1.4. Plasma Sustaining of Combustion in Low-Speed Gas Flows	760
10.6. Energy and Hydrogen Production from Hydrocarbons with Carbon Bonding in Solid Suboxides and without CO ₂ Emission	732	11.1.5. Kinetic Features of Plasma-Assisted Ignition and Combustion	761
10.6.1. Highly Ecological Hydrogen Production by Partial Oxidation of Hydrocarbons without CO ₂ Emission: Plasma Generation of Carbon Suboxides	732	11.1.6. Combined Non-Thermal/Quasi-Thermal Mechanism of Flame Ignition and Stabilization: “Zebra” Ignition and Application of Non-Equilibrium Magnetic Gliding Arc Discharges	763
10.6.2. Thermodynamics of the Conversion of Hydrocarbons into Hydrogen with Production of Carbon Suboxides and without CO ₂ Emission	732	11.1.7. Magnetic Gliding Arc Discharge Ignition of Counterflow Flame	765
10.6.3. Plasma-Chemical Conversion of Methane and Coal into Carbon Suboxide	734	11.1.8. Plasma Ignition and Stabilization of Combustion of Pulverized Coal: Application for Boiler Furnaces	768
10.6.4. Mechanochemical Mechanism of Partial Oxidation of Coal with Formation of Suboxides	735	11.2. Mechanisms and Kinetics of Plasma-Stimulated Combustion	770
10.6.5. Kinetics of Mechanochemical Partial Oxidation of Coal to Carbon Suboxides	736	11.2.1. Contribution of Different Plasma-Generated Chemically Active Species in Non-Equilibrium Plasma Ignition and Stabilization of Flames	770
10.6.6. Biomass Conversion into Hydrogen with the Production of Carbon Suboxides and Without CO ₂ Emission	737	11.2.2. Numerical Analysis of Contribution of Plasma-Generated Radicals to Stimulate Ignition	770

11.2.3. Possibility of Plasma-Stimulated Ignition Below the Auto-Ignition Limit: Conventional Kinetic Mechanisms of Explosion of Hydrogen and Hydrocarbons	771	11.5.4. Electric Conductivity of Working Fluid in Plasma MHD Generators	802
11.2.4. Plasma Ignition in H ₂ –O ₂ –He Mixtures	773	11.5.5. Plasma Thermionic Converters of Thermal Energy into Electricity: Plasma Chemistry of Cesium	803
11.2.5. Plasma Ignition in Hydrocarbon–Air Mixtures	774	11.5.6. Gas-Discharge Commutation Devices	804
11.2.6. Analysis of Subthreshold Plasma Ignition Initiated Thermally: The “Bootstrap” Effect	775	11.6. Plasma Chemistry in Lasers and Light Sources	804
11.2.7. Subthreshold Ignition Initiated by Plasma-Generated Radicals	776	11.6.1. Classification of Lasers: Inversion Mechanisms in Gas and Plasma Lasers and Lasers on Self-Limited Transitions	804
11.2.8. Subthreshold Ignition Initiated by Plasma-Generated Excited Species	778	11.6.2. Pulse-Periodic Self-Limited Lasers on Metal Vapors and on Molecular Transitions	805
11.2.9. Contribution of Plasma-Excited Molecules into Suppressing HO ₂ Formation During Subthreshold Plasma Ignition of Hydrogen	779	11.6.3. Quasi-Stationary Inversion in Collisional Gas-Discharge Lasers: Excitation by Long-Lifetime Particles and Radiative Deactivation	806
11.2.10. Subthreshold Plasma Ignition of Hydrogen Stimulated by Excited Molecules Through Dissociation of HO ₂	781	11.6.4. Ionic Gas-Discharge Lasers of Low Pressure: Argon and He–Ne Lasers	806
11.2.11. Subthreshold Plasma Ignition of Ethylene Stimulated by Excited Molecules Effect of NO	783	11.6.5. Inversion Mechanisms in Plasma Recombination Regime: Plasma Lasers	807
11.2.12. Contribution of Ions in the Subthreshold Plasma Ignition	784	11.6.6. Plasma Lasers Using Electronic Transitions: He–Cd, He–Zn, He–Sr, and Penning Lasers	807
11.2.13. Energy Efficiency of Plasma-Assisted Combustion in Ram/Scramjet Engines	785	11.6.7. Plasma Lasers Based on Atomic Transitions of Xe and on Transitions of Multi-Charged Ions	808
11.3. Ion and Plasma Thrusters	787	11.6.8. Excimer Lasers	809
11.3.1. General Features of Electric Propulsion: Ion and Plasma Thrusters	787	11.6.9. Gas-Discharge Lasers Using Vibrational–Rotational Transitions: CO ₂ Lasers	810
11.3.2. Optimal Specific Impulse of an Electric Rocket Engine	788	11.6.10. Gas-Discharge Lasers Using Vibrational–Rotational Transitions: CO Lasers	811
11.3.3. Electric Rocket Engines Based on Ion Thrusters	789	11.6.11. Plasma Stimulation of Chemical Lasers	811
11.3.4. Classification of Plasma Thrusters: Electrothermal Plasma Thrusters	790	11.6.12. Energy Efficiency of Chemical Lasers: Chemical Lasers with Excitation Transfer	812
11.3.5. Electrostatic Plasma Thrusters	791	11.6.13. Plasma Sources of Radiation with High Spectral Brightness	814
11.3.6. Magneto-Plasma-Dynamic Thrusters	791	11.6.14. Mercury-Containing and Mercury-Free Plasma Lamps	815
11.3.7. Pulsed Plasma Thrusters	792	11.6.15. Plasma Display Panels and Plasma TV	816
11.4. Plasma Applications in High-Speed Aerodynamics	792	11.7. Non-Thermal Plasma in Environmental Control: Cleaning Exhaust Gas of SO ₂ and NO _x	817
11.4.1. Plasma Interaction with High-Speed Flows and Shocks	792	11.7.1. Industrial SO ₂ Emissions and Plasma Effectiveness of Cleaning Them	817
11.4.2. Plasma Effects on Shockwave Structure and Velocity	793	11.7.2. Plasma-Chemical SO ₂ Oxidation to SO ₃ in Air and Exhaust Gas Cleaning Using Relativistic Electron Beams	818
11.4.3. Plasma Aerodynamic Effects in Ballistic Range Tests	793	11.7.3. SO ₂ Oxidation in Air to SO ₃ Using Continuous and Pulsed Corona Discharges	819
11.4.4. Global Thermal Effects: Diffuse Discharges	795	11.7.4. Plasma-Stimulated Liquid-Phase Chain Oxidation of SO ₂ in Droplets	820
11.4.5. High-Speed Aerodynamic Effects of Filamentary Discharges	795	11.7.5. Plasma-Catalytic Chain Oxidation of SO ₂ in Clusters	822
11.4.6. Aerodynamic Effects of Surface and Dielectric Barrier Discharges: Aerodynamic Plasma Actuators	797	11.7.6. Simplified Mechanism and Energy Balance of the Plasma-Catalytic Chain Oxidation of SO ₂ in Clusters	823
11.4.7. Plasma Application for Inlet Shock Control: Magneto-Hydrodynamics in Flow Control and Power Extraction	798	11.7.7. Plasma-Stimulated Combined Oxidation of NO _x and SO ₂ in Air: Simultaneous Industrial Exhaust Gas Cleaning of Nitrogen and Sulfur Oxides	824
11.4.8. Plasma Jet Injection in High-Speed Aerodynamics	799		
11.5. Magneto-Hydrodynamic Generators and Other Plasma Systems of Power Electronics	799		
11.5.1. Plasma Power Electronics	799		
11.5.2. Plasma MHD Generators in Power Electronics: Different Types of MHD Generators	800		
11.5.3. Major Electric and Thermodynamic Characteristics of MHD Generators	801		

11.7.8. Plasma-Assisted After Treatment of Automotive Exhaust: Kinetic Mechanism of Double-Stage Plasma-Catalytic NO _x and Hydrocarbon Remediation	825	12.1.7. Plasma Species and Factors Active for Sterilization: Effect of Ultraviolet Radiation	858
11.7.9. Plasma-Assisted Catalytic Reduction of NO _x in Automotive Exhaust Using Pulsed Corona Discharge: Cleaning of Diesel Engine Exhaust	827	12.2. Effects of Atmospheric-Pressure Air Plasma on Bacteria and Cells: Direct Versus Indirect Treatment, Surface Versus In-Depth Treatment, and Apoptosis Versus Necrosis	859
11.8. Non-Thermal Plasma Treatment of Volatile Organic Compound Emissions, and Some Other Plasma-Ecological Technologies	830	12.2.1. Direct and Indirect Effects of Non-Thermal Plasma on Bacteria	859
11.8.1. General Features of the Non-Thermal Plasma Treatment of Volatile Organic Compound Emissions	830	12.2.2. Two Experiments Proving Higher Effectiveness of Direct Plasma Treatment of Bacteria	862
11.8.2. Mechanisms and Energy Balance of the Non-Thermal Plasma Treatment of VOC Emissions: Treatment of Exhaust Gases from Paper Mills and Wood Processing Plants	830	12.2.3. Surface Versus In-Depth Plasma Sterilization: Penetration of DBD Treatment into Fluid for Biomedical Applications	863
11.8.3. Removal of Acetone and Methanol from Air Using Pulsed Corona Discharge	832	12.2.4. Apoptosis Versus Necrosis in Plasma Treatment of Cells: Sublethal Plasma Treatment Effects	865
11.8.4. Removal of Dimethyl Sulfide from Air Using Pulsed Corona Discharge	833	12.3. Non-Thermal Plasma Sterilization of Air Streams: Kinetics of Plasma Inactivation of Biological Micro-Organisms	866
11.8.5. Removal of α -Pinene from Air Using Pulsed Corona Discharge; Plasma Treatment of Exhaust Gas Mixtures	835	12.3.1. General Features of Plasma Inactivation of Airborne Bacteria	866
11.8.6. Treatment of Paper Mill Exhaust Gases Using Wet Pulsed Corona Discharge	836	12.3.2. Pathogen Detection and Remediation Facility for Plasma Sterilization of Air Streams	867
11.8.7. Non-Thermal Plasma Control of Diluted Large-Volume Emissions of Chlorine-Containing VOCs	839	12.3.3. Special DBD Configuration – the Dielectric Barrier Grating Discharge – Applied in PDRF for Plasma Sterilization of Air Streams	869
11.8.8. Non-Thermal Plasma Removal of Elemental Mercury from Coal-Fired Power Plants and Other Industrial Offgases	843	12.3.4. Rapid and Direct Plasma Deactivation of Airborne Bacteria in the PDRF	870
11.8.9. Mechanism of Non-Thermal Plasma Removal of Elemental Mercury from Exhaust Gases	844	12.3.5. Phenomenological Kinetic Model of Non-Thermal Plasma Sterilization of Air Streams	871
11.8.10. Plasma Decomposition of Freons (Chlorofluorocarbons) and Other Waste Treatment Processes Organized in Thermal and Transitional Discharges	845	12.3.6. Kinetics and Mechanisms of Rapid Plasma Deactivation of Airborne Bacteria in the PDRF	872
Problems and Concept Questions	846	12.4. Plasma Cleaning and Sterilization of Water: Special Discharges in Liquid Water Applied for Its Cleaning and Sterilization	874
12 Plasma Biology and Plasma Medicine	848	12.4.1. Needs and General Features of Plasma Water Treatment: Water Disinfection Using UV Radiation, Ozone, or Pulsed Electric Fields	874
12.1. Non-Thermal Plasma Sterilization of Different Surfaces: Mechanisms of Plasma Sterilization	848	12.4.2. Electrical Discharges in Water	875
12.1.1. Application of Low-Pressure Plasma for Biological Sterilization	848	12.4.3. Mechanisms and Characteristics of Plasma Discharges in Water	876
12.1.2. Inactivation of Micro-Organisms by Non-Equilibrium High-Pressure Plasma	850	12.4.4. Physical Kinetics of Water Breakdown	878
12.1.3. Plasma Species and Factors Active for Sterilization: Direct Effect of Charged Particles	851	12.4.5. Experimental Applications of Pulsed Plasma Discharges for Water Treatment	879
12.1.4. Plasma Species and Factors Active for Sterilization: Effects of Electric Fields, Particularly Related to Charged Plasma Particles	854	12.4.6. Energy-Effective Water Treatment Using Pulsed Spark Discharges	880
12.1.5. Plasma Species and Factors Active for Sterilization: Effect of Reactive Neutral Species	855	12.5. Plasma-Assisted Tissue Engineering	882
12.1.6. Plasma Species and Factors Active for Sterilization: Effects of Heat	858	12.5.1. Plasma-Assisted Regulation of Biological Properties of Medical Polymer Materials	882
		12.5.2. Plasma-Assisted Attachment and Proliferation of Bone Cells on Polymer Scaffolds	884
		12.5.3. DBD Plasma Effect on Attachment and Proliferation of Osteoblasts Cultured over Poly- ϵ -Caprolactone Scaffolds	885
		12.5.4. Controlling of Stem Cell Behavior on Non-Thermal Plasma Modified Polymer Surfaces	887

Contents

12.5.5. Plasma-Assisted Bio-Active Liquid Microxerography, Plasma Bioprinter	888
12.6. Animal and Human Living Tissue Sterilization	888
12.6.1. Direct Plasma Medicine: Floating-Electrode Dielectric Barrier Discharge	888
12.6.2. Direct Plasma-Medical Sterilization of Living Tissue Using FE-DBD Plasma	889
12.6.3. Non-Damage (Toxicity) Analysis of Direct Plasma Treatment of Living Tissue	890
12.7. Non-Thermal Plasma-Assisted Blood Coagulation	892
12.7.1. General Features of Plasma-Assisted Blood Coagulation	892
12.7.2. Experiments with Non-Thermal Atmospheric-Pressure Plasma-Assisted In Vitro Blood Coagulation	892
12.7.3. In Vivo Blood Coagulation Using FE-DBD Plasma	893
12.7.4. Mechanisms of Non-Thermal Plasma-Assisted Blood Coagulation	894
12.8. Plasma-Assisted Wound Healing and Tissue Regeneration	896
12.8.1. Discharge Systems for Air-Plasma Surgery and Nitrogen Oxide (NO) Therapy	896
12.8.2. Medical Use of Plasma-Generated Exogenic NO	898
12.8.3. Experimental Investigations of NO Effect on Wound Healing and Inflammatory Processes	899
12.8.4. Clinical Aspects of Use of Air Plasma and Exogenic NO in Treatment of Wound Pathologies	900
12.8.5. Air Plasma and Exogenic NO in Treatment of Inflammatory and Destructive Illnesses	904
12.9. Non-Thermal Plasma Treatment of Skin Diseases	906
12.9.1. Non-Thermal Plasma Treatment of Melanoma Skin Cancer	906
12.9.2. Non-Thermal Plasma Treatment of Cutaneous Leishmaniasis	908
12.9.3. Non-Equilibrium Plasma Treatment of Corneal Infections	910
12.9.4. Remarks on the Non-Thermal Plasma-Medical Treatment of Skin	911
Problems and Concept Questions	912
References	915
Index	963