

CONTENTS

PREFACE TO <i>CHEMICAL SENSORS: FUNDAMENTALS OF SENSING MATERIALS</i>	xi
PREFACE TO <i>VOLUME 1: GENERAL APPROACHES</i>	xiii
ABOUT THE EDITOR	xv
CONTRIBUTORS	xvii
1 BASIC PRINCIPLES OF CHEMICAL SENSOR OPERATION	1
<i>M. Z. Atashbar</i>	
<i>S. Krishnamurthy</i>	
<i>G. Korotcenkov</i>	
1 Introduction	1
2 Electrochemical Sensors	1
2.1 Amperometric Sensors	3
2.2 Conductometric Sensors	4
2.3 Potentiometric Sensors	5
3 Capacitance Sensors	8
4 Work-Function Sensors	9
5 Field-Effect Transistor Sensors	12
6 chemFET-Based Sensors	15
7 Schottky Diode-Based Sensors	16
8 Catalytic Sensors	19
9 Conductometric Sensors	20
10 Acoustic Wave Sensors	24
10.1 Thickness Shear Mode Sensors	25
10.2 Surface Acoustic Wave Sensors	27

11	Mass-Sensitive Sensors	31
12	Optical Sensors	33
12.1	Fiber Optic Chemical Sensors	36
12.2	Fluorescence Fiber Optic Chemical Sensors	38
12.3	Absorption Fiber Optic Chemical Sensors	39
12.4	Refractometric Fiber Optic Chemical Sensors	39
12.5	Absorption-Based Sensors	39
12.6	Surface Plasmon Resonance Sensors	43
13	Photoacoustic Sensors	45
14	Thermoelectric Sensors	45
15	Thermal Conductivity Sensors	47
16	Flame Ionization Sensors	49
17	Langmuir-Blodgett Film Sensors	50
	References	52
2	DESIRED PROPERTIES FOR SENSING MATERIALS	63
	<i>G. Korotcenkov</i>	
1	Introduction	63
2	Common Characteristics of Metal Oxides	65
2.1	Crystal Structure of Metal Oxides	65
2.2	Electronic Structure of Metal Oxides	68
2.3	Role of the Electronic Structure of Metal Oxides in Surface Processes	70
3	Surface Properties of Sensing Materials	77
3.1	Electronic Properties of Metal Oxide Surfaces	77
3.2	Role of Adsorption/Desorption Parameters in Gas-Sensing Effects	79
3.3	Catalytic Activity of Sensing Materials	84
4	Stability of Parameters in Sensing Materials	88
4.1	Thermodynamic Stability	88
4.2	Chemical Stability	92
4.3	Long-Term Stability	94
5	Electrophysical Properties of Sensing Materials	97
5.1	Oxygen Diffusion in Metal Oxides	97
5.2	Conductivity Type	101
5.3	Band Gap	106

5.4	Electroconductivity	107
5.5	Other Important Parameters for Sensing Materials	110
6	Structural Properties of Sensing Materials	112
6.1	Grain Size	113
6.2	Crystal Shape	120
6.3	Surface Geometry	123
6.4	Film Texture	127
6.5	Surface Stoichiometry (Disordering)	129
6.6	Porosity and Active Surface Area	131
6.7	Agglomeration	140
7	Outlook	144
8	Acknowledgments	144
	References	145
3	COMBINATORIAL CONCEPTS FOR DEVELOPMENT OF SENSING MATERIALS	159
	<i>R. A. Potyrailo</i>	
1	Introduction	159
2	General Principles of Combinatorial Materials Screening	160
3	Opportunities for Sensing Materials	162
4	Designs of Combinatorial Libraries of Sensing Materials	163
5	Discovery and Optimization of Sensing Materials Using Discrete Arrays	165
5.1	Radiant Energy Transduction Sensors	165
5.2	Mechanical Energy Transduction Sensors	177
5.3	Electrical Energy Transduction Sensors	183
6	Optimization of Sensing Materials Using Gradient Arrays	192
6.1	Variable Concentration of Reagents	192
6.2	Variable Thickness of Sensing Films	193
6.3	Variable 2-D Composition	194
6.4	Variable Operation Temperature and Diffusion-Layer Thickness	196
7	Emerging Wireless Technologies for Combinatorial Screening of Sensing Materials	196
8	Summary and Outlook	202
9	Acknowledgments	203
	References	203

4	SYNTHESIS AND DEPOSITION OF SENSOR MATERIALS	215
	<i>G. Korotcenkov</i>	
	<i>B. K. Cho</i>	
1	Deposition Technology: Introduction and Overview	215
2	Vacuum Evaporation and Vacuum Deposition	216
2.1	Principles of Film Deposition by the Vacuum Evaporation Method	216
2.2	Disadvantages of the Vacuum Evaporation Method	216
2.3	Film Deposition by Thermal Evaporation	218
3	Sputtering Technology	219
3.1	Principles of Deposition by Sputtering	219
3.2	Sputtering Techniques	221
3.3	Advantages and Disadvantages of Sputtering Technology	224
3.4	Properties of Films Deposited by Sputtering	225
4	The RGTO Technique	227
4.1	Particulars of the RGTO Method	227
4.2	Advantages and Disadvantages of RGTO	229
5	Laser Ablation or Pulsed Laser Deposition	229
5.1	Principles of Pulsed Laser Deposition	229
5.2	Advantages and Disadvantages of PLD	231
5.3	Technical Approaches to Improving PLD Results	231
5.4	Some Particulars of Film Deposition by the PLD Method	232
6	Ion-Beam-Assisted Deposition (IBAD)	233
6.1	Introduction	233
6.2	Principles of the IBAD Method	233
7	Chemical Vapor Deposition	235
7.1	Introduction	235
7.2	Principles of the CVD Process	235
7.3	Chemical Precursors and Reaction Chemistry	237
7.4	Particulars of CVD Technology	237
7.5	Advantages and Disadvantages of CVD	239
7.6	Variants of CVD Methods	241
8	Deposition from Aerosol Phase	245
8.1	Introduction	245
8.2	Principles and Mechanism of the Deposition Process	246
8.3	Atomization Techniques	248
8.4	Advantages and Disadvantages of Deposition from an Aerosol Phase	252

8.5	Technology of the Pyrolysis Process	253
8.6	Regularities of Metal Oxide Growth During Spray Pyrolysis Deposition	255
9	Deposition from Aqueous Solutions	259
9.1	Introduction	259
9.2	Chemical Bath Deposition (CBD)	259
9.3	Selective Ion-Layer Adsorption and Reaction (SILAR) or Successive Ionic-Layer Deposition (SILD)	262
9.4	Liquid-Phase Deposition (LPD)	264
9.5	Electroless Deposition (ED)	265
9.6	Electrochemical Deposition (ECD)	267
9.7	Ferrite Plating	269
9.8	Liquid Flow Deposition (LFD)	269
9.9	Electrophoretic Deposition (EPD)	270
9.10	Photochemical Deposition (PCD). Applying External Forces or Fields	271
9.11	Summary	272
10	The Sol-Gel Process	272
10.1	Introduction	272
10.2	Principles of the Sol-Gel Process	273
10.3	Sol-Gel Chemistry and Technology	273
10.4	Advantages and Disadvantages of Sol-Gel Techniques	275
10.5	Calcination of Sol-Gel–Obtained Oxides	277
10.6	Organic–Inorganic Hybrid Materials (OIHM)	279
10.7	Summary	280
11	Powder Technology	280
11.1	Introduction	280
11.2	Gas Processing Condensation (GPC)	280
11.3	Chemical Vapor Condensation (CVC)	282
11.4	Microwave Plasma Processing (MPP)	283
11.5	Combustion Flame Synthesis (CFS)	283
11.6	Nanopowder Collection	285
11.7	Mechanical Milling of Powders	285
11.8	Summary	287
12	Polymer Technology	288
12.1	Introduction	288
12.2	Methods of Polymer Synthesis	288
12.3	Fabrication of Polymer Films	292

13	Deposition on Fibers	294
13.1	Specifics of Film Deposition on Fibers	294
13.2	Coating Design and Tooling	295
14	Outlook	298
15	Acknowledgments	301
	References	301
5	MODIFICATION OF SENSING MATERIALS: METAL OXIDE MATERIALS ENGINEERING	313
	<i>G. Korotcenkov</i>	
1	Introduction	313
2	Control of Sensor Response Through Structural Engineering of Metal Oxides	314
2.1	Structural Engineering—What Does It Mean?	314
2.2	Structural Engineering of Metal Oxides—Technical Approaches	321
3	Sensor Response Control Through Modification of Metal Oxide Composition	331
3.1	Phase Modification of Metal Oxides	331
3.2	Methods of Phase Modification	332
3.3	Influence of Additives on Structural Properties of Multicomponent Metal Oxides	333
3.4	Gas-Sensing Properties of Multicomponent Metal Oxides	337
4	Sensor Response Control Through Surface Modification of Metal Oxides	344
4.1	Methods of Surface Modification	345
4.2	Influence of Surface Modification on Gas-Sensing Properties of Metal Oxides	348
4.3	Surface Additives as Active and Passive Filters	355
5	Improved Operating Characteristics of Gas Sensors Through Materials Engineering of Metal Oxides: What Determines the Choice?	357
5.1	Device Application	358
5.2	The Nature of the Gas to Be Detected	359
5.3	Detection Mechanism	361
5.4	Environmental Conditions During Use	361
5.5	Required Rate of Sensor Response	365
5.6	Required Sensitivity	366
5.7	Sensor Response Selectivity	367
5.8	Compatibility with Peripheral Measuring Devices	368
6	Summary	368
7	Acknowledgments	370
	References	370

CONTENTS

PREFACE TO <i>CHEMICAL SENSORS: FUNDAMENTALS OF SENSING MATERIALS</i>	xi
PREFACE TO <i>VOLUME 2: NANOSTRUCTURED MATERIALS</i>	xiii
ABOUT THE EDITOR	xv
CONTRIBUTORS	xvii
1 INTRODUCTION TO NANOMATERIALS AND NANOTECHNOLOGY	1
<i>G. Korotcenkov</i>	
<i>B. K. Cho</i>	
1 What Are Nanomaterials?	1
2 A Brief History of Nanotechnology	7
3 What Distinguishes Nanomaterials from Bulk Materials?	10
4 Nanomaterials Manufacturing	14
5 Nanotechnology and Its Possibilities	17
6 Nanotechnology: Future Trends	19
7 Acknowledgments	23
References	24
2 QUASI-ONE-DIMENSIONAL METAL OXIDE STRUCTURES: SYNTHESIS, CHARACTERIZATION, AND APPLICATION AS CHEMICAL SENSORS	29
<i>Pai-Chun Chang</i>	
<i>Dongdong Li</i>	
<i>Jia G. Lu</i>	
1 Introduction	29
2 Synthesis of Q1D Nanomaterials	30

2.1	Vapor-Phase Growth Methods	31
2.2	Solution-Phase Growth Methods	41
2.3	Template-Based Growth Methods	43
3	Electrical Transport Properties and Optical Characteristics	47
3.1	Nanowire Field-Effect Transistors and Electrical Properties	47
3.2	Photoluminescence Characteristics	52
4	Metal Oxide Nanowire Chemical Sensors	53
4.1	Sensor Device Fabrication	55
4.2	Mechanism of Nanowire Sensor Detection	56
4.3	Other Types of Q1D Structured Sensors	70
5	Summary and Future Outlook	72
	References	73
3	CARBON NANOTUBES AND FULLERENES IN CHEMICAL SENSORS	87
	<i>G. P. Kotchey</i>	
	<i>A. Star</i>	
1	Introduction	87
1.1	History of Fullerenes and Carbon Nanotubes	87
1.2	Structure of Fullerenes	88
1.3	Structure of Carbon Nanotubes	88
2	Synthesis of Fullerenes and Carbon Nanotubes	89
2.1	Synthesis of Fullerenes	89
2.2	Synthesis of Carbon Nanotubes	90
3	Properties of Carbon Nanotubes	94
3.1	Physical/Mechanical Properties	94
3.2	Electronic Properties	94
3.3	Spectroscopic Properties	96
4	Chemical Modification and Functionalization of Carbon Nanotubes	98
4.1	Introduction	98
4.2	Noncovalent Functionalization	98
4.3	Covalent Functionalization	100
5	Solid-State Electrical Conductivity CNT Sensors	101
5.1	Nanotube FET for Gas-Sensing Applications	101
5.2	NO ₂ Detection Using Resistivity Measurements	102
5.3	Gas and Vapor Detection Using Functionalized CNTs	103
5.4	Chemicapacitors	105

5.5	Nanotube FETs for Detecting DNA Hybridization	108
5.6	Employing NTFETs for Protein Detection	110
5.7	Conductometric Glucose Biosensor	114
6	Raman Sensors	115
6.1	A Surface-Enhanced Raman Scattering (SERS)–Based pH Sensor	115
6.2	“Multicolored” Raman Probes for Biological Imaging and Detection	117
7	Optical Sensors	120
7.1	Employing SWNTs as Fluorophores for Long-Term Optical Glucose Sensing	120
7.2	Employing Spectroscopic Properties of SWNTs to Detect DNA Hybridization	122
8	Electrochemical Sensors	123
8.1	Employing Electrochemistry to Monitor DNA Hybridization	123
8.2	Electrochemical-Based Glucose Sensing	126
9	Field-Emission Sensors	128
9.1	A CNT-Based Triode Sensor That Employs the Field-Emission Effect to Detect Gas Density	128
10	Electromechanical Resonators	130
10.1	Nanomechanical Nanotube Resonators for the Detection of Evaporated Chromium Atoms	130
10.2	Surface Acoustic Wave (SAW) Devices That Employ Buckminsterfullerene (C ₆₀) for the Detection of Toxic Organic Vapors	132
11	Outlook	133
	References	135
4	SENSORS BASED ON MONOLAYER-CAPPED METALLIC NANOPARTICLES	141
	<i>U. Tisch</i>	
	<i>H. Haick</i>	
1	Introduction	141
2	Synthesis of MCNPs and Deposition of Solid MCNP Films	142
2.1	Synthesis of MCNPs	143
2.2	Surface Functionalization of Metal Nanoparticles	144
2.3	Methods of MCNP Film Deposition	145
3	Four Good Reasons to Use Monolayer-Capped Metallic Nanoparticles for Chemical Sensing	147
3.1	Controllable Chemical Composition	147

3.2	Controllable Size and Shape	147
3.3	Controllable Nanoparticle Assembly	149
3.4	Biocompatibility	151
4	Chemical Sensors Based on MCNPs	151
4.1	Basic Principles	151
4.2	“Lock-and-Key” Sensor Versus “Electronic Nose”	152
4.3	The Role of the Number of Nanoparticles in Chemical Sensing	153
5	Categories of MCNP-Based Chemical Sensors	153
5.1	Optical Sensors	153
5.2	Chemiresistors	170
5.3	Electrochemical Sensors	180
5.4	Piezoelectric Sensors	185
6	Concluding Remarks	188
7	Acknowledgments	190
	References	190
5	POROUS SEMICONDUCTORS: ADVANTAGES AND DISADVANTAGES FOR GAS SENSOR APPLICATIONS	203
	<i>G. Korotcenkov</i>	
1	Introduction	203
2	Porous Semiconductors: Principles of Fabrication and Properties	205
2.1	Principles of Porous Silicon Fabrication	205
2.2	Properties of Porous Silicon	208
2.3	Techniques for Forming the Porous Silicon Layer	210
2.4	Porosification of Standard Semiconductors	220
3	Gas Sensors Based on Porous Semiconductors—Approaches and Characteristics	226
3.1	Capacitance-Type Gas Sensors	226
3.2	Gas Sensors Employing Photoluminescence Quenching	232
3.3	Sensors Based on Optical Measurements	237
3.4	Conductometric-Type Gas Sensors	243
3.5	Gas Sensors Based on Schottky Barriers and Heterostructures	250
3.6	Gas Sensors Based on Measurement of Contact Potential Difference	257
3.7	Gas Sensors Based on Simultaneous Control of Several Parameters of the Porous Material	258
3.8	Disadvantages of Porous Semiconductor Gas Sensors	259

3.9	Surface Modification of Porous Semiconductors to Improve Gas-Sensing Characteristics	265
4	Advantages of Porous Silicon for Applications in Micromachining Sensor Technology	269
5	Outlook	274
6	Acknowledgments	276
	References	276
6	ORDERED MESOPOROUS FILMS AND MEMBRANES: SYNTHESIS, PROPERTIES, AND APPLICATIONS IN GAS SENSORS	291
	<i>M. Tiemann</i>	
1	Introduction	291
2	Porosity in Resistive Gas Sensors	292
2.1	Categories of Porosity	292
2.2	Gas Diffusion in Porous Materials	293
2.3	Porous Films for Selective Gas Sensing	293
2.4	Other Porosity-Related Nanostructural Aspects	296
3	Synthesis Methods	297
3.1	Mesoporous Metal Oxides by Conventional Synthesis Methods	297
3.2	Mesoporous Materials by Supramolecular Structure Directors	299
3.3	Mesoporous Materials by Structure Replication	302
4	Summary	303
	References	304
7	CHEMICAL SENSORS BASED ON ZEOLITES	311
	<i>R. Moos</i>	
	<i>K. Sahner</i>	
1	Introduction	311
2	Zeolites—Properties and Applications	312
3	Zeolites as an Auxiliary Phase in Chemical Sensors	316
3.1	Zeolites as Host Materials	316
3.2	Zeolites as Filters	319
3.3	Zeolites as Preconcentrators	321
3.4	Zeolites as Templates	321

4	Zeolites as the Functional (Sensitive) Phase	322
4.1	Adsorptivity	322
4.2	Ionic Conductivity	323
4.3	Catalytic Activity	326
5	Conclusion	328
	References	328
8	NANOCOMPOSITES: FROM FABRICATION TO CHEMICAL SENSOR APPLICATIONS	335
	<i>Rajesh</i>	
	<i>T. Ahuja</i>	
	<i>D. Kumar</i>	
1	Introduction	335
2	Types of Nanocomposites	337
3	General Approaches to Nanocomposite Fabrication	338
4	Metal Oxide–Based Nanocomposites	339
4.1	Synthesis	339
4.2	Properties	340
4.3	Application in Chemical Sensors	341
5	Polymer-Based Nanocomposites	344
5.1	Synthesis	344
5.2	Properties	346
5.3	Application in Chemical Sensors	347
6	Carbon Nanotube–Based Nanocomposites	349
6.1	Synthesis	350
6.2	Properties	352
6.3	Application in Chemical Sensors	353
7	Noble Metal–Based Nanocomposites	355
7.1	Synthesis	357
7.2	Properties	358
7.3	Application in Chemical Sensors	359
8	Outlook	361
9	Acknowledgment	361
	References	362
	INDEX	369

CONTENTS

PREFACE TO <i>CHEMICAL SENSORS: FUNDAMENTALS OF SENSING MATERIALS</i>	xi
PREFACE TO <i>VOLUME 3: POLYMERS AND OTHER MATERIALS</i>	xiii
ABOUT THE EDITOR	xv
CONTRIBUTORS	xvii
1 POLYMERS IN CHEMICAL SENSORS	1
<i>B. Adhikari</i>	
<i>P. Kar</i>	
1 Introduction	1
2 What Are Polymers?	3
3 Parameters of Polymers Promising for Chemical Sensor Application	4
4 Synthesis of Polymers	7
5 Deposition of Polymers	9
6 Functionalization of Polymers	13
6.1 Structure Modification	13
6.2 Surface Modification	14
6.3 Composition Modification	15
7 Polymers in Chemical Sensors	16
7.1 Optical and Fiber Optic Polymer-Based Sensors	20
7.2 Conductometric Gas Sensors	27
7.3 SAW and QCM Polymer-Based Sensors	40
7.4 Electrochemical Polymer-Based Sensors	45
7.5 Chemically Sensitive FET-Based Sensors	57
8 Outlook	61
9 Acknowledgments	61
References	62

2	MOLECULAR IMPRINTING (TEMPLATING)—A PROMISING APPROACH FOR DESIGN OF POLYMER-BASED CHEMICAL SENSORS	77
	<i>G. Korotcenkov</i>	
	<i>B. K. Cho</i>	
1	Introduction	77
2	General Principles of Molecular Imprinting (Templating)	79
3	Methods of Imprinting (Templating)	80
3.1	In-Block Imprinted Polymers	80
3.2	<i>In Situ</i> Imprinted Polymers	82
3.3	Polymer-Imprinted Beads	82
4	Components of Imprinting Technology	83
4.1	Target Molecules	83
4.2	The Imprinting Matrix	85
4.3	Cross-Linkers	86
4.4	Solvents (Porogens)	88
4.5	Initiators	89
5	MIP Preparation Methods	89
6	Combination of MIPs and Monomolecular Host Molecules	91
7	Control of the Imprinting Effect	92
8	Application of Imprinting Polymers in Chemical Sensors	92
8.1	Advantages of MIP-Based Chemical Sensors	92
8.2	Detection Principles Used in MIP Chemical Sensors	93
8.3	Interfacing the MIP with the Transducer	99
8.4	Factors Controlling the Sensing Characteristics of MIPs-Based Chemical Sensors	101
8.5	Micro- and Nanofabricated MIPs	103
9	Outlook	106
10	Acknowledgments	108
	References	109
3	CALIXARENE-BASED MATERIALS FOR CHEMICAL SENSORS	117
	<i>H. M. Chawla</i>	
	<i>N. Pant</i>	
	<i>S. Kumar</i>	
	<i>D. StC. Black</i>	
	<i>N. Kumar</i>	
1	Introduction	117

2	Molecular Receptors and Generation of Signal for Sensing Target Species	119
3	Calixarenes and Thiocalixarenes	120
4	Synthesis of Calix[<i>n</i>]arenes	123
4.1	Base-Catalyzed Condensation Reactions	123
4.2	Acid-Catalyzed Condensation Reactions	124
5	Synthesis of Thiocalix[<i>n</i>]arenes (Sulfur-Bridged Calixarenes)	124
6	Physical Properties of Calixarenes and Tetrathiocalixarenes	127
6.1	Melting points	127
6.2	Solubilities and pK_a Values	127
7	Spectral Properties and Characterization of Calixarenes	128
7.1	Infrared Spectra	128
7.2	Ultraviolet Spectra	128
7.3	NMR Spectra	129
8	Conformational Structures of Calixarenes and Thiocalixarenes	129
9	Conformational Characterization of Calix[<i>n</i>]arenes	132
10	Calixarenes as Materials for Chemical Sensors	132
11	Calixarene-Based Materials for Recognition of Alkali and Alkaline Earth Metal Ions	133
12	Calixarene-Based Materials for Recognition of Transition and Heavy-Metal Ions	137
13	Calixarene-Based Materials as Dual Probes for Sensing and Extraction	139
14	Calixarene-Based Materials for Sensing Lanthanides and Actinides	139
15	Sensor Materials Based on Polymeric Calixarenes	143
16	Naked-Eye Sensing: Calixarene-Based Chromogenic Materials for Sensing Ions and Molecules	143
17	Calixarene-Based Electroactive Sensing Materials	156
18	Calixarene-Based Materials for Sensing Anions	161
18.1	Calixarene-Based Electron-Deficient or Positively Charged Anion Receptors	161
18.2	Calixarene-Based Neutral Anion Receptors	165
18.3	Calixarene-Based Ditopic Molecular Receptors	175
19	Calixarene-Based Sensor Materials for Neutral Molecules and Biological Amines	176
20	Calixarene-Based Materials for Gas Sensors	179
21	Outlook	181

22 Acknowledgments	181
References	182
4 BIOLOGICAL AND BIOMIMETIC SYSTEMS IN CHEMICAL SENSORS	201
<i>R. Jelinek</i>	
<i>S. Kolusheva</i>	
1 Introduction	201
2 Polymers and Polymer/Biomolecule Assemblies	202
2.1 Conductive Polymers	202
2.2 Luminescent Conjugated Polymers	205
3 Membranes in Chemical Sensors	210
3.1 Chemical Membranes	210
3.2 Biological Membranes	213
4 Biomimetic Systems for Molecular and Ionic Recognition	219
4.1 Biological Receptors and Channels	219
4.2 Synthetic Receptors	221
4.3 Biomimetic Enzyme-Based Sensors	223
4.4 Nanobiosensors	225
4.5 Other Biomimetic Sensors	232
5 Monolayers and Films	242
5.1 Self-Assembled Monolayers	242
5.2 Langmuir-Blodgett Films	244
6 Challenges and Limitations of Biosensors	247
7 Conclusions and Outlook	248
References	248
5 NOVEL SEMICONDUCTOR MATERIALS FOR THE DEVELOPMENT OF CHEMICAL SENSORS	263
<i>N. Chaniotakis</i>	
<i>N. Sofkiti</i>	
<i>V. Vamvakaki</i>	
1 Introduction	263
2 The Silicon Era—Classical Semiconductors in Chemical Sensing	265
3 Fundamentals of Sensor Development	269
4 Surface Chemistry of Semiconductors in Chemical Sensing	269
5 Band Gap Theory and Its Relationship to Sensor Design	271
6 Pinning of the Surface Fermi Level	272

7	New Semiconductor Substrates	273
7.1	Diamond	274
7.2	Silicon Carbide	277
7.3	Gallium Nitride and III-Nitrides	279
8	Nanosemiconductor Structures in Chemical Sensors	281
9	Forecasting the Future	283
	References	284
6	ION CONDUCTORS AND THEIR APPLICATIONS IN CHEMICAL SENSORS	291
	<i>R. V. Kumar</i>	
	<i>C. Schwandt</i>	
1	Introduction	291
1.1	Solid Electrolytes	292
1.2	Chemical Sensors	293
2	Ionic Conduction in Solids	294
3	Oxygen Ion-Conducting Solid Electrolytes	296
3.1	Zirconia-Based Solid Electrolytes	297
3.2	Defect Chemistry of Stabilized Zirconia	304
3.3	Preparation of Stabilized Zirconia	305
3.4	Oxygen Sensors Based on Stabilized Zirconia	308
4	Proton-Conducting Solid Electrolytes	319
4.1	High-Temperature Proton-Conducting Solid Electrolytes	319
4.2	Defect Chemistry of Substituted Perovskites	320
4.3	Preparation of Substituted Perovskites	323
4.4	Hydrogen Sensors Based on Substituted Perovskites	324
4.5	Low-Temperature Proton-Conducting Solid Electrolytes	330
5	Metal Ion-Conducting Solid Electrolytes	332
5.1	Defect Chemistry and Preparation of β -Aluminas	332
5.2	Sensors Based on β -Aluminas	337
6	Outlook and Future Trends	343
	References	344
7	SENSOR MATERIALS: SELECTION GUIDE	351
	<i>G. Korotcenkov</i>	
1	Acceptable Materials for Chemical Sensors	351
2	Which Metal Oxides Are Better for Gas Sensors?	358

3	Choosing a Polymer for a Chemical Sensor Application	362
4	Technological Limitations in Sensing Material Applications	362
5	Future Trends	363
6	Toward a Theory of Chemical Sensors	368
7	Summary	370
8	Acknowledgments	370
	References	370

CONTENTS

PREFACE TO <i>CHEMICAL SENSORS: COMPREHENSIVE SENSORS TECHNOLOGIES</i>	xv
PREFACE TO <i>VOLUME 4: SOLID-STATE DEVICES</i>	xix
ABOUT THE EDITOR	xxi
CONTRIBUTORS	xxiii
1 INTRODUCTION TO CHEMICAL SENSOR TECHNOLOGIES	1
<i>G. Korotcenkov</i>	
<i>B. K. Cho</i>	
1 Definitions and Classifications	1
2 A Brief History of Chemical Sensors	7
3 Motivations for Design of Chemical Sensors	9
4 What Determines Success in Chemical Sensor Design?	15
5 Materials for Chemical Sensors	17
5.1 Metal Oxides	17
5.2 Polymers	19
5.3 New Trends in Sensing Materials	21
6 Some Useful Definitions	29
7 Acknowledgments	34
References	34
2 SENSING AND SAMPLING STRATEGIES	39
<i>M. Z. Atashbar</i>	
<i>S. Krishnamurthy</i>	
1 Introduction	39
2 Sensing Parameters	39
2.1 Sensitivity	40

2.2	Selectivity	40
2.3	Response and Recovery Rates	41
2.4	Saturation	42
2.5	Resolution	42
2.6	Noise	42
3	Sensor Fundamentals	43
4	Sensor Test Methods	43
5	Sensor Calibration	44
6	Repeatability and Stability of Sensors	44
7	Signal Sampling and Data Processing	45
8	Signal Processing for Single Sensors	48
9	Signal Processing in a Multisensor Environment	49
	References	51
3	CONDUCTOMETRIC METAL OXIDE GAS SENSORS: PRINCIPLES OF OPERATION AND APPROACHES TO FABRICATION	53
	<i>G. Korotcenkov</i>	
	<i>V. Sysoev</i>	
1	Introduction	53
2	Fundamentals of Gas Sensing Effects in Metal Oxide–Based Sensors: Main Principles of Metal Oxide Gas Sensor Operation	54
2.1	Bulk-Conduction Model: Solid Electrolyte–Based Conductometric Gas Sensors (High-Temperature Operation)	54
2.2	Ionsorption Model (Chemiresistors, Low-Temperature Operation)	55
2.3	Requirements for Metal Oxides to be Used at Low and High Temperatures	65
2.4	Advantages and Disadvantages of Low- and High-Temperature Operation of Gas Sensors	66
3	Metal Oxides Employed in Conductometric Gas Sensors	67
3.1	High-Temperature Sensors (Solid Electrolyte–Based Sensors)	67
3.2	Low-Temperature Sensors (Chemiresistors)	70
4	Approaches to Gas Sensor Fabrication	77
4.1	Ceramic Sensors	78
4.2	Planar Sensors	81
4.3	Features of Thick-Film Technology	86
4.4	Thin-Film Technology	90
4.5	Kinetics of Metal Oxide Gas Sensor Response: Processes Controlling the Rate of Sensor Response	93

4.6	The Role of Thermal Treatments in Gas Sensor Fabrication	96
4.7	Material Requirements for Packaging of Gas Sensors	98
5	Other Approaches to the Design of Conductometric Gas Sensors	99
5.1	Conductometric Sensors Based on 1-D Nanostructures	99
5.2	One-Electrode Gas Sensors	105
6	Miniaturization and Microfabrication	118
6.1	Microfabrication	118
6.2	Integrated Conductometric Gas Sensors	126
6.3	Advantages and Disadvantages of Microfabrication	128
7	Approaches to Optimization (Improvement) of Conductometric Gas Sensor Parameters	129
7.1	Structure Control	129
7.2	Bulk Doping and Surface Modification	139
7.3	Engineering Approaches to Improving Sensitivity	144
7.4	Approaches for Improving Gas Sensor Selectivity	147
7.5	Approaches to Optimizing the Rate of Sensor Response	153
7.6	Stability	154
8	Sensor Manufacturers	160
9	Outlook for the Future	161
	References	161
4	WORK FUNCTION–BASED GAS SENSORS: SCHOTTKY- AND FET-BASED DEVICES	187
	<i>C. Senft</i>	
	<i>P. Iskra</i>	
	<i>I. Eisele</i>	
	<i>W. Hansch</i>	
1	Introduction	187
2	Theoretical Background: Gas Adsorption and Work Function Change	189
2.1	Gas Adsorption on Solid Surfaces	189
2.2	The Work Function	191
3	Transducers	192
3.1	Basic Principles of Gas-Sensing Devices	192
3.2	Transducers for Interfacial Work Function Changes	193
3.3	Transducers for Surface Work Function Changes	197
3.4	Transducers for High-Temperature Operation	203
4	Application Example: The Temperature-Controlled Phase-Transition FET (TPT-FET)	211
4.1	Introduction	211
4.2	The Sensing Effect	213

4.3	Fabrication of the Sensor	214
4.4	Work Function Change at Constant Temperature	214
4.5	Temperature Dependence of the Work Function Change	218
4.6	Operation of Temperature-Controlled Sensors	219
4.7	Response Time	221
4.8	The TPT-FET: A Benchmark	222
5	Summary	223
	References	223
5	CAPACITANCE-TYPE CHEMICAL SENSORS	229
	<i>S. Chatzandroulis</i>	
	<i>V. Tsouti</i>	
	<i>I. Raptis</i>	
	<i>D. Goustouridis</i>	
1	Introduction	229
2	Permittivity Sensors	230
2.1	Parallel-Plate Sensors	231
2.2	Interdigitated Electrode Sensors	232
2.3	Capacitance-Type Chemical Sensors on Flexible Substrates	237
2.4	Materials Used in Capacitance-Type Chemical Sensors	238
3	Bimorph Capacitance-Type Chemical Sensors	244
3.1	Parameters for Effective Chemical Sensing	245
3.2	Cantilever Bimorph Sensors	247
3.3	Membrane Bimorph Sensors	249
4	Outlook for Capacitance-Type Chemical Sensors	252
	References	255
6	GAS SENSORS USING PYROELECTRIC AND THERMOELECTRIC EFFECTS	261
	<i>W. Shin</i>	
	<i>M. Nishibori</i>	
	<i>I. Matsubara</i>	
1	Fundamentals of Sensor Operation	261
1.1	Pyroelectricity	261
1.2	Thermoelectricity	262
2	Materials of Thermal Energy Conversion	262
2.1	Pyroelectric Materials	263
2.2	Thermoelectric Materials	264

3	Fabrication and Packaging	266
3.1	Transducer Films	266
3.2	Catalyst Deposition	267
3.3	Membrane Structure by Bulk Wet Etching	268
4	Parameters	269
4.1	Transducer Performance	269
4.2	Detectivity of Pyroelectric Devices	270
4.3	Seebeck Coefficients of Thermoelectric Devices	270
4.4	Catalyst Performance	271
4.5	Catalyst Parameters	272
5	Approaches to Optimization of Sensor Parameters	272
5.1	Pyroelectric Sensors	272
5.2	AC Pyroelectric Sensors	273
5.3	Thermoelectric Sensors	274
5.4	Long-Term Stability of the Ceramic Catalyst	277
5.5	Gas Selectivity	279
6	Fields of Application and Market for Sensors	280
7	Summary	283
	References	283
7	CALORIMETRIC SENSORS	287
	<i>R. E. Cavicchi</i>	
1	Introduction	287
2	Fundamentals of Calorimetric Sensor Operation	288
3	Catalytic Bead Devices	292
4	Thin-Film and MEMS Devices	292
5	Materials	299
6	Poisoning	301
7	Signal Analysis and Operating Modes	303
8	Packaging	305
9	Applications	309
9.1	Gas Detection	309
9.2	Biological Applications	312
9.3	Safety	313
10	Conclusions	315
	References	315

8	MICROCANTILEVER-BASED CHEMICAL SENSORS	321
	<i>S. K. Vashist</i>	
	<i>G. Korotcenkov</i>	
1	Introduction	321
2	Microcantilevers and Their Modes of Operation	322
2.1	Operating Modes for Cantilever Mass Sensors	323
3	Microcantilever Deflection Detection Methods	324
3.1	Optical Method	325
3.2	Piezoresistive Method	326
3.3	Capacitive Method	327
3.4	Piezoelectric Method	328
3.5	Interferometry Method	328
3.6	Optical Diffraction Grating Method	328
3.7	Charge-Coupled Device Detection Method	328
4	Resonant Operating Mode	329
4.1	Mechanical Properties of Microcantilevers	329
4.2	Mass Resolution Limitations	330
4.3	Influence of Surrounding Conditions	331
5	Bending Behavior of Microcantilevers	332
6	Excitation Techniques	334
7	Fabrication of Microcantilevers	335
7.1	Silicon-Based Microcantilevers	337
7.2	Polymer-Based Microcantilevers	340
8	Surface Functionalization	342
8.1	General Strategy	342
8.2	Sorption-Induced Effects and Their Influence on Cantilever Operation	343
8.3	Functionalization Methods	345
8.4	Immobilization of Bioreceptors	348
9	Microcantilever-Based Sensors	349
10	Applications of Cantilever-Based Chemical Sensors	351
10.1	Gas Sensing	351
10.2	Detection of Herbicides	355
10.3	Detection of Metal Ions	355
10.4	Humidity Sensing	356
10.5	Detection of Volatile Organic Compounds	356
10.6	Detection of Tributyrin	359
10.7	Monitoring of Missile Storage and Maintenance Needs	359
10.8	pH Sensing	359

11	Biosensing Applications	360
11.1	Detection of DNA	360
11.2	Detection of Prostate-Specific Antigen	361
11.3	Detection of Hydrogen Peroxide	361
11.4	Detection of Myoglobin	362
11.5	Detection of Lipoproteins	362
11.6	Detection of Glucose	362
12	Ultrasensitive Nanocantilevers	363
13	An Electronic Nose Based on a Micromechanical Cantilever Array	364
14	Commercial Status	367
15	Outlook and Future Trends	367
	References	368
9	THE QUARTZ CRYSTAL MICROBALANCE	377
	<i>M. Voinova</i>	
	<i>M. Jonson</i>	
1	Introduction	377
1.1	Short History of the QCM Approach	378
1.2	Principle of Biosensing	380
2	Piezoelectric Materials	381
2.1	Piezoelectric Materials Other Than Quartz	381
2.2	Quartz as a Piezoelectric Material	384
3	Basics of QCM Operation	386
3.1	Principles of the QCM	386
3.2	Construction and Stability of the QCM	387
3.3	Configuration of QCM Electrodes	391
3.4	Miniaturization and Integration in Arrays; the MQCM	394
3.5	QCM-D Technique	395
3.6	Some Disadvantages of the QCM	397
4	Theoretical Analysis of the QCM Response	397
4.1	Physical Analysis of the Propagation of Transverse Shear Waves in a Loaded Quartz Resonator	397
4.2	Equivalent Circuit Models	403
4.3	Simultaneous Viscoelastic and Liquid Loading of the Quartz Resonator: Three Models	406
4.4	Newtonian Liquid-Loaded Quartz Resonator	407
4.5	Thin Viscoelastic Layer Loading	409
4.6	Mass Loading of the Quartz Resonator: A Short Summary	410

5	Applications of QCM-Based Sensors	410
5.1	Gas Sensors	410
5.2	QCM Coatings: Basic Requirements for Sensing Layer	414
5.3	Liquid-Phase Measurements; Electrochemical QCM	415
5.4	Nanotribology Challenges	416
5.5	QCM Biosensors: Selected Examples	421
6	Outlook	428
7	Quartz Crystal and Quartz Crystal Microbalance Companies	429
8	Nomenclature	429
9	Acknowledgments	431
10	Recommendations for Further Reading	431
	References	431
10	SURFACE ACOUSTIC WAVE SENSORS FOR CHEMICAL APPLICATIONS	447
	<i>Adeel Afzal</i>	
	<i>Franz L. Dickert</i>	
1	Introduction	447
2	State-of-the-Art SAW Sensors	448
2.1	Principle—The Piezoelectric Effect	448
2.2	Piezoelectric Materials	448
2.3	Design—Interdigital Transducers	449
2.4	Fabrication—Photolithography	450
2.5	Sensor Effect—The Sauerbrey Equation	451
2.6	SAW Sensors in Liquids	455
2.7	SAW Sensor Characteristics	456
3	Coating Materials	457
3.1	Nonselective Polymers	457
3.2	Conductive Polymers	458
3.3	Host–Guest Chemistry	459
3.4	Imprinting	460
3.5	Self-Assembled Monolayers	462
3.6	Other Coating Materials	463
4	Applications	464
4.1	Gases	464
4.2	Organic Vapors	466
4.3	Liquids	471
5	Comparing Surface and Bulk Acoustic Wave Devices	471

6	The Market for SAW Sensors	471
7	Abilities and Limitations of SAW Sensors	473
8	Outlook	475
	References	475
11	INTEGRATED CHEMICAL SENSORS	485
	<i>M. E. Zaghloul</i>	
	<i>I. Voiculescu</i>	
1	Introduction	485
2	CMOS Technology	486
2.1	Overview of CMOS Technology	486
2.2	Micromachining CMOS	487
2.3	Gas Sensor Fabricated Using Industrial CMOS Technology Developed at Eth Zürich	489
2.4	Electrochemical Sensors Fabricated Using Standard CMOS Technology	492
3	NIST CMOS MEMS Technology	494
3.1	Peculiarities of NIST CMOS MEMS Technology	495
3.2	Conductometric Chemical Gas Sensor Using NIST CMOS MEMS Technology	497
4	CMU CMOS MEMS Technology	498
4.1	CMU CMOS MEMS Fabrication Technology Overview	500
4.2	Resonant Microbeam Gas Sensor Fabricated Using CMU CMOS MEMS Technology	503
5	Jazz SiGe BiCMOS Technology	504
5.1	Jazz SiGe BiCMOS Technology Overview	505
5.2	Gas Sensor Fabricated Using Jazz SiGe BiCMOS Technology	505
6	Other Types of MEMS Gas Sensors Integrated in CMOS Technology	507
6.1	SAW Resonator as Chemical Gas Sensor Integrated in Industrial CMOS Technology	508
6.2	Optical Chemical Sensors in CMOS Technology	509
7	Conclusions	511
	References	511

CONTENTS

PREFACE TO <i>CHEMICAL SENSORS: COMPREHENSIVE SENSORS TECHNOLOGIES</i>	xv
PREFACE TO <i>VOLUME 5: ELECTROCHEMICAL AND OPTICAL SENSORS</i>	xix
ABOUT THE EDITOR	xxi
CONTRIBUTORS	xxiii
I ELECTROCHEMICAL GAS SENSORS: FUNDAMENTALS, FABRICATION, AND PARAMETERS	1
<i>J. R. Stetter</i>	
<i>G. Korotcenkov</i>	
<i>X. Zeng</i>	
<i>Y. Tang</i>	
<i>Y. Liu</i>	
1 Introduction	1
2 Fundamentals of Electrochemistry for Gas Sensors	2
2.1 Potential and Potentiometry	3
2.2 Current, Charge, and Amperometry	5
2.3 Conductivity/Resistance and Conductometry	7
3 Types of Gaseous Interactions in Sensing	7
3.1 Gas/Electrolyte Interactions	8
3.2 Gas/Electrode Interactions	12
4 Fundamentals of Electrochemical Gas Sensors	15
4.1 Amperometric Gas Sensors	15
4.2 Potentiometric Gas Sensors	19
4.3 Conductometric Gas Sensors	22
5 Analytes	23
6 Electrochemical Gas Sensor Designs and Materials	23
6.1 Electrolytes	24
6.2 Membranes	38
6.3 Electrodes	38

7	Analytical Characteristics of Electrochemical Sensors	44
7.1	Sensitivity (Lower Detection Limit)	45
7.2	Selectivity	46
7.3	Precision and Accuracy	47
7.4	Stability	48
8	Examples of Electrochemical Gas Sensors	49
8.1	Electrochemical H ₂ Sensors with Liquid Electrolytes	49
8.2	Characteristics of Electrochemical H ₂ Sensors Fabricated Using Polymer Electrolytes	53
8.3	High-Temperature H ₂ Sensors	62
9	MEMS and Nanotechnology in Electrochemical Gas Sensor Fabrication	67
10	Electrochemical Sensor Applications	70
11	Parameters in Gas Sensor Application	71
11.1	Temperature	71
11.2	Humidity	72
11.3	Pressure	72
11.4	Calibration	72
11.5	Sensor Failure Mechanisms	73
11.6	Sensor Life	74
12	Market for Electrochemical Gas Sensors	74
13	Outlook and Future Trends	76
	References	78
2	STABILIZED ZIRCONIA-BASED GAS SENSORS	91
	<i>S. Zhuiykov</i>	
1	Introduction	91
2	Fundamentals of Sensor Operation	92
2.1	Nernstian Behavior	92
2.2	Non-Nernstian Behavior	96
3	Potentiometric Non-Nernstian Gas Sensors	98
3.1	Mixed-Potential Gas Sensors	98
3.2	Differential Electrode Equilibria Gas Sensors	101
4	Amperometric Gas Sensors	102
5	Impedance-Based Gas Sensors	105
6	Use of Nanostructured Oxides for Sensing Electrodes	109
7	Zirconia Sensors Operating in Real Industrial Applications	112
7.1	Inaccuracy of the Oxygen Probe Resulting from Catalyzed SE/Gas Reactions	113

7.2	Sensor Errors Caused by Improper Operating Conditions and Probe Deterioration	114
8	Markets for Zirconia-Based Sensors	116
9	Summary and Outlook	117
10	Acknowledgments	118
	References	119
3	ELECTROCHEMICAL SENSORS FOR LIQUID ENVIRONMENTS	125
	<i>V. K. Gupta</i>	
	<i>L. P. Singh</i>	
1	Introduction	125
2	Sensors for Liquid Environments	126
2.1	Potentiometric Sensors	126
2.2	Conductometric Sensors	127
2.3	Voltammetric and Amperometric Sensors	127
2.4	FET-Based Sensors	127
3	Chronological Progress in Design of Sensors for Liquid Environments	128
3.1	Design of Ion-Selective Electrodes	128
4	The Role of the Membrane in Sensors for Liquid Environments	130
5	Classification of Ion-Selective Electrodes	130
5.1	Liquid Membrane Electrodes	131
5.2	Solid-State Electrodes	131
6	Polymeric Membranes	131
6.1	The Ionophore	131
6.2	The Polymeric Matrix	133
6.3	The Plasticizer	134
6.4	The Lipophilic Additive	134
7	Theory and Methodology	135
7.1	Potential of an Ion-Exchange Membrane	135
7.2	Selectivity of Electrodes	136
8	Experimental Aspects	141
8.1	Pre-Starting Procedure	141
8.2	Methodology of Measurements	141
8.3	Maintenance and Storage of Ion-Selective Electrodes	142
8.4	Sources of Error	142
8.5	Precautions	144
9	Literature on Ion-Selective Electrodes	144
9.1	Glass Electrodes	144

9.2	Homogeneous Solid-State Electrodes	145
9.3	Heterogeneous Solid-State Electrodes	146
9.4	Electrodes for Alkali Metal Ions	146
9.5	Electrodes for Alkaline Earth Metals	149
9.6	Electrodes for Heavy Metals	151
10	Conclusion	159
11	Nomenclature	159
	References	160
4	ION-SENSITIVE FIELD-EFFECT TRANSISTOR (ISFET)–BASED CHEMICAL SENSORS	171
	<i>V. K. Khanna</i>	
1	Introduction	171
2	Different Structural Versions of the ISFET Concept, and a Historical Survey	174
2.1	Front-Side and Back-Side Connected ISFETs	174
2.2	The Extended-Gate Field-Effect Transistor (EGFET)	175
2.3	Use of Macroporous Silicon for Field-Effect pH Sensor Fabrication	175
2.4	Layer-by-Layer Nano Self-Assembly ISFET	177
2.5	Light-Addressable Potentiometric Sensor (LAPS)	177
2.6	Region Ion-Sensitive Field-Effect Transistor (RISFET)	178
2.7	Organic-Based Field-Effect Transistors and New Materials for ISFETs	179
3	Fundamentals of MOSFET Operation	180
3.1	MOS Capacitor with Zero Gate Voltage	181
3.2	MOS Capacitor with Applied Gate Voltage	181
3.3	Capacitance of the MOS Capacitor	185
3.4	Channel Conductance	185
3.5	Flat-Band and Threshold Voltages	186
3.6	Depletion- and Enhancement-Mode MOSFETs	188
3.7	Static Characteristics of the MOS Transistor	189
4	Theory of pH Sensitivity of the ISFET	191
4.1	Site Binding Model	193
4.2	Gouy-Chapman-Stern Model	198
4.3	pH Sensitivity of the ISFET	200
4.4	Mathematical Formulation in Terms of the pH at the Point of Zero Charge for the Relation between ψ_0 and pH	200
4.5	ISFET Circuit Models	203
5	ISFET/EGFET Gate Dielectric Materials	205
5.1	Silicon Dioxide	206
5.2	Silicon Nitride and Silicon Oxynitrides	206
5.3	Aluminum Oxide	206
5.4	Tantalum Pentoxide	207

5.5	Tertiary Amines	207
5.6	Other Dielectrics	208
5.7	Dielectrics for the EGFET	210
6	ISFET Design Considerations	210
6.1	Design Parameters and Design Procedure	210
6.2	ISFET Design Specifications	213
7	Fabrication of the ISFET	213
7.1	Chip Fabrication	215
7.2	ISFET Encapsulation Materials	222
7.3	O-Ring Packaging: The State of the Art	223
8	ISFET Biasing/Readout Circuit and Instrumentation	225
8.1	Source Follower Circuit	225
8.2	Circuit with Buffer Amplifier Stages	226
8.3	EGFET Readout Circuit	228
8.4	Readout Circuits in CMOS Technology	229
9	Influence of Ion-Selective Membranes and Other Coatings on ISFET Gate Dielectrics	231
9.1	The Need for Membranes, and Membrane Materials	231
9.2	Membrane Potential	233
9.3	Membrane Selectivity	235
9.4	Membranes of ISFET-Based Biosensors	237
9.5	Problems with Membranes	238
10	ISFET-Based Sensors for Positive Ions	239
10.1	Ammonium Ion, NH_4^+ Sensor	239
10.2	Cadmium Ion, Cd^{2+} Sensor	239
10.3	Calcium Ion, Ca^{2+} Sensor	240
10.4	Cationic Surfactant Sensor	240
10.5	Chromium Ion, Cr^{6+} Sensor	241
10.6	Cupric Ion, Cu^{2+} Sensor	241
10.7	Heavy-Metal Ion (Cd^{2+} , Pb^{2+}) Sensor	242
10.8	Iron (Fe^{3+}) Ion Biosensor	242
10.9	Mercuric Ion, Hg^{2+} Biosensor	242
10.10	Potassium Ion, K^+ Sensor	243
10.11	Silver Ion, Ag^+ Sensor	243
10.12	Sodium Ion, Na^+ Sensor	244
11	ISFET-Based Sensors for Negative Ions	244
11.1	Chloride ISFET	244
11.2	Cyanide Ion, CN^- Sensor	244
11.3	Fluoride (F^-) ISFET	244
11.4	Nitrate (NO_3^-) Sensor	245

11.5	Organic Anion Sensor	246
11.6	Phosphate (H_2PO_4^-) Sensor	246
11.7	Sulfate (SO_4^{2-}) Sensor	246
12	ISFET-Based Sensors for Biomolecules	246
12.1	Acetylcholine Biosensor	246
12.2	Adenosine Sensor	247
12.3	Adenosine Triphosphate (ATP) Sensor	247
12.4	Creatinine Biosensor	248
12.5	DNA Sensor	248
12.6	Dopamine Sensor	248
12.7	Glucose Biosensor	249
12.8	Glutamate Biosensor	249
12.9	Lactate Biosensor	250
12.10	Penicillin Biosensor	250
12.11	Triglyceride Biosensor	250
12.12	Trypsin Biosensor	250
12.13	Urea Biosensor	251
13	ISFET-Based Gas Sensors	251
13.1	Ammonia Sensor	251
13.2	H_2 Gas Sensor	252
13.3	Sensor for Dissolved Oxygen	252
13.4	Transcutaneous CO_2 Sensor	252
13.5	Flow-Through-Type pH/ CO_2 Sensor System Based on the ISFET	252
14	Temperature Effects on the ISFET	253
15	Light Effects on the ISFET	254
16	Reference Electrode-Related Problems	255
17	ISFET-REFET Combinations	255
18	Deviations, Repeatability, and Variability in Ta_2O_5 Gate ISFET-Reference Electrode Assemblies and Calibration of pH-Standard Buffers	256
18.1	ISFET Storage-Time Effects	256
18.2	ISFET Storage in Air	257
18.3	Estimation of ISFET Deviation Rate	258
18.4	Adverse Storage Environment Effects	259
18.5	pH Changes of Buffer Solutions in Ambient Atmosphere	259
18.6	Measurements by the Same or Different ISFETs	260
19	Identification of ISFET Malfunctions	262
20	ISFET Applications and Market	263
20.1	Water Analysis and Environmental Monitoring	263

20.2	Diagnostic and Health-Care Applications	263
20.3	Biotechnological Process Monitoring	264
20.4	Soil Analysis, Evaluation, and Agriculture	264
21	Conclusions and Outlook	264
22	Dedication	265
23	Acknowledgments	265
24	Nomenclature	265
	References	268
5	MICROFLUIDIC CHIPS AS NEW PLATFORMS FOR ELECTROCHEMICAL SENSING	275
	<i>M. Hervás</i>	
	<i>M. Ángel López</i>	
	<i>A. Escarpa</i>	
1	Introduction	275
2	General Outlines of Microfabrication of Microfluidic Platforms	278
2.1	Microfabrication of Glass Microfluidic Platforms	278
2.2	Microfabrication of Polymer Microfluidic Platforms	280
3	Microfluidic Platforms for Electrochemical Sensing: Designs and Applications	282
3.1	Voltammetric Microfluidic Sensors	290
3.2	Potentiometric Microfluidic Sensors	305
3.3	Conductometric Microfluidic Sensors	306
4	Strengths, Weaknesses, and Future Trends	306
	References	307
6	OPTICAL AND FIBER OPTIC CHEMICAL SENSORS	311
	<i>G. Korotcenkov</i>	
	<i>B. K. Cho</i>	
	<i>R. Narayanaswamy</i>	
	<i>F. Sevilla III</i>	
1	Introduction	311
2	Optical Transduction Principles	312
2.1	Absorption	313
2.2	Fluorescence	314
2.3	Chemiluminescence	315
2.4	Scattering	316
2.5	Reflection and Refraction	317
3	Instrumentation	318
4	Molecular Recognition Element	320

5	Sensor Configurations	321
6	Absorption-Based Sensors	324
6.1	Infrared and Near-Infrared Absorption	324
6.2	UV Absorption	330
6.3	Gas Analyzers of Absorption Type	333
6.4	Global Remote Control Using Absorption Spectroscopy	338
7	Luminescence (Fluorescence)-Based Sensors	343
8	Chemiluminescence-Based Sensors	347
9	Surface Plasmon Resonance Sensors	349
10	Raman Scattering in Optical Chemical Sensing	352
11	Ellipsometry	355
12	Optical Fiber Chemical Sensors	356
12.1	Optical Fibers	356
12.2	Classification of Fiber Optic Sensors	360
12.3	Advantages and Disadvantages of Fiber Optic Chemical Sensors	380
13	Planar Waveguide-Based Sensor Platforms	382
13.1	Fluorescence-Based PWCS	386
13.2	Absorption-Based PWCS	387
13.3	Refractometric PWCS	388
13.4	Interferometric PWCS	391
13.5	Integrated Optical Sensors	393
14	Design and Fabrication of Optical Sensors	400
14.1	General Comments	400
14.2	Reasons for Uncontrolled Intensity Modulation in Optical Sensors	406
14.3	Sensing Materials	407
14.4	Fiber Selection and Features of Fiber Preparation	412
14.5	Immobilization Techniques	416
15	Sensors for Flowing Systems	420
16	Optical Multiple-Chemical Sensing	423
17	The Optoelectronic Nose: Sensor Arrays	425
18	Optical Sensors for Portable Instruments Acceptable in Field Applications	429
19	Examples of Optical Chemical Sensors	433
19.1	Fields of Optical Chemical Sensor Applications	433
19.2	pH Sensors	434
19.3	Metal-Ion Sensing	435
19.4	Anion Sensing	438

19.5	Gas Sensors	439
19.6	Humidity Sensors	443
19.7	Vapor Sensors	445
19.8	Other Molecular Sensors	447
19.9	Optical Biosensors	447
19.10	Biomedical Sensors	452
20	Conclusions and Prospects	455
	References	456
7	CHEMILUMINESCENCE CHEMICAL SENSING: FUNDAMENTALS OF OPERATION AND APPLICATION FOR WATER POLLUTANTS CONTROL	477
	<i>J.-M. Lin</i>	
	<i>L. Zhao</i>	
1	Introduction	477
2	Fundamentals of Chemiluminescence Sensing	478
2.1	Principle of CL Analysis	478
2.2	Classical Chemiluminescence Reagents	481
3	Methodology of Chemical Analysis Using Chemiluminescence Sensing	484
4	Application of Chemiluminescence Sensors for Water Pollutants Control	485
4.1	Metals	486
4.2	Hydrogen Peroxide	488
4.3	Chemical Oxygen Demand	488
4.4	Pesticides and Herbicides	489
4.5	Phenols	491
4.6	Nitrogen Compounds	491
4.7	Estrogens	493
4.8	Fungoids	494
5	Outlook	494
	References	495