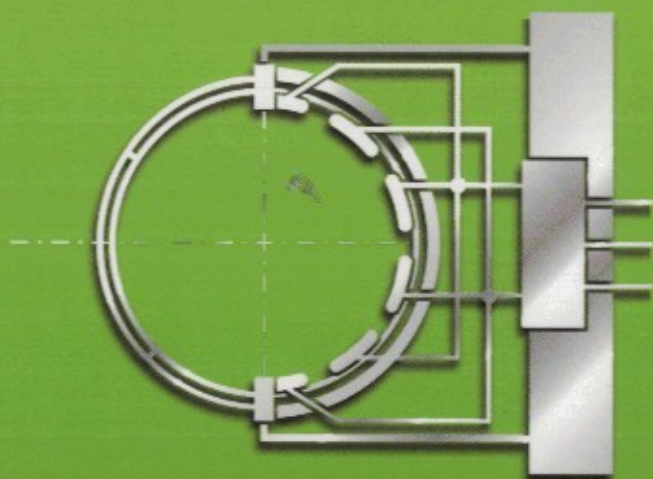


THIRD EDITION

HANDBOOK OF MODERN SENSORS

Physics, Designs, and Applications



JACOB FRADEN

Contents

Preface	VII
1 Data Acquisition	1
1.1 Sensors, Signals, and Systems	1
1.2 Sensor Classification	7
1.3 Units of Measurements	9
References	11
2 Sensor Characteristics	13
2.1 Transfer Function	13
2.2 Span (Full-Scale Input)	15
2.3 Full-Scale Output	16
2.4 Accuracy	17
2.5 Calibration	18
2.6 Calibration Error	19
2.7 Hysteresis	20
2.8 Nonlinearity	20
2.9 Saturation	22
2.10 Repeatability	23
2.11 Dead Band	23
2.12 Resolution	23
2.13 Special Properties	24
2.14 Output Impedance	24
2.15 Excitation	25
2.16 Dynamic Characteristics	25
2.17 Environmental Factors	29
2.18 Reliability	31
2.19 Application Characteristics	33
2.20 Uncertainty	33
References	35

3	Physical Principles of Sensing	37
3.1	Electric Charges, Fields, and Potentials	38
3.2	Capacitance	44
3.2.1	Capacitor	45
3.2.2	Dielectric Constant	46
3.3	Magnetism	50
3.3.1	Faraday's Law	52
3.3.2	Solenoid	54
3.3.3	Toroid	55
3.3.4	Permanent Magnets	55
3.4	Induction	56
3.5	Resistance	59
3.5.1	Specific Resistivity	60
3.5.2	Temperature Sensitivity	62
3.5.3	Strain Sensitivity	64
3.5.4	Moisture Sensitivity	65
3.6	Piezoelectric Effect	66
3.6.1	Piezoelectric Films	72
3.7	Pyroelectric Effect	76
3.8	Hall Effect	82
3.9	Seebeck and Peltier Effects	86
3.10	Sound Waves	92
3.11	Temperature and Thermal Properties of Materials	94
3.11.1	Temperature Scales	95
3.11.2	Thermal Expansion	96
3.11.3	Heat Capacity	98
3.12	Heat Transfer	99
3.12.1	Thermal Conduction	99
3.12.2	Thermal Convection	102
3.12.3	Thermal Radiation	103
3.12.3.1	Emissivity	106
3.12.3.2	Cavity Effect	109
3.13	Light	111
3.14	Dynamic Models of Sensor Elements	113
3.14.1	Mechanical Elements	115
3.14.2	Thermal Elements	117
3.14.3	Electrical Elements	118
3.14.4	Analogies	119
	References	119
4	Optical Components of Sensors	123
4.1	Radiometry	125
4.2	Photometry	129
4.3	Windows	132
4.4	Mirrors	134

4.5	Lenses	136
4.6	Fresnel Lenses	137
4.7	Fiber Optics and Waveguides	140
4.8	Concentrators	144
4.9	Coatings for Thermal Absorption	145
4.10	Electro-optic and Acousto-optic Modulators	146
4.11	Interferometric Fiber-optic Modulation	148
	References	149
5	Interface Electronic Circuits	151
5.1	Input Characteristics of Interface Circuits	151
5.2	Amplifiers	156
5.2.1	Operational Amplifiers	156
5.2.2	Voltage Follower	158
5.2.3	Instrumentation Amplifier	159
5.2.4	Charge Amplifiers	161
5.3	Excitation Circuits	164
5.3.1	Current Generators	165
5.3.2	Voltage References	169
5.3.3	Oscillators	171
5.3.4	Drivers	174
5.4	Analog-to-Digital Converters	175
5.4.1	Basic Concepts	175
5.4.2	V/F Converters	176
5.4.3	Dual-Slope Converter	181
5.4.4	Successive-Approximation Converter	183
5.4.5	Resolution Extension	185
5.5	Direct Digitization and Processing	186
5.6	Ratiometric Circuits	190
5.7	Bridge Circuits	192
5.7.1	Disbalanced Bridge	193
5.7.2	Null-Balanced Bridge	194
5.7.3	Temperature Compensation of Resistive Bridge	195
5.7.4	Bridge Amplifiers	200
5.8	Data Transmission	201
5.8.1	Two-Wire Transmission	202
5.8.2	Four-Wire Sensing	203
5.8.3	Six-Wire Sensing	204
5.9	Noise in Sensors and Circuits	204
5.9.1	Inherent Noise	205
5.9.2	Transmitted Noise	207
5.9.3	Electric Shielding	212
5.9.4	Bypass Capacitors	214
5.9.5	Magnetic Shielding	215
5.9.6	Mechanical Noise	217

5.9.7	Ground Planes	218
5.9.8	Ground Loops and Ground Isolation	219
5.9.9	Seebeck Noise	221
5.10	Batteries for Low Power Sensors	222
5.10.1	Primary Cells	223
5.10.2	Secondary Cells	224
	References	225
6	Occupancy and Motion Detectors	227
6.1	Ultrasonic Sensors	228
6.2	Microwave Motion Detectors	228
6.3	Capacitive Occupancy Detectors	233
6.4	Triboelectric Detectors	237
6.5	Optoelectronic Motion Detectors	238
6.5.1	Sensor Structures	240
6.5.1.1	Multiple Sensors	241
6.5.1.2	Complex Sensor Shape	241
6.5.1.3	Image Distortion	241
6.5.1.4	Facet Focusing Element	242
6.5.2	Visible and Near-Infrared Light Motion Detectors	243
6.5.3	Far-Infrared Motion Detectors	244
6.5.3.1	PIR Motion Detectors	245
6.5.3.2	PIR Sensor Efficiency Analysis	247
	References	251
7	Position, Displacement, and Level	253
7.1	Potentiometric Sensors	254
7.2	Gravitational Sensors	256
7.3	Capacitive Sensors	258
7.4	Inductive and Magnetic Sensors	262
7.4.1	LVDT and RVDT	262
7.4.2	Eddy Current Sensors	264
7.4.3	Transverse Inductive Sensor	266
7.4.4	Hall Effect Sensors	267
7.4.5	Magnetoresistive Sensors	271
7.4.6	Magnetostrictive Detector	274
7.5	Optical Sensors	275
7.5.1	Optical Bridge	275
7.5.2	Proximity Detector with Polarized Light	276
7.5.3	Fiber-Optic Sensors	278
7.5.4	Fabry-Perot Sensors	278
7.5.5	Grating Sensors	281
7.5.6	Linear Optical Sensors (PSD)	283
7.6	Ultrasonic Sensors	286
7.7	Radar Sensors	289

7.7.1	Micropower Impulse Radar	289
7.7.2	Ground-Penetrating Radar	291
7.8	Thickness and Level Sensors	293
7.8.1	Ablation Sensors	293
7.8.2	Thin-Film Sensors	296
7.8.3	Liquid-Level Sensors	296
	References	298
8	Velocity and Acceleration	301
8.1	Accelerometer Characteristics	303
8.2	Capacitive Accelerometers	305
8.3	Piezoresistive Accelerometers	307
8.4	Piezoelectric Accelerometers	309
8.5	Thermal Accelerometers	309
8.5.1	Heated-Plate Accelerometer	309
8.5.2	Heated-Gas Accelerometer	310
8.6	Gyroscopes	313
8.6.1	Rotor Gyroscope	313
8.6.2	Monolithic Silicon Gyroscopes	314
8.6.3	Optical Gyroscopes	317
8.7	Piezoelectric Cables	319
	References	321
9	Force, Strain, and Tactile Sensors	323
9.1	Strain Gauges	325
9.2	Tactile Sensors	327
9.3	Piezoelectric Force Sensors	334
	References	336
10	Pressure Sensors	339
10.1	Concepts of Pressure	339
10.2	Units of Pressure	340
10.3	Mercury Pressure Sensor	341
10.4	Bellows, Membranes, and Thin Plates	342
10.5	Piezoresistive Sensors	344
10.6	Capacitive Sensors	349
10.7	VRP Sensors	350
10.8	Optoelectronic Sensors	352
10.9	Vacuum Sensors	354
10.9.1	Pirani Gauge	354
10.9.2	Ionization Gauges	356
10.9.3	Gas Drag Gauge	356
	References	357

11	Flow Sensors	359
11.1	Basics of Flow Dynamics	359
11.2	Pressure Gradient Technique	361
11.3	Thermal Transport Sensors	363
11.4	Ultrasonic Sensors	367
11.5	Electromagnetic Sensors	370
11.6	Microflow Sensors	372
11.7	Breeze Sensor	374
11.8	Coriolis Mass Flow Sensors	376
11.9	Drag Force Flow Sensors	377
	References	378
12	Acoustic Sensors	381
12.1	Resistive Microphones	382
12.2	Condenser Microphones	382
12.3	Fiber-Optic Microphone	383
12.4	Piezoelectric Microphones	385
12.5	Electret Microphones	386
12.6	Solid-State Acoustic Detectors	388
	References	391
13	Humidity and Moisture Sensors	393
13.1	Concept of Humidity	393
13.2	Capacitive Sensors	396
13.3	Electrical Conductivity Sensors	399
13.4	Thermal Conductivity Sensor	401
13.5	Optical Hygrometer	402
13.6	Oscillating Hygrometer	403
	References	404
14	Light Detectors	407
14.1	Introduction	407
14.2	Photodiodes	411
14.3	Phototransistor	418
14.4	Photoresistors	420
14.5	Cooled Detectors	423
14.6	Thermal Detectors	425
14.6.1	Golay Cells	426
14.6.2	Thermopile Sensors	427
14.6.3	Pyroelectric Sensors	430
14.6.4	Bolometers	434
14.6.5	Active Far-Infrared Sensors	437
14.7	Gas Flame Detectors	439
	References	441

15 Radiation Detectors	443
15.1 Scintillating Detectors	444
15.2 Ionization Detectors	447
15.2.1 Ionization Chambers	447
15.2.2 Proportional Chambers	449
15.2.3 Geiger-Müller Counters	450
15.2.4 Semiconductor Detectors	451
References	455
16 Temperature Sensors	457
16.1 Thermoresistive Sensors	461
16.1.1 Resistance Temperature Detectors	461
16.1.2 Silicon Resistive Sensors	464
16.1.3 Thermistors	465
16.1.3.1 NTC Thermistors	465
16.1.3.2 Self-Heating Effect in NTC Thermistors	474
16.1.3.3 PTC Thermistors	477
16.2 Thermoelectric Contact Sensors	481
16.2.1 Thermoelectric Law	482
16.2.2 Thermocouple Circuits	484
16.2.3 Thermocouple Assemblies	486
16.3 Semiconductor P-N Junction Sensors	488
16.4 Optical Temperature Sensors	491
16.4.1 Fluoroptic Sensors	492
16.4.2 Interferometric Sensors	494
16.4.3 Thermochromic Solution Sensor	494
16.5 Acoustic Temperature Sensor	495
16.6 Piezoelectric Temperature Sensors	496
References	497
17 Chemical Sensors	499
17.1 Chemical Sensor Characteristics	500
17.2 Specific Difficulties	500
17.3 Classification of Chemical-Sensing Mechanisms	501
17.4 Direct Sensors	503
17.4.1 Metal-Oxide Chemical Sensors	503
17.4.2 ChemFET	504
17.4.3 Electrochemical Sensors	505
17.4.4 Potentiometric Sensors	506
17.4.5 Conductometric Sensors	507
17.4.6 Amperometric Sensors	508
17.4.7 Enhanced Catalytic Gas Sensors	510
17.4.8 Elastomer Chemiresistors	512
17.5 Complex Sensors	512
17.5.1 Thermal Sensors	513

17.5.2	Pellister Catalytic Sensors	514
17.5.3	Optical Chemical Sensors	514
17.5.4	Mass Detector	516
17.5.5	Biochemical Sensors	519
17.5.6	Enzyme Sensors	520
17.6	Chemical Sensors Versus Instruments	520
17.6.1	Chemometrics	523
17.6.2	Multisensor Arrays	524
17.6.3	Electronic Noses (Olfactory Sensors)	524
17.6.4	Neural Network Signal (Signature) Processing for Electronic Noses	527
17.6.5	“Smart” Chemical Sensors	530
	References	530
18	Sensor Materials and Technologies	533
18.1	Materials	533
18.1.1	Silicon as a Sensing Material	533
18.1.2	Plastics	536
18.1.3	Metals	540
18.1.4	Ceramics	542
18.1.5	Glasses	543
18.2	Surface Processing	543
18.2.1	Deposition of Thin and Thick Films	543
18.2.2	Spin-Casting	544
18.2.3	Vacuum Deposition	544
18.2.4	Sputtering	545
18.2.5	Chemical Vapor Deposition	546
18.3	Nano-Technology	547
18.3.1	Photolithography	548
18.3.2	Silicon Micromachining	549
	18.3.2.1 Basic Techniques	549
	18.3.2.2 Wafer bonding	554
	References	555
Appendix		557
Table A.1	Chemical Symbols for the Elements	557
Table A.2	SI Multiples	558
Table A.3	Derivative SI Units	558
Table A.4	SI Conversion Multiples	559
Table A.5	Dielectric Constants of Some Materials at Room Temperature	564
Table A.6	Properties of Magnetic Materials	564
Table A.7	Resistivities and Temperature Coefficients of Resistivity of Some Materials at Room Temperature	565
Table A.8	Properties of Piezoelectric Materials at 20°C	565

Table A.9	Physical Properties of Pyroelectric Materials	566
Table A.10	Characteristics of Thermocouple Types	566
Table A.11	Thermoelectric Coefficients and Volume Resistivities of Selected Elements	567
Table A.11a	Thermocouples for Very Low and Very High Temperatures	567
Table A.12	Densities of Some Materials	568
Table A.13	Mechanical Properties of Some Solid Materials	568
Table A.14	Mechanical Properties of Some Crystalline Materials	569
Table A.15	Speed of Sound Waves	569
Table A.16	Coefficient of Linear Thermal Expansion of Some Materials	569
Table A.17	Specific Heat and Thermal Conductivity of Some Materials	570
Table A.18	Typical Emissivities of Different Materials	571
Table A.19	Refractive Indices of Some Materials	572
Table A.20	Characteristics of C-Zn and Alkaline Cells	573
Table A.21	Lithium-Manganese Dioxide Primary Cells	573
Table A.22	Typical Characteristics of "AA"-Size Secondary Cells	573
Table A.23	Miniature Secondary Cells and Batteries	574
Table A.24	Electronic Ceramics	576
Table A.25	Properties of Glasses	577

Index	579
--------------------	-----