Christina Belisario
Research Coordinator
Morrison Foerster
12531 High Bluff Drive, Suite 200
San Diego, CA 92130-2040
USA

21 November 2025

Dear Christina

**Handbook of Modern Sensors: Physics, Designs and Applications, 4th edition by Jacob Fraden – Springer Science + Business Media, 2010. Shelf mark: (B) 681.2**

According to our records, this item was receipted by The British Library in **April 2011** and would have been available for public use from then. Unfortunately the exact day was missing from the stamp. Another stamp appears to show 10 May 2011

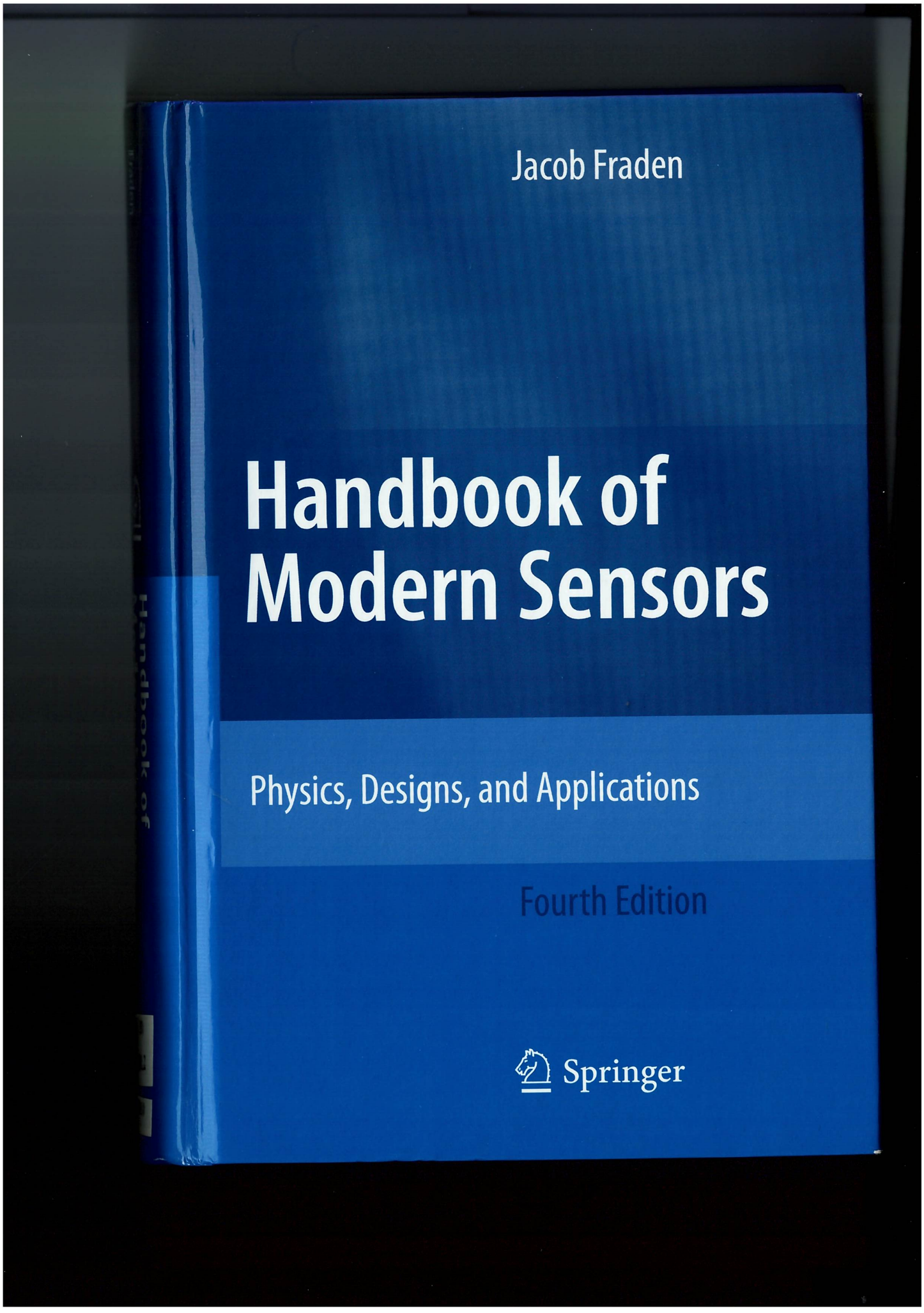
I am attaching copies of the cover, copyright pages and contents pages showing the date stamps along with the selected text required.

Please note that we can only provide the date that the British Library made this item available for public use; for the actual date of publication, please contact the publisher.

Yours sincerely

**Tony Corsini**

British Library Research Service
Tel: +44 (0) 20 7412 7903 bipc-research@bl.uk


Jacob Fraden
Handbook of Modern Sensors
Physics, Designs, and Applications
Fourth Edition
Springer

Jacob Fraden

# Handbook of Modern Sensors

## Physics, Designs, and Applications

Fourth Edition



Amazon EX1034 Page 3

15761657 (B) 681.2

Jacob Fraden
jacob@fraden.com

ISBN 978-1-4419-6465-6 e-ISBN 978-1-4419-6466-3
DOI 10.1007/978-1-4419-6466-3
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2010932807

© Springer Science+Business Media, LLC 2010
All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.
The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)



Pref

Since
logies
higher
What
still ar
lived,
"*Oh L*
the la
becon
that fo
since
revise
obsol
Th
micro
life. I
parts,
tempe
signa
repre
functi
not el
intell
are th
that '
senso
In
woul
impo
find
in se

# Preface

Since publication of the previous, the 3rd edition of this book, the sensor technologies have made a remarkable leap ahead. The sensitivity of the sensors became higher, the dimensions – smaller, the selectivity – better, and the prices – lower. What have not changed, are the fundamental principles of the sensor design. They still are governed by the laws of Nature. Arguably one of the greatest geniuses ever lived, Leonardo Da Vinci had his own peculiar way of praying. It went like this, "*Oh Lord, thanks for Thou don't violate Thy own laws.*" It is comforting indeed that the laws of Nature do not change with time, it is just that our appreciation of them becomes refined. Thus, this new edition examines the same good old laws of Nature that form the foundation for designs of various sensors. This has not changed much since the previous editions. Yet, the sections that describe practical designs are revised substantially. Recent ideas and developments have been added, while obsolete and less important designs were dropped.

This book is about devices commonly called *sensors*. The invention of a microprocessor has brought highly sophisticated instruments into our everyday life. Numerous computerized appliances, of which microprocessors are integral parts, wash clothes and prepare coffee, play music, guard homes, and control room temperature. Sensors are essential components in any device that uses a digital signal processor. The processor is a device that manipulates binary codes generally represented by electric signals. Yet, we live in an analog world, where such devices function among objects that are mostly not digital. Moreover, this world is generally not electrical (apart from the atomic level). Digital systems, however complex and intelligent they might be, must receive information from the outside world. Sensors are the interface devices between various physical values and electronic circuits that "understand" only a language of moving electrical charges. In other words, sensors are eyes, ears, and noses of silicon chips.

In the course of my engineering work, I often felt a strong need for a book which would combine practical information on diversified subjects related to the most important physical principles, design and use of various sensors. Surely, I could find almost all I had to know by surfing Internet or browsing library bookshelves in search for texts on physics, electronics, technical magazines, manufacturer's



Amazon EX1034 Page 5

catalogues and websites. However, the information is scattered over many publications, and almost every question I was pondering required substantial research work. Little by little, I have been gathering practical information on everything, which in anyway was related to various sensors and their applications to scientific and engineering measurements. Soon, I realized that the information I collected might be quite useful to more than one person. This idea prompted me to write this book and this 4th edition is the proof that I was not mistaken.

In setting my criteria for selecting various sensors for the new edition, I attempted to keep the scope of this book as broad as possible, opting for many different designs described briefly (without being trivial, I hope), rather than fewer treated in greater depth. This volume attempts (immodestly perhaps) to cover a very broad range of sensors and detectors. Many of them are well known, but describing them is still useful for students and those who look for a convenient reference. It is the author's intention to present a comprehensive and up-to-date account of the theory (physical principles), design, and practical implementations of various (especially, the newest) sensors for scientific, industrial, and consumer applications. The topics included in the book reflect the author's own preferences and interpretations. Some may find a description of a particular sensor either too detailed or too broad or, on the contrary, too brief. In most cases, the author tried to strike a balance between a detailed description and simplicity of coverage.

It is clear that one book cannot embrace the whole variety of sensors and their applications, even if it would be called something like *"The Encyclopedia of Sensors."* This is a different book and the author's task was much less ambitious. Here, an attempt has been made to generate a reference text, which could be used by students, researchers interested in modern instrumentation (applied physicists and engineers), sensor designers, application engineers and technicians whose job is to understand, select and/or design sensors for practical systems.

The prior editions of this book have been used quite extensively as desktop references and textbooks for the related college courses. Comments and suggestions from the sensor designers, professors, and students prompted me to implement several changes and correct errors. I am deeply grateful to those who helped me to make further improvements in this new edition. I owe a debt of gratitude and many thanks to Drs. Ephraim Suhir and David Pintsov for assisting me in mathematical treatment of transfer functions and to Drs. Todd E. Mlsna and Sanjay V. Patel for their invaluable contribution to the chapter on chemical sensors.

Even though the book is intended for the scientific and engineering communities, as a rule, technical descriptions and mathematic treatments do not require a background beyond a high school curriculum. Simplicity of description and intuitive approach were the key requirements that I set for myself while working on the manuscript. My true goal was not to pile up a collection of information but rather to entice the reader into a creative process. As Plutarch said nearly two millennia ago, *"The mind is not a vessel to be filled but a fire to be kindled..."*

San Diego, California
April, 2010

Jacob Fraden

Amazon EX1034 Page 6

Preface

ver many publica-
bstantial research
on on everything,
tions to scientific
nation I collected
d me to write this

e new edition, I
opting for many
rather than fewer
s) to cover a very
n, but describing
nt reference. It is
e account of the
ions of various
ner applications.
s and interpreta-
o detailed or too
strike a balance

ensors and their
*Encyclopedia of*
less ambitious.
ould be used by
l physicists and
whose job is to

ely as desktop
nd suggestions
to implement
o helped me to
tude and many
l mathematical
ay V. Patel for

g communities,
not require a
tion and intui-
vorking on the
n but rather to
millennia ago,

Jacob Fraden

# Contents

The British Library
10 MAY 2011

**1 Data Acquisition** ..... 1
1.1 Sensors, Signals, and Systems ..... 1
1.2 Sensor Classification ..... 7
1.3 Units of Measurements ..... 11
References ..... 12

**2 Sensor Characteristics** ..... 13
2.1 Transfer Function ..... 13
2.1.1 Mathematical Model ..... 14
2.1.2 Functional Approximations ..... 15
2.1.3 Polynomial Approximations ..... 16
2.1.4 Sensitivity ..... 17
2.1.5 Linear Piecewise Approximation ..... 18
2.1.6 Spline Interpolation ..... 19
2.1.7 Multidimensional Transfer Functions ..... 19
2.2 Calibration ..... 20
2.2.1 Computation of Transfer Function Parameters ..... 22
2.2.2 Linear Regression ..... 25
2.3 Computation of Stimulus ..... 26
2.3.1 Computation from Linear Piecewise Approximation ..... 26
2.3.2 Iterative Computation of Stimulus (Newton Method) ..... 28
2.4 Span (Full-Scale Full Scale Input) ..... 30
2.5 Full-Scale Output ..... 31
2.6 Accuracy ..... 31
2.7 Calibration Error ..... 34
2.8 Hysteresis ..... 35
2.9 Nonlinearity ..... 36
2.10 Saturation ..... 37
2.11 Repeatability ..... 38
2.12 Dead Band ..... 38
2.13 Resolution ..... 38



Amazon EX1034 Page 7

2.14 Special Properties ..... 39
2.15 Output Impedance ..... 40
2.16 Output Format ..... 40
2.17 Excitation ..... 40
2.18 Dynamic Characteristics ..... 41
2.19 Environmental Factors ..... 41
2.20 Reliability ..... 45
2.21 Application Characteristics ..... 47
2.22 Uncertainty ..... 49
References ..... 50
..... 52

**3 Physical Principles of Sensing** ..... 53
3.1 Electric Charges, Fields, and Potentials ..... 54
3.2 Capacitance ..... 60
3.2.1 Capacitor ..... 62
3.2.2 Dielectric Constant ..... 63
3.3 Magnetism ..... 67
3.3.1 Faraday Law ..... 69
3.3.2 Solenoid ..... 71
3.3.3 Toroid ..... 72
3.3.4 Permanent Magnets ..... 72
3.4 Induction ..... 73
3.5 Resistance ..... 77
3.5.1 Specific Resistivity ..... 79
3.5.2 Temperature Sensitivity ..... 80
3.5.3 Strain Sensitivity ..... 84
3.5.4 Moisture Sensitivity ..... 85
3.6 Piezoelectric Effect ..... 86
3.6.1 Ceramic Piezoelectric Materials ..... 89
3.6.2 Polymer Piezoelectric Films ..... 93
3.7 Pyroelectric Effect ..... 96
3.8 Hall Effect ..... 103
3.9 Thermoelectric Effects ..... 106
3.9.1 Seebeck Effect ..... 106
3.9.2 Peltier Effect ..... 111
3.10 Sound Waves ..... 113
3.11 Temperature and Thermal Properties of Materials ..... 116
3.11.1 Temperature Scales ..... 117
3.11.2 Thermal Expansion ..... 118
3.11.3 Heat Capacity ..... 120
3.12 Heat Transfer ..... 121
3.12.1 Thermal Conduction ..... 122
3.12.2 Thermal Convection ..... 125
3.12.3 Thermal Radiation ..... 126

Amazon EX1034 Page 8

..... 39
..... 40
..... 40
..... 41
..... 41
..... 45
..... 47
..... 49
..... 50
..... 52

..... 53
..... 54
..... 60
..... 62
..... 63
..... 67
..... 69
..... 71
..... 72
..... 72
..... 73
..... 77
..... 79
..... 80
..... 84
..... 85
..... 86
..... 89
..... 93
..... 96
..... 103
..... 106
..... 106
..... 111
..... 113
..... 116
..... 117
..... 118
..... 120
..... 121
..... 122
..... 125
..... 126





3.13 Light ..... 135
3.13.1 Light Polarization ..... 136
3.13.2 Light Scattering ..... 137
3.14 Dynamic Models of Sensor Elements ..... 138
3.14.1 Mechanical Elements ..... 139
3.14.2 Thermal Elements ..... 141
3.14.3 Electrical Elements ..... 142
3.14.4 Analogies ..... 143
References ..... 144

**4 Optical Components of Sensors** ..... 147
4.1 Radiometry ..... 149
4.2 Photometry ..... 154
4.3 Windows ..... 157
4.4 Mirrors ..... 158
4.5 Lenses ..... 161
4.6 Fresnel Lenses ..... 163
4.7 Fiber Optics and Waveguides ..... 165
4.8 Concentrators ..... 169
4.9 Coatings for Thermal Absorption ..... 170
4.10 Nano-optics ..... 172
References ..... 172

**5 Interface Electronic Circuits** ..... 173
5.1 Input Characteristics of Interface Circuits ..... 173
5.2 Amplifiers ..... 178
5.2.1 Operational Amplifiers ..... 178
5.2.2 Voltage Follower ..... 181
5.2.3 Instrumentation Amplifier ..... 182
5.2.4 Charge Amplifiers ..... 183
5.3 Light-to-Voltage Converters ..... 186
5.4 Excitation Circuits ..... 188
5.4.1 Current Generators ..... 188
5.4.2 Voltage References ..... 192
5.4.3 Oscillators ..... 192
5.4.4 Drivers ..... 194
5.4.5 Optical Drivers ..... 196
5.5 Analog-to-Digital Converters ..... 196
5.5.1 Basic Concepts ..... 196
5.5.2 V/F Converters ..... 198
5.5.3 Dual-Slope Converters ..... 203
5.5.4 Successive Approximation Converter ..... 203
5.5.5 Resolution Extension ..... 205
5.6 Direct Digitization ..... 207


Amazon EX1034 Page 9

5.7 Capacitance-to-Voltage Converters ..... 208
5.8 Integrated Interfaces ..... 210
5.9 Ratiometric Circuits ..... 211
5.10 Differential Circuits ..... 214
5.11 Bridge Circuits ..... 215
5.11.1 General Concept ..... 215
5.11.2 Disbalanced Bridge ..... 216
5.11.3 Null-Balanced Bridge ..... 218
5.11.4 Bridge Amplifiers ..... 218
5.12 Data Transmission ..... 220
5.12.1 Two-Wire Transmission ..... 220
5.12.2 Four-Wire Sensing ..... 221
5.12.3 Six-Wire Sensing ..... 222
5.13 Noise in Sensors and Circuits ..... 223
5.13.1 Inherent Noise ..... 223
5.13.2 Transmitted Noise ..... 227
5.13.3 Electric Shielding ..... 231
5.13.4 Bypass Capacitors ..... 234
5.13.5 Magnetic Shielding ..... 235
5.13.6 Mechanical Noise ..... 237
5.13.7 Ground Planes ..... 237
5.13.8 Ground Loops and Ground Isolation ..... 238
5.13.9 Seebeck Noise ..... 240
5.14 Calibration ..... 242
5.15 Batteries for Low-Power Sensors ..... 243
5.15.1 Primary Cells ..... 244
5.15.2 Secondary Cells ..... 245
References ..... 246

**6 Occupancy and Motion Detectors** ..... 247
6.1 Ultrasonic Detectors ..... 249
6.2 Microwave Motion Detectors ..... 249
6.3 Capacitive Occupancy Detectors ..... 254
6.4 Triboelectric Detectors ..... 258
6.5 Optoelectronic Motion Detectors ..... 260
6.5.1 Sensor Structures ..... 261
6.5.2 Visible and Near IR Light Motion Detectors ..... 264
6.5.3 Far-Infrared Motion Detectors ..... 267
6.6 Optical Presence Sensors ..... 274
6.7 Pressure-Gradient Sensors ..... 276
References ..... 278

**7 Position, Displacement, and Level** ..... 279
7.1 Potentiometric Sensors ..... 280
7.2 Capacitive Sensors ..... 284

Amazon EX1034 Page 10

..... 208
..... 210
..... 211
..... 214
..... 215
..... 215
..... 216
..... 218
..... 218
..... 220
..... 220
..... 221
..... 222
..... 223
..... 223
..... 227
..... 231
..... 234
..... 235
..... 237
..... 237
..... 238
..... 240
..... 242
..... 243
..... 244
..... 245
..... 246

..... 247
..... 249
..... 249
..... 254
..... 258
..... 260
..... 261
..... 264
..... 267
..... 274
..... 276
..... 278

..... 279
..... 280
..... 284



7.3 Inductive and Magnetic Sensors ..... 288
7.3.1 LVDT and RVDT ..... 288
7.3.2 Eddy Current Sensors ..... 290
7.3.3 Transverse Inductive Sensor ..... 292
7.3.4 Hall Effect Sensors ..... 293
7.3.5 Magnetoresistive Sensors ..... 297
7.3.6 Magnetostrictive Detector ..... 300
7.4 Optical Sensors ..... 302
7.4.1 Optical Bridge ..... 302
7.4.2 Proximity Detector with Polarized Light ..... 303
7.4.3 Fiber-Optic Sensors ..... 304
7.4.4 Fabry-Perot Sensors ..... 306
7.4.5 Grating Sensors ..... 308
7.4.6 Linear Optical Sensors ..... 310
7.5 Ultrasonic Sensors ..... 314
7.6 Radar Sensors ..... 316
7.6.1 Micropower Impulse Radar ..... 316
7.6.2 Ground Penetrating Radars ..... 318
7.7 Thickness and Level Sensors ..... 320
7.7.1 Ablation Sensors ..... 320
7.7.2 Thin Film Sensors ..... 322
7.7.3 Liquid Level Sensors ..... 323
7.8 Pointing Devices ..... 324
7.8.1 Optical Pointing Devices ..... 324
7.8.2 Magnetic Pickup ..... 325
7.8.3 Inertial and Gyroscopic Mice ..... 325
References ..... 325

**8 Velocity and Acceleration** ..... 327
8.1 Accelerometer Characteristics ..... 329
8.2 Capacitive Accelerometers ..... 332
8.3 Piezoresistive Accelerometers ..... 334
8.4 Piezoelectric Accelerometers ..... 335
8.5 Thermal Accelerometers ..... 336
8.5.1 Heated Plate Accelerometer ..... 336
8.5.2 Heated Gas Accelerometer ..... 337
8.6 Gyroscopes ..... 339
8.6.1 Rotor Gyroscope ..... 340
8.6.2 Monolithic Silicon Gyroscopes ..... 341
8.6.3 Optical (Laser) Gyroscopes ..... 344
8.7 Piezoelectric Cables ..... 346
8.8 Gravitational Sensors ..... 348
References ..... 351

Amazon EX1034 Page 11

**9 Force, Strain, and Tactile Sensors** ..... 353
9.1 Strain Gauges ..... 353
9.2 Tactile Sensors ..... 355
9.2.1 Switch Sensors ..... 357
9.2.2 Piezoelectric Sensors ..... 358
9.2.3 Piezoresistive Sensors ..... 359
9.2.4 MEMS Sensors ..... 362
9.2.5 Capacitive Touch Sensors ..... 364
9.2.6 Acoustic Touch Sensors ..... 365
9.2.7 Optical Sensors ..... 369
9.3 Piezoelectric Force Sensors ..... 369
References ..... 370
..... 372

**10 Pressure Sensors** ..... 375
10.1 Concepts of Pressure ..... 375
10.2 Units of Pressure ..... 377
10.3 Mercury Pressure Sensor ..... 378
10.4 Bellows, Membranes, and Thin plates ..... 379
10.5 Piezoresistive Sensors ..... 381
10.6 Capacitive Sensors ..... 387
10.7 VRP Sensors ..... 388
10.8 Optoelectronic Pressure Sensors ..... 390
10.9 Indirect Pressure Sensor ..... 391
10.10 Vacuum Sensors ..... 393
10.10.1 Pirani Gauge ..... 393
10.10.2 Ionization Gauges ..... 395
10.10.3 Gas Drag Gauge ..... 396
10.10.4 Membrane Vacuum Sensors ..... 396
References ..... 397

**11 Flow Sensors** ..... 399
11.1 Basics of Flow Dynamics ..... 399
11.2 Pressure Gradient Technique ..... 402
11.3 Thermal Transport Sensors ..... 404
11.3.1 Hot-Wire Anemometers ..... 405
11.3.2 Three-Part Thermoanemometer ..... 409
11.3.3 Two-Part Thermoanemometer ..... 411
11.3.4 Microflow Thermal Transport Sensors ..... 414
11.4 Ultrasonic Sensors ..... 416
11.5 Electromagnetic Sensors ..... 418
11.6 Breeze Sensor ..... 420
11.7 Coriolis Mass Flow Sensors ..... 422
11.8 Drag Force Sensors ..... 423
11.9 Dust and Smoke Detectors ..... 424

Amazon EX1034 Page 12

..... 353
..... 355
..... 357
..... 358
..... 359
..... 362
..... 364
..... 365
..... 369
..... 369
..... 370
..... 372

..... 375
..... 375
..... 377
..... 378
..... 379
..... 381
..... 387
..... 388
..... 390
..... 391
..... 393
..... 393
..... 395
..... 396
..... 396
..... 397

..... 399
..... 399
..... 402
..... 404
..... 405
..... 409
..... 411
..... 414
..... 416
..... 418
..... 420
..... 422
..... 423
..... 424





11.9.1 Ionization Detector ..... 424
11.9.2 Optical Detector ..... 426
References ..... 428

**12 Acoustic Sensors** ..... 431
12.1 Resistive Microphones ..... 432
12.2 Condenser Microphones ..... 432
12.3 Fiber-Optic Microphone ..... 434
12.4 Piezoelectric Microphones ..... 435
12.5 Electret Microphones ..... 437
12.6 Dynamic Microphones ..... 439
12.7 Solid-State Acoustic Detectors ..... 440
References ..... 443

**13 Humidity and Moisture Sensors** ..... 445
13.1 Concept of Humidity ..... 445
13.2 Capacitive Sensors ..... 448
13.3 Electrical Conductivity Sensors ..... 452
13.4 Thermal Conductivity Sensor ..... 455
13.5 Optical Hygrometer ..... 456
13.6 Oscillating Hygrometer ..... 458
References ..... 459

**14 Light Detectors** ..... 461
14.1 Introduction ..... 461
14.2 Photodiodes ..... 465
14.3 Phototransistor ..... 471
14.4 Photoresistors ..... 472
14.5 Cooled Detectors ..... 475
14.6 Image Sensors ..... 478
14.6.1 CCD Sensor ..... 479
14.6.2 CMOS-Imaging Sensors ..... 480
14.7 Thermal Detectors ..... 481
14.7.1 Golay Cells ..... 482
14.7.2 Thermopile Sensors ..... 483
14.7.3 Pyroelectric Sensors ..... 487
14.7.4 Bolometers ..... 491
14.7.5 Active Far-Infrared Sensors ..... 494
14.8 Optical Design ..... 497
14.9 Gas Flame Detectors ..... 498
References ..... 500

**15 Radiation Detectors** ..... 503
15.1 Scintillating Detectors ..... 504


Amazon EX1034 Page 13

15.2 Ionization Detectors ..... 507
15.2.1 Ionization Chambers ..... 508
15.2.2 Proportional Chambers ..... 509
15.2.3 Geiger–Müller Counters ..... 510
15.2.4 Semiconductor Detectors ..... 512
15.3 Cloud and Bubble Chambers ..... 516
References ..... 518

**16 Temperature Sensors** ..... 519
16.1 Coupling with Object ..... 519
16.2 Temperature Reference Points ..... 526
16.3 Thermoresistive Sensors ..... 528
16.3.1 Resistance Temperature Detectors ..... 528
16.3.2 *Silicon* Resistive PTC Sensors ..... 529
16.3.3 Thermistors ..... 532
16.4 Thermoelectric Contact Sensors ..... 549
16.4.1 Thermoelectric Laws ..... 550
16.4.2 Thermocouple Circuits ..... 552
16.4.3 Thermocouple Assemblies ..... 554
16.5 Semiconductor *pn*-Junction Sensors ..... 556
16.6 Optical Temperature Sensors ..... 560
16.6.1 Fluoroptic Sensors ..... 561
16.6.2 Interferometric Sensors ..... 562
16.6.3 Thermochromic Solution Sensor ..... 563
16.7 Acoustic Temperature Sensor ..... 564
16.8 Piezoelectric Temperature Sensors ..... 565
References ..... 566

**17 Chemical Sensors** ..... 569
17.1 Overview ..... 570
17.2 History ..... 570
17.3 Chemical Sensor Characteristics ..... 571
17.4 Classes of Chemical Sensors ..... 572
17.4.1 Electrical and Electrochemical Transducers ..... 572
17.4.2 Elastomer Chemiresistors ..... 581
17.4.3 Photoionization Detector ..... 585
17.4.4 Physical Transducers ..... 586
17.4.5 Optical Transducers ..... 595
17.5 Biochemical Sensors ..... 597
17.5.1 Enzyme Sensors ..... 597
17.6 Multisensor Arrays ..... 598
17.7 Electronic Noses and Tongues ..... 599
17.8 Specific Difficulties ..... 602
References ..... 603

Amazon EX1034 Page 14

..... 507
..... 508
..... 509
..... 510
..... 512
..... 516
..... 518

..... 519
..... 519
..... 526
..... 528
..... 528
..... 529
..... 532
..... 549
..... 550
..... 552
..... 554
..... 556
..... 560
..... 561
..... 562
..... 563
..... 564
..... 565
..... 566

..... 569
..... 570
..... 570
..... 571
..... 572
..... 572
..... 581
..... 585
..... 586
..... 595
..... 597
..... 597
..... 598
..... 599
..... 602
..... 603



**18 Sensor Materials and Technologies** ..... 607
18.1 Materials ..... 607
18.1.1 Silicon as Sensing Material ..... 607
18.1.2 Plastics ..... 611
18.1.3 Metals ..... 615
18.1.4 Ceramics ..... 617
18.1.5 Glasses ..... 617
18.1.6 Optical Glasses ..... 618
18.1.7 Nanomaterials ..... 620
18.2 Surface Processing ..... 621
18.2.1 Deposition of Thin and Thick Films ..... 621
18.2.2 Spin Casting ..... 621
18.2.3 Vacuum Deposition ..... 622
18.2.4 Sputtering ..... 623
18.2.5 Chemical Vapor Deposition ..... 624
18.2.6 Electroplating ..... 625
18.3 Microtechnology ..... 626
18.3.1 Photolithography ..... 627
18.3.2 Silicon Micromachining ..... 628
References ..... 635

**Appendix** ..... 637

**Index** ..... 653

Amazon EX1034 Page 15



ısor, a device which

on ion transport,
perator). In man-
ı electrical form,
d in the artificial
h they are inter-
sensor should be
displacement of
ct a sensor to an
electrochemical
ewhat narrower

*ith an electrical*

e clearly under-
is received and
use a different
tress on quanti-

ere information is



The purpose of a sensor is to respond to some kind of an input physical property (stimulus) and to convert it into an electrical signal that is compatible with electronic circuits. We may say that a sensor is a translator of a generally nonelectrical value into an electrical value. When we say "electrical," we mean a signal, which can be channeled, amplified, and modified by electronic devices. The sensor's output signal may be in the form of voltage, current, or charge. These may be further described in terms of amplitude, polarity, frequency, phase, or digital code. This set of characteristics is called the *output signal format*. Therefore, a sensor has input properties (of any kind) and electrical output properties.

Any sensor is an energy converter. No matter what you try to measure, you always deal with energy transfer from the object of measurement to the sensor. The process of sensing is a particular case of information transfer, and any transmission of information requires transmission of energy. Of course, one should not be confused by an obvious fact that transmission of energy can flow both ways – it may be with a positive sign as well as with a negative sign; that is, energy can flow either from an object to the sensor or from the sensor to the object. A special case is when the net energy flow is zero, which also carries information about existence of that particular case. For example, a thermopile infrared radiation sensor will produce a positive voltage when the object is warmer than the sensor (infrared flux is flowing to the sensor) or the voltage is negative when the object is cooler than the sensor (infrared flux flows from the sensor to the object). When both the sensor and the object are at the same temperature, the flux is zero and the output voltage is zero. This carries a message that the temperatures are the same.

The term *sensor* should be distinguished from *transducer*. The latter is a converter of any one type of energy into another, whereas the former converts any type of energy into electrical energy. An example of a transducer is a loudspeaker, which converts an electrical signal into a variable magnetic field and, subsequently, into acoustic waves.[2] This is nothing to do with perception or sensing. Transducers may be used as *actuators* in various systems. An actuator may be described as an opposite to a sensor; it converts electrical signal into generally nonelectrical energy. For example, an electric motor is an actuator; it converts electric energy into mechanical action. Another example is a pneumatic actuator that is enabled by an electric signal.

Transducers may be parts of complex sensors (Fig. 1.2). For example, a chemical sensor may have a part, which converts the energy of a chemical reaction into heat (transducer) and another part, a thermopile, which converts heat into an electrical signal. The combination of the two makes a chemical sensor, a device which produces electrical signal in response to a chemical reagent. Note that in the above example a chemical sensor is a complex sensor; it is comprised of a nonelectrical transducer and a simple (direct) sensor converting heat to electricity. This suggests that many sensors incorporate at least one direct-type sensor and a

[2]It is interesting to note that a loudspeaker, when connected to an input of an amplifier, may function as a microphone. In that case, it becomes an acoustical sensor.

Amazon EX1034 Page 16

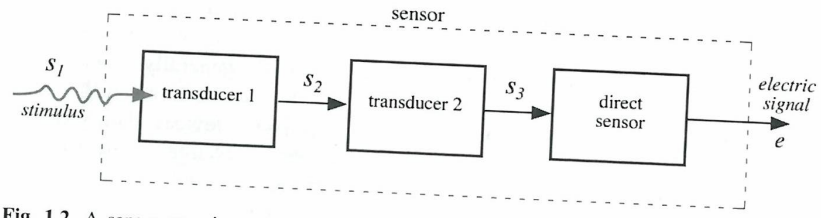



**Fig. 1.2** A sensor may incorporate several transducers. $s_1$, $s_2$, and so on are various types of energy. Note that the last part is a direct sensor producing electrical output $e$

number of transducers. The direct sensors are those that employ certain physical effects to make a direct energy conversion into an electrical signal generation or modification. Examples of such physical effects are photoeffect and Seebeck effect. These will be described in Chap. 3.

In summary, there are two types of sensors; direct and complex. A direct sensor converts a stimulus into an electrical signal or modifies an electrical signal by using an appropriate physical effect, whereas a complex sensor in addition needs one or more transducers of energy before a direct sensor can be employed to generate an electrical output.

A sensor does not function by itself; it is always a part of a larger system that may incorporate many other detectors, signal conditioners, signal processors, memory devices, data recorders, and actuators. The sensor's place in a device is either intrinsic or extrinsic. It may be positioned at the input of a device to perceive the outside effects and to signal the system about variations in the outside stimuli. Also, it may be an internal part of a device that monitors the devices' own state to cause the appropriate performance. A sensor is always a part of some kind of a data acquisition system. Often, such a system may be a part of a larger control system that includes various feedback mechanisms.

To illustrate the place of sensors in a larger system, Fig. 1.3 shows a block diagram of a data acquisition and control device. An object can be anything: a car, space ship, animal or human, liquid, or gas. Any material object may become a subject of some kind of a measurement. Data are collected from an object by a number of sensors. Some of them (2, 3, and 4) are positioned directly on or inside the object. Sensor 1 perceives the object without a physical contact and, therefore, is called a noncontact sensor. Examples of such a sensor are a radiation detector and a TV camera. Even if we say "noncontact," we remember that energy transfer always occurs between any sensor and an object.

Sensor 5 serves a different purpose. It monitors internal conditions of a data acquisition system itself. Some sensors (1 and 3) cannot be directly connected to standard electronic circuits because of inappropriate output signal formats. They require the use of interface devices (signal conditioners). Sensors 1, 2, 3, and 5 are passive. They generate electric signals without energy consumption from the electronic circuits. Sensor 4 is active. It requires an operating signal, which is provided by an excitation circuit. This signal is modified by the sensor in

Amazon EX1034 Page 17

The specific heat describes the material while a thermal capacity describes an object, which is made of that material. Strictly speaking, specific heat is not constant over an entire temperature range of a specific phase of the material. It may change dramatically when a phase of the material changes, say from solid to liquid. Microscopically, specific heat reflects structural changes in the material. For instance, the specific heat of water is almost constant between 0°C and 100°C (liquid phase). Almost, but not exactly- it is higher near freezing, and decreases slightly when the temperature goes to about 35°C and then slowly rises again from 38° to 100°. Remarkably, the specific heat of water is the lowest near 37°C, a biologically optimal temperature of the warm-blooded animals.[22]

Table A.17 gives the specific heat for various materials in cal/(g°C). Some other tables provide specific heat in SI units of energy which is joule/g °C. The relationship between cal/(g°C) and j/(g°C) is as follows:

$$1\frac{\text{j}}{\text{g}^{\text{o}}\text{C}} = 0.2388\frac{\text{cal}}{\text{g}^{\text{o}}\text{C}}. \tag{3.117}$$

It may be noted that generally the heavier the material the lower is its specific heat. A concept of thermal capacity is very important for development of temperature sensors. It follows from (3.116) that for the same temperature increase, a smaller thermal energy need be transferred from the object to a lighter sensor with smaller specific heat. Hence, a temperature sensor having smaller heat capacity will disturb the measured object to a lesser degree.

## 3.12 Heat Transfer

There are two fundamental properties of heat, which should be well recognized:
1. The heat is totally not specific, that is, once it is produced, it is impossible to say what origin it has, and
2. The heat can not be contained, which means that it flows spontaneously from warmer to the cooler part of the system and there is no method known to modern science to stop the heat flow entirely.

Thermal energy may be transferred from one object to another by three ways: conduction, convection, and radiation. While conduction and radiation relate to solids, liquids, and gases, convection can transfer heat by an intermediate fluid (liquid or gas). A measurement of any physical quantity always requires transfer of energy. Naturally, one of the objects involved in thermal exchange may be a thermal sensor. Its purpose would be to measure the amount of heat, which represents certain

[22]Likely, this is because of a better compatibility between the animal protein molecules and structures of the water crystals at that temperature.

Amazon EX1034 Page 18

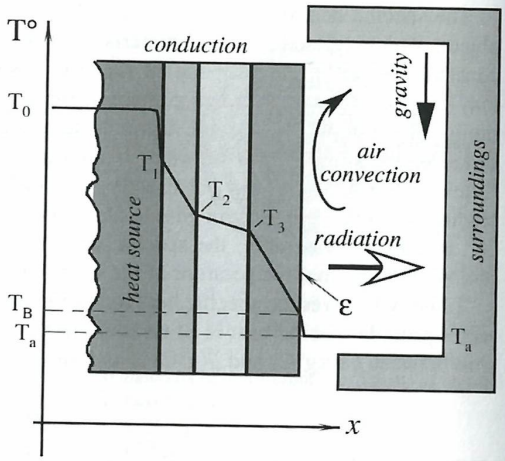



**Fig. 3.39** Temperature profile in laminated materials

information about the object producing that heat. Such information may be the temperature of an object, chemical reaction, position of the object, etc.

Let us consider a sandwich-like multilayer object, where each layer is made of a different material. When heat moves through the layers, a temperature profile within each material depends on its thickness and thermal conductivity. Figure 3.39 shows three laminated layers where the first layer is attached to a heat source (a device having an "infinite" heat capacity and a high thermal conductivity). One of the best solid materials to act as an infinite heat source is a thermostatically controlled bulk copper. In liquids, an "infinite" heat capacity can be attributed to a stirred liquid, like water in a temperature-controlled bath. Temperature within the source is higher and constant, except of a thin boundary region at the joint of the laminated materials. Heat propagates from one material to another by conduction, gradually dropping toward ambient temperature. The temperature within each material drops with different rates depending on the thermal properties of the material. The last layer loses heat to air through the natural (gravitational) convection and to the surrounding objects through the infrared (thermal) radiation. Thus, Fig. 3.39 illustrates all three possible ways to transfer heat from one object to another: conduction, convection, and radiation.

### 3.12.1 Thermal Conduction

Heat conduction requires a physical contact between two bodies. Thermally agitated particles in a warmer body jiggle and transfer kinetic energy to a cooler body by agitating its particles. As a result, the warmer body loses heat while the cooler body gains heat. Heat transfer by conduction is analogous to water flow or to

Amazon EX1034 Page 19

electric current. For instance, heat passage through a rod is governed by a law, which is similar to Ohm's law. A heat flow rate (thermal "current") is proportional to a thermal gradient (thermal "voltage") across the material ($dT/dx$) and a cross-sectional area $A$:

$$H = \frac{dQ}{dt} = -kA\frac{\Delta T}{dx}, \tag{3.118}$$

where $k$ is called thermal conductivity. The minus sign indicates that heat flows in the direction of temperature decrease (a negative derivative is required to cancel the minus sign). A good thermal conductor has a high $k$ (most of metals) while thermal insulators (most of dielectrics) have a low $k$. Thermal conductivity is considered constant, however, it somewhat increases with temperature. To calculate heat conduction through, say, an electric wire, temperatures at both ends ($T_1$ and $T_2$) must be used in equation

$$H = kA\frac{T_1 - T_2}{L}, \tag{3.119}$$

where $L$ is the length of the wire. Quite often, a thermal resistance $r$ is used instead of a thermal conductivity

$$r = \frac{L}{k}, \tag{3.120}$$

then (3.119) can be rewritten as

$$H = A\frac{T_1 - T_2}{r} \tag{3.121}$$

Values of thermal conductivities for some materials are shown in Table A.17.

Figure 3.39 shows an idealized temperature profile within the layers of laminated materials having different thermal conductivities. In the real world, heat transfer through an interface of two adjacent materials may be different from that idealized case. If we join together two materials and observe the heat propagation through the assembly, a temperature profile may look like the one shown in Fig. 3.40a. If the sides of the materials are well insulated, under steady-state conditions, the heat flux must be the same through both materials. The sudden temperature drop at the boundary region, having surface area, $a$, is the result of a thermal contact resistance. Heat transfer through the assembly can be described as

$$H = \frac{T_1 - T_3}{R_A + R_c + R_B}, \tag{3.122}$$

where $R_A$ and $R_B$ are thermal resistances of two materials and $R_c$ is the contact resistance

Amazon EX1034 Page 20

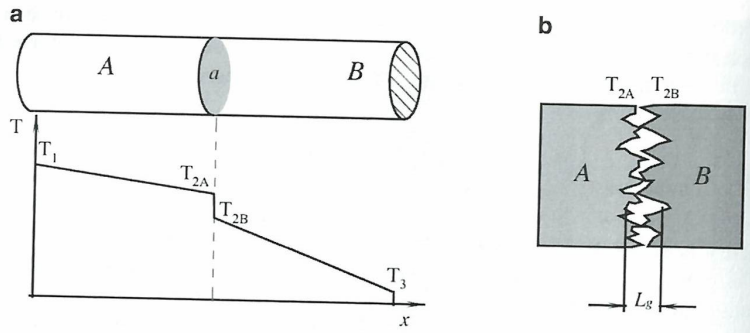



**Fig. 3.40** Temperature profile in a joint (**a**) and a microscopic view of a surface contact (**b**)

$$R_c = \frac{1}{h_c a}. \tag{3.123}$$

The quantity $h_c$ is called the contact coefficient. This factor can be very important in a number of sensor applications because of many heat-transfer situations, which involve mechanical joining of two materials. Microscopically, the joint may look like the one shown in Fig. 3.40b. No real surface is perfectly smooth, and the actual surface roughness is believed to play a central role in determining the contact resistance. There are two principal contributions to the heat transfer at the joint:

1. The material-to-material conduction through the actual physical contact
2. The conduction through trapped gases (air) in the void spaces created by the rough surfaces

Since thermal conductivity of gases is very small as compared with many solids, the trapped gas creates the most resistance to heat transfer. Then, the contact coefficient can be defined as

$$h_c = \frac{1}{L_g}\left(\frac{a_c}{a}\frac{2k_A k_B}{k_A + k_B} + \frac{a_v}{a}k_f\right), \tag{3.124}$$

where $L_g$ is the thickness of the void space, $k_f$ is the thermal conductivity of the fluid (for instance, air) filling the void space, $a_c$ and $a_v$ are areas of the contact and void, respectively, and $k_A$ and $k_B$ are the respective thermal conductivities of the materials. The main problem with this theory is that it is very difficult to determine experimentally areas $a_c$ and $a_v$, and distance $L_g$. This analysis, however, allows us to conclude that the contact resistance should increase with a decrease in the ambient gas pressure. On the other hand, contact resistance decreases with an increase in the joint pressure. This is a result of a deformation of the high spots of the contact surface, which leads to enlarging $a_c$ and creating a greater contact area between the materials. To decrease the thermal resistance, a dry contact between materials should be avoided. Before joining, surfaces may be coated with

Amazon EX1034 Page 21

fluid having low thermal resistance. For instance, silicone thermal grease is often used for the purpose.

### 3.12.2 Thermal Convection

Another way to transfer heat is convection. Convection requires an intermediate agent (fluid: gas or liquid), which takes heat from a warmer body, carries it to a cooler body, releases heat, and then may or may not return back to a warmer body to pick up another portion of heat. Heat transfer from a solid body to a moving agent or within the moving agent is also called convection. Convection may be natural (gravitational) or forced (produced by a mechanism). With the natural convection of air, buoyant forces produced by gravitation act upon air molecules. Warmed up air rises carrying heat away from a warm surface. Cooler air descends toward the warmer object. Forced convection of air is produced by a fan or blower. Forced convection is used in liquid thermostats to maintain the temperature of a device at a predetermined level. The efficiency of a convective heat transfer depends on the rate of media movement, temperature gradient, surface area of an object, and thermal properties of moving medium. An object whose temperature is different from the surroundings will lose (or receive) heat, which can be determined from the Newton's law of cooling, which is governed by equation similar to that of a thermal conduction

$$H = \alpha A(T_1 - T_2), \tag{3.125}$$

where convective coefficient $\alpha$ depends on the fluid's specific heat, viscosity, and a rate of movement. The coefficient is not only gravity dependent, its value changes somewhat with the temperature gradient. For a horizontal plate in air the value of $\alpha$ for the gravitational convection may be estimated from

$$\alpha = 2.49\sqrt[4]{T_1 - T_2}\ \mathrm{W/m^2K}, \tag{3.126}$$

while for a vertical plate it is:

$$\alpha = 1.77\sqrt[4]{T_1 - T_2}\ \mathrm{W/m^2K}. \tag{3.127}$$

It should be noted however that these values are applicable for one side of a plate only, assuming that the plate is a surface of an infinite heat source (that is, its temperature doesn't depend on heat loss) and the surroundings have constant temperature. If volume of air is small, like in the air gap between two surfaces of different temperatures, movement of gaseous molecules becomes very restricted due to viscosity and convective heat transfer becomes insignificant. In these cases, thermal conductivity of air and radiative heat transfer should be considered instead.

Amazon EX1034 Page 22

# Chapter 6
# Occupancy and Motion Detectors

*"Never confuse motion with action".*

- Ernest Hemingway

September 11 has changed the way people think about airport, aviation, and security in general. The threat is expanding interest in more reliable systems to detect presence of people within the protected perimeters. The occupancy sensors detect the presence of people (and sometimes animals) in a monitored area. Motion detectors respond only to moving objects. A distinction between the two is that the occupancy sensors produce signals whenever an object is stationary or not, while the motion detectors are selectively sensitive to moving objects. The applications of these sensors include security, surveillance, energy management (electric lights control ), personal safety, friendly home appliances, point-of-sale advertisements, interactive toys, novelty products, etc. Depending on the applications, presence of humans may be detected through any means that is associated with some kind of a human body's property or body's actions [1]. For instance, a detector may be sensitive to body weight, heat, sounds, dielectric constant, etc. The following types of detectors are presently used for the occupancy and motion sensing of people:

1. *Air pressure sensors:* detect changes in air pressure resulted from opening doors and windows
2. *Capacitive:* detectors of human body capacitance
3. *Acoustic:* detectors of sound produced by people
4. *Photoelectric:* interruption of light beams by moving objects
5. *Optoelectric:* detection of variations in illumination or optical contrast in the protected area
6. *Pressure mat switches:* pressure sensitive long strips used on floors beneath the carpets to detect weight of an intruder
7. *Stress detectors:* strain gauges imbedded into floor beams, staircases, and other structural components
8. *Switch sensors:* electrical contacts connected to doors and windows

J. Fraden, *Handbook of Modern Sensors*,
DOI 10.1007/978-1-4419-6466-3_6, © Springer Science+Business Media, LLC 2010



Amazon EX1034 Page 23

9. *Magnetic switches:* a noncontact version of switch sensors
10. *Vibration detectors:* react to the vibration of walls or other building structures. Also, may be attached to doors or windows to detect movements
11. *Glass breakage detectors:* sensors reacting to specific vibrations produced by shattered glass
12. *Infrared motion detectors:* devices sensitive to heat waves emanated from warm or cold moving objects
13. *Microwave detectors:* active sensors responsive to microwave electromagnetic signals reflected from objects
14. *Ultrasonic detectors:* devices similar to microwave detectors except that instead of electromagnetic radiation, ultrasonic waves are used
15. *Video motion detectors:* a video equipment that compares a stationary image stored in memory with the current image from a protected area
16. *Video face recognition system:* image analyzers that compare facial features with database
17. *Laser system detectors:* similar to photoelectric detectors, except that they use narrow light beams and combinations of reflectors
18. *Triboelectric detectors:* sensors capable of detecting static electric charges carried by moving objects

One of the major aggravations in detecting occupancy or intrusion is a false-positive detection . The term "false-positive" means that the system indicates an intrusion when there is none. In some noncritical applications where false positive detections occur once in a while, for instance, in a toy or a motion switch controlling electric lights in a room, this may be not a serious problem: the lights will be erroneously turned on for a short time, which unlikely do any harm[1]. In other systems, especially used for the security and military purposes, false-positive detections, while generally not as dangerous as false negative ones (missing an intrusion), may become a serious problem[2]. While selecting a sensor for critical applications, considerations should be given to its reliability, selectivity, and noise immunity. It is often a good practice to form a multiple sensor arrangement with symmetrical interface circuits. It may dramatically improve a reliability of a system, especially in the presence of external transmitted noise. Another efficient way to reduce erroneous detections is to use sensors operating on different physical principles [2], for instance, combining capacitive and infrared detectors is an efficient combination as they are receptive to different kinds of transmitted noise.

[1]Perhaps just steering up some suspicion about living in a haunted house.

[2]A very nice movie "*How to Steal a Million*" (1966) was based on a plot where multiple false-positive alarms were so irritating that officials disabled the electronic protection system, exactly what the perpetrator was looking for.

Amazon EX1034 Page 24

pulses compatible with the control input of the multiplexer. A phase of the zero-crossing detector should be trimmed for the zero output at the central position of the core. The output amplifier can be trimmed to a desirable gain to make the signal compatible with the next stages. The synchronized clock to the multiplexer means that the information presented to the *RC*-filter at the input of the amplifier is amplitude- and phase-sensitive. The output voltage represents how far the core is from the center and on which side.

For LVDT to measure transient motions accurately, the frequency of the oscillator must be at least ten times higher than the highest significant frequency of the movement. For a slow-changing process, stable oscillator may be replaced by coupling to a power line frequency of 60 or 50 Hz.

The advantages of the LVDT and RVDT are the following: (1) the sensor is a noncontact device with no or very little friction resistance with small resistive forces; (2) hysteresis (magnetic and mechanical) are negligible; (3) output impedance is very low; (4) low susceptibility to noise and interferences; (5) construction is solid and robust; and (6) infinitesimal resolution is possible.

One useful application for the LVDT sensor is in the so-called gauge heads, which are used in tool inspection and gauging equipment. In that case, the inner core of the LVDT is spring loaded to return the measuring head to a preset reference position.

The RVDT operates on the same principle as LVDT, except that a rotary ferromagnetic core is used. The prime use for the RVDT is the measurement of angular displacement. A typical linear range of measurement is about $\pm$ 40° with a nonlinearity error of about 1%.

### 7.3.2 Eddy Current Sensors

Eddy current is an electrical phenomenon discovered in 1851 by French physicist Léon Foucault. Thus, this current sometimes is called *Foucault current*. It appears in two cases: (1) when a conductor is exposed to a changing magnetic field due to relative motion of the field source and conductor and (2) due to changing intensity of the magnetic field. These effects cause a circulating flow of electrons, or a current, within the body of the conductor. These circulating eddies of current create induced magnetic fields that oppose the change of the original magnetic field due to Lenz's law, causing repulsive or drag forces between the conductor and the magnet. The stronger the applied magnetic field, or the greater the electrical conductivity of the conductor, or the faster the field that the conductor is exposed to changes, then the greater the currents that are developed and the greater the opposing field.

To sense proximity of nonmagnetic but conductive materials, the effect of eddy currents is employed in a dual-coil sensor (Fig. 7.13a). One coil is used as a reference, while the other is for sensing the magnetic currents induced in the conductive object. Eddy currents produce the magnetic field, which opposes that of the sensing coil, thus resulting in a disbalance with respect to the reference coil.

Amazon EX1034 Page 25

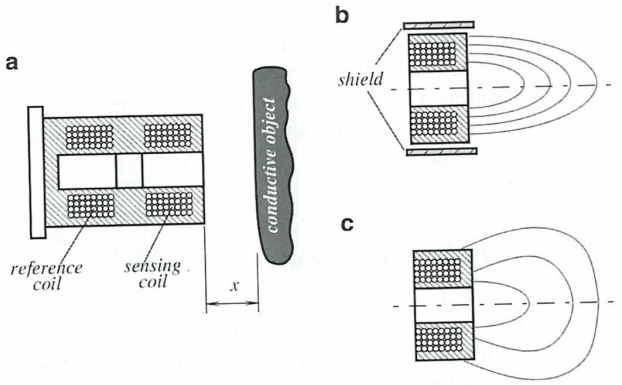



**Fig. 7.13** Electromagnetic proximity sensor with eddy currents (**a**). Sensor with the shielded front end (**b**); Unshielded sensor (**c**)

The closer the object to the coil the larger the change in the magnetic impedance. The depth of the object where eddy currents are produced is defined by

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}, \tag{7.7}$$

where $f$ is the frequency and $\sigma$ is the target conductivity. Naturally, for the effective operation, the object thickness should be larger than that depth. Hence, eddy detectors should not be used for detecting film metallized or foil objects. Generally, the relationship between the coil impedance and distance to the object $x$ is nonlinear and temperature-dependent. The operating frequency range of the eddy current sensors ranges from 50 kHz to 10 MHz.

Figure 7.13b and c show two configurations of the eddy current sensors: with and without the shield. The shielded sensor has a metal guard around the ferrite core and the coil assembly. It focuses and directs the electromagnetic field to the front of the sensor. This allows the sensor to be installed and even imbedded into a metal structure without influencing the detection range. The unshielded sensor can sense at its sides as well as from the front. As a result, the detecting range of an unshielded sensor is usually somewhat greater than that of the shielded sensor of the same diameter, however, to operate properly, the unshielded sensors require nonmetallic surrounding objects.

In addition to position detection, eddy sensors can be used to determine material thickness, nonconductive coating thickness, conductivity and plating measurements, and cracks in the material. Crack detection and surface flaws become the most popular applications for the sensors. Cracks interrupt flow of eddy currents and result in abrupt change in the sensor's output signal.

Depending on the applications, eddy probes may be of many coil configurations: very small in diameter (2–3 mm) or quite large (25 mm). Some companies even make custom-designed probes to meet unique requirements of the customers

Amazon EX1034 Page 26

(www.olympus-ims.com). One important advantage of the eddy current sensors is that they do not need magnetic material for the operation, thus they can be quite effective at high temperatures (well exceeding Curie temperature of a magnetic material), and for measuring a distance to or level of conductive liquids, including molten metals. Another advantage of the detectors is that they are not mechanically coupled to the object and thus the loading effect is very low.

### 7.3.3 Transverse Inductive Sensor

Another electromagnetic position-sensing device is called a transverse inductive proximity sensor. It is useful for sensing relatively small displacements of ferromagnetic materials. As the name implies, the sensor measures the distance to an object, which alters the magnetic field in the coil. The coil inductance is measured by an external electronic circuit (Fig. 7.14). A self-induction principle is the foundation for the operation of the sensor. When it moves into the vicinity of a ferromagnetic object, its magnetic field changes, thus altering the inductance of the coil. The advantage of the sensor is that it is a noncontact device whose interaction with the object is only through the magnetic field. An obvious limitation is that it is useful only for the ferromagnetic objects at relatively short distances.

A modified version of the transverse transducer is shown in Fig. 7.15a. To overcome the limitation for measuring only ferrous materials, a ferromagnetic disk is attached to a displacing object while the coil has a stationary position. Alternatively, the coil may be attached to the object and the core is stationary. This proximity sensor is useful for measuring small displacements only, as its linearity is poor in comparison with LVDT. However, it is quite useful as a proximity detector for the indication of close proximity to an object, which is made of any solid material. A magnitude of the output signal as function of distance to the disk is shown in Fig. 7.15b.

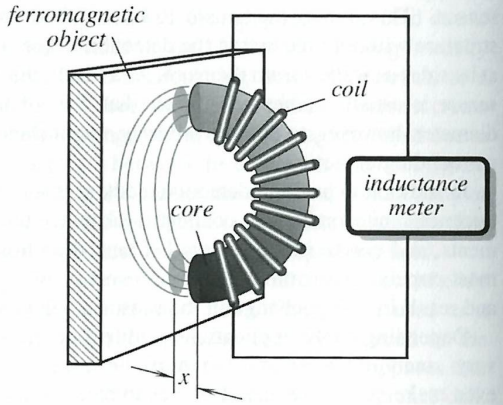



**Fig. 7.14** Transverse inductive proximity sensor

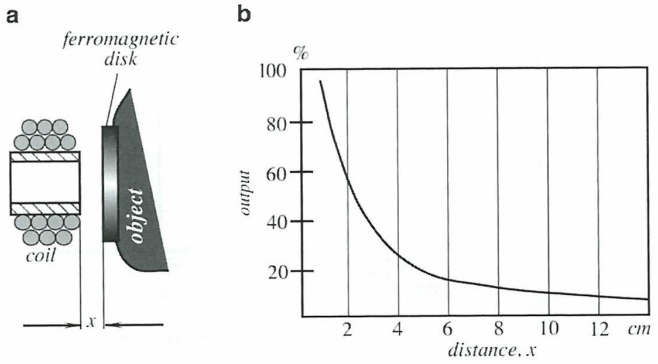



**Fig. 7.15** Transverse sensor with an auxiliary ferromagnetic disc (**a**) and the output signal as function of distance (**b**)

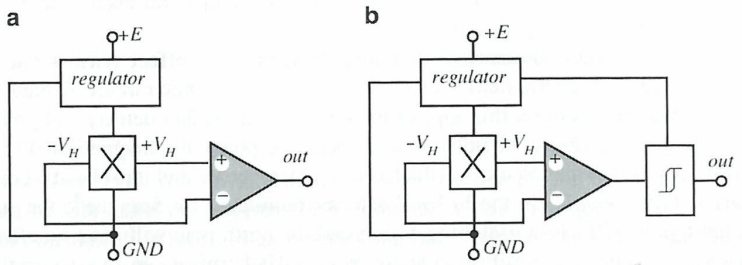



**Fig. 7.16** Circuit diagrams of a linear (**a**) and threshold (**b**) Hall effect sensors

### 7.3.4 *Hall Effect Sensors*

Probably the most widely used magnetic sensors are the Hall effect sensors.[2] There are two types of the Hall sensors: analog and bi-level (Fig. 7.16). Analog sensors usually incorporate amplifiers for easier interface with the peripheral circuits. In comparison with a basic sensor (Fig. 3.30), the analog sensor operates over a broader voltage range and more stable in a noisy environment. These sensors are not quite linear (Fig. 7.17a) with respect to the magnetic field density and, therefore, for precision measurements require a calibration. A bi-level sensor in addition to the amplifier contains a Schmitt trigger with a built-in hysteresis of the threshold level. The output signal as function of a magnetic field density is shown in Fig. 7.17b. The signal is two-level and has clearly pronounced hysteresis with respect to the magnetic field. When the applied magnetic flux density exceeds a certain threshold, the trigger provides a clean transient from the OFF to ON

[2]See Sect. 3.8 for the operating principle.

Amazon EX1034 Page 28

# Chapter 11
# Flow Sensors

*A distinguished scientist was asked which two questions he would ask God?*
*– Oh, I would ask him to explain the theory which links quantum mechanics and general relativity.*
*– And the second question? Would you ask Him to explain turbulence?*
*– No, I don't wish to embarrass Him...*

## 11.1 Basics of Flow Dynamics

One of the fundamentals of physics is that mass is a conserved quantity. It cannot be created or destroyed. In the absence of sources or sinks of mass, its quantity remains constant regardless of boundaries. However, if there is influx or outflow of mass through the boundaries, the sum of influx and efflux must be zero. Whatever mass comes in, must go out. When both are measured over the same interval of time, mass entering the system ($M_{in}$) is equal to mass leaving the system ($M_{out}$) [1]. Therefore,

$$\frac{dM_{in}}{dt} = \frac{dM_{out}}{dt}. \tag{11.1}$$

In mechanical engineering, moving media whose flow is measured are liquids (water, oil, solvents, gasoline, etc.), air, gases (oxygen, nitrogen, CO, $CO_2$, methane $CH_4$, water vapor, etc.).

In a steady flow, the velocity at a given point is constant in time. We can draw a streamline through every point in a moving medium (Fig. 11.1a). In steady flow, the line distribution is time-independent. A velocity vector is tangent to a stream line in every point $z$. Any boundaries of flow which envelop a bundle of streamlines are called a tube of flow. Since the boundary of such a tube consists of streamlines, no fluid (gas) can cross the boundary of a tube of flow and the tube behaves something

J. Fraden, *Handbook of Modern Sensors*,
DOI 10.1007/978-1-4419-6466-3_11, © Springer Science+Business Media, LLC 2010



Amazon EX1034 Page 29

strain gages that should be physically protected from interaction with moving fluids.

The drag force $F$, exerted by incompressible fluid on a solid object exposed to it is given by the drag equation:

$$F_D = C_D \rho A V^2, \tag{11.39}$$

where $\rho$ is fluid density, $V$ is fluid velocity at the point of measurement, $A$ is projected area of the body normal to the flow, and $C_D$ is the overall drag coefficient. $C_D$ is a dimensionless factor, whose magnitude depends primarily on the physical shape of the object and its orientation relative to the fluid stream. If mass of the supporting beam is ignored, the developed strain is

$$\varepsilon = \frac{3 C_D \rho A V^2 (L - x)}{E a^2 b}, \tag{11.40}$$

where $L$ is the beam length, $x$ is the point coordinate on the beam where the strain gauges are located, $E$ is the Young's modulus of elasticity, $a$ and $b$ are the geometry target factors. It is seen that the strain in a beam is a square law function of the fluid flow rate.

## 11.9 Dust and Smoke Detectors

Smoke and air gas impurity sensors are intended for detecting presence of small airborne particles and have wide range of applications. Even though these detectors do not monitor air flow, their operation essentially requires movement of gas through the detection chamber of the sensor. By far the most popular are the smoke detectors. Such a detector is positioned on or near a ceiling (Fig. 11.22a). It has an inlet for air that can flow through the detector passively or can be drown by a forced convection with help from a fan or blower. Airborne particles greatly vary in size depending on their origin. Table 11.1 exemplifies some contaminants that either may present health hazard or are manifestations of troubling events (e.g., a fire). To detect presence of small particles suspended in air, nowadays two types of sensors are widely employed: ionization and optical detectors.

### *11.9.1 Ionization Detector*

This detector is especially useful for detecting smoke composed of very small particles (submicron) like those generated by large hot fires. The key part of this type of sensor is an ionization chamber containing less than a milligram of

Amazon EX1034 Page 30

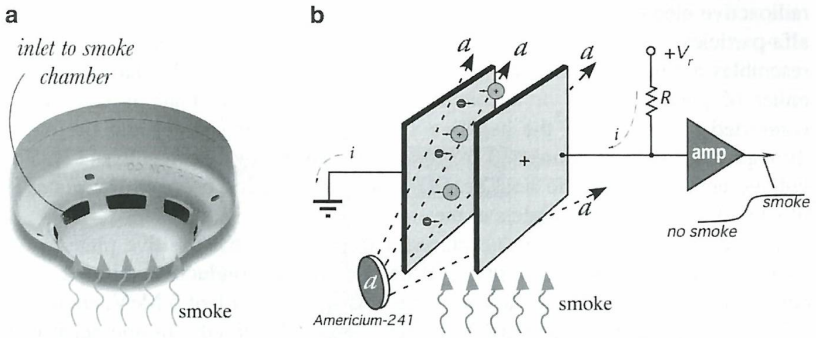



**Fig. 11.22** Smoke detector (**a**) and a concept of the ionization smoke sensor (**b**)

**Table 11.1** Sizes of some airborne contaminants

| Particle | Particle size (μm) | Particle | Particle size (μm) |
|---|---|---|---|
| Glass wool | 1,000 | Coal dust | 1–100 |
| Spanish moss pollen | 150–750 | Smoke from synthetic materials | 1–50 |
| Beach sand | 100–10,000 | Face powder | 0.1–30 |
| Mist | 70–350 | Asbestos | 0.7–90 |
| Pollens | 10–1,000 | Calcium zinc dust | 0.7–20 |
| Textile fibers | 10–1,000 | Paint pigments | 0.1–5 |
| Fiberglass insulation | 1–1,000 | Car emission | 1–150 |
| Grain dusts | 5–1,000 | Clay | 0.1–50 |
| Human hair | 40–300 | Humidifier | 0.9–3 |
| Dust mites | 100–300 | Copier toner | 0.5–15 |
| Saw dust | 30–600 | Liquid droplets | 0.5–5 |
| Cement dust | 3–100 | Insecticide dusts | 0.5–10 |
| Mold spores | 10–30 | Anthrax | 1–5 |
| Textile dust | 6–20 | Yeast cells | 1–50 |
| Spider web | 2–3 | Carbon black dust | 0.2–10 |
| Spores | 3–40 | Atmospheric dust | 0.001–40 |
| Combustion-related carbon monoxide from motor vehicles, wood burning, open burning, industrial processes | Up to 2.5 | Smoldering or flaming cooking oil | 0.03–0.9 |
| Sea salt | 0.035–0.5 | Combustion | 0.01–0.1 |
| Bacteria | 0.3–60 | Smoke from natural materials | 0.01–0.1 |
| Burning wood | 0.2–3 | Tobacco smoke | 0.01–4 |
| Coal flue gas | 0.08–0.2 | Viruses | 0.005–0.3 |
| Oil smoke | 0.03–1 | Pesticides and herbicides | 0.001 |

Amazon EX1034 Page 31

radioactive element Americium-241 ($Am^{241}$). This element is a natural source of alfa-particles resulted from the so-called alfa decay. The ionization chamber resembles a capacitor with two opposite electrodes (Fig. 11.22b) having shapes either of parallel plates or a coaxial cylinder, where one plate is electrically connected to ground (or the negative side of the power source) and the other, through resistor $R$, is connected to a positive voltage $+V_r$ (few volts) [17]. The voltage creates an electric field between the plates. Space between the plates is filled with air drawn from inlets at the sides of the plates.

If alfa-particles are absent, no current can pass from the positive plate to the grounded plate, because air normally is not electrically conductive. Alfa-particles emanated by the radioactive element have kinetic energy about 5 MeV, enough to ionize air molecules by breaking them into positively charged ions and negatively charged electrons. The charged ions and electrons are being pulled by the electric field in the opposite directions; electrons to the positive plate and ions to the grounded plate. This results in small constant electric current $i$ flowing from the voltage source $V_r$, through resistor $R$, the air-filled space between the plates, and to the "ground." As a result, the input voltage at the amplifier "amp" drops, indicating that no smoke is present in the ionization chamber.

When smoke is drawn into the ionization chamber between the plates, the smoke particles absorb alfa-radiation, thus reducing air ionization and subsequently current $i$ drops. This increases voltage at input of the amplifier, manifesting presence of smoke inside the ionization chamber. Since Americium-241 has a half-life of 432.2 years, the life time of the ionization source is long enough for all practical purposes.

The reasons why alpha radiation is used instead of beta or gamma is twofold: a higher ability of alfa radiation to ionize air and low penetrating power of the alfa particles,[4] so the radiation will be absorbed by the smoke detector housing, reducing a potential harm to humans.

### 11.9.2 Optical Detector

Another type of a smoke or dust detector is based on measuring scattering of light (see Sect. 3.13.2). An optical detector includes a light emitter (incandescent bulb, infrared LED or a laser diode) and a photosensor, usually a photodiode or phototransistor (Fig. 11.23). The light emitter and detector are positioned inside a light-tight enclosure in such a way as to prevent any photons reaching the detector directly from the emitter or by reflections from the enclosure inner walls. The enclosure should also protect the photosensor from ambient light. To achieve these difficult requirements, the light emitter and photosensor are positioned inside the

[4] Alfa radiation consists of Helium-4 positively charged nucleus and due to high mass travels with the speed of only about 15,000 km/s. Thus, it easily can be stopped by just a thin tissue paper and, due to collisions with air molecules, travels in air at distances no farther than few centimeters.

Amazon EX1034 Page 32

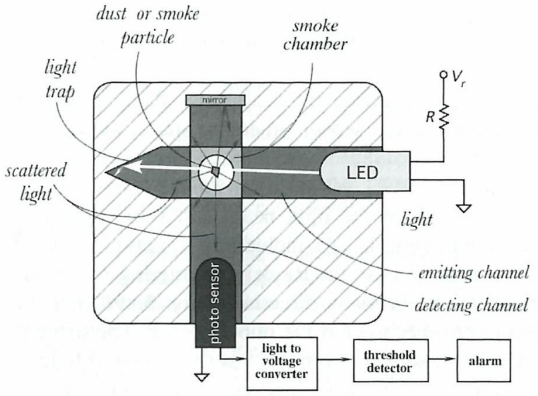



**Fig. 11.23** Optical smoke detector

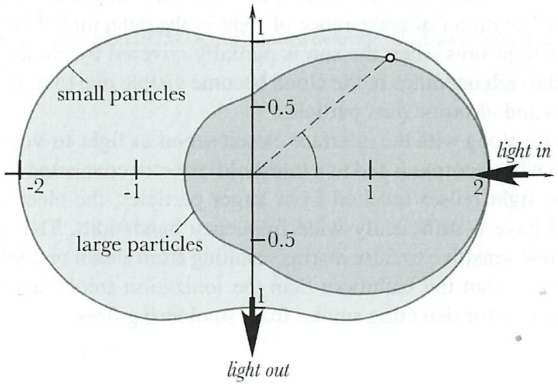



**Fig. 11.24** Scattering directional diagram

individual emitting and detecting channels which cross each other preferably at a 90° angle. This is not an optimal angle since light scattering is not the strongest at 90° (Fig. 11.24) but this is the best angle for minimizing a chance for stray light passing from the photo emitter to the photo sensor. Many practical optical smoke detectors [18] use smaller angles on the expense of a larger size and mechanical complexity: to trap the unwanted light before it reaches a photo sensor.

The interior walls of the channels have low light reflectivity surfaces. In addition, the emitting channel has the far end that is conically shaped to prevent a spurious light reflection toward the photo sensor. This shape is called a light trap. The emitter and photo sensor may have built-in lenses to shape the narrow-angle beams, thus assuring that very little light strikes the chamber walls. The space where two channels cross is called a "scattering chamber" or "smoke chamber,"

Amazon EX1034 Page 33

which is open to ambient air or connected to the source of tested air. The smoke chamber has the inlets and outlets for air passing through, but shielded from ambient light.

In presence of clean air inside the scattering chamber, light beams from the emitter cannot reach the photo sensor (in empty space, light cannot go around the corner) and thus the photo sensor produces a very low output current, called the dark current (see Sect. 14.2). When dust or smoke enters the scattering chamber, it appears across the path of the light beam and some light is scattered by the particles in all directions (Fig. 11.24), including a direction toward the photo sensor. Smaller airborne particles cause the Rayleigh scattering while the larger particles cause specular reflections in many directions (Fig. 3.49), including the direction along the detecting channel toward the photo sensor. The detecting channel may have a mirror at the opposite end to bounce some scattered light toward the photo sensor, thus increasing the sensor's sensitivity. Whatever is the physical nature of scattering, thanks to air impurities the photo sensor now sees some light "in the tunnel." Small particles being much more numerous create a relatively constant shift in the photo current, while the larger particles will glitter and result in a pulsing photo current. The effect of appearance of light in the detecting channel resembles appearance of light rays when the sun is partially covered by clouds: the sunlight rays passing through openings in the cloud become visible due to light scattering by water droplets and airborne dust particles.

A photodiode along with the interface circuit serves as light-to-voltage converter (see Sect. 5.3) whose output is fed to a threshold detector connected to an alarm. To respond to the light pulses resulted from larger particles, the electronic interface circuit should have a sufficiently wide frequency bandwidth. The optical smoke detectors are less sensitive to false alarms resulting from steam or cooking fumes in kitchen or steam from the bathroom than the ionization smoke alarms. They are especially efficient for detecting smoke from smoldering fires.

## References

1. Benedict RP (1984) Fundamentals of temperature, pressure, and flow measurements, 3rd edn. Wiley, New York
2. Cho ST, Wise KD (1991) A high performance microflowmeter with built-in self test. In: Transducers'91. International conference on solid-state sensors and actuators. Digest of Technical Papers, pp 400–403, IEEE, 1991
3. Bruun HH (1995) Hot-wire anemometry. Principles and signal analysis. Oxford Science, Oxford
4. King LV (1914) On the convention of heat from small cylinders in a stream of fluid. Philos Trans R Soc A214:373
5. Collis DC, Williams MJ (1959) Two-dimensional convection from heated wires at low Reynolds' numbers. J Fluid Mech 6:357
6. Fraden J, Rutstein A (2007) Clogging detector for air filter. US Patent 7178410, 20 Feb
7. Fraden J (2009) Detector of low levels of gas pressure and flow. US Patent 7490512, 17 Feb

Amazon EX1034 Page 34

# Chapter 14
# Light Detectors

*There is nothing more practical than a good theory.*

– Kurt Lewin

## 14.1 Introduction

Detectors of electromagnetic radiation in the spectral range from ultraviolet to far infrared are called light detectors. From the standpoint of a sensor designer, absorption of photons by a sensing material may result in either a quantum or thermal response. Therefore, all light detectors are divided into two major groups that are called quantum and thermal. The quantum detectors operate from the ultraviolet to mid-infrared spectral ranges, while thermal detectors are most useful in the mid- and far-infrared spectral ranges where their efficiency at room temperatures exceeds that of the quantum detectors. In this chapter, we cover both types. For description of highly sensitive photon sensors called photomultipliers refer to Sect. 15.1.

Solid-state quantum detectors (photovoltaic and photoconductive devices) relay on the interaction of individual photons with a crystalline lattice of semiconductor materials. Their operations are based on the photoeffect that was discovered by Albert Einstein, which won him the Nobel Prize. In 1905, he made a remarkable assumption about the nature of light that at least under certain circumstances, its energy was concentrated into localized bundles, later named photons. The energy of a single photon is given by

$$E = h\nu, \tag{14.1}$$

where $\nu$ is the frequency of light, and $h = 6.626075 \times 10^{-34}$ Js (or $4.13567 \times 10^{-15}$ eVs) is Planck's constant derived on the basis of the wave theory of light. When a photon strikes a surface of a conductor, it may result in the generation of a

J. Fraden, *Handbook of Modern Sensors*,
DOI 10.1007/978-1-4419-6466-3_14, © Springer Science+Business Media, LLC 2010



Amazon EX1034 Page 35

chopping frequency and the spectral content must be also specified. The detectivity is expressed in the units of $Hz^{-2}/W$. It can be said that the higher the value of $D^*$, the better the detector.

*IR cutoff wavelength* ($\lambda_c$) represents the long-wavelength limit of spectral response, and often is listed as the wavelength at which the detectivity drops by 10% of the peak value.

*Maximum current* is specified for photoconductive detectors (such as HgCdTe) that operate at constant currents. The operating current never should exceed the maximum limit.

*Maximum reverse voltage* is specified for Ge and Si photodiodes and photoconductive cells. Exceeding this voltage can cause the breakdown and severe deterioration of the sensor's performance.

*Radiant responsivity* is the ratio of the output photocurrent (or output voltage) divided by the incident radiant power at a given wavelength, expressed in A/W or V/W.

*Dark current* $I_D$ for photodiodes is a leakage current at a reverse voltage when the diode is in complete darkness. This current generally is temperature dependent and may vary from pA to μA. It approximately doubles for every 10°C increase in temperature.

*Field of view* (FOV) is the angular measure of the volume of space where the sensor can respond to the source of radiation.

*Junction capacitance* ($C_j$) is similar to the capacitance of a parallel plate capacitor. It should be considered whenever a high-speed response is required. The value of $C_j$ drops with reverse bias and is higher for the larger diode areas.

## 14.2 Photodiodes

Photodiodes are semiconducting optical sensors, which if broadly defined may even include solar batteries. However, here we consider only the information aspect of these devices rather than the power conversion. In a simple way, the operation of a photodiode can be described as follows.

If a pn-junction is forward biased (positive side of a battery is connected to the p side) and is exposed to light of proper frequency, the current increase will be very small with respect to a dark current. In other words, the bias current is much greater than the current generated by light, and the diode is just a diode, not really useful for sensing light.

If the junction is reverse biased (Fig. 14.3), when light strikes the semiconductor, the current will increase quite noticeably. Impinging photons create electron–hole pairs on both sides of the junction. When electrons enter the conduction band, they start flowing toward the positive side of the battery. Correspondingly, the created holes flow to the negative terminal, meaning that photocurrent $i_p$ flows in the network. Under dark conditions, dark current $i_0$ is independent of applied voltage and mainly is the result of thermal generation of charge carriers. Thus, a

Amazon EX1034 Page 36

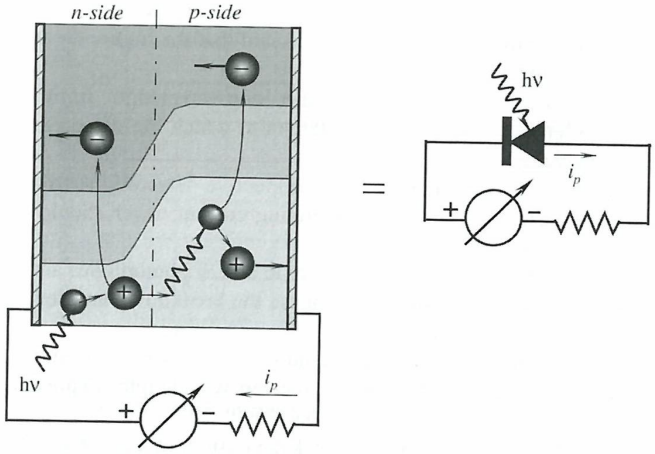



**Fig. 14.3** Structure of a photodiode

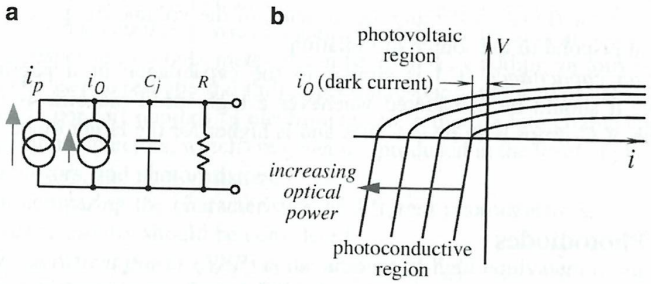



**Fig. 14.4** An equivalent circuit of a photodiode (**a**) and its volt-ampere characteristic (**b**)

reverse-biased photodiode electrical equivalent circuit contains two current sources and a *RC* network (Fig. 14.4a).

The process of optical detection involves the direct conversion of optical energy (in the form of photons) into an electrical signal (in the form of electrons). If the probability that a photon of energy $hv$ will produce an electron in a detection is $\eta$ then the average rate of the production of electrons $\langle r \rangle$ for an incident beam of optical power $P$ is given by [2]

$$\langle r \rangle = \frac{\eta P}{hv} \tag{14.6}$$

The production of electrons due to the incident photons at constant rate $<r>$ is randomly distributed in time and obeys Poisson statistics, so that the probability of the production of $m$ electrons in some measurement interval $\tau$ is given by

Amazon EX1034 Page 37

Fig. 14.6. An example is a device TSL257T from TAOS (www.taosinc.com), which operates primarily in the visible spectral range from 400 to 800 nm.

## 14.3 Phototransistor

A photodiode directly converts photons into charge carriers, specifically one electron and one hole (hole–electron pair) per a photon. The phototransistors can do the same, and in addition to provide current gain, resulting in a much higher sensitivity. The collector–base junction is a reverse-biased diode that functions as described earlier. If the transistor is connected into a circuit containing a battery, a photoinduced current flows through the loop, which includes the base–emitter region. This current is amplified by the transistor in the same manner as in a conventional transistor, resulting in a significant increase in the collector current.

The energy bands for the phototransistor are shown in Fig. 14.9. The photon-induced base current is returned to the collector through the emitter and the external circuitry. In so doing, electrons are supplied to the base region by the emitter where they are pulled into the collector by the electric field. The sensitivity of a phototransistor is a function of the collector–base diode quantum efficiency and also of the dc current gain of the transistor. Therefore, the overall sensitivity is a function of collector current.

When subjected to varying ambient temperature, collector current changes linearly with a positive slope of about 0.00667 per °C. The magnitude of this temperature coefficient is primarily a result of the increase in current gain versus temperature, since the collector–base photocurrent temperature coefficient is only about 0.001 per °C. The family of collector current versus collector voltage characteristics is very much similar to that of a conventional transistor. This implies that circuits with phototransistors can be designed by using the regular methods of

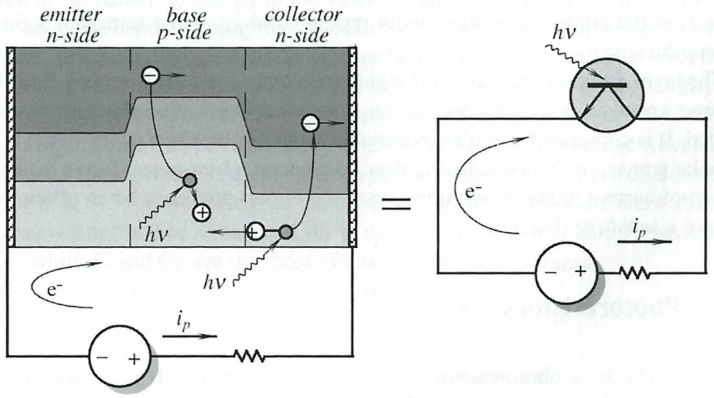



**Fig. 14.9** Energy bands in a phototransistor

Amazon EX1034 Page 38

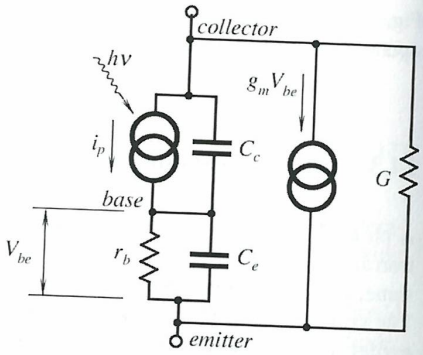



**Fig. 14.10** Equivalent circuit of a phototransistor

transistor circuit techniques, except that its base should be used as an input of a photoinduced current that is supplied by its collector. Since the actual photogeneration of carriers occurs in the collector–base region, the larger the area of this region, the more carriers are generated; thus, the phototransistor is designed so to offer a large area to impinging light. A phototransistor can be either a two-lead or a three-lead device. In the latter case, the base lead is available, and the transistor may be used as a standard bipolar transistor with or without the additional capability of sensing light, thus giving a designer greater flexibility in circuit development. However, a two-lead device is the most popular as a dedicated photosensor.

When the base of the transistor is floating, it can be represented by an equivalent circuit shown in Fig. 14.10. Two capacitors $C_c$ and $C_e$ represent base–collector and base–emitter capacitances, which are the speed-limiting factors. Maximum frequency response of the phototransistor may be estimated from

$$f_1 \approx \frac{g_m}{2C_e}, \tag{14.13}$$

where $f_I$ is the current-gain-bandwidth product and $g_m$ is the transistor's forward transconductance.

Whenever a higher sensitivity of a photodetector is required, especially if high-response speed is not of a concern, an integrated Darlington detector is recommended. It is comprised of a phototransistor whose emitter is coupled to the base of a bipolar transistor. Since a Darlington connection gives current gain equal to a product of current gains of two transistors, the circuit proves to be an efficient way to make a sensitive detector.

## 14.4 Photoresistors

As a photodiode, a photoresistor is a photoelectric device. It is a resistor whose resistance is called photoresistance $R_p$ that changes as the function of incident light. The most common materials for its fabrication are cadmium sulfide (CdS) and

Amazon EX1034 Page 39

## 14.6 Image Sensors

The charge-coupled device (CCD)[1] and complementary metal oxide semiconductor (CMOS) image sensors are two different technologies presently used for capturing images digitally. Each has unique strengths and weaknesses giving advantages in different applications.

Both types of imagers convert light into electric charge and process it into electronic signals. In a CCD sensor, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. Then, the analog signal is digitized by an external A/D converter. All of the pixels can be devoted to light capture, and the output's uniformity (a key factor in image quality) is high. In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise correction, and digitization circuits, so that the chip outputs digital bits. These other functions increase the design complexity and reduce the area available for light capture. With each pixel doing its own conversion, uniformity is lower. But the chip can be built to require less off-chip circuitry for basic operation.

CMOS imagers offer more integration (more functions on the chip), lower power dissipation (at the chip level), and the possibility of smaller system size, but they have often required trade-offs between image quality and device cost. CMOS cameras may require fewer components and less power, but they still generally require companion chips to optimize image quality, increasing cost and reducing the advantage they gain from lower power consumption. CCD devices are less complex than CMOS, so they cost less to design. CCD fabrication processes also tend to be more matured and optimized; in general, it will cost less (in both design and fabrication) to yield a CCD than a CMOS imager for a specific high-performance application. The choice continues to depend on the application and the vendor more than the technology.

CCDs and CMOS imagers were both invented in the late 1960s and 1970. CCD became dominant, primarily because they gave far superior images with the fabrication technology available. CMOS image sensors required more uniformity and smaller features that the silicon wafer foundries could not produce at the time. Nowadays, renewed interest in CMOS was based on expectations of lowered power consumption, camera-on-a-chip integration, and lowered fabrication costs.

Both CCDs and CMOS imagers can offer excellent imaging performance when designed properly. CCDs have traditionally provided the performance benchmarks in the photographic, scientific, and industrial applications that demand the highest image quality (as measured in quantum efficiency and noise) at the expense of system size. Astronomers say that CCDs have a high-quantum efficiency (QE), meaning that a large percentage of incoming photons are actually detected. While photographic plates might capture *one* photon out of every 100, modern CCDs

[1] In 2009, Willard S. Boyle and George E. Smith received a Nobel Prize for their invention of CCD in 1969.

Amazon EX1034 Page 40

would capture 80 photons out of every 100. This allows for a substantial decrease in exposure time. CCDs are also linear in nature, meaning that the signal they produce is directly proportional to the amount of light collected. This makes it easier to calculate the number of photons that hit the detector in the time of an exposure.

### 14.6.1 CCD Sensor

A CCD chip is divided into pixels. Each pixel has a potential well that collects the electrons produced by the photoelectric effect. At the end of an exposure (frame), each pixel has collected an amount of electrons (i.e., charge) proportional to the amount of light that fell onto it. The CCD is then read out by cycling the voltages applied to the chip in a process called "clocking." Due to the structure of a CCD, clocking causes the charge in one pixel to be transferred to an adjacent pixel. To understand how the whole chip can operate, consider the following analogy suggested by Jerome Kristian and shown in Fig. 14.16.

The incoming photons are represented by the raindrops, and the CCD chip is a 2D array of buckets. Each bucket represents a pixel, and the water it collects is the combined charge accumulation due to photoelectrons. Once the rain has stopped (the shutter is closed), conveyor belts move the columns of buckets down one row (the gates are clocked). The water in the buckets at the edge of the array pours into more buckets on a horizontal conveyor belt. This conveyor belt then pours these buckets one at a time into a container on a scale, which is a graduated cylinder (the readout electronics). The volume of water from each bucket is measured and rounded to the nearest milliliter [corresponding to the digital output of a CCD, which reports the counts, or analog-to-digital units (ADUs), from each pixel]. Then, the image is formed by reconstructing the distribution of rainfall on the array.

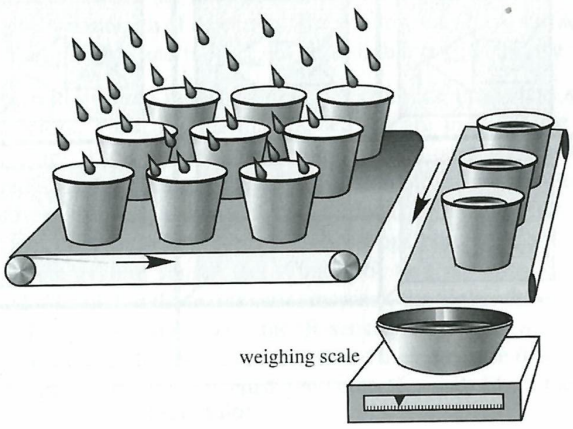



**Fig. 14.16** Analogy of the CCD operation

Amazon EX1034 Page 41

Most CCDs have a setting called binning that causes them to read out in a slightly different manner. When binning is used, blocks of pixels are grouped together into "superpixels." Each superpixel acts as one large pixel, with several results. Read times are faster, since fewer actual measurements of charge are performed. Each superpixel is also more sensitive, since it can collect more photons for a given exposure time, but this comes at the cost of resolution.

### 14.6.2 CMOS-Imaging Sensors

Like CCDs, these imagers are made from silicon, but as the name implies, the process they are made in is called CMOS. This process is today the most common method of making processors and memories, meaning CMOS imagers take advantage of the process and cost advancements created by these other high-volume devices. Because CMOS imagers are created in the same process as processors, memories, and other major components, CMOS imagers can integrate with these same components onto a single piece of silicon. Like CCDs, CMOS imagers include an array of photosensitive diodes (PD), one diode within each pixel. Unlike CCDs, however, each pixel in a CMOS imager has its own individual amplifier integrated inside (Fig. 14.17). Since each pixel has its own amplifier, the pixel is referred to as an "active pixel." In addition, each pixel in a CMOS imager can be read directly on an $x$–$y$ coordinate system, rather than through the "bucket-brigade" process of a CCD. This means that while a CCD pixel always transfers a charge, a

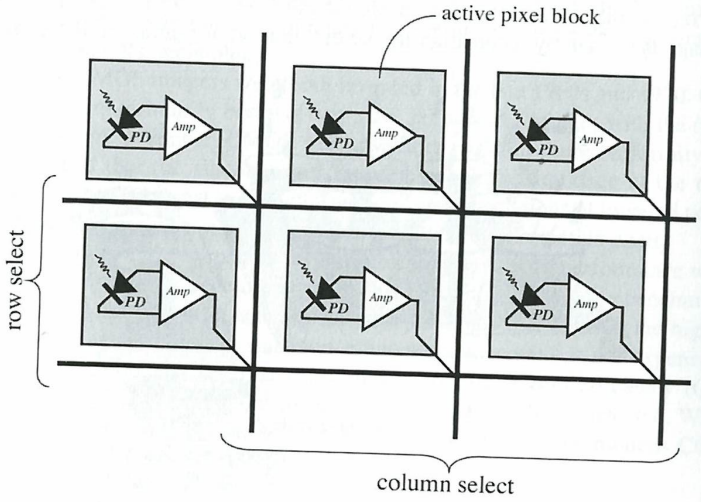



**Fig. 14.17** Organization of a CMOS-imaging sensor

Amazon EX1034 Page 42

CMOS pixel always detects a photon directly, converts it to a voltage, and transfers the information directly to the output.

## 14.7 Thermal Detectors

Thermal-infrared detectors are primarily used for detecting infrared radiation in mid- and far-infrared spectral ranges and noncontact temperature measurements, which have been known in industry for about 60 years under the name of *pyrometry* from the Greek word $\pi\upsilon\rho$ (fire). The respective thermometers are called *radiation* pyrometers. Today, noncontact methods of temperature measurement embrace a very broad range, including subzero temperatures, which are quite far away from that of flame. Therefore, it appears that *radiation thermometry* is a more appropriate term for this technology.

A typical infrared temperature sensor consists of the following:

1. A *sensing element* – a component that is responsive to electromagnetic radiation in the selected wavelength range from visible to far infrared, depending on the temperature range of the instrument. The main requirements to the element are fast, predictable and strong response to thermal radiation, and a good long-term stability.
2. A *supporting structure* to hold the sensing element and to expose it to thermal radiation. The structure should have low thermal conductivity to minimize heat loss.
3. A *housing* that protects the sensing element from the environment. It usually should be hermetically sealed and often filled with either dry air or inert gas such as argon or nitrogen.
4. A *protective window* that is impermeable to environmental factors and transparent in the wavelength of detection. The window may have surface coatings to improve transparency and to filter out undesirable portions of the spectrum.

Below the mid-infrared range, thermal detectors are much less sensitive than quantum detectors. Thus, the thermal IR sensors are used for the wavelengths longer than 1 μm. Their operating principle is based on a sequential conversion of thermal radiation into heat, and then, conversion of heat magnitude or heat flow into an electrical signal by employing conventional methods of heat detection. In other words, a thermal-radiation sensor in its operating principle resembles a conventional temperature sensor (see Chap. 16) that converts temperature into electric signal. The higher the temperature increase, the higher the electrical output. This sets the design criterion – make the IR-sensing element to respond with high-temperature increase or decrease as practical and then measure that increase with a conventional, albeit specially designed, temperature sensor like a thermocouple or thermistor.

According to (3.133), the infrared flux that is absorbed by a thermal detector is proportional to a geometry factor $A$, which for a uniform spatial distribution of

Amazon EX1034 Page 43

radiation is equal to the sensor's area. For instance, if a thermal-radiation-sensing element of a 5 $mm^2$ surface area and ideal absorptivity at the initial temperature 25°C is placed inside an enclosed chamber whose temperature is 100°C, the sensor will receive the initial radiative power of 3.25 mW. Depending on the element's thermal capacity, its temperature will rise exponentially until thermal equilibrium between the element and its environment occurs. That is, the element will reach temperature of 100°C because its thermal coupling to the enclosed chamber is total – 100%. In practice, the sensing element's temperature never reaches that of an object because a thermal coupling between the sensing element and the object is never 100%. Unlike a hypothetical sensing element that is placed inside a radiative chamber, a real-sensing element is rather poorly thermally coupled to the heat source. The sensing element is usually positioned inside the radiation thermometer that may be at ambient temperature, while the object is remote and may be either very hot or very cold.

While the sensing element exchanges heat by radiation, a substantial portion of the absorbed heat is lost through a supporting structure and wires, as well as through gravitational convection and also through stray radiation. Thus, the equilibrium temperature is always somewhere in-between the object's temperature and the initial temperature of the thermal-sensing element.

All thermal-radiation detectors can be divided into two classes: passive-infrared (PIR) and active-far-infrared (AFIR) detectors. Passive detectors absorb incoming radiation and convert it to heat, while active detectors generate heat from the excitation circuit and measures heat loss that depends on the environment and the object.

### 14.7.1 Golay Cells

The Golay cells are the broadband detectors of infrared radiation. They are extremely sensitive, but also extremely delicate. The operating principle of the cell is based on the detection of a thermal expansion of gas trapped inside an enclosure. This is why these detectors sometimes are called thermopneumatic detectors. Figure 14.18 depicts an enclosed chamber having two membranes – the upper and lower. The upper membrane is coated with a radiative heat absorber (e.g., goldblack), while the lower membrane has a mirror surface (e.g., coated with aluminum).

The mirror is illuminated by a light source. The incident light beam is reflected from the mirror and impinges on a position-sensitive detector (PSD). The upper membrane is exposed to infrared radiation that is absorbed by the coating and elevates temperature of the membrane. This, in turn, warms up gas that is trapped inside the sensor's chamber. Gas expands and its pressure goes up. The increase in the internal pressure deflects the lower membrane that bulges out. A change in the mirror curvature deflects the reflected light beam. The reflected light impinges on the PSD at various locations, depending on the degree of bulging of the membrane, and therefore of the intensity of the absorbed radiation. The entire sensor may be micromachined using modern MEMS technology (see Chap. 18). The degree of the

Amazon EX1034 Page 44

Coefficient $\alpha_s$ has a meaning of thermal conductivity from the AFIR-sensing element to the environment (housing).

Contrary to a PIR detector, an AFIR sensor is active and can generate a signal only when works in orchestra with the control circuit. The control circuit must include the following essential components: a reference to set the preset temperature, an error amplifier, and a driver stage. In addition, it may include an *RC* network for correcting a loop response function and for stabilizing its operation; otherwise, an entire system may be prone to oscillations [17].

It may be noted that an AFIR sensor along with its control circuit is a direct converter of thermal radiative power into electric voltage and quite efficient one. Its typical responsivity is in the range of 3,000 V/W, which is much higher when comparing with a thermopile whose typical responsivity is in the range of 100 V/W. An efficient way to fabricate an AFIR sensor would be by MEMS technology. In fact, an AFIR sensor is a close relative to a bolometer as described in the previous section. It just needs to be provided with a heater that can be deposited beneath the bolometer-sensing element.

## 14.8 Optical Design

An optical sensor usually operates in conjunction with some kind of an optical system that may be as simple as a window or spectral filter. Often, an optical system includes lenses, mirrors, fiber optics, and other elements that alter direction of light. In many applications, the sensor works together with a special light source whose properties must be matched to the sensor both spectrum-wise and space-wise.

Several factors are critical in designing the optical components for an optical sensor. Let us, for instance, take a point light source that should be detected by a photodetector (Fig. 14.30a). In most cases, the sensor's output signal is proportional to the received photonic power, which, in turn, proportional to the sensor's surface

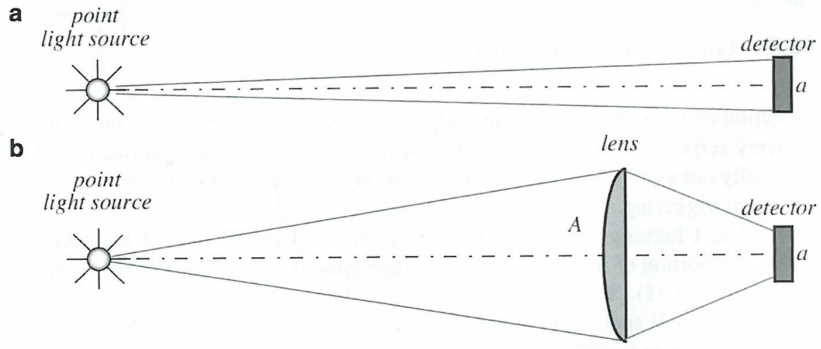



**Fig. 14.30** Efficiency of a detector depends on (**a**) its surface area *a* and (**b**) the input aperture *A* of the focusing system

Amazon EX1034 Page 45

area (input aperture). Yet, the sensing area is usually small. For example, a thermopile pixel of the sensor shown in Fig. 14.21a has a sensing area 0.022 mm$^2$, and thus it will receive a very small portion of the photon flux emanated from the object. Figure 14.30b shows that the use of a focusing lens can dramatically increase the received light flux. This is because the entire lens aperture receives the flux and, like a funnel, brings it to a small sensor. Efficiency of a single lens depends on its refractive index $n$ (see Chap. 4). The overall improvement in the sensitivity can be estimated by use of (4.5) and (4.8):

$$k \approx \frac{A}{a}\left[1 - 2\left(\frac{n-1}{n+1}\right)^2\right], \tag{14.31}$$

where $A$ and $a$ are respective effective areas (apertures) of the lens and the sensing area of a photodetector.

For glasses and most plastics operating in the visible- and near-infrared spectral ranges, the equation can be simplified to

$$k \approx 0.92\frac{A}{a}. \tag{14.32}$$

Thus, the amount of light received by the sensing element is proportional to the lens aperture area. That is why good photographic lenses have quite large apertures. It should be pointed out that arbitrary placement of a lens may be more harmful than helpful. That is, a lens system must be carefully planed to be effective. For instance, many photodetectors have built-in lenses that are effective for parallel rays. If an additional lens is introduced in front of such a detector, it will create nonparallel rays at the input resulting in misalignment of the optical system and poor performance. Thus, whenever additional optical devices need to be employed, detector's own optical properties must be considered.

## 14.9 Gas Flame Detectors

Detection of a gas flame is very important for security and fire prevention systems. In many respects, it is a more sensitive way to detect fire than a smoke detector, especially outdoors where smoke concentration may not reach a threshold level for the alarm triggering.

To detect burning gas, it is possible to use a unique feature of the flame, a noticeable portion of its optical spectrum is located in the ultraviolet (UV) spectral range (Fig. 14.31). Sunlight, after passing through the atmosphere loses a large portion of its UV spectrum located below 250 nm, while a gas flame contains UV components down to 180 nm. This makes it possible to design a narrow-bandwidth element for the UV spectral range that is selectively sensitive to flame and not sensitive to the sunlight or electric lights.

Amazon EX1034 Page 46