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Dear Christina

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Jacob Fraden

Handbook of Modern Sensors

Physics, Designs, and Applications

Fourth Edition

 Springer

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Preface

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Contents

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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

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

3.13 Light	
3.13.1	
3.13.2	
3.14 Dynamic	
3.14.1	
3.14.2	
3.14.3	
3.14.4	
Reference	
4 Optical	4.1
4.1 Rad	
4.2 Phot	
4.3 Win	
4.4 Mirr	
4.5 Lens	
4.6 Fres	
4.7 Fibe	
4.8 Con	
4.9 Coal	
4.10 Nan	
Reference	
5 Interface	5.1
5.1 Input	
5.2 Ampl	
5.2.1	
5.2.2	
5.2.3	
5.2.4	
5.3 Light	
5.4 Excit	
5.4.1	
5.4.2	
5.4.3	
5.4.4	
5.4.5	
5.5 Anal	
5.5.1	
5.5.2	
5.5.3	
5.5.4	
5.5.5	
5.6 Direct	

.....	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

5.7 Capacitance-to-Voltage Converters	208	7.3 Ind
5.8 Integrated Interfaces	210	7.3
5.9 Ratiometric Circuits	211	7.3
5.10 Differential Circuits	214	7.3
5.11 Bridge Circuits	215	7.3
5.11.1 General Concept	215	7.3
5.11.2 Disbalanced Bridge	216	7.3
5.11.3 Null-Balanced Bridge	218	7.3
5.11.4 Bridge Amplifiers	218	7.4 Op
5.12 Data Transmission	220	7.4
5.12.1 Two-Wire Transmission	220	7.4
5.12.2 Four-Wire Sensing	221	7.4
5.12.3 Six-Wire Sensing	222	7.4
5.13 Noise in Sensors and Circuits	223	7.4
5.13.1 Inherent Noise	223	7.5 Ult
5.13.2 Transmitted Noise	227	7.6 Ra
5.13.3 Electric Shielding	231	7.6
5.13.4 Bypass Capacitors	234	7.6
5.13.5 Magnetic Shielding	235	7.7 Th
5.13.6 Mechanical Noise	237	7.7
5.13.7 Ground Planes	237	7.7
5.13.8 Ground Loops and Ground Isolation	238	7.7
5.13.9 Seebeck Noise	240	7.8 Poi
5.14 Calibration	242	7.8
5.15 Batteries for Low-Power Sensors	243	7.8
5.15.1 Primary Cells	244	7.8
5.15.2 Secondary Cells	245	Referer
References	246	
6 Occupancy and Motion Detectors	247	8 Velocit
6.1 Ultrasonic Detectors	249	8.1 Ac
6.2 Microwave Motion Detectors	249	8.2 Ca
6.3 Capacitive Occupancy Detectors	254	8.3 Pie
6.4 Triboelectric Detectors	258	8.4 Pie
6.5 Optoelectronic Motion Detectors	260	8.5 Th
6.5.1 Sensor Structures	261	8.5
6.5.2 Visible and Near IR Light Motion Detectors	264	8.5
6.5.3 Far-Infrared Motion Detectors	267	8.6 Gy
6.6 Optical Presence Sensors	274	8.6
6.7 Pressure-Gradient Sensors	276	8.6
References	278	8.6
7 Position, Displacement, and Level	279	8.7 Pie
7.1 Potentiometric Sensors	280	8.8 Gr
7.2 Capacitive Sensors	284	Referer

Contents

.....	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

Contents

xi

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

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

.....	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

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 <i>Silicon</i> 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 <i>pn</i> -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

18	Sensor	
	18.1 M	18
		18
		18
		18
		18
		18
	18.2 Su	18
		18
		18
		18
		18
	18.3 M	18
		18
	Referer	

Contents

.....	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

Contents

xv

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

Examples of some sound levels are given in Table 3.3. Since the response of a human ear is not the same at all frequencies, sound levels are usually referenced to I_0 at 1 kHz where the ear is most sensitive.

3.11 Temperature and Thermal Properties of Materials

Our bodies have a sense of temperature, which by no means is an accurate method to measure outside heat. Human senses are not only nonlinear, but relative with respect to our previous experience. Nevertheless, we can easily tell the difference between warmer and cooler objects. Then, what is going on with these objects that they produce different perceptions?

Every single particle in this universe exists in perpetual motion. The temperature of a volume of a material, in the simplest way, can be described as measure of an average kinetic energy of vibrating particles. The stronger the movement the higher the temperature. Of course, molecules and atoms in a given volume of material do not move with equal intensities. That is, microscopically, they all are at different temperatures. The average kinetic energy of a large number of moving particles determines macroscopic temperature of an object. These processes are studied by a thermodynamics and statistical mechanics. Here, however, we are concerned with methods and devices that are capable of measuring the macroscopic average kinetic energy of vibrating particles, which is the other way to say the temperature of the object. Since temperature is related to the movement of molecules, it is closely associated with pressure, which is defined as the force applied by moving molecules per unit area.

When atoms and molecules in a material move, they interact with other molecules that happen to be brought in contact with them. A jiggling atom agitates a neighboring atom and transfers to it portion of its kinetic energy, so the neighbor starts vibrating more intensely. This agitation propagates through the material, elevating the temperature. Since an atom contains moving electrons swirling around its nucleus like a cloud of electric current, thermal agitation causes that current to produce electromagnetic wave. Hence, every vibrating atom acts as a microscopic radio-transmitter, which emanates electromagnetic radiation to the surrounding space. These two types of activities form a basis for heat transfer from warmer to cooler objects: conduction and radiation. The stronger the atomic movement the hotter the temperature and the stronger the electromagnetic radiation. A special device (we call it a thermometer), which either contacts the object or receives its electromagnetic radiation, then produces a physical response, or signal. That signal becomes a measure of the object's temperature.

The word thermometer first appeared in literature in 1624 in a book by J. Leurechon, entitled *La Récréation Mathématique* [29]. The author described a glass water-filled thermometer whose scale was divided by 8° . The first

pressure-independent thermometer was built in 1654 by Ferdinand II, Grand Duke of Tuscany¹⁶ in form of an alcohol-filled hermetically sealed tube.

Thermal energy is what we call heat. Heat is measured in calories.¹⁷ One calorie (cal) is equal to amount of heat, which is required to warm up by 1°C 1 g of water at normal atmospheric pressure. In the United States, a British unit of heat is generally used, which is 1 Btu (British thermal unit): 1 Btu=252.02 cal.

3.11.1 Temperature Scales

There are several scales to measure temperature. To make a linear scale (for convenience, all thermometers have linear scales), at least two reference points are required. Usually one of these points is called a zero point. A first zero for a scale was established in 1664 by Robert Hooke at a point of freezing distilled water. In 1694 Carlo Renaldi of Padua suggested to take a melting point of ice (zero point) and a boiling point of water (second point) to define a span of his thermometer. He divided the span by 12 equal parts. Unfortunately, his suggestion had been forgotten for almost 50 years. In 1701, Newton also suggested for the zero point to use the temperature of melting ice and for the second point he chose the armpit temperature of a "healthy Englishman," he labeled that point "12." At Newton's scale, water was boiling at point No. 34. Daniel Gabriel Fahrenheit, a Dutch instrument maker, in 1706 selected zero for his thermometer at the coldest temperature he could produce by a mixing water, ice, and sal-ammoniac or household salt. For the sake of convenience, he established the other point at 96°, which was "found in the blood of a healthy man."¹⁸ On his scale, the melting point of water was at 32° and boiling at 212°. In 1742, Andreas Celsius, professor of astronomy at the University of Uppsala (Sweden), proposed a scale with zero as the melting point of ice and 100° at boiling point of water. He divided the span by 100 equal parts – degrees.

Nowadays, in science and engineering, Celsius and Kelvin scales are generally employed. The Kelvin scale is arbitrarily based on the so-called triple point of water. There is a fixed temperature at a unique pressure of 4.58 mmHg where water vapor, liquid, and ice can coexist. This unique temperature is 273.16 K (degrees kelvin), which approximately coincides with 0°C. The Kelvin scale is linear with zero intercept (0 K) at a lowest temperature where kinetic energy of all moving

¹⁶More precisely, not "by him" but rather "for him".

¹⁷A *calorie* that measures energy in food is actually equal to 1,000 physical calories, which is called a *kilocalorie*.

¹⁸After all, Fahrenheit was a toolmaker and for him 96 was a convenient number because to engrave the graduation marks, he could easily do so by dividing a distance between the marks by two: 96, 48, 24, etc. With respect to nationality of the blood, he did not care if it was blood of an Englishman or not. Now, it is known that blood temperature of a healthy person is not really constant. It varies between approximately 97°F and 99.5°F (36°C and 37.5°C) but during his times, Fahrenheit could not find a better thermostat than a human body.

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 (λ_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

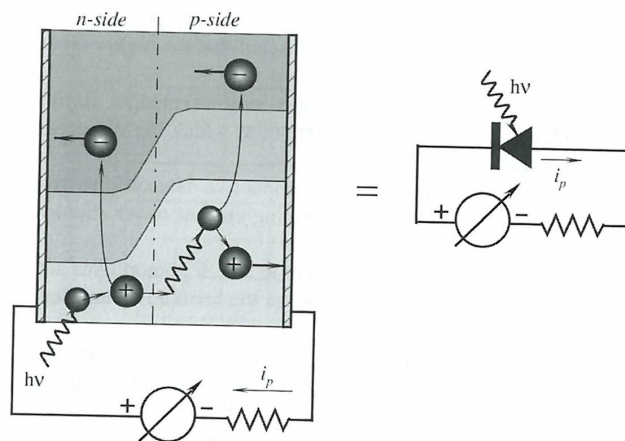


Fig. 14.3 Structure of a photodiode

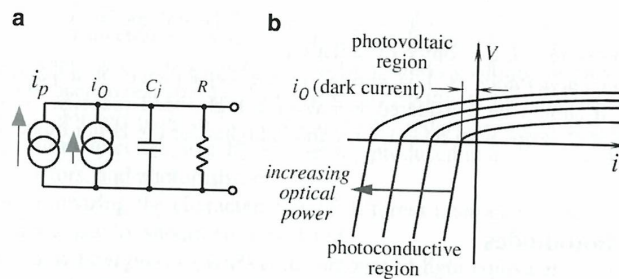


Fig. 14.4 An equivalent circuit of a photodiode (a) and its volt-ampere characteristic (b)

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 $h\nu$ will produce an electron in a detection is η then the average rate of the production of electrons $\langle r \rangle$ for an incident beam of optical power P is given by [2]

$$\langle r \rangle = \frac{\eta P}{h\nu} \quad (14.6)$$

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

$$p(m, \tau) = (\langle r \rangle \tau)^m \frac{1}{m!} e^{-\langle r \rangle \tau} \quad (14.7)$$

The statistics involved with optical detection are very important in the determination of minimum detectable signal levels, and hence the ultimate sensitivity of the sensors. At this point, however, we just note that the electrical current is proportional to the optical power incident on the detector:

$$i = \langle r \rangle e = \frac{\eta e P}{h\nu}, \quad (14.8)$$

where e is the charge of an electron. A change in input power ΔP (due to intensity modulation in a sensor, for instance) results in the output current Δi . Since power is proportional to squared current, the detector's electrical power output varies quadratically with input optical power, making it a "square-law" optical power detector.

The voltage-to-current response of a typical photodiode is shown in Fig. 14.4b. If we attach a high-input-impedance voltmeter to the diode (corresponds to the case when $i = 0$), we will observe that with increasing optical power, the voltage changes in a quite nonlinear fashion. In fact, variations are logarithmic. However, for the short circuit conditions ($V = 0$), that is, when the diode is connected to a current-to-voltage converter (such as in Fig. 5.12b), current varies linearly with the optical power. The current-to-voltage response of the photodiode is given by [3]

$$i = i_0 \left(e^{eV/k_b T} - 1 \right) - i_s, \quad (14.9)$$

where i_0 is a reverse "dark current," which is attributed to the thermal generation of electron-hole pairs, i_s is the current due to the detected optical signal, k_b is Boltzmann constant, and T is the absolute temperature. Combining (14.8) and (14.9) yields

$$i = i_0 \left(e^{eV/k_b T} - 1 \right) - \frac{\eta e P}{h\nu}, \quad (14.10)$$

which is the overall characteristic of a photodiode. An efficiency of the direct conversion of optical power into electric power is quite low. Typically, it is in the range of 5–10%; however, it is reported that some experimental photocells were able to reach efficiency as high as 90%. In the sensor technologies, however, the photocells are generally not used.

There are two general operating modes for a photodiode: the photoconductive (PC) and the photovoltaic (PV). No bias voltage is applied for the photovoltaic mode. The result is that there is no dark current, so there is only thermal noise present. This allows much better sensitivities at low-light levels. However, the speed response is worst due to an increase in C_j and responsively to longer wavelengths is also reduced.

Figure 14.5a shows a photodiode connected in a PV mode. In this connection, the diode operates as a current-generating device, which is represented in the

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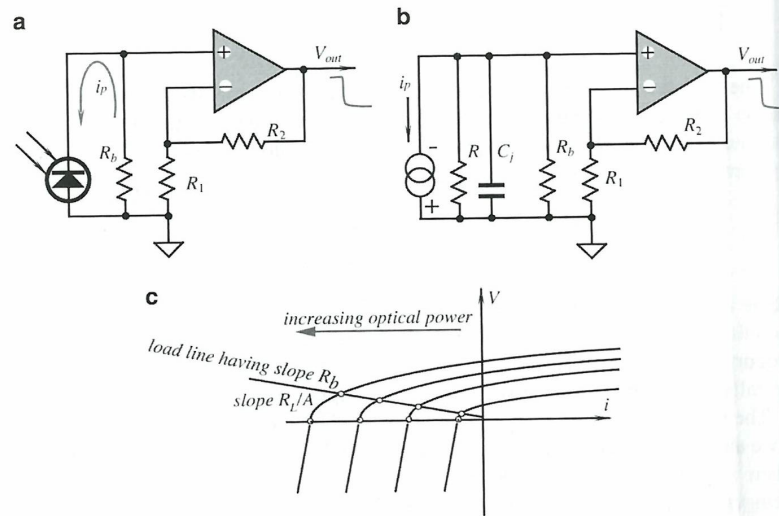


Fig. 14.5 Connection of a photodiode in a photovoltaic mode to a noninverting amplifier (a); equivalent circuit (b); and loading characteristic (c)

equivalent circuit by a current source i_p in Fig. 14.5b. The load resistor R_b determines the voltage developed at the input of the amplifier, and the slope of the load characteristic is proportional to that resistor (Fig. 14.5c).

When using a photodiode in a photovoltaic mode, its large capacitance C_j may limit the speed response of the circuit. During the operation with a direct resistive load, as in Fig. 14.5a, a photodiode exhibits a bandwidth limited mainly by its internal capacitance C_j . The equivalent circuit of Fig. 14.5b models such a bandwidth limit. The photodiode acts primarily as a current source. A large resistance R and the diode capacitance shunt the source. The capacitance ranges from 2 to 20,000 pF depending for the most part on the diode area. In parallel with the shunt is the amplifier's input capacitance (not shown) that results in a combined input capacitance C . The net input network determines the input circuit response rolloff.

To avoid the effect of input capacitance, it is desirable to develop input voltage across the resistor and prevent it from charging the capacitances. This can be achieved by employing a current-to-voltage amplifier (I/V) as shown in Fig. 14.6a. The amplifier and its feedback resistor R_L translate the diode current into a buffered output voltage with excellent linearity. Added to the figure is a feedback capacitor C_L that provides a phase compensation. An ideal amplifier holds its two inputs at the same voltage (ground in the figure), thus the inverting input that is not directly connected to ground is called a virtual ground. The photodiode operates at zero voltage across its terminals, which improves the response linearity

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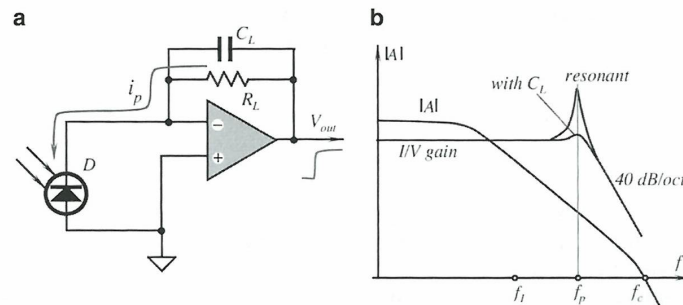
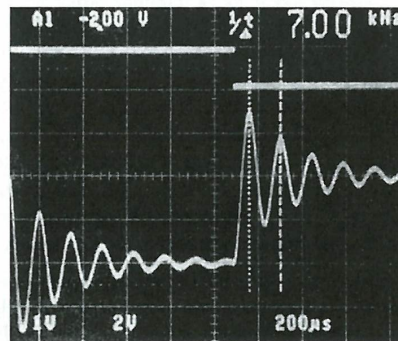


Fig. 14.6 Use of current-to-voltage converter (a) and the frequency characteristics (b)

Fig. 14.7 Response of a photodiode with uncompensated circuit (courtesy of Hamamatsu Photonics K.K.)



and prevents charging the diode capacitance. This is illustrated in Fig. 14.7c where the load line virtually is parallel to the current axis, because the line's slope is inversely proportional to the amplifier's open-loop gain A .

In practice, the amplifier's high but finite open-loop gain A limits the performance by developing small albeit nonzero voltage across the diode. Then, the break frequency is defined as

$$f_p = \frac{A}{2\pi R_L C} \approx A f_i \quad (14.11)$$

where A is the open-loop gain of the amplifier. Therefore, the break frequency is increased by a factor A when compared with f_i . It should be noted that when frequency increases, gain A declines, and the virtual load attached to the photodiode appears to be inductive. This results from the phase shift of gain A . Over most of the amplifier's useful frequency range, A has a phase lag of 90° . The 180° phase inversion by the amplifier converts this to a 90° phase lead that is specific for the inductive impedance. This inductive load resonates with the capacitance of the input

circuit at a frequency equal to f_p (Fig. 14.6b) and may result in an oscillating response (Fig. 14.7) or the circuit instability. To restore stability, a compensating capacitor C_L is placed across the feedback resistor. Value of the capacitor can be found from

$$C_L = \frac{1}{2\pi R_L f_p} = \sqrt{CC_c} \quad (14.12)$$

where $C_c = 1/(2\pi R_L f_c)$ and f_c is the unity-gain crossover frequency of the operational amplifier. The capacitor boosts the signal at the inverting input by shunting R_L at higher frequencies.

When using photodiodes for the detection of low-level light, noise floor should be seriously considered. There are two main components of noise in a photodiode: shot noise and Johnson noise (see Sect. 5.13/1). Besides the sensor, the amplifier's and auxiliary component noise should also be accounted for [see (5.52)].

For the photoconductive operating mode (PC), a reverse bias voltage is applied to the photodiode. The result is a wider depletion region, lower junction capacitance C_j , lower series resistance, shorter rise time, and linear response in photocurrent over a wider range of light intensities. However, as the reverse bias is increased, shot noise increases as well due to increase in a dark current. The PC mode circuit diagram is shown in Fig. 14.8a, and the diode's load characteristic is in Fig. 14.8b. The reverse bias moves the load line into the third quadrant where the response linearity is better than that for the PV mode (the second quadrant). The load lines cross the voltage axis at the point corresponding to the bias voltage E , while the slope is inversely proportional to the amplifier's open-loop gain A . The PC mode offers bandwidths to hundreds of MHz, providing an accompanying increase in the signal-to-noise ratio.

Presently, photodiodes together with interface electronic circuits are available in integral forms and known as light-to-voltage converters. Such an integrated circuit is comprised of a photodiode and current-to-voltage converter as shown in

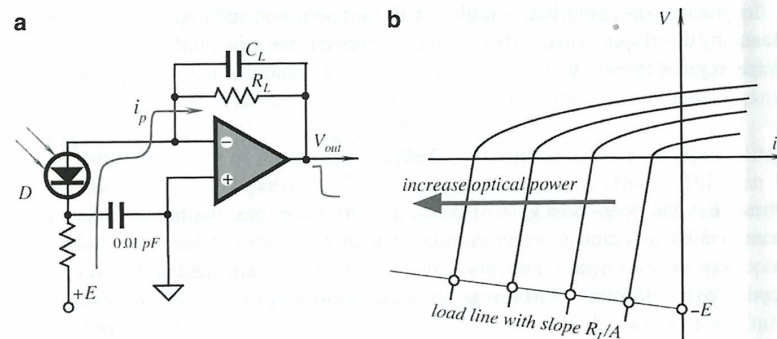


Fig. 14.8 Photoconductive operating mode. Circuit diagram (a) and load characteristic (b)

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

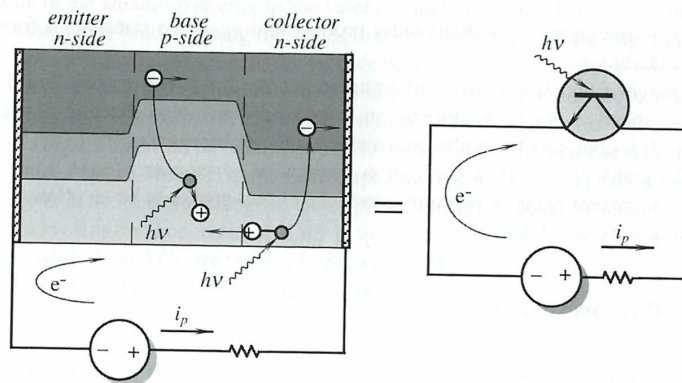


Fig. 14.9 Energy bands in a phototransistor