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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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Jacob Fraden

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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

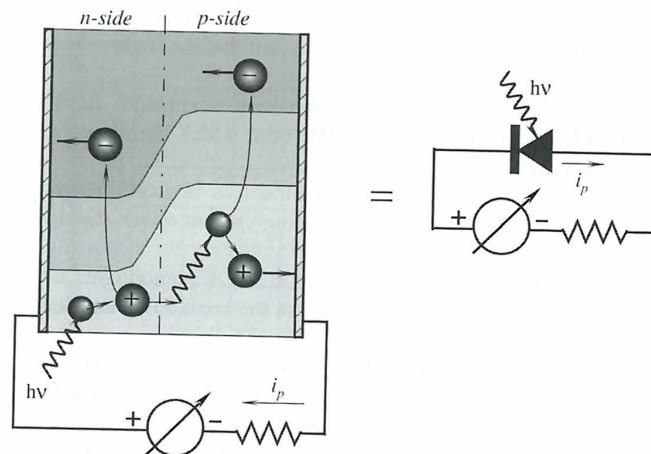


Fig. 14.3 Structure of a photodiode

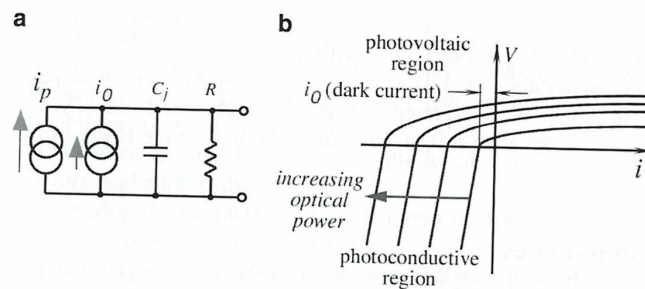


Fig. 14.4 An equivalent circuit of a photodiode (a) and its volt-ampere characteristic (b)

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 responsivity 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

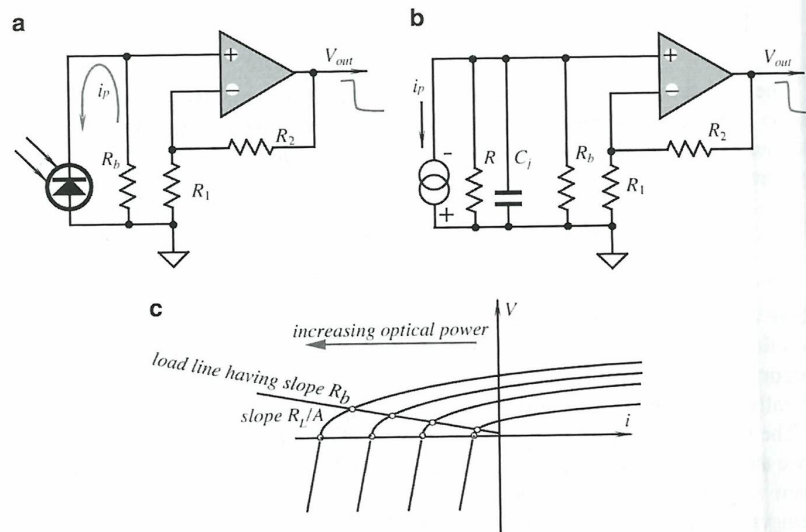


Fig. 14.5 Connection of a photodiode in a photovoltaic mode to a noninverting amplifier (a); equivalent circuit (b); and loading characteristic (c)

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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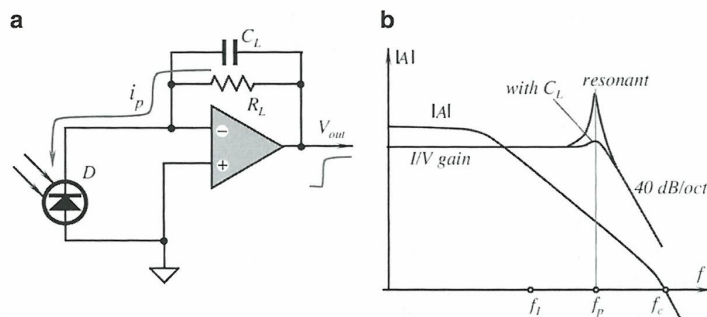
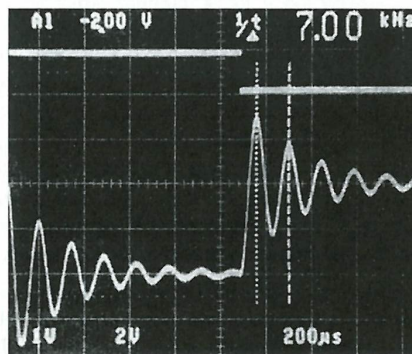


Fig. 14.6 Use of current-to-voltage converter (a) and the frequency characteristics (b)

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

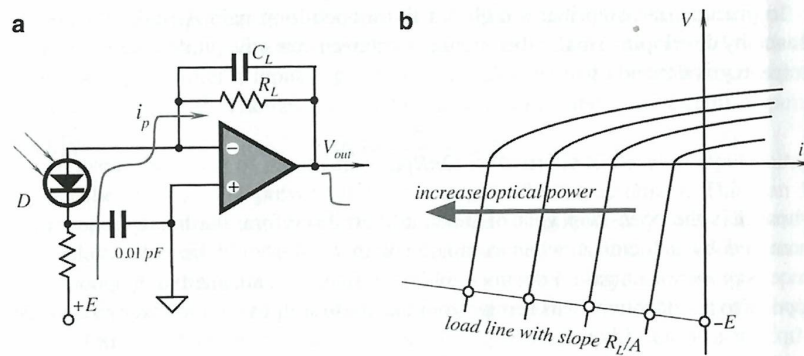


Fig. 14.8 Photoconductive operating mode. Circuit diagram (a) and load characteristic (b)

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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

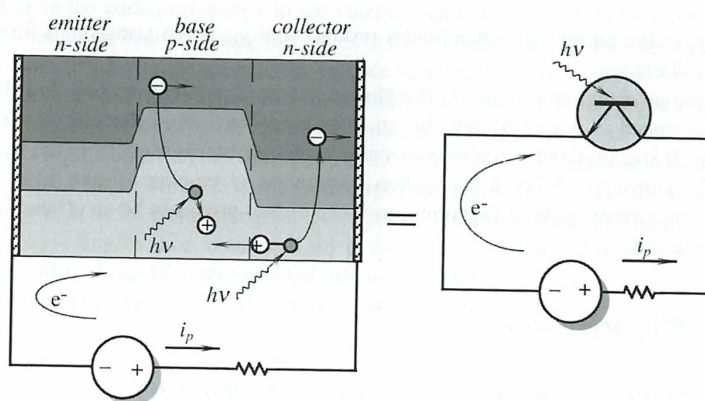


Fig. 14.9 Energy bands in a phototransistor