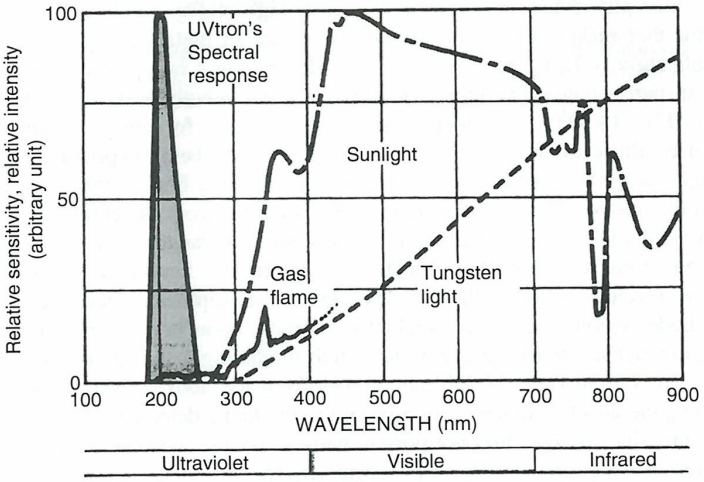


Fig. 14.31 Electromagnetic spectra of various sources (courtesy of Hamamatsu Photonics K.K.)

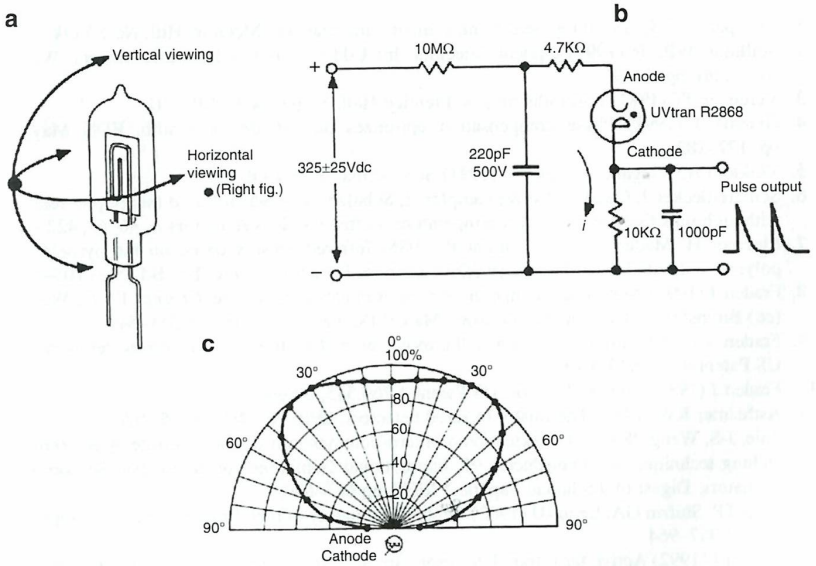


Fig. 14.32 UV flame detector glass-filled tube (**a**); angle of view in horizontal plane (**b**); and recommended operating circuit (**c**) (courtesy of Hamamatsu Photonics K.K.)

Amazon EX1034 Page 47

An example of such a device is shown in Fig. 14.32a. The element is a UV detector that makes use of a photoelectric effect in metals along with the gas multiplication effect (see Chap. 15). The detector is a rare-gas-filled tube. The UV-transparent housing assures wide angles of view in both horizontal and vertical planes (Fig. 14.32c). The device needs high voltage for operation and under normal conditions is not electrically conductive. Upon being exposed to a flame, the high-energy UV photons strike the cathode-releasing free electrons to the gas-filled tube interior. Gas atoms receive an energy burst from the emitted electrons, which results in gas luminescence in the UV spectral range. This, in turn, cause more electrons to be emitted, which cause more UV luminescence. Thus, the element develops a fast avalanche-type electron multiplication making the anode–cathode region electrically conductive. Hence, upon being exposed to a gas flame, the element works as a current switch producing a strong positive voltage spike at its output (Fig. 14.30b). It follows from the above description that the element generates UV radiation in response to the flame detection. Albeit being of a low intensity, the UV does not present harm to people; however, it may lead to cross-talk between the similar neighboring sensors.

References

1. Chappell A (ed) (1978) Optoelectronics: theory and practice. McGraw Hill, New York
2. Spillman WB, Jr (1991) Optical detectors. In: Udd Eric (ed) Fiber optic sensors. Wiley, New York pp. 69–97
3. Verdeyen JT (1981) Laser electronics. Prentice-Hall, Englewood Cliffs, NJ
4. Graeme J (1992) Phase compensation optimizes photodiode bandwidth. EDN May 7, pp. 177–183
5. Völklein A, Wiegand A, Baier V (1991) Sens Actuators A 29:87–91
6. Schieferdecker J, Quad R, Holzenkämpfer E, Schulze M (1995) Infrared thermopile sensors with high sensitivity and very low temperature coefficient. Sens Actuators A, 46–47, 422–427
7. Meixner H, Mader G, Kleinschmidt P (1986) Infrared sensors based on the pyroelectric polymer polyvinylidene fluoride (PVDF). Siemens Forsch-u Entwicl Ber Bd 15(3):105–114
8. Fraden J (1991) Noncontact temperature measurements in medicine. Chapter 17, In: Wise D (ed) Bioinstrumentation and biosensors. Marcel Dekker, New York, pp 511–549
9. Fraden J (1989) Infrared electronic thermometer and method for measuring temperature. US Patent 4,797,840, 10 Jan
10. Fraden J (1988) Motion detector. US Patent 4,769,545, 6 Sept
11. Astheimer RW (1984) Thermistor infrared detectors. SPIE No. 443, pp 95–109
12. Shie, J-S, Weng PK (1991)Fabrication of micro-bolometer on silicon substrate by anizotropic etching technique. In: Transducers'91. International Conference on Solid-state Sensors and Actuators. Digest of Technical Papers. ©IEEE, pp 627–630
13. Vogl TP, Shifrin GA, Leon BJ (1962) Generalized theory of metal-film bolometers. J Opt Soc Am 52:957–964
14. Fraden J (1992) Active far infrared detectors. In: Schooley JF (ed) Temperature. Its measurement and control in science and industry, vol. 6, part 2, ©American Institute of Physics, pp 831–836
15. Fraden J (1989) Radiation thermometer and method for measuring temperature. US Patent 4,854,730 8 Aug

Amazon EX1034 Page 48

Chapter 15
Radiation Detectors

To understand something,
means to derive it from quantum mechanics,
which nobody understands.

– Joe Fineman

Figure 3.41 shows a spectrum of the electromagnetic waves. On its left-hand side, there is a region of the γ-radiation. Then, there are the X-rays that depending on the wavelengths are divided into hard, soft, and ultrasoft rays. However, a spontaneous radiation from the matter not necessarily should be electromagnetic: There is the so-called nuclear radiation, which is emission of particles from the atomic nuclei. A spontaneous decay can be of two types: The charged particles (α and β particles, and protons) and uncharged particles that are the neutrons. Some particles are complex like the α particles, which are the nuclei of helium atoms consisting of two neutrons, while other particles are generally simpler, like the β particles that are either electrons or positrons. Ionizing radiations are given that name because as they pass through various media that absorb their energy, additional ions, photons, or free radicals are created.

Certain naturally occurring elements are not stable but slowly decompose by throwing away a portion of their nucleus. This is called radioactivity. It was discovered in 1896 by Henry Becquerel while working on phosphorescent materials. These materials glow in the dark after exposure to light, and he thought that the glow produced in cathode ray tubes by X-rays might be connected with phosphorescence. He wrapped a photographic plate in black paper and placed various phosphorescent minerals on it. All results were negative until he used uranium ($Z = 92$)[1] salts. The result with these compounds was a deep blackening of the plate. These radiations were called Becquerel rays.

Besides the naturally occurring radioactivity, there are many man-made nuclei that are radioactive. These nuclei are produced in nuclear reactors, which may yield

[1] Z is the atomic number.

J. Fraden, *Handbook of Modern Sensors*,
DOI 10.1007/978-1-4419-6466-3_15, © Springer Science+Business Media, LLC 2010

Amazon EX1034 Page 49

highly unstable elements. The other source of radiation is the space from which the earth is constantly bombarded by the particles.

Regardless of the sources or ages of radioactive substances, they decay in accordance with the same mathematical law. The law is stated in terms of number N of nuclei still undecayed, and dN the number of nuclei that decay in a small interval dt. It was proven experimentally that

$$dN = -\lambda N dt, \tag{15.1}$$

where λ is a decay constant specific for a given substance. From (15.1), it can be defined as the fraction of nuclei that decay in unit time

$$\lambda = -\frac{1}{N}\frac{dN}{dt}. \tag{15.2}$$

The SI unit of radioactivity is the *becquerel* (Bq), which is equal to the activity of radionuclide decaying at the rate of one spontaneous transition per second. Thus, the becquerel is expressed in a unit of time: $\text{Bq} = \text{s}^{-1}$. To convert to the old historical unit, which is the *curie*, the becquerel should be multiplied by 3.7×10^{10} (Table A.4).

The absorbed dose is measured in *grays* (Gy). A gray is the absorbed dose when the energy per unit mass imparted to matter by ionizing radiation is 1 J/kg. That is, Gy = J/kg.

When it is required to measure exposure to X- and γ-rays, the dose of ionizing radiation is expressed in coulombs per kg, which is an exposure resulting in the production of 1 C of electric charge per 1 kg of dry air. In SI, a unit of C/kg replaces an older unit of *roentgen*.

The function of any radiation detector depends on the manner in which the radiation interacts with the material of the detector itself. There are many excellent texts available on the subject of detecting radioactivity, for instance [1, 2].

There are four general types of radiation detectors: the scintillation detectors, the gaseous detectors, the liquid detectors, and the semiconductor detectors. Further, all detectors can be divided into two groups according to their functionality: the collision detectors and the energy detectors. The former merely detect the presence of a radioactive particle, while the latter can measure the radiative energy. That is, all detectors can be either quantitative or qualitative.

15.1 Scintillating Detectors

The operating principle of these detectors is based on the ability of certain materials to convert nuclear radiation into light. Thus, an optical photon detector in a combination with a scintillating material can form a radiation detector. It should be noted, however, that despite of a high efficiency of the conversion, the light intensity resulting from the radiation is extremely small. This demands photomultipliers to magnify signals to a detectable level.

Amazon EX1034 Page 50

The ideal scintillation material should posses the following properties:

1. It should convert the kinetic energy of charged particles into detectable light with a high efficiency.
2. The conversion should be linear. That is, the light produced should be proportional to the input energy over a wide dynamic range.
3. The postluminescence (the light decay time) should be short to allow fast detection.
4. The index of refraction of the material should be near that of glass to allow efficient optical coupling of the light to the photomultiplier tube.

The most widely used scintillators include the inorganic alkali halide crystals (of which sodium iodine is the favorite) and organic-based liquids and plastics. The inorganics are more sensitive, but generally slow, while organics are faster, but yield less light.

One of the major limitations of scintillation counters is their relatively poor energy resolution. The sequence of events that leads to the detection involves many inefficient steps. Therefore, the energy required to produce one information carrier (a photoelectron) is in the order of 1,000 eV or more, and the number of carriers created in a typical radiation interaction is usually no more than a few thousand. For example, the energy resolution for sodium iodine scintillators is limited to about 6% when detecting 0.662 MeV γ-rays and is largely determined by the photoelectron statistical fluctuations. The only known way to reduce the statistical limit on energy resolution is to increase the number of information carriers per pulse. This can be accomplished by the use of semiconductor detectors that are described in the later paragraphs.

A general simplified arrangement of a scintillating sensor is shown in Fig. 15.1 in conjunction with a photomultiplier. The scintillator is attached to the front end of the photomultiplier (PM). The front end contains a photocathode that is maintained at a ground potential. There is a large number of special plates called dynodes positioned inside the PM tube in an alternating pattern, reminding a shape of a

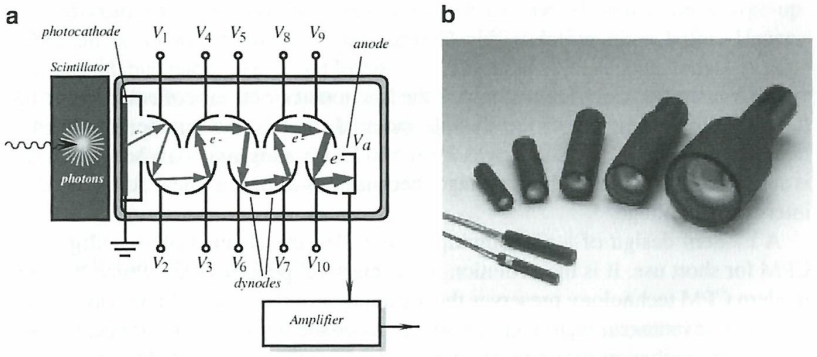


Fig. 15.1 Scintillation detector with a photomultiplier

Amazon EX1034 Page 51

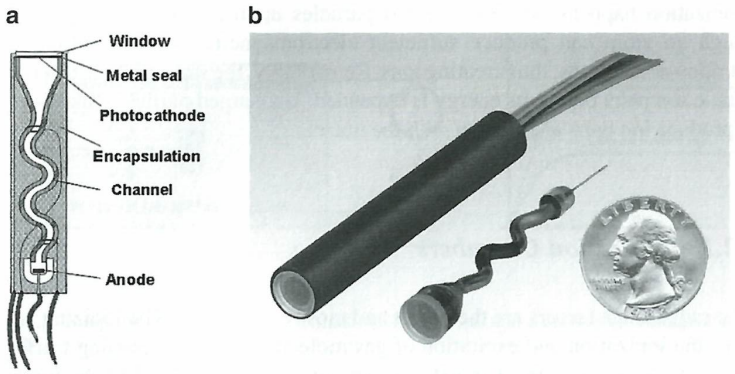


Fig. 15.2 Channel photomultiplier: Cross-sectional view (**a**) and external view with a potted encapsulation at left and with no encapsulation at right (**b**) (Courtesy of PerkinElmer, Inc.)

in a vacuum toward the anode by an electrical field. Instead of the complicated dynode structure, there is a bent, thin semiconductive channel, which the electrons have to pass. Each time when electrons hit the wall of the channel, secondary electrons are emitted from the surface. At each collision, there is a multiplication of the secondary electrons, resulting in an avalanche effect. Ultimately, an electron multiplication of 10^9 and more can be obtained. The resulting current can be read out at the anode. The CPM detector is potted with encapsulation material and is quite rugged when compared to the fragile PM. Magnetic field disturbance is negligibly small. Figure 15.2a shows pictures of the CPM. An important advantage of the CPM technology is its very low background noise. The term background noise refers to the measured output signal in the absence of any incident light. With classical PMs, the background noise originating from the dynode structure is generally a non-negligible part of the total background. As a result, the only effective source of background for the CPM is generated from the thermal emission of the photocathode. Since the CPM is manufactured in a monolithic semiconductive channel structure, no charge-up effects can occur as known of classical PMs with isolating glass bulbs. Hence, extremely stable background conditions are observed. No sudden bursts occur. Also, due to the absence of dynode noise, a very clean separation between an event created from a photoelectron and electronic noise can be performed. This leads to high stability of the signal over time.

15.2 Ionization Detectors

These detectors rely on the ability of some gaseous and solid materials to produce ion pairs in response to the ionization radiation. Then, positive and negative ions can be separated in an electrostatic field and measured.

Amazon EX1034 Page 52

Ionization happens because charged particles upon passing at a high velocity through an atom can produce sufficient electromagnetic forces, resulting in the separation of electrons, thus creating ions. Remarkably, the same particle can produce multiple ion pairs before its energy is expended. Uncharged particles (like neutrons) can produce ion pairs at collision with the nuclei.

15.2.1 Ionization Chambers

These radiation detectors are the oldest and most widely used. The ionizing particle causes the ionization and excitation of gas molecules along its passing track. As a minimum, the particle must transfer an amount of energy equal to the ionization energy of the gas molecule to permit the ionization process to occur. In most gasses of interest for radiation detection, the ionization energy for the least tightly bound electron shells is between 10 and 20 eV [2]. However, there are other mechanisms by which the incident particle may lose energy within gas that do not create ions, for instance, moving gas electrons to a higher energy level without removing it. Therefore, the average energy lost by a particle per ion pair formed (called W value) is always greater than the ionizing energy. The W value depends on gas (Table 15.1), the type of radiation, and its energy.

In the presence of an electric field, the drift of the positive and negative charges represented by the ions end electrons constitutes an electric current. In a given volume of gas, the rate of the formation of the ion pair is constant. For any small volume of gas, the rate of formation will be exactly balanced by the rate at which ion pairs are lost from the volume, either through recombination, or by diffusion or migration from the volume. If recombination is negligible and all charges are effectively collected, the steady-state current produced is an accurate measure of the rate of ion pair formation. Figure 15.3a illustrates a basic structure of an ionizing chamber and the current/voltage characteristic.

A volume of gas is enclosed between the electrodes, which produce an electric field. An electric current meter is attached in series with the voltage source E and the electrodes. There is no electrical conduction and no current under the no-ionization conditions. Incoming radiation produces, in the gas, positive and negative ions that are pulled by the electric field toward the corresponding electrodes forming an electric current. The current vs. voltage characteristic of the chamber is

Table 15.1 W values for different gases (adapted from [2])

Gas	W value (in eV/ion pair)	
	Fast electrons	Alphas
A	27.0	25.9
He	32.5	31.7
N_2	35.8	36.0
Air	35.0	35.2
CH_4	30.2	29.0

Amazon EX1034 Page 53

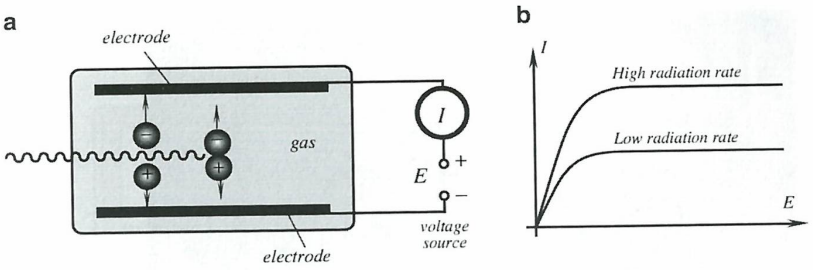


Fig. 15.3 Simplified schematic of an ionization chamber (**a**) and a current vs. voltage characteristic (**b**)

shown in Fig. 15.3b. At relatively low voltages, the ion recombination rate is strong and the output current is proportional to the applied voltage, because higher voltage reduces the number of recombined ions. A sufficiently strong voltage completely suppresses all recombinations by pulling all available ions toward the electrodes, and the current becomes voltage-independent. However, it still depends on the intensity of irradiation. This region is called saturation and where the ionization chamber normally operates.

15.2.2 Proportional Chambers

The proportional chamber is a type of a gas-filled detector that almost always operates in a pulse mode and relies on the phenomenon of a gas multiplication. This is why these chambers are called the proportional counters. Due to gas multiplication, the output pulses are much stronger than in conventional ion chambers. These counters are generally employed in the detection and spectroscopy of low-energy X radiation and for the detection of neutrons. Contrary to the ionization chambers, the proportional counters operate at higher electric fields, which can greatly accelerate electrons liberated during the collision. If these electrons gain sufficient energy, they may ionize a neutral gas molecule, thus creating an additional ion pair. Hence, the process is of an avalanche type resulting in a substantial increase in the electrode current. The name for this process is Townsend avalanche. In the proportional counter, the avalanche process ends when the electron collides with the anode. Since the electron must reach the gas ionization level in the proportional counter, there is a threshold voltage after which the avalanche process occurs. In typical gases at atmospheric pressure, the threshold field level is on the order of 10^6 V/m.

Differences between various gas counters are illustrated in Fig. 15.4. At very low voltages, the field is insufficient to prevent the recombination of ion pairs. In the saturation level, all ions are drifted to the electrodes. A further increase in voltage results in gas multiplication. Over some region of the electric field, the gas

Chapter 16
Temperature Sensors

When a scientist thinks of something, he asks, – "Why?"
When an engineer thinks of something, he asks, – "Why not?"

From prehistoric times people were aware of heat and trying to assess its intensity by measuring temperature. Perhaps the simplest and certainly the most widely used phenomenon for temperature sensing is thermal expansion. This forms the basis of the liquid-in-glass thermometers. For the electrical transduction, different methods of sensing are employed. Some of them are the resistive, thermoelectric, semiconductive, optical, acoustic, and piezoelectric detectors.

16.1 Coupling with Object

Taking a temperature essentially requires the transmission of a small portion of the object's thermal energy to the sensor whose function is to convert that energy into an electrical signal. When a contact sensor (probe) is placed inside or on the object, heat conduction takes place through the boundary between the object and the probe. The sensing element in the probe warms up or cools down, i.e., it exchanges heat with the object. The same happens when heat is transferred by means of radiation – thermal energy in the form of infrared light is exchanged between the sensor and the object. Any sensor, no matter how small, will disturb the measurement site and thus cause some error in temperature measurement. This applies to any method of sensing: conductive, convective, and radiative. Thus, it is an engineering task to minimize the error by an appropriate sensor design and a correct measurement technique of which the coupling between the sensor and object is most critical.

When a contact temperature sensor responds to heat, two basic methods of the signal processing can be employed: equilibrium and predictive. In the equilibrium method, a temperature measurement is complete when no significant thermal

J. Fraden, *Handbook of Modern Sensors*,
DOI 10.1007/978-1-4419-6466-3_16, © Springer Science+Business Media, LLC 2010

Amazon EX1034 Page 55

gradient exists between the measured surface and the sensing element inside the probe. In other words, a thermal equilibrium is reached between the sensor and object of measurement when energy exchange becomes negligible. In the predictive method, the equilibrium is not reached during the measurement time. The equilibrium level is anticipated via a computation through the rate of the sensor's temperature change. After the initial probe placement, reaching a thermal equilibrium between the object and sensor may be a slow process, especially if the contact area is dry. Hence, the process of temperature equalization may take significant time. For instance, a contact medical electronic thermometer may take temperature from a water bath within about 5 s (good thermal coupling), but it will be at least 3 min when temperature is measured axillary (under the armpit) by the same probe (poor thermal coupling).

Let us discuss what affects the accuracy of a temperature measurement. If a sensor is coupled not only to the object whose temperature is measured, but to some other items as well, an error is introduced. To be sure, a temperature sensor is *always* attached to something else besides the object of measurement. An example of another item is a connecting cable (Fig. 16.1a). The sensor is coupled to the object (with an adhesive, for example). After the moment of coupling or after the object temperature changes, the sensor's temperature at any moment of time is T_S, while the object has true temperature T_B. Almost never these two temperatures are really equal. The goal of the equilibrium measurement is to bring T_S as close to T_B as possible. In any practical system, one end of the cable is connected to the sensor while the other end is subjected to another temperature, for example, the ambient temperature T_0 that may be quite different from that of the object. The cable conducts both an electric signal and some heat from or to the sensor. Figure 16.1b shows a thermal circuit that includes the object, sensor, environment, and thermal resistances r_1 and r_2. Thermal resistances should be clearly understood. A thermal resistance represents the ability of a matter to conduct thermal energy and is inversely related to thermal conductivity, that is, $r = 1/\alpha$. If an object is warmer than the environment, heat flows in the direction indicated by an arrow.

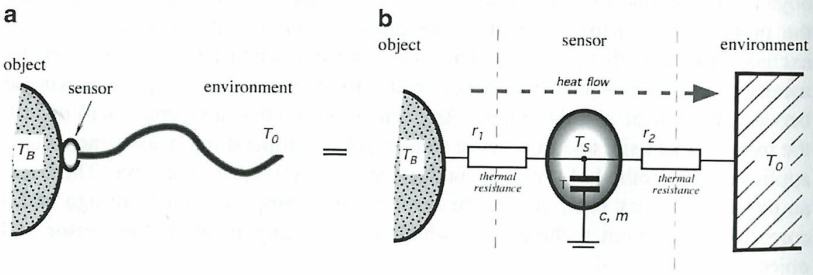


Fig. 16.1 Temperature sensor has thermal contacts with both the object and the connecting cable (**a**); equivalent thermal circuit (**b**)

Amazon EX1034 Page 56

The circuit of Fig. 16.1b resembles an electric circuit and indeed its properties can be evaluated by using the laws of electric circuits such as Kirchhoff's[1] and Ohm's laws. Note that a thermal capacitance is represented by a capacitor. Assuming that we wait sufficiently long and all temperatures are settled on some steady-state levels, and also assuming that the object and environment temperatures are stable and not affected by their interconnection by the sensor, for such a steady state, we may apply the law of conservation of energy. Consider that the thermal energy that flows from the object to the sensor is equal to the energy that outflows from the sensor to the environment. This allows us to write the balance equation:

$$\frac{T_B - T_S}{r_1} = \frac{T_B - T_0}{r_1 + r_2} \tag{16.1}$$

from which we derive the sensor's temperature as

$$T_S = T_B - (T_B - T_0)\frac{r_1}{r_2} = T_B - \Delta T \frac{r_1}{r_2}, \tag{16.2}$$

where ΔT is a thermal gradient between the object and the surroundings. Let us take a closer look at (16.2). We can draw several conclusions from it. The first is that the sensor temperature T_s is different from that of the object. The only exception is when the environment is at the same temperature as the object (a special case when $\Delta T = T_{Bc} - T_0 = 0$). The second conclusion is that T_s will closely approach T_B regardless of the temperature gradient ΔT when the ratio r_1/r_2 approaches zero. This means that for minimizing the measurement error one must improve a thermal coupling between the object and the sensor and decouple the sensor from the surroundings as much as practical. Often, it is not easy to do.

The best way to bring ΔT closer to zero is to imbed the sensor into the object as shown in Fig. 16.2b. A cavity is formed inside the object where the sensor is placed, preferably with a thermal grease, epoxy, or other method is used the thermally bond the sensor with the cavity walls. The cable near the sensor is formed as a loop and also placed inside the cavity. This allows equalizing temperatures of the sensor, cable and cavity. Since the sensor and portion of the cable are not exposed to the external temperature, the measurement becomes significantly more accurate.

Forming a cavity inside the object is not always possible that makes the surface measurement the only practical choice. This is not a desirable arrangement. Yet, there is a powerful technique to form a "virtual cavity" at the object's surface, forcing $\Delta T \to 0$. In a practical circuit, the prime sensor is provided with a thermal shied shown in Fig. 16.2b. This is a conceptual equivalent to a driven capacitive shield (for example, see Figs. 5.4b and 6.7). The thermal shield is fabricated of a metal having a good thermal conductivity (e.g., aluminum) and contains the imbedded heater (and/or cooler) and another temperature sensor called the shield

[1]Kirchhoff's law was originally developed not for the electrical circuits but for plumbing.

Amazon EX1034 Page 57

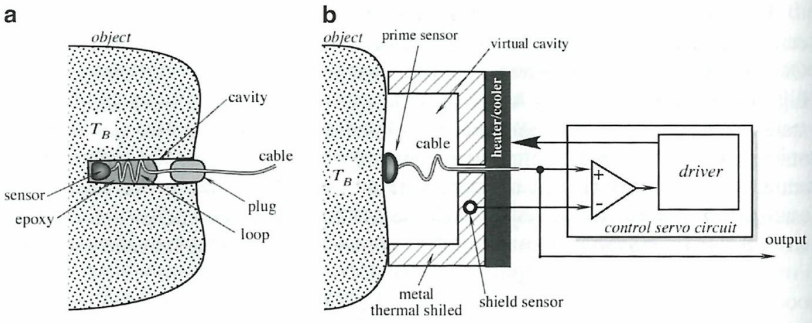


Fig. 16.2 Imbedded temperature sensor (**a**) and surface temperature sensor with an active driven thermal shield (**b**)

temperature sensor. Both sensors provide signals to the control servo-circuit that supplies power to the heater/cooler. The servo-circuit works to minimize the thermal gradient ΔT between the prime sensor and shield sensors. Preferably, the shield touches the object and thus protects the prime sensor from the environment. The object surface and the shield form a virtual thermostatic cavity around the measurement site. When the thermal gradient between both sensors approaches zero, the prime sensor becomes nearly totally thermally decoupled from the environment. It is very important to thermally decouple the prime sensor from the thermal shield; otherwise, the circuit may become unstable. This method was implemented in a medical body core thermometer. The prime sensor was placed inside the ear canal touching the skin, while the thermal shield with a heater was attached to the ear helix [1]. This sensor allowed accurate continuous noninvasive monitoring of temperature inside the patient's head without penetrating the scull.

Above, we evaluated the static condition of the sensor, now let us consider a dynamic case when temperatures change with time. This occurs when either the object or the surrounding temperatures change or the sensor was recently attached to the object and its temperature is not yet stabilized.

Initially, let us consider an ideal case that requires making two assumptions: (1) A thermal resistance between the sensor and the environment is infinitely large ($r_2 \to \infty$) and (2) the object's temperature does not change after the sensor is attached. In other words, the object is considered being much larger than the sensor and acting as an "infinite" heat source/sink. In other words, it is having an infinitely large thermal capacity and infinitely large thermal conductivity. At a starting time $t = 0$, the temperature sensor having the initial temperature T_1 comes in contact with the object having temperature T_B. After that according to Newton's law of cooling the incremental amount of transferred heat to the sensor is proportional to a temperature gradient between the instant sensor temperature T_s at a particular moment and temperature of the object T_B:

$$dQ = \alpha_1 (T_B - T_S) dt, \tag{16.3}$$

Amazon EX1034 Page 58

where $\alpha_1 = 1/r_1$ is the thermal conductivity of the sensor–object boundary. Note that T_s is changing. If the sensor has an average specific heat c and mass m, the heat absorbed by the sensor is

$$dQ = mcdT. \tag{16.4}$$

Equations (16.3) and (16.4) are equal and yield the first-order differential equation

$$\alpha_1(T_B - T_s)dt = mcdT. \tag{16.5}$$

We denote thermal time constant τ_T as

$$\tau_T = \frac{mc}{\alpha_1} = mcr_1, \tag{16.6}$$

then the differential equation takes form

$$\frac{dT}{T_B - T_s} = \frac{dt}{\tau_T}. \tag{16.7}$$

This equation has a solution

$$T_s = T_B - \Delta T e^{-\frac{t}{\tau_T}}. \tag{16.8}$$

The time transient of the sensor's temperature that corresponds to the above solution is shown in Fig. 16.3. One time constant τ_T is equal to the time required for temperature T to reach about 63.2% of the initial gradient $\Delta T = T_b - T_1$. The smaller the time constant the faster the sensor responds to a change in temperature. The time constant can be minimized by reducing the size of the sensor (smaller m) and by improving its coupling with the object (smaller r_1).

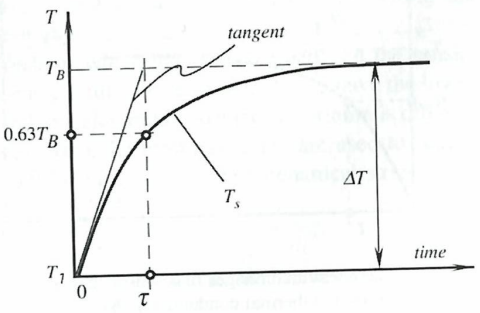


Fig. 16.3 Temperature changes of a sensor (the sensor is ideally coupled to an ideal object)

If we wait for a long time ($t \to \infty$) after attaching the sensor, (16.8) states then temperature of the sensor approaches temperature of the object: $T_s = T_B$ and the sensor reading can be used to compute the object's temperature. Theoretically, it takes infinite time to reach a perfect equilibrium between T_s and T_B – hardly anyone can wait that long! Fortunately, since only a finite accuracy is usually required, for most practical cases a quasi-equilibrium state may be considered after 5–10 time constants. For instance, after the waiting time $t = 5\tau$, the sensor's temperature will differ from that of the object by 0.7% of the initial gradient, while after 10 time constants it will be within 0.005%.

Now, we will study a more realistic case. Let us remove the first of the above assumptions and consider that a thermal coupling with the environment is not extremely large, that is, $r_2 \neq \infty$. Then, the thermal time constant should be determined from

$$\tau_T = \frac{mc}{\alpha_1 + \alpha_2} = mc\frac{r_1}{1 + \frac{r_1}{r_2}} \tag{16.9}$$

and the sensor's response is shown in Fig. 16.3a. Note that now the sensor temperature never reaches exactly that of the object, no matter how long we wait. Hence, even at the equilibrium state, there will be a remaining thermal gradient δT, which is the measurement error due to a poor decoupling from the environment.

Now, we will remove the second assumption; we consider the object not an ideal heat source or sink. This means that the object is not dramatically larger than the sensor or its thermal conductivity is not very large. As a result of this "imperfection," the sensor will disturb, at least temporarily, the measurement site after its attachment. Figure 16.4 shows that upon the sensor attachment, the object's temperature at the point of contact deflects and then will gradually return to some steady-state level. This causes a deviation of the sensor's temperature profile from the ideal exponential function and a concept of a thermal time constant (τ_T) will be no longer applicable. In practice, this deviation becomes significant if one wishes to employ a predictive algorithm as mentioned above, or a fast temperature tracking is

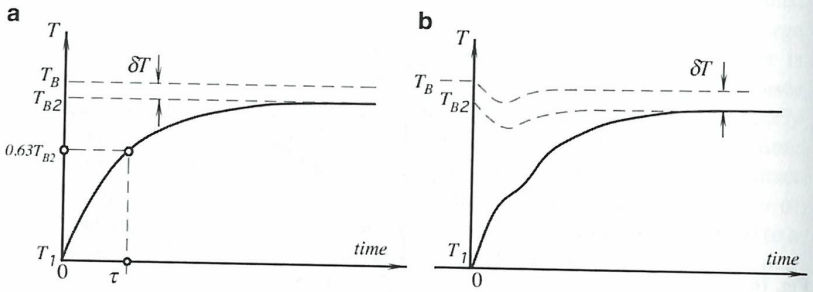


Fig. 16.4 Temperature changes of a sensor that is coupled to the environment (**a**) and when the object has a limited thermal conductivity (**b**)

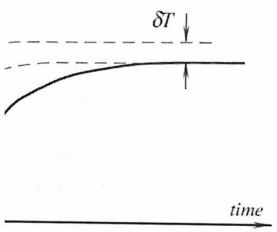
Amazon EX1034 Page 60

the sensor, (16.8) states then
the object: $T_s = T_B$ and the
temperature. Theoretically, it
en T_s and T_B – hardly anyone
uracy is usually required, for
e considered after 5–10 time
the sensor's temperature will
gradient, while after 10 time

emove the first of the above
with the environment is not
al time constant should be

(16.9)

Note that now the sensor
no matter how long we wait.
naining thermal gradient δT,
ing from the environment.
nsider the object not an ideal
dramatically larger than the
s a result of this "imperfec-
e measurement site after its
ttachment, the object's tem-
ll gradually return to some
r's temperature profile from
al time constant (τ_T) will be
s significant if one wishes to
a fast temperature tracking is



e environment (**a**) and when the

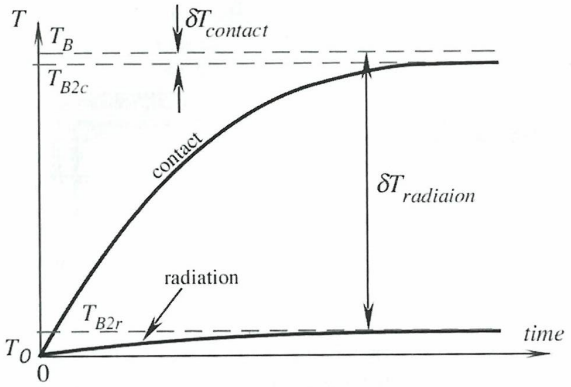


Fig. 16.5 Difference in thermal responses between contact and noncontact (IR radiation) temperature sensors

required. Predictive algorithms require knowledge of the sensor dynamic response function. The algorithm will be resulting in large errors if the real function differs from the preprogrammed functional. Again, the best known solutions for this problem are to use either an imbedded sensor or a dynamic thermal shield [1] that are shown in Fig. 16.2.

Note that the above discussion is equally applicable to all temperature sensors – either contact or noncontact infrared. The only difference is that for a contact sensor, typically $r_1 \ll r_2$, while for a noncontact IR sensor $r_1 \gg r_2$. In other words, a typical contact sensor is much better thermally coupled with the object than with the environment, while the IR sensor is very poorly thermally coupled with the object and much stronger coupled with its immediate surroundings (environment).[2] This difference is illustrated in Fig. 16.5.

A typical contact temperature sensor consists of the following components (Fig. 16.6a):

1. A sensing element – a device whose electrical properties vary somewhat in response to changes in temperature. A good sensing element should have low specific heat, very small mass, high thermal conductivity, and strong and predictable sensitivity to temperature.
2. Terminals are the conductive pads or wires that interface between the sensing element and the external electronic circuit. The terminals should have the lowest possible thermal conductivity and low electrical resistance (platinum is often the best compromise, yet expensive). Also, the terminals often are used to support the sensing element so they should have a reasonable mechanical strength and stability.

[2]This is the reason why an IR thermometer requires an ambient sensor that is thermally connected to the IR sensor.

Amazon EX1034 Page 61

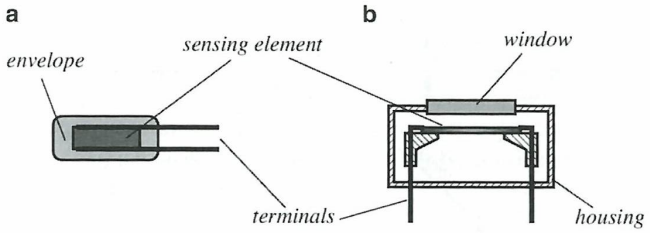


Fig. 16.6 General structures of temperature sensors: Contact sensor (**a**) and noncontact thermal IR radiation sensor (**b**)

3. A protective envelope is either housing or coating, which physically separates the sensing element from the environment. A good envelope must have low thermal resistance (high thermal conductivity) and high electrical isolation properties. It must be environmentally stable and impermeable to moisture and other compounds that may spuriously affect the sensing element.

A noncontact temperature sensor (Fig. 16.6b) is an optical thermal radiation sensor whose designs are covered in detail in Chap. 13. Like a contact sensor, it also contains a sensing element that is responsive to its own temperature. The difference is in the way of a heat transfer from an object to the element: in a contact sensor it is through thermal conduction by way of a physical contact, while in a noncontact sensor it is through thermal radiation (optically).

To improve a response time of a thermal radiation sensor, thickness of the sensing element is minimized, while for a better sensitivity its surface area is maximized. In addition to a sensing element, the noncontact thermal sensor may have an optical window and a built-in interface circuit. The interior of the sensor's housing is usually filled with dry air or nitrogen.

All temperature sensors can be divided into two classes: the absolute sensors and the relative sensors. An absolute temperature sensor measures temperature that is referenced to the absolute zero or any other point on the absolute temperature scale, for example 0°C (273.15°K), 25°C or a selected calibration temperature. Examples of the absolute sensors are thermistors and resistance temperature detectors (RTDs). A relative sensor measures a temperature difference between two objects where one object is called the reference. An example of a relative sensor is a thermocouple.

16.2 Temperature Reference Points

For calibration of any temperature sensor, a precision reference is required. Typically, a reference sensor is some kind of a very stable reference probe that, in turn, must be calibrated to even more stable and predictable reference. In science and

Amazon EX1034 Page 62

16.3.3 Thermistors

The term *thermistor* is a contraction of words *thermal* and *resistor*. The name is usually applied to metal-oxide sensors fabricated in forms of droplets, bars, cylinders, rectangular flakes, and thick films. Thermistors can be also fabricated of silicon and germanium. A thermistor belongs to class of the *absolute* temperature sensors, that is, it can measure temperature that is referenced to an absolute temperature scale. All thermistors are divided into two groups: NTC and PTC. Only the NTC thermistors are useful for precision temperature measurements.

16.3.3.1 NTC Thermistors

A conventional metal-oxide thermistor has a NTC, that is, its resistance decreases with the increase in temperature. The NTC thermistor's resistance, as of any resistor, is determined by its physical dimensions and the material resistivity. The relationship between the resistance and temperature is highly nonlinear (Fig. 3.18).

Whenever a high accuracy is required, or the operating temperature range is wide, thermistor characteristics should not be taken directly from a manufacturer's data sheet. Typical tolerances of the nominal resistance (at 25°C) for the mass-produced thermistors are rather wide: ±10% is quite common, however, for a higher price a 1% or even better thermistors are readily available. Unless it was adjusted at a factory to a better tolerance, to reach a high accuracy, each low-tolerance thermistor needs to be individually calibrated over the entire operating temperature range. Manufacturers can trim a thermistor by grinding its body to a required dimension that directly controls the nominal value of resistance at a set temperature. This, however, increases cost. An alternative approach for an end user is to individually calibrate the thermistors. Calibration means that a thermistor has to be subjected to a precisely known temperature (a stirred water bath is often employed[5]) and its resistance is measured. This is repeated at several temperatures if a multipoint calibration is needed (see Sect. 2.2). Naturally, a thermistor calibration is as good as the accuracy of a reference thermometer used during the calibration. To measure resistance of a thermistor, it is attached to a measurement circuit that passes through it an electric current. Depending on the required accuracy and the production cost restrictions, a thermistor calibration can be based on use of one of several known approximations (models) of its temperature response.

When a thermistor is used as a temperature sensor, we assume that all its characteristics are based on the so-called zero-power resistance, meaning that electric current passing through a thermistor does not result in any noticeable temperature increase (self-heating) that may affect accuracy of measurement.

[5]Actually, water is not used. Mineral oil or Fluorinert® electronic fluid is more of practical liquid.

Amazon EX1034 Page 63

A static temperature increase in a thermistor due to self-heating is governed by the following equation:

$$\Delta T_H = r\frac{N^2V^2}{S}, \tag{16.15}$$

where r is a thermal resistance to surroundings, V is the applied dc voltage during the resistance measurement, S is the resistance of a thermistor at a measured temperature, and N is a duty cycle of measurement (for example, $N = 0.1$ means that constant voltage is applied to a thermistor only during 10% of the time). For a dc measurement, $N = 1$.

As follows from (6.15), a zero-power can be approached by selecting high-resistance thermistors, increasing coupling to the object of measurement (reducing r), and measuring its resistance at low voltages applied during short time intervals. At the end of this chapter, we will show the effects of self-heating on the thermistor response, but for now, we assume that a self-heating results in a negligibly small error.

To use a thermistor in the actual device, its transfer function (temperature dependence of a resistance) must be accurately established. Since that function is highly nonlinear (Fig. 16.15) and generally specific for each particular sensor, an analytical equation connecting the resistance and temperature is highly desirable. Several mathematical models of a thermistor transfer function have been proposed. It should be remembered, however, that any model is only an approximation, and generally the simpler the model, the lesser the accuracy should be expected. On the other hand, at a more complex model, calibration and the use of a thermistor become more difficult. All present models are based on the experimentally established fact that logarithm of a thermistor's resistance S relates to its absolute temperature T by a polynomial equation

$$\ln S = A_0 + \frac{A_1}{T} + \frac{A_2}{T^2} + \frac{A_3}{T^3}. \tag{16.16}$$

From this basic equation, three computational models have been proposed.

16.3.3.2 Simple Model

Over a relatively narrow temperature range and assuming that some accuracy may be lost, we can eliminate two last terms in (16.16) and arrive at [4]:

$$\ln S \cong A + \frac{\beta_m}{T}, \tag{16.17}$$

Amazon EX1034 Page 64

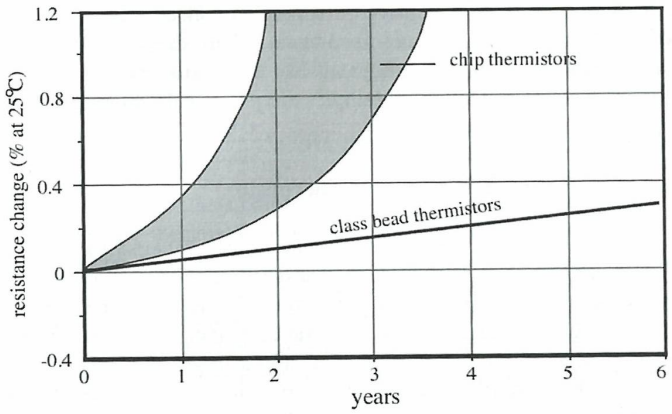


Fig. 16.12 Long-term stability of thermistors

+1%/year. Figure 16.12 shows typical percentage changes in resistance values for the epoxy-encapsulated chip thermistors when compared with the sintered glass encapsulated thermistors. A good environmental protection and preaging is a powerful method of sensor characteristic stabilizing. During preaging, the thermistor is maintained at +300°C for at least 700 h. For the better protection, it may be further encapsulated into a stainless steel jacket and potted with epoxy. After preaging and encapsulation in glass and then into a stainless steel tube, a thermistor may have a drift as low as few millidegree per year.

16.3.3.6 Germanium and Silicon NTC Thermistors

High-quality NTC thermistors may be successfully fabricated from monocrystalline or polycrystalline germanium or silicon [9, 10]. These thermistors have several advantages, some of them are very high sensitivity (typical β exceeds 6,000 K at 25°C), tight manufacturing tolerances, very small sizes, low cost, and ability to operate at cryogenic and high temperatures, from as low as 1 mK to as high as 500°C. Currently, these sensors are produced by AdSem, Inc. (www.adsem.com).

16.3.3.7 Printed Thermistors

A thermistor can be produced in a technique similar to conventional thick-film resistor [31]. The process involves screen-printing on a ceramic substrate. The ink for printing contains a powder with thermistor characteristics, glass powder, and organic binder. The thermistor powder is composed of oxides of Mn, Co, Ni, oxides of some noble metals such as Ru and other materials [11]. After printing, the

Amazon EX1034 Page 65

That characteristic is usually plotted on log–log coordinates, where lines of constant resistance have a slope of +1 and lines of constant power have slope of −1 (Fig. 16.14).

At very low currents (left side of the Fig. 16.14), the power dissipated by the thermistor is negligibly small, and the characteristic is tangential to a line of constant resistance of the thermistor at a specified temperature. Thus, the thermistor behaves as a simple resistor. That is, voltage drop V_T is proportional to current i.

As the current increases, the self-heating increases as well. This results in a decrease in the resistance of the thermistor. Since the resistance of the thermistor is no longer constant, the characteristics start to depart from the straight line. The slope of the characteristic (dV_T/di), which is the resistance, drops with increase in current. The current increase leads to further resistance drop, which, in turn, increases the current. Eventually, current will reach its maximum value i_p at a voltage maximum value V_p. It should be noted that, at this point, a resistance of the thermistor is zero. Further increase in current i_p will result in continuing decrease in the slope, which means that the resistance has a negative value (right side of Fig. 16.14). An even further increase in current will produce another reduction in resistance, where leadwire resistance becomes a contributing factor. A thermistor should never be operated under such conditions. A thermistor manufacturer usually specifies the maximum power rating for thermistors.

According to (16.36), self-heating thermistors can be used to measure variations in δ, ΔT, or V_T. The applications where δ varies include vacuum manometers (Pirani gauges), anemometers, flow meters, fluid level sensors, etc. Applications where ΔT is the stimulus include microwave power meters, AFIR detectors, etc. The applications where V_T varies are in some electronic circuits: Automatic gain control, voltage regulation, volume limiting, etc.

16.3.3.9 PTC Thermistors

All metals may be called PTC materials. Their temperature coefficients of resistivity (TCR) are quite low (Table A.7), thus making them not very useful for temperature sensing that require high sensitivity. The RTDs as described earlier also have small PTCs. In contrast, ceramic PTC materials in a certain temperature range are characterized by a very large temperature dependence. The PTC thermistors are fabricated of polycrystalline ceramic substances, where the base compounds, usually barium titanate or solid solutions of barium and strontium titanate (highly resistive materials) made semiconductive by the addition of dopants [12]. Above the Curie temperature of a composite material, the ferroelectric properties change, rapidly resulting in a rise in resistance, often several orders of magnitude. A typical transfer function curve for the PTC thermistor is shown in Fig. 16.15 in comparison with the NTC and platinum RTD responses. The shape of the curve does not lend itself to an easy mathematical approximation; therefore, manufacturers usually specify PTC thermistors by a set of numbers:

Amazon EX1034 Page 66

eliminate a dry contact. The terminals of the thermistor are connected to a voltage source whose value may be estimated from the following formula

$$E \geq 2\sqrt{\delta(T_\tau - T_a)R_{25}}, \tag{16.40}$$

where δ is the heat dissipation constant, which depends on thermal coupling to the environment and T_a is the ambient temperature. The thermostat's set point is determined by the physical properties of the ceramic material (Curie temperature) and due to internal thermal feedback, the device reliably operates within relatively large range of power supply voltages and ambient temperatures. Naturally, ambient temperature must be always less than T_τ.

3. Time delay circuits can be created with the PTC thermistors thanks to a relatively long transition time between the application of electric power in its heating and a low-resistance point.
4. Flowmeter and liquid-level detectors that operate on principle of heat dissipation (thermo-anemometers as described in Sect. 11.3) can be made very simple with the PTC thermistors.

16.4 Thermoelectric Contact Sensors

A thermoelectric contact sensor is called a *thermocouple* because at least two dissimilar conductors are joined to form a junction (a couple). However, at least two of these junctions are needed to make a practical sensor. A thermocouple is a passive sensor. It generates voltage in response to temperature and does not require any external excitation power. In other words, a thermocouple is a direct converter of thermal energy into electrical energy and because it is a voltage-generating sensor, sometimes thermocouple is called a "thermal battery."

The thermoelectric sensors belong to class of the *relative* sensors, because the voltage produced depends on a temperature difference between two thermocouple junctions, in large part regardless of the absolute temperature of each junction. To measure temperature with a thermocouple, one junction will serve as a reference and its absolute temperature must be measured by a separate absolute sensor such a thermistor, RTD, etc. or coupled to a material that is in a state of a known reference temperature (Table 16.1). Section 3.9 provides a physical background for better understanding of the thermoelectric effect, and Table A.10 lists some popular thermocouples[8] that are designated by letters originally assigned by the Instrument Society of America (ISA) and adopted by an American Standard in ANSI MC 96.1. Detailed description of various thermocouples and their applications can be found in many excellent texts, for instance in [2, 13, 14]. In the following paragraphs, we summarize the most important recommendations for the use of these sensors.

[8] A lot of very valuable information can be found in www.temperatures.com

Amazon EX1034 Page 67

Type T: Cu (+) versus constantan (−), are resistant to corrosion in moist atmosphere and are suitable for subzero temperature measurements. Their use in air in oxidizing environment is restricted to 370°C (700°F) due to the oxidation of the copper thermoelement. They may be used to higher temperatures in some other atmospheres.

Type J: Fe (+) versus constantan (−) are suitable in vacuum and in oxidizing, reducing, or inert atmospheres, over the temperature range of 0 to 760°C (32–1,400°F). The rate of oxidation in the iron thermoelement is rapid above 540°C (1,000°F), and the use of heavy-gage wires is recommended when long life is required at the higher temperatures. This thermocouple is not recommended for use below the ice point because rusting and embrittlement of the iron thermoelement make its use less desirable than Type T.

Type E: 10%Ni/Cr (+) versus constantan (−), are recommended for use over the temperature range of −200 to 900°C (−330 to 1,600°F) in oxidizing or inert atmospheres. In reducing atmospheres, alternately oxidizing or reducing atmospheres, marginally oxidizing atmospheres, and in vacuum, they are subject to the same limitations as type K. These thermocouples are suitable to subzero measurements since they are not subject to corrosion in atmospheres with a high-moisture content. They develop the highest e.m.f. per degree of all the commonly used types and are often used primarily because of this feature (see Fig. 3.36).

Type K: 10%Ni/Cr (+) versus 5%Ni/Al/Si (−), are recommended for use in an oxidizing or completely inert atmosphere over a temperature range of −200 to 1,260°C (−330 to 2,300°F). Due to their resistance to oxidation, they are often used at temperatures above 540°C. However, type K should not be used in reducing atmospheres, in sulfurous atmospheres, and in a vacuum.

Types R and S: Pt/Rh (+) versus Pt (−), are recommended for continuous use in oxidizing or inert atmospheres over a temperature range of 0–1,480°C (32–2,700°F).

Type B: 30%Pt/Rh (+) versus 6%Pt/Rh (−) are recommended for continuous use in oxidizing or inert atmospheres over the range of 870–1,700°C (1,000–3,100°F). They are also suitable for short term use in a vacuum. They should not be used in reducing atmospheres, nor those containing metallic or nonmetallic vapors. They should never be directly inserted into a metallic primary protecting tube or well.

16.4.1 Thermoelectric Laws

For practical purposes, an application engineer must be concerned with three basic laws that establish the fundamental rules for proper connection of the thermocouples. It should be stressed, however, that an electronic interface circuit must always be connected to two *identical* conductors; otherwise, two parasitic thermocouples will be formed at the circuit. These identical conductors may be formed from one of the thermocouple loop arms. That arm is broken to connect the metering device to the circuit. The broken arm is indicated as material *A* in Fig. 16.18.

Amazon EX1034 Page 68

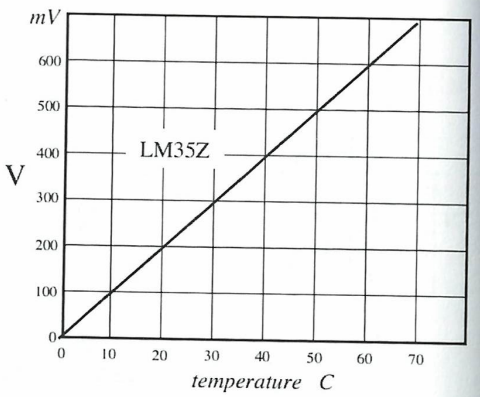


Fig. 16.26 A typical transfer function of a LM35DZ semiconductor temperature sensor (from National Semiconductors, Inc.)

and may be precisely trimmed during the manufacturing process for a desired slope I_T/T. The current I_T may be easily converted into voltage. If, for example, a 10 kΩ resistor is connected in series with the sensor, the voltage across that resistor will be a linear function of absolute temperature.

The simplified circuit of Fig. 16.25a will work according to the abovementioned equations only with the perfect transistors ($\beta = \infty$). Practical monolithic sensors contain many additional components to overcome limitations of the real transistors. Several companies produce temperature sensors based on this principle. Examples are LM35 from National Semiconductors (voltage output circuit) and AD590 from Analog Devices (current output circuit).

Figure 16.26 shows a transfer function of a LM35Z temperature sensor, which has a linear output internally trimmed for the Celsius scale with a sensitivity of 10 mV per °C. The function is quite linear where the nonlinearity error is confined within ± 0.1°. The function can be modeled by

$$V_{out} = V_0 + at, \tag{16.51}$$

where t is the temperature in degrees C. Ideally, V_0 should be equal to zero; however, part-to-part variations of its value may be as large as ±10 mV, which correspond to an error of 1°C. Slope a may vary between 9.9 and 10.1 mV/°C; hence, for a high-accuracy application, this sensor still may require a calibration to determine V_0 and a.

16.6 Optical Temperature Sensors

Temperature can be measured by contact and noncontact methods. The noncontact instruments are generally associated with the infrared optical sensors that we covered in Sects. 3.12.3 and 14.7. A need for the noncontact temperature sensors

Amazon EX1034 Page 69

exists when the measurement must be done fast. Also, they are needed for determining temperatures at hostile environments where very strong electrical, magnetic or electromagnetic fields, or very high voltages make measurements either too susceptible to interferences, or too dangerous for the operator. Also, there are situations when it is just difficult to reach an object during a routine measurement. Besides the infrared methods of temperature measurements, there are sensors that are contact by nature but still use photons as carriers of thermal information. These are discussed below.

16.6.1 Fluoroptic Sensors

The fluoroptic sensors rely on the ability of a special phosphor compound to give away a fluorescent signal in response to light excitation. The compound can be directly painted over the measured surface and illuminated by an ultraviolet (UV) pulse, while observing the afterglow. The shape of the response afterglow pulse is the function of temperature. The decay of the response afterglow is highly reproducible over a wide temperature range [17, 18]. As a sensing material, magnesium fluoromagnetite activated with tetravalent manganese is used. This is phosphor, long known in the lighting industry as a color corrector for mercury vapor street lamps, prepared as a powder by a solid-state reaction at approximately 1,200°C. It is thermally stable, relatively inert and benign from a biological standpoint, and insensitive to damage by most chemicals or by prolonged exposure to ultraviolet UV radiation. It can be excited to fluoresce by either UV or blue radiation. Its fluorescent emission is in the deep red region, and the fluorescent decay is essentially exponential.

To minimize crosstalk between the excitation and emission signals, they are passed through the bandpass filters, which reliably separate the related spectra (Fig. 16.27a). The pulsed excitation source, a xenon flash lamp, can be shared among a number of optical channels in a multisensor system. The temperature measurement is made by measuring the rate of decay of the fluorescence, as shown in Fig. 16.27b. In other words, a temperature is represented by a time constant τ, which drops fivefold over the temperature range from -200 to $+400$°C. Since measurement of time is usually the simplest and most precise operation that can be performed by an electronic circuit, the temperature can be measured with a good resolution and accuracy: About ± 2°C over the above range without calibration.

Since the time constant is independent of excitation intensity, a variety of designs is possible. For instance, the phosphor compound can be directly coated onto the surface of interest and the optic system can take measurement without a physical contact (Fig. 16.28a). This makes possible the continuous temperature monitoring without disturbing the measured site. In another design, a phosphor is coated on the tip of a pliable probe that can form a good contact area when touches the object (Fig. 16.28b, c).

Amazon EX1034 Page 70

before the wave arrives to its surface and converts it into an electrical transient, which is amplified and sent to the control circuit. The control circuit calculates the speed of sound by determining propagation time along the tube. Then, the corresponding temperature is determined from the calibration numbers stored in a look-up table. In another design, the thermometer may contain only one ultrasonic crystal, which alternatively acts either as a transmitter or as a receiver. In that case, the tube has a sealed empty end. The ultrasonic waves are reflected from the end surface and propagate back to the crystal, which before the moment of the wave arrival is turned into a reception mode. An electronic circuit [23] converts the received pulses into a signal that corresponds to the tube temperature.

A miniature temperature sensor can be fabricated with the surface acoustic waves (SAW) and plate waves (PW) techniques (see Section 12.7). The idea behind such a sensor is in the temperature modulation of some mechanical parameters of a time-keeping element in the electronic oscillator [24, 25]. This leads to a change in the oscillating frequency. In effect, such an integral acoustic sensor becomes a direct converter of temperature into frequency. A typical sensitivity is in the range of several kilohertz per degree Kelvin.

16.8 Piezoelectric Temperature Sensors

Piezoelectric effect, in general, is a temperature-dependent phenomenon. Thus, a temperature sensor based on variability of oscillating frequency of a quartz crystal can be designed. Since the quartz is an anisotropic medium, the resonant frequency of a plate is highly dependent on the crystallographic orientation of the plate, the so-called angle of cut. Thus, by selecting a cut, negligibly small temperature sensitivity may be achieved (*AT*- and *BT*-cuts), or just the opposite – a cut with pronounced temperature dependence may be selected. Temperature dependence of the resonant frequency may be approximated by a third-order polynomial

$$\frac{\Delta f}{f_0} = a_0 + a_1 \Delta T + a_2 \Delta T^2 + a_3 \Delta T^3, \tag{16.53}$$

where ΔT and Δf are the temperature and frequency shifts, respectively, f_0 is the calibrating frequency, and a values are the coefficients. The first utilization of temperature dependence was made in 1962 by utilizing a nonrotated Y-cut crystal [26]. A very successful development of a linear temperature coefficient-cut (LC) was made by Hewlett–Packard [27]. The second- and third-order coefficients had been eliminated by selecting a doubly rotated *Y*-cut. The sensitivity (a_1) of the sensor is 35 ppm/°C, and the operating temperature range is from −80 to 230°C with calibration accuracy of 0.02°C. With the advent of microprocessors, linearity became a less important factor and more sensitive, yet somewhat nonlinear quartz temperature sensors had been developed by using a slightly singly rotated *Y*-cut

Amazon EX1034 Page 71

($Q = -4°$) with sensitivity of 90 ppm/°C [28] and by utilizing a tuning-fork resonators in flexural and torsional modes [29, 30].

It should be noted, however, that thermal coupling of the object of measurement with the oscillating plate is always difficult and; thus, all piezoelectric temperature sensors have relatively slow response when compared with thermistors and thermoelectrics.

References

1. Fraden J, Ferlito RK (2007) Ear temperature monitor and method of temperature measurement. US Patent 7,306,565, 11 Dec
2. Benedict RP (1984) Fundamentals of temperature, pressure, and flow measurements, 3rd edn. Wiley, New York
3. Callendar HL (1887) On the practical measurement of temperature. Philos Trans R Soc Lond 178:160
4. Sapoff M (1999) Thermistor thermometers. In: Webster JG (ed) The measurement, instrumentation and sensors handbook. CRC Press, Boca Raton, FL, pp 32.25–32.41
5. Fraden J (2000) A two-point calibration of negative temperature coefficient thermistors. Rev Sci Instrum 71(4):1901–1905
6. Steinhart JS, Hart SR (1968) Deep Sea Res 15:497
7. Mangum BW (1983) Rev Sci Instrum 54(12):1687
8. Sapoff M, Siwek WR, Johnson HC, Slepian J, Weber S (1982) In: Schooley JE (ed) Temperature. Its measurement and control in science and industry. American Institute of Physics, Washington, DC, vol 5, p 875
9. Villemant CM, Gaultier M (1971) Thermistor. US Patent 3,568,125, 2 Mar
10. Silver EH et al (2007) Method for making an epitaxial germanium temperature sensor. US Patent 7,232,487, 19 Jun
11. Tosaki H et al Thick film thermistor composition. US Patent 4,587,040, 6 May 1986
12. Keystone NTC PTC thermistors (1984) Catalogue © Keystone Carbon Company, St. Marys, PA
13. Caldwell FR (1962) Thermocouple materials. NBS monograph 40. National Bureau of Standards. March 1
14. Manual on the use of thermocouples in temperature measurement (1993) 4th edn. ASTM Manual Series: MNL: 12–93, ASTM, Philadelphia, PL
15. Sachse HB (1975) Semiconducting temperature sensors and their applications. Wiley-Interscience, New York
16. Timko MP (1976) A two terminal IC temperature transducer. IEEE J Solid-State Circuits SC-11:784–788
17. Wickersheim KA, Sun MH (1987) Fluoroptic thermometry. Med Electron 84–91
18. Fernicola VC et al (2000) Investigations on exponential lifetime measurements for fluorescence thermometry. Rev Sci Instrum 71(7):2938–2943
19. Schultheis L, Amstutz H, Kaufmann M (1988) Fiber-optic temperature sensing with ultrathin silicon etalons. Opt Lett 13(9):782–784
20. Wolthuis RA, Mitchell GL, Saaski E, Hartl JC, Afromowitz MA (1991) Development of medical pressure and temperature sensors employing optical spectral modulation. IEEE Trans Biomed Eng 38(10):974–981
21. Beheim G, Fritsch K, Azar MT (1990) A sputtered thin film fiber optic temperature sensor. Sensors 37–43
22. Hao T, Lui CC (1990) An optical fiber temperature sensor using a thermochromic solution. Sens Actuators A 24:213–216

Amazon EX1034 Page 72

Chapter 17
Chemical Sensors[1]

Of all smells, bread;
Of all tastes, salt.

–George Herbert, English poet

Sensors for measuring and detecting chemical substances are pervasively employed yet are, for the most part, unobtrusive. They are used to help run our cars more efficiently, track down criminals, and monitor our environment and health. Examples of uses include monitoring of oxygen in automobile exhaust systems, glucose levels in samples from diabetics, and carbon dioxide in the environment. In the laboratory, chemical detectors are the heart of key pieces of analytical equipment employed in the development of new chemicals and drugs and to monitor industrial processes. Progress has been impressive, and the literature is full of interesting developments. Recent developments include a broad spectrum of technologies, including improved screening systems for security applications [1] and miniaturization of systems once only used in laboratories [2]. Chemical sensors respond to stimuli produced by various chemicals or chemical reactions. These sensors are intended for identification and quantification of chemical species (including both liquid and gaseous phases).

In industry, chemical sensors are used for process and quality control during plastics manufacturing and in the production of foundry metals where the amount of diffused gasses affects metal characteristics such as brittleness. They are used for environmental monitoring of workers to control their exposure to dangers and limit health risks. Chemical sensors find many new applications as electronic noses. An electronic nose generally uses different types of sensor technologies [3] in order to mimic the olfaction capabilities of mammals [4]. In medicine, chemical sensors are used to determine patient health by monitoring oxygen and trace gas content in the lungs and in blood samples. These sensors are often used for breathalyzers to test

[1]This chapter is written in collaboration with Prof. Todd E. Mlsna (Mississippi State University, tmlsna@chemistry.msstate.edu) and Dr. Sanjay V. Patel (Seacoast Science, Inc., sanjay@seacoastscience.com).

J. Fraden, *Handbook of Modern Sensors*,
DOI 10.1007/978-1-4419-6466-3_17, © Springer Science+Business Media, LLC 2010

Amazon EX1034 Page 73

for blood alcohol levels and as indicators of the digestion problems of patients. In the military, chemical sensors are used to detect fuel dumps and to warn soldiers of the presence of airborne chemical warfare agents. Chemical sensors are used to detect trace contaminants in liquids, and, for example, they are used to search for and monitor ground water contamination near military, civilian, and industrial sites, where significant amounts of chemicals are stored, used, or dumped [5]. Combinations of liquid and gas sensors are used in experimental military applications to monitor compounds produced from refineries and nuclear plants to verify compliance with weapons treaties.

17.1 Overview

Traditionally, chemical sensing of unknown substances is done in an analytical laboratory with complex benchtop equipment including, for example, mass spectrometry, chromatography, nuclear magnetic resonance, X-ray, and infrared technology. These methods are very accurate, and it is possible to identify most classes of unknown chemicals with a high degree of confidence. However, the instruments are often expensive and require trained personnel to operate. Considerable efforts have been devoted to developing miniaturized low-cost sensing systems to address specific markets. Impressive advances have been made and many sensor systems are available at low cost, but these miniaturized systems traditionally have problems with sensitivity, selectivity, baseline stability, and reproducibility. Here, we provide an overview of chemical sensors and sensing systems for both the analytical laboratory and the miniaturized systems for specific applications.

17.2 History

The history of man benefiting from sensing chemicals is rich and colorful. The first examples involved clever use of the animal kingdom including the miner's canary [6] employed to monitor air quality (Fig. 17.1a). Early miners often worked in dangerous conditions without the benefit of modern ventilation systems. For hundreds of years, miners would work side by side with caged canaries to warn of dangerous environmental conditions. Canaries are more sensitive than man to low levels of methane, carbon monoxide, and diminished oxygen levels that can occur with a tunnel collapse or the release of pockets of trapped gases. As long as the canary lived the miner knew his air supply was safe. A dead canary alerted the miners of a potentially dangerous situation. In modern mines, most canaries have been replaced with various types of personal, portable, and fixed gas-monitoring equipment [7].

Since prehistoric times, canines were used for finding and tracking game. Today, trained dogs are used for finding explosives and drugs in airports and other public

Amazon EX1034 Page 74

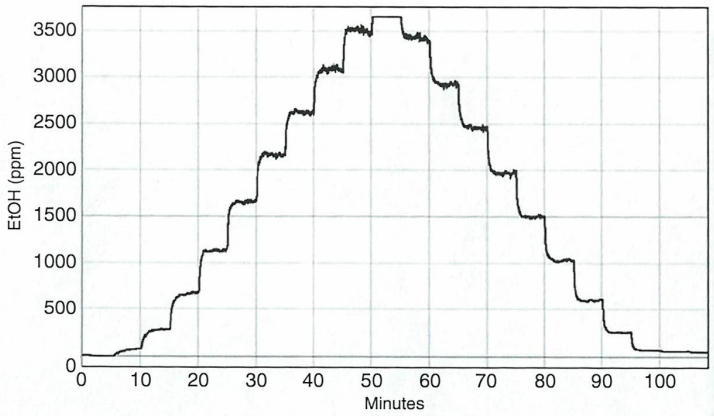


Fig. 17.2 Metal-oxide-semiconductor-based sensor response to increasing and decreasing concentrations of ethanol

when the transfer function of a sensor is linear. For the chemical sensors, sensitivity is the synonym of resolution.

17.4 Classes of Chemical Sensors

There is no universally accepted method to categorize the complete list of chemical detectors. For the purpose of this chapter, we have grouped them into two main sections, one being transduction method and the other being method of implementation. We have further divided the methods of transduction into three classes, including (1) sensors that measure electrical or electrochemical properties, (2) those that measure a change in a physical property, (3) and those that rely on optical absorption. An impressive range of sensor technologies have been developed to respond to different chemical, physical, and optical properties to aid in the detection of chemical analytes. Some of these technologies, for example microcantilevers, can be used to measure chemical and/or physical properties and thus are not easily classified.

17.4.1 Electrical and Electrochemical Transducers

Sensors that directly measure the electrical properties of a target analyte or the effect of the analyte on the electrical properties of another material are often the least expensive commercially available detectors. With these sensors, detection can be a reversible or a destructive irreversible process resulting in analyte decomposition.

Amazon EX1034 Page 75

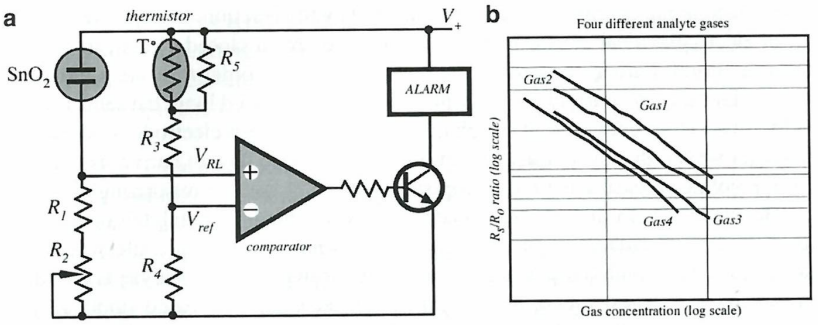


Fig. 17.4 SnO_2 Wheatstone bridge circuit (**a**) used for metal-oxide sensors and responses to different gases (**b**)

change of the conductivity may be used to differentiate gases and concentrations [13]. The bulk conductivity can drift for these devices, but the rate of change of that conductivity when driven by a pulsed input is more stable and reproducible.

These solid-state sensors have the advantage of being small, having low power consumption, low in cost, and can be easily batch fabricated. The control and measurement circuitry can be fabricated on the silicon microchip as well, providing opportunities to deploy sensor packages containing monolithically integrated arrays of sensing elements along with on-chip data acquisition and control systems. Several references to thin and thick film sensors on silicon devices have appeared based on a number of different materials for sensing a variety of gases [14, 15]. Tin oxide is the most prevalent pure film material studied [16, 17, 18, 19, 20]. In addition, Pt-doped [21, 22] and Pd-doped tin oxide films [23, 24] have been used to sense carbon monoxide, hydrogen, and hydrocarbons. Titania, in various forms and environments, has been used for sensing oxygen [25]. Rhodium-doped TiO_2 has been used to sense hydrogen [26]. Zinc oxide has been used to sense hydrogen, carbon monoxide and hydrocarbons [27]. The electrical properties of these materials change with the adsorption, absorption, desorption, rearrangement, and reaction of gases on the surface or in the bulk. Many of these materials have catalytic properties, and the adsorption and/or surface reactions of gases contribute to changes in electrical conductivity.

17.4.1.2 Electrochemical Sensors

The electrochemical sensors are commercially available and very versatile. Depending on the operating mode, they are divided into sensors that measure voltage (potentiometric), those that measure electric current (amperometric), and those that rely on the measurement of conductivity or resistivity (conductometric). In all these methods, special electrodes are used, where either a chemical reaction

Amazon EX1034 Page 76

takes place or the charge transport is modulated by the reaction. A fundamental rule of an electrochemical sensor is that it always requires a closed circuit, that is, an electric current (either dc, or ac) must be able to flow in order to make a measurement. Since electric current flow essentially requires a closed loop, the sensor needs at least two electrodes, one of which often is called a return electrode. It should be noted, however, that even if in a potentiometric sensor no flow of current is required for the voltage measurement, the loop still must be closed for measuring voltage.

The electrodes in these sensing systems are often made of catalytic metals such as platinum or palladium, or they can be carbon-coated metals. Electrodes are designed to have high-surface area to react with as much of the analyte as possible, producing the largest measurable signal. Electrodes can be treated (modified) to improve their reaction rates and extend their working life spans. The working electrode (WE) is where the targeted chemical reactions take place (Fig. 17.5). The electrical signal is measured with respect to a counter or auxiliary electrode (AE) that is not intended to be catalytic, and in the case of three-electrode systems, a third reference electrode (RE) is employed to measure and correct for electrochemical potentials generated by each electrode and the electrolyte. The third electrode improves operation by correcting for error introduced by a polarization of the working electrode. Newer electrochemical sensors employ thick-film, screen-printed electrode sets to make manufacturing simpler and more robust.

The electrolyte is a medium that carries charges using ions instead of electrons. This directly limits the reactions that can take place and is the first stage of lending selectivity to the electrochemical sensor. The sensor formed by this collection of

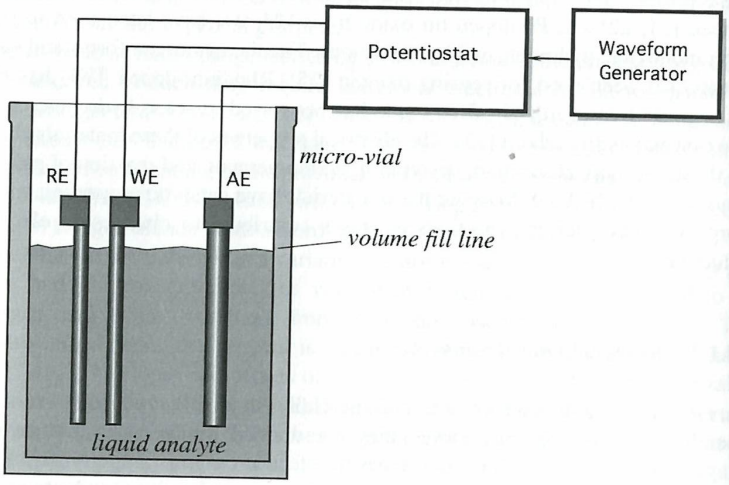


Fig. 17.5 Electrochemical-sensor electrode set

Amazon EX1034 Page 77

electrodes and electrolytes is called an electrochemical cell and may be operated in several ways depending upon the electrical characteristic being observed (resistance, potential, current, capacitance, etc.). The more comprehensive measurements are captured using various forms of voltammetry discussed later in this chapter.

A simple liquid electrochemical sensor (cell) uses two electrodes immersed in an electrolyte solution. Gas analytes, such as CO, react at the working electrode and produces CO_2 and free electrons. Charges and charged species migrate to the other (counter) electrode where water is produced if oxygen is present. The reaction converts CO to CO_2 (17.2). If the electrodes are connected in series to a resistor and the potential drop across the resistor is measured, it will be proportional to the current flowing making it a function of analyte gas present.

$$CO + H_2O \leftrightarrow CO_2 + 2H^+ + 2e^- \tag{17.2}$$

17.4.1.3 Potentiometric Sensors

These sensors use the effect of the concentration on the equilibrium of the redox reactions occurring at the electrode–electrolyte interface in an electrochemical cell. An electrical potential may develop at this interface due to the redox reaction that takes place at the electrode surface, where *Ox* denotes the oxidant, Ze^- is the number of electrons involved in the redox reaction, and *Red* the reduced product [28]

$$Ox + Ze^- = Red. \tag{17.3}$$

This reaction occurs at one of the electrodes (cathodic reaction in this case) and is called a half-cell reaction. Under thermodynamical quasiequilibrium conditions, the Nernst equation is applicable and can be expressed as

$$E = E_0 + \frac{RT}{nF} \ln \frac{C_O^*}{C_R^*}, \tag{17.4}$$

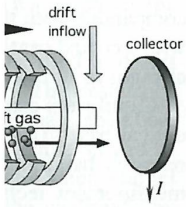
where C_O^* and C_R^* are the concentrations of *Ox* and *Red*, respectively, n is the number of electrons transferred, F is the Faraday constant, R is the gas constant, T is the absolute temperature, and E_0 is the electrode potential at a standard state. In a potentiometric sensor, two half-cell reactions will take place simultaneously at each electrode. However, only one of the reactions should involve the sensing species of interest, while the other half-cell reaction is preferably reversible, non-interferring, and known.

The measurement of the cell potential of a potentiometric sensor should be made under zero-current or quasiequilibrium conditions; thus, a very high input impedance amplifier (which is called an electrometer) is generally required. There are two

Amazon EX1034 Page 78



ed from Battiston et al.



ngs

all ion beams are
e ion current I is
ion mobility spec-
istic measure for a
of $R > 20$ (17.14):

(17.14)

sured at half of the

nd screening appli-
xplosives detection
ıchtop instruments.

Research and development of this detection technology remains very active with several groups around the world dedicated to advancing this analytical approach. Variations include different methods of ionization, the addition of chemicals to enhance ionization, and alternating electric fields to improve ion separation [67].

17.4.4.4 Thermal Sensors

When the internal energy of a system changes, it is accompanied by an absorption or evolution of heat (as defined by the first law of thermodynamics). Therefore, a chemical reaction, which is associated with heat, can be detected by an appropriate thermal sensor, such as those described in Chap. 16. These sensors operate on the basic principles that form the foundation of a microcalorimetry. The operating principle of a thermal sensor is simple: A temperature probe is coated with a chemically selective layer. Upon the introduction of a sample, the probe measures transfer of heat during the reaction between the sample and the coating.

A simplified drawing of such a sensor is shown in Fig. 17.19. It contains a thermal shield to reduce heat loss to the environment and thermistor coated by a catalytic layer. The layer may be an enzyme immobilized into a matrix. An example of such a sensor is the enzyme thermistor using an immobilized glucose oxidase (GOD). The enzymes are immobilized on the tip of the thermistor, which is then enclosed in a glass jacket in order to reduce heat loss to the surrounding solution. Another similar sensor with similarly immobilized bovine serum albumin is used as a reference. Both thermistors are connected as the arms of a Wheatstone bridge [68]. The temperature increase, dT, as a result of a chemical reaction is proportional to the incremental change in the enthalpy dH

$$dT = \frac{1}{C_p} dH, \tag{17.15}$$

where C_p is the heat capacity.

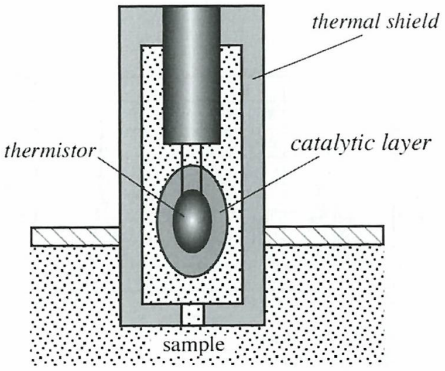


Fig. 17.19 Schematic diagram of a chemical thermal sensor

Amazon EX1034 Page 79

The chemical reaction in the coating is

$$\beta - \text{D-glucose} + H_2O + O_2 \xrightarrow{\text{GOD}} H_2O + \text{D-gluconic acid}, \Delta H_1, \quad (17.16)$$

and

$$H_2O_2 \xrightarrow{\text{catalase}} \frac{1}{2}O_2 + H_2O, \Delta H_2, \quad (17.17)$$

where ΔH_1 and ΔH_2 are partial enthalpies, the sum of which (for the above reaction) is approximately -80 kJ/mol. The sensor responds linearly with the dynamic range depending on the concentration of hydrogen peroxide (H_2O_2).

17.4.4.5 Pellister Catalytic Sensors

Pellisters and other catalytic sensors operate on the principle similar to thermal enzymatic sensors. Heat is liberated as a result of a catalytic reaction taking place at the surface of the sensor and the related temperature change inside the device is measured. On the other hand, the chemistry is similar to that of high temperature metal-oxide sensors. Catalytic gas sensors have been designed specifically to detect low concentrations of flammable gases in ambient air inside mines. These sensors often are called pellisters [69]. The platinum coil is imbedded in a pellet of ThO_2/Al_2O_3 coated with a porous catalytic metal: palladium or platinum (Fig. 17.20). The coil acts as both the heater and the resistive temperature detector (RTD). Naturally, any other type of heating element and temperature sensor can be successfully employed. When the combustible gas reacts at the catalytic surface, the heat evolved from the reaction increases the temperature of the pellet and of the platinum coil, thus increasing its resistance. There are two possible operating modes of the sensor. One is isothermal, where an electronic circuit controls the current through the coil to maintain a constant temperature. In the nonisothermal

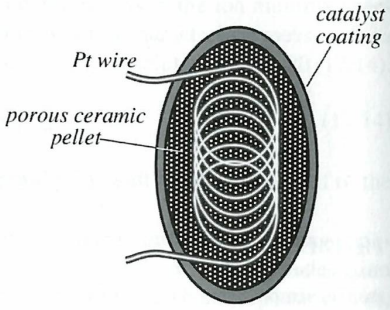


Fig. 17.20 Pellister or catalytic type detector

Chapter 18
Sensor Materials and Technologies

Any sufficiently advanced technologyis in distinguishable from magic.

– Arthur C. Clarke

Methods of sensor fabrication are numerous and specific for each particular design. They comprise processing of semiconductors, optical components, metals, ceramics, and plastics. Here, we briefly describe some materials and the most often used techniques.

18.1 Materials

18.1.1 Silicon as Sensing Material

Silicon is present in the sun and stars and is a principal component of a class of meteorites known as aerolites. Silicon is the second most abundant material on Earth, being exceeded only by oxygen – it makes up to 25.7% of the earth's crust, by weight. Silicon is not found free in nature but occurs chiefly as the oxide and as silicates. Some oxides are sand, quartz, rock crystal, amethyst, clay, mica, etc. Silicon is prepared by heating silica and carbon in an electric furnace using carbon electrodes. There are also several other methods for preparing the element. Crystalline silicon has a metallic luster and grayish color.[1] The Czochralski process is commonly used to produce single crystals of silicon used for the solid-state semiconductors and micromachined sensors. Silicon is a relatively inert element, but it is attacked by halogens and diluted alkali. Most acids, except hydrofluoric, do not affect it. Elemental silicon transmits infrared radiation and is commonly used as windows and lenses in the mid- and far-infrared sensors.

[1]Silicon should not be confused with *silicone* that is made by hydrolyzing *silicon* organic chloride such as dimethyl silicon chloride. Silicones are used as insulators, lubricants, and for production of silicone rubber.

J. Fraden, *Handbook of Modern Sensors*,
DOI 10.1007/978-1-4419-6466-3_18, © Springer Science+Business Media, LLC 2010

Amazon EX1034 Page 81