CHAPTER 8.4
TRANSDUCERS FOR ACOUSTIC, OPTICAL, AND ELECTRICAL QUANTITIES

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TRANSDUCERS FOR ACOUSTIC QUANTITIES

Terminology

Sound is an oscillation in pressure, stress, particle displacement, or other physical characteristics, in an elastic or viscous medium. *Sound sensation* is the auditory sensation evoked by the oscillations associated with sound. *Sound pressure* is the total instantaneous pressure at a given point, in the presence of a sound wave, minus the static pressure at that point. *Sound pressure level* (SPL or L_p) is 20 times the logarithmic ratio of the mean-square sound pressure p to a mean-square reference pressure p_{ref}. It is normally expressed in decibels as SPL = 20 log ($p_{rms}/p_{ref.rms}$). The reference pressure is usually specified as 2×10^{-4} μbar, sometimes as 1 μbar (0.1 Pa). *Sound level* is a weighted sound-pressure-level reading obtained with a meter complying with a standard, e.g., ANSI Standard S1.4, Specification for General-Purpose Sound Level Meters.

Sound-Pressure Transducers

The sensing element of a sound-pressure transducer is almost invariably a diaphragm. The reference cavity behind the diaphragm is vented to the ambient atmosphere by means of a small hole in the transducer case so that static pressures on both sides of the diaphragm are equalized and only sound pressure is sensed.

A perforated cap over the diaphragm protects the diaphragm mechanically and, by its shape and geometry of perforations, provides some control over the transducer's directivity characteristics.

Sound-pressure transducers can be described, essentially, as special-purpose gage-pressure transducers. *Capacitive sound-pressure transducers* (usually called *condenser microphones*) use the sensing diaphragm as one electrode of a capacitor and a rigidly supported back plate, insulated from the rest of the structure but provided with a connecting lead or terminal, as the other electrode. A dc polarization voltage, applied across the two electrodes through a high-series resistance, maintains a constant charge on them. Capacitance changes due to diaphragm deflection cause changes in the voltage across the electrodes. The transducer output is first fed to an emitter follower so as to reduce the output impedance to a workable value. The output is the amplified. The emitter-follower (or cathode-follower) circuitry is sometimes built into the transducer case to keep the coupling path short. A shielded cable connects the transducer to the amplifier.

Piezoelectric and, to a limited extent, *inductive pressure transducers* have also been designed as sound-pressure transducers. Some piezoelectric designs have sealed cases, primarily to protect the internal components from atmospheric moisture and contaminants. The absence of a gage vent, however, necessitates correction of output readings when the transducer is used at low ambient pressures (e.g., high altitudes). Piezoelectric transducers do not require an excitation power supply but do require an amplifier.

The primary performance characteristics of sound-pressure transducers are range, output, frequency response, and directivity (directional response). Output is usually expressed as sensitivity or sensitivity level, sometimes as full-scale output for a stated range of sound pressures or sound-pressure levels.

Sound-Level Meters

Sound-level meters are complete, self-contained measuring systems, typically battery-operated and portable. A sound-level meter consists of a sound-pressure transducer (microphone), amplifier, standardized weighting networks, a calibrated attenuator, and an indicating meter. The sound-level range is always referred to a sound pressure of 10^{-4} μbar. The weightings denote different frequency-response characteristics of the measuring system. Referred to merely as A, B, or C, they are defined in a national standard as, for the United States, ANSI Standard S1.4.

Underwater Sound Detectors

Underwater sound detectors are used either for listening (*hydrophone*) or, in conjunction with an *underwater sound projector*, in sonar (*so*und *n*avigation *a*nd *r*anging) systems. The transmitting and receiving function in a sonar system are frequently combined in a single device (sound transceiver). In the sonar field, underwater sound detectors, as well as projectors and transceivers, are commonly referred to as *transducers*.

TRANSDUCERS FOR OPTICAL QUANTITIES

Terminology

Light is a form of radiant energy, an electromagnetic radiation whose wavelength is between approximately 100 and 0.01 μm. By strict definition, only visible light (0.4 to 0.76 μm wavelength) can be considered as light, and infrared or ultraviolet light is then termed *radiation*. The light spectrum, in terms of wavelengths, frequency, photon energy, and blackbody temperature (all interrelated by physical laws), is illustrated in Fig. 8.4.1 with the visible-light spectrum (color spectrum) brought out in detail.

The transduction elements of light sensors (photocells, photosensors, *photodetectors*, light detectors) also act as sensing elements since they convert electromagnetic radiation into a usable electrical output. Four transduction principles are commonly used: photovoltaic, photoconductive, photoconductive junction, and photoemissive (see Fig. 8.4.2).

Photovoltaic Light Sensors

Photovoltaic light sensors are self-generating in that their output voltage is a function of the illumination of a junction between two dissimilar materials. These materials are semiconductive, either nonmetallic or metal compounds (Fig. 8.4.2*a*). Photons (particles of light) first pass through a thin conductive layer, and then impinge on the junction, causing an electron flow across the junction area so that the conductive layer becomes the negative terminal of the sensor. Various materials constitute the conductive and semiconductive portions of a photovoltaic light sensor.

The *silicon cell* (silicon photovoltaic cell, silicon solar cell) uses an arsenic-doped *n*-type silicon wafer. Boron is diffused into the upper (light-receiving) surface to create a thin *p*-type silicon layer. The *pn* junction between the layer and the wafer acts as a permanent electric field. Photons incident upon the junction cause a

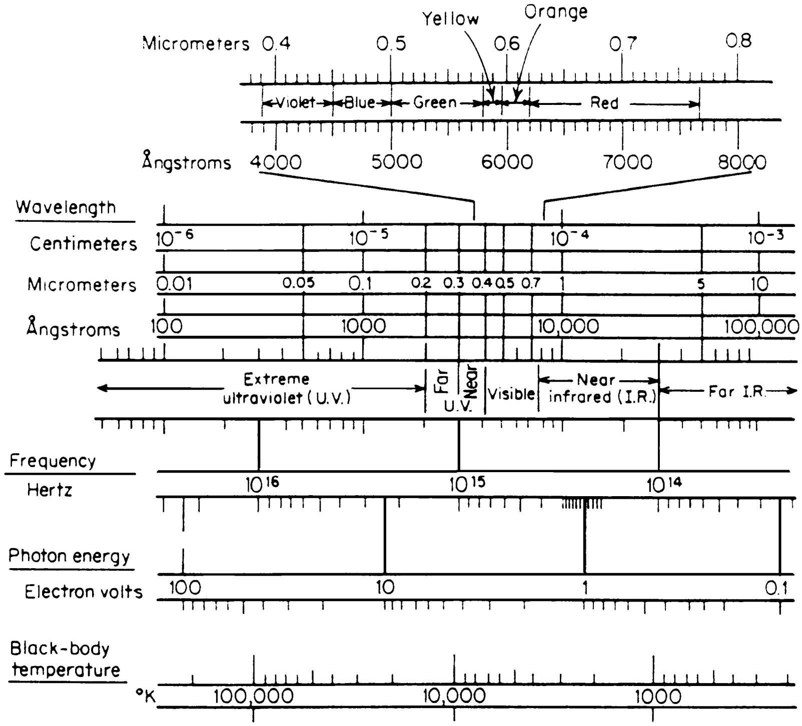

FIGURE 8.4.1 The light spectrum. (*From Ref. 1 by permission*)

flow of positive and negative charges. The *pn* junction, acting as an electric field, directs the positive charges into the *p*-type material (nickel plating around its edge forms the positive connecting terminal) while directing the negative charges into the *n*-type material (solder around the bottom edge of the silicon wafer forms the negative connecting terminal). The third connecting pin serves as a case connection.

Germanium photovoltaic light sensors are similar to silicon types but have a different spectral response (a peak near 1.55 μm, as compared with 0.8 to 0.9 μm for silicon). Special "blue-enhanced" silicon cells have spectral responses with their peak as low as 0.56 μm (the nominal peak of the human eye's response). *Indium-arsenide* (InAs) and *indium-antimonide* (InSb) photovoltaic sensors have spectral-response peaks near 3.5 and 6.8 μm, respectively, at room temperature. They are single-crystal *pn* junction semiconductors, used primarily for infrared-light sensing. In such applications they are often cooled artificially to increase their sensitivity.

Photoconductive Light Sensors

Photoconductive light sensors are widely used for conrol functions, such as automatic exposure control in cameras, in addition to their photometric (light-measurement) applications. The photoconductors are polycrystalline films or bulk single-crystal materials which, when contained between two conductive electrodes, act as light-sensitive resistors (Fig. 8.4.2*b*) whose resistance decreases as incident illumination increases. *Cadmium sulfide* (CdS) and *cadmium selenide* (CdSe) are popular because of their spectral-response peaks in the visible-light region (approximately 0.6 μm for CdS, 0.72 μm for CdSe) and because of their relatively high output without artificial cooling. Some photoconductive sensors use mixed CdS–CdSe crystals to obtain a response peak around 0.66 μm.

Lead sulfide (PbS) and *lead selenide* (PbSe) photoconductive cells are used for infrared-light sensing because their spectral-response peaks are close to 2.2 μm. The spectral-response curve of PbSe, however, is shallow enough to provide good sensitivity between about 1.8 and 3.6 μm, and its time constant is less than

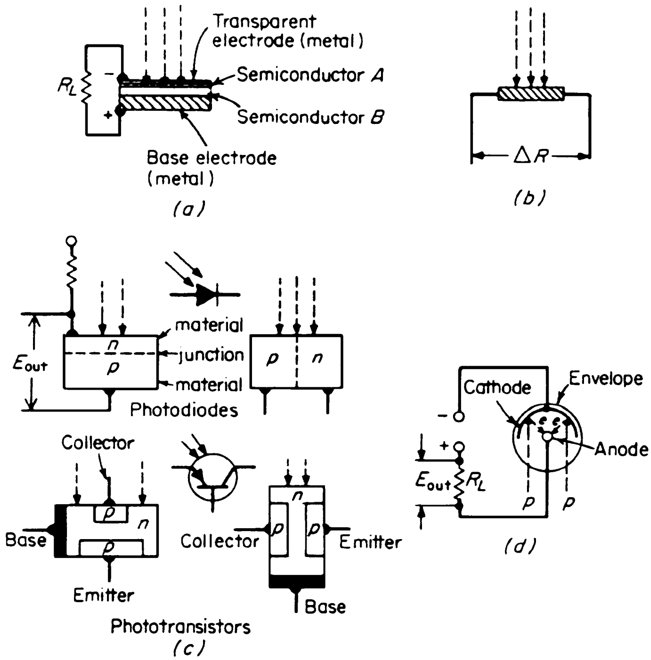

FIGURE 8.4.2 Basic methods of light transduction: (*a*) photovoltaic; (*b*) photoconductive; (*c*) photoconductive junction semiconductor; (*d*) photoemissive. (*From Ref. 1 by permission*)

one-tenth that of PbS. *Mercury-doped-germanium* (HgGe) photoconductive sensors have been used for far-infrared measurements while being cooled to cryogenic temperatures. *Lead-tin-telluride* (PbSnTE) sensors are always cooled to 77 K and have a spectral response in the 8- to 12-μm region. *Mercury-cadmium-telluride* sensors operate at 77 to 120 K and have a spectral response within the overall region of 2 to 14 μm adjustable by varying the proportions of the three materials.

Photoconductive Junction Sensors

In these devices the resistance across the junction in a semiconductor device changes as a function of incident light (Fig. 8.4.2*c*). Increasing incident illumination causes the junction photocurrent to increase. This category of photosensors includes *photodiodes* and *npn* as well as *pnp phototransistors.* They are made of silicon, with a spectral peak near 1.0 μm, except when germanium must be used to raise the spectral peak to about 1.6 μm. Time constants of photodiodes and phototransistors are less than 1 μs (compared with 10 μs for PbSe photoconductive sensors; 100 to 700 μs for PbS photoconductive sensors; 10 ms for CdSe photoconductive cells; and 100 ms for CdS cells but around 20 μs for silicon photovoltaic cells). Transistors also provide some amplification of the light-induced signal. Both types are usually sealed into a standard transistor can, sometimes furnished with a lens or window. A special silicon photodiode design has also been developed for ultraviolet measurements (0.06- to 0.25-μ region).

Photoemissive Sensors

The earliest *photoemissive light sensor* was the phototube, in which electrons are emitted by the cathode of a vacuum (or gas-filled) diode tube when photons impinge on the cathode surface (Fig. 8.4.2*d*). When a closely spaced anode is at a positive potential with respect to the cathode, the anode collects some of these electrons, and the resulting anode current can produce an output voltage as an *IR* drop across a suitable load resistor (R_L).

The photoemissive principle is now employed mostly by *photomultiplier* tubes, in which additional electrodes (*dynodes*) are placed between cathode (*photocathode*) and anode to amplify the electron current by means of secondary emission. An additional dynode is located behind the anode. A voltage divider network is used to apply a successively higher voltage to each of the dynodes as they approach the anode in proximity. Various spectral-response peaks can be obtained, depending on the photocathode material and material of that portion of the sealed envelope directly in front of the cathode (the *window*). Photomultiplier tubes are particularly useful in the visible-light and ultraviolet regions. They can provide very high sensitivities without artificial cooling.

Selection criteria for light sensors are, primarily, spectral-response characteristics and sensitivity and, secondarily, operating temperatures, relative complexity of associated circuitry, ruggedness, and cost. Where the spectral-response must be limited to only a portion of a sensor's basic response capabilities, a window can be placed in front of the sensing surface. Windows are optical filters which have spectral-response characteristics of their own, depending on their material. Typical window spectral responses are 0.2 to 1.4 μm (quartz crystal or fused silica), 0.4 to 1.2 μm (borosilicate glass), 0.15 to 1.6 μm (cultured sapphire), 0.11 to 1.8 μm (lithium fluoride), 0.12 to 11 μm (calcium fluoride), and 0.25 to 50 μm (cesium iodide).

Spectrometers and Colorimeters

Light sensors in conjunction with light sources are used in a number of measuring devices other than for photometry. In optical *spectrometers* the incident light is passed through a *monochromator,* which can be a filter or set of filters, or a grating or prism whose angular displacement relative to the incoming light beam can be closely correlated with the single wavelength (or narrow band of wavelengths) it sends on to the light sensor. The latter, in turn, is selected so that its spectral responses match the wavelegth (or wavelengths) of interest. The angular motion of the prism or grating can be mechanized so that a given spectrum is scanned at a known rate over a known time interval. The wavelength of an observed peak can then be determined from the time counted from the start of a scan. Spectrometers can be called *spectrophotometers* when their spectral range extends anywhere between ultraviolet to infrared. They are really a subclass of *spectroradiometers* whose spectra can include any electromagnetic radiation from gamma rays to microwaves. Spectroradiometers are widely used to determine chemical composition from the spectral distribution of electromagnetic energy.

Spectrophotometers exist in the following three basic categories: (1) In an *absorption spectrophotometer* the collimated beam from an artificial light source passes through a monochromator, then through the sample whose composition is to be determined, and finally to the light sensor (photodetector). (2) In an *emission spectrophotometer* the polychromatic light from a hot or heated sample (or body) is collimated and passed through the monochromator to the photodetector. (3) In a *fluorescence spectrophotometer* monochromatic wavelengths are selected from the polychromatic emissions of a light source (or other source of electromagnetic radiation) by the *excitation monochromator.* The collimated monochromatic beam is directed at the sample in which fluorescence will occur. The fluorescent light is then analyzed for spectral content by a second monochromator (*emission monochromator*) in conjunction with the photodetector. Spectroradiometers, including those operating in nonoptical wavelengths, are described in more detail in Ref. 2.

The *colorimeter* is a specialized type of spectrophotometer whose light-source-filter-photodetector combination simulates the tristimulus functions of human visual color perception (*tristimulus colorimeter*). Three filters and either one or three photodetectors are used to obtain three separate outputs which represent (in their simplest form) the amount of "red," "green," and "blue" reflected from a sample.

Interaction of Light with Substances

A light-source-photodetector combination is also used for material characterization in instruments other than colorimeters and spectrophotometers. The most common application of such instruments is in the detection of particulates in gases and liquids. The *turbidimeter, opacity sensor,* and *transmittance sensor* all employ the same operating principle: The collimated beam from a light source passes through the sample onto a photodetector. The latter sees maximum light intensity when the sample is perfectly clear. When the (gaseous or liquid) sample contains solid particles, the amount of light received by the photodetector is attenuated. The attenuation is due primarily to *absorption* or *scattering* or a combination of both. In a *nephelometer* the photodetector is mounted normal to the axis of the light beam entering the sample. Thus, the photodetector responds to light scattered from the sample at 90°, and its output increases with increasing turbidity in the sample. The detection threshold can be improved by adding a second photodetector at 180° to the first one. The transmitted light is either absorbed by a hood or sensed by an additional photodetector for reference purposes. The *fluorimeter* employs a source of ultraviolet light to cause *fluorescence* in a sample; i.e., the light is first absorbed and then is reemitted after a very short time (about 10^{-8} s). When the time of reemission is much longer, the phenomenon is known as *phosphorescence.* The incoming light is first passed through a filter for wavelength selection. The reemitted light is sensed (after filtering to exclude nonfluorescent products) by a photodetector mounted normal to the axis of the incident light beam. A *refractometer* measures the *index of refraction* of a sample, usually by having its photodetector sense the light reflected from the boundary between two media of different density (and, hence, a different index of refraction). As more light is lost because of refraction in the second medium, less light is reflected back to the photodetector. Its output is then typically compared with that of a reference photodetector that receives all the light from the light source. For more details on these, as well as other analysis instruments, see Ref. 2.

TRANSDUCERS FOR ELECTRICAL QUANTITIES

Current Sensors

Current measurements can be made by various devices acting as transducers. A *series resistance,* inserted into the conductor where current is to be measured, provides a usable voltage across it because of the *IR* drop caused by the resistance. When the series resistance is relatively low, it is referred to as a *shunt.*

If it is necessary to keep the measurement circuit electrically isolated from the measured circuit (which is always desirable), a differential amplifier can be used, with its input terminals closely coupled across the series resistance so that its output terminals can be isolated from the measured circuit, and so that a signal sufficient for telemetry can be provided without inserting too high a series resistance into the measured circuit. This method is usable for both ac and dc currents. Other isolating current transducers are the *saturable reactor,* an adjustable inductor in which the input-current versus output-voltage relationship is adjusted by controlled magnetomotive forces applied to the core, and the *Hall effect* current transducer, in which an output-voltage change is produced by measured-current-originated electromagnetic effects on a semiconductor placed in a magnetic field. The *current transformer* can be used to convert the measured current, with circuit isolation, into an output current or voltage.

Electrometers

Small currents (down to 10^{-15} A) can be measured by means of an *electrometer tube* or by special semiconductor devices such as an amplifier with varactor diodes, metal-oxide semiconductor field-effect transistors (MOSFET), or junction field-effect transistors. All these devices require output amplification to provide signals suitable for remote measurement. When current must be measured on the high-voltage secondary side of a transformer, the current in the low-voltage primary can often be measured instead, and a suitable calibration used to correlate the two currents.

Voltage Sensors

DC and ac voltages can be monitored by means of a voltage divider connected across the two terminals to be measured. A voltage divider consists of two resistors in series, with the output taken across only one of the two resistors when a signal lower than the actual voltage is required by the measurement system. AC voltages are most frequently sensed by a *voltage transformer* or by Hall effect devices.

Frequency Converters and Dividers

Frequency can be converted into a voltage signal by use of a tuned discriminator or of integrating circuitry. When a digital signal is required, the measured frequency can be passed through an electronic "gate" which is "opened" for a fixed period of time. The pulse count over the gated period is then indicative of the frequency. If the measuring system can accept a frequency, but one much lower than the measured frequency, a *frequency divider* circuit can be used to provide an output frequency which is a fixed fraction of the input frequency.

Power Sensors

Power measurements have often been derived from simultaneous but separate voltage and current measurements. *Hall multipliers* are now in common use for power measurements. In these devices voltage changes are transformed into excitation current changes; simultaneously, current changes are used to change the magnetic field applied to the Hall device. Power (especially at microwave frequencies) is also measured by using a portion of the power to raise the temperature of a resistive temperature transducer (e.g., a thermistor), then measuring the temperature change, which can be correlated to measured power by a suitable calibration. Such a sensor is often referred to as a *bolometer.*

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