2.0 Introduction

The front-end of all biomedical instruments includes either a sensor or actuator, or both. In this course we will focus on sensing systems where the front-end is some form of electric transducer, converting a physical/chemical parameter into an electric signal (i.e., current or voltage). In this chapter we introduce some common biosensors to measure displacement, temperature, radiation intensity, optical intensity, etc.

2.1 Displacement Measurements

Motion is one of the most fundamental physical concepts used to characterize biological systems. Displacement sensors are employed in both direct and indirect measurement systems to monitor mechanical stimulus (i.e., force or pressure) and response (i.e., displacement, deformation, flow, etc.).

In this chapter we’ll introduce basic resistive, inductive, capacitive, and piezoelectric devices for displacement sensing. We’ll use macroscopic structures to introduce these devices. Many of these principles, however, translate to microscopic scales. For example, the semiconductor strain gage presented below can be easily miniaturized using modern silicon processing technology. Many of these basic principles apply to MEMS devices.

2.2 Resistive Sensors

Three types of potentiometric devices for measuring displacement are show below.

![Diagram showing three types of potentiometric devices for measuring displacements.](image)

**Figure 2.1** Three types of potentiometric devices for measuring displacements (a) Translational. (b) Single-turn. (c) Multi-turn. (From Measurement Systems: Application and Design, by E. O. Doebelein. Copyright © 1990 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Co.)
a.) Translation - a simple linear pot produces an output voltage proportional to the output position \( x \) (\( x_0 \) is the total length of the pot) as:

\[
v_0 = v_i \frac{x}{x_0}
\]

b/c.) Rotation - a single-turn pot, or multi-turn helical pot, produces an output voltage proportional to rotational displacements \( \phi \) (\( \phi_0 \) is the total length of the pot) as:

\[
v_0 = v_i \frac{\phi}{\phi_0}
\]

Both the source and output voltages can be direct current (DC) or alternating current (AC). The resolution of these devices is determined by the potentiometer material and dimensions. Typically, these simple devices are used to measure fairly large displacements with modest resolution (e.g., 0.05-0.1 mm).

More precise displacement measurements are usually obtained with strain gages. When a fine wire (typically from 5 \( \mu \)m to 25 \( \mu \)m thick) is strained within its elastic limit, the wire’s resistance changes because of alterations in its diameter, length and resistivity. With a properly designed device, displacements as small as several nanometers can be reproducibly recorded. Consider a simple cylindrical wire of resistivity \( \rho \) (ohms-meter), length \( L \) (meters), and cross-sectional area \( A \) (meter\(^2\)). The resistance is:

\[
R = \frac{\rho L}{A}
\]

The differential change in the resistance due to parametric variations is:

\[
dR = \frac{\rho dL}{A} - \rho A^{-2} dA + \frac{L d\rho}{A}
\]

Normalizing this change to the resistance and introducing incremental changes in device parameters using \( \Delta \) notation, we get

\[
\frac{\Delta R}{R} = \frac{\Delta L}{L} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho}
\]

The Poisson’s ratio \( \mu \) of a material relates the change in diameter to the change in length (\( \Delta D/D = -\mu \Delta L/L \)). Using this material parameter, the relative resistance change becomes:

\[
\frac{\Delta R}{R} = (1 + 2\mu) \frac{\Delta L}{L} + \frac{\Delta \rho}{\rho}
\]

The first term on the right hand side is the resistance change due to dimensional (i.e., geometric strain) effects and the second term is the change due to piezoresistive effects. The gage factor (ratio of normalized resistance change to applied strain) quantifies this relation for different materials:

\[
G = \frac{\Delta R / R}{\Delta L / L} = (1 + 2\mu) + \frac{\Delta \rho / \rho}{\Delta L / L}
\]
Two types of materials are most common for practical strain gages. Metals have a gage factor dominated by dimensional effects. In contrast, semiconductor materials have a much larger gage factor dominated by piezoresistive effects. Semiconductor devices are more sensitive. However, the resistivity varies with temperature much more in semiconductors than metals. This means strain gages made from semiconductors will be much more sensitive than equivalent metal ones but they must include temperature compensation to insure accurate results.

Strain gages are classified as bonded or unbonded. Bonded gages are cemented to the strained surface under investigation. Unbonded gages are free standing for such applications as converting blood pressure to diaphragm movement, to resistance change, then to an electrical signal. An example of an unbonded gage is presented below.

Figure 2.2 (a) Unbonded strain-gage pressure sensor. The diaphragm is directly coupled by an armature to an unbonded strain-gage system. With increasing pressure, the strain on gage pair B and C is increased, while that on gage pair A and D is decreased. (b) Wheatstone bridge with four active elements. $R_1 = B$, $R_2 = A$, $R_3 = D$, and $R_4 = C$ when the unbonded strain gage is connected for translational motion. Resistor $R_y$ and potentiometer $R_x$ are used to initially balance the bridge. $v_i$ is the applied voltage and $\Delta v_o$ is the output voltage on a voltmeter or similar device with an internal resistance of $R_i$. 
The four sets of strain-sensitive wires (a) are connected to form a Wheatstone bridge circuit (b). The wires are mounted under stress between the frame and the moveable armature such that the preload is greater than an expected external compressive load. Pressure applied to the diaphragm differentially deforms the wires to produce a voltage across the bridge. The bridge circuit will be analyzed below.

Typical bonded strain gages are illustrated below.

![Figure 2.3 Typical bonded strain-gage units](image)

(a) Resistance-wire type. (b) Foil type. (c) Helical-wire type. Arrows above units show direction of maximal sensitivity to strain. [Parts (a) and (b) are modified from *Instrumentation in Scientific Research*, by K. S. Lion. Copyright © 1959 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Co.]

These devices must be temperature compensated for most applications. One common method for temperature compensation uses a second strain gage as a “dummy”, which is subjected to the same temperature conditions as the active sensor but is not subjected to strain. When possible, the four arm bridge with four active sensors shown above should be used because it provides not only temperature compensation but also four times greater output if all four arms contain active gages - more on this later.

Semiconductor strain gages use the same principles as the wire/foil gages shown above. In addition to large gage factors, however, these devices can be integrated in complete electro-mechanical systems using silicon technology. The figure below illustrates a typical semiconductor strain gage configuration. The integrated pressure sensor (c) has the gages directly integrated into the diaphragm transducing pressure into displacement. The gages near the edge sense a radial stress whereas those at the center experience a tangential stress. The placement of the eight diffused strain-gage units gives high sensitivity and good temperature compensation.

Elastic strain gages are typically linear within 1% for 10% of maximum extension. As the extension increases to 30% of maximum, the nonlinearity reaches 4% of full scale. Overall, strain gages provide good linearity over a wide dynamic range. Foil gages are
selected over semiconductor gages only for macroscopic applications where significant pressure or displacement/velocity must be recorded.

2.3 Bridge Circuits

The Wheatstone bridge is ideal to measure small changes in resistance. Consider the simple bridge circuit of Figure 2.2b above. The resistors $R_y$ and $R_x$ are included for bridge balancing. If we ignore these components for the moment, the bridge reduces to the simple circuit shown below. For the bridge to be balanced (i.e., $V_0 = 0$), the loop equation reduces to:

$$\frac{R_3}{R_2 + R_3} = \frac{R_4}{R_1 + R_4}$$

or,

$$\frac{R_1}{R_2} = \frac{R_4}{R_3}$$
If the bridge resistors are sensors, then changes in the bridge voltage ($V_0$) can be simply related to changes in resistance. For example, assume that all bridge resistors equal $R_0$. As increase in resistance, $\Delta R$, of all resistance still results in a balanced bridge. However, if $R_1$ and $R_3$ increase by $\Delta R$, and $R_2$ and $R_4$ decrease by $\Delta R$, then

$$\Delta V_0 = \frac{\Delta R}{R_0} V_i$$

Consequently, $\Delta V_0$ is linearly related to $\Delta R$. Also, note that using a balanced bridge in this way assures that the sensor is temperature compensated if all four sensors in the bridge have the same temperature coefficient of resistivity. An example of a bridge balanced strain gage for plethysmography (i.e., displacement or volume sensor) is illustrated in the figure below.

Figure 2.5  Mercury-in-rubber strain-gage plethysmography  (a) Four-lead gage applied to human calf. (b) Bridge output for venous-occlusion plethysmography. (c) Bridge output for arterial-pulse plethysmography. [Part (a) is based on D. E. Hokanson, D. S. Sumner, and D. E. Strandness, Jr., “An electrically calibrated plethysmograph for direct measurement of limb blood flow.” 1975, BME-22, 25–29; used with permission of IEEE Trans. Biomed. Eng., 1975, New York.]
2.4 Inductive Sensors

The inductance of a coil is simply related to the coil parameters:

\[ L = n^2 G \mu \]

where \( n \) is the number of turns in the coil, \( G \) is the geometric form factor, and \( \mu \) is the effective permeability of the medium. Each of these parameters can be changed by mechanical means so that changes in inductance can be used to sense displacement/force.

The figure below shows self-inductance (a), mutual-inductance (b), and differential transformer (c) types of inductive displacement sensors. Note that a mutual-inductance device becomes a self-inductance device when terminals b-c are connected.

![Figure 2.6 Inductive displacement sensors](image)

(a) Self-inductance. (b) Mutual inductance. (c) Differential transformer.

An inductive sensor has an advantage in not being affected by the dielectric properties of its environment. However, it may be affected by external magnetic fields due to the proximity of magnetic materials. The basic principles of operation for each type of inductive sensor are cataloged below:

Self-inductance:

⇒ Change geometric form factor of coil or move magnetic core within coil to change inductance.
⇒ Inductance change is not linearly related to displacement
⇒ Inherently low power devices (low loss across single coil)

Mutual-inductance:

⇒ Induced voltage in the secondary coils is a function of the coil geometries (i.e., coil separation and axial alignment), the number of primary and secondary turns, and the frequency and amplitude of the excitation voltage.
⇒ Inductance voltage is not linearly related to displacement (i.e., coil separation)
⇒ Output voltage is detected with standard demodulator and amplifier circuits.

Differential- Transformer:

⇒ Linear variable differential transformer (LVDT) is most common type consisting of a primary coil and two secondary coils connected in series.
⇒ Coupling between these two coils is changed by the motion of a high-permeability alloy slug between them. The two secondary coils are connected in opposition to produce a wider linearity region.
⇒ The device is excited by a sinusoidal voltage typically in the frequency range from 60 Hz to 20 kHz. The output voltage $V_{cd}$ is zero when the slug is symmetrically placed, and changes linearly as the slug displaces from this position.
⇒ The output signal from this device is complicated, as illustrated below, and requires complex demodulation for proper interpretation. More about this type of signal processing later in the course.

![Diagram showing displacement and voltage](image)

**Figure 2.7** (a) As $x$ moves through the null position, the phase changes $180^\circ$, while the magnitude of $v_o$ is proportional to the magnitude of $x$. (b) An ordinary rectifier-demodulator cannot distinguish between (a) and (b), so a phase-sensitive demodulator is required.
2.5 Capacitive Sensors

The capacitance between two parallel plates of area A separated by a distance x is:

\[ C = \varepsilon_0 \varepsilon_r \frac{A}{x} \]

where \( \varepsilon_0 \) is the dielectric constant of free space and \( \varepsilon_r \) is the relative dielectric constant of the insulator between the plates. Displacement is commonly sensed with a capacitor by measuring capacitance changes as the plate separation is changed. The sensitivity of the sensor, therefore, is:

\[ K = \frac{\Delta C}{\Delta x} = -\varepsilon_0 \varepsilon_r \frac{A}{x^2} \]

or the relative change in capacitance for a relative displacement change is:

\[ \frac{\Delta C}{C} = -\frac{\Delta x}{x} \]

Capacitance sensors are most commonly used to monitor dynamic displacement changes. For example, the capacitance microphone shown in the figure below is commonly used to measure AC displacements. The circuit is DC excited (i.e., \( V_1=E \) when the capacitor is stationary). A change in position \( \Delta x \) produces a voltage \( V_0=V_1-E \). The dynamics of this sensor are determined by the RC time constant of the sensor/pre-amp configuration.

![Capacitance sensor for measuring dynamic displacement changes](image)

Traditional capacitance sensors operating at fairly low frequencies are often large devices. Modern MEMS devices use very small capacitors operating at high frequencies (typically in the MHz range) for sensing applications. One example is a capacitive transducer used for ultrasonic imaging. Modern MEMS structures consisting of many small capacitors operating in phase can form a macroscopic transducer with efficiencies rivaling state of the art piezoelectric transducers. Since silicon based capacitive microphones can be easily integrated into integrated electronic microsystems, this type of transducer is being investigated for several integrated sensing applications. The primary limitation of these devices is that the capacitor must be DC excited. To get high conversion efficiencies, the voltage is often quite high. Piezoelectric devices often aren’t compatible with silicon based technologies, but they do remove the need for DC excitation. More on this in the next section.
2.6 Piezoelectric Sensors

Piezoelectric sensors act like capacitive sensors without the need for DC excitation. Piezoelectric materials generate an electric potential when mechanically strained (sensor applications), and conversely an electric potential can cause physical deformation of the material (actuator applications). The deformation energy and electrical energy are reciprocal variables in these materials, but the extrinsic strain to voltage or voltage to strain conversion efficiencies are not reciprocal. This means for practical applications that some materials are good as piezoelectric sensors and different materials are good as piezoelectric actuators.

For sensor applications, the constitutive relation in a piezoelectric material relates the charge \( q \) to the applied force \( F \).

\[
q = k F
\]

where \( k \) is the piezoelectric constant in units of coulombs/newton. The associated voltage can be found by assuming that the system acts like a parallel-plate capacitor, yielding

\[
V = \frac{k F}{C} = \frac{k F x}{\varepsilon_0 \varepsilon_r A}
\]

For a parallel plate configuration, the equivalent circuit of a piezoelectric sensor is given below:

![Equivalent circuit of piezoelectric sensor](image)

**Figure 2.9** (a) Equivalent circuit of piezoelectric sensor, where \( R_s = \) sensor leakage resistance, \( C_s = \) sensor capacitance, \( C_c = \) cable capacitance, \( C_a = \) amplifier input capacitance, \( R_a = \) amplifier input resistance, and \( q = \) charge generator. (b) Modified equivalent circuit with current generator replacing charge generator. (From Measurement Systems: Application and Design, by E. O. Doebelin. Copyright © 1990 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Co.)
Note that the equivalent circuit acts as a first order system, where the sensitivity is simply proportional to the piezoelectric constant and the time constant of the system is simply the RC product of the equivalent circuit. The time response of this system to a step displacement excitation is illustrated below.

**Figure 2.10** Sensor response to a step displacement  (From Doebelin, E. O. 1990. *Measurement Systems: Application and Design*, New York: McGraw-Hill.)

For high frequency applications of piezoelectric sensors (e.g., ultrasonic sensors used in Doppler flow systems), mechanical resonance in the parallel plate configuration must be taken into account to describe the full dynamic response of the sensor. For these applications a 2nd order model is more appropriate, as illustrated below.

**Figure 2.11** (a) High-frequency circuit model for piezoelectric sensor. $R_s$ is the sensor leakage resistance and $C_s$ the capacitance. $L_m$, $C_m$, and $R_m$ represent the mechanical system. (b) Piezoelectric sensor frequency response. (From *Transducers for Biomedical Measurements: Principles and Applications*, by R. S. C. Cobbold. Copyright © 1974, John Wiley and Sons, Inc. Reprinted by permission of John Wiley and Sons, Inc.)
2.7 Fiber Optic Displacement Sensors

With the advent of high stability, low cost, and small semiconductor lasers, fiber optic resonators can be used for displacement measurements when high resolution measurements are needed over a relatively small dynamic range. Some form of optical resonator is incorporated into the fiber for sensing. The basic principle for this type of displacement sensor is illustrated below.

An optical etalon (i.e., resonator) is formed with two reflecting mirrors placed on opposite surfaces of a transparent medium. As illustrated in the top left, an incident laser source illuminates the resonator. The wavelength of the incident light is chosen so that the reflected light is determined by the resonator curve illustrated in the lower right. The quiescent operating point is placed at the maximum slope region of the resonator. As the front surface of the resonator displaces with respect to the back surface, the cavity thickness changes and the output intensity changes as illustrated in the lower right. Very high resolution measurements can be made with this system, but only over the limited operating range (i.e., dynamic range) of the resonance curve. Such sensors are used in high frequency applications such as optical microphones.

These same type of sensors can be used for precise temperature measurements. If the optical material of the resonator is chosen to have a high coefficient of thermal expansion, then the resonator thickness, and hence the output intensity, will vary linearly with temperature over the operating range of the resonator.
2.8 Temperature Measurements

The temperature of the whole body, and of particular tissue structures relative to their surroundings, is one of the most important physiologic parameters of clinical interest. There are a number of temperature sensors; each is chosen based on the application, where the usual tradeoffs include size, sensitivity and reproducibility. Integrated fiber-optic and MEMS sensors are rapidly replacing traditional sensors for most applications. The basic principles for traditional and modern sensors are presented below.

2.9 Thermocouple

Thermocouples use the Seebeck effect to convert temperature into an electro-motive force (emf - i.e., voltage output). The Seebeck effect, which describes the electrical potential developed across the junctions of dissimilar electrical conductors, is the sum of two phenomena. The first, discovered by Peltier, is an induced emf simply proportional to the difference between the temperatures of two equivalent junctions. The second, discovered by Lord Kelvin, is the emf due to temperature gradients along each single conductor. The net emf for this effect is proportional to the difference between the square of the absolute junction temperatures.

The Seebeck voltage between two different junctions, therefore, can be simply modeled as

\[ E = aT + \frac{1}{2} bT^2 \]

where \( T \) is temperature in °C and the reference junction is maintained at 0 °C. The first circuit in the figure below exploits this relation to measure the temperature difference between two different junctions at different temperatures \( T_1 \) and \( T_2 \). If one junction is maintained at a constant temperature, then the output voltage simply measures the temperature at the second junction.

![Thermocouple circuits](image)

**Figure 2.12 Thermocouple circuits** (a) Peltier emf. (b) Law of homogeneous circuits. (c) Law of intermediate metals. (d) Law of intermediate temperatures.

The remaining circuits in this figure illustrate three thermocouple laws that should help identify problems in practical uses of thermocouples for temperature measurements. The law of homogeneous circuits, illustrated in circuit (b), states that in a circuit of a
single homogeneous metal, an electric current cannot be produced from heat alone. The output of this circuit is independent of the temperature $T_3$ along the homogeneous wire.

The law of intermediate metals, illustrated in circuit (c) states that the net emf in a circuit with a number of connections of unlike metals is zero if the metals are maintained at the same temperature. This means lead wires can be attached to thermocouple materials with no adverse consequences as long as the connections are maintained at the same temperature.

The law of intermediate temperatures, illustrated in circuit (d), is just a physical statement of the simple algebraic expression that if $E_1 = K(T_2 - T_1)$ and $E_2 = K(T_3 - T_2)$, then $E = E_1 + E_2 = K(T_3 - T_1)$. This principle makes it possible to use calibration curves acquired at one temperature to be used at a different temperature.

The sensitivity of a thermocouple temperature sensor is determined by the Seebeck coefficient of the materials used to form the junction,

$$\alpha = \frac{\partial E}{\partial T} = a + bT$$

The sensitivities of common thermocouples range from 6.5 to 80 $\mu$V/°C at 20 °C, with accuracies from 0.25% to 1%. To increase sensitivity, many thermocouples can be added in series. This increases the spatial extent of the measurement but with improved sensitivity and accuracy. An arrangement of multiple thermocouples is often referred to as a thermopile.

## 2.10 Thermistors

Thermistors exploit the strong temperature dependence of the resistance in semiconductors. A very small current (i.e., almost zero-power condition so there is little self heating of the thermistor) passed through a semiconductor will produce a voltage proportional to the resistance, where the temperature dependence of the resistor is:

$$R_T = R_0 e^{\left(\frac{\beta(T_0 - T)}{T}\right)}$$

with $\beta =$ material constant and $T_0$ is the reference temperature defining the reference resistance $R_0$. This relationship is illustrated in plot (a) of the figure below.
The temperature coefficient for a thermistor is simply

\[ \alpha = \frac{1}{R_T} \frac{\partial R_T}{\partial T} = -\frac{\beta}{T^2} \]

The voltage-versus-current characteristics of thermistors, as shown in panel (b) of the figure above, are linear up to the point at which self-heating becomes a problem. When there is large self-heating, the thermistor voltage drop decreases as the current increases. This portion of the curve exhibits a negative-resistance characteristic.

Modern MEMS temperature sensors combine junction sensors and thermistors. Very small p-n junctions are the primary component of the sensor, where the highly nonlinear relation between temperature and junction current dominates the temperature coefficient of the sensor. Since a junction device dominates sensor sensitivity, the same empirical thermocouple laws presented above apply to these integrated sensors.

### 2.11 Radiative Thermometry

The spectrum of black body radiation is shaped by the temperature of the body. This effect was first described by Planck and was one of the early triumphs of quantum theory. The effect can be used in reverse to measure the temperature of a black body. This idea was exploited to measure the background temperature of the cosmos remnant from the big bang. Planck’s law states that the radiant flux per unit area, per unit wavelength \( W_\lambda \) at a wavelength \( \lambda \) (\( \mu \)m) is:

\[ W_\lambda = \frac{\varepsilon C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \]

where \( C_1 \) and \( C_2 \) are universal constants, \( T \) is the temperature of the black body, and \( \varepsilon \) the relative emissivity (i.e., the extent which a surface deviates from a black body - for a true black body, \( \varepsilon = 1 \)). For a given temperature, the wavelength at which a black body maximally radiates can be simply obtained by differentiating the above equation with respect to wavelength and setting the resultant equal to zero. The wavelength satisfying this relation is:

\[ \lambda_m = \frac{2898}{T} \text{ (\( \mu \)m)} \]

The figure below shows the spectrum indicating this maximal wavelength for a black body at approximately room temperature. The maximal wavelength is about 9.66 \( \mu \)m, in the infrared range.

Also in panel (a) of this figure the percentage of total radiant power for room-temperature objects is plotted versus wavelength. Note that approximately 80\% of the total radiant power is found in the wavelength band from 4 to 25 \( \mu \)m. Determining the effect of changes in surface emissivity with wavelength is important to accurately determine the temperature of a given source. For example, at 300 °K and \( \lambda = 3 \mu \)m, a 5\% change in \( \varepsilon \) is equivalent to a temperature change of about 1 °C.

To detect IR emissivity for an object, IR cameras are used. The lenses in these cameras must be carefully selected to pass radiation over the IR range. For example, conventional glasses are not good IR lenses - you already know this from the “car heating” effect. Also, photodetectors must be chosen to operate in this wavelength range. Typically III-IV semiconductors such as InSb are used for these applications.
The photodetector in an IR camera is constructed like other photodiode detectors, where the semiconductor material for IR is a III-V compound to match to the optical wavelength for this application and the semiconductor for visible, near IR and near UV detection is usually silicon. Photojunction sensors are formed from p-n junctions. If a photon has sufficient energy to jump the band gap, hole-electron pairs are produced that modify junction characteristics. If the junction is reversed biased, the reverse photocurrent flowing from the cathode to anode increases linearly with increasing incident optical flux. Other semiconductor photodetectors use MOS capacitors (CCDs) as the primary sensing element. High spatial integration can be realized with CCD structures, but usually at the expense of response time compared to junction sensors. A typical photodiode operating curve is illustrated in the figure below.

Figure 2.14  (a) Spectral radiant emittance versus wavelength for a blackbody at 300 K on the left vertical axis; percentage of total energy on the right vertical axis. (b) Spectral transmission for a number of optical materials. (c) Spectral sensitivity of photon and thermal detectors. [Part (a) is from Transducers for Biomedical Measurements: Principles and Applications, by R. S. C. Cobbold. Copyright © 1974, John Wiley and Sons, Inc. Reprinted by permission of John Wiley and Sons, Inc. Parts (b) and (c) are from Measurement Systems: Application and Design, by E. O. Doebelin. Copyright © 1990 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Co.]
Other devices are used for photosensing, such as photomultipliers, for specialty applications requiring short response time. A typical photomultiplier has a response time less than 10 nsec. Because we will not require such short response times, we will only consider simple photodiode sensors in this course.

A typical IR camera system used for temperature sensing is illustrated in the figure below. A mirror focuses the radiant energy from the source onto a photodiode detector. A blackened chopper time modulates the light first to produce an AC output from the detector. Phase-sensitive detection is then performed for optimal sensitivity. More about phase-sensitive detection two chapters from now when we consider signal processing systems.

**Figure 2.22** Voltage-current characteristics of irradiated silicon p–n junction  
For 0 irradiance, both forward and reverse characteristics are normal. For 1 mW/cm², open-circuit voltage is 500 mV and short-circuit current is 0.8 μA. For 10 mW/cm², open-circuit voltage is 600 mV and short-circuit current is 8 μA.

**Figure 2.15** Stationary chopped-beam radiation thermometer  
2.12 Fiber-Optic Temperature Sensors

There are two basic forms of optical temperature sensors. The first exploits temperature dependencies in optoelectronic materials. One example is presented in the figure below. Here light is coupled from an input fiber into an output fiber through a double mirror constructed from a III-IV semiconductor (typically GaAs). As light propagates through the semiconductor, it is attenuated since there is a finite probability that a photon will be absorbed to promote valence band electrons into the conduction band. Since the band gap is highly temperature dependent, the absorption probability, and hence the optical attenuation, is a function of temperature. By monitoring changes in the transmitted intensity, the temperature of the medium in thermal contact with the GaAs sensor is measured.

A second form of optical temperature sensor uses the same type of resonator structure at the end of an optical fiber as the optical displacement sensor presented in section 2.7. For temperature sensing, however, the resonator is thermally coupled to the object of interest and the resonator material is chosen to be a transparent elastomer. Such polymers have a very large coefficient of thermal expansion. As the temperature changes, the resonator thickness will change. Light reflected from the resonator will vary intensity according to the response curve described in section 2.7.

Both types of optical sensor are used for a range of applications. Note that optical sensors are immune to ambient electromagnetic radiation and consequently are most attractive in systems combining sensing with some form of electromagnetic ablation therapy (e.g., RF cardiac ablation).

2.13 Optical Measurements

The displacement sensor of section 2.7 and the temperature sensors of section 2.12 are examples of optical sensors. Nearly all optical sensors have the same 3 general components: optical source, filter, optical detector. The filter is the primary sensing element, where some optical property is changed in response to a physical or chemical characteristic of the system. The figure below illustrates a typical optical sensing system. This figure from the book is a little out of date - modern instruments are almost exclusively solid state. The source is either a light emitting diode (LED) or a semiconductor laser. As the power available from semiconductor lasers is rising rapidly, almost all systems will replace LEDs with diode lasers of comparable intensity. For the purposes of this course, however, we will always assume that the light source is either a light emitting diode or a diode laser.
The primary goal of the optical delivery and detection system is to efficiently bring light to the filter/sensor, collect all light passing through the filter, and efficiently transfer it to the photo sensor. The spectrophotometer system presented in section 2.13 is an example of an optical sensor using geometrical optics for the delivery and collection system. The semiconductor temperature sensor in section 2.12 is an example of an optical sensor using fibers for the delivery and collection systems. Both types of delivery and collection system are commonly used in clinical instruments.

Geometrical systems use the focusing characteristics of a lens to deliver and collect light efficiently. In the spectrophotometer of section 2.13, the delivery lens uniformly illuminates the sample by placing the optical source at its focus. A lens converts a point source into a plane wave source, so it is ideal for this application. On the collection side, another lens accepts plane waves transmitted through the sample and focuses them to a small area, efficient photodetector. For maximum efficiency, the detector is placed at the focus of the collection lens. If space is not an issue (e.g., table-top instruments), then the efficient delivery and collection capabilities of a geometrical, lens-based system are usually best.

For applications where space is a major issue (e.g., catheter-based instruments), fiber delivery and collection systems are most efficient. Fibers consist of a plastic or glass core.
with refractive index $n_1$ surrounded by a cladding of lower refractive index $n_2$. By Snell’s law, as illustrated in the figure below, optical rays must satisfy the relation:

$$n_2 \sin \theta_2 = n_1 \sin \theta_1$$

where $\theta$ is the angle of incidence. Because $n_1 > n_2$, $\sin \theta_2 > \sin \theta_1$. This means $\sin \theta_2 = 1.0$ for a value of $\theta_1$ less than $90^\circ$. For values of $\theta_1$ greater than this, $\sin \theta_2$ is greater than unity (impossible). Consequently, for these angles, the ray is internally reflected. The critical angle for reflection ($\theta_{ic}$) is found by setting $\theta_2 = 1.0$, which gives

$$\sin \theta_{ic} = \frac{n_2}{n_1}$$

A ray is internally reflected for all angles of incidence greater than $\theta_{ic}$.

![Figure 2.20 Fiber optics](image)

The solid line shows refraction of rays that escape through the wall of the fiber. The dashed line shows total internal reflection within a fiber.

Rays entering over a fairly large cone are accepted into the fiber ($\theta_3$) because they are refracted from air ($n=1.0$) into glass ($n=1.62$). Rays entering the end of the fiber at larger angles ($\theta_4$) are not transmitted down the fiber - they escape through the walls. Internal losses within the fiber have been greatly reduced over the years, where current single mode fibers can transmit light over 1 m long fibers with efficiencies of 70% or greater. Also, fibers are often directly coupled to the source and/or detector. Consequently, modern fiber systems can provide efficiencies approaching geometrical optics systems.

2.15 Course Connection

We will use the following types of sensors in this term’s experiments.

- Strain Gage
- Pressure Transducer (Lab VIII)
- Piezoelectric Transducer
- Ultrasound Doppler Flow Sensor (Lab IX)
- Optical Sensor
- Chemical Sensor (Lab X)