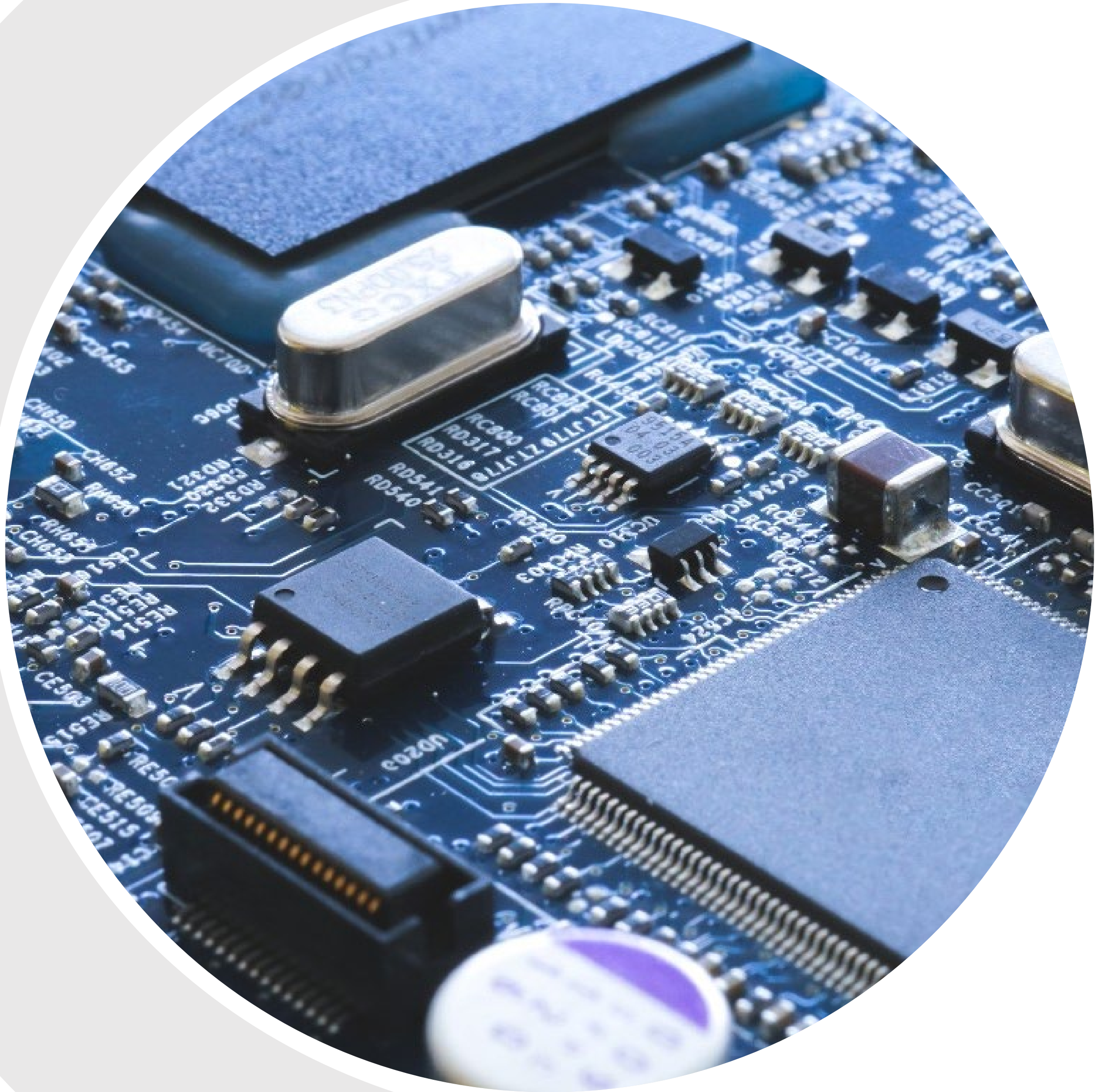


ANJUMAN
Institute of Technology
and Management

Bhatkal, Karnataka, India

BASIC ELECTRONICS

(BBEE103/BBEE203)

Mr. Shrishail Bhat
Assistant Professor
Department of Electronics and Communication Engineering

Module 5
INTRODUCTION TO TRANSDUCERS

SYLLABUS

Introduction to Transducers

Introduction, Resistive Transducers, Inductive Transducers, Capacitive Transducers, Thermal transducers, Optoelectronic transducer, and Piezoelectric transducers.

Text Book

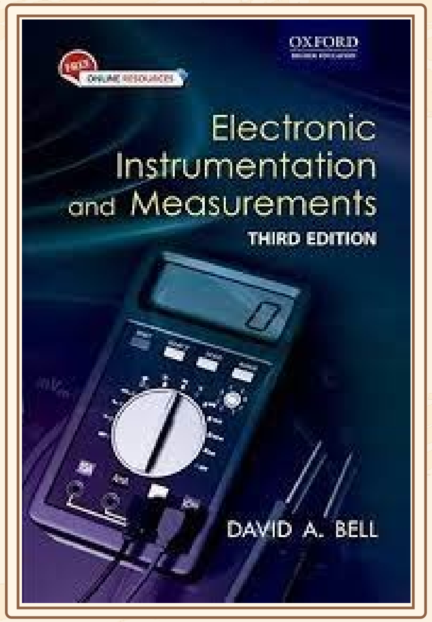
Electronic Instrumentation and Measurements

David A. Bell

Third Edition

Oxford University Press

2013



Introduction

Transducers

- An *electrical transducer* may be defined as a device that monitors a quantity and converts it into an electrical signal for measurement or for controlling an industrial operation.

Classification of Transducers

- Based on quantity monitored:
  - Force, pressure, displacement, temperature, humidity, liquid level, velocity, etc.
- Based on method of operation:
  - Resistive, inductive, capacitive, thermal, optical
- Based on energy source
  - Active or Passive

Classification of Transducers

- Active Transducer
  - Produces an output without any external electrical supply
- Passive Transducer
  - Requires an external energy source to operate
- Most electrical transducers are passive
- Few are active, such as piezoelectric devices and thermocouples

Classification of Transducers

- Each transducer may be defined in terms of sensitivity, range, linearity and accuracy.
- Size and cost are also factors of consideration

Resistive Transducers

Potentiometer-Type Transducer

- A straight potentiometer can be used as a position, or displacement transducer as shown in the figure.
- A shaft is connected to the potentiometer moving contact or wiper.
- The potentiometer has a supply voltage (E), and so the position of the wiper determines the output voltage (V_o).
- The shaft displacement can be measured electrically and the measurement can be displayed or transmitted for further processing.

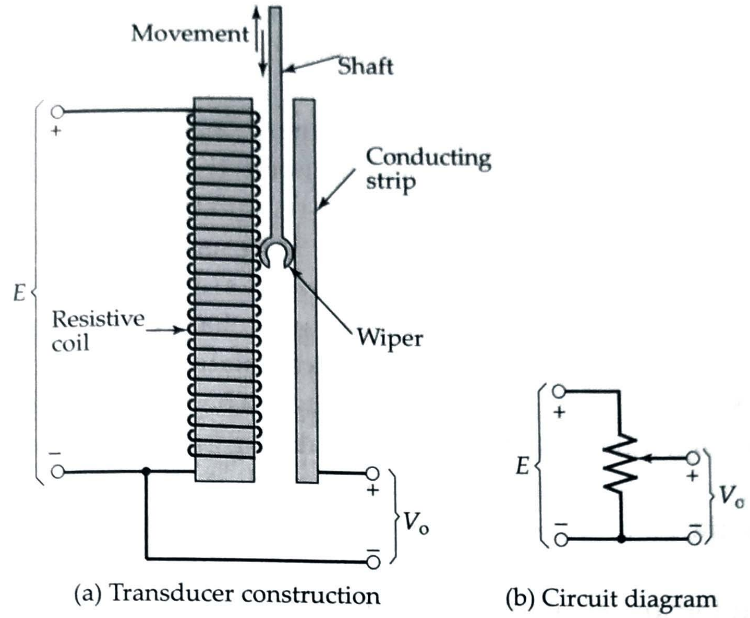


Figure 18-1 Potentiometer used as a position transducer. The output voltage gives an indication of the shaft displacement.

Potentiometer-Type Transducer

- Advantages:
  - It can be as large or as small as required
  - It can be perfectly linear, thus giving linear sensitivity
    - Sensitivity – ratio of output voltage to displacement
- Disadvantages:
  - Output voltage changes in steps as the wiper is moved between potentiometer coils
    - The transducer resolution depends upon the number of turns on the potentiometer winding.

Strain Gauges

- A strain gauge uses the resistance change in a wire when it is strained to measure the physical change that produces the strain.
- Classified as *bonded* and *unbonded*.
  - Bonded strain gauge is bonded (glued) on to the physical quantity under investigation.
    - For example, the strain or compression in a metal beam may be investigated by bonded strain gauge.
  - Unbonded strain gauge is normally part of an individual transducer used to investigate an applied force.

Unbonded Strain Gauges

- Figure shows the construction of one type of unbonded strain gauge.
- Four nickel alloy wires, typically $25\mu m$ in diameter, are tightly stretched between posts on a metal frame and movable armature.
- An external force, when applied, causes two of the wires to be positively strained (increased in length) and the other two wires to be negatively strained (shortened).
- The lengthened wires show an increase in resistance and the shortened wires show a decreased resistance.
- By connecting the wires into a Wheatstone bridge, the resistance change can be measured and the force that produced the change can be calculated.

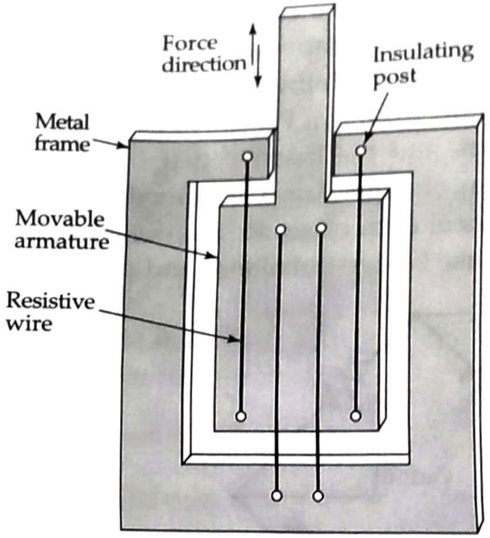


Figure 18-2 Unbonded strain gauge. The tightly strung resistive wires stretch or shrink when the movable armature is subjected to a force. The wire diameter is also altered, and its resistance changes give an indication of the actual displacement.

Bonded Strain Gauges

- Figure shows a bonded strain gauge.
- The resistive material can be either a wire or a foil bonded on the insulating base, which is then bonded to the surface of the item to be investigated.
- In some cases, the resistive material can be a semiconductor layer diffused into a silicon base.
- The strain gauge must be placed longitudinally on the investigated item, so that the longest parts of the conductors are stretched when the item is stretched, and compressed when the item is compressed.

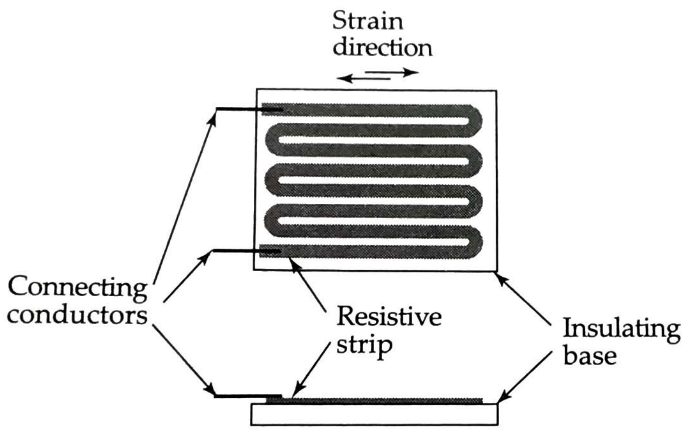


Figure 18-3 Bonded strain gauge consisting of conducting material bonded to an insulating base.

Strain Gauges

- Since the resistance changes are very small, the resistance changes by temperature effects can introduce measurement errors.
- One way of dealing with this is by connecting two identical strain gauges into a Wheatstone bridge.
- Only the active gauge is set up to measure the strain.
- Any changes due to temperature occur in both gauges, and they cancel each other.
- Resistance changes due to strain on the active gauge will cause bridge unbalance and produce an output voltage.

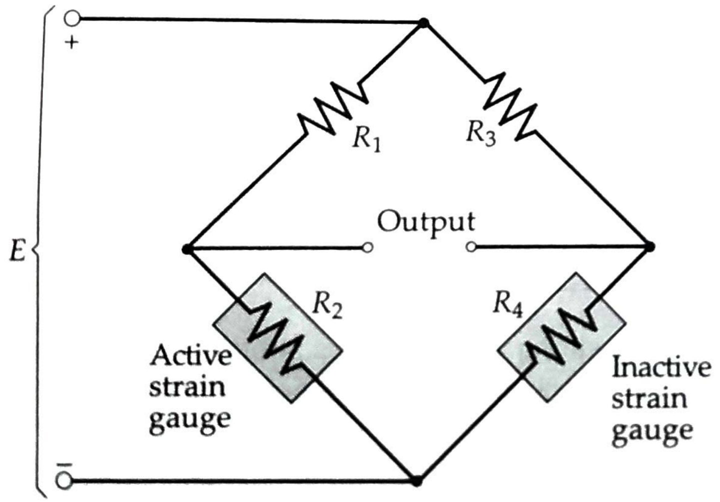


Figure 18-4 Strain gauge temperature errors may be avoided by the use of a Wheatstone bridge.

Strain Gauges

- The equation for the resistance of the wire is

$$R = \frac{\rho l}{A}$$

Where ρ is the specific resistance of the wire in Ωm

l is the total length in m

A is the cross-sectional area of wire in m^2

Strain Gauges

- Substituting for A, we get

$$R = \frac{\rho l}{(\pi d^2/4)}$$

Where d is the diameter of wire in m

Strain Gauges

- When the resistance wire is strained positively, its length is increased and its diameter is decreased, and as a result, the wire resistance is increased.
- The new length is $(l + \Delta l)$, the new diameter is $(d - \Delta d)$ and the increased resistance is $(R + \Delta R)$.

Strain Gauges

- Gauge Factor (GF) is the ratio of ΔR to R divided by the ratio of Δl to l

$$GF = \frac{\Delta R/R}{\Delta l/l}$$

- Poisson's Ratio (μ) is the ratio of Δd to d divided by the ratio of Δl to l

$$\mu = \frac{\Delta d/d}{\Delta l/l}$$

Strain Gauges

- The relationship between GF and μ can be shown to be

$$GF = 1 + 2\mu$$

- Also for increased resistance, we can write

$$R + \Delta R = \frac{\rho(l + \Delta l)}{(\pi/4)(d - \Delta d)^2}$$

Numerical Example 1 (on Strain Gauge)

- A strain gauge with a $40\ cm$ wire length and a $25\ \mu m$ wire diameter has a resistance of $250\ \Omega$ and a gauge factor of 2.5. Calculate the change in wire length and diameter when the resistance change is measured as $0.5\ \Omega$. Assume that the complete length of wire is strained positively.

Numerical Example 2 (on Strain Gauge)

- A strain gauge with a gauge factor of 2 is subject to a $0.28\ mm$ strain. The wire dimensions are $50\ cm$ length and $30\ \mu m$ diameter, and the unstrained wire resistance is $55\ \Omega$. Calculate the change in wire resistance and diameter if the entire length of the wire is strained positively.

Inductive Transducers

Variable Reluctance Transducer

- A variable reluctance transducer uses the change in reluctance of an air gap in a magnetic path to measure displacement.
- It consists of an iron target piece and a U-shaped iron core with a coil.
- Two air gaps are maintained between the target and the iron core, and the target displacement varies the length of the air gaps, and thus changes the reluctance of the magnetic circuit.

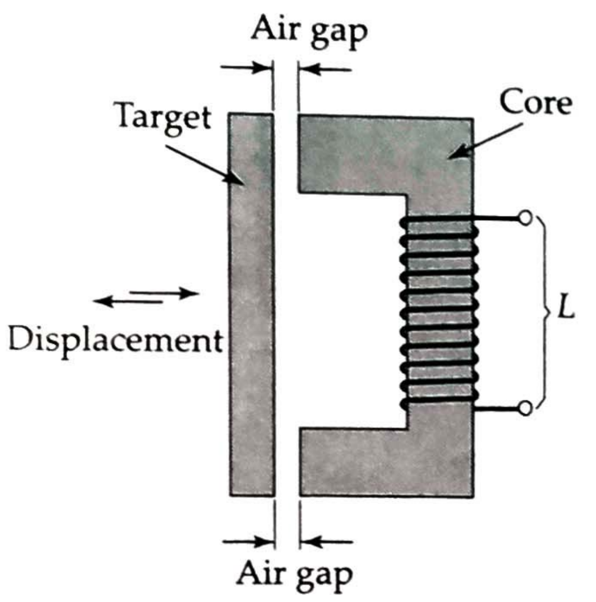


Figure 18-5 A variable reluctance transducer consists of a magnetic core with a coil, and a soft iron target. The length of the air gaps dictates the inductance of the coil, and so the target displacement can be indicated by the coil inductance.

Variable Reluctance Transducer

- The magnetic path reluctance is given by

$$R_m = \frac{l}{\mu_o A}$$

Where l is the total length of air gap

μ_o is the permeability of free space

A is the cross-sectional area of air gap

Variable Reluctance Transducer

- The inductance at the coil terminals is inversely proportional to the reluctance.

$$L = \frac{N^2}{R_m} = \frac{N^2 \mu_o A}{l}$$

Where N is the number of turns on the coil.

- Since N, μ_o and A are all constants, we can write

$$L = \frac{K}{l}$$

Where K is a constant

Variable Reluctance Transducer

- Since the coil inductance is inversely proportional to the air gap length, the target displacement can be measured by monitoring the coil inductance.

Numerical Example 1
(on Variable Reluctance Transducer)

- The coil in a variable reluctance transducer has a $1\ mH$ inductance when the total air gap length is $1\ mm$. Calculate the inductance change when the air gap is reduced by $0.2\ mm$.

Numerical Example 2
(on Variable Reluctance Transducer)

- The coil in a variable reluctance transducer has a $0.5\ mH$ inductance when the total air gap length is $1.3\ mm$. The inductance increases to $0.55\ mH$ when the target is moved closer to the core. Calculate the movement of the target.

Linear Variable Differential Transducer (LVDT)

- A linear variable differential transducer (LVDT) is a transformer with one primary winding, two secondary windings and an adjustable iron core.
- The secondary output voltages v_1 and v_2 are equal in magnitude when the movable core is situated with equal sections of core opposite to each secondary winding.
- Output v_1 is in phase with the primary input v_i and v_2 is in antiphase to v_i.
- The secondary windings are connected in series, so that the voltages cancel to produce zero output when they are equal and in antiphase.

Linear Variable Differential Transducer (LVDT)

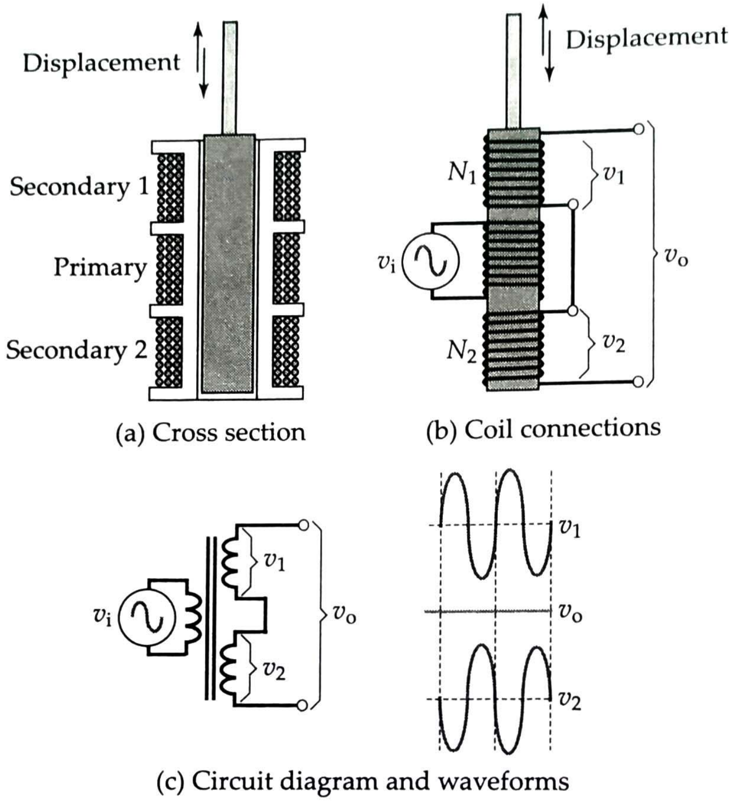


Figure 18-6 A linear variable differential transducer (LVDT) has a primary winding, two secondary windings, and a movable iron core. The two output waveforms are in antiphase.

Linear Variable Differential Transducer (LVDT)

- When the LVDT core is displace upward, there is an increase in the flux from the primary linking to secondary N_1 and a decrease in that linking to N_2.
  - This causes an increase in the amplitude of v_1 and a decrease in v_2, thus producing a difference output voltage v_o.
- Similarly, when the core is displaced in a downward direction, v_2 increases and v_1 decreases.
  - In this case, v_o increases but with a $180°$ phase shift from the input.
- So the output voltage amplitude and phase give a measure of the core displacement and direction of motion.

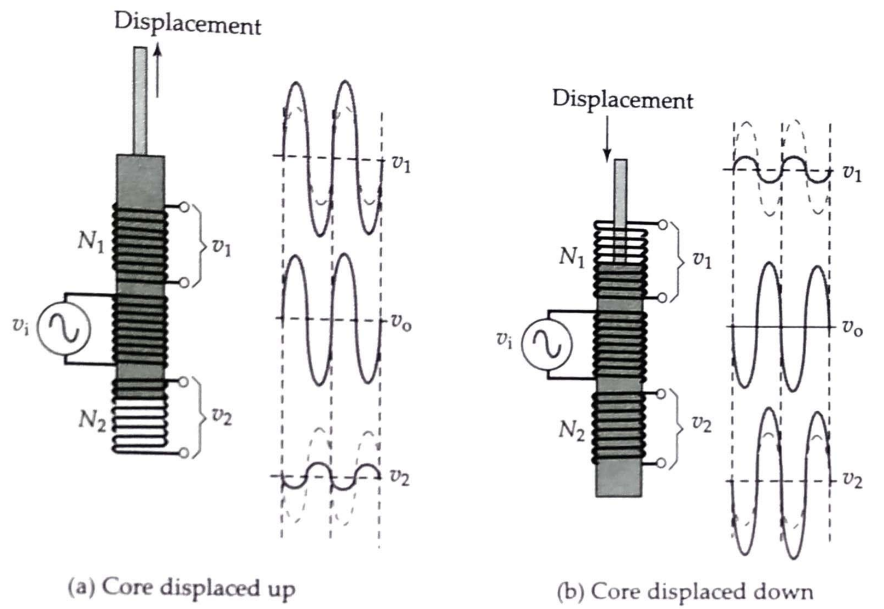


Figure 18-7 When the LVDT core is moved, one output voltage increases and the other decreases. The output voltage amplitude and phase give a measure of the core displacement and direction of motion.

Linear Variable Differential Transducer (LVDT)

- The graph of the output voltage v_o versus the core displacement d is mostly linear, but becomes nonlinear at large displacements.
- Also the output voltage cannot be reduced completely to zero.

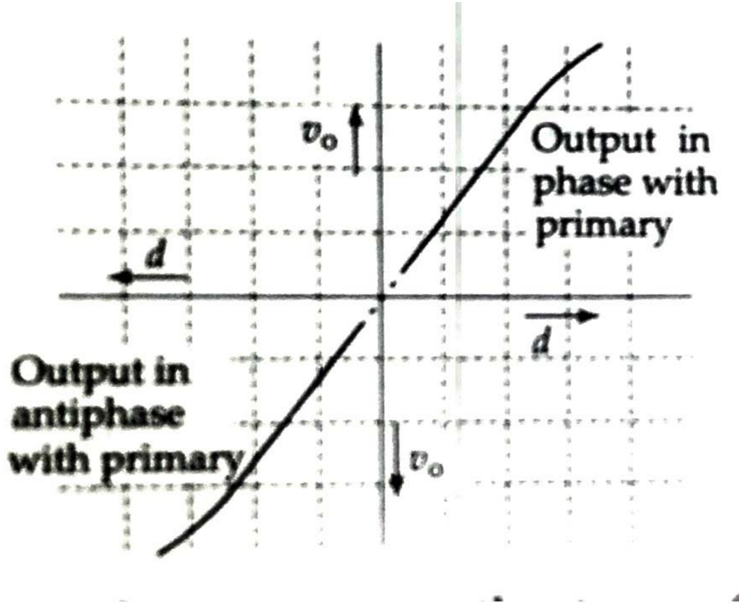


Figure 18-8 LVDT output voltage (v_o) plotted against core displacement (d).

Linear Variable Differential Transducer (LVDT)

- Advantages of LVDT
  - Ruggedness
  - High sensitivity
    - (Sensitivity=ratio of output voltage to displacement, $S = \frac{v_o}{d}$)
  - Good linearity
  - Infinite resolution
  - Low power consumption

Linear Variable Differential Transducer (LVDT)

- Disadvantages of LVDT
  - Relatively large core movements are required to produce a measurable output
  - The core mass limits its dynamic response

Numerical Example 1 (on LVDT)

- A $50\ mV$ output is produced by an LVDT when the core displacement is $10\ mm$ from its zero position. Calculate the core displacement when the output is $35\ mV$.

Numerical Example 2 (on LVDT)

- An LVDT with $0.5\ V/mm$ sensitivity has its output amplified by a factor of 50 and applied to a meter which can display a minimum of $1\ mV$. Calculate the overall sensitivity of the system, and determine the minimum detectable core displacement.

Capacitive Transducers

Capacitive Displacement Transducers

- Capacitance of a parallel plate capacitor is given by

$$C = \frac{\varepsilon_o \varepsilon_r A}{d}$$

Where ε_o is the permittivity of free space (8.84×10^{-12})

ε_r is the relative permittivity of the dielectric

A is the area of the plates

d is the distance between the plates

Capacitive Displacement Transducers

- Figure shows several parallel-plate capacitors and illustrates how they might be adjusted when used in a displacement transducer.

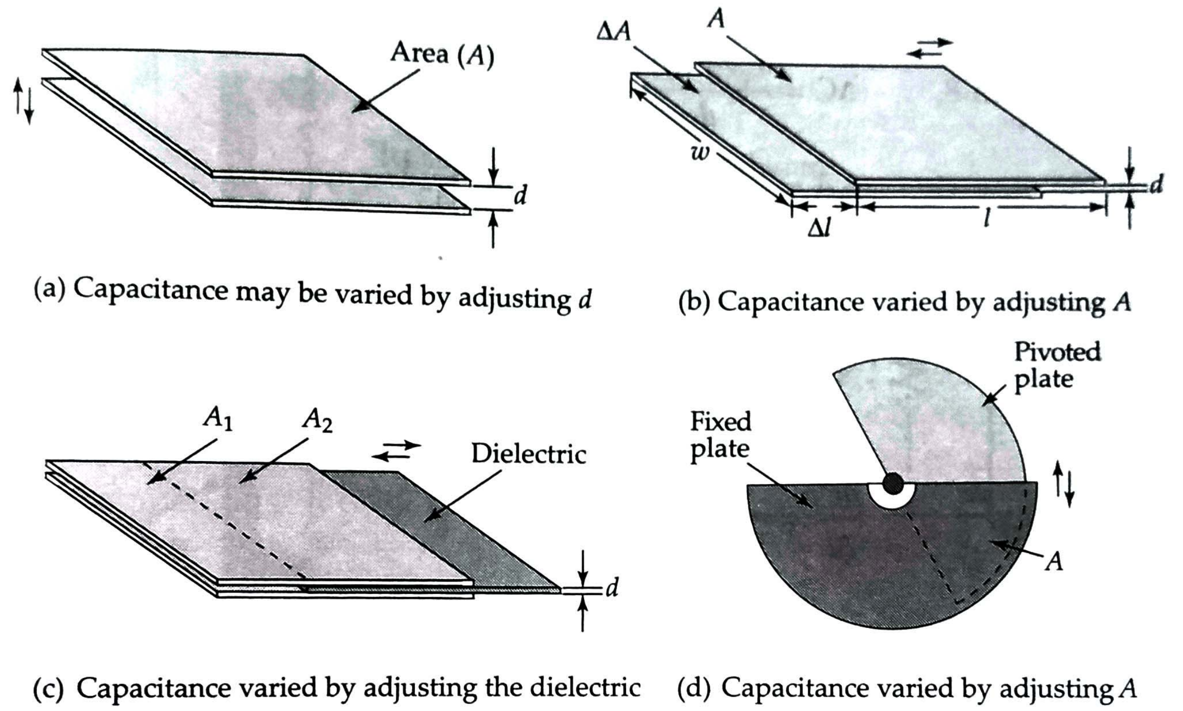


Figure 18-9 Capacitive displacement transducers. The capacitance depends upon the plate displacement, and so the capacitance can be used as an indication of displacement.

Capacitive Displacement Transducers

a) Adjustment of the distance d between the plates gives a capacitance variation (ΔC) inversely proportional to Δd.

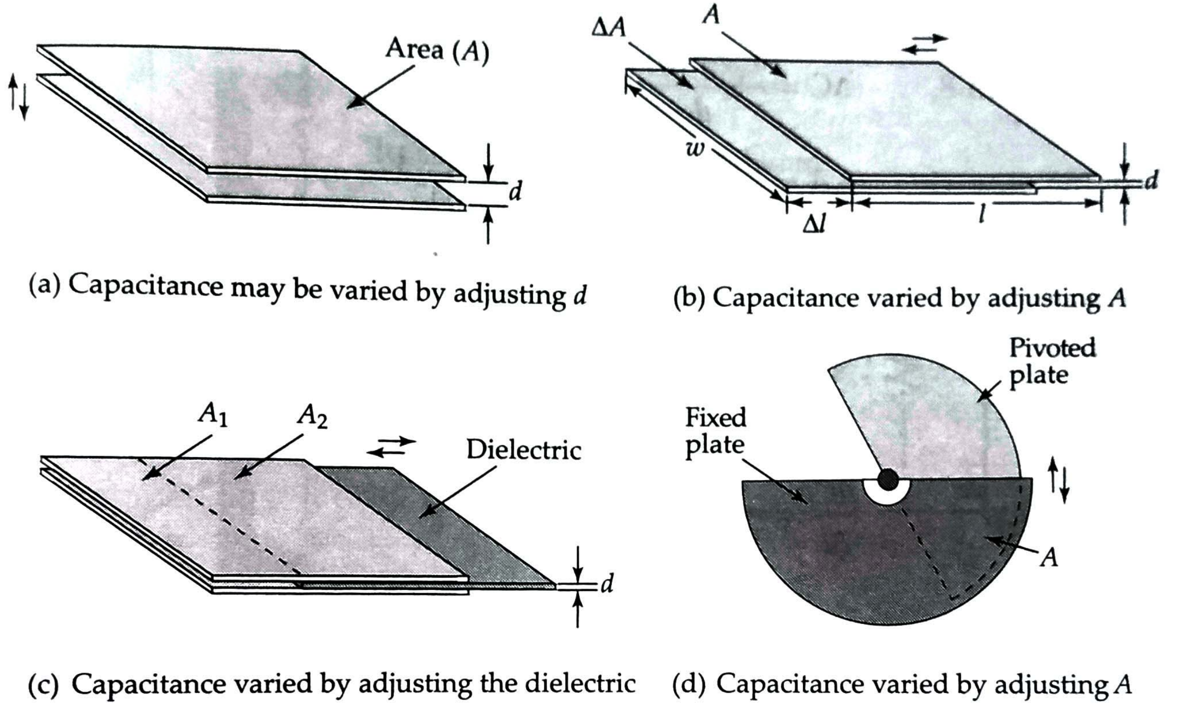


Figure 18-9 Capacitive displacement transducers. The capacitance depends upon the plate displacement, and so the capacitance can be used as an indication of displacement.

Capacitive Displacement Transducers

b) Adjustment of the facing plate area A gives a capacitance variation (ΔC) proportional to ΔA.

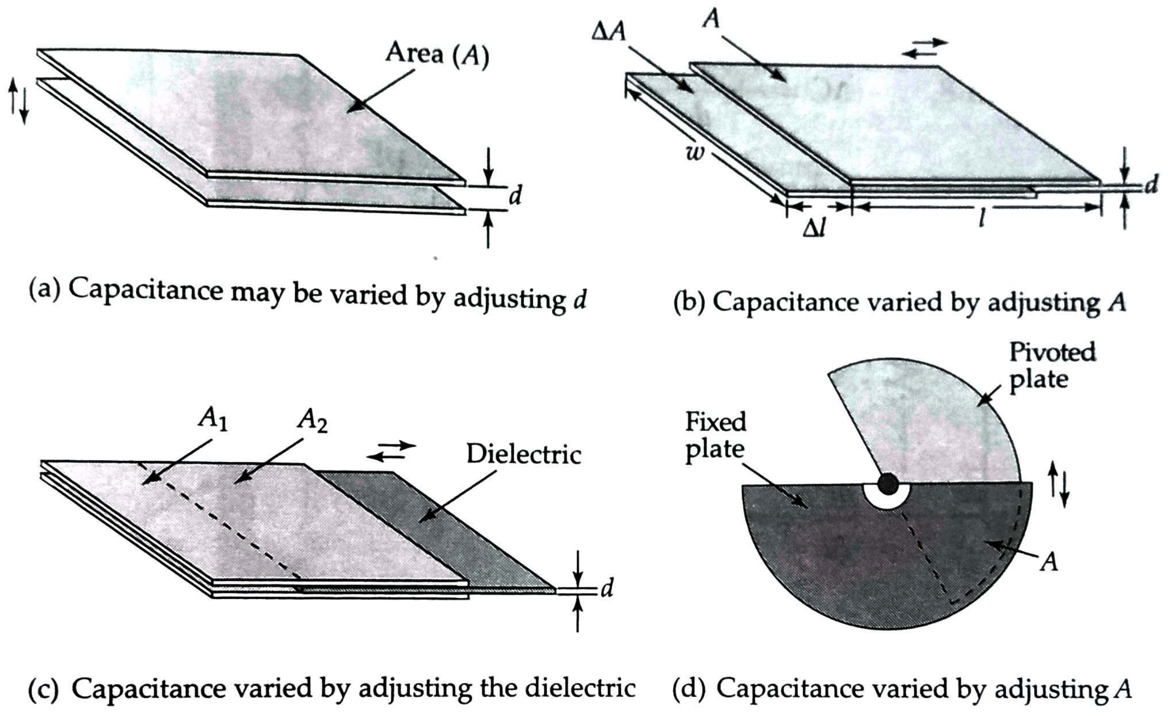


Figure 18-9 Capacitive displacement transducers. The capacitance depends upon the plate displacement, and so the capacitance can be used as an indication of displacement.

Capacitive Displacement Transducers

c) This shows a movable dielectric between the plates. This gives two separate plate areas: A_1 with an air dielectric, and A_2 with a solid dielectric. There are two different capacitances in parallel, and increasing the area of one reduces the area of the other. ΔC is proportional to ΔA.

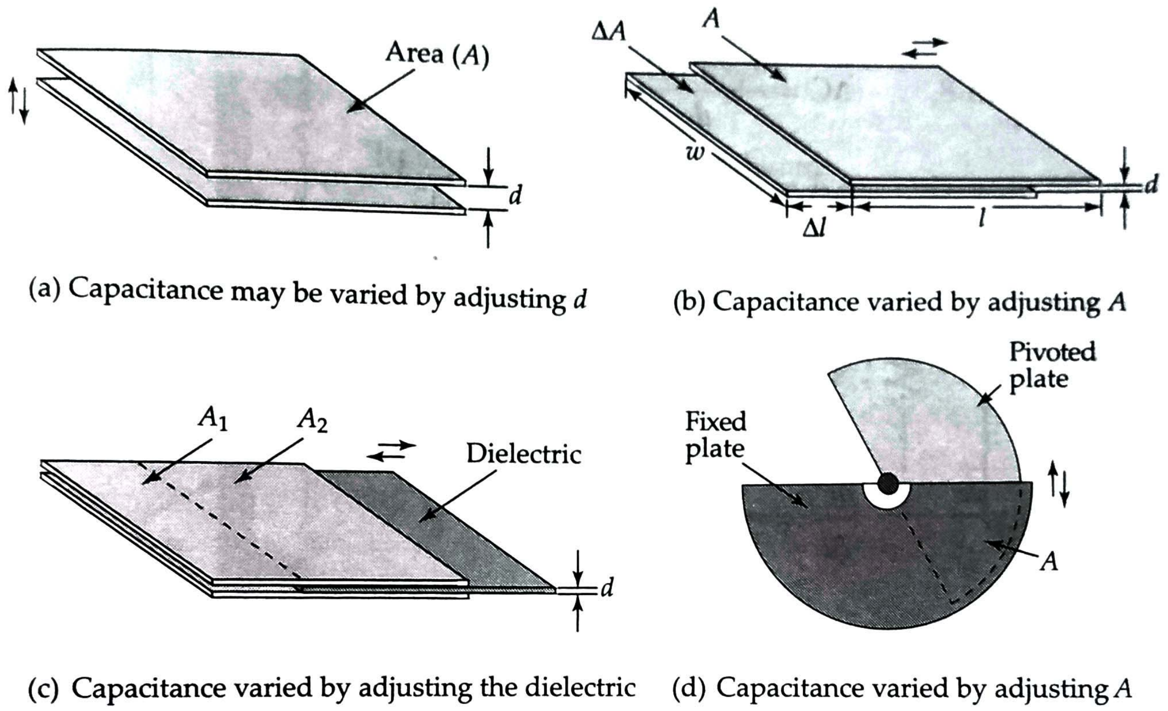


Figure 18-9 Capacitive displacement transducers. The capacitance depends upon the plate displacement, and so the capacitance can be used as an indication of displacement.

Capacitive Displacement Transducers

d) This shows an air dielectric capacitor constructed of half-disc shaped plates. The movable plates may be rotated, thus adjusting the facing plate area, and giving a capacitance variation (ΔC) proportional to ΔA.

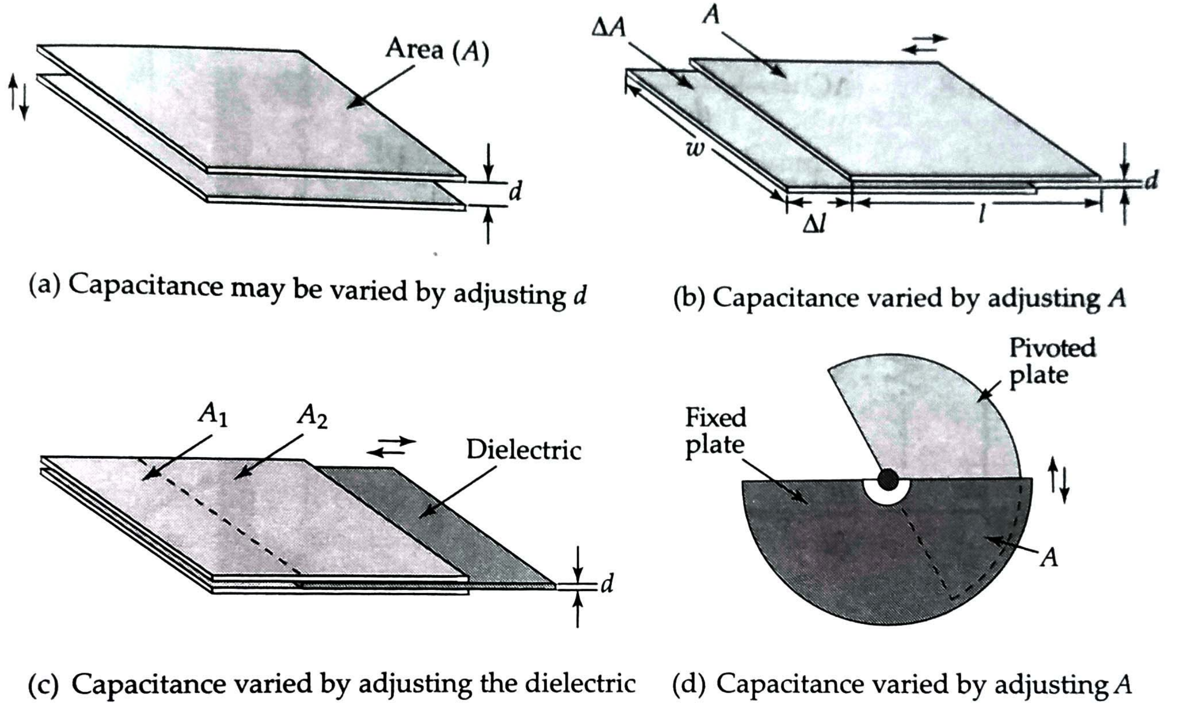


Figure 18-9 Capacitive displacement transducers. The capacitance depends upon the plate displacement, and so the capacitance can be used as an indication of displacement.

Capacitive Displacement Transducers

- In the case of a capacitive displacement transducer which varies the distance between the plates (Δd), the sensitivity is $\Delta C/\Delta d$, possibly expressed in $pF/\mu m$.
- For a transducer which varies the capacitor area, the sensitivity is $\Delta C/\Delta A$, and this can be further reduced to $\Delta C/\Delta l$.

Numerical Example 1 (on Capacitive Displacement Transducers)

- A parallel plate capacitive transducer has a plate area $(l\ x\ w) = (40mm\ x\ 40mm)$ and plate spacing $d = 0.5\ mm$. Calculate the device capacitance and displacement (Δd) that causes the capacitance to change by $5\ pF$. Also determine the transducer sensitivity.

Numerical Example 2 (on Capacitive Displacement Transducers)

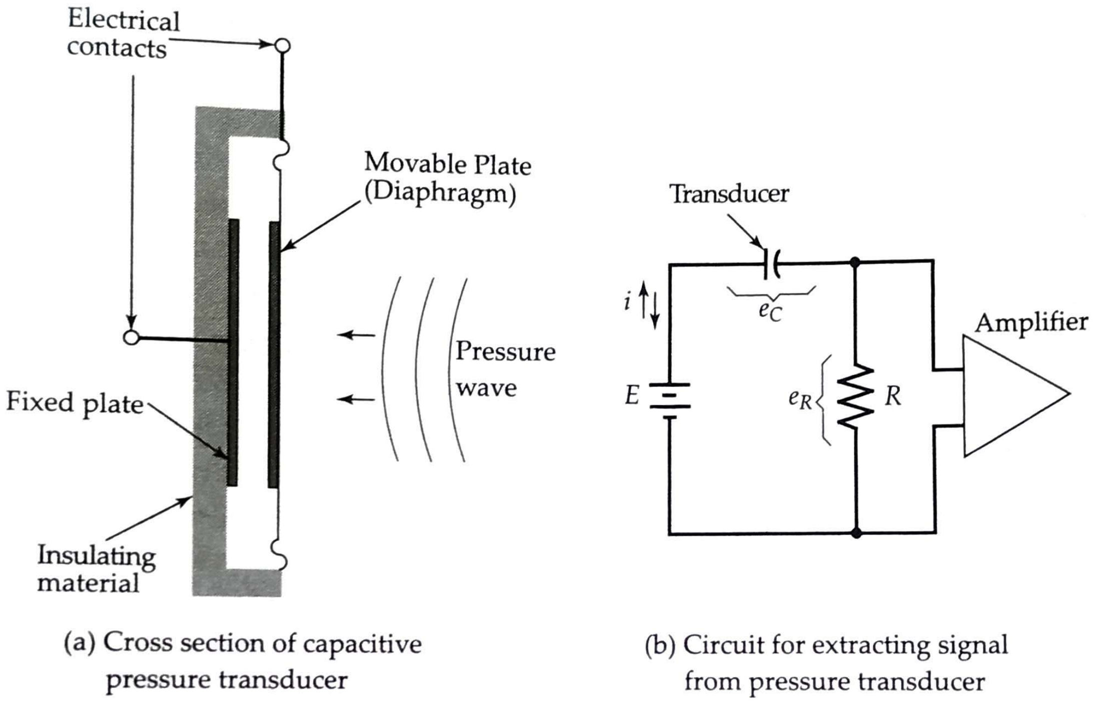
- For the capacitive transducer in the previous example, calculate the change in length (Δl) that produces the same $(5\ pF)$ capacitance change. Also, determine the new transducer sensitivity.

Numerical Example 3 (on Capacitive Displacement Transducers)

- A capacitive transducer is constructed of two half-disc plates. The plates are 2 mm apart, and each has an area of $1.4 \times 10^{-3}\ m^2$. Calculate the maximum capacitance, and the transducer sensitivity in pF/degree.

Capacitive Pressure Transducers

- Figure shows the cross section of a pressure transducer which consists of a flat fixed plate and a plastic diaphragm with a metal film as a movable plate.



(a) Cross section of capacitive pressure transducer

(b) Circuit for extracting signal from pressure transducer

Figure 18-10 A capacitance microphone is a capacitive pressure transducer. The capacitance varies as a result of the input pressure variation.

Capacitive Pressure Transducers

- This is a capacitive microphone designed to receive sound waves as a pressure variation on its diaphragm.
- The gap between the plates changes when the diaphragm is pressured, consequently, the transducer capacitor changes.
- The capacitance becomes charged to the level of the supply voltage $(e_C = E)$, so that, in the absence of a pressure variation, there is no current flow and no resistor voltage drop (e_R).

Capacitive Pressure Transducers

- The capacitor charge equation is $Q = CE$.
- So as C varies with the varying pressure, the charge on C must also vary, and this produces a varying current (i) from the supply.
- The current causes a varying voltage drop across R which can be amplified and further processed.
- The frequency range of this transducer is $40\ Hz$ to $15\ kHz$, which approximately matches the human hearing range.

Capacitive Pressure Transducers

- Capacitive transducers can be used for measurement of very small displacements, and they can be much more sensitive than other transducer types.

Thermal Transducers

Resistance Thermometer

- The resistance temperature coefficient α of a metal defines how the resistance changes with temperature change.
- All pure metals have positive temperature coefficient.
  - Their resistance increases as the temperature increases.
- Some materials, like semiconductors, have negative temperature coefficient.
  - Their resistance decreases as the temperature increases.

TABLE 18-1 Temperature coefficients for metals

Metal	α at 0°C	α at 20°C
Platinum	0.00391	0.00373
Copper	0.00426	0.00393
Nickel	0.0068	0.006

Resistance Thermometer

- For a resistance of $R_1\ \Omega$, the resistance change ΔR for a given temperature change ΔT is

$$\Delta R = R_1 \times \alpha \times \Delta T$$

And the new resistance value is

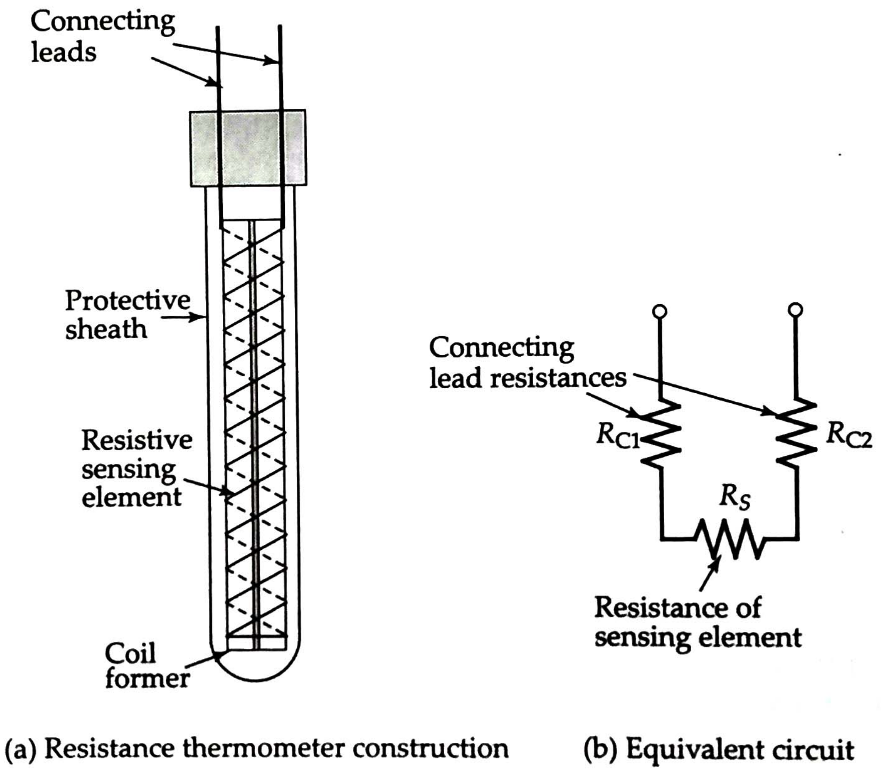
$$R_2 = R_1 + \Delta R = R_1 + R_1 \alpha \Delta T$$

Or

$$R_2 = R_1(1 + \alpha \Delta T)$$

Resistance Thermometer

- The figure shows the basic construction of a resistance thermometer, also known as a resistance temperature detector (RTD).



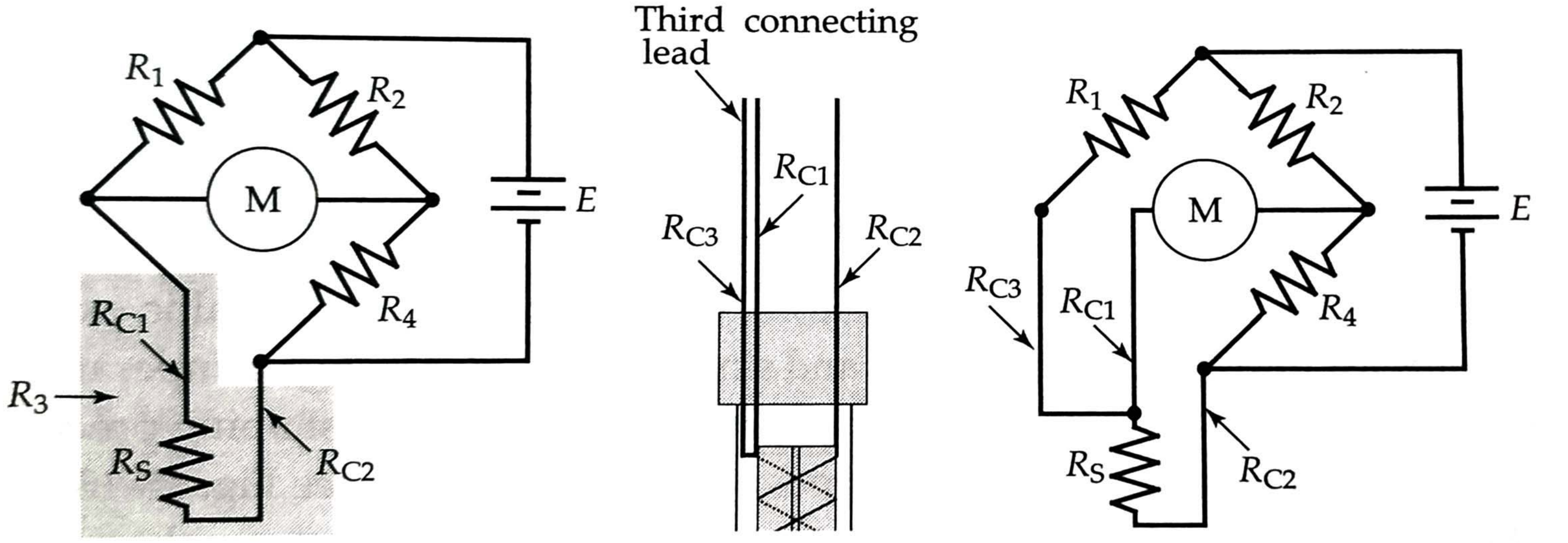
(a) Resistance thermometer construction (b) Equivalent circuit

Figure 18-11 A resistance thermometer consists of a length of resistive wire wound upon a high temperature former. The wire resistance may be used as an indication of temperature.

Resistance Thermometer

- The resistive temperature-sensing element, often very pure platinum, is in the form of a coiled wire held in position inside a protective sheath.
- The sheath may be glass or stainless steel, or any other suitable material.
- The sensing element wire is wound on a mica former.
- Insulated connecting leads are provided, and these must have a much lower resistance than the sensing element.
- An RTD is usually connected into a Wheatstone bridge circuit.
- This allows for detection of very small changes in the resistance of the sensing element, and the meter M used to measure the bridge unbalance voltage can be calibrated to indicate temperature.

Resistance Thermometer



(a) Connecting lead resistances produce errors

(b) Third connecting lead added

(c) R_{C3} balances R_{C2}

Figure 18-12 The resistance of connecting leads can introduce errors in a resistance thermometer. The errors may be eliminated by the use of a third connecting lead.

Resistance Thermometer

- Errors can be introduced by the connecting lead resistances R_{C1} and R_{C2} as they are in series with the element resistance R_S.
- A three-wire connection arrangement can be used to deal with this, wherein, a third connecting lead is added to the circuit.
- Resistance R_{C3} is in series with R_1 in the bridge circuit, and R_{C2} is in series with R_S, so that R_{C2} and R_{C3} balance out.
- Resistance R_{C1} is part of the voltage measuring circuit, and is not involved in the bridge balance.

Resistance Thermometer

- Advantages:
  - Can be employed over a wide temperature range
    - From $-200\ ^\circ\text{C}$ to over $+650\ ^\circ\text{C}$
  - Tough
  - Extremely accurate
- Disadvantages
  - More expensive
    - They need a power supply and bridge

Numerical Example 1
(on Resistance Thermometer)

- The resistance of a coil of nickel wire is $25\ \Omega$ at $20\ ℃$. This rises to $37\ \Omega$ when the coil has been submerged in a liquid for some time. Calculate the temperature of the liquid.

Numerical Example 2 (on Resistance Thermometer)

- A resistance thermometer has a temperature coefficient of 0.0039 at $20\ ℃$ and a resistance of $130\ \Omega$. Calculate the temperature when its resistance measures $175\ \Omega$.

Thermistor

- A thermistor is a thermally sensitive resistor.
- It is a resistor with important thermal characteristics.
- Most thermistors have a negative temperature coefficient, but some have positive temperature coefficient.
- Thermistors are widely used in measurement and control of temperature, liquid level, etc.

Thermistor

- In the manufacturing of thermistors, various mixtures of metallic oxides are pressed into the desired shapes and sintered (baked) at a high temperature.
- Electric wire contact leads are usually included during the shaping process, or else metallic film contacts are deposited after sintering.
- Thermistors are produced in the shape of beads, probes, discs, washers, etc.

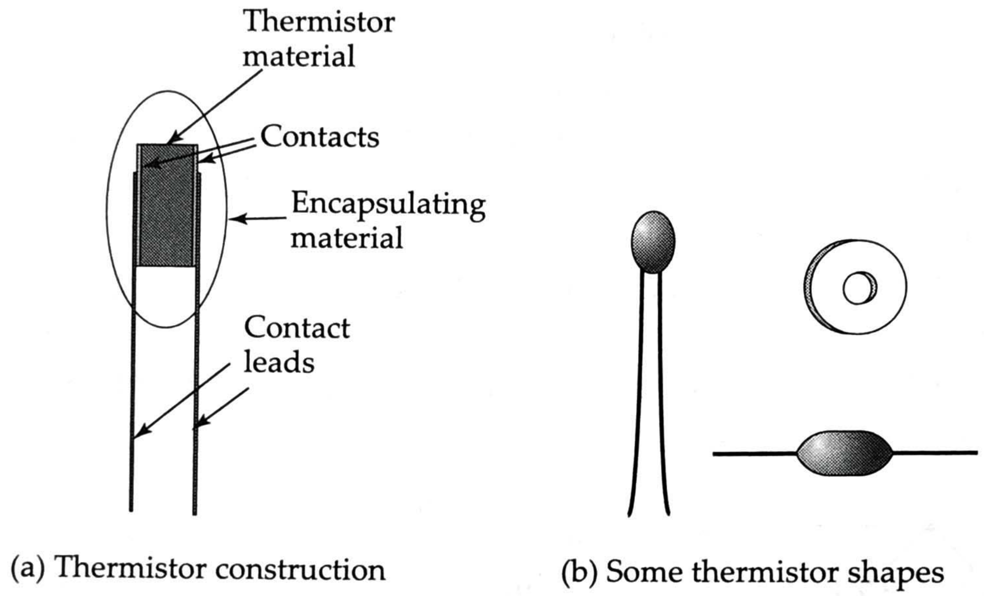


Figure 18-13 Thermistors are resistors constructive of a material that is very sensitive to temperature.

Thermistor

- The figure shows the typical thermistor resistance/temperature characteristics.
- The device resistance (R) decreases substantially when its temperature increases.
- At $0\ °C$, $R \approx 1.5\ k\Omega$ and at $60\ °C$, $R \approx 70\ \Omega$.

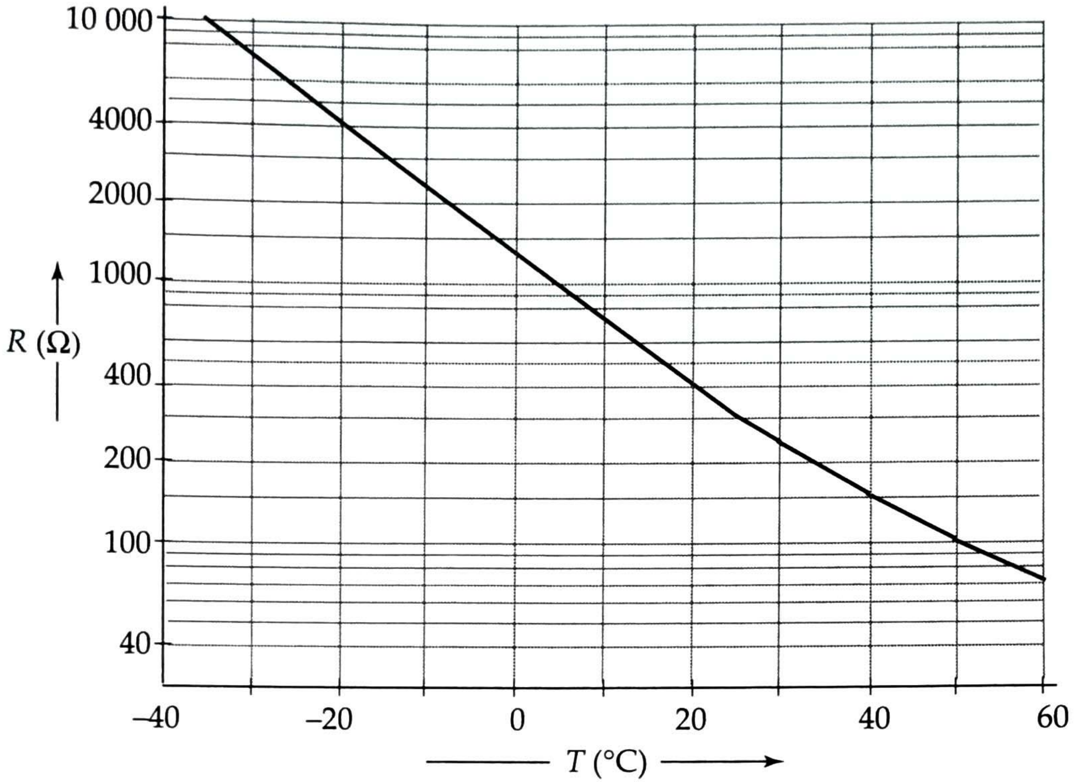


Figure 18-14 Typical thermistor resistance/temperature characteristics.

Thermistor

- The equation that relates resistance values at different temperatures is given by

$$\ln\frac{R_1}{R_2} = \beta\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

where R_1 is the resistance at temperature T_1

R_2 is the resistance at temperature T_2

T_1 and T_2 are absolute temperatures (in Kelvin)

β is a constant which defines the resistance change with temperature

Thermistor

TABLE 18-2 Typical thermistor specifications

Thermistor	Zero power resistance at 25°C	Resistance ratio 25°C /125°C	β (0°C to 50°C)	Maximum working temperature	Dissipation constant
44002A	300 Ω	15.15	3118	100°C	1 mW in still air 8 mW in moving liquid
44008	30 kΩ	29.15	3810	150°C	

Thermistor

- *Zero power resistance at* $25\ ^\circ\mathrm{C}$ is the value of resistance for which there must be effectively zero power dissipation in the thermistor.
- The *dissipation constant* is the device power dissipation that can raise its temperature through $1\ ^\circ\mathrm{C}$.
- The *resistance ratio at* $25^\circ\mathrm{C}/125^\circ\mathrm{C}$ gives an indication of how much the thermistor resistance changes when temperature changes from $25^\circ\mathrm{C}$ to $125^\circ\mathrm{C}$.

Thermistor

- Advantages:
  - Quick response
  - Good sensitivity
  - High resistance
  - Less errors
  - Low cost
  - Small size
- Disdvantages:
  - Smaller range
  - Non-linear

Numerical Example 1 (on Thermistor)

- Calculate the resistance of the $300\ \Omega$ thermistor at temperatures of $20\ °C$ and $30\ °C$.

Numerical Example 2 (on Thermistor)

- Calculate the resistance of the $30\ k\Omega$ thermistor at $50\ ℃$.

Thermocouple Thermometer

- A thermocouple consists of the junction of two dissimilar metal wires welded to a heating wire which carries the current to be measured.
- It is based on *Seebeck effect*, which states that a junction of two dissimilar metals develops an emf when heated.
- Instead of using a current to heat the thermocouple junction, the junction might be placed in a situation where it is heated directly by the environment, like boiling water.
- The displayed output can then be calibrated to indicate the temperature of the junction.

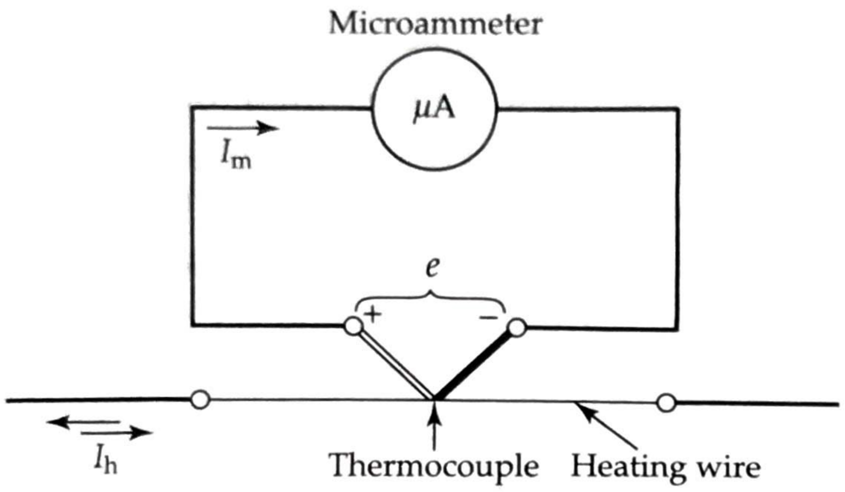


Figure 3-18 Basic thermocouple instrument. The current to be measured is passed through a wire that heats the junction of two dissimilar metals, thus producing a measurable emf.

Thermocouple Thermometer

- Advantages:
  - Ruggedness
  - Relatively inexpensive
  - Usable over a wide range of temperature (from $-200°\text{C}$ to $+2800°\text{C}$)
- Disadvantages:
  - Low-level output (requires amplification)
  - Lower accuracy

Semiconductor Temperature Sensor

- Integrated circuit precision temperature sensors are available that produce a stable output voltage with a predictable temperature coefficient.
- The LM135 manufactured by National Semiconductor is one such IC.
- With a typical output of $2.98\ V$, it operates with a supply current ranging from $400\ \mu A$ to $5\ mA$, and it has a $+10\ mV/°\mathrm{C}$ temperature coefficient.
- Since the LM135 behaves like a Zener diode, a modified Zener diode symbol is used to represent it.
- An additional *adjustment (adj)* terminal allows the temperature coefficient to be calibrated at a convenient temperature.

Semiconductor Temperature Sensor

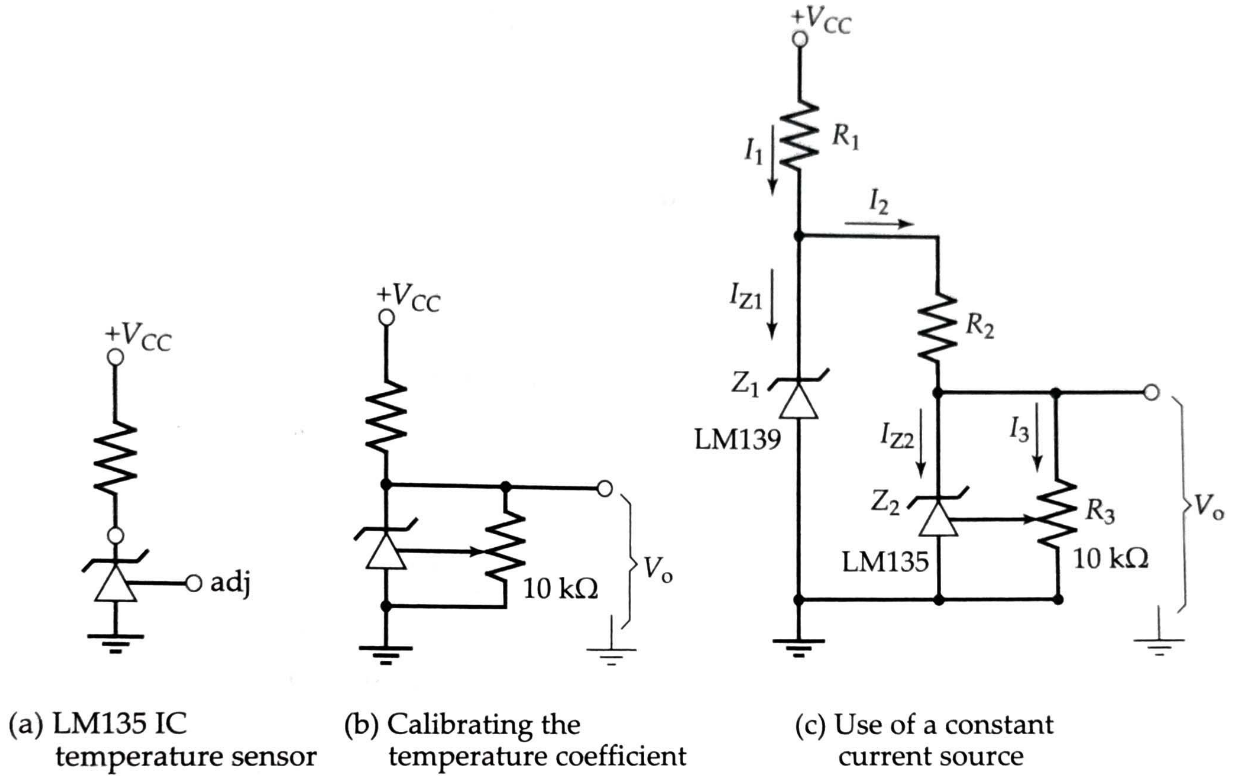


Figure 18-16 The LM135 integrated circuit temperature sensor behaves like a Zener diode that may have its temperature coefficient calibrated.

Semiconductor Temperature Sensor

- The output voltage at any temperature (T_2) can be calculated from

$$V_{o(T2)} = V_{o(T1)} \times \frac{T_2}{T_1}$$

Where T_1 and T_2 are in Kelvin

T_1 is the reference temperature

$V_{o(T1)}$ is the output voltage at the reference temperature

Semiconductor Temperature Sensor

- For calibration, a potentiometer is connected in parallel with the output, and its moving contact is connected to the adj terminal.
- The use of a constant current source also helps ensure a stable temperature coefficient.
- The LM139 (Z_1) is a Zener diode providing a constant voltage to R_2, regardless of supply voltage variations.
- Thus, there is a constant voltage drop across R_2, resulting in a constant current through LM135 (Z_2).

Semiconductor Temperature Sensor

- The LM135 operates over a temperature range of $-55°\mathrm{C}$ to $+150°\mathrm{C}$.
- Its output voltage can be processed to indicate the temperature of its environment.
- It can also be used together with a voltage level detector, to control a heater.
  - For example, by switching it ON when air temperature drops below a given point, and switching OFF again when the temperature rises to the desired level.

Optoelectronic Transducers

Light Units

- The total light energy output, or *luminous flux* (ϕ_s), from a source can be measured in *milliwatts* (mW) or in *lumens* (lm).
  - $1\ lm = 1.496\ mW$
- The luminous intensity (E_s), or illuminance of a light source is defined as the luminous flux density per unit solid angle emitting from the source.
  - It is measured in candelas (cd), where one candela is equal to one lumen per unit solid angle (assuming a point source that emits light evenly in all directions).

$$E_s = \frac{\phi_s}{4\pi}$$

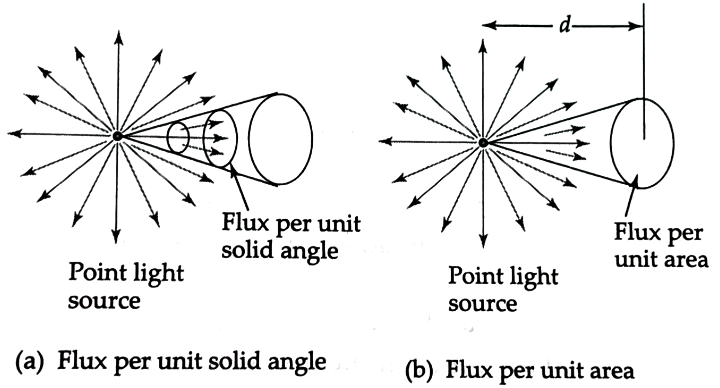


Figure 18-17 Light intensity may be expressed in flux per unit solid angle, or in flux per unit area.

Light Units

- The light intensity (E_A) on an area at a given distance from the source is determined from the surface area of a sphere surrounding the source.
- At a distance of r meters, the luminous flux is spread over a spherical area of $4\pi r^2$ square meters.
- Therefore,

$$E_A = \frac{\phi_s}{4\pi r^2}$$

- When the total flux is expressed in lumens, this equation gives the luminous intensity in *lumens per square meters* (lm/m^2), also termed *lux* (lx)
- The luminous intensity can also be measured in *milliwatts per square centimeter* (mW/cm^2) or *lumens per square foot* (lm/ft^2), also known as a *foot candle* (fc)
  - $1\ fc = 10.764\ lx$

Light Units

- Light energy is electromagnetic radiation.
- It is in the form of electromagnetic wave.
- So it can be defined in terms of frequency and wavelength, as well as intensity.
- Wavelength, frequency and velocity are related by the equation

$$c = f\lambda$$

where c = velocity = $3 \times 10^8\ m/s$ for electromagnetic waves

f = frequency in Hz

λ = wavelength in m

Numerical Example on Light Units

- Calculate the light intensity $3\ m$ from a lamp that emits $25\ W$ of light energy. Determine the total luminous flux striking an area of $0.25\ m^2$ at $3\ m$ from the lamp.

Photoconductive Cell

- A photoconductive cell is based on the *photoconductive effect*:
  - Light striking the surface of a material can provide sufficient energy to cause electrons within the material to break away from their atoms.
  - Thus, free electrons and holes are created within the materials, and its resistance is reduced.
- The construction of a typical photoconductive cell is as shown in the figure.
- Light-sensitive material is arranged in the form of a long strip zigzagged across a disc-shaped base.
- The connecting terminals are fitted to the conducting material on each side of the strip.

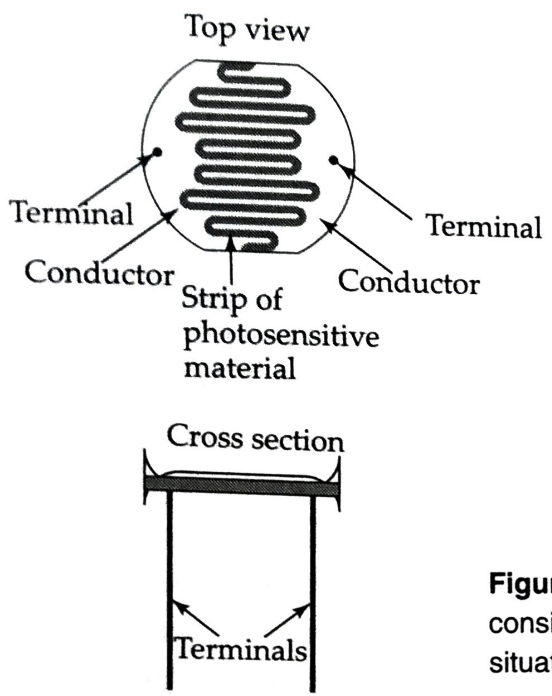


Figure 18-18 A photoconductive cell consists of a strip of light-sensitive material situated between two conductors.

Photoconductive Cell

- Cadmium Sulfide (CdS) and Cadmium Selenide (CdSe) are the two materials normally used in photoconductive cells.
- Both respond slowly to changes in light intensity.
- The response time (t_{res}) for cadmium selenide is about $10\ ms$ and for cadmium sulfide, it is about $100\ ms$.
- Cadmium selenide has larger temperature sensitivity compared to cadmium sulfide.

Photoconductive Cell

- Typical illumination characteristics for a photoconductive cell are shown in the figure.
- When the cell is not illuminated, its resistance can be greater than $100\ k\Omega$.
    - This is known as the dark resistance of the cell.
- When the cell is illuminated, its resistance may fall to a few hundred ohms.

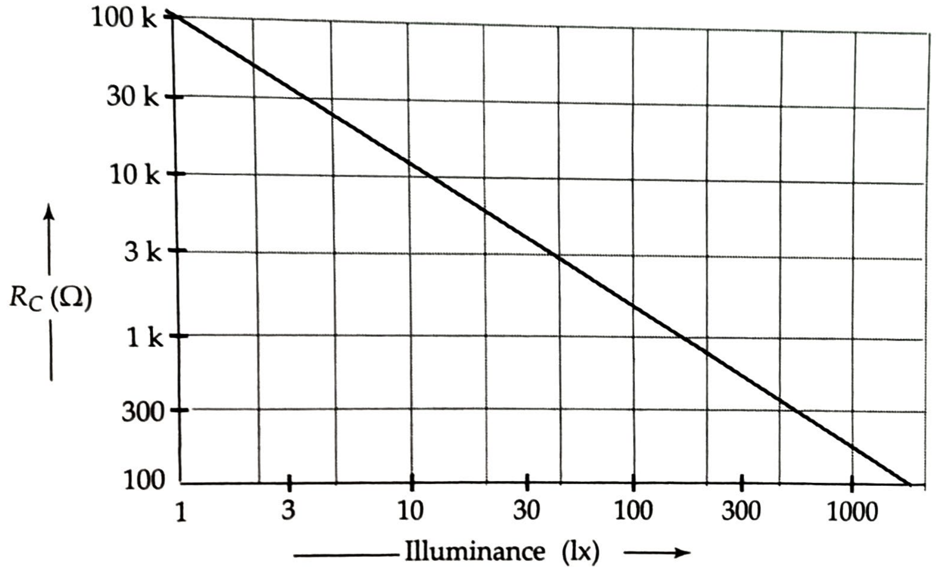
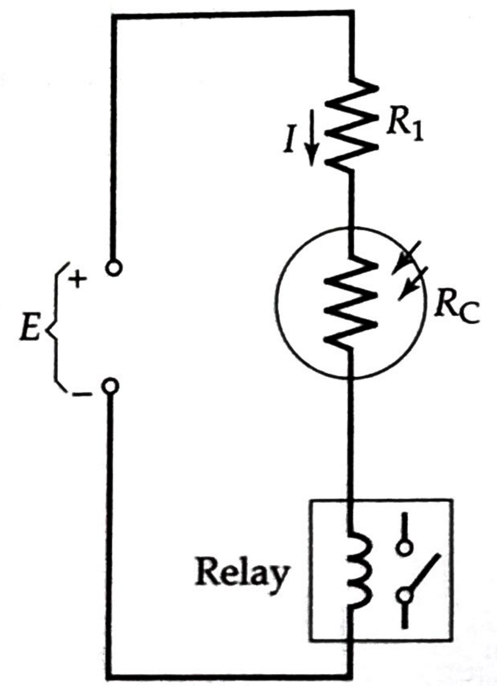


Figure 18-19 Typical photoconductive cell illumination characteristics. The resistance is usually very high when the cell is dark, and relatively low when the cell is illuminated.

Photoconductive Cell

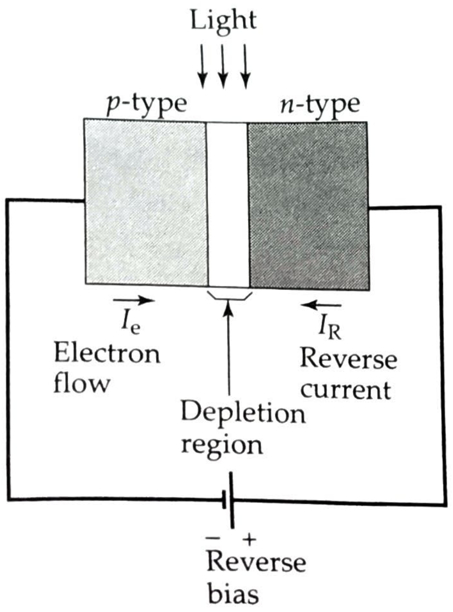
- Figure shows the circuit of a photoconductive cell used for relay control.
- When the cell is illuminated, its resistance is low and the relay current is at its maximum.
  - Thus the relay is energized.
- When the cell is dark, its high resistance keeps the current too low.
  - So the relay is not energized.



(a) Relay control circuit

Photodiodes

- Photodiodes are diodes designed to be sensitive to illumination.
- When a pn-junction is reverse biased, there is a small reverse current due to minority charge carriers.
- When light energy is incident on the junction, more electron-hole pairs are generated, and so the reverse current is increased.
- Increasing the junction illumination increases the reverse current flow.



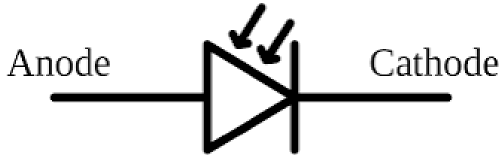


Figure 18-21 A photodiode has a reverse-biased pn-junction designed to be light sensitive.

Photodiodes

- Figure shows the typical photodiode illumination characteristics.
- The left side of the characteristics shows reverse current (I_R) plotted against reverse voltage (V_R).
- At an illumination level (H) of $5\ mW/cm^2$, I_R is approximately $2.2\ mA$ and at $H = 20\ mW/cm^2$, I_R is $10\ mA$.
- Increasing V_R does not increase I_R significantly.

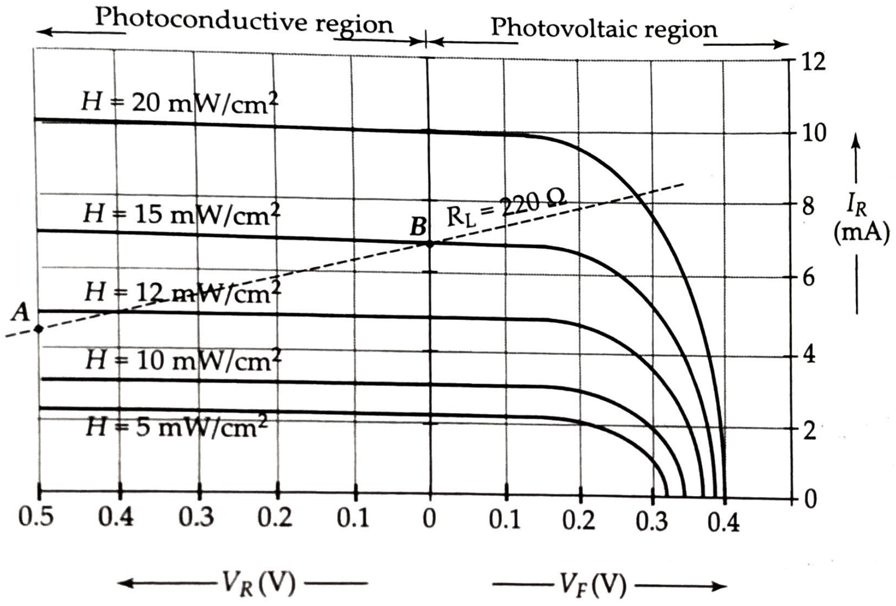


Figure 18-22 Photodiode characteristics have a photoconductive region and a photovoltaic region.

Photodiodes

- Figure shows a simple photodiode circuit.
- When the reverse-bias voltage, reduced to zero, the reverse current continues to flow while the diode is illuminated.
- This means that the device is behaving as a voltage cell.
- So the photodiode is a photovoltaic device as well as photoconductive device.

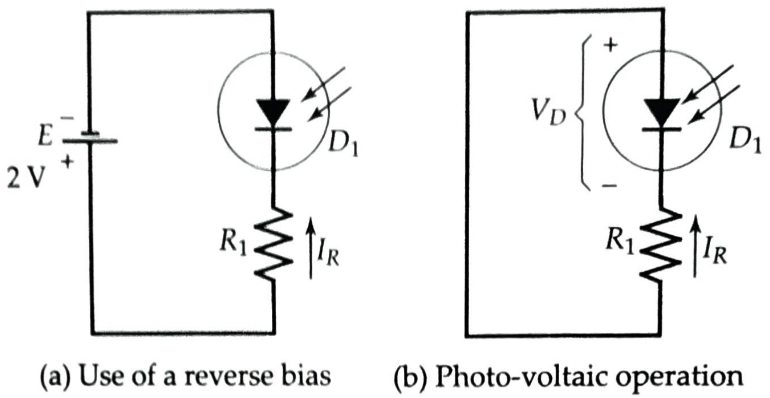


Figure 18-23 Photodiode with reverse bias operates as a photoconductive device. Without a bias voltage, the photodiode behaves as a photovoltaic device.

Photodiodes

- Figure shows the cross-section of a diffused photodiode.
- A thin, heavily doped p-type layer is situated at the top, where it is exposed to incident light.
- The junction depletion region deeply penetrates into the lightly doped n-type layer.
- This is in contact with a lower, heavily doped n-type layer, which connects to a metal film contact.
- A ring-shaped contact is provided at the top of the p-type layer.
- Low-current photodiodes are usually contained in a TO-type can with a lens at the top.
- Just like photodiodes, phototransistors are also available in the form of BJTs and FETs.

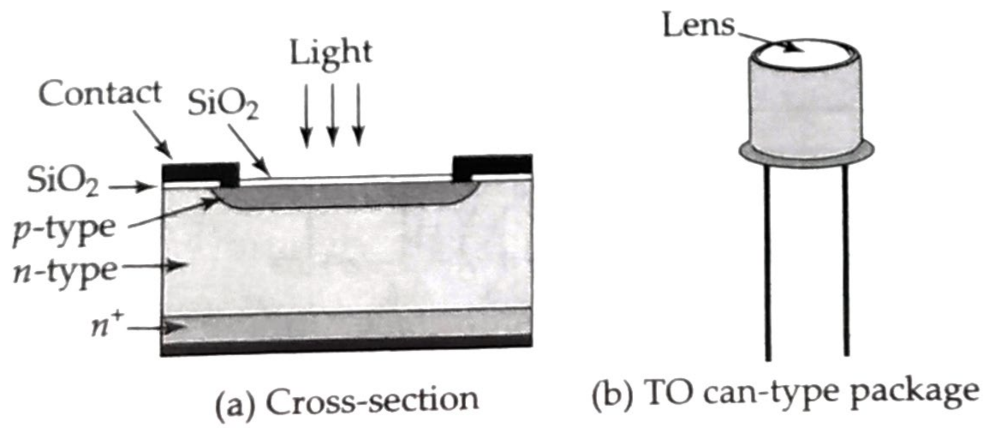


Figure 18-24 Photodiode cross section and typical package.

Photomultiplier

- A photomultiplier tube consists of an evacuated glass cylinder containing a *photocathode*, an *anode*, and several additional electrodes known as *dynodes*.
- The cathode and anode are at opposite ends of the tube and the anode is at a very high positive voltage with respect to the cathode.
- The dynodes are biased to voltage levels distributed between the cathode and anode voltages.

Photomultiplier

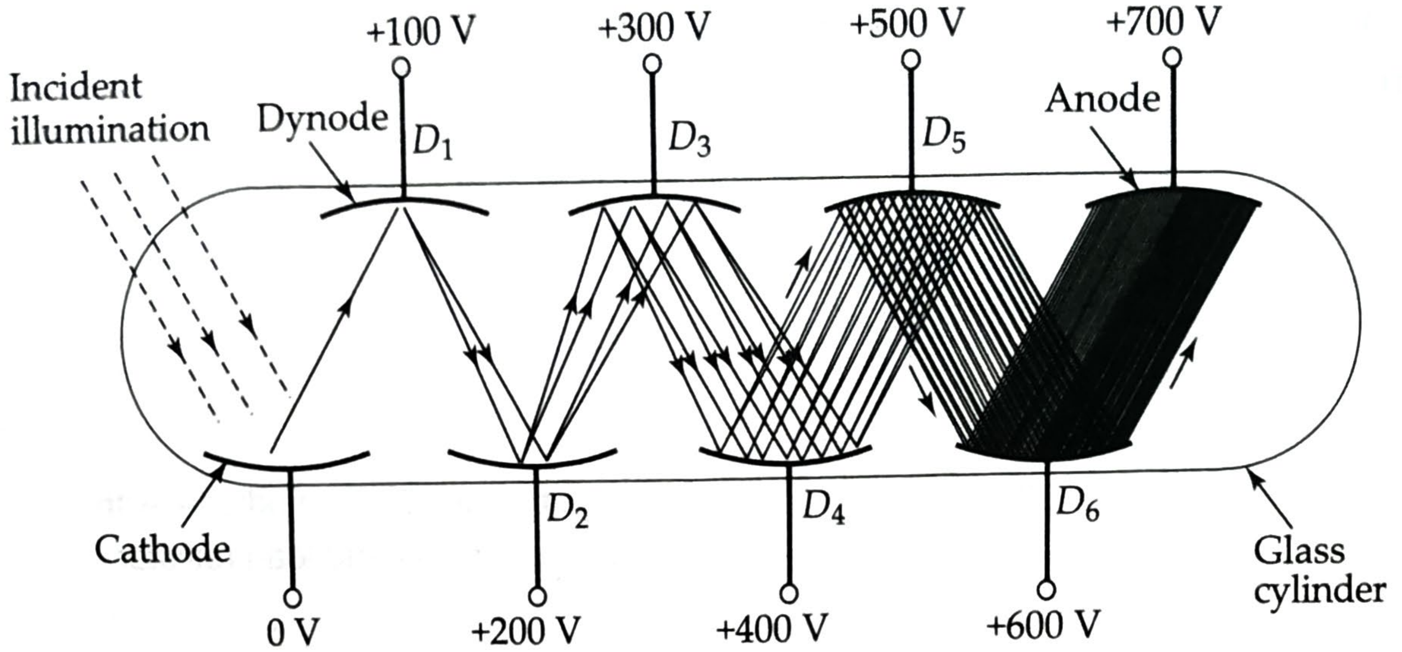


Figure 18-26 Operation of a photomultiplier tube. Cathode illumination causes electrons to be emitted and accelerated toward dynode 1. At the dynode the incident electrons produce a larger number of secondary electrons, which are accelerated toward dynode 2. The process continues up to the anode with increased emission generated at each dynode.

Photomultiplier

- Radiation striking the photocathode imparts energy to electrons within the cathode surface material, causing them to be emitted.
- The positive voltage on the dynode 1 accelerates the electrons from the cathode toward the dynode.
- The dynode surface material facilitates secondary emission and the number of secondary electrons exceeds the number of primary electrons from the cathode.
- The secondary electrons emitted from dynode 1 are accelerated toward the more positive dynode 2, where further increased secondary emission is produced.

Photomultiplier

- The process of increasing levels of secondary emission continues between successive dynodes until the electrons arrive at the anode, where they are collected.
- The number of electrons arriving at the anode far exceeds the number emitted from the cathode.
- So, the original electrons have been multiplied, or in other words the photoemission current has been amplified.
- Current amplifications of the range of 10^7 are possible depending on the number of dynodes and the applied voltage levels.

Photomultiplier

- The typical photomultiplier tube characteristics in the figure shows anode currents ranging approximately from 1 mA to 4 mA for incident light levels of 25 to 100 microlumens.
- The dark current occurs when the cathode is not illuminated.
- The anode current is directly proportional to the incident illumination level.
- The phototomultiplier tube is extremely sensitive and are appropriate for the detection of fast, low-level occurrences.

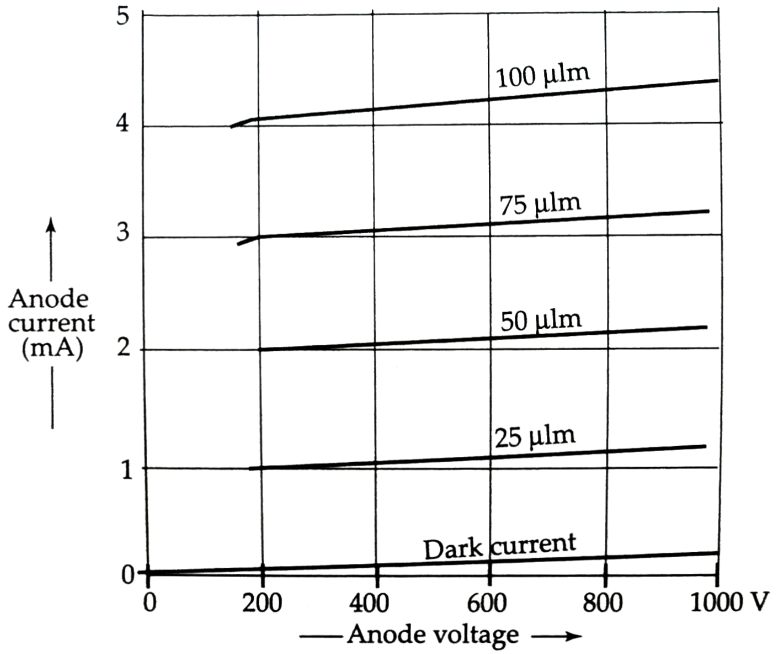
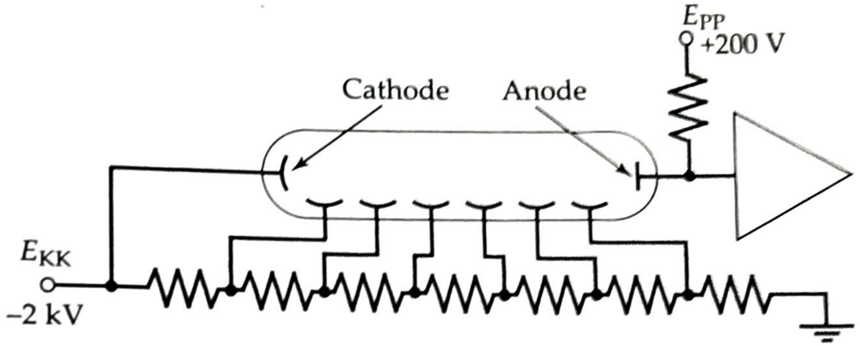
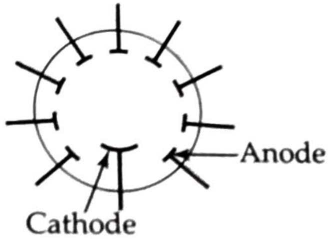


Figure 18-27 Typical photomultiplier tube current/voltage characteristics. The dark current occurs when there is zero cathode illumination. The anode current increases with increased illumination levels.

Photomultiplier



(a) Photomultiplier circuit



(b) Alternative photomultiplier symbol

Figure 18-28 Photomultiplier circuit and alternative graphic symbol. In this circuit the cathode is supplied from a –2 kV source and the anode has a +200 V supply. A voltage divider is used to bias the dynodes to levels between ground and –2 kV.

Piezoelectric Transducers

Piezoelectric Transducers

- If a mechanical stress is applied to a wafer of quartz crystal, a voltage proportional to the stress appears at the surfaces of the crystal.
  - When the stress is removed, the voltage disappears.
- The crystal also vibrates, or resonates, when an alternating voltage with the natural resonance frequency of the crystal is applied to its surfaces.
- The materials that exhibit this behaviour are called *piezoelectric* materials.
- Since the crystal resonance frequency is extremely stable, piezoelectric crystals are widely used to stabilize the frequency of oscillators.
- They are also used in pressure transducers.

Piezoelectric Transducers

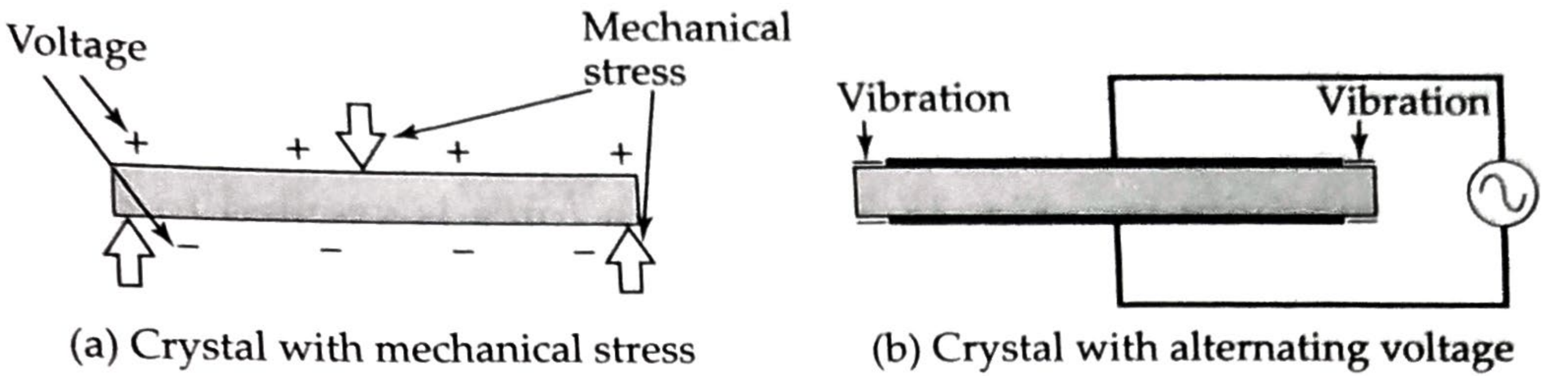


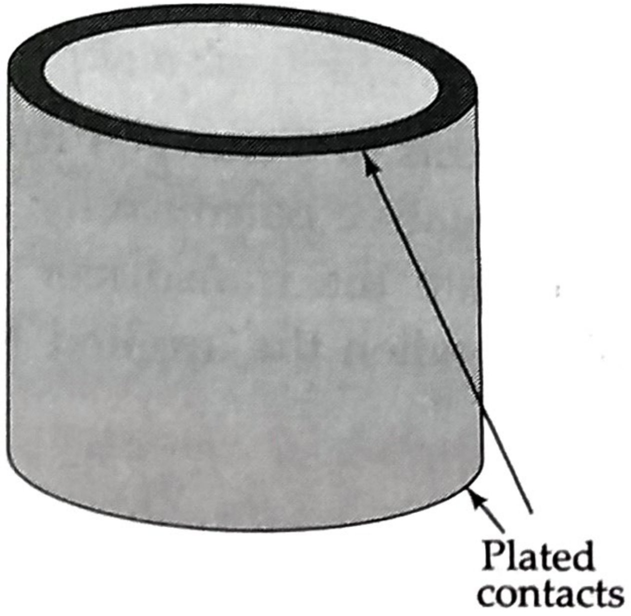
Figure 18-29 A piezoelectric crystal under stress produces a surface voltage. It also vibrates when an alternating voltage is applied to its surfaces.

Piezoelectric Transducers

- Piezoelectric wafers cut from quartz and other natural materials are limited in shape and thus limited in applications.
- Synthetic piezoelectric devices can be manufactured in almost any desired shape.
- The manufacture of synthetic piezoelectric devices involves pressing powdered ceramic material, such as barium titanate, into require shapes, the firing it at high temperatures while subjected to a high direct electric field.
- The high voltage aligns the atomic structure of the material into a shape that can produce the piezoelectric effect.

Piezoelectric Transducers

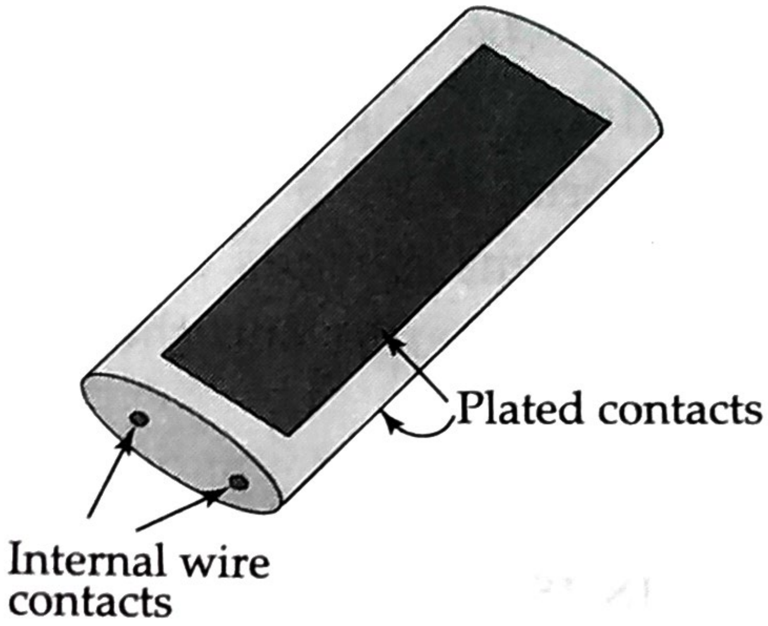
- Figure shows a cylinder-shaped synthetic piezoelectric device with electrical contact plates on each end.
- One application of this is as a pressure transducer for listening to sea noises.
  - With a preamplifier inserted inside, the cylinder ends are sealed, and the device is suspended at the end of a long cable from a boat or a buoy.
  - The pressure variations (due to ship engine noise for example) generate electrical signals at the transducer terminals.
  - These are amplified and fed to the surface for processing.



(a) Cylindrical transducer

Piezoelectric Transducers

- Figure shows a ceramic device known as bimorph.
- When supported at one end, electrical signals are generated at the internal and external electrodes by vibrations applied to the other end.
- This is used in record player cartridge.
  - The minute vibrations generated as the stylus moves in a record track are converted into electrical signals which are then amplified and applied to speakers.



(b) Bimorph

Piezoelectric Transducers

- A piezoelectric transducer is basically a layer of crystal material between two metal plates.
- Since the crystal material is a dielectric, the device has a capacitance that can be calculated from its dimensions and relative permittivity.
- When a force is applied to distort the crystal, a charge is accumulated on the electrodes.
- The charge can be calculated from

$$Q = dF$$

where Q is charge in coulombs

d is charge sensitivity in C/N

F is the force in newtons

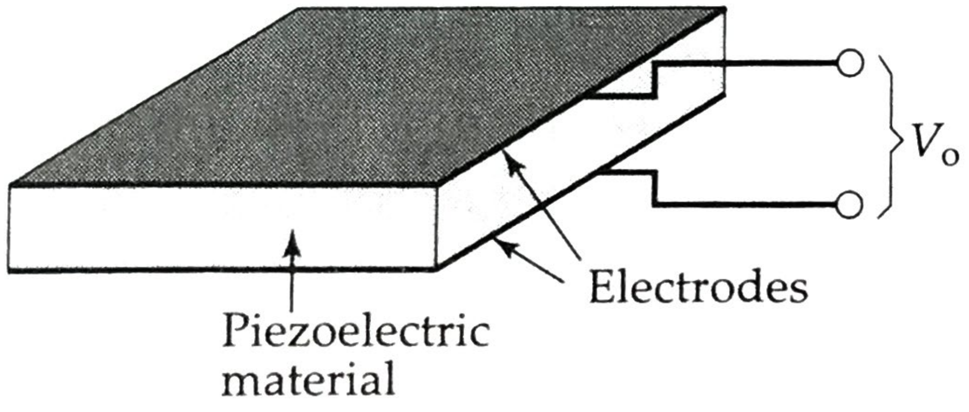


Figure 18-31 Piezoelectric transducer in the form of a wafer of piezoelectric material situated between two plated electrodes.

Piezoelectric Transducers

- An equation for charge can also be written as

$$Q = C_T V_o$$

where C_T is the transducer capacitance.

- The equation for capacitance is

$$C = \frac{\varepsilon_o \varepsilon_r A}{t}$$

where ε_r is the dielectric relative permittivity

ε_o is the permittivity of free space

A is the plate area

t is the dielectric thickness

Piezoelectric Transducers

- So,

$$V_o = \frac{Q}{C_T} = \frac{dF}{(\varepsilon_o \varepsilon_r A/t)}$$

$$V_o = \frac{dtP}{\varepsilon_o \varepsilon_r}$$

where P is the pressure (F/A)

- This gives

$$V_o = gtP$$

where $g = \frac{d}{\varepsilon_o \varepsilon_r}$ is a constant called voltage sensitivity (in Vm/N)

Numerical Example 1
(on Piezoelectric Transducers)

- A piezoelectric transducer has plate dimensions of $5\ mm \ \times 4\ mm$. The crystal material has a $3\ mm$ thickness and a relative permittivity of 800. The voltage sensitivity is $0.04\ Vm/N$. Calculate the transducer charge sensitivity, the charge, and the output voltage when the applied force is $8\ N$.

Numerical Example 2 (on Piezoelectric Transducers)

- A piezoelectric transducer has a crystal material with a $2\ mm$ thickness and a relative permittivity of 5. The voltage sensitivity is $0.045\ Vm/N$. Calculate the transducer charge sensitivity and the output voltage when the applied pressure is $0.5\ \times 10^6\ N/m^2$.

References

- David A. Bell, "*Electronic Instrumentation and Measurements*", 3rd Edition, Oxford University Press, 2013