Sahand University of Technology

Chapter 2

Basic Sensors And Principles

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Basic Sensors And Principles

- Transducer: a device that converts energy from one form to another
- Sensor: converts a physical parameter to an electric output
- Actuator: converts an electric signal to a physical output

- ***Measurements***:
  - *Displacement Measurements*
  - *Temperature Measurements*
  - *Optical Measurements*

Displacement Measurements

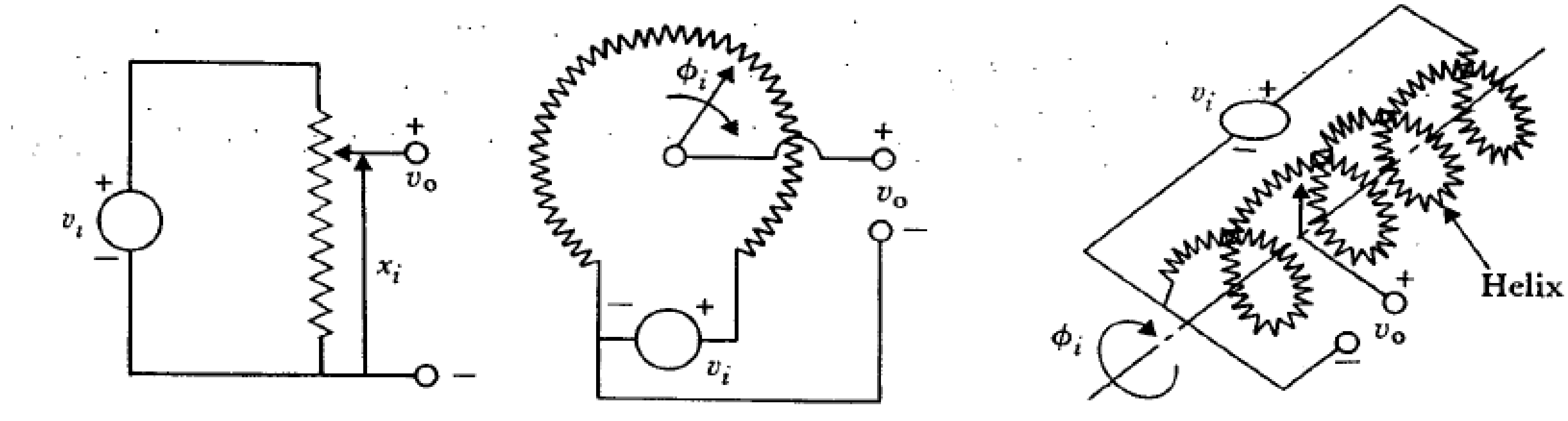
- Purpose:
  - The physician and biomedical researcher are interested in measuring the size, shape, and position of the organs and tissues of the body.
  - Variations in these parameters are important in discriminating normal from abnormal function.
- Displacement Sensors:
  - Direct (exp. Determine the change in diameter of blood vessels and the changes in volume and shape of cardiac chambers)
  - Indirect (exp. used to quantify movements of liquids through heart valves)

Displacement Measurements –p2

- Methods:
  - Resistive
  - Inductive
  - Capacitive
  - Piezoelectric

Displacement Meas. - Resistive Sensors - p1

- Potentiometers
  - These potentiometers produce a linear output (within 0.01% of full scale) as a function of displacement, provided that the potentiometer is not electrically loaded.



(a) Translational (b) Single-turn (c) Multi-turn

Displacement Meas. - Resistive Sensors – p2

- Strain Gages
  - When a fine wire (25 μm)is *strained within its elastic limit, the wire's resistance* changes because of changes in the diameter, length, and resistivity.
  - measure extremely small displacements on the order of nanometers
- Equations: $R = \frac{\rho L}{A}$

length L (meters)

ρ (ohms · meter)

A (meters squared)

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

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

Displacement Meas. - Resistive Sensors – p3

- Equation: Poisson's ratio μ relates the change in diameter ΔD to the change in length,

  Substituting this: $$\Delta D/D = -\mu\,\Delta L/L$$

$$\frac{\Delta R}{R} = \underbrace{(1+2\mu)\frac{\Delta L}{L}}_{\text{Dimensional effect}} + \underbrace{\frac{\Delta\rho}{\rho}}_{\text{Piezoresistive effect}}$$

Changes in the lattice structure of the material,

Gage Factor: $$G = \frac{\Delta R/R}{\Delta L/L} = (1+2\mu) + \frac{\Delta\rho/\rho}{\Delta L/L}$$

Table 2.1 Properties of Strain-gage Materials

Material	Composition (%)	Gage Factor	Temperatur Coefficient [of] Resistivity (°C^{-1} – 10^{-5})
Constantan (advance)	Ni_{45}, Cu_{55}	2.1	±2
Isoelastic	Ni_{36}, Cr_8 (Mn, Si, Mo)$_4$ Fe_{52}	3.52 to 3.6	+17
Karma	Ni_{74}, Cr_{20}, Fe_3 Cu_3	2.1	+2
Manganin	Cu_{84}, Mn_{12}, Ni_4	0.3 to 0.47	±2
Alloy 479	Pt_{92}, W_8	3.6 to 4.4	+24
Nickel	Pure	−12 to −20	670
Nichrome V	Ni_{80}, Cr_{20}	2.1 to 2.63	10
Silicon	(*p* type)	100 to 170	70 to 700
Silicon	(*n* type)	−100 to −140	70 to 700
Germanium	(*p* type)	102	
Germanium	(*n* type)	−150	

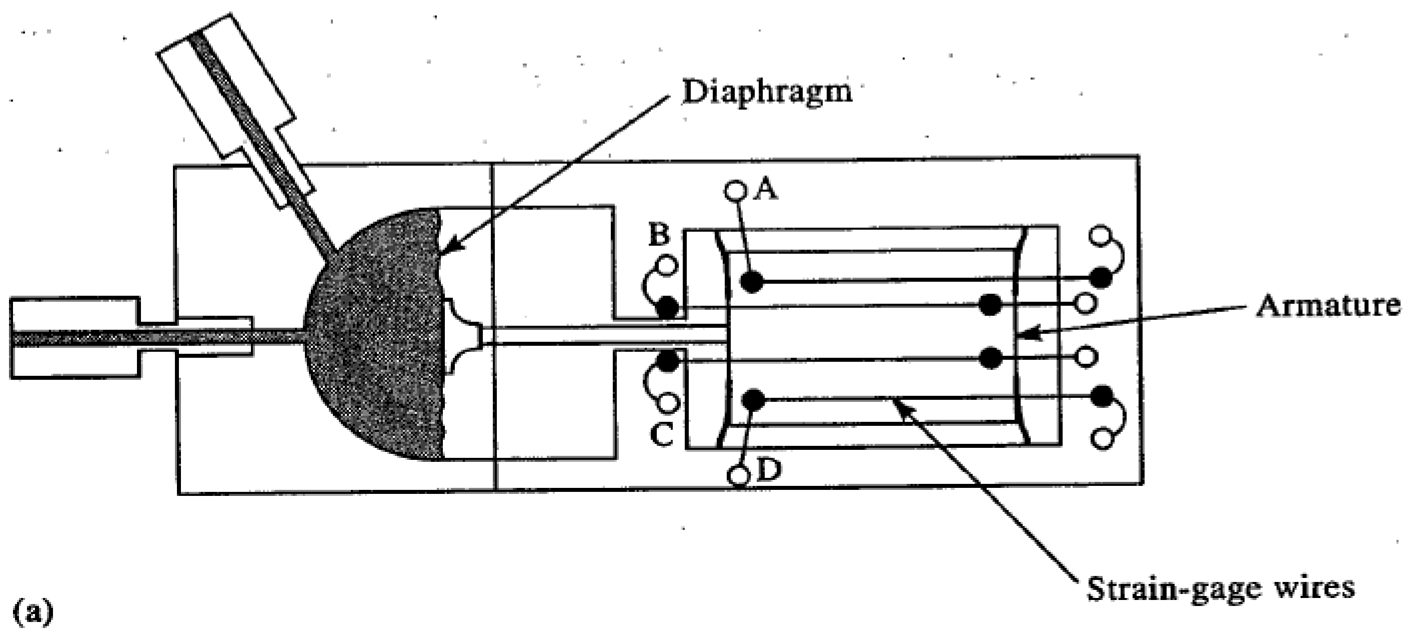
SOURCE: From R. S. C. Cobbold, *Transducers for Biomedical Measurements,* 1974, Wiley; us[ed] with permission of John Wiley and Sons, Inc., New York.

Displacement Meas. - Resistive Sensors – p5

- Notes:
  - Note that the gage factor for semiconductor materials is approximately 50 to 70 times that of the metals. Also note that the gage factor for metals is primarily a function of dimensional effects.
  - For most metals, μ= 0.3 and thus G is at least 1.6, whereas for semiconductors, the piezoresistive effect is dominant.

Displacement Meas. - Resistive Sensors – p6

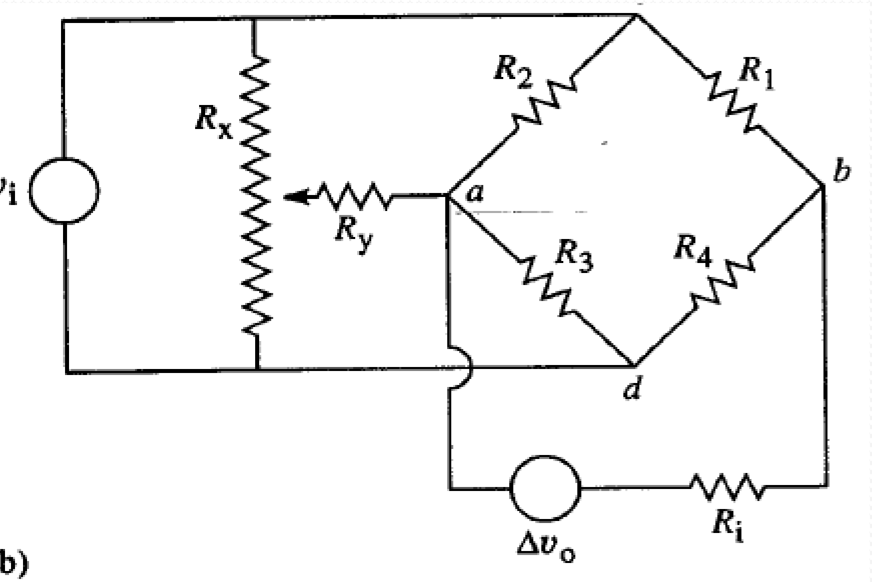
- Classification of Strain gages:
  - Unbonded
  - Bonded
- Unbonded



Displacement Meas. - Resistive Sensors – p7

- Unbonded (electrical Circuit)

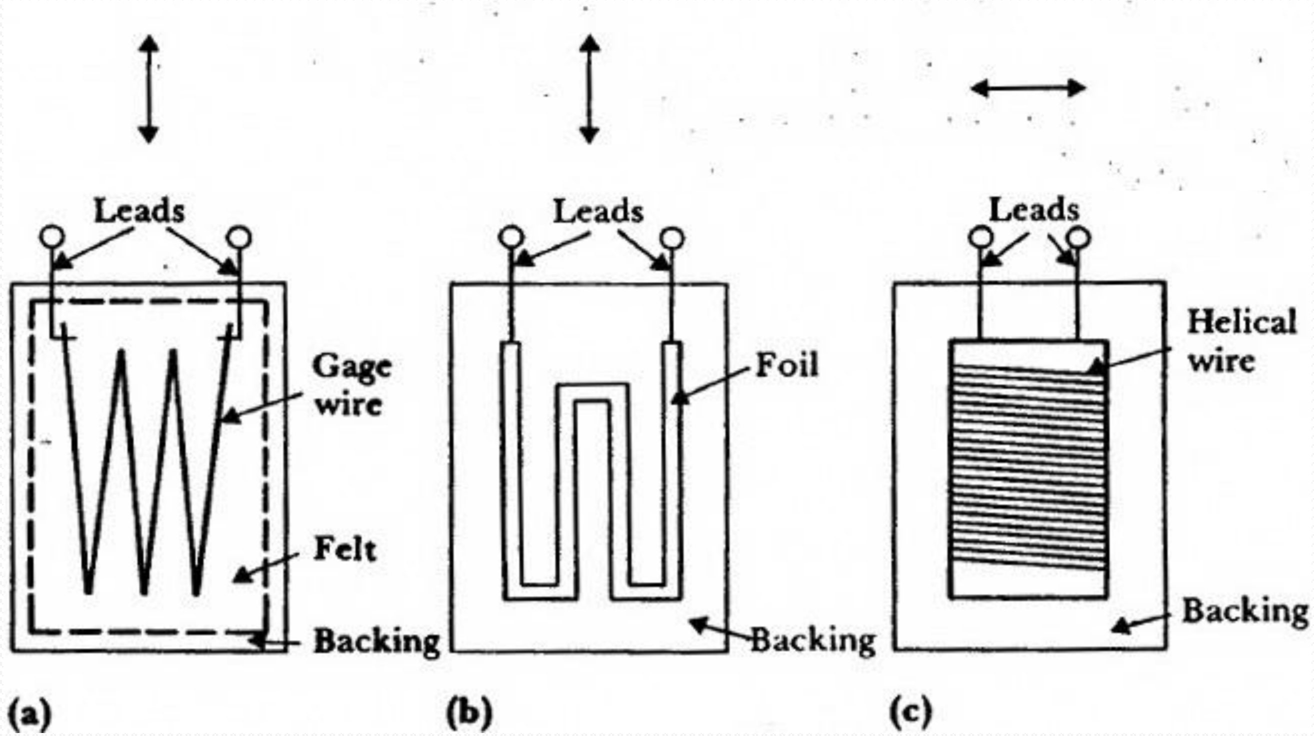
Wheatstone bridge with four active elements.



(b)

Displacement Meas. - Resistive Sensors – p8

- Bonded
  - consisting of a metallic wire, etched foil, vacuum-deposited film, or semiconductor bar, is cemented to the strained surface

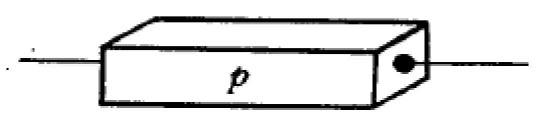


Displacement Meas. - Resistive Sensors – p9

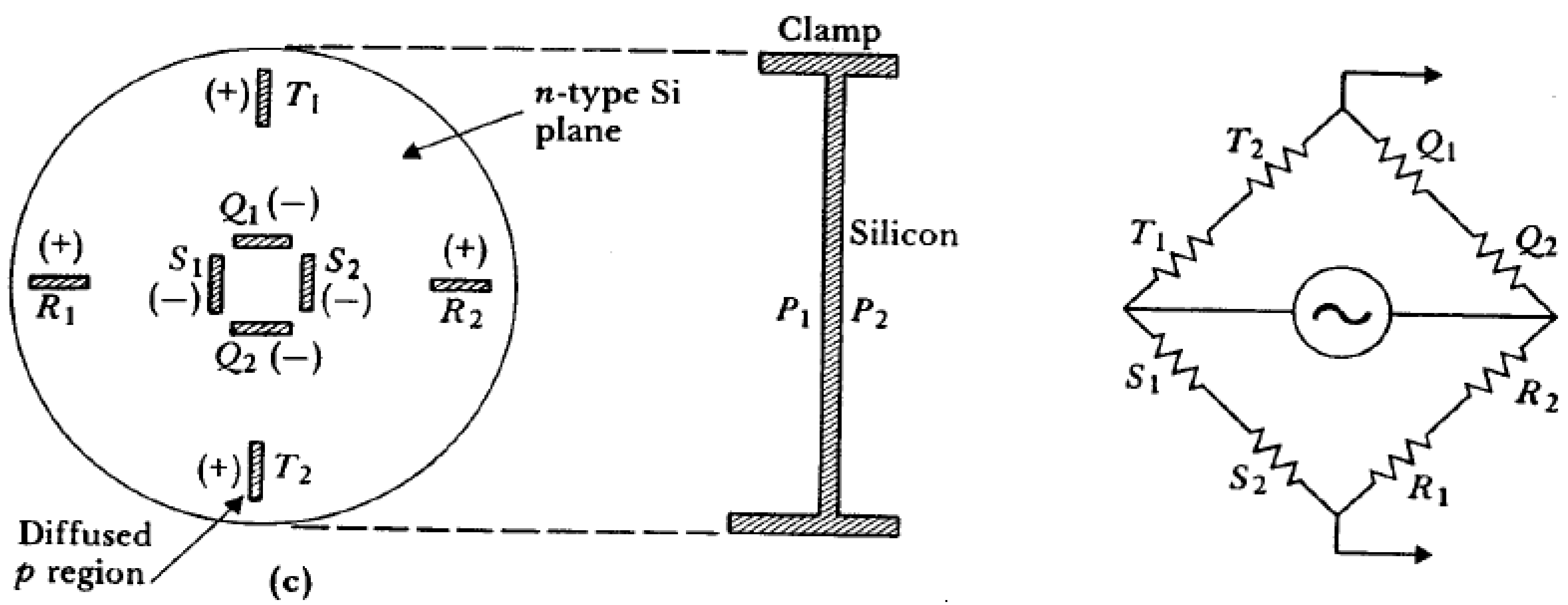
- method of temperature compensation for the natural temperature sensitivity of bonded strain gages: a second strain gage as a dummy element that is also exposed to the temperature variation, but not to strain
- Elastic-resistance strain gages are extensively used in biomedical applications, especially in cardiovascular and respiratory dimensional and plethysmographic (volume-measuring) determinations.
- These systems normally consist of a narrow silicone-rubber tube (0.5 mm ID, 2 mm OD) from 3 to 25 cm long and filled with mercury or with an electrolyte or conductive paste. The ends of the tube are sealed with electrodes (amalgamated copper, silver, or platinum).

Displacement Meas. - Resistive Sensors – p10

- Unbonded uniformly



- Intergrated Pressure Sensor



Displacement Meas. – Inductive Sensors – p1

- An inductance L can be used to measure displacement by varying any three of the coil parameters:

$$L = n^2 G \mu$$

n = number of turns of coil

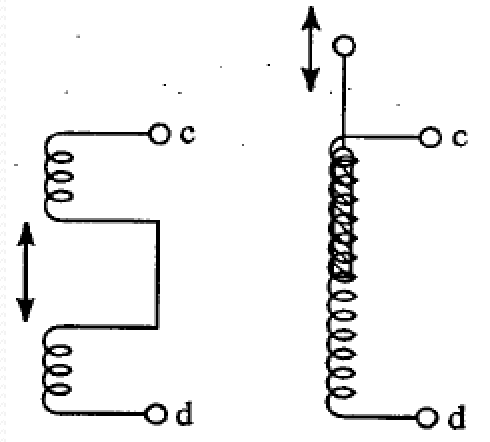
G = geometric form factor

μ = effective permeability of the medium

- Each of these parameters can be changed by mechanical means.
- Types :
  - Self-inductance
  - Mutual Inductance
  - Differential Transformer

Displacement Meas. – Inductive Sensors – p2

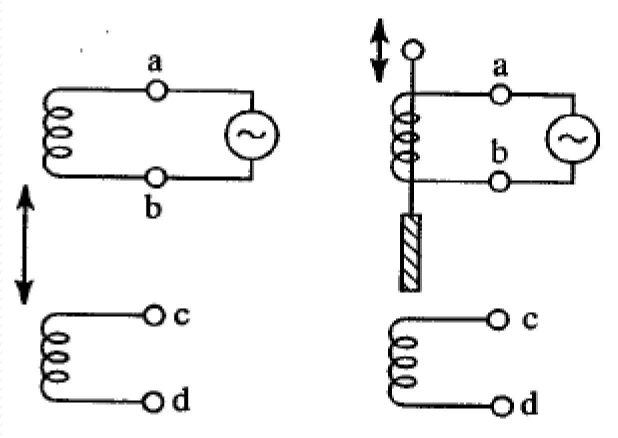
- Self-Inductance



- Changing the geometric form factor or the movement of a magnetic core within the coil
- The change in inductance for this device is not linearly related to displacement.
- These devices have low power requirements and produce large variations in inductance makes them attractive for radiotelemetry applications.

Displacement Meas. – Inductive Sensors – p3

- Mutual-inductance:
  - employs two separate coils and uses the variation in their mutual magnetic coupling to measure displacement.

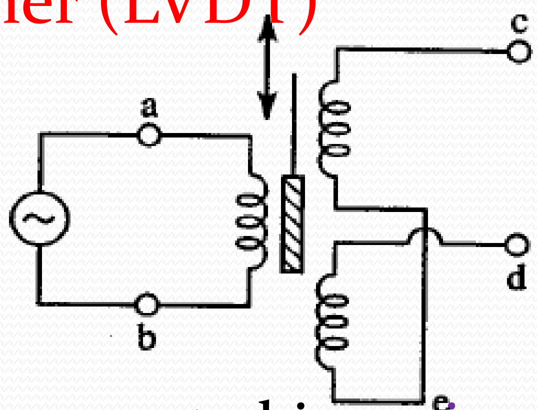


  - Measures cardiac dimensions, monitoring infant respiration, and ascertaining arterial diameters.
  - Measures changes in dimension of internal organs (kidney, major blood vessels, and left ventricle).

Displacement Meas. – Inductive Sensors – p4

- The induced voltage in the secondary coil is a function of the geometry of the coils (separation and axial alignment), The number of primary- and secondary turns, and the frequency and amplitude of the excitation voltage.
- The induced voltage in the secondary coil is a nonlinear function of the separation of the coils.
- In order to maximize the output signal, a frequency is selected that causes the secondary coil (tuned circuit) to be in resonance.
- The output voltage is detected with standard demodulator and amplifier circuits.

Displacement Meas. – Inductive Sensors – p5



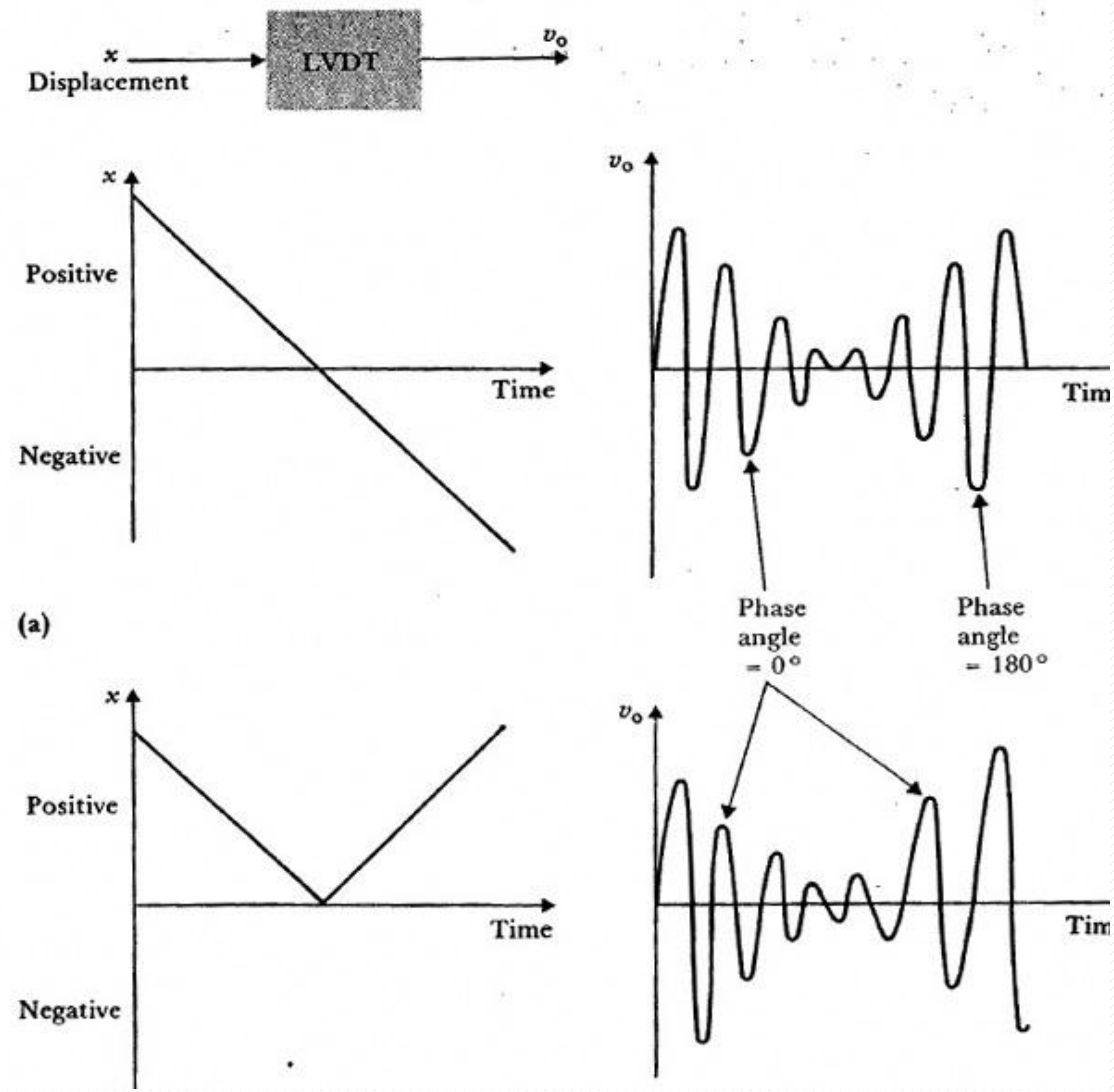
- Linear Variable Differential Transformer (LVDT)
- widely used in physiological research and clinical medicine to measure pressure, displacement, and force
- composed of a primary coil (terminals a-b) and two secondary coils (c-e and d-e) connected in series.
- The two secondary coils are connected in opposition in order to achieve a wider region of linearity.
- The primary coil is sinusoidally excited, with a frequency between 60 Hz and 20 kHz.
- A change of phase by 180 degree when the core passes through the center position, and saturation on the ends.

Displacement Meas. – Inductive Sensors – p6

- Notice:

(a) *As x moves through the null position, the phase changes 180°,* while the magnitude of *Vo 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.



Displacement Meas. – Capacitive Sensors – p1 (Basic)

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

$$C = \epsilon_0 \epsilon_r \frac{A}{x}$$

- In principle it is possible to monitor displacement by changing any of the three parameters. However, the method that is easiest to implement and that is most commonly used is to change the separation between the plates.
- The sensitivity K of a capacitive sensor to changes in plate separation Δx is found by differentiating

$$K = \frac{\Delta C}{\Delta x} = -\epsilon_0 \epsilon_r \frac{A}{x^2}$$

- Note that the sensitivity increases as the plate separation decreases.

Displacement Meas. – Capacitive Sensors – p2

- Equations: (Capacitance sensor for measuring dynamic dsiplacement changes)

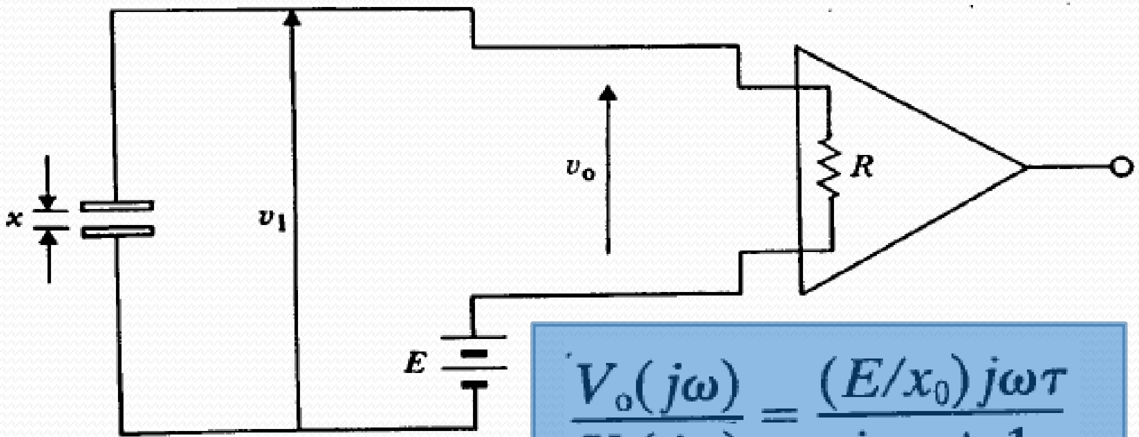
$$C = \epsilon_0 \epsilon_r \frac{A}{x}$$

$$K = \frac{\Delta C}{\Delta x} = -\epsilon_0 \epsilon_r \frac{A}{x^2}$$

$$\frac{dC}{dx} = \frac{-C}{x}$$

or

$$\frac{dC}{C} = \frac{-dx}{x}$$



Typically, *R is 1 MΩ or higher,*

$$\frac{V_o(j\omega)}{X_1(j\omega)} = \frac{(E/x_0)\, j\omega\tau}{j\omega\tau + 1}$$

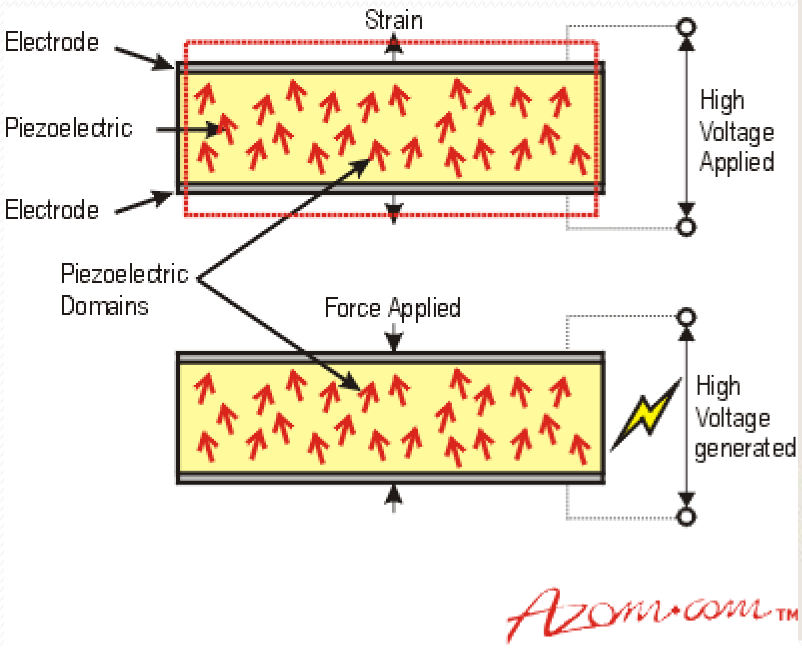
$$\tau = RC = R\epsilon_0\epsilon_r A/x_0$$

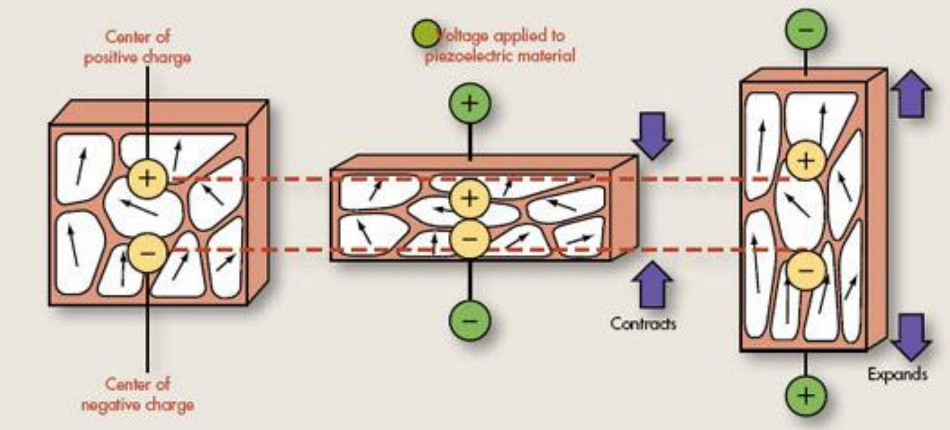
$$x_0 \rightarrow v_1 = E \qquad \Delta x = x_1 - x_0 \rightarrow v_o = v_1 - E$$

Displacement Meas. – Piezoelectric Sensors – p1

- used to measure physiological displacements and record heart sounds.

- Principle:
  - Piezoelectric materials generate an electric potential when mechanically strained, and conversely an electric potential can cause physical deformation of the material.
  - The principle of operation is that, when an asymmetrical crystal lattice is distorted, a charge reorientation takes place, causing a relative displacement of negative and positive charges. The displaced internal charges induce surface charges of opposite polarity on opposite sides of the crystal.
  - Surface charge can be determined by measuring the difference in voltage between electrodes attached to the surfaces.





The piezoelectric effect causes crystal materials like quartz to generate an electric charge when the crystal material is compressed, twisted, or pulled. The reverse also is true, as the crystal material compresses or expands when an electric voltage is applied.

Electronicdesign.com

Displacement Meas. – Piezoelectric Sensors – p2

- Modeling:
  - we assume infinite leakage resistance.
  - the total induced charge *q* is directly proportional to the applied force *f*

$$q = kf$$

  - where *k* is the piezoelectric constant, C/N
  - The change in voltage can be found by assuming that the system acts like a parallel-plate.

$$v = \frac{kf}{C} = \frac{kfx}{\epsilon_0 \epsilon_r A}$$

  - Notice: Piezoelectric materials have a high but finite resistance.

Displacement Meas. – Piezoelectric Sensors – p3

- Equivalent circuit of piezoelectric sensor,

  where *Rs* = sensor leakage resistance, *Cs* = sensor capacitance, *Cc* = cable capacitance, *Ca* =amplifier input capacitance, *Ra* = amplifier input resistance, *and q* = charge generator.

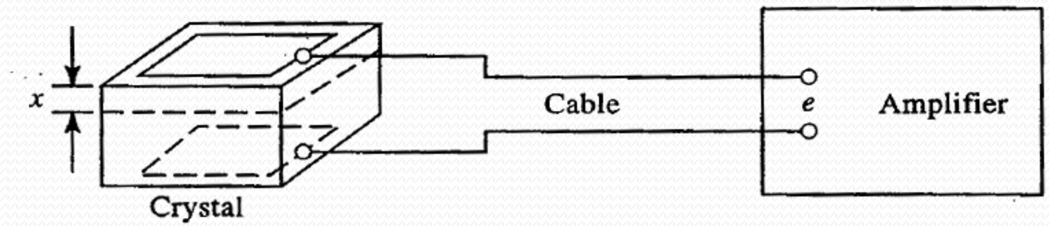
- This circuit has a charge generator *q* defined by:

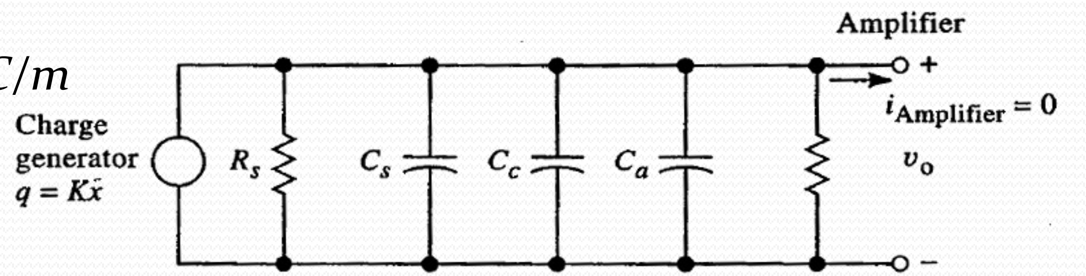
$$q = Kx$$

where:

K = proportionality constant, C/m

x = deflection



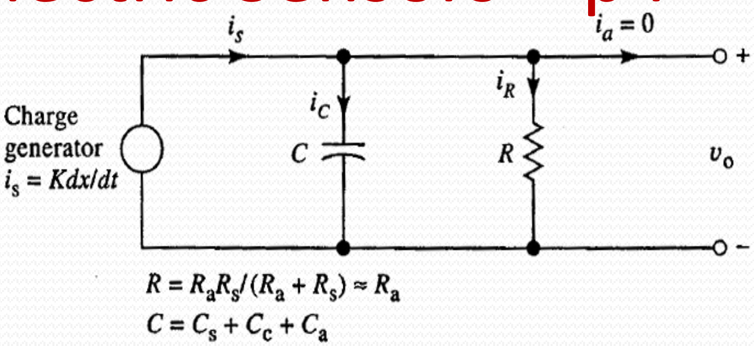


The circuit may be simplified by converting the charge generator to a current generator

$$i_s = \frac{dq}{dt} = K\frac{dx}{dt}$$

Displacement Meas. – Piezoelectric Sensors – p4

- **Modified circuit:**
- Combined elements
- Assuming that the amplifier current = Zero



$$i_s = i_C + i_R$$

$$v_o = v_C = \left(\frac{1}{C}\right) \int i_C \, dt$$

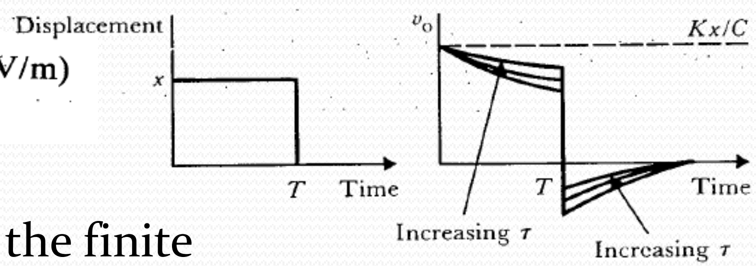
$$i_s - i_R = C\left(\frac{dv_o}{dt}\right) = K\frac{dx}{dt} - \frac{v_o}{R}$$

$$\frac{V_o(j\omega)}{X(j\omega)} = \frac{K_s j\omega\tau}{j\omega\tau + 1}$$

$K_s = K/C$ (sensitivity, V/m)

$\tau = RC$ (time constant)

Sensor response to a step displacement



- The output decays exponentially because of the finite internal resistance of the piezoelectric material.
- At time equal to T the force is released, and a displacement restoration results that is equal and opposite to the original displacement.
- This causes a sudden decrease in voltage of magnitude Kx/C, with a resulting undershoot equal to the decay prior to the release of the displacement.
- The decay and undershoot can be minimized by increasing the time const, $\tau = RC$.
- The simplest approach to increasing τ is to add a parallel capacitor.

Displacement Meas. – Piezoelectric Sensors – p5

- Example:

A piezoelectric sensor has C = 500 *pF*. The sensor leakage resistance is 10 GΩ. The amplifier input impedance is 5 MΩ. What is the low corner frequency?

- Answer:
- We may use the modified equivalent circuit of the piezoelectric sensor given in Figure 2.9(b) for this calculation.

$$f_c = 1/(2\pi RC) = 1/[2\pi(5 \times 10^6)(500 \times 10^{-12})] = 64 \text{ Hz}$$

Temperature Measurements

- A patient's body temperature gives the physician important information about the physiological state of the individual
- A drop in the big-toe temperature is a good early clinical warning of shock.
- Infections, on the other hand, are usually reflected by an increase in body temperature, with a hot, flushed skin and loss of fluids
- Increased ventilation, perspiration, and blood flow to the skin result
- high fevers destroy temperature-sensitive enzymes and proteins & Etc….
- Types
  - Thermocouples
  - Thermistor
  - Radiation Thermometry
  - Fiber-Optic Temperature Sensors

Temperature Measurements – Thermocouples p1

- ***Principles***:
  - *Thermoelectric thermometry* is based on the discovery of *Seebeck* in 1821. He observed that an *electromotive force (emf)* exists across a junction of two dissimilar metals.
- **Effects**:
  - **Net Peltier *emf***:
    - The first effect, discovered by Peltier, is an emf due solely to the contact of two unlike metals and the junction temperature. The net Peltier emf is roughly proportional to the difference between the temperatures of the two junctions.
  - **Net Thomson *emf* (Lord Kelvin):**
    - The second effect, credited to Thomson (Lord Kelvin), is an emf due to the temperature gradients along each single conductor. The net Thomson *emf* is proportional to the difference between the squares of the absolute junction temperatures.

Temperature Meas. – Thermocouples p2

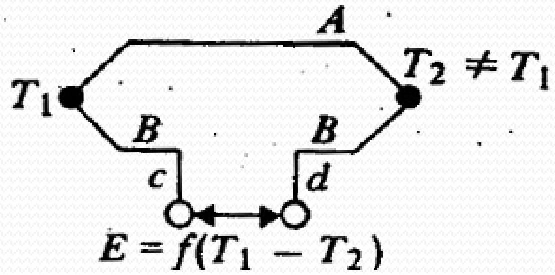
- *Empirical Calibration:*
  - data are usually curve-fitted with a power series expansion that yields the Seebeck voltage:

$$E = aT + \tfrac{1}{2}bT^2 + \cdots$$

  - where T is in degrees Celsius and the reference junction is maintained at 0 °C.
  - A thermocouple circuit with two dissimilar metals,
  - In the practical situation, one junction is held

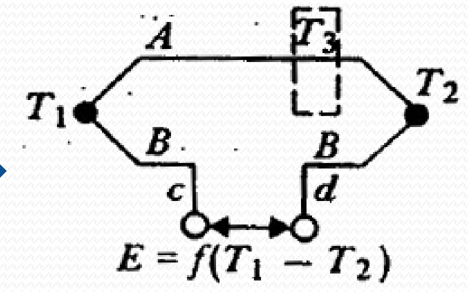
at a constant known temperature

(by an ice bath or controlled oven)

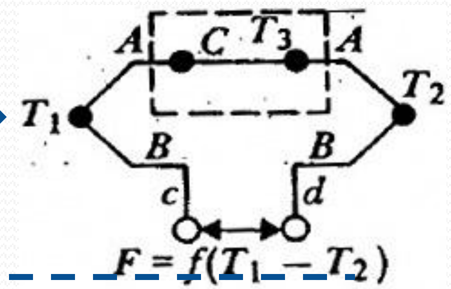


Temperature Meas. – Thermocouples p3

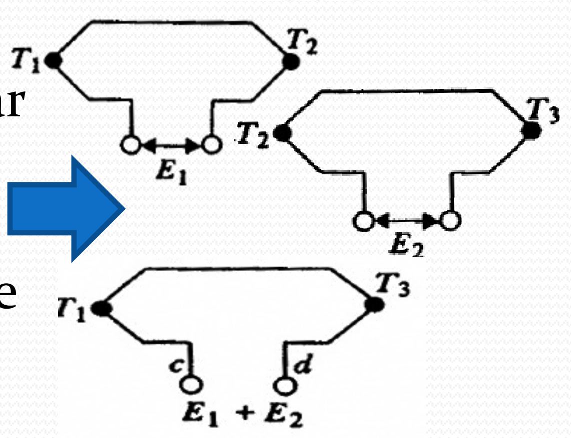
- *Empirical thermocouple laws:*
  - *Homogeneous circuits:* States that in a circuit composed of a single homogeneous metal, on cannot maintain an electric current by the application of heat alone.



  - *Intermediate metals:* states that the net emf in a circuit consisting of an interconnection of a number of unlike metals, maintained at the same temperature, is zero.



  - *Successive or intermediate temperatures:* States that *emf E1* is generated when two dissimilar metals have junctions at temperatures *T1* and *T2* and emf *E2* results for temperatures *T2* and *T3*. It follows that an emf *E1* + *E2* results at *c-d* when the junctions are at temperatures *T1* and *T3*



Temperature Meas. – Thermocouples p4

- *Thermoelectric sensitivity* α (also called the thermoelectric power or the Seebeck coefficient):
  - is found by differentiating
  - with respect to T

$$\alpha = dE/dT = a + bT + \cdots$$

- *Thermometers in series:* Sensitivity Increased

  All of them measuring the same temperature and using the same reference junction.

- *Thermopile:*

  An arrangement of multiple-junction thermocouples is referred to as a *thermopile.*

- *Parallel combinations:*

  May be used to measure average temperature.

Temperature Meas. – Thermocouples p4

- Advantages:
  - fast response time (time constant as small as 1 ms)
  - small size (down to 12 μm diameter)
  - Ease of fabrication
  - Long-term stability.
- Disadvantages:
  - Small output voltage
  - Low sensitivity
  - The need for a reference temperature.
- Note: Thermocouples can be made small in size, so they can be inserted into catheters and hypodermic needles.

Temperature Measurements – Thermistors p1

- Thermistors are semiconductors made of **ceramic materials** that are thermal resistors with a **high negative temperature coefficient.**
- That is **opposite** to the way **metals react** to such changes.
- The resistivity of thermistor semiconductors used for biomedical applications is between **0.1 and 100 Ωm.**
- The **empirical relationship between** the thermistor resistance *Rt* and absolute temperature *T* in kelvins *(K)* is:

$$R_t = R_0 e^{[\beta(T_0 - T)/TT_0]}$$

β = material constant for thermistor, K

T_0 = standard reference temperature, K

- The **temperature coefficient** can be found by differentiating with respect to *T* and dividing by *Rt*. Thus

$$\boxed{\alpha = \frac{1}{R_t}\frac{dR_t}{dT} = -\frac{\beta}{T^2}\,(\%/\mathrm{K})}$$

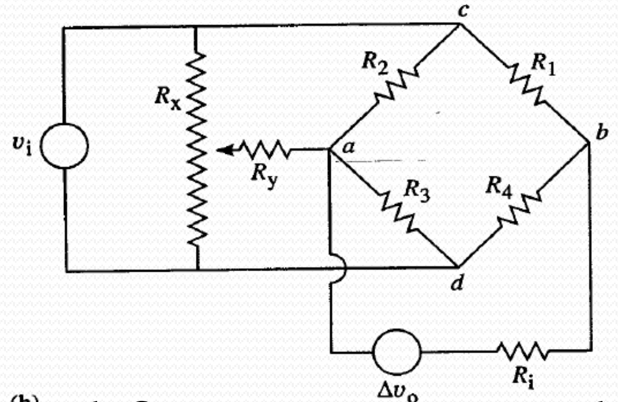
- That α is a nonlinear function of temperature.

Temperature Measurements – Thermistors p2

- **Advantages:**
  - These devices are **small in size** (they can be made less than 0.5 mm in diameter)
  - Have a relatively **large sensitivity to temperature** changes
  - Excellent **long-term stability** characteristics (±0.2% of nominal resistance value per year).
- **Disadvantages:**
  - **Time delays** from milliseconds to several minutes are possible with thermistor circuits.
  - **Nonlinear characteristic** (Various circuit schemes for linearizing the resistance-versus-temperature characteristics of thermistors are necessary)

Temperature Meas. – Thermistors p3 (linearizing)

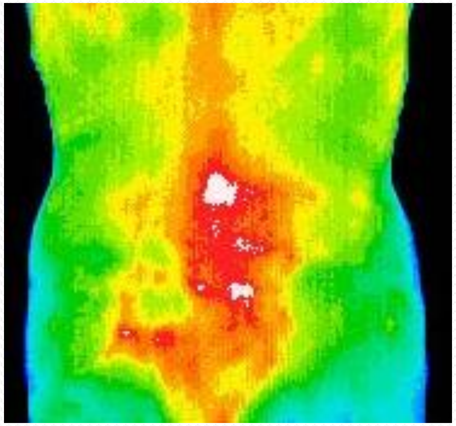
- Bridge circuits give high sensitivity and good accuracy. The bridge circuit shown in Figure could be used with $R3 = Rt$ and $R4$ = the thermistor resistance at the midscale value.

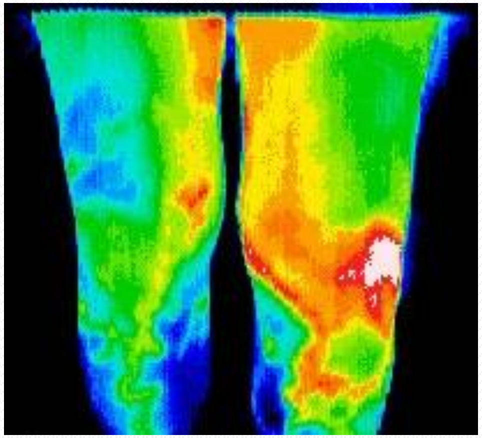


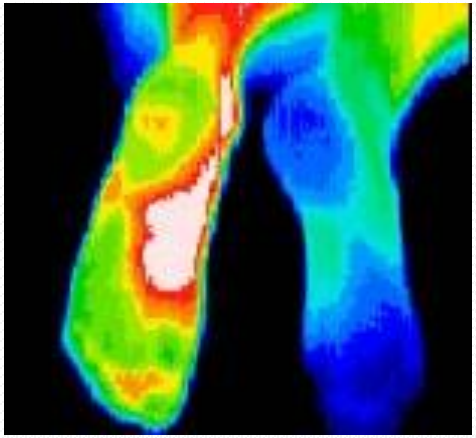
- Operational-amplifier circuits may be used to measure the current in a thermistor as a function of temperature.

Temperature Meas. – Radiation Thermometry

- Principle:
  - The basis of **radiation thermometry** is that there is a known relationship between the **surface temperature** of an object and its **radiant power**.
  - This principle makes it possible to **measure the temperature** of a **body without physical contact with it.**
  - Medical **thermography** is a technique whereby the temperature distribution of the body is mapped with a **sensitivity** of a few tenths of a kelvin







Temperature Meas. – Radiation Thermometry p2

- Every body that is **above absolute zero radiates electromagnetic power**, the amount being **dependent** on the body's **temperature** and **physical properties**.
- A **blackbody** is an **ideal thermal radiator**
- The **radiation emitted** from a body is given by **Planck's law** multiplied by emissivity ε. This expression relates the radiant flux per unit area per unit wavelength Wλ at a wavelength λ *(μm) and is stated as:*

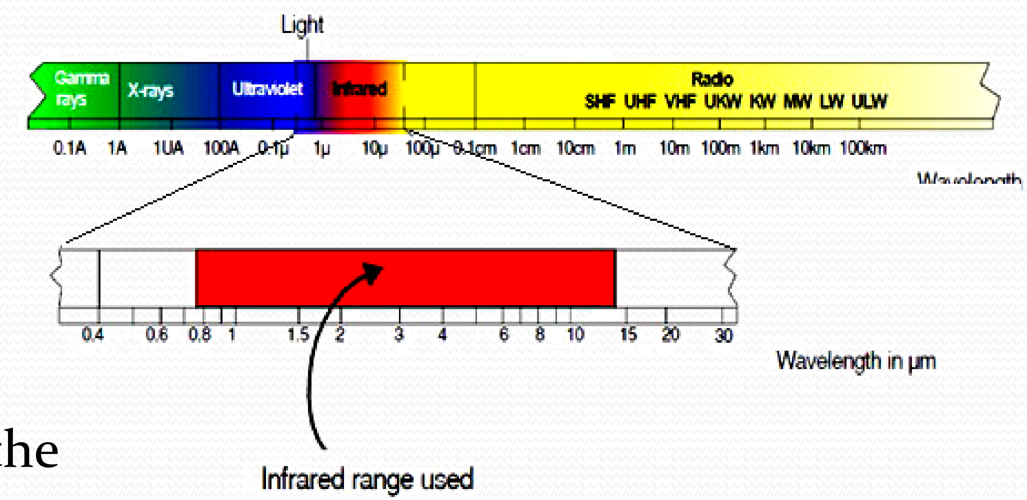
$$W_\lambda = \frac{\epsilon C_1}{\lambda^5(e^{C_2/\lambda T} - 1)} \qquad (\mathrm{W/cm^2 \cdot \mu m})$$

$C_1 = 3.74 \times 10^4 \qquad (\mathrm{W \cdot \mu m^4/cm^2})$

$C_2 = 1.44 \times 10^4 \qquad (\mu\mathrm{m \cdot K})$

T = blackbody temperature, K

ϵ = emissivity blackbody ($\epsilon = 1$)

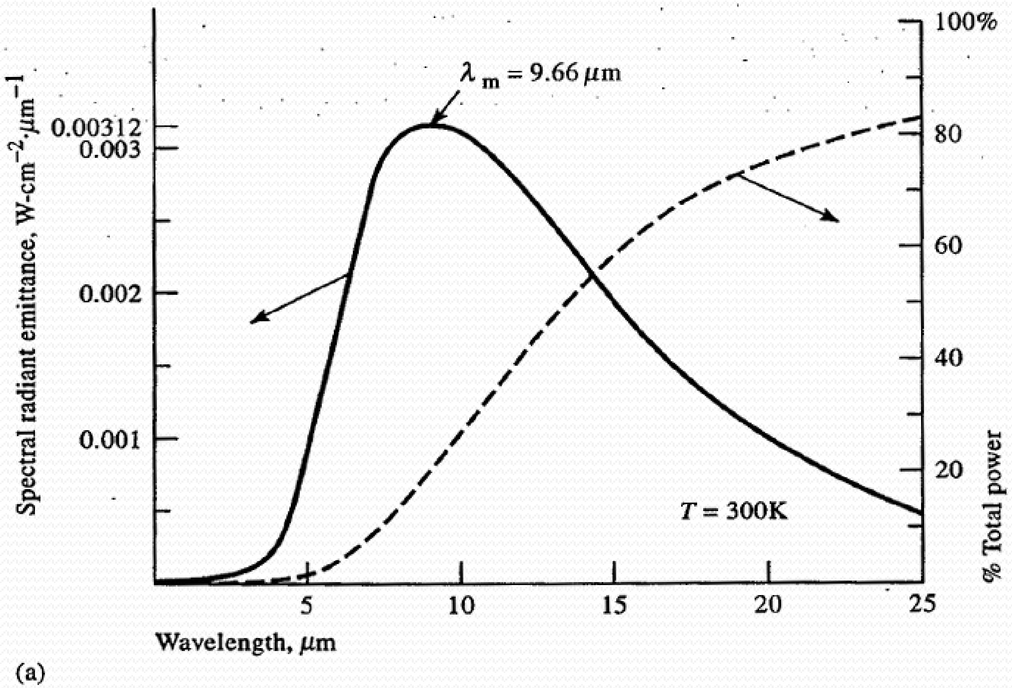


- Wien's displacement law gives the wavelength for which Wλ is a maximum.
- λm is inversely related to *T*

$$\lambda_m = \frac{2898}{T} \qquad (\mu\mathrm{m})$$

Temperature Meas. – Radiation Thermometry p3

- λm is inversely related to *T*



$$\lambda_m = \frac{2898}{T} \qquad (\mu m)$$

Temperature Meas. – Radiation Thermometry p4

- **Thermography Camera (Thermal Camera)**

Public Safety and Rescue

Temperature Meas. – Radiation Thermometry p5

- Infrared detectors and instrument systems must be designed with a **high sensitivity** because of the weak signals.
- These devices must have a **short response time** and appropriate **wavelength-bandwidth** requirements that match the **radiation source**.
- Suitable instrumentation must be used to **amplify**, **process**, and **display** these weak signals from radiation detectors.
- Most radiometers make use of a **beam-chopper** system to **interrupt** the **radiation at a fixed rate** (several hundred hertz).

1
2
3
4

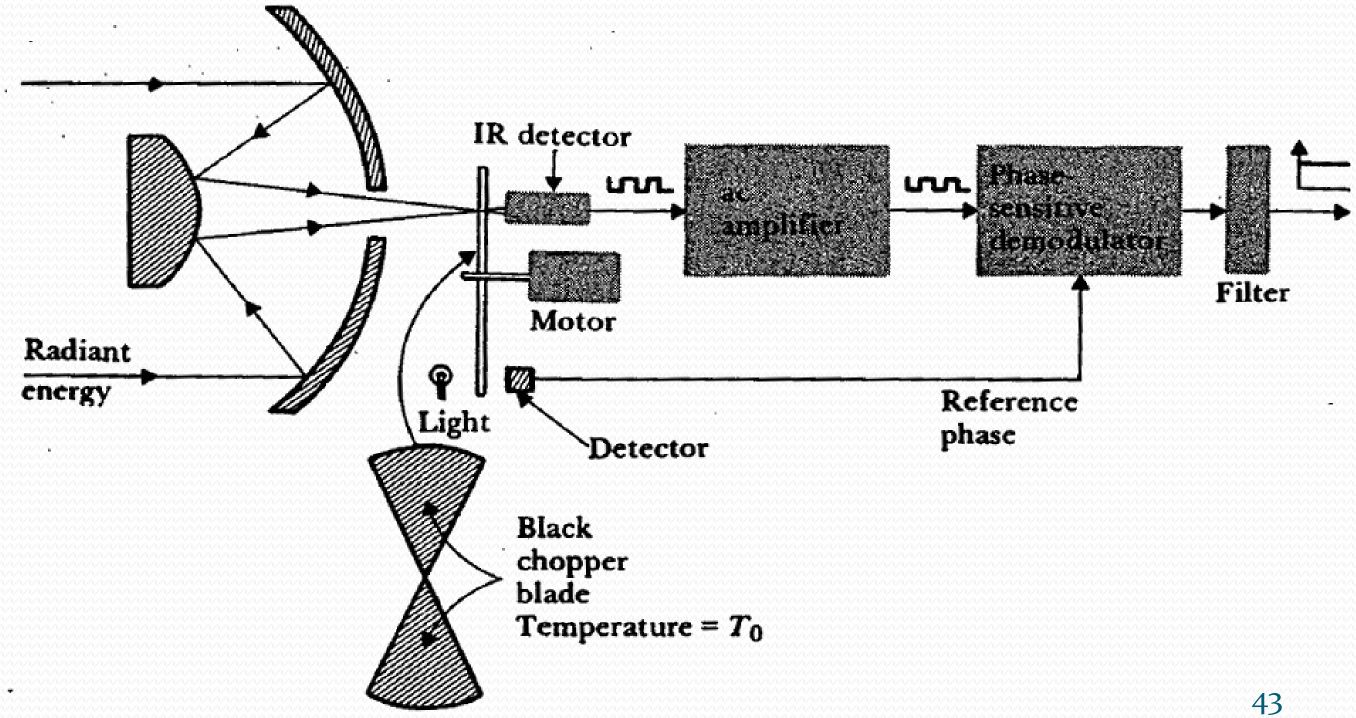
- Allows the use of **high-gain ac amplifiers** without the **inherent problems of stability in dc amplifiers.**
- **Comparison of reference sources** and techniques of **temperature compensation** are more applicable **to ac-instrumentations**

- ***Stefan-Boltzmann law:*** $W_t = \epsilon\sigma T^4 \quad (\mathrm{W/cm^2})$

where σ is the Stefan-Boltzmann constant

$$\sigma = 5.67 \times 10^{-12}\ \mathrm{W/(cm^2 \cdot K^4)}$$

- **Typical chopped-beam radiation-thermometer system**



Radiation Thrm. p6 - **Chopped-Beam Radiation-Thermometer**

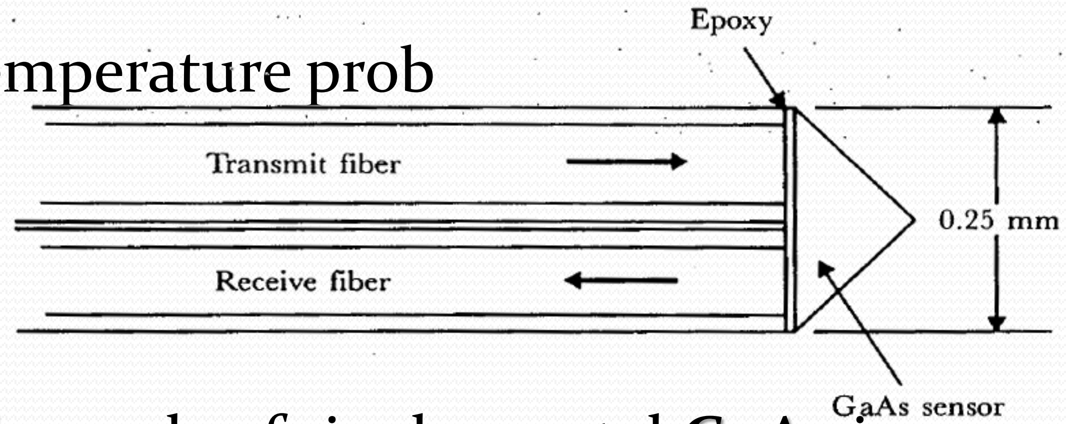
- A **mirror focuses** the radiation on the **detector** (a blackened chopper interrupts the radiation beam at a constant rate)
- The **output of the detector** circuit is a series of pulses with **amplitude dependent** on the **strength** of the **radiation source.**
- This **AC signal** is amplified, while the **mean value**, which is subject to **drift**, is **blocked**.
- A **reference-phase signal**, used to **synchronize** the **phase-sensitive demodulator,** is generated in a special circuit consisting of a **light source** and **detector**.
- This signal is then **filtered** to provide a **dc signal proportional** to the **target temperature**.
- This signal can then be **displayed or recorded**.

Radiation Thrm. p6 Application of Radiation Thermometry

- An instrument that determines the internal or core body temperature of the human by **measuring the magnitude** of **infrared** radiation emitted from the **tympanic membrane** and **surrounding ear canal**.
- **The infrared thermometry** device detects emitted energy that **is proportional to the actual temperature of the subject.** (not the sensor temperature)
- It has a **response time** in the order of **0.1 s** and an **accuracy** of approximately **0.1 °C**.
- It requires a **calibration target** in order to maintain their **high accuracy.**
- Independent of user technique and **degree of patient activity or cooperation**

FIBER-OPTIC TEMPERATURE SENSORS p1

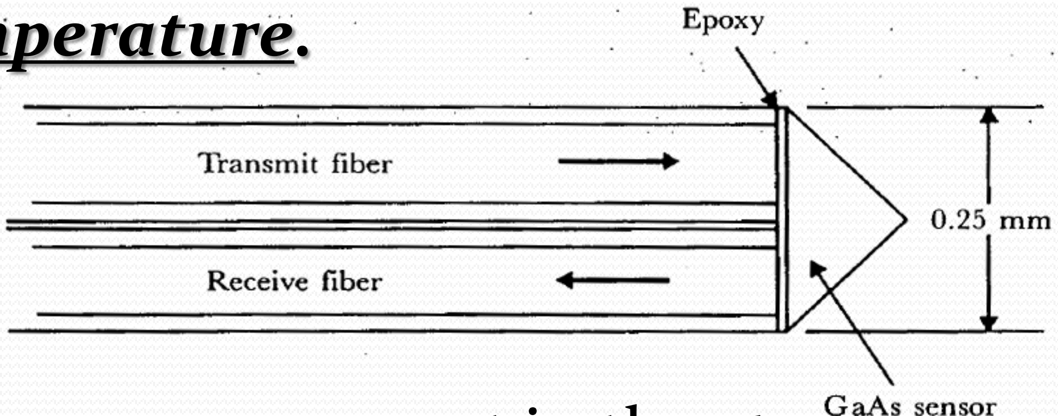
- GaAs semiconductor temperature prob



- A small **prism-shaped** sample of single-crystal **GaAs** is epoxied at the ends of two **side-by-side optical fibers**
- These can be quite small, compatible with biological implantation after being sheathed.
- One **fiber transmits** light from a light-emitting diode source to the sensor, where it is passed through the GaAs and collected by the other fiber for detection in the **readout instrument**.

Fiber-Optic Temperature Sensors- p2

- Notes:
- Some of the **optical power traveling** through the **semiconductor is absorbed**, by the process of **raising valence-band electrons**, across the forbidden energy gap into the **conduction band**. Because the forbidden energy gap is a **sensitive function of the material's temperature**, ***The amount of power absorbed increases with temperature*.**

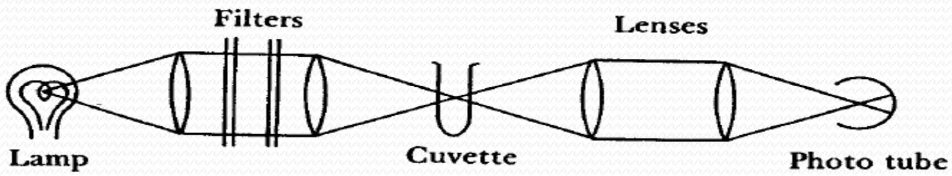


- Suited for temperature measurement in the **strong electromagnetic heating fields**

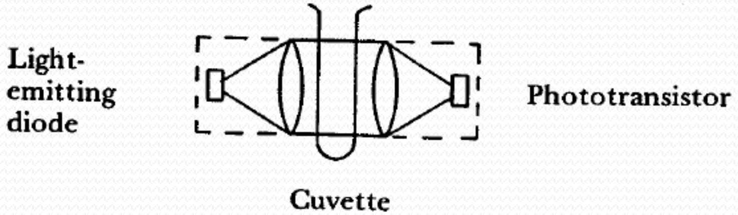
Optical Measurements p1

- In the clinical-chemistry lab
- Analyze samples of blood and tissues removed from the body
- Measure the oxygen saturation of hemoglobin and to measure cardiac output
- Usual optical instrument has a source, filter, and detector.

- A common arrangement of components.



- The function of source, filter, sample, and detector may be accomplished by solid-state components



Radiation Source - p1- Tungsten Lams

- The **most commonly** used sources of radiation.
- Radiant **output** varies with **temperature and wavelength**, as given by

$$W_\lambda = \frac{\epsilon C_1}{\lambda^5(e^{C_2/\lambda T} - 1)} \qquad (\text{W/cm}^2 \cdot \mu\text{m})$$

- For **higher temperatures**, λm, **the maximal wavelength** of the radiant-output curves, shifts to a **shorter wavelength**,

$$\lambda_m = \frac{2898}{T} \qquad (\mu\text{m})$$

- **Low temperatures**, then, yield a **reddish color** (**infrared lamps**), whereas **high temperatures** yield a **bluish color** (**photoflood lamps**).
- The total radiant power ***Wt*** can be found by: $W_t = \epsilon\sigma T^4 \qquad (\text{W/cm}^2)$
- Filaments are usually **coiled** to increase their **emissivity and efficiency**. For use in instruments, short linear coils may be arranged within a compact, nearly square area lying in a single plane.

Radiation Source - p2- Fluorescent Lamp

- The fluorescent lamp is filled with a **low-pressure Ar-Hg** mixture.
- **Electrons are accelerated** and **collide** with the **gas atoms**, which are **raised to an excited level**.
- As a given atom's electron **undergoes** a transition from a **higher level to a lower level**, the atom **emits a quantum of energy.**
- A **phosphor** on the inside of the glass bulb **absorbs** this **ultraviolet radiation** and **emits light of longer, visible wavelength**
- The fluorescent lamp has **low radiant output per unit area**, so it is **<u>not used</u>** in **optical instruments**.
- It can be **rapidly turned on and off** in about **20μs.**

Radiation Source - p3- Light-Emitting Diodes (LEDs)

- **LEDs** are **p-n** junction devices that are optimized for **radiant output**. The ordinary silicon p-n junction emits radiant power when a current (typically 20 mA) passes in the forward direction.
- **Spontaneous recombination** of injected hole and electron pairs results in the **emission of radiation.**
- Because the **silicon band gap** is **1.1 ev**, the wavelength is at about **1100 nm**. The silicon device **is not efficient.**
- ***GaAs*** has a slightly **higher band gap**, and therefore radiates at **900 nm(is not visible),** the efficiency is high and is **widely used**. It can be switched in less than **10 ns**.
- The ***GaP*** LEDs has a band gap **of 2.26 ev,** and is electro-luminescent **at 700 nm**

Radiation Source - p3- LASER

(*Light Amplification by Stimulated Emission of Radiation*)

- The **end faces** that are **perpendicular to the *p-n* junction** are **polished** to serve as **partial mirrors**, thus forming a **resonant optical cavity.**
- ***Stimulated emission:*** The **forward current pumps** a large **population of the molecules** to an excited energy level. Radiation incident on the molecules causes the **production** of **additional radiation** that is identical in character.
- **Laser output** is **<u>highly monochromatic, collimated (parallel), and phase-coherent.</u>**
- ***p-n* junction** lasers are **not widely used** because they **operate in the infrared and require current densities of 1000A/cm2** or **more**

Radiation Source – p4- LASER

- Commonly used:

Type	Wavelength	Application	Power
He-Ne	633 nm	red region	100 mW
Argon	515 nm	diabetic retinopathy.	highest continuous-power levels (1-15 W)
CO2	10600 nm	cutting plastics, rubber, and metals up to 1 cm thick	50-500 W of CW
Ruby	693 nm	red region	(l-mJ)
(Nd: YAG) yttrium aluminum garnet	1064 nm	infrared region	High (2-W/mm)

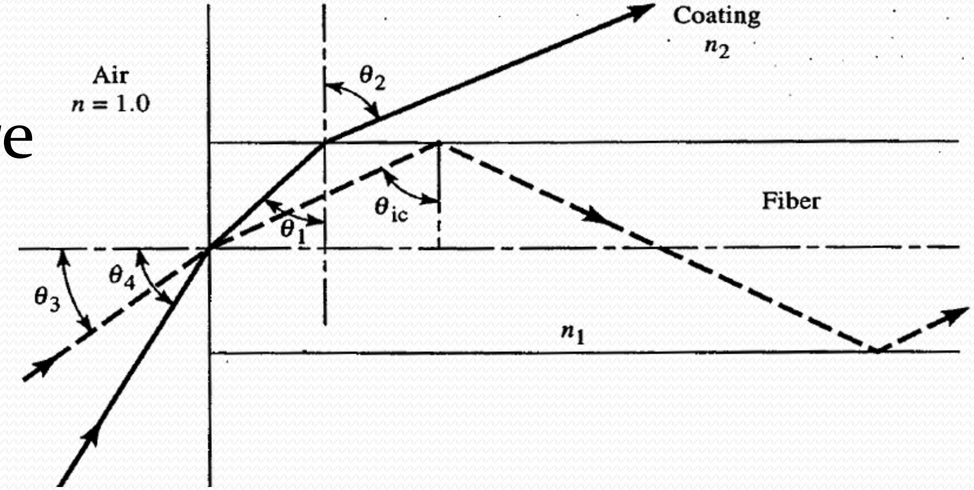
- There are a number of **geometric factors** that modify the power transmitted between the source and the detector.
- ***f* number** (ratio of focal length to diameter)
- ***collimated*** (that is, the rays are parallel).
- **Focus**
- **Scatter**
- Full mirrors & Half mirrors

Geometrical and Fiber Optics-p2- Fiber Optics

- Fiber optics are an efficient way of transmitting radiation from one point to another
- **Transparent glass or plastic fiber** with a **refractive** index ***n1*** is coated or surrounded by a second material of a lower refractive index **n2**. By Snell's law,

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

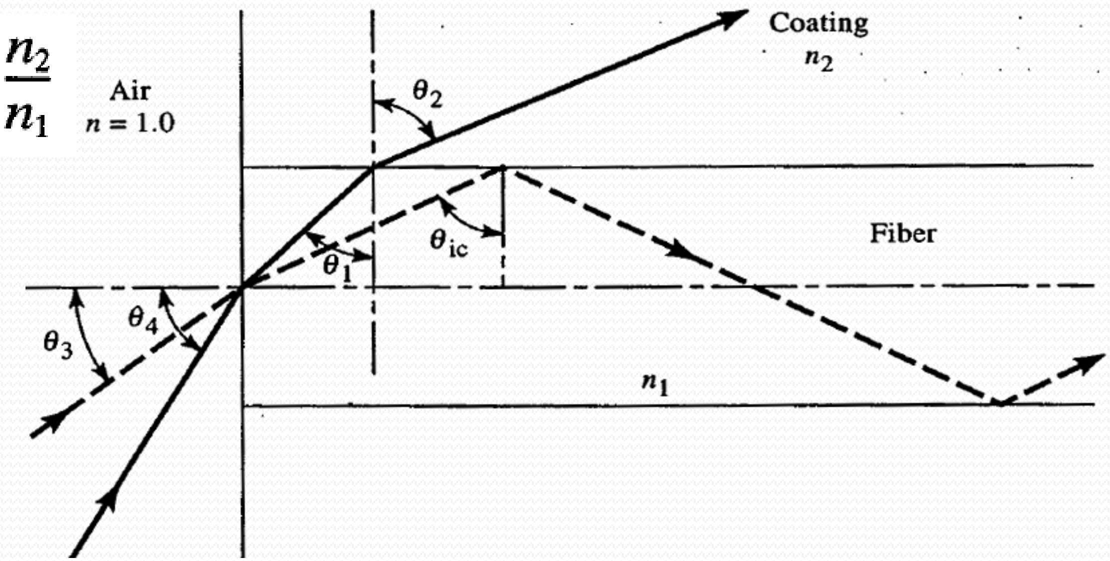
- where θ is the angle of incidence shown in Figure



Geometrical and Fiber Optics-p3- Fiber Optics

- Because $n_1 > n_2$, $\sin\theta_2 > \sin\theta_1$, so $\sin\theta_2 = 1.0$ for a value of θ_1 that is less than 90°.
- For values of θ_1 greater than this, $\sin\theta_2$ is greater than unity, which is impossible, and the ray **is internally reflected**.
- The critical angle for reflection (θ_{ic}) is found by setting $\sin\theta_2 = 1.0$, which g

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



- Rays entering the end of the fiber at larger angles (θ_4) are not transmitted down the fiber; they **escape through the walls**.

Geometrical and Fiber Optics-p4- Fiber Optics

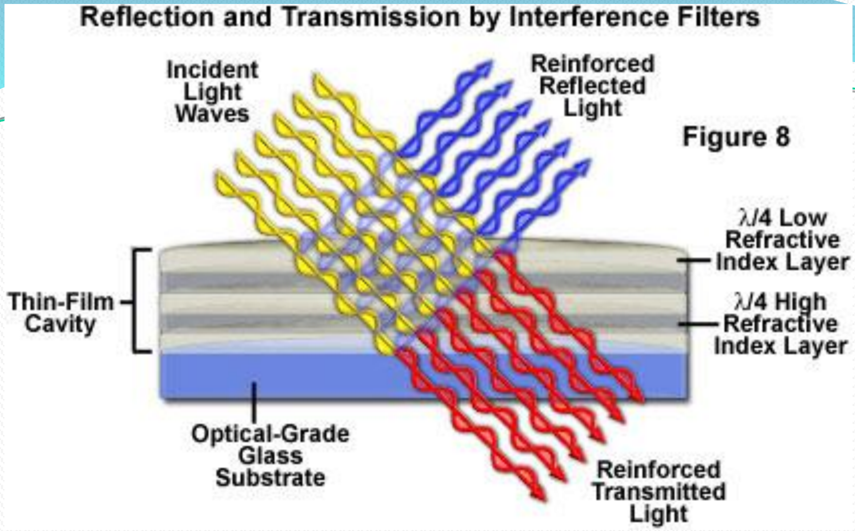
- Fiber-optic (FO) sensors are replacing some conventional sensors for measuring a variety of **electrical**, **electronic**, **mechanical, pneumatic, and hydraulic variables**
- **Types:**
  - ***Noncoherent bundles (called light guides),***
    - **No correlation** between a fiber's spatial position at the **input** and at the **output**,
    - **useful only for transmitting radiation**
  - ***Coherent-fiber bundles,***
    - The fibers occupy the **same relative position at both end faces**.
    - An **image** at one end is **faithfully transmitted** to the other **end**.

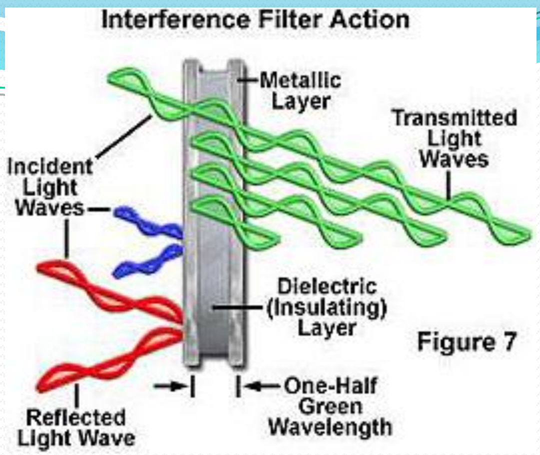
Optical Filters - p1

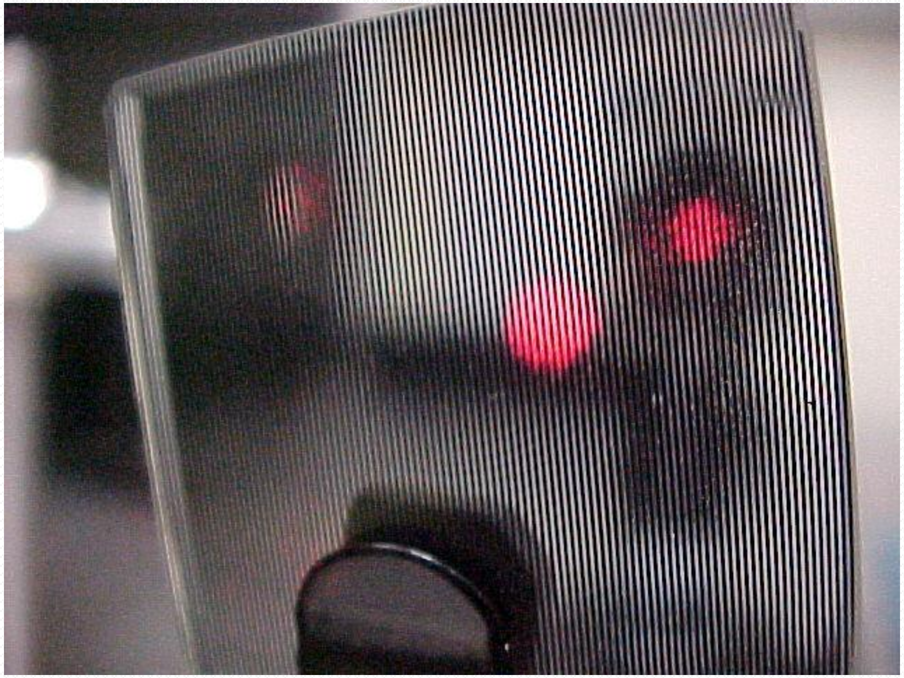
- Filters are frequently inserted in the optical system to control the distribution of radiant power or wavelength.
- When glass is partially silvered, most of the power is reflected and the desired fraction of the power is transmitted.
- When carbon particles are suspended in plastic, most of the power is absorbed and the desired fraction of the power is transmitted.
- Two Polaroid filters may also be used to attenuate the light

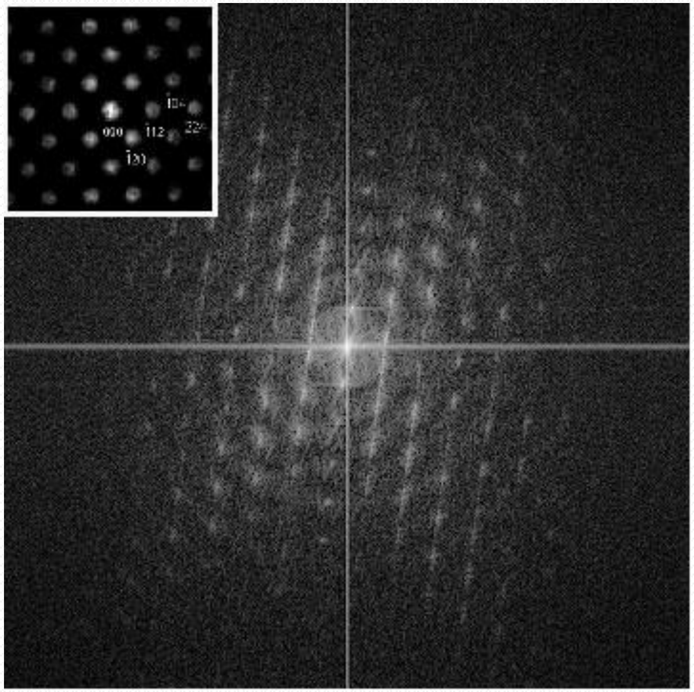
Optical Filters – p2

- ***Color filters*** transmit certain wavelengths and reject others.
  - ***Gelatin filters*** are the most common type of absorption filters (An organic dye is dissolved in an aqueous gelatin solution, and a thin film is dried on a glass substrate.)
  - ***Glass filters***, made by combining additives with the glass itself in its molten state, are extensively used
  - ***Interference filters*** *are formed by depositing a reflective stack of layers on* both sides of a thicker spacer layer. (reduce heat within the optical system without sacrificing the useful light)
  - ***Diffraction gratings*** are widely employed to produce a wavelength spectrum in the spectrometer.
    - Plane gratings are formed by cutting thousands of closely spaced parallel grooves in a material.


Reflection and Transmission by Interference Filters
Incident Light Waves
Reinforced Reflected Light
Figure 8
λ/4 Low Refractive Index Layer
Thin-Film Cavity
λ/4 High Refractive Index Layer
Optical-Grade Glass Substrate
Reinforced Transmitted Light


Interference Filter Action
Metallic Layer
Transmitted Light Waves
Incident Light Waves
Dielectric (Insulating) Layer
Figure 7
One-Half Green Wavelength
Reflected Light Wave





Radiation Sensors - p1

- Radiation sensors may be classified into two general categories:
  - **Thermal sensors**
  - **Quantum sensors**

Radiation Sensors – p2 – Thermal Sensors

- ***<u>The thermal sensor</u>*** **absorbs radiation** and **transforms it** into **heat**, thus causing a **rise in temperature** in the sensors. (Typical Types: the **thermistor** and the **thermocouple**)
  - The **sensitivity** of such a sensor **<u>does not change</u>** with(is flat with) **wavelength,** and the sensor **has slow response**
- ***The pyroelectric*** sensor absorbs radiation and converts it into heat.
  - rise in **temperature changes the polarization** of the **crystals**, which produces a **current proportional** to the rate **of change of temperature**.
  - As it is for the piezoelectric sensor, **dc response is zero**, so a **chopper is** required for dc measurements.

Radiation Sensors – p3 – Quantum Sensors

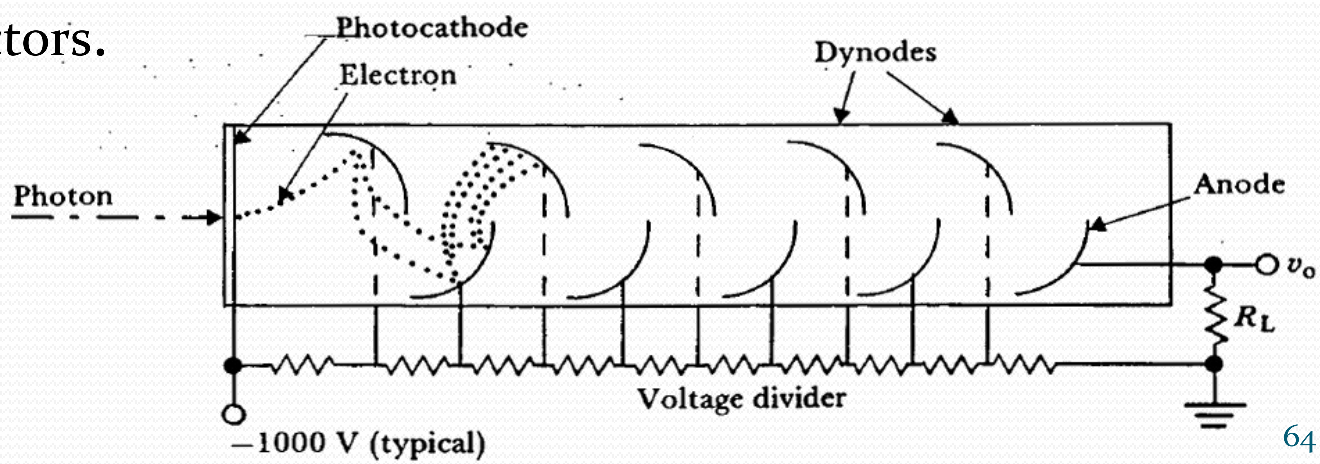
- ***Quantum sensors*** absorb energy from individual photons and use it to release electrons from the sensor material
- Typical quantum sensors are **the eye**, **the phototube**, **the photodiode**, and **photographic emulsion**.
- Such sensors are **sensitive over only a restricted band of wavelengths**; **most respond rapidly**.
- Changes in **ambient temperature** cause only a **second-order change in sensitivity of these sensors**.

Radiation Sensors – p4 – Photoemissive Sensors

- ***Photoemissive sensors*** *(exp.* ***Phototube****) have photocathodes* coated with alkali metals.

photons —Sufficient energy→ photocathode → forces that bind electrons → emits electrons

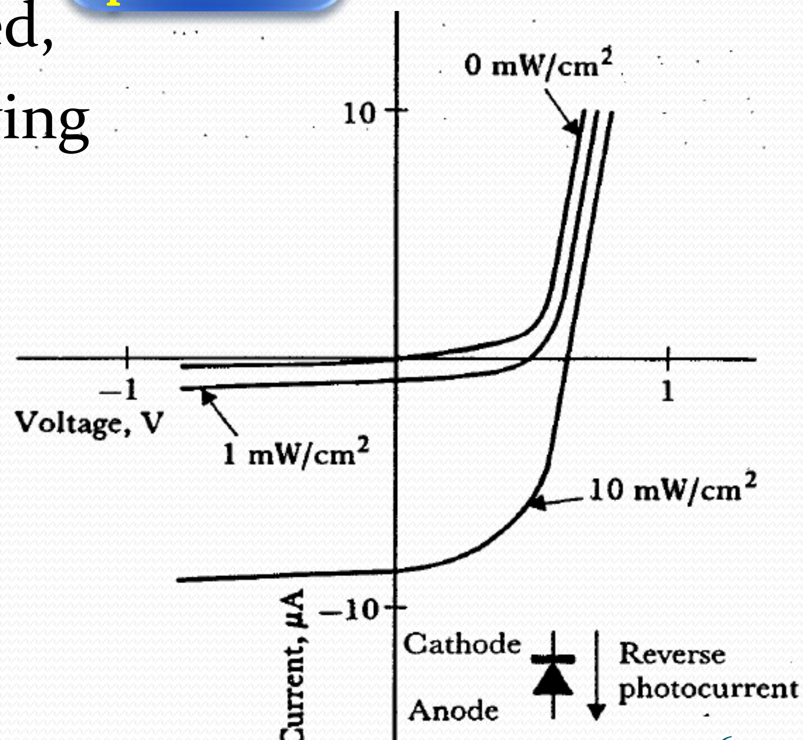
- ***Photomultiplier***
  - is a phototube combined with an **electron multiplier**
  - Each **accelerated electron** hits the **first dynode** with **enough energy** to **liberate several electrons** by **secondary emission.**
  - These electrons are accelerated to the **second dynode**, where the **process is repeated**, and so on.
  - **Time response** is less than 10 ns and are the **most sensitive** photodetectors.



- ***Photojunction sensors*** are formed from *p-n* junctions and are usually made of silicon

photons $\xrightarrow{\text{Sufficient energy}}$ **Jump the band gap** → **hole-electron pairs are produced** → **emits electrons**

  - If the junction is reverse-biased, the reverse photo current flowing from the cathode to the anode **increases linearly** with an **increase in radiation.**
  - He resulting photo diode responds in about **1 µs**



Radiation Sensors – p5 - Photojunction Sensors

- ***Photovoltaic Sensors***
  - The same silicon *p-n* junction can be used in the photovoltaic mode
  - There is an open-circuit voltage when the junction receives radiation.
  - The **voltage rises logarithmically** from *100 to 500 mV* as the ***input radiation increases by a factor of 10000***.
  - This is the principle of the **solar cell** that is used for direct conversion of the **sun's radiation** into **electric power.**