# 의 용 계 측

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# Chapter 2

# BASIC SENSORS AND PRINCIPLES

○ basic mechanisms and principles of the sensors used in medical instruments.

○ *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

# 2.1 displacement measurements

- direct system:
  - -change in diameter of blood vessel
  - -change in volume and shape of cardiac chamber.

- indirect system:-movement of liquids through heart valve
  (ex : heart murmur detection by microphone diaphragm movement)

# 2.2 resistive sensors

① ***Potentiometer***:

-Translational, Single-turn, Multi-turn.

-Mechanical contact problem (접촉 불량,wire-wound type 의 경우 one turn 간격이  resolution)

② ***Strain Gage***

-*gage factor*: useful factor, useful in comparing various strain gage material

-Material

metal: dimensional effect, G≈1.6 (μ=0.3)

semiconductor: piezoresistive effect, G≈100(for *p*-type), G≈-100(for *n*-type),

(high temperature coefficient of resistivity) ->temperature compensation 이 필수)

$$R = \rho \frac{L}{A}, \quad \rho\text{:resistivity}[\Omega \cdot \mathrm{m}]$$

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

using Poisson ratio $\mu$ : $\frac{\Delta D}{D} = -\mu \frac{\Delta L}{L}$ (D:diameter, L:length)

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

$$(\because A = \frac{\pi}{4}D^2, \frac{\Delta A}{A} = \frac{\frac{\pi}{2}D \cdot \Delta D}{\frac{\pi}{4}D^2} = 2\frac{\Delta D}{D})$$

gauge factor $G = \dfrac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} = (1+2\mu) + \dfrac{\frac{\Delta \rho}{\rho}}{\frac{\Delta L}{L}}$

-Type

metal:비접합형(unbonded)
접합형(bonded) : strain gage element cemented to the strained surface

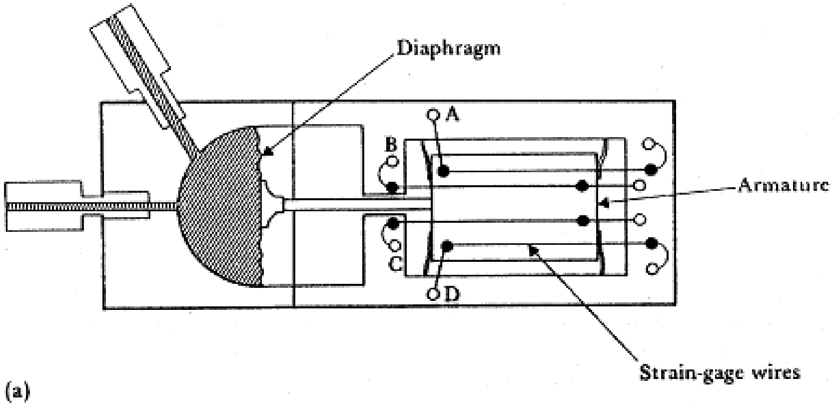


Fig. 2.2 (a) Unbonded strain-gage pressure sensor.

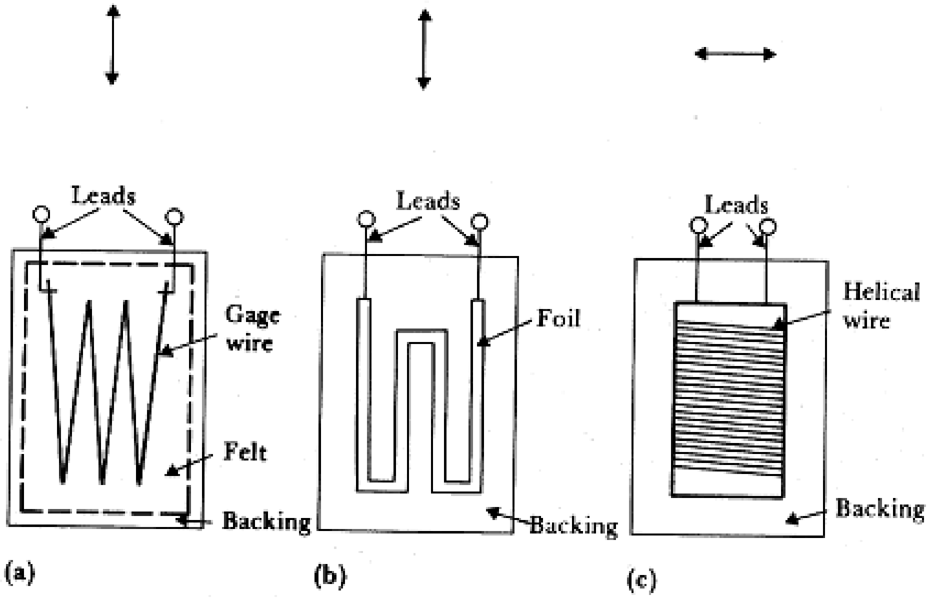


Fig. 2.3 Typical bonded strain-gage unit.

***semiconductor***: 접합형
비접합형
IC형: P-type or n-type substrate
as a diaphragm structure
(Pressure transducer-catheter tip)

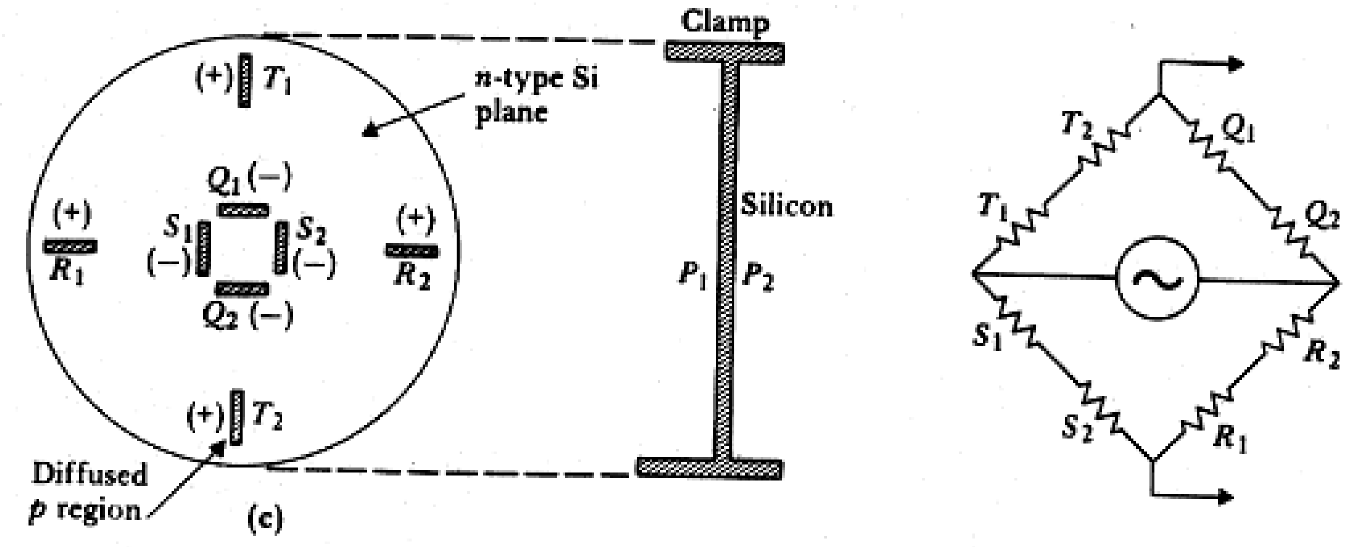


Fig. 2.4 (c) Integrated pressure sensor

***Elastic-resistance strain gage***

◦ 구조:-narrow silicon rubber tube(0.5㎜ 1D 2㎜ 0D)
-from 3 to 25 ㎝ long
-filled with mercury, electrolyte, conductive paste
-sealed with electrodes at the end.

◦ 원리 :tube stretch->diameter decrease->length increase -> R ↑ (0.02 ~ 2 Ω /㎝ )

◦ 응용:-Cardiovascular or respiratory dimensional plethysmography (volume-measuring)

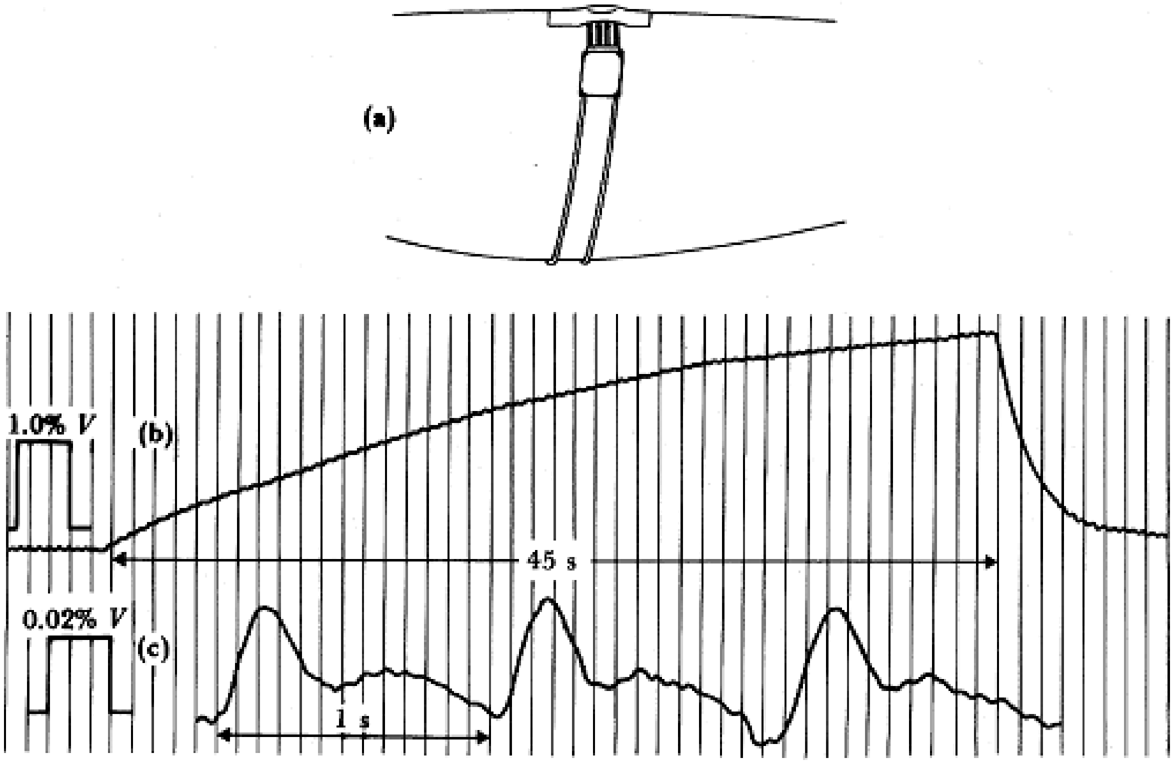
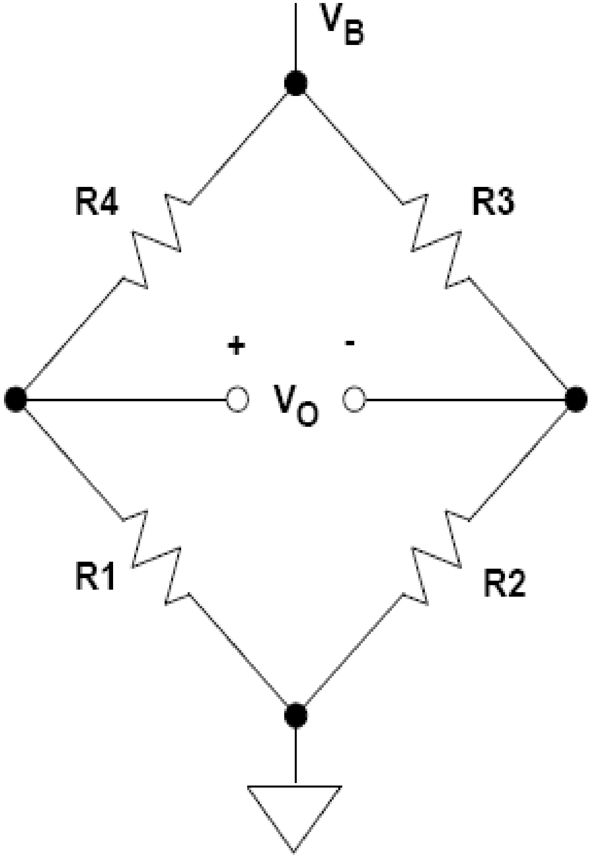


Fig. 2.5 Mercury-in-rubber strain-gage plethysmography

# 2.3 bridge circuit

**THE WHEATSTONE BRIDGE**



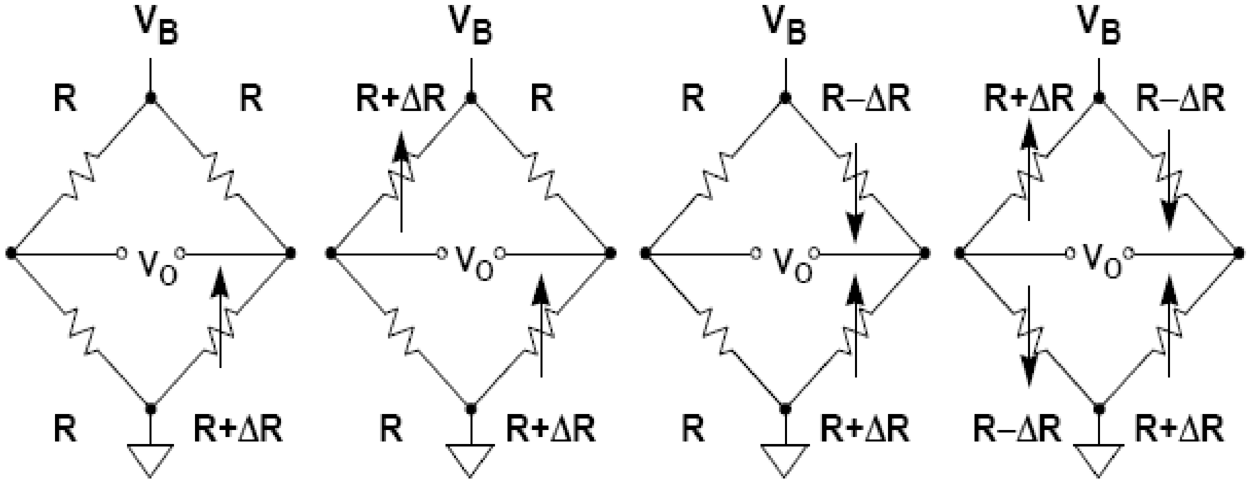
$$V_O = \frac{R1}{R1+R4}V_B - \frac{R2}{R2+R3}V_B$$

$$= \frac{\frac{R1}{R4} - \frac{R2}{R3}}{\left(1+\frac{R1}{R4}\right)\left(1+\frac{R2}{R3}\right)}V_B$$

AT BALANCE,

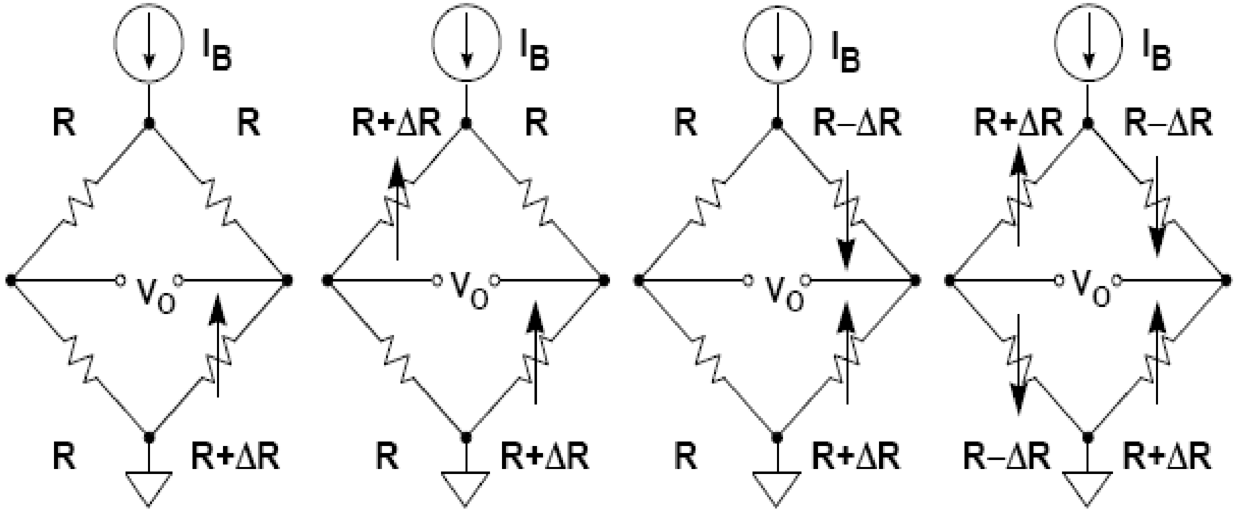
$$V_O = 0 \quad \text{IF} \quad \frac{R1}{R4} = \frac{R2}{R3}$$

# OUTPUT VOLTAGE AND LINEARITY ERROR FOR CONSTANT VOLTAGE DRIVE BRIDGE CONFIGURATIONS



| | | | | |
|---|---|---|---|---|
| $V_O$: | $\frac{V_B}{4}\left[\frac{\Delta R}{R+\frac{\Delta R}{2}}\right]$ | $\frac{V_B}{2}\left[\frac{\Delta R}{R+\frac{\Delta R}{2}}\right]$ | $\frac{V_B}{2}\left[\frac{\Delta R}{R}\right]$ | $V_B\left[\frac{\Delta R}{R}\right]$ |
| Linearity Error: | 0.5%/% | 0.5%/% | 0 | 0 |
| | (A) Single-Element Varying | (B) Two-Element Varying (1) | (C) Two-Element Varying (2) | (D) All-Element Varying |

# OUTPUT VOLTAGE AND LINEARITY ERROR FOR CONSTANT CURRENT DRIVE BRIDGE CONFIGURATIONS



|  | (A) Single-Element Varying | (B) Two-Element Varying (1) | (C) Two-Element Varying (2) | (D) All-Element Varying |
|---|---|---|---|---|
| $V_O$: | $\frac{I_B R}{4}\left[\frac{\Delta R}{R + \frac{\Delta R}{4}}\right]$ | $\frac{I_B}{2}\left[\Delta R\right]$ | $\frac{I_B}{2}\left[\Delta R\right]$ | $I_B\left[\Delta R\right]$ |
| Linearity Error: | 0.25%/% | 0 | 0 | 0 |

# 2.4 inductive transducers

- $L = n^2 G\mu$

where n=number of turns of coil

G=geometric form factor

μ=effective permeability of the medium

-Type : self inductance

mutual inductance

linear variable differential transformer (LVDT)

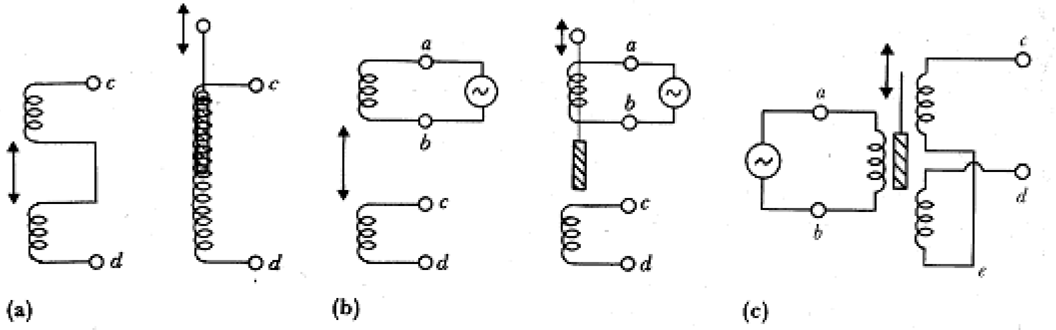


Fig. 2.6 Inductive displacement sensors (a) self-inductance, (b) Mutual inductance. (c) Differential transformer,

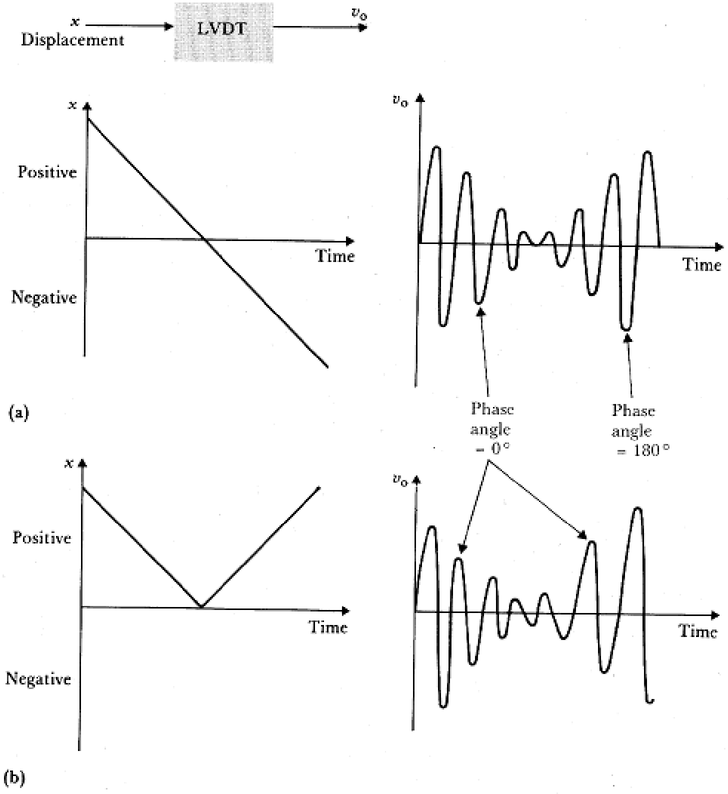
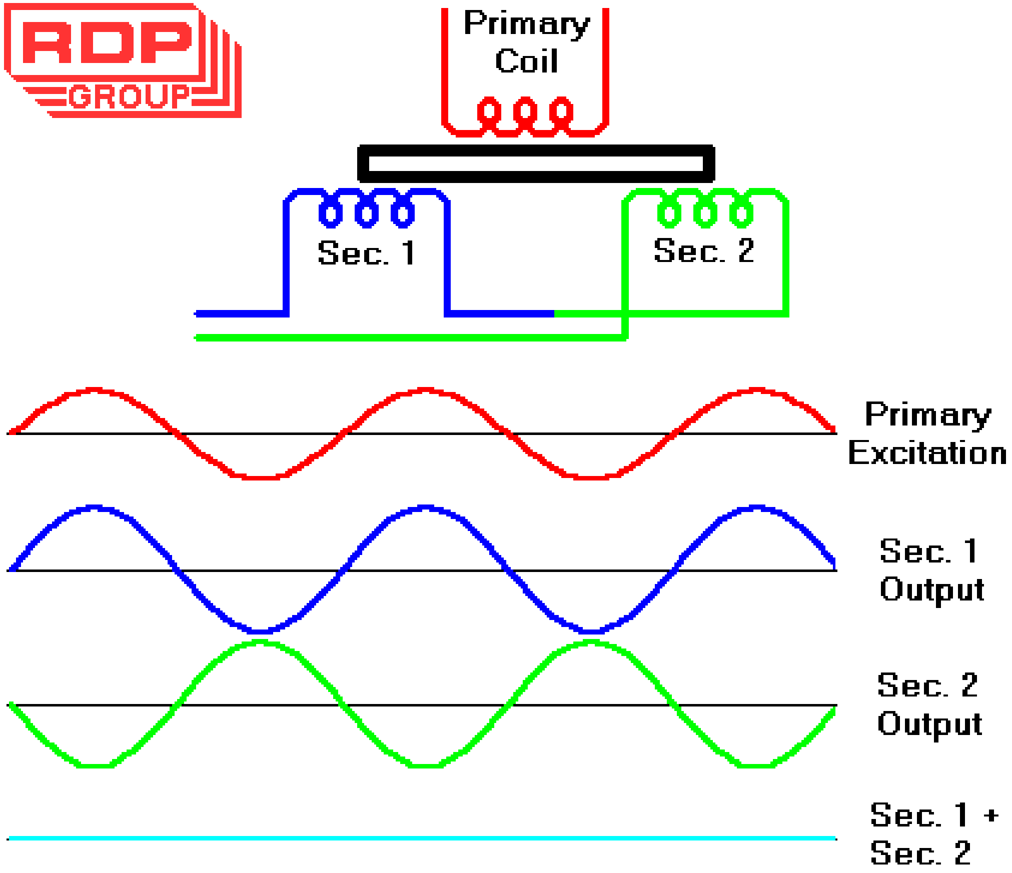


Fig. 2.7 LVDT output demodulator should distinguish (a) and (b), so a phase-sensitive demodulator is required.

# Principle of Operation of LVDT



# 2.5 capacitive transducers

- Capacitive Microphone(콘덴서 마이크)
- Capacitance : $C = \varepsilon_0 \varepsilon_r \dfrac{A}{x}$
- Sensitivity of Capacitive transducer

$$K = \frac{\Delta C}{\Delta x} == \varepsilon_0 \varepsilon_r \frac{A}{x^2}$$

$$\frac{dC}{dx} = -\frac{C}{x} \quad \text{or} \quad \frac{dC}{C} = -\frac{dx}{x}$$

$$(x = x_0,\ \ v_1 = E) \rightarrow (\Delta x = x_1 - x_0,\ v_0 = v_1 - E)$$

$$\mathrm{F}[\frac{v_0(t)}{x_1(t)}] = \frac{V_0(\omega)}{X_1(\omega)} = \frac{(\frac{E}{x_0}) j\omega\tau}{j\omega\tau + 1}$$

$$\text{where } \tau = RC = R\varepsilon_0 \varepsilon_r \frac{A}{x_0}$$

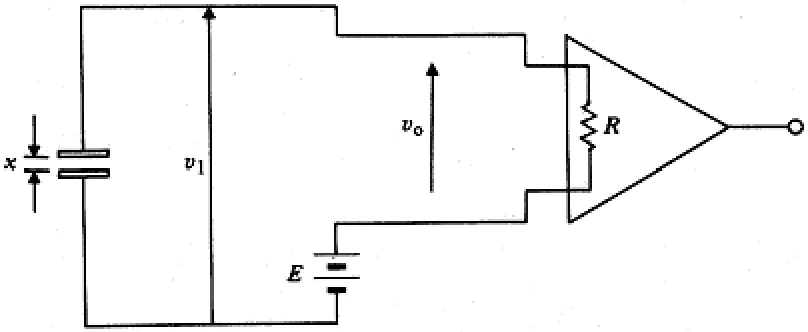


Fig. 2.8 Capacitance sensor for measuring dynamic displacement changes.

->high pass characteristic : adequate for microphone (∴<20 Hz no interest )

-Extension of frequency response to DC

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{C_i}{C_x}$$

$$V_o(j\omega) = -C_i \frac{xV_i(j\omega)}{\varepsilon_0 \varepsilon_r A} = C_i K x V_i(j\omega)$$

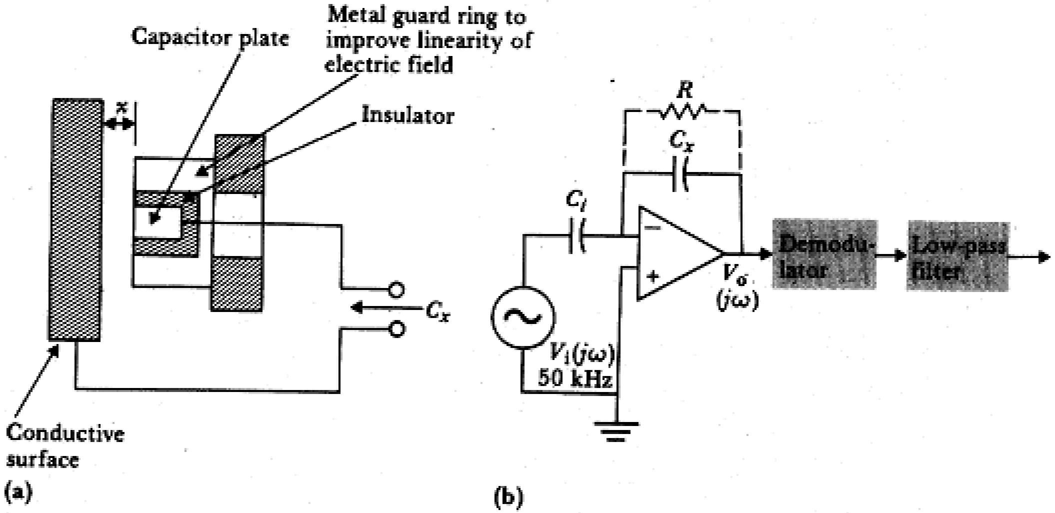


Fig. 2.9 (a) Guarded parallel-plate displacement sensor. (b) Instrumentation system with output proportional to capacitance displacement

# -Differential Capacitor system

$$C_1 = \frac{\varepsilon_0 \varepsilon_r A}{d - x}, C_2 = \frac{\varepsilon_0 \varepsilon_r A}{d + x}$$

$$\frac{x}{d} = \frac{C_1 - C_2}{C_1 + C_2}$$

After adjusting $C_3$ for $v_a = \frac{1}{2} v_i$,

$$V_o = \frac{1}{2} V_i - \frac{\frac{1}{sC_1}}{\frac{1}{sC_1} + \frac{1}{sC_2}} V_i$$

$$= \left(\frac{1}{2} - \frac{C_2}{C_1 + C_2}\right) V_i$$

$$= \frac{C_1 - C_2}{C_1 + C_2} \frac{V_i}{2}$$

$$\therefore V_o = \frac{V_i}{2d} x$$

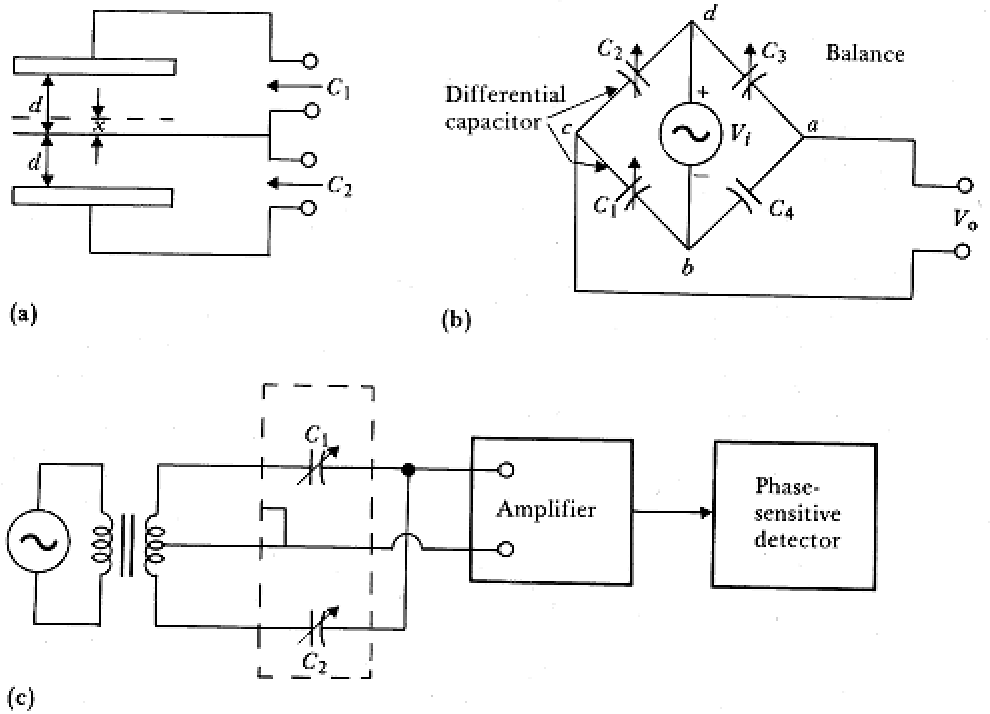


Fig. 2.10. (a) Differential three-terminal capacitor. (b) Capacitance-bridge circuit with output proportional to fractional difference in capacitance. (c) transformer ratio-arm bridge

# 2.6 piezoelectric transducers

- $q = kf$

  q: 유도 전하(induced charge)

  k: 압전 상수 (C/N) (Piezoelectric constant)

  f: applied force

- Physical deformation -> asymmetrical crystal lattice distorted
  -> charge reorientation -> relative displacement of internal charge
  -> induce surface charge displacement

- $$v = \frac{q}{C} = \frac{kf}{\frac{\varepsilon_0 \varepsilon_r A}{x}} = \frac{kf}{\varepsilon_0 \varepsilon_r A} x$$

  C: parallel plate capacitor

- Equivalent circuit

- Application : Phonocardiagraphy
  - Internal : intracardiac
  - Body surface : external

  Korotkoff sound detector

  Accelerometer

  Ultrasonic equipment

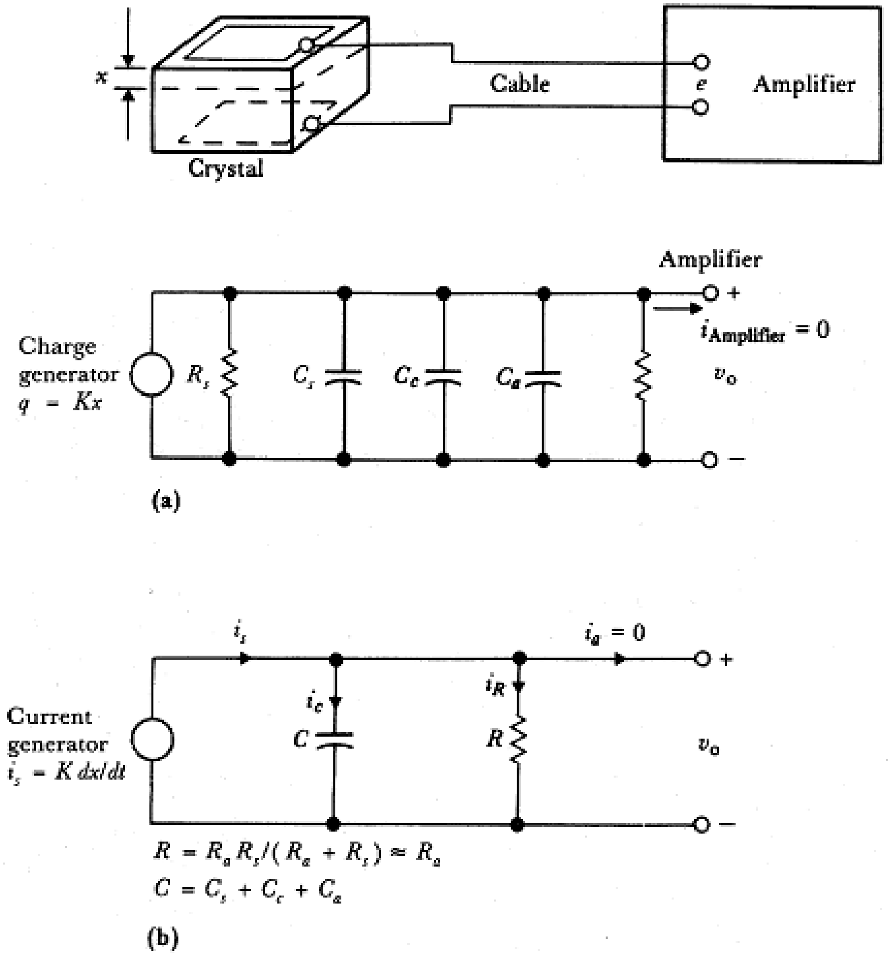


Fig. 2.11 (a) Equivalent circuit of piezoelectric sensor, where Rs = sensor leakage resistance, Cs = sensor capacitance, Cc = cable capacitance, Ca = amplifier input capacitance, Ra = amplifier input resistance, and q= charge generator. (b) Modified equivalent circuit with current generator replacing charge generator

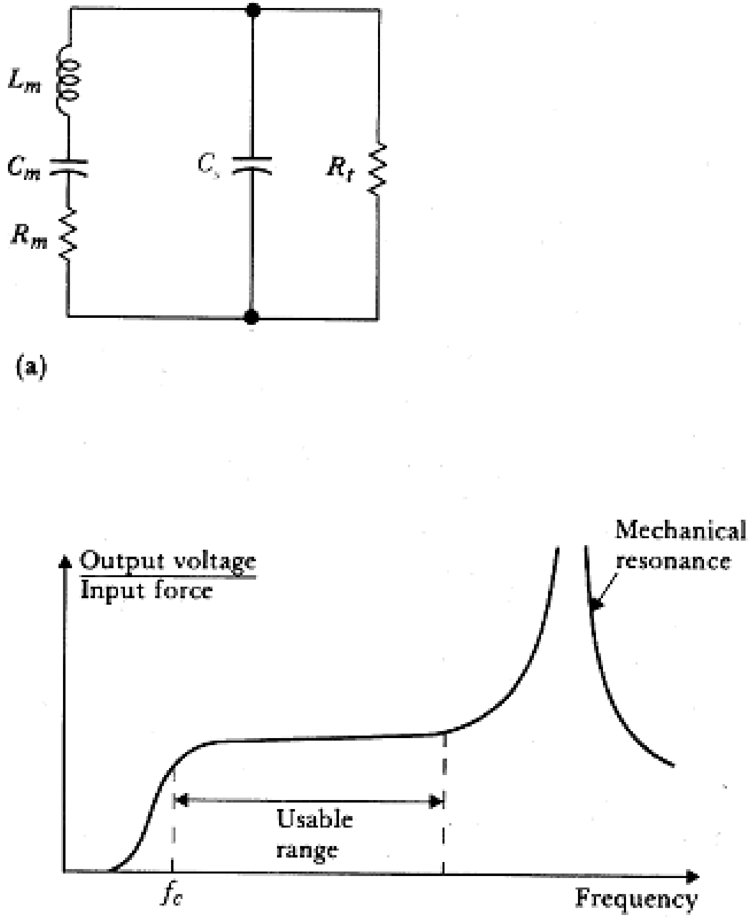


Fig. 2.13 (a) High-frequency circuit model for piezoelectric sensor. Rs is the sensor leakage resistance and Cs the capacitance. Lm, Cm, and Rm represent the mechanical system.

# 2.7 temperature measurement

Evaluate patients in shock

(Shock -> peripheral blood flow ↓ -> big-toe temperature↓)

Infection

Inflammation

# 2.8 thermocouple

-1821 Seeback

Observed an electromotive force (emf) exist across a junction of two dissimilar metals

-emf = Peltier emf + Thomson emf

Peltier emf : due to contact of two unlike metals and the junction temperature

Thomson emf : Temperature gradient along each single conductor

-Reference junction : triple -point - of - water ≈ 0.01 ± 0.0005 ˚C

- In practical application, empirical calibration data are usually curve-fitted with a power series expansion

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

- Advantage : fast response ( $\tau \cong 1\text{ms}$ )
  small size (12μm in diameter)
  easy fabrication
  long term stability

-Disadvantage : small output voltage
  low sensitivity
  need for a reference temperature

# 2.9 thermistors

-Semiconductor made of ceramic materials that are thermal resistors with a high *negative temperature coefficient*.
(cf. metal : positive T coefficient)

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

where $\beta$ = material constant for thermistor($^\circ K$)

$T_0$ = standard reference temperature($^\circ K$)

$R_t$ = zero-power resistance (thermistor operating at a very small amount of power such that there is negilgible self-heating

- Temperature coefficient

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

- Linearization of Thermistor Response

$$R_{ab} = R_p // R_t$$

with inflection point at $T_m$

$$\therefore R_p = R_{t,m}\frac{\beta - 2T_m}{\beta + 2T_m}$$

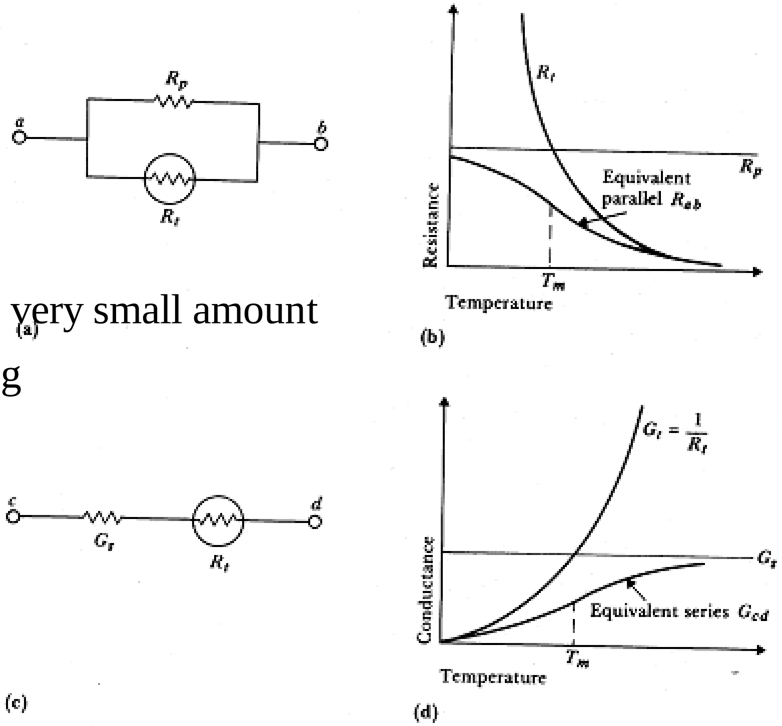


Fig. 2.16 Various linearization schemes of thermistor characteristics

# 2.10 radiation thermometry

- radiation thermometry : based on the relationship between the surface temperature of an object and its radiant power. (every body above absolute zero radiates electromagnetic power)
- medical thermography : temperature distribution of the body is mapped. (for early detection of breast cancer with controversy)
- Plank's law, Wien's displacement law, Stefan-Boltzmann law
- percentage of total radiant power vs. wavelength (Fig. 2.18(a)) : approximately 80% of the total radiant power in the wavelength band from 4~25㎛.
- absolute temperature : variation in ε(emissivity) with λ should be found.
  relative temperature : only if ε remains constant over the surface.
- Fig. 2-18(b) : spectral transmission of optical materials
- instrument : beam-chopper + ac amplifier
- human core body temperature : magnitude of infrared radiation emitted from the tympanic membrane and surrounding ear canal → accurate(0.1℃, perfused by same vasculature as hypothalamus,body's main thermostat), fast(0.1 sec)

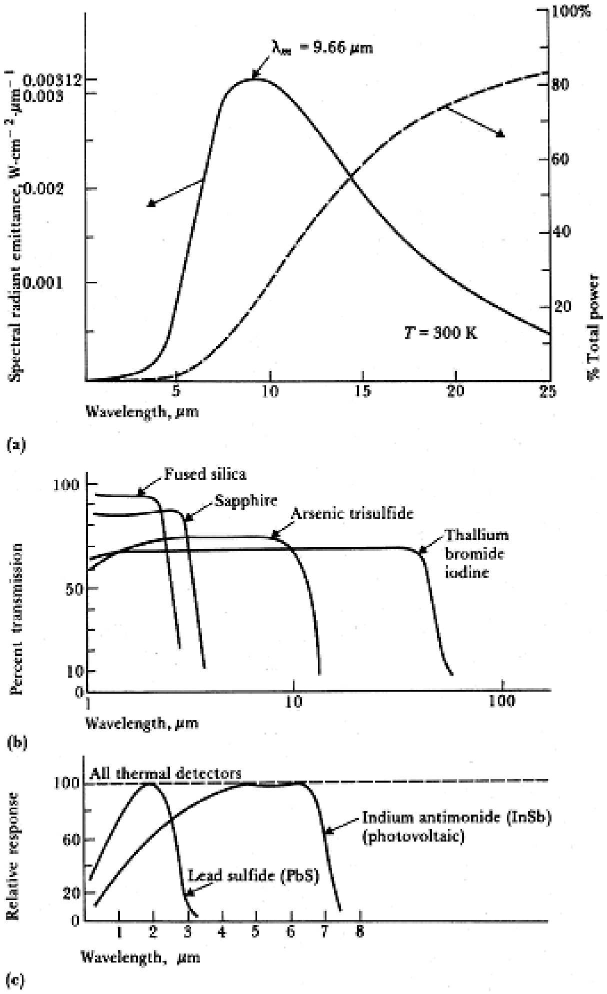


Fig. 2.18 (a) Spectral radiant emittance versus wavelength for a blackbody at 300K on the left vertical axis; percentage of total energy on the right vertical axis. (b) Spectral transmission for a number of optical materials. (c) Spectral sensitivity of photon and thermal detector

# 2.11 fiber-optic temperature sensors

-Fig. 2-20 : GaAs sensor where the amount of power absorbed increases with temperature ( forbidden energy gap is sensitive function of the material's T)

-nonmetalic probe : suitable in the strong electromagnetic filed.

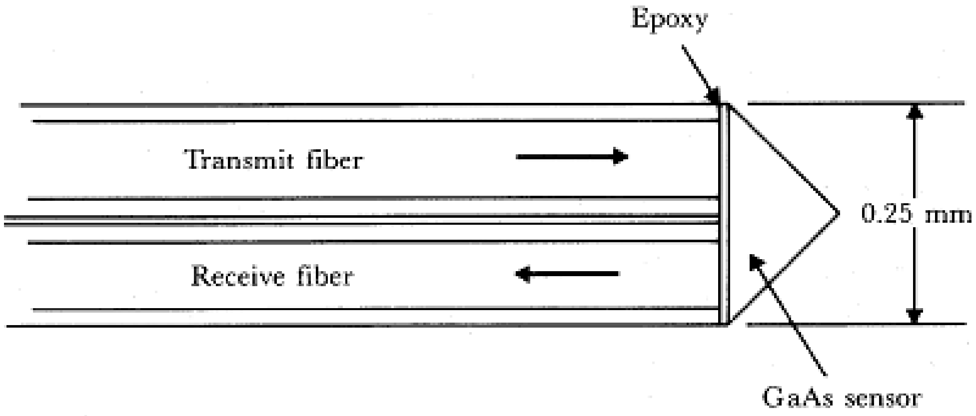


Fig. 2.20 Details of the fiber/sensor arrangement for the GaAs semiconductor temperature probe.

# 2.12 optical measurements

- Fig. 2-21 : typical optical instrument (for clinical-chemistry lab)

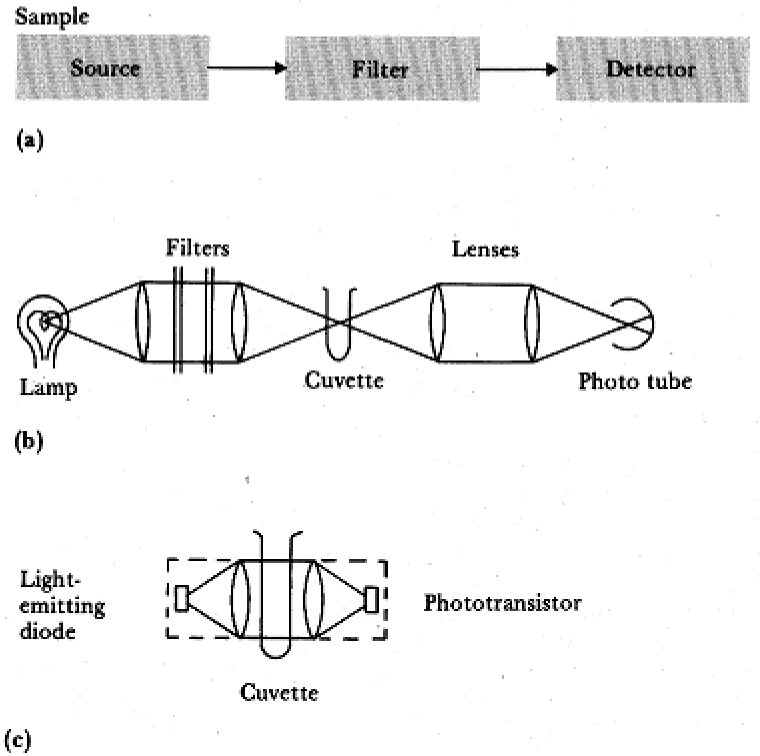


Fig. 2.21 (a) General block diagram of an optical instrument. (b) Highest efficiency is obtained by using an intense lamp, lenses to gather and focus the light on the sample in the cuvette, and a sensitive detector. (c) Solid-state lamps and detectors may simplify the system

# 2.13 radiation sources

(1) Tungsten Lamps
- incandescent tungsten-wire filament lamp(백열전구)
- color dependency on temperature : reddish (infrared lamp) at low T, bluish at high T
- tungsten-halogen lamp : high radiation output(90%) through lifetime.

(2) Arc Discharges
- low pressure :low radiation output density( fluorescent lamp/Ar-Hg mixture, neon lamp, sodium-vapor lamp, laser)
- high pressure : compact, high output density, important for optical instrument (Hg lamp/bluish-green, Na lamp/yellow, Xenon/white)

(3) LEDs
- compact, rugged, economical, nearly monochromatic

(4) **LASER (Light Amplification by Stimulates Emission of Radiation)**- *monochromatic (frequency), coherent (phase)*

① He-Ne : 633nm, red, low pressure arc as neon, 100mW
② Ar : 515 nm, blue/green, 1-15W, coagulation, rebonding
③ $CO_2$ : infrared, 50-500W, absorbed by water, cutting
④ solid state
    ruby : 693 nm, red,
    NdYAG (neodymium in yttrium aluminum garnet) : 1064 nm, infrared, between $CO_2$ and Ar, optical fiber 사용가능

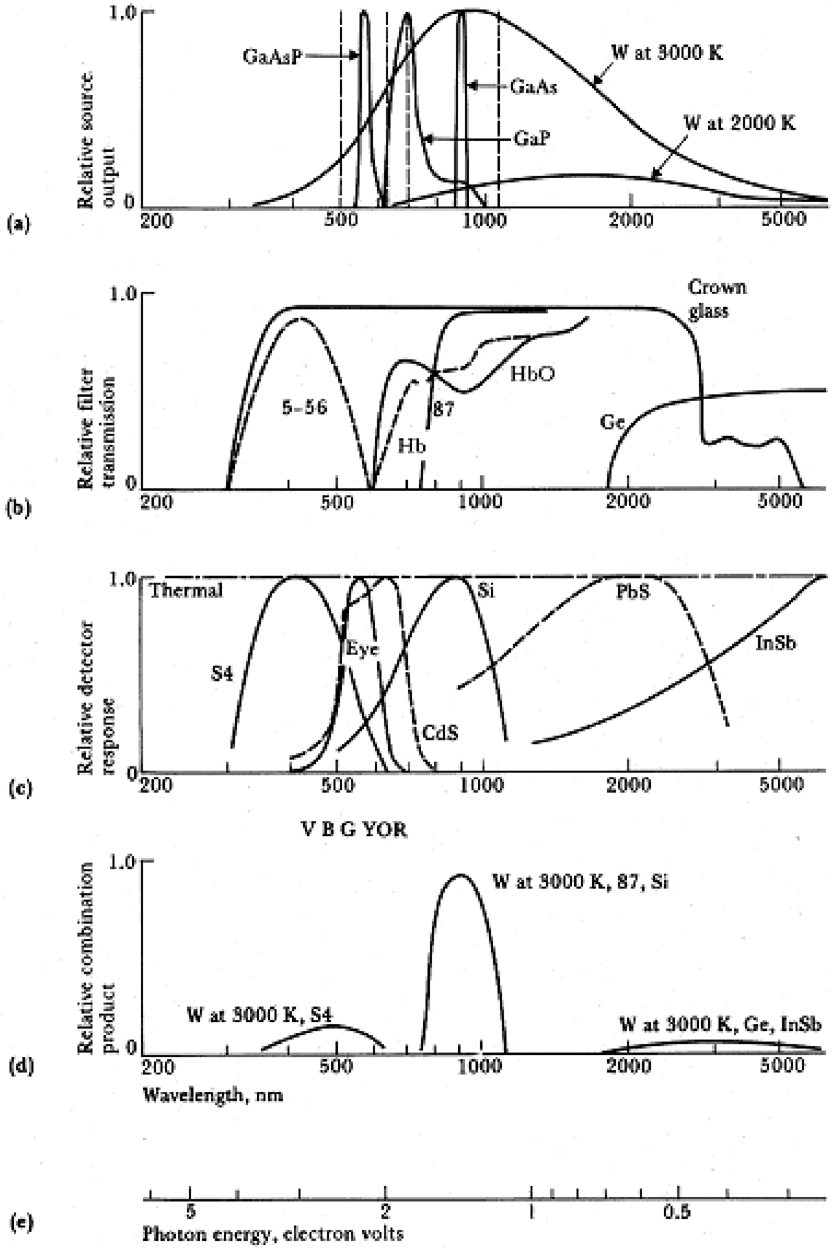


Fig. 2.22 Spectral characteristics of sources, filters, detectors, and combinations thereof (a) Light sources, (b) Filter, (c) Detector, (d) Combination, (e) photon energy

# 2.14 geometrical & fiber optics

(1) Geometrical Optics : lenses and mirrors to modify the power transmission between the source and the detector.

(2) Fiber Optics :

-efficient way of transmitting radiation from one point to another.

-total reflection condition : by Snell's law

- chemically inert, free from EM interference
- ① 50cm glass fiber : transmission exceeding 60% for 400~1200nm
- ② 50cm plastic fiber : 70% for 500~850 nm
- ③ noncoherent bundles : light guide, only transmitting radiation no positional correlation
- ④ coherent bundles : same relative position, image transmission, endoscopy

(3) Liquid Crystal : modify passive scattering or absorption of light

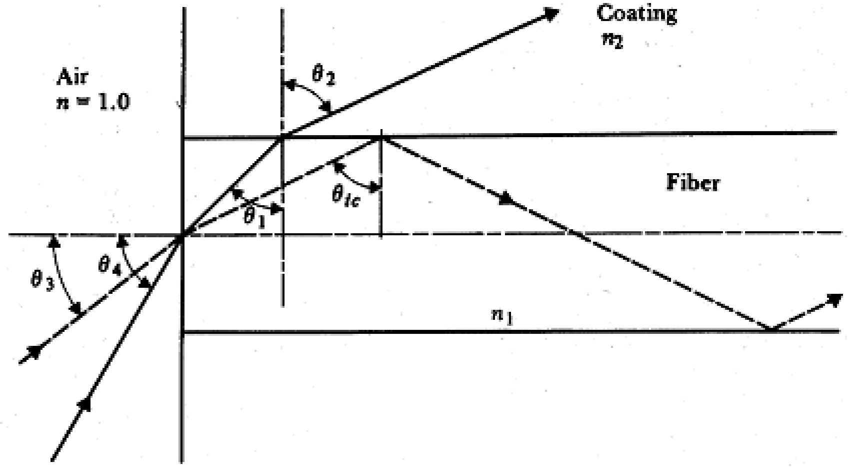


Fig. 2.24 Fiber optics.

Problem) Find the angle θ3 for the largest cone of light accepted from a medium of refractive index n that is totally reflected within a glass fiber of refractive index n1 with a coating of refractive index n2.

Answer) At the interface of medium n and the glass, Snell's law yields;

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

$$n \sin\theta_3 = n_1 \sin(\theta_{ic} - 90^\circ) = n_1 \cos\theta_{ic}$$

Substituting this result into $\sin\theta_{ic} = \dfrac{n_2}{n_1}$ yields

$$\frac{n_2}{n_1} = \sin\theta_{ic} = (1 - \cos^2\theta_{ic})^{1/2} = (1 - \frac{n^2}{n_1^2}\sin^2\theta_3)^{1/2}$$

$$\frac{n_2^2}{n_1^2} = 1 - \frac{n^2}{n_1^2}\sin^2\theta_3$$

Rearranging and taking the square root,

$$\frac{n}{n_1}\sin\theta_3 = \frac{(n_1^2 - n_2^2)^{1/2}}{n_1}$$

$$\therefore \sin\theta_3 = \frac{(n_1^2 - n_2^2)^{1/2}}{n}$$

# 2.15 optical filters

- to control the distribution of radiant power or wavelength
- neutral density filter, partially silvered mirror, carbon particle in plastic, Polaroid filter
- color filter, interference filter, diffraction filter

# 2.16 radiation sensors

(1) Thermal Sensors

- absorbs radiation → heat : thermistor, thermocouple, pyroelectric sensor (Passive InfraRed sensor)

(2) Quantum Sensors

- absorb energy from individual photon → electron from the sensor material : eye, phototube, photodiode, photographic emulsion

(3) Photoemissive Sensors

-phototube, photomultiplier

(4) Photoconductive Cells

- photoresistor : CdS, PbS, photon → increase conductivity

(5) Photojunction Sensors

- photodiode, photo TR, photon c

(6) Photovoltaic Sensors

- solar cell

(7) Spectral Response

- Fig. 2-22(c)

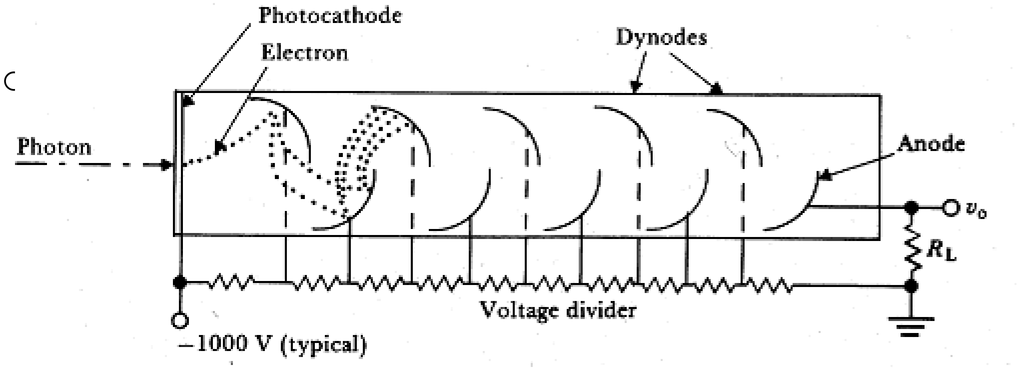


Fig. 2-25 Photomultiplier

# 2.17 optical combination

- To specify the combination of sources, filters, and sensors characteristics
- The total effective irradiance,

$$E_e = \sum S_\lambda F_\lambda D_\lambda \Delta\lambda$$

where

$S_\lambda =$ relative source output

$F_\lambda =$ relative filter transmission

$D_\lambda =$ relative sensor responsivity