SENSORS and TRANSDUCERS

Tadeusz Stepinski, Signaler och system

- The Optical Energy Domain
  - Physics
  - Photoeffects in silicon and other materials
  - Photoconductive sensors
  - Photoemissive sensors
  - Photovoltaic sensors

Optical Energy Domain - Physics

- Energy of photon $E = h\nu = \frac{hc}{\lambda}$

h - Planck's constant ($6.6326\ 10^{-34}$ W s^2)
ν - frequency
λ - wavelength in m
Frequency range for optoelectronic devices from 10^{23} to 10^{12} Hz

Name	Frequency (Hz)	Wavelength (m)	Wavelength (Å)
Cosmic rays	$> 10^{23}$ - 10^{22}	$< 10^{-15} – 10^{-14}$	$< 10^{-5} – 10^{-4}$
X-rays	$10^{21} – 10^{16}$	$10^{-13} – 10^{-8}$	$10^{-3} – 100$
UV	$10^{17} – 10^{15}$	$10^{-9} – 10^{-7}$	$10 – 1000$
Visible	$10^{15} – 0.5 \cdot 10^{14}$	$10^{-7} – 2 \cdot 10^{-6}$	$1000 – 20\ 000$
IR	$0.5 \cdot 10^{14} – 0.5 \cdot 10^{11}$	$2 \cdot 10^{-6} – 2 \cdot 10^{-3}$	$20\ 000 – 2 \cdot 10^{7}$

Optical Energy Domain - Physics

- Mechanisms describing interaction between radiation and solid state
  - *Refraction* - governed by Snell's law defining the relationship between incident and transmitted rays at the interface of two media

    $n_i \sin\varphi_i = n_t \sin\varphi_t$ where n_i, n_t - indices of refraction

  - *Absorbtion of photons* - results in attenuation of the incident radiation due to the interaction of the photons with the underlaying atoms of the material

    $I(x) = I_s \cdot e^{-\alpha \cdot x}$ *I(x)* - intensity of the radiation at the depth *x*

  - *Inerference* - interaction of two waves with equal frequencies but different phases
  - *Polarization* - propagation of a transverse wave in a fixed plane

Optical Energy Domain - Physics

Review of known physical effects in the radiant domain

Name of effect	Notation	Description
Photovoltaic	[ra, el, 00]	A voltage is generated by incident radiation at the junction of two dissimilar materials
Photomagnetoelectric	[ra, el, ma]	An electrical field is generated by both a magnetic field and incident radiation
Photoconductivity	[el, el, ra]	Electrical conductivity is increased due to incident radiation
Photoelectric	[el, el, ra]	Electrons and holes are generated and separated in a junction area by incident radiation
Photodielectric	[el, el, ra]	The change of a dielectric constant due to incident radiation
Laser	[el, el, ra]	En energy is generated by an optical resonance cavity
Photoluminescence	[ra, ra, 00]	Radiant energy is emitted by incident radiation with shorter wavelength
Radioluminescence	[ra, ra, 00]	Visible radiant energy is emitted by incident x-rays or γ rays
Radiation heating	[ra, th, 00]	The increase of temperature of a material by incident radiation

Optical Energy Domain - Physics

- Review of known physical effects in the radiant domain

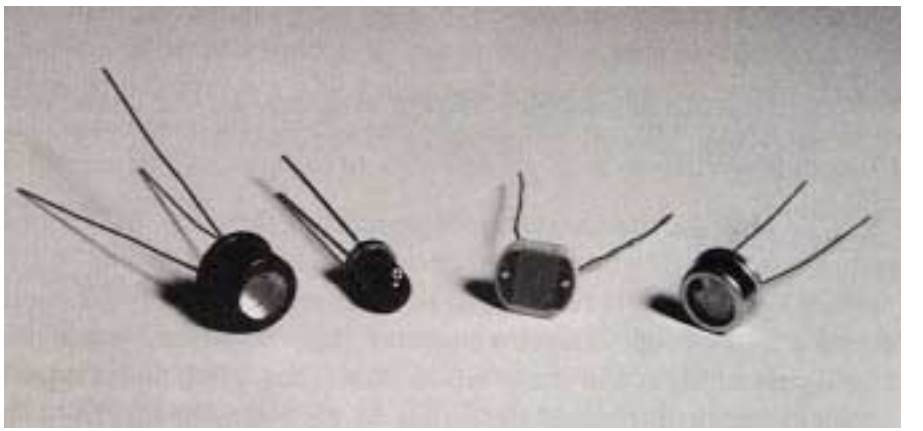
Name of effect	Notation	Description
Photomagnetic	[ra, ma, 00]	The change of magnetization by incident radiation
Photochemical	[ra, ch, ma]	The change of structure due to incident radiation
Electroluminescence (Destriau)	[el, ra, 00]	The illuminating excitation of a material due to an alternating electrical field
p-n luminescence (Lossev)	[el, ra, 00]	The radiation of recombination energy in a forward-biased p-n junction
Incandescence	[el, ra, 00]	The emission of radiation by thermal movement of atoms activated by an electric current
Kerr electro-optic	[ra, ra, el]	The generation of double refraction of radiation due to an electrical field
Kerr magneto-optic	[ra, ra, ma]	The change of a polarization plane of polarized radiation due to a magnetic field
Faraday	[ra, ra, ma]	As for Kerr magneto-optic effect
Pockel's effect	[ra, ra, el]	The rotation of polarization of polarized radiation by an electrical field
Cotton-Mouton	[ra, ra, ma]	The generation of double refraction of radiation in a liquid due to a magnetic field

Photoconductive sensors

- Photoresistor

  A piece of semiconductor material placed between two conducting end plates, forming a sandwich.

  - Materials used:
    - ✓ Cadmium sulfide (CdS)
    - ✓ Cadmium selenide (CdSe)
    - ✓ Germanium
    - ✓ Silicon

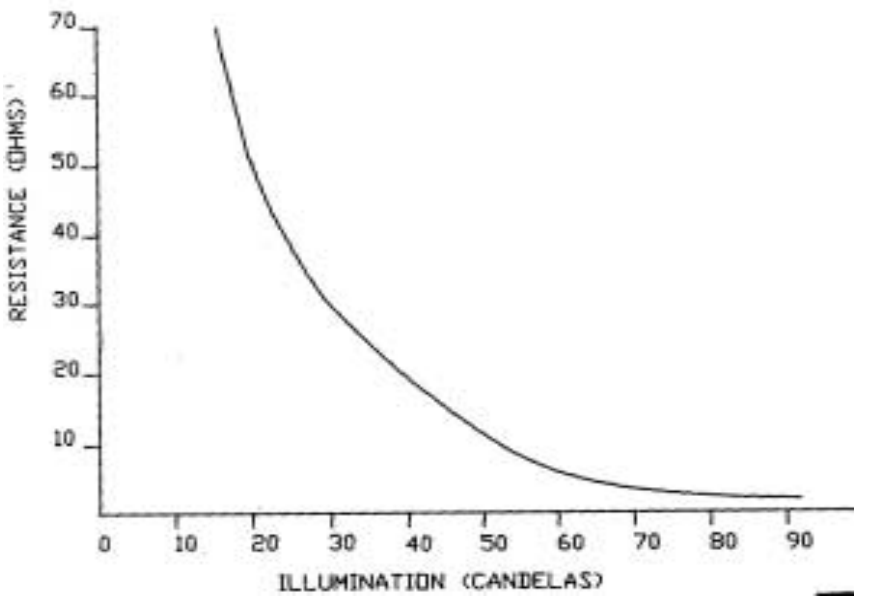


  - The presence of excited electrons in the conduction band causes an decrease in electrical resistance

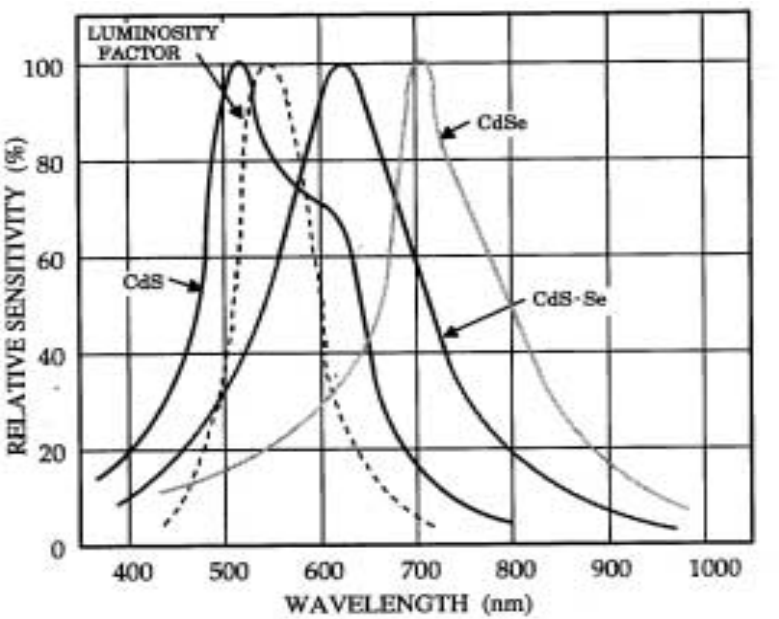
Photoconductive sensors

- Photoresistor

Illumination sensitivity

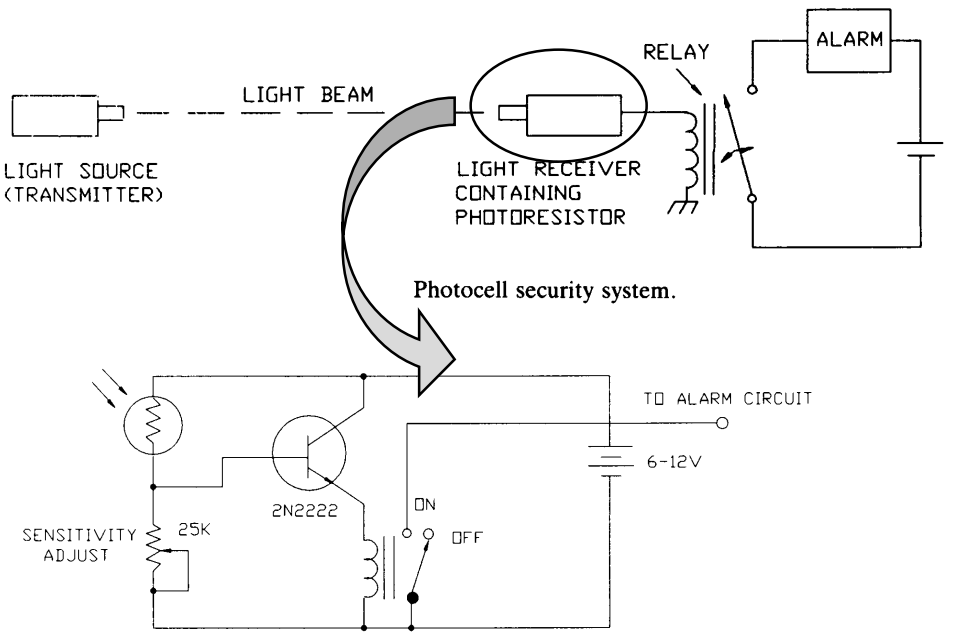


Spectral response (4000 - 8000 Å)



Photoconductive sensors

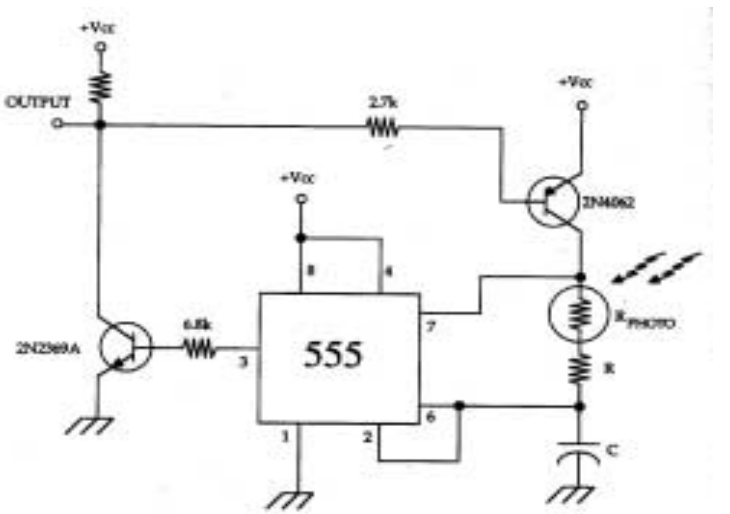
- Photoresistor - application examples



Photocell security system.

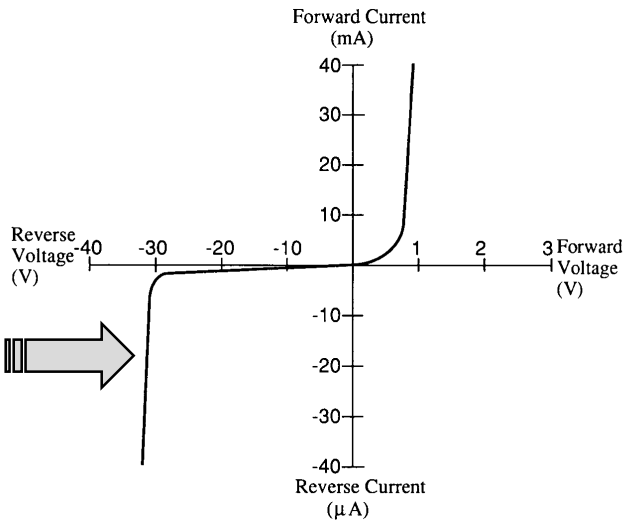
Amplifier circuit for relay-operated photocell system.

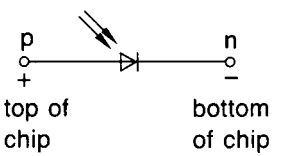
- Light-intensity transmitter using astable multivibrator 555

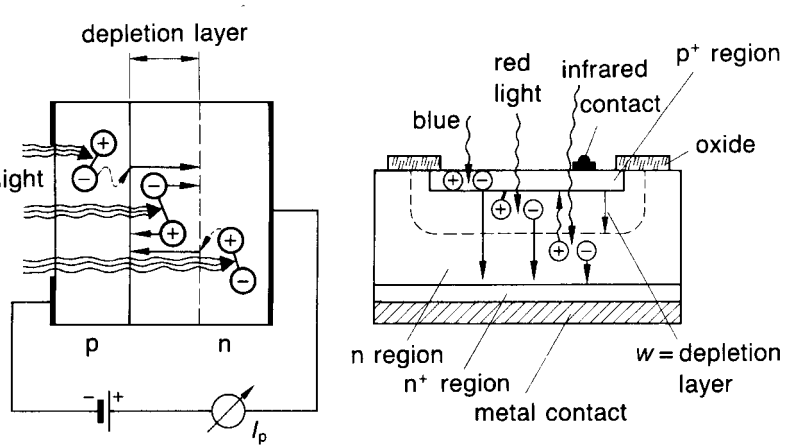


Photoconductive sensors

- Photodiodes operate with reverse biasing





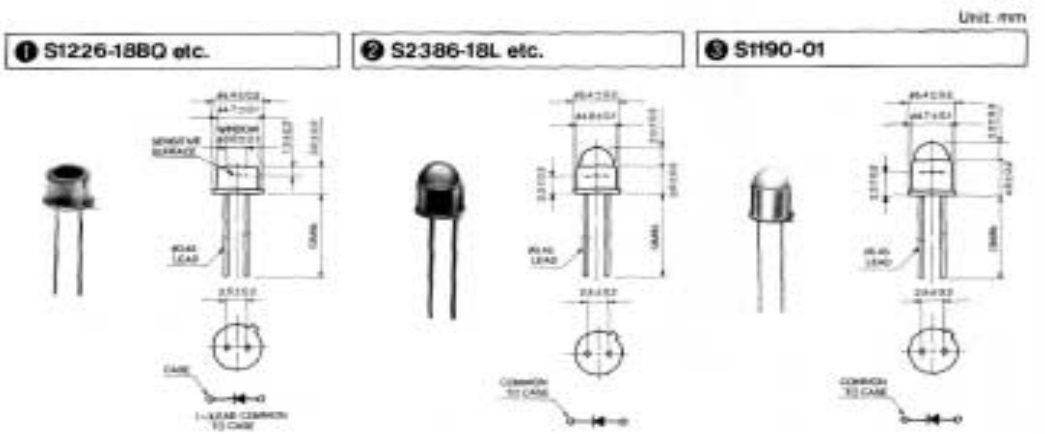


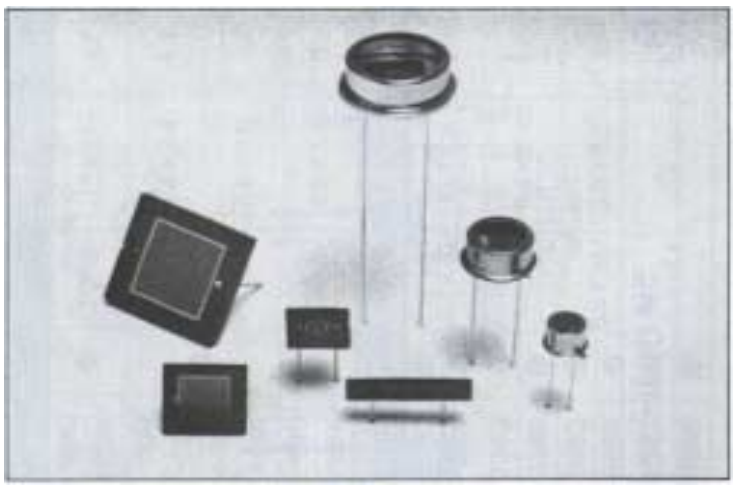
Construction and operating principles of a planar photodiode.

- Operating range 14 000 to 20 000 Å (beyond infrared portion of spectrum)
- Features : fast response and low dark current (even 1 nA)

Photoconductive sensors

- Photodiodes



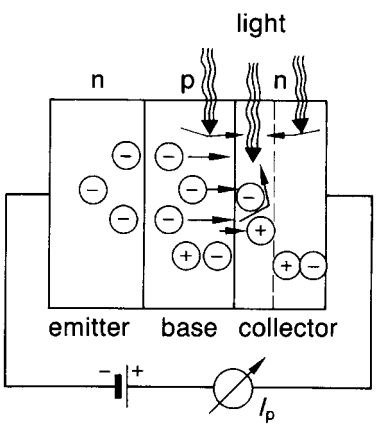


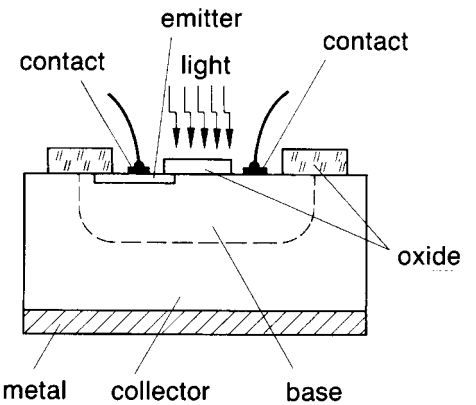
  - Characteristics: *fast but low current sensitivity*
  - Applications
    - ✓ Fiber optic communication
    - ✓ Compact disc player

Photoconductive sensors

- Phototransistor
  - A transistor with base current controlled by photons

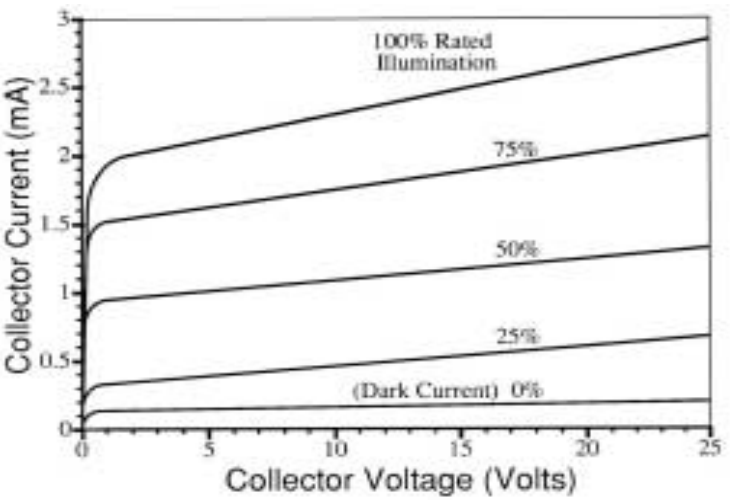
$$I_{CE} = I_{CB}(1+\beta)$$





Construction and operating principle of a phototransistor.

- Operating characteristics:
  - ✓ high current sensitivity
  - ✓ response time longer than diode's (10^{-8} s)



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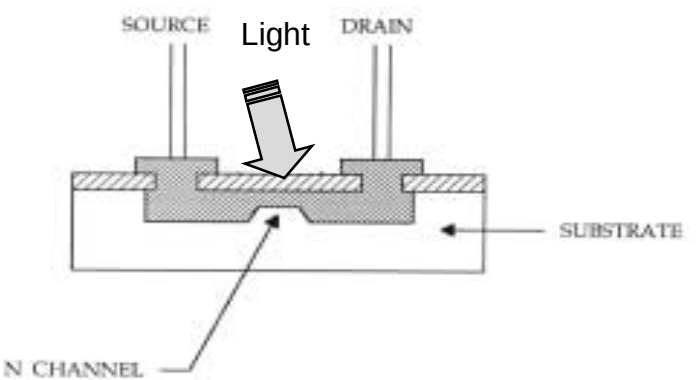
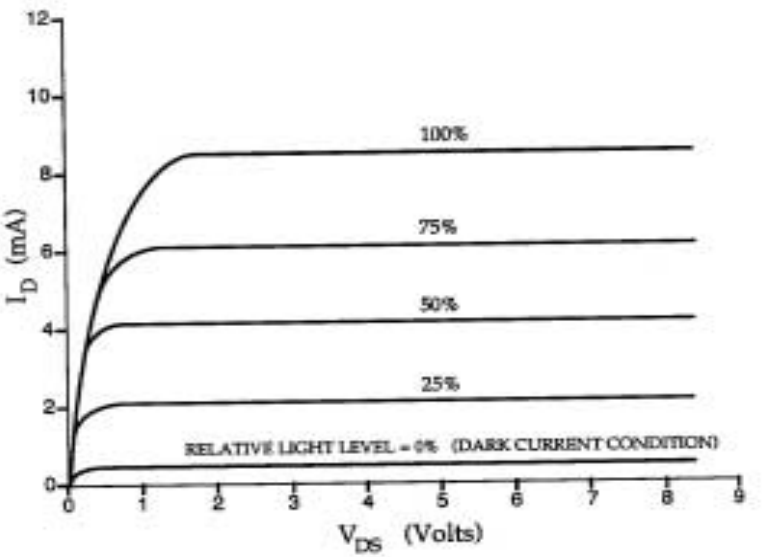
Photoconductive sensors

- PhotoFET
  - A FET with drain current controlled by photons

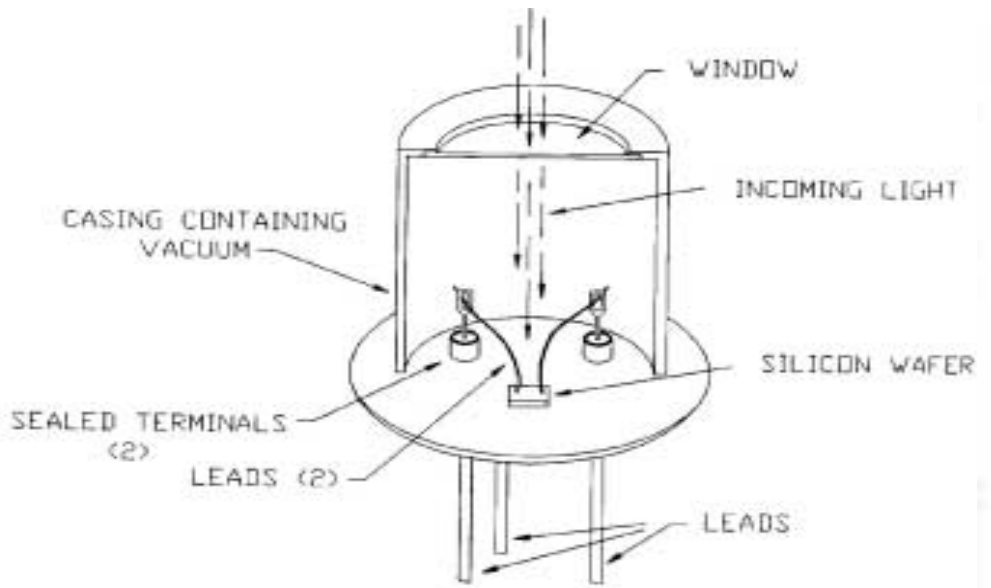


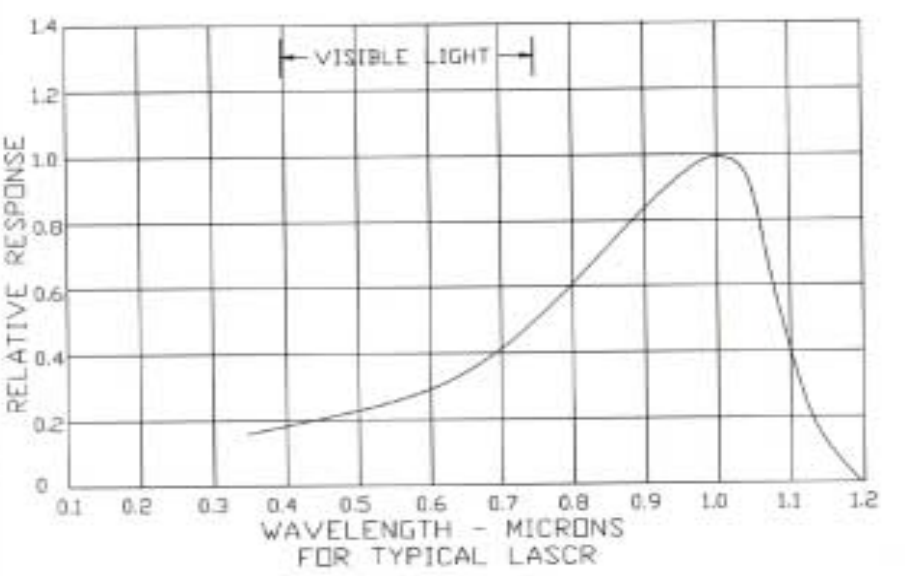


  - Operating characteristics:
    - ✓ similar to phototransistor

Photoconductive sensors

- LASCR *(light-activated silicon-controlled rectifier)*
  - *photo SCR* - an SCR device having its gating junction sensitive to light

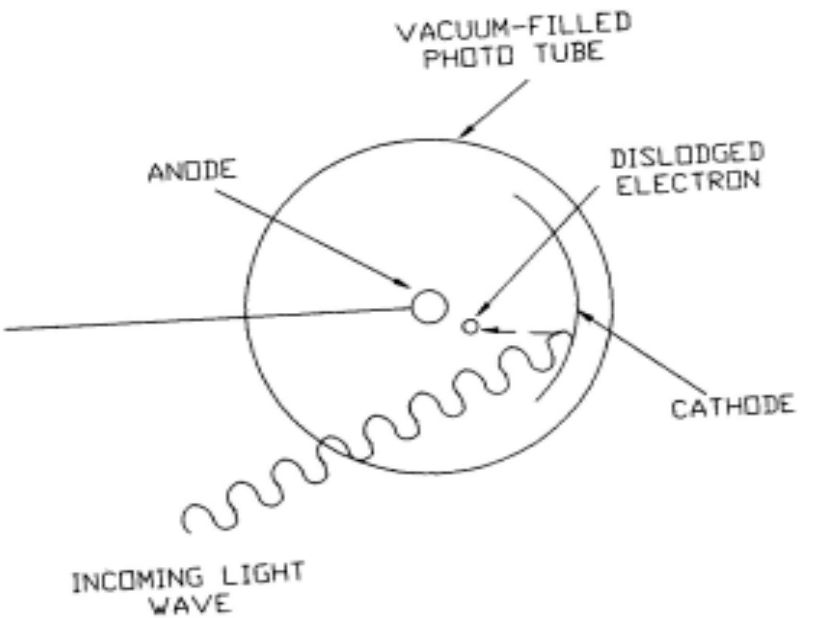




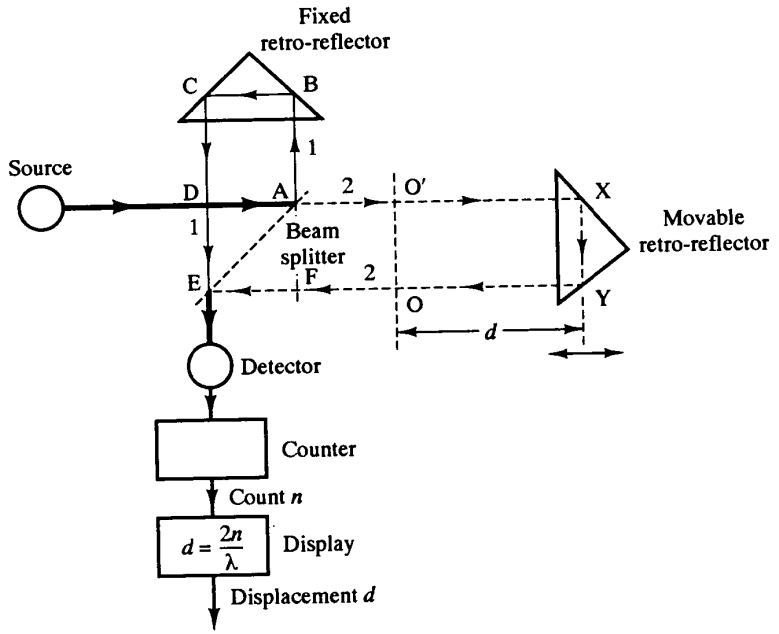
Photoemissive sensors

- Vacuum photodiode

  Light enters through a transparent window and strikes the cathode. Photoelectrons are dislodged from the cathode's surface that become attracted by the anode.



Michelson Interferometer



- Michelson Interferometer for accurate measurement of displacement
  - distance O'X is measured
  - interference of two beams summed at point E
  - counter for counting interference maxima

$$x = x_2 - x_1 = \text{AXYFE} - \text{ABCDE}$$
$$= (\text{AX} + \text{XY} + \text{YF} + \text{FE}) - (\text{AB} + \text{BC} + \text{CD} + \text{DE})$$

Since XY = DE, FE = BC then

$$x = (\text{AX} + \text{YF}) - (\text{AB} + \text{CD}) = 2\text{AX} - 2\text{AB}$$

If displacement d is measured from the line OO′, where AO′ = AB then AX = AB + d and

$$\boxed{x = 2(\text{AB} + d) - 2\text{AB} =} \; 2d$$

Example:

λ =633 nm; d =1 mm

$$n = \frac{d}{\lambda/2} = \frac{2 \times 10^{-3}}{633 \times 10^{-9}} = \frac{2 \times 10^{6}}{633} = 3159.56$$

Interferometers

- Interference of two harmonic waves ϕ_1 and ϕ_2

$$\phi_1 = a \sin\left(\omega t - \frac{2\pi}{\lambda} x_1\right), \quad \phi_2 = a \sin\left(\omega t - \frac{2\pi}{\lambda} x_2\right)$$

so that the resultant light beam incident on the detector is given by:

$$\phi = \phi_1 + \phi_2 = a\left\{\sin\left(\omega t - \frac{2\pi}{\lambda} x_1\right) + \sin\left(\omega t - \frac{2\pi}{\lambda} x_2\right)\right\}$$

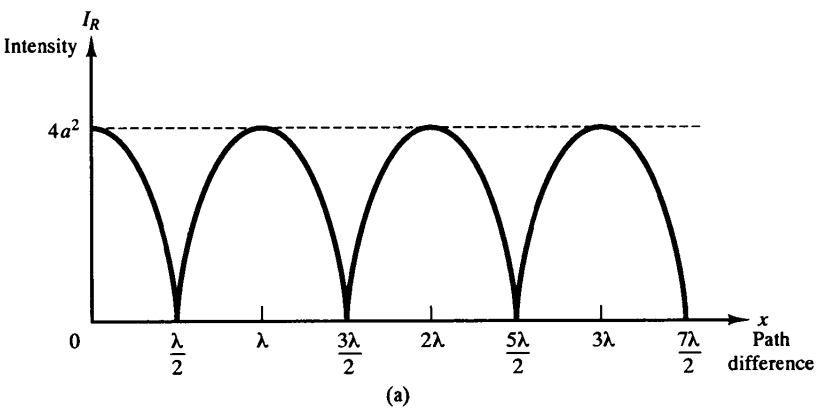
$$= 2a \cos \frac{2\pi}{\lambda} \frac{(x_2 - x_1)}{2} \sin\left[\omega t - \frac{2\pi}{\lambda} \frac{(x_1 + x_2)}{2}\right]$$

This has amplitude:

$$a_R = 2a \cos \frac{\pi}{\lambda} x$$

where x = optical path difference $x_2 - x_1$, and intensity:

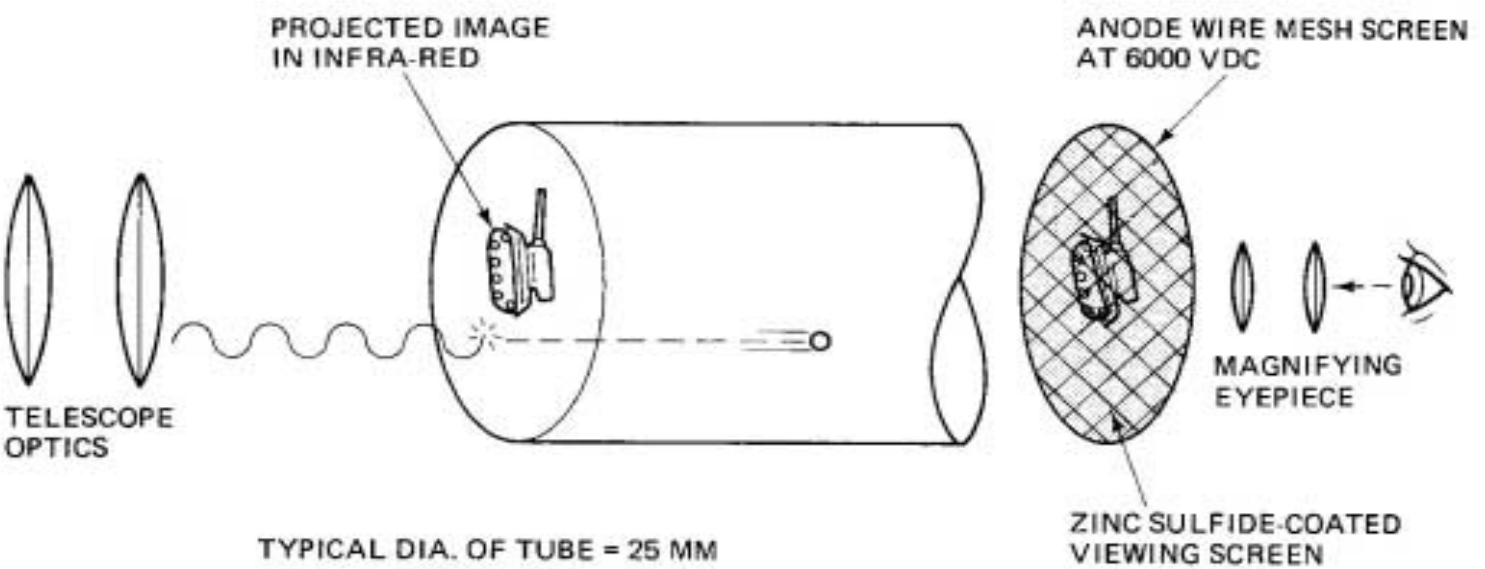
$$I_R = a_R^2 = 4a^2 \cos^2 \frac{\pi}{\lambda} x$$



(a)

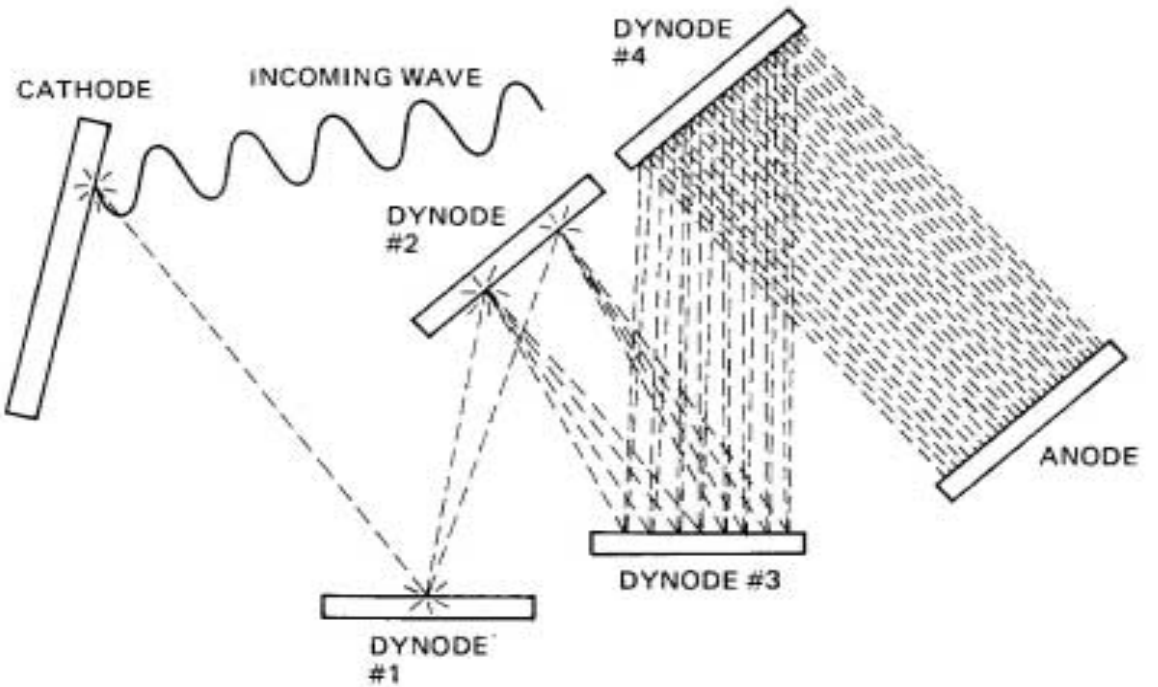
Photoemissive sensors

- Image converter tubes



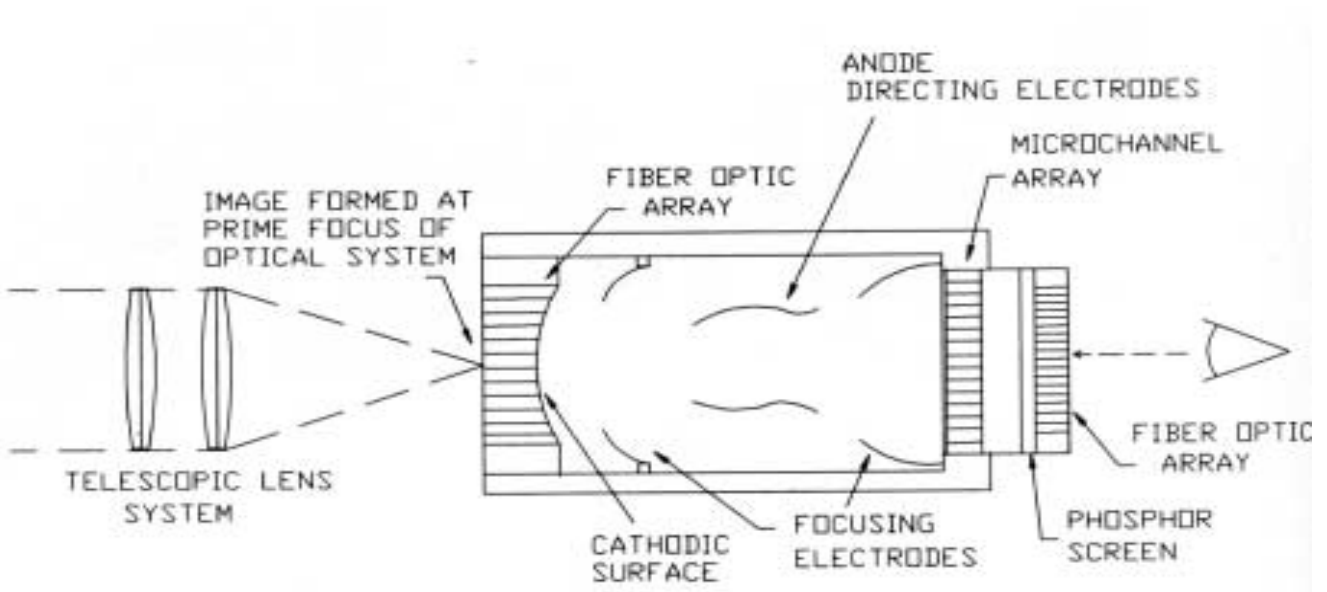
Photoemissive sensors

- Photomultiplier tube



Photoemissive sensors

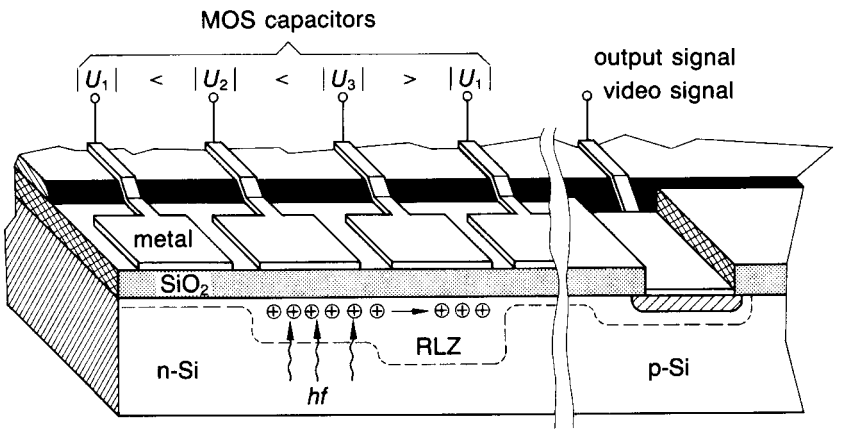
- Image intensifier tube



Photoemissive sensors

- Charge-coupled-device (CCD)

  A dynamic memory chip that is light sensitive



Diagrammatic structure of a CCD

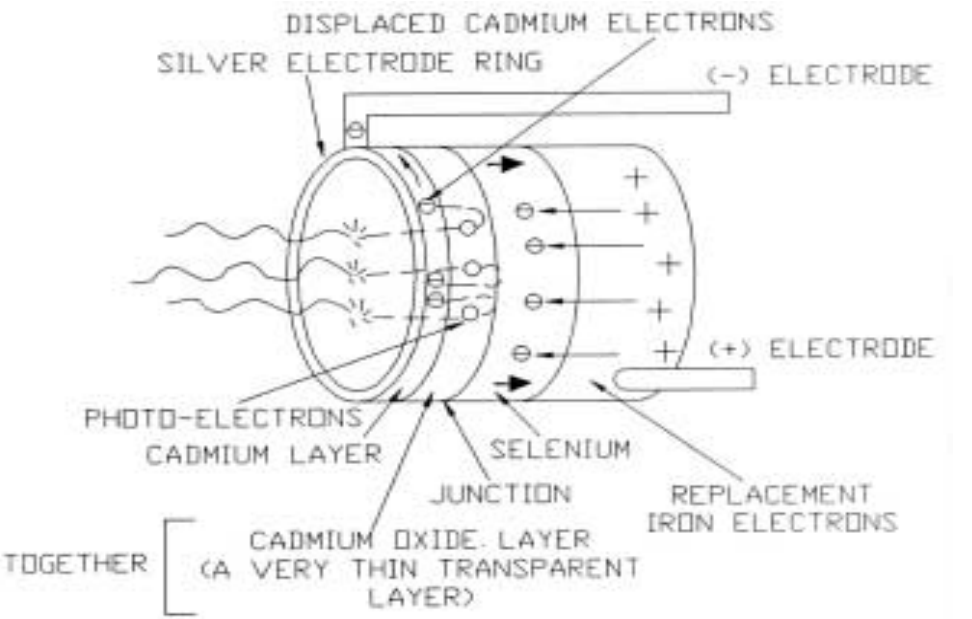
- Principle
  - ✓ Minority carriers are created at the areas where photons enter the structure
  - ✓ Minority carriers are collected and stored in a localized potential well at a Si-SiO_2 junction
  - ✓ The charges are shifted from one cell to another by applying the appropriate voltages at the metal electrodes
  - ✓ The analog shift register enables serial readout of information

Photovoltaic sensors

- PHOTOVOLTAIC SENSOR - a device that generates DC voltage with magnitude depending on the intensity of light illuminating the device.
- Selenium cell - a classical design

  The element selenium was discovered in Sweden in 1817; used for rectifiers since 1930s

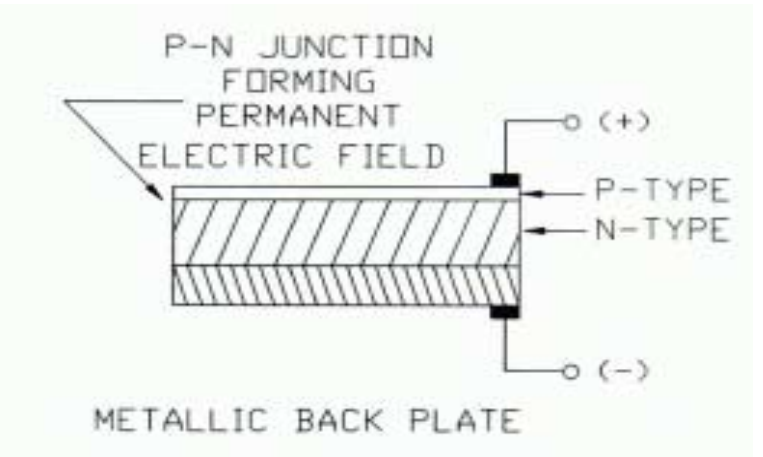
Entering light displaces electrons in cadmium-cadmium oxide junction. Selenium acts as a rectifier and electrons flow into cadmium to the ring electrode.



Photovoltaic sensors

- Silicon cell
  - n -type silicon wafer doped with arsenic
  - p -type silicon doped with boron (light entering surface)

Silicon photovoltaic cell

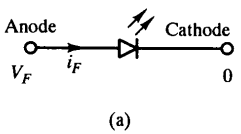


- Most photovoltaic silicon cells behave in a fashion similar to the ordinary *pn* diode.
- Main difference: diode's bias voltage comes from the light striking the diode rather than from the external voltage source.

2

Data presentation devices

- Light emitting diode (LED) displays



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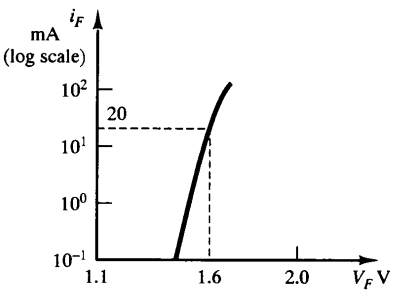

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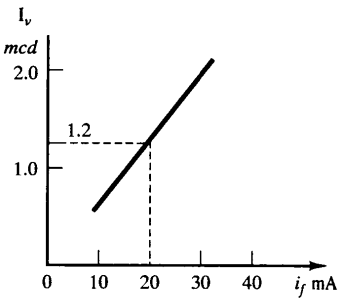

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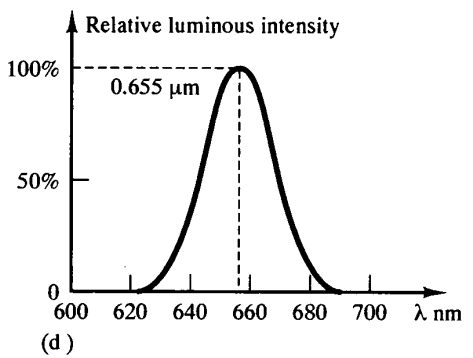

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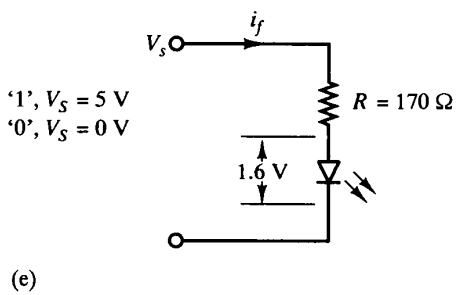
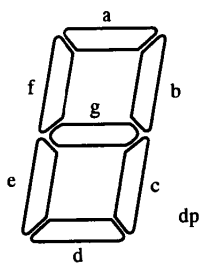


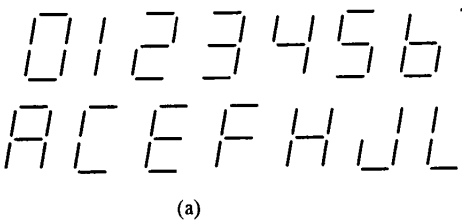
(e)

- Light-emitting diodes have a special property:
- when forward biased they emit electromagnetic radiation over a certain band of wavelengths
- Gallium arsenide phosphide (GaAsP) - red light
- Gallium phosphide (GaP) - green or yellow light

Data presentation devices

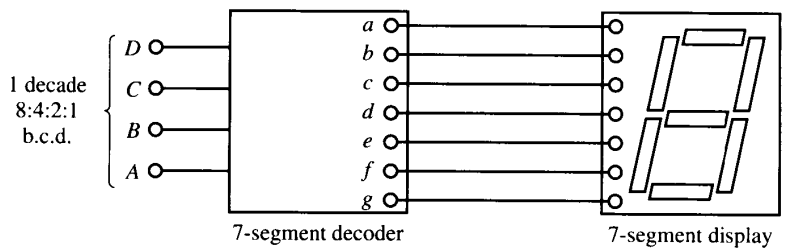
- Segment displays





(a)

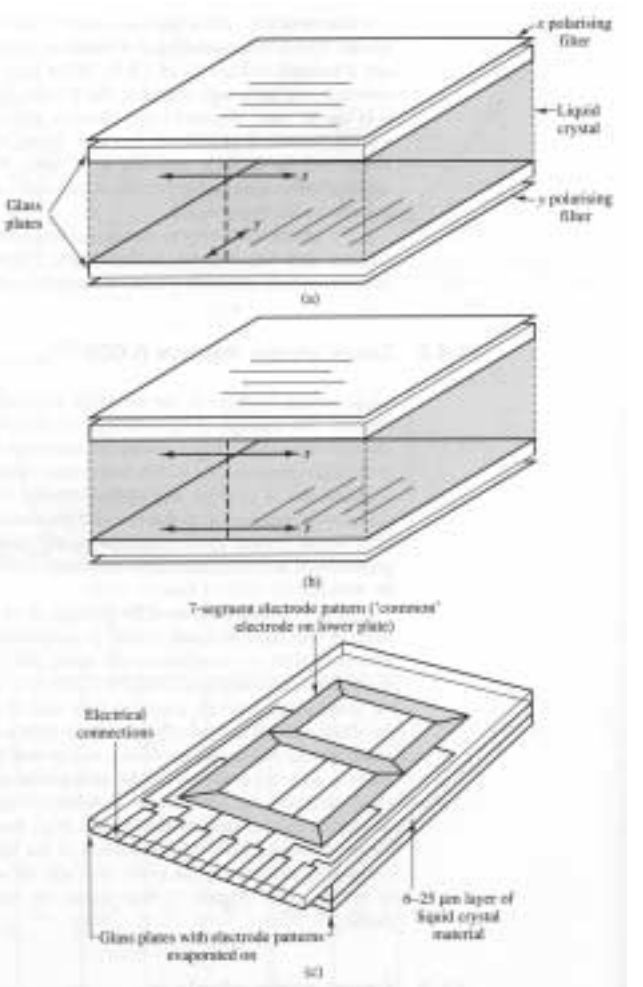
- 7 segment character format



- driver for 7 character display with bcd code driver
- 0 0 0 0 0
- 1 0 0 0 1
- ….
- 8 1 0 0 0

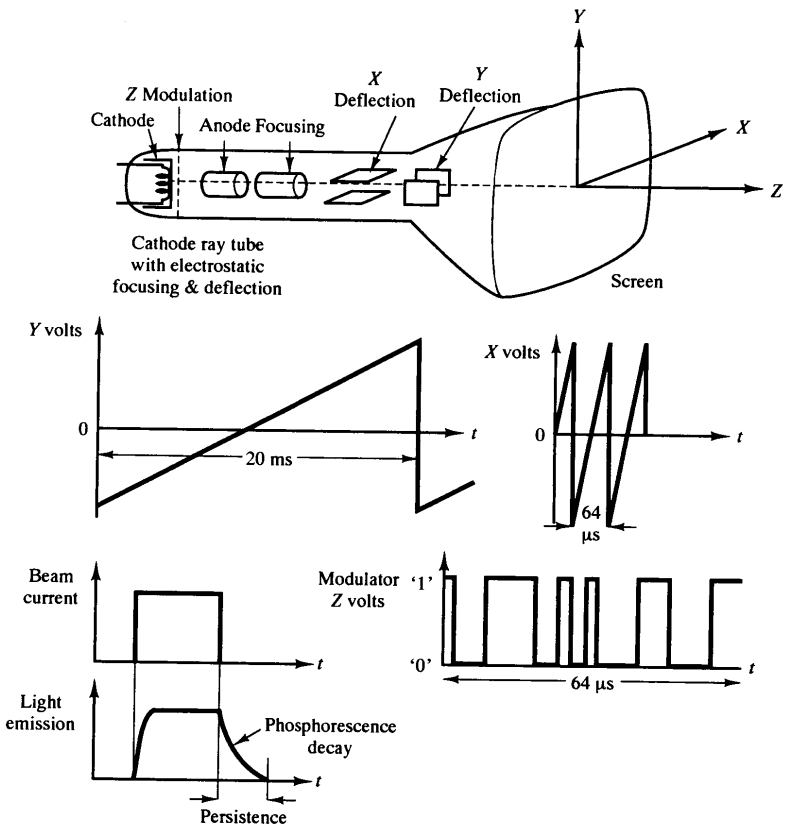
Data presentation devices

- Liquid crystal displays (LCD)
  - LCD does not emit light, they use the incident light
  - upper layer transmits only light with an electromagnetic component along the *x* direction
  - lower layer transmits only light with an electromagnetic component along the *y* direction
  - no field applied - liquid crystals rotate the plane of polarization from *x* to *y*, light is transmitted
  - applied field - liquid crystals align themselves with the field and cannot rotate the plane of polarization, light is absorbed



Data presentation devices

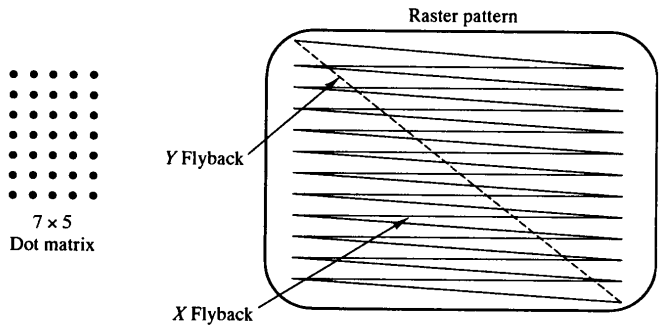
- Monitors based on cathode-ray tube (CRT)

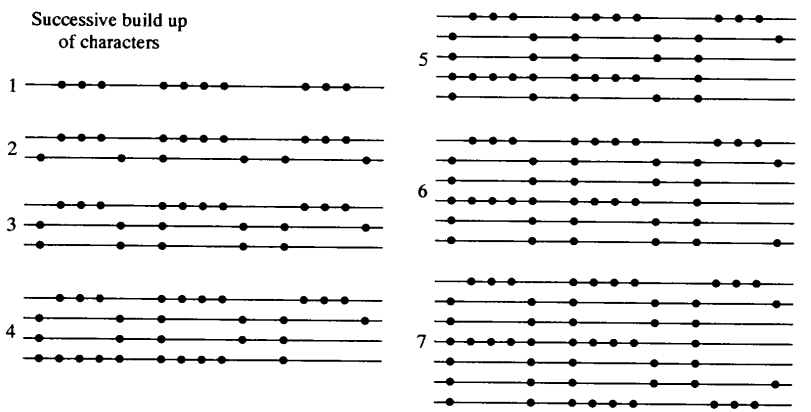


- Electrons are emitted at the cathode and accelerated to the anode
- grid controls the number of electrons (modulates beam) that passes:
  - a focusing system, and
  - X and Y deflection systems
  - and reaches the inside surface of the screen covered with phosphor dots (pixels)
  - phosphor dots emit a visible radiation

Data presentation devices

- Monitors based on cathode-ray tube (CRT)





- Raster display and character generation using 7 x 5 dot-matrix format

Optical Energy Domain - Review questions

- Explain difference between photovoltaic and photoelectric effect, define Miller index for both
- Explain function of a photoconductive sensor
- Explain the nature of photodiodes dark current
- Advantages of phototransistor comparing to photodiode
- Operation principle of image converter
- What is the purpose of dynode in a photoemission tube
- Operation principle of CCD
- Operation principle of a photovoltaic sensor (selenium or silicon cell)