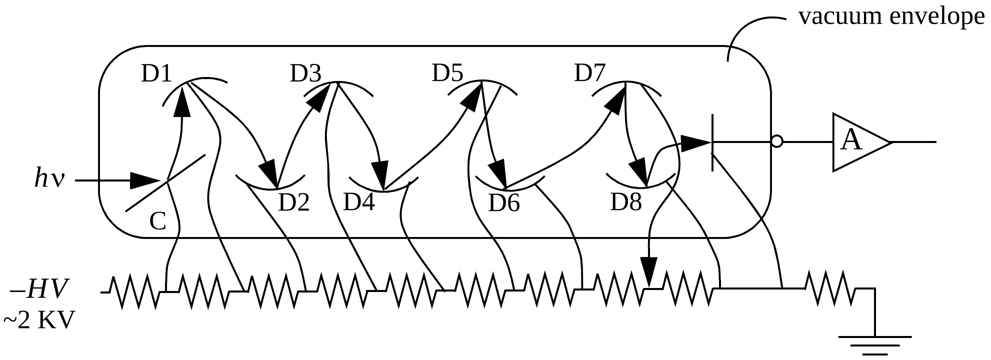
Chapter 4
OPTICAL DETECTORS

(Reference: *Optical Electronics in Modern Communications*, A. Yariv, Oxford, 1977, Ch. 11.)

Photomultiplier Tube (PMT)

- Highly sensitive detector for light from near infrared → ultraviolet
- Can detect as little as 10^{-19} Watt!



Voltage divider chain to bias dynodes

R chosen to have ~100V drop per dynode

Photocathode C:– absorbs photon → ejects electron

– work function ϕ is the minimum energy needed to eject an electron

– the photon energy must exceed the work function $h\nu > \phi$ to get photoelectrons

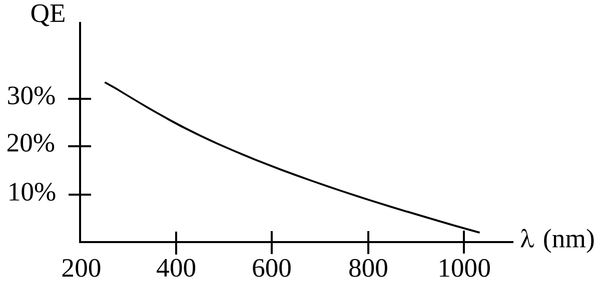
Dynodes D1-D8:Secondary electron emission. Electron from cathode accelerated by ~100 eV. Impact into dynode surface causes ejection of multiple electrons, $\delta \cong 5$.

For N dynodes, the total gain is then δ^N.

Photocathode quantum efficiency: $QE \equiv$ probability a photon will eject one electron

$0 \le QE \le 1$

Typical photocathode response



Sensitivity:

For 10 dynodes, $\delta = 5$, $G = 5^{10} \cong 10^7$.

Take 2eV photons (620 nm), 1 picoW = 10^{-12}W = 10^{-12}J/s

With $QE = 30\%$, Anode current is

Phototube **dark current**:1) random thermal excitation of electrons from photocathode

2) cosmic rays, ambient radioactivity

- Thermal excitation rate is proportional to , where Φ represents the cathode work function

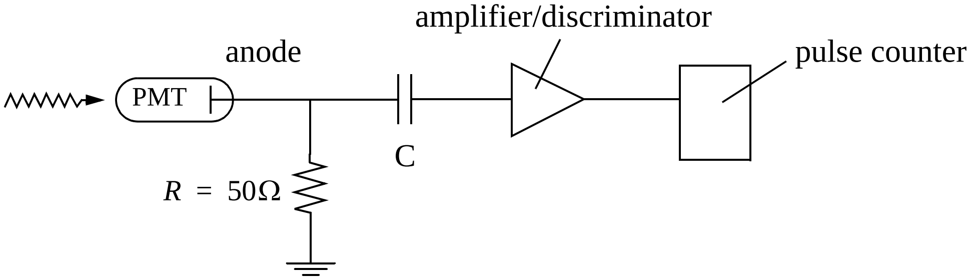
  so lower work function → IR sensitivity, **but** larger dark current
- For room temperature, typical cathode dark current, I_{cd}, is $\approx 10^4$ electrons/sec. Anode dark current is then
- Dark current sets a lower limit to phototube sensitivity to low light levels. To distinguish a light signal above the background dark current, the photoelectric cathode current must exceed the dark current. If I_{cd} is $\approx 10^4$e/sec, then the sensitivity to light can be $\sim 3 \times 10^4$ photons/sec (assuming QE = 30%). 3×10^4 red photons/s $\cong$ **10^{-14} W**!
- Dark current can be reduced by *cooling*. Using thermoelectric cooling $T \equiv -40\mathrm{C}$ is easily obtained. Assume a work function of $\Phi = 1.5$ eV

$$\frac{I_{cd}(260K)}{I_{cd}(300K)} = \frac{e^{-1.5/0.0225}}{e^{-1.5/0.026}} = e^{-1.5(44.4-38.5)} = e^{-8.8} \cong 1.4 \times 10^{-4}$$

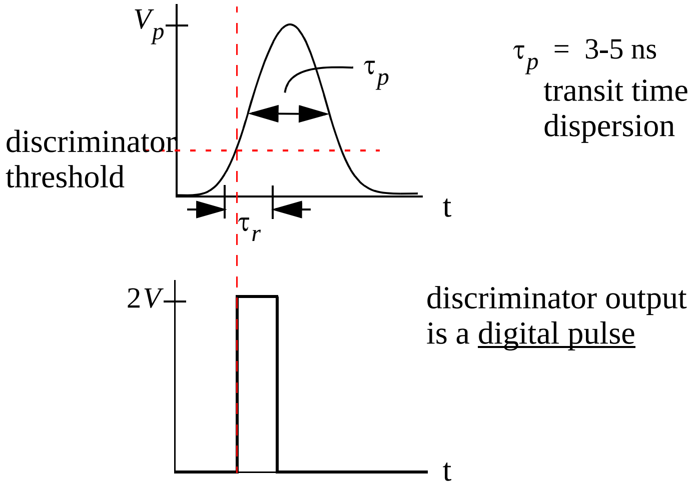
Dark current is reduced by this amount! → down to ~1 e/sec. Minimum detectable power become < 10^{-18} W!

Photon counting: PMT is so sensitive, we are really counting photons. Often, PMT circuits are specifically optimized to do this.

Photon counting system:

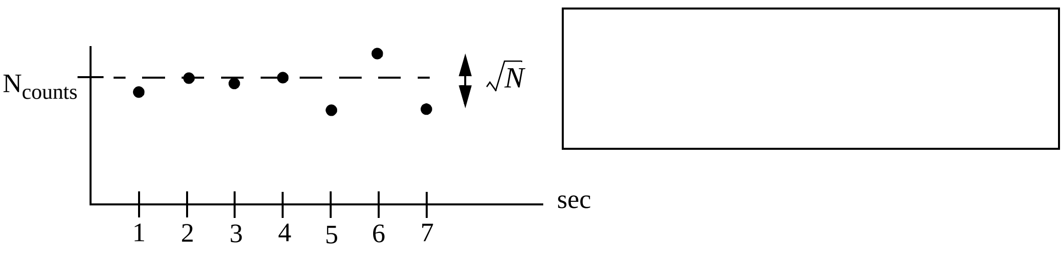


PMT output pulse



- How big is the PMT output pulse from one photon? For $G \sim 10^7$, we get 10^7 electrons $\cong 10^{-12}$C. For $\tau_p = 10^{-8}$ sec, $I_{apk} \sim 10^{-4}$A. For $R = 50\Omega$, $V_p \sim 5$ mV.
- Discriminator eliminates electrical noise in < 1mV range. V_p has a variation due to statistical nature of gain process. Discriminator also eliminates this.

  Shot noise: Photon arrival is always statistical. Generally it follows Poisson statistics. Then if the photon arrival rate is N ph/sec, and we count for 1 sec, we get N on average. The standard deviation will be found to be $\sqrt{N}$. This means we have noise.



Shot noise is universal for light detection. Even if photons are not explicitly counted, the shot noise is a fundamental limit. It is most significant at low light levels, though, due to $\sqrt{N}$ dependence.

Johnson noise: Random thermal noise in any resistor, R

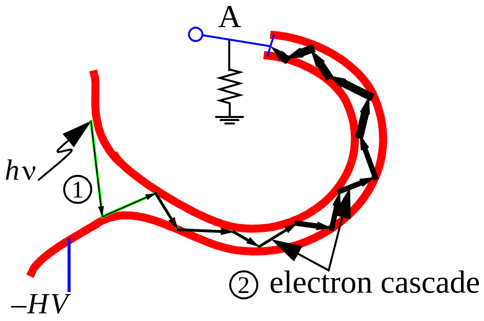
$$I_{RMS} = \sqrt{\frac{4kT}{R}B} \qquad V_{RMS} = \sqrt{4kTRB}$$

B: bandwidth (Hz)

Equivalent model of noise as either current or voltage source.

Channel Electron Multiplier (Channeltron)

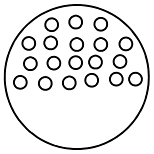
Single monolithic device functions as a PMT:

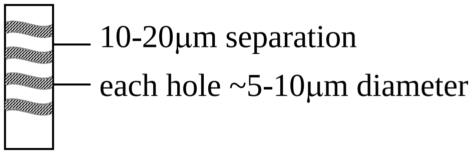


Glass tube bent around curve. One end open as a funnel shape. Coating acts as photocathode **and** secondary electron emitter. Also, coating has high, but not infinite electrical resistance.

1. Photon hits funnel portion
2. Electrons are accelerated into the bent tube by bias field
3. Secondary electron emission gives gain at each electron collision with wall
4. Must be operated in vacuum
5. Typical gain $\sim 10^4$
6. More compact and rugged than PMT

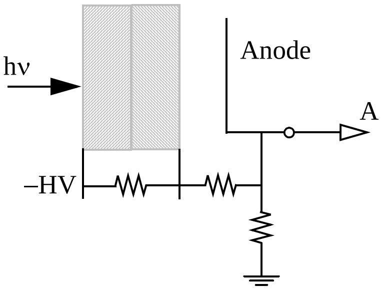
<u>Microchannel plate MCP</u> – array of *channeltrons*





– each channel is a miniature channeltron

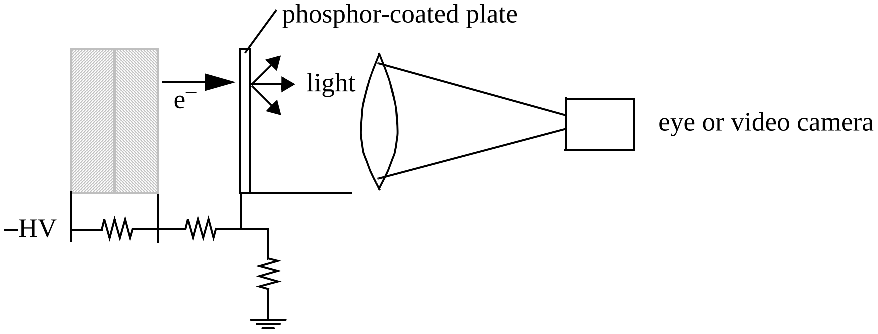
– gain $\sim 10^3$



gain $\sim 10^6$ HV ~1-2KV

Dual Plate MCP Detector

MCP Image Intensifier



Single or Dual Plate MCP

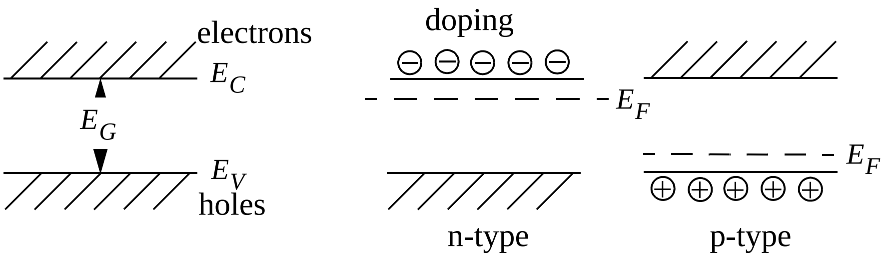
- Electrons accelerated out of back of MCP into phosphor
- Phosphor QE ~50% photons/electrons

Image intensification

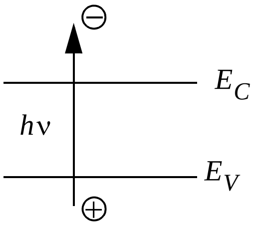
→ Night vision goggles

Semiconductor Photodetectors

- Seimiconductor band structure



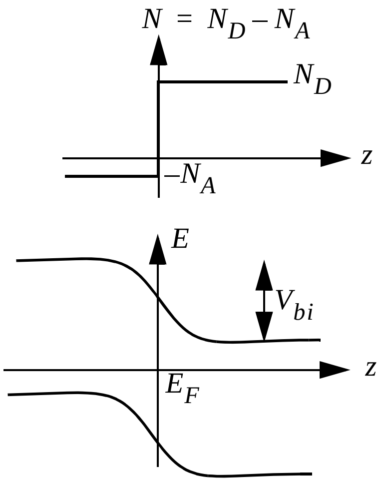
- Optical absorption across the bandgap



If $h\nu > E_G$, an electron and hole (pair) is created after photon absorption.

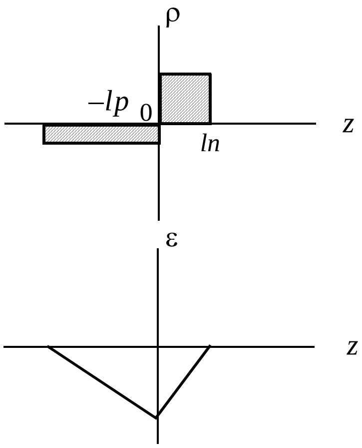
In a suitable structure, the electron and the hole can contribute to an electric current through the device.

- p-n Junction

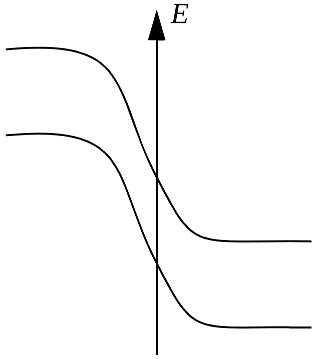


equilibrium

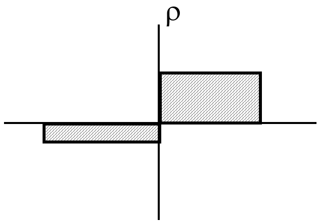
- Depletion approximation: Assumes carriers diffuse across junction and create regions that are totally devoid of free carriers



- Reverse bias



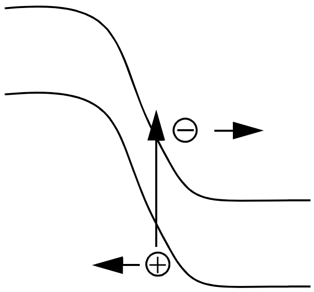
Under reverse bias, no current flows because the barrier to diffusion increases. Under forward bias, barrier to diffusion is *reduced*.

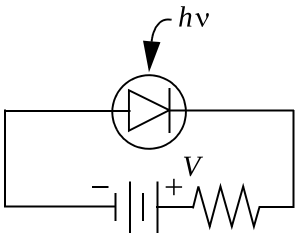


depletion widths wider

Photodiode

Reverse bias condition: electron and hole created in the depletion region follow the electric field and separate.

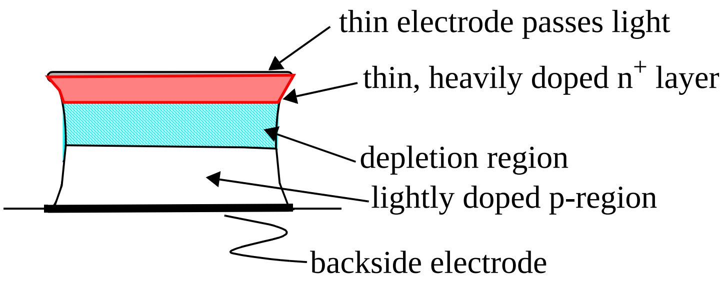




These carriers are pulled apart by the field.

The electric field exists *only* inside the depletion region. So the light absorption must also occur there to create current.

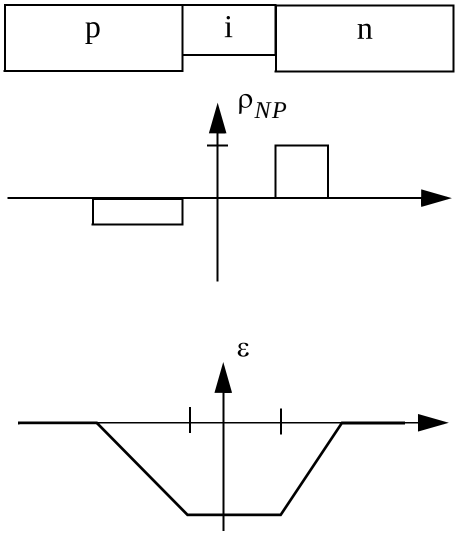
Construction



- Photodiodes can be used at longer wavelength than photomultiplier – $E_G < \Phi$
- Typically fast response time < 10 nsec

- Compact, inexpensive

p-i-n photodiode

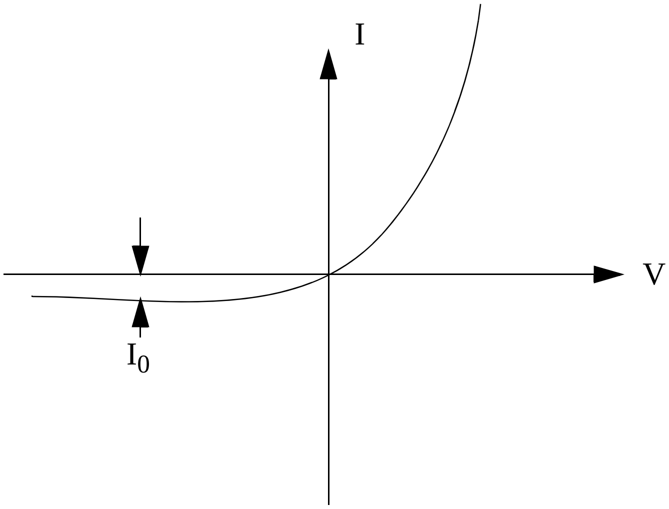


constant ε-field in the i-layer

Solar cells

(Reference: *Solar electricity, 2nd edition, Tomas Markvart, ed., John Wiley, 2000*)

silicon p-n juntion diode:



Solar radiation -

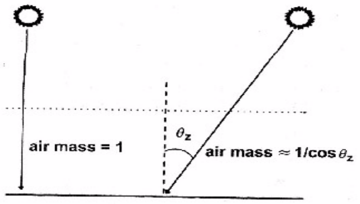


Fig. 2.2

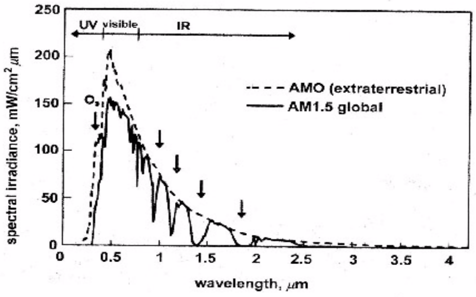


Fig. 2.3 The solar spectrum

AM 1.5 - on a clear day, the typical maximum solar irradiance is ~1kW/m^2 or 100 mW/cm^2, which translates to ~4.4X10^{17} photons/cm^2-sec.

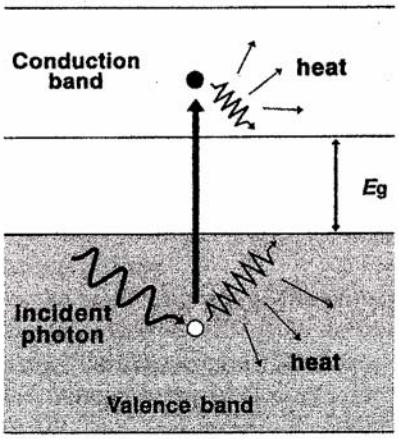


Fig. 3.8 The generation of electron–hole pairs by light

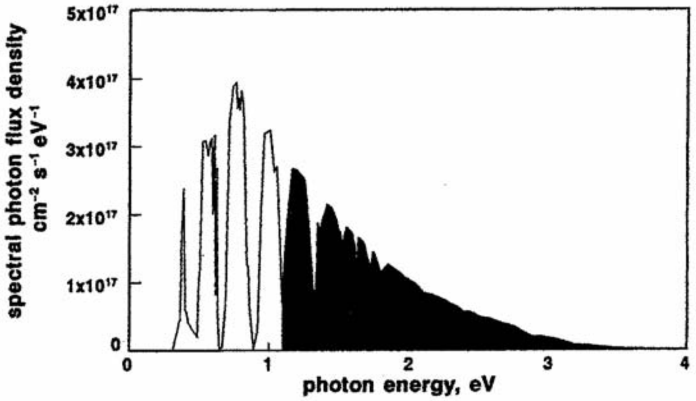


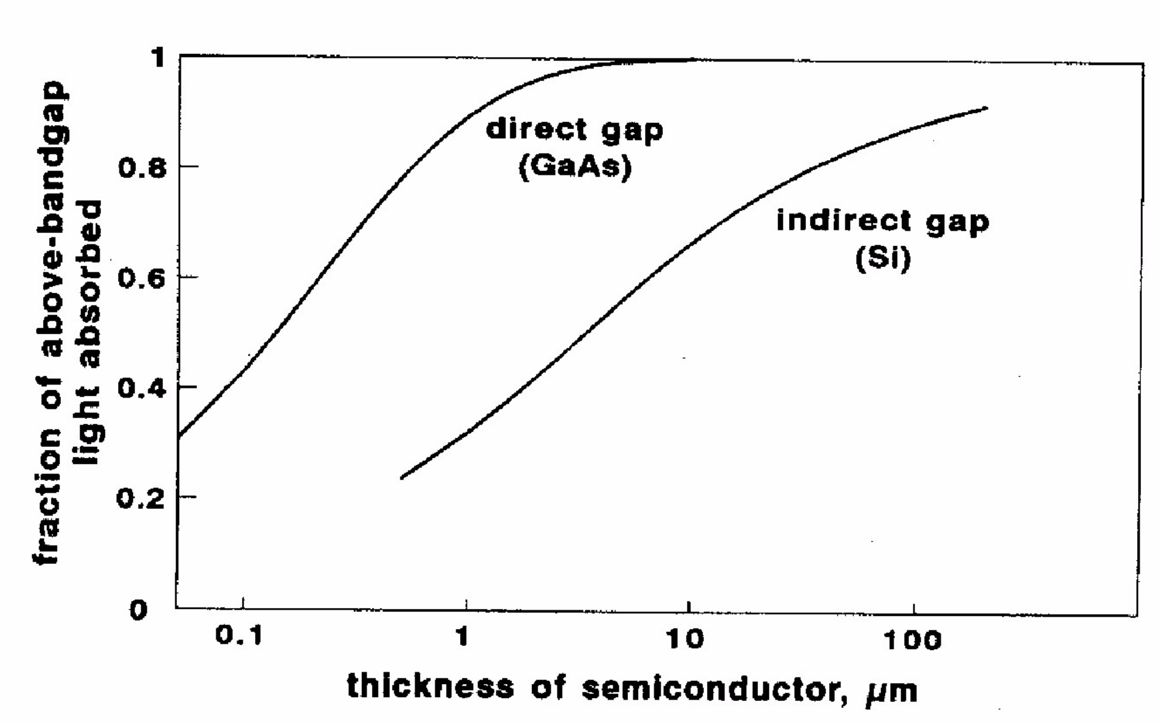
Fig. 3.9 Photon flux utilised by a silicon solar cell

In principle, when absorbed, this photon flux could produce a 'generation current' of

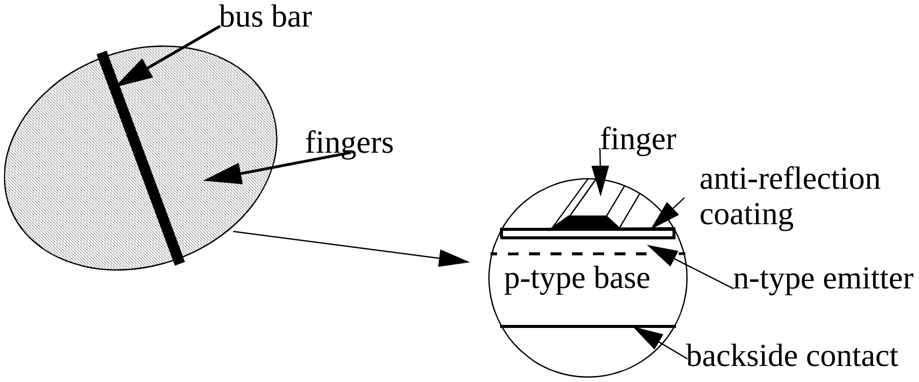
where *N* is the number of photons absorbed per second, and *A* is the area that is exposed to light. For the entire solar spectrum, this corresponds to about 70mA/cm^2. The band gap for crystalline silicon is 1.1 eV, so only the part of the spectrum shown above that is shaded in black can be absorbed. Thus, for silicon, the maximum generation current is about 44 mA/cm^2.

Direct vs. indirect gap

Some semiconductors are good absorbers, and absorb all above-bandgap light in a layer of a few microns thick. These are called direct-bandgap semiconductors. In others, called indirect-gap semiconductors, which include crystalline silicon, the absorption process is weaker. In this case, a phonon (a quantum of the lattice vibration) is necessary to conserve momentum in the light absorption process. In silicon, a layer several hundred microns thick is required.



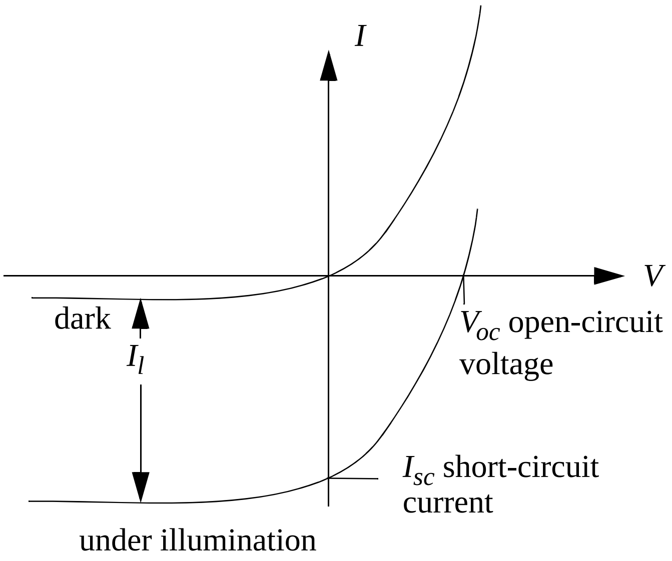
Solar cell structure



The top contact structure typically consists of widely spaced thin metal strips to allow the light to pass through, with a larger bus bar connecting them all to extract the current. An anti-reflection coating on top of the cell can be used to minimize reflection loss from the top surface.

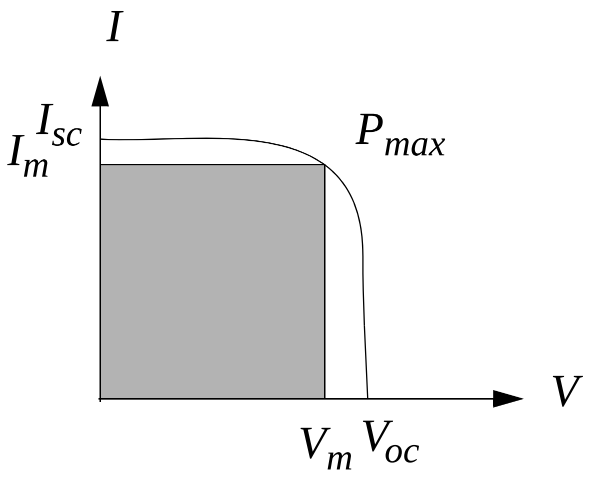
The light generation current in the diode is in the reverse direction, so we can write to total current as the difference between the two:

The I-V characteristic now looks like this:



Maximum power point

No power is generated under open or short circuit. The maximum power P_{max} is produced by the device at a point on the characteristic where the product *IV* is maximized. The position of the maximum power point represents the largest area of the rectangle shown in the figure below. The 'fill factor', FF is commonly defined by:



The efficiency of a solar cell, η, is defined as P_{max} produced by the cell under standard test conditions, divided by the power of the radiation incident. Usually, the standard conditions are: irradiance of 100 mW/cm^2, standard reference AM1.5 spectrum and temperature of 25C.

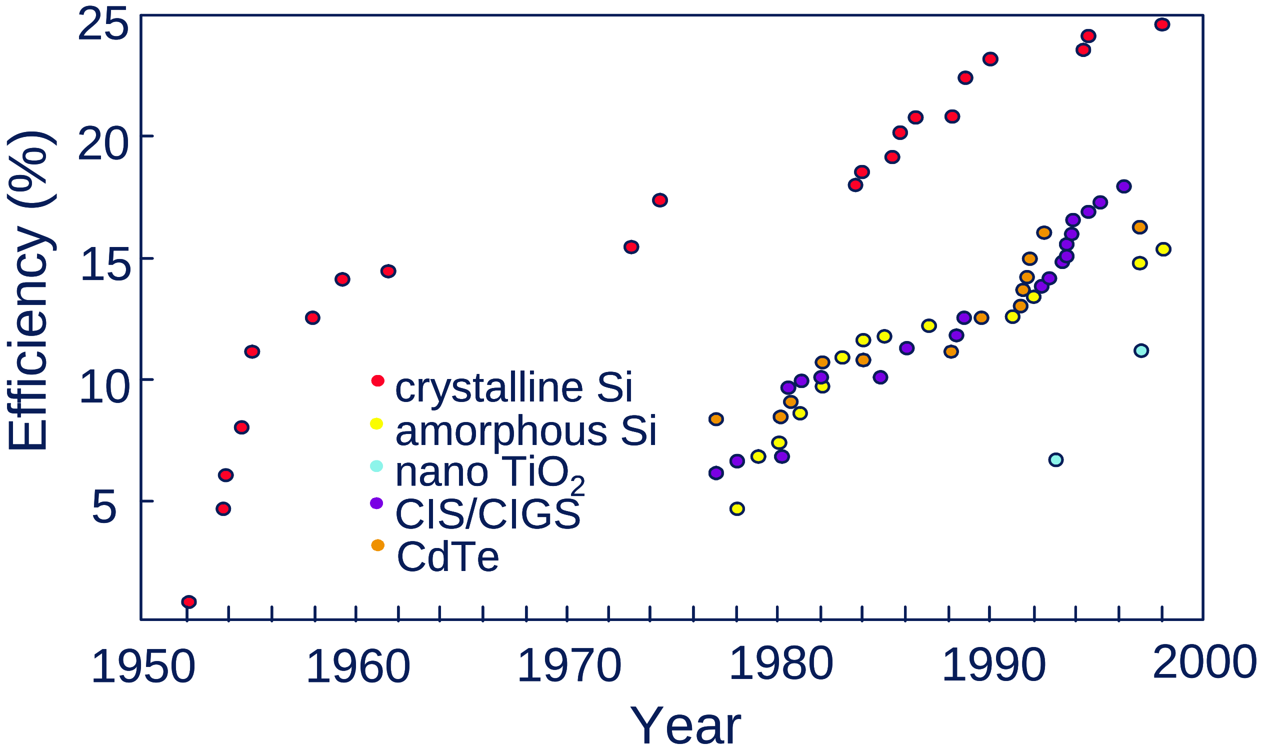
Some common solar cell types

High quality crystalline silicon and gallium arsenide solar cells can achieve efficiencies approaching 25%, but are relatively expensive because the cost of growing and processing large single-crystal wafers is high. The p-i-n structure is used for silicon cells in order to get an active light absorbing layer that is over 100 microns thick.

Thin-film solar cells can be much cheaper, but are not as efficient (10-15%). A very common material for thin-film cells is amorphous silicon. Silicon is a four-fold coordinated atom that is normally tetrahedrally bonded to four neighboring silicon atoms. In crystalline silicon this tetrahedral structure is continued over a large range, forming a well-ordered lattice (crystal). In amorphous silicon this long range order is not present and the atoms form a continuous random network. Not all the atoms within amorphous silicion are four-fold coordinated. Due to the disordered nature of the material some atoms have a dangling bond. These dangling bonds are defects in the continuous random network, which cause undesired (electrical) behaviour. The material can be passivated by hydrogen, which bonds to the dangling bonds and neutralises this defect. Hydrogen passivated amorphous silicon has a sufficiently low amount of defects to be used within devices. Amorphous silicon can be deposited over large areas using chemical vapor deposition methods.

Amorphous silicon (a-Si) becomes a direct-gap semiconductor with an band gap of about 1.75 eV. Absorption is higher in a-Si compared to crystal silicon (c-Si), but p-i-n structures are generally still used. The transport properties of a-Si are inferior to c-Si and so many carriers can recombine before they reach the contacts, reducing the efficiency of the cell.

Solar cell efficiency progress



Brief discussion of global solar energy

Total average global power consumption in 1990: 12 TW. Projected to grow to 28 TW by 2050.

$1.2x10^5$ TW of solar energy potential globally

Generating $2x10^1$ TW with 10% efficient solar farms requires $2x10^2/1.2x10^5$ = 0.16% of Globe = $8x10^{11}$ m^2 (i.e., 8.8 % of U.S.A)

Generating $1.2x10^1$ TW (1998 Global Primary Power) requires $1.2x10^2/1.2x10^5$= 0.10% of Globe = $5x10^{11}$ m^2 (i.e., 5.5% of U.S.A.)

U.S. Land Area: $9.1x10^{12}$ m^2 (incl. Alaska)

Average solar irradiance: 200 W/m^2

2000 U.S. Primary Power Consumption: =3.3 TW

1999 U.S. Electricity Consumption = 0.4 TW

Hence:

$3.3x10^{12}$ W/($2x10^2$ W/m^2 x 10% Efficiency) = $1.6x10^{11}$ m^2

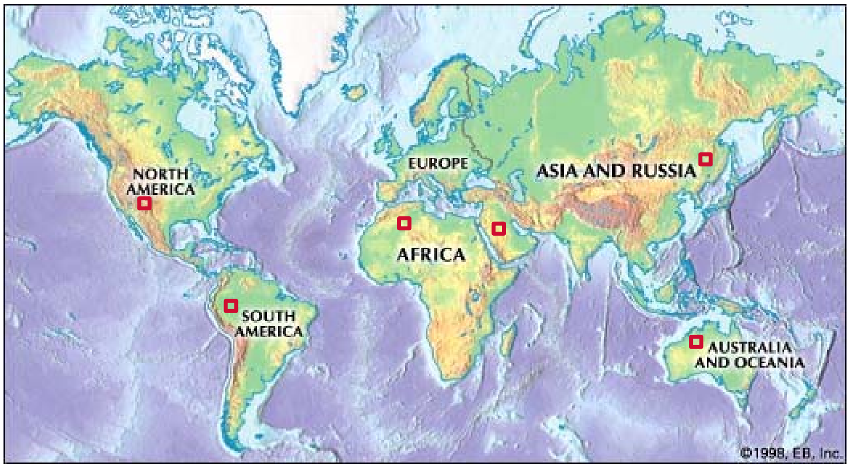
Requires 1.6x10^{11} m^{2}/ 9.1x10^{12} m^{2} = 1.7% of Land

7x10^{7} detached single family homes in U.S.

˜2000 sq ft/roof = 44ft x 44 ft = 13 m x 13 m = 180 m^{2}/home

= 1.2x10^{10} m^{2} total roof area

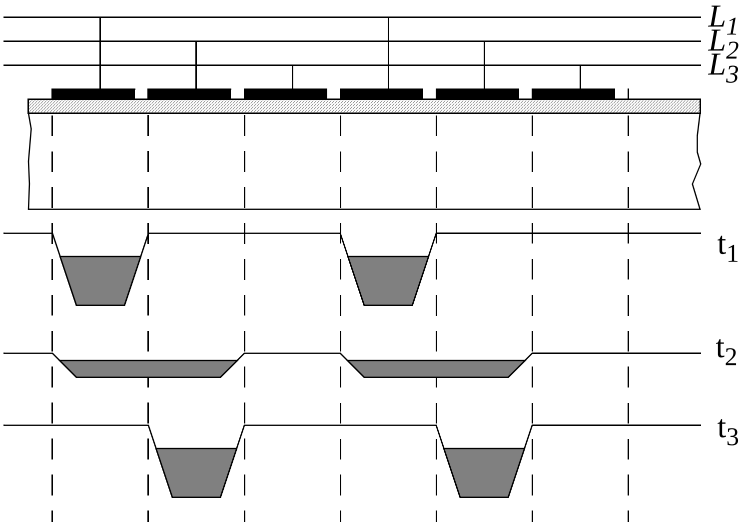
Hence can (only) supply 0.25 TW, or ˜1/10$^{\text{th}}$ of 2000 U.S. Primary Energy Consumption



6 boxes at 3.3 TW each

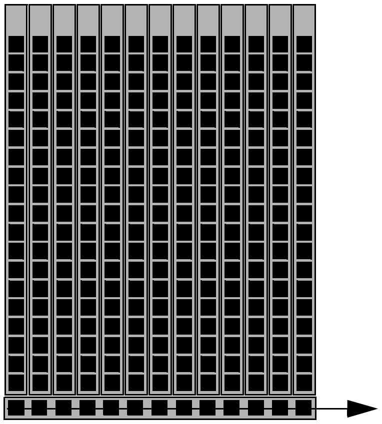
Charge coupled device (CCD)

The basic CCD is composed of a linear array of MOS capacitors. It functions as an analog memory and shift register. The operation is indicated in the diagram below:



3 phase CCD clocking

In the fashion indicated, charge is transferred down the line. In the modern CCD image sensor, there is one such CCD transfer line for each column of the array. During the image exposure, one phase in each column is biased in deep depletion. Light passes through the gate electrodes, which are made thin enough so that most of the light creates electron-hole pairs in the substrate, which are then collected under the gates. To read out the array, each column is clocked down by one. At the bottom, there is one extra CCD line oriented in the horizontal direction. The columns deposit their charge in this horizontal array, which then clocks out to a charge sensitive amplifier and then off-chip. In turn, the array is read out one line at a time in this fashion.



to readout amplifier

Spatial Light Modulator (SLM)

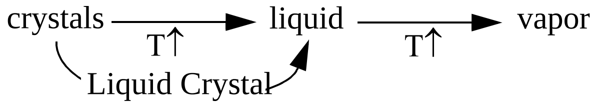
Electro-optic devices that can modulate certain properties of an optical wavefront: amplitude, intensity, phase, or polarization

Liquid Crystal Display – Liquid Crystal Light Valve

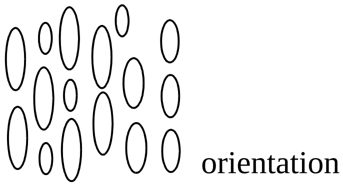
By using two polarizers, twisted nematic liquid crystal and applied electric field, modulation of light intensity can be achieved

Advantage of LCD	**Disadvantage**
a) size and weight	a) viewing angle
b) low power consumption	b) high cost
c) color performance	c) low temperature operation
d) low cost due to mass production	

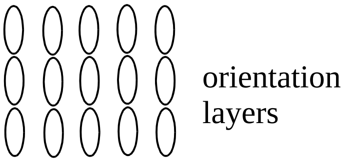
Liquid Crystal



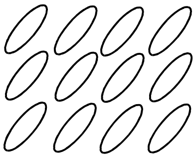
nematic Liquid Crystal



semectic LC

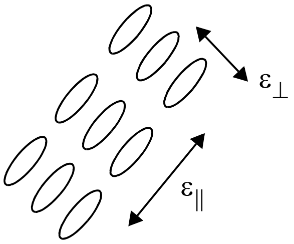


cholesteric LC



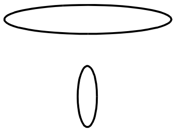
Properties of LC

Dielectric anisotropy



$$\Delta\varepsilon = \varepsilon_\perp - \varepsilon_\parallel > 0$$

Optical anisotropy (birefringence)

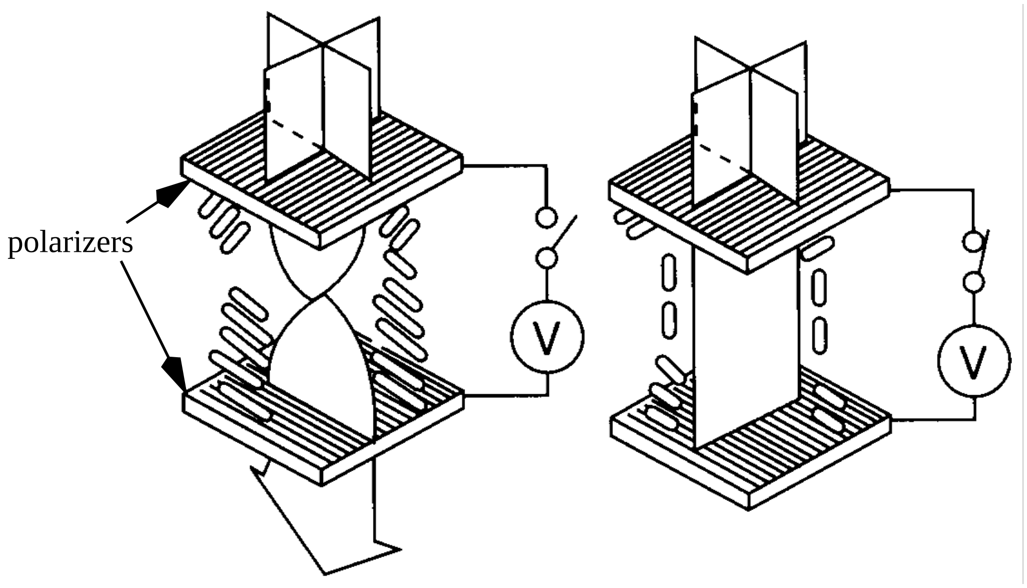


extraordinary (n_e)

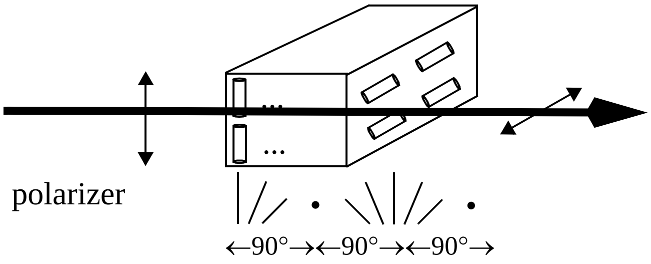
ordinary (n_o)

$$\Delta n = n_e - n_o > 0$$

Twisted nematic Liquid Crystal (90° rotation)

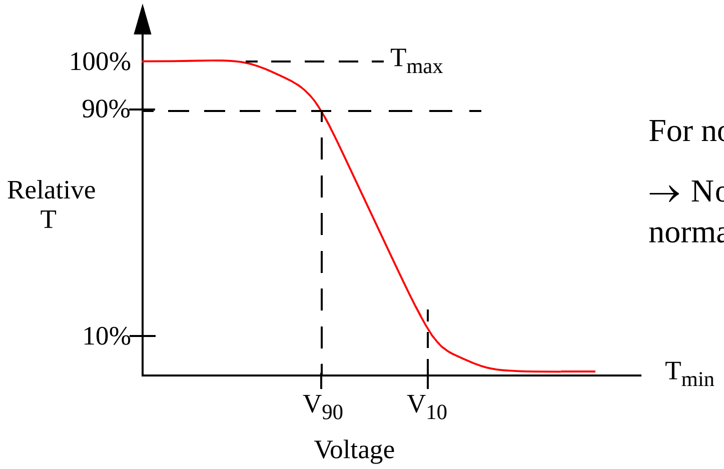


Super twisted nematic Liquid Crystal (180 - 270° rotation)



270° change of polarization

Electro-optic response of a TN LC cell



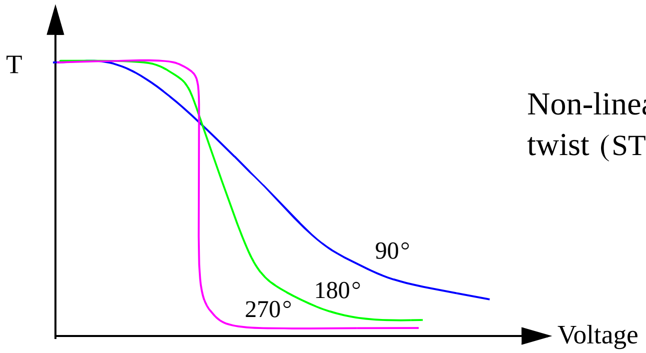
For normally-white case.

→ Normally-black is a mirror image of normally white.

- contrast ratio = T_{max}/T_{min}
- grayscale achieved with intermediate value of V.

Example:

Electro-optic response: Effect of twist

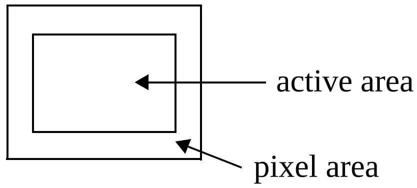


Non-linearity increases as increasing twist (STN > TN).

- steep electro-optic response is needed for high-contrast passive-matrix displays ⇒ NO CROSSTALK– advantage of using STN-LC.

Pixel – Smallest resolvable spatial information element

- May be subdivided to achieve color or gray scales
- Active area can be less than pixel area (~30%).



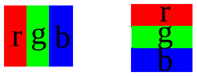
You can calculate the pixel size for a given display type and size.

CGA	640 × 200(V)
VGA	640 × 480(V)
SVGA	800 × 600(V)
XGA	1024 × 768(V)
SXGA	1280 × 1024(V)
VXGA	1600 × 1280(V)

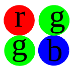
Pixel arrangement for color displays

Triad

Stripe

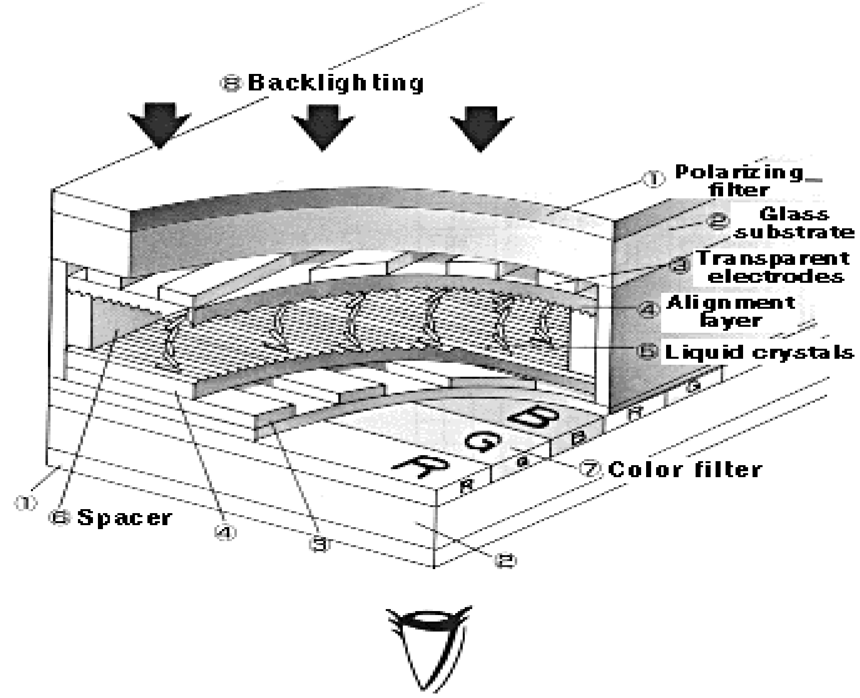


Quad



⇒ human eyes pick up green more

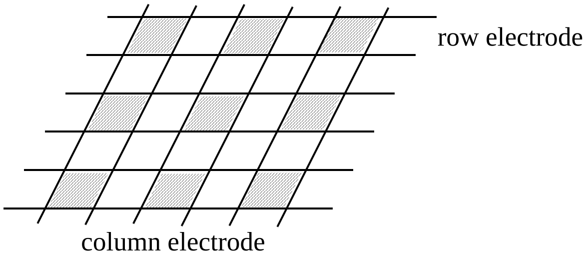
Cross-section of LCD (typical)



Matrix Addressing Mode

Passive Matrix

Example: Earlier laptop display, PDAs



- stripes of conductor on opposing glass plates
- pixels defined by intersection of electrodes

- Non-linearity requirement for PM LCD
  - want to have high non-linearity to reduce cross-talk
- Discrimination ratio (D): , where L = luminance (transmitted)
- Pixel Contrast Ratio (PCR): , where M = number of display rows

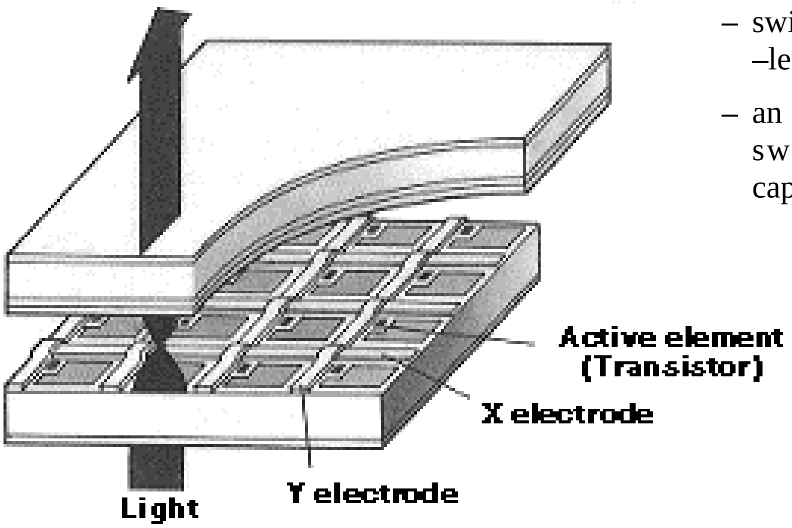
–TN LCD:Low PCR and D

STN LCD:High PCR and D

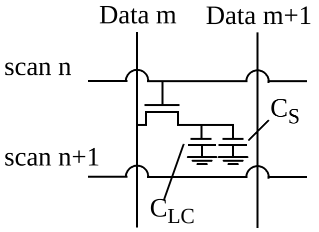
Active Matrix

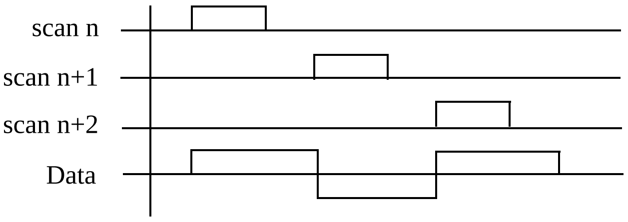
Example: Laptop display, desktop monitor

- array of pixel electrodes on one glass plate
- switch at each pixel for isolation –less crosstalk
- an active element is used as a switch to store charge on LC capacitor



- switching element = thin-film transistor (TFT)





C_{LC}: liquid crystal capacitance
C_S: storage capacitance