MIS capacitor

- Elementary device

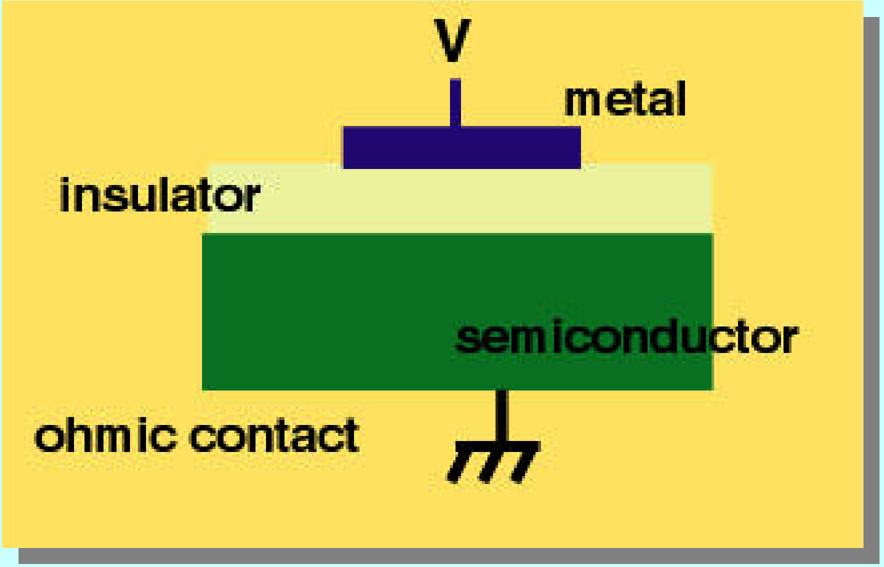
  oxide well matched to silicon

  transparent to wide λ range

  excellent insulator

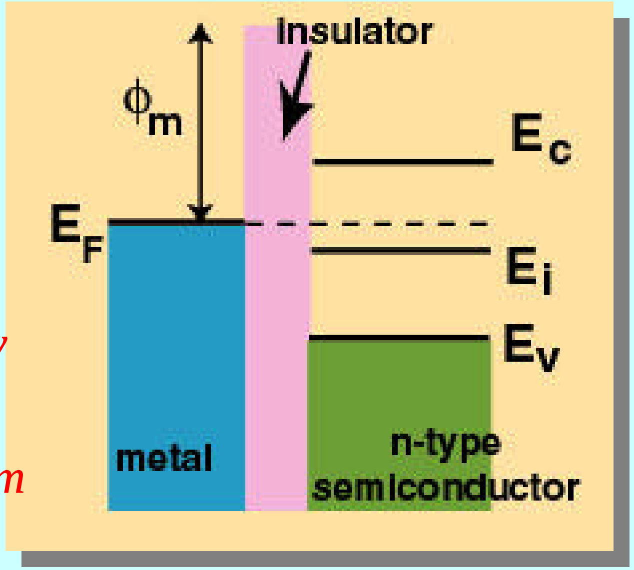
  nitride frequently used in addition

  larger ε



		SiO_2	Si_3N_4
Density	$g.cm^{-3}$	2.2	3.1
Refractive index		1.46	2.05
Dielectric constant		3.9	7.5
Dielectric strength	V/cm	10^7	10^7
Energy gap	eV	9	~5.0
DC resistivity at 25C	Ω. cm	10^{14}-10^{16}	~10^{14}

Energy band diagram



MOS capacitor characteristics

- Apply bias voltage to influence charge under oxide

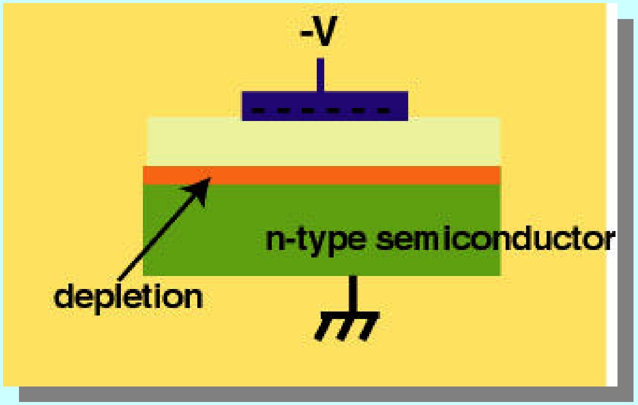
  depletion - potential well which can store charge

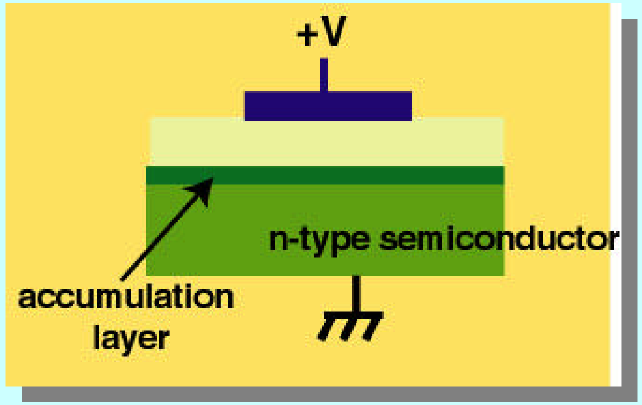
  inversion - thin sheet of charge with high density

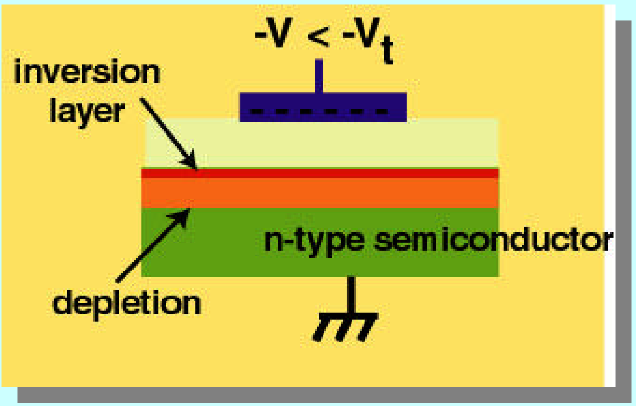
    allows conduction in transistor

    very close to Si-SiO_2 interface

Basis of MOS transistor operation

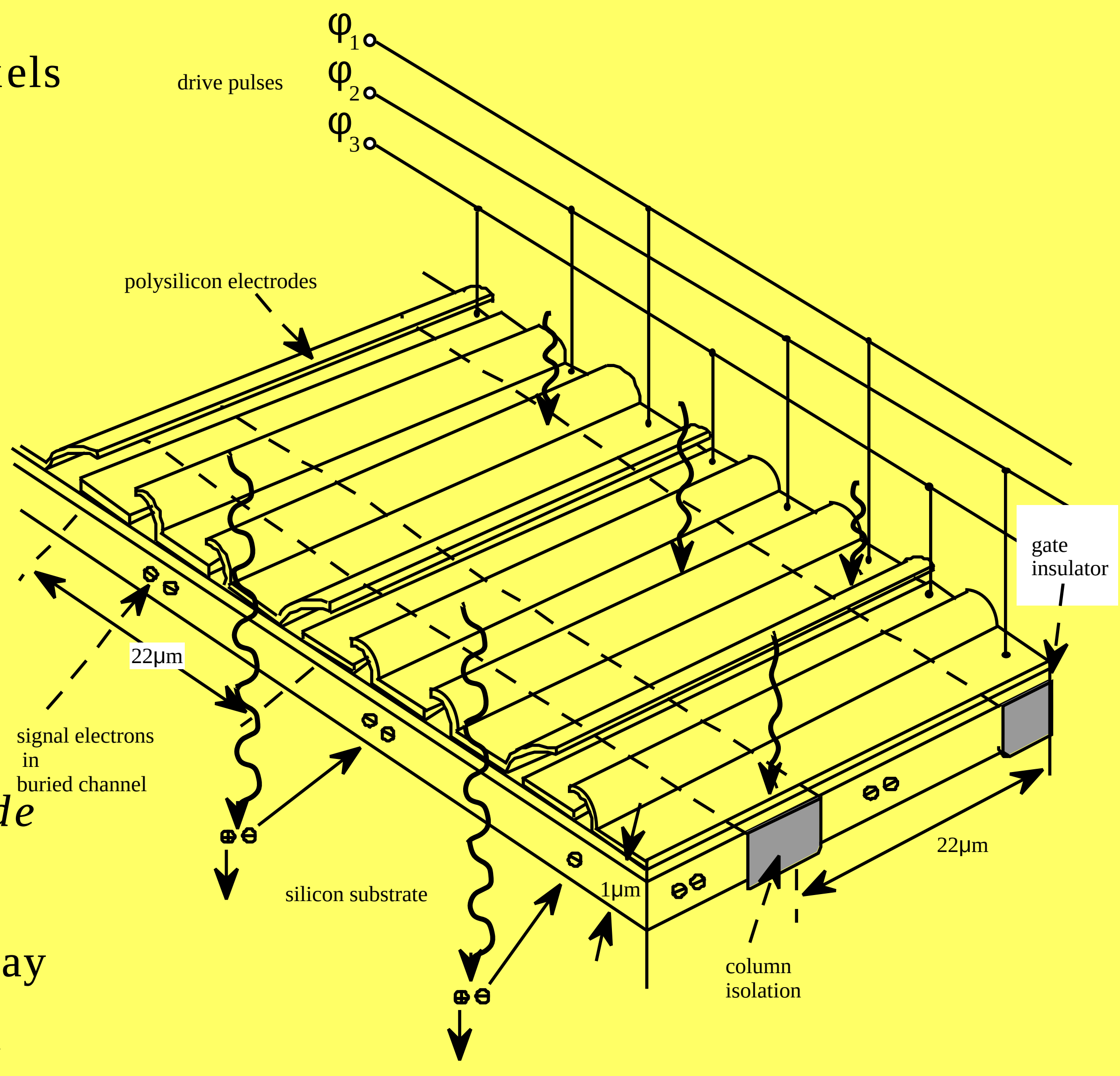






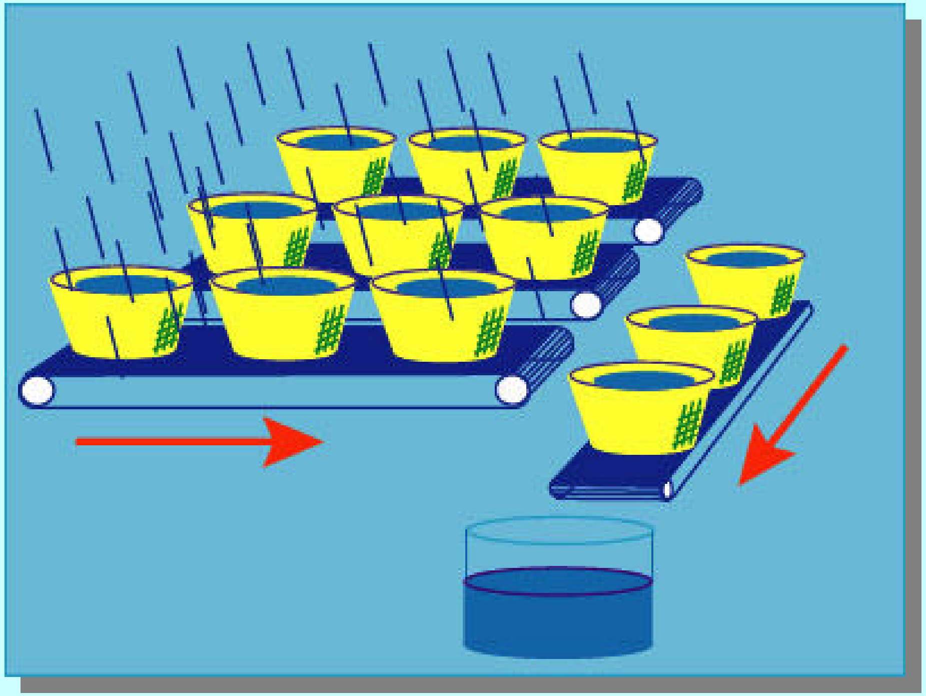
CCD - Charge Coupled Device

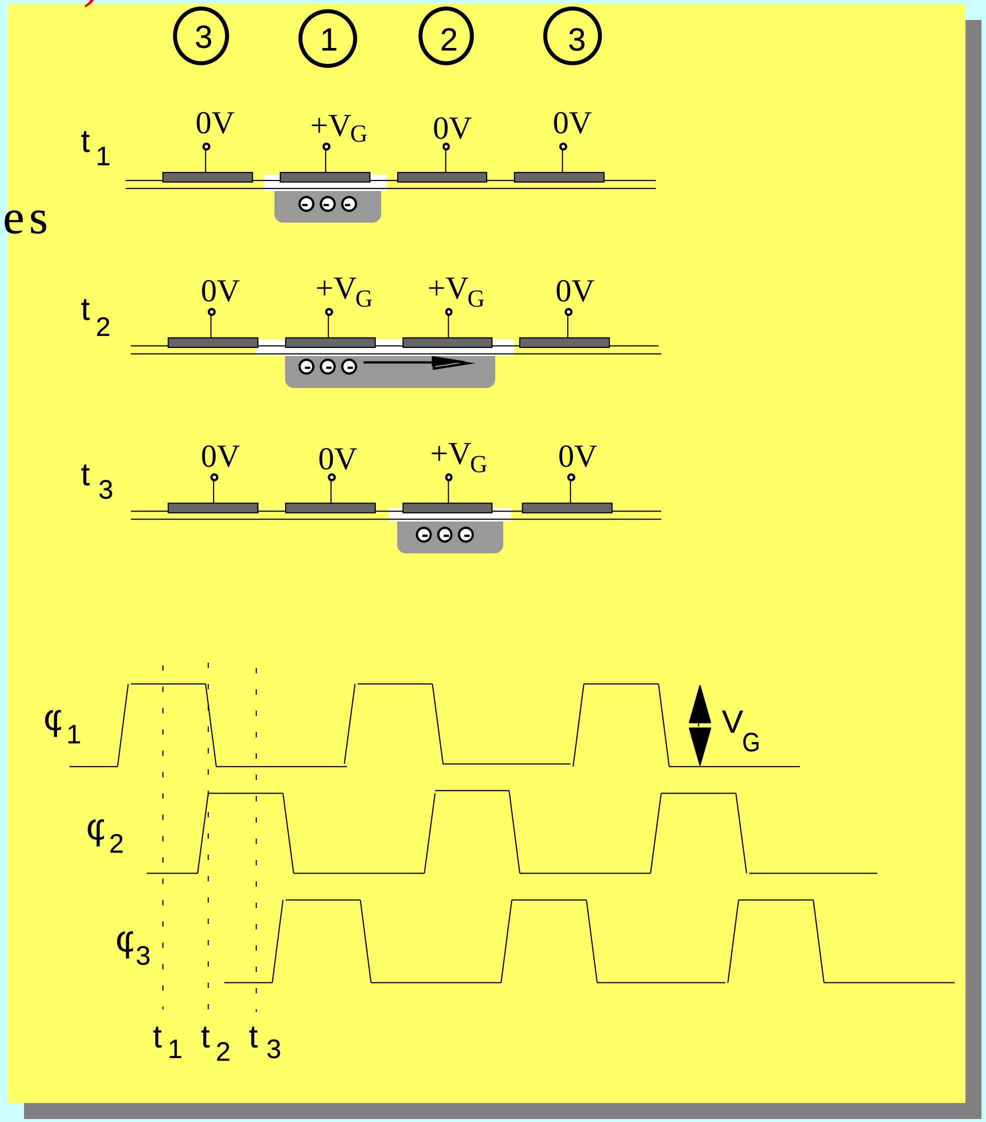
- 2-d array of MOS capacitors
  - electrode structures isolate pixels
  - allow to transfer charge
  - thin sensitive region
  - *signals depend on application*
  - *low noise, especially if cooled*
- Video requirements different to scientific imaging
  - persistent image
  - smaller area & pixels
  - Readout time long *ms-s*
  - *all pixels clocked to readout node*
- Applications
  - astronomy, particle physics, x-ray detection, digital radiography,...



CCD charge transfer

- Change voltages on pixels in regular way ("clock")
  - 3 gates per pixel
  - 3 phases per cycle
  - depletion depth in adjacent regions changes
  - E field transfers charge to next pixel
  - - finally to output register





Silicon detector radiation damage

•As with all sensors, prolonged exposure to radiation creates some permanent damage
- two main effects

Surface damage Extra positive charge collects in oxide

all ionising particles generate such damage

MOS devices - eg CCDs - are particularly prone to such damage

Microstrips - signal sharing & increased interstrip capacitance - noise

Bulk damage atomic displacement damages lattice and creates traps in band-gap

only heavy particles (p, n, π, ...) cause significant damage

increased leakage currents - increased noise

changes in substrate doping

Signals

- Signal

  generalised name for input into instrument system

- Might seem logical to consider signals before sensors but can now see

  wide range of signal types are possible

  depend on sensor

  depend on any further transformation - eg light to electrical

- Most common types of signal

  short, random pulses, usually current, amplitude carries information

  typical of radiation sensors

  trains of pulses, often current, usually binary

  typical of communication systems

  continuous, usually slowly varying, quantity - eg. current or voltage

  slow - typical of monitoring instruments

  fast - eg cable TV, radio

- terms like “slow”, “fast” are very relative!

Typical signals

- Some examples

Signal source	Duration
Inorganic scintillator	$e^{-t/\tau}$ τ ~ few µs
Organic scintillator	$e^{-t/\tau}$ τ ~ few ns
Cerenkov	~ns
Gaseous	few ns - µs
Semiconductor	~10ns
Thermistors	continuous
Thermocouple	continuous
Laser	pulse train ~ps rise time
	or short pulses ~fs

- However, we will find later that speed of signal is not always sufficient to build fast responding systems

Signal formation

- Issues in practical applications

duration

radiation: depends on transit time through sensor and details of charge induction process in external circuit

linearity

most radiation sensors characterised, or chosen for linearity

for commercial components can expect non-linearity, offset and possible saturation

reproducibility

eg. many signals are temperature dependent in magnitude - mobility of charges

other effects easily possible

ageing

sensor signals can change with time for many reasons

natural degradation of sensor, variation in operating conditions, radiation damage,...

- all these effects mean one should always be checking or calibrating measurements intended for accuracy as best one can

Optical transmitters

- **Semiconductor lasers most widely used**

  Now dominate telecomms industry

  » *Gb/s operation*

- **Principle**

  Forward biased p-n diode

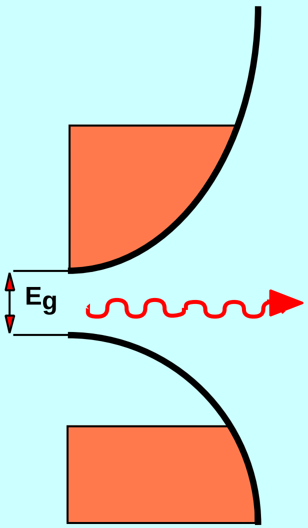
  => *population inversion*

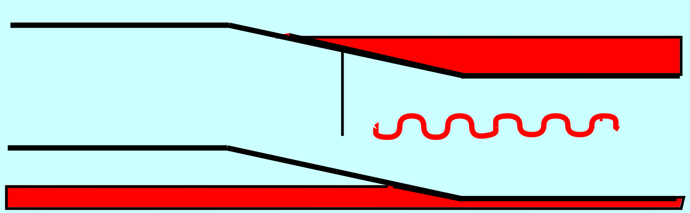
  direct band gap material

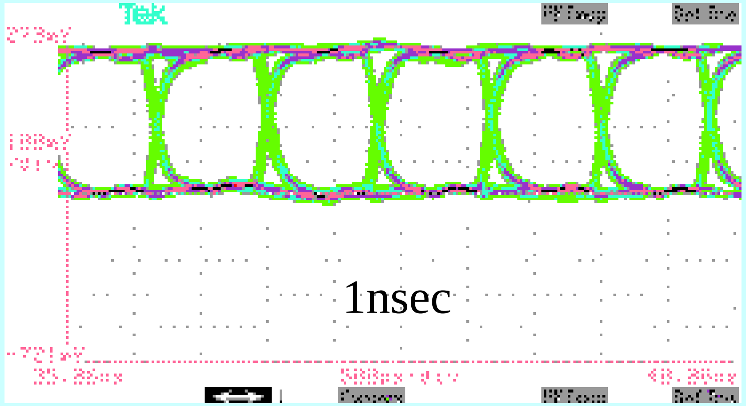
  GaAs ~850nm

  GaAlAs ~ 600-900nm

  In, Ga, As, P ~0.55-4µm







- **+ polished optical facets**

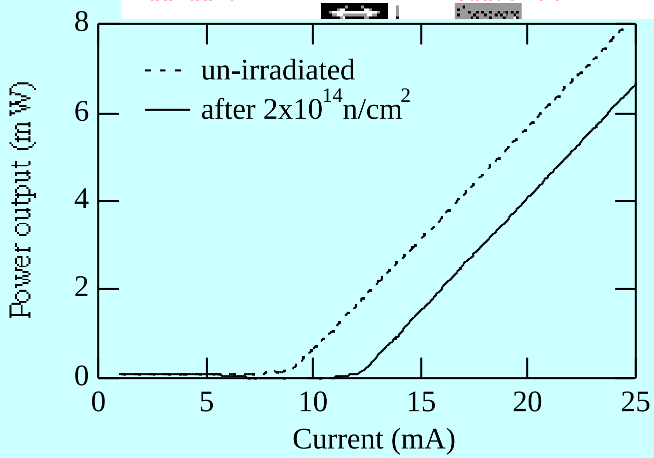
  => Fabry-Perot cavity

  optical oscillator

  lase at $I > I_{threshold}$

  photon losses from cavity or absorption

  often very linear



Modern semiconductor lasers

•Quantum well structures

confine charge carriers to active layer

refractive index difference

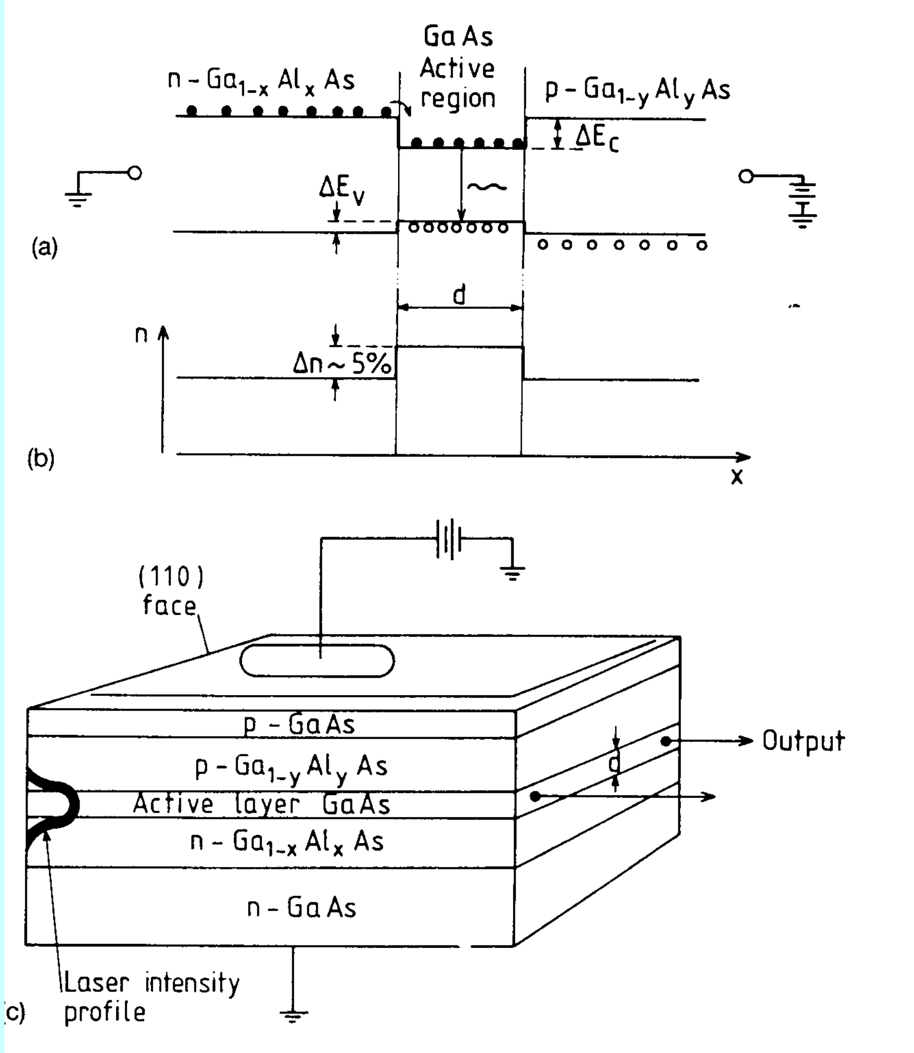
=> waveguide confines light

minimise lateral dimensions for efficiency

& low $I_{threshold}$

=>low power (~mW), miniature devices

well matched for optical fibre transmission



•VCSELs Vertical Cavity Surface Emitting Laser

emit orthogonal to surface

ultra-low power

cheap to make (test on wafer)

can be made in arrays

non-linear L-I characteristic

but very suitable for digital applications

Passage of radiation through matter

- Need to know a few elementary aspects of signal formation whether interested in light or other radiation

  How far does radiation penetrate?

  How much of incident energy is absorbed?

- Signal current - duration and magnitude

  consequence of charge carriers generated

  electrons + holes (semiconductor) or ions (gases, liquids)

  current duration depends on

  distance over which charge deposited

  rapid absorption or thin sensor give fast signals

  electric field

  only charges in motion generate currents

  current in external circuit is **induced**

Light

- $I \sim I_0 \exp(-L/L_{abs})$

  $1/L_{abs} = N_{atom}\sigma$ $N_{atom} = \rho N_{Avogadro}/A$ = no. atoms per unit volume

- Photoabsorption

  E ~ eV- 100keV atom ionised in single process, all photon energy transferred

  at low energies depends on atomic properties of material

  at higher energies $\sigma_{pa} \sim Z^{4\text{-}5}/E_\gamma^3$ above K-shell edge

- Compton scattering

  ~MeV quantum collision of photon with charged particle, usually e^-

  transfer of part of photon energy, often small

- Pair production

  >> MeV

  all energy transferred to e+e- pair

  to conserve momentum and energy, needs recoil

  must take place in field of nucleus or electron

Light absorption-

•Low energies

see consequence of atomic behaviour

eg silicon bandgap

NB strong dependence on wavelength in near-visible regions

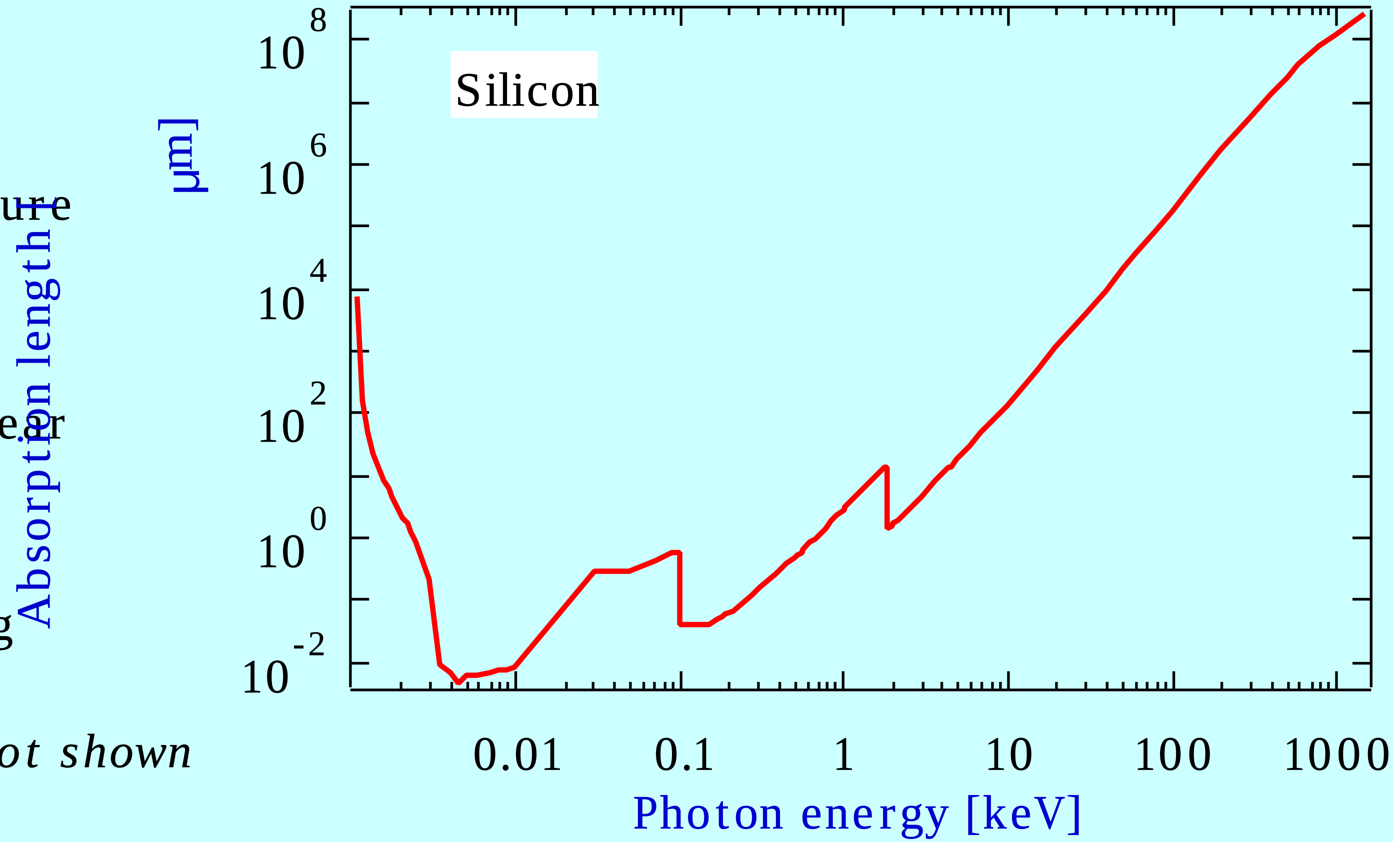
•High energies

atomic shell structure visible

then electrons appear as quasi-free

Compton scattering starts to dominate

at ~60keV - not shown



Light absorption

•Far UV to x-ray energies

atomic shell structure

photo-absorption

coherent = Rayleigh scattering

atom neither ionised nor nor excited

incoherent = Compton

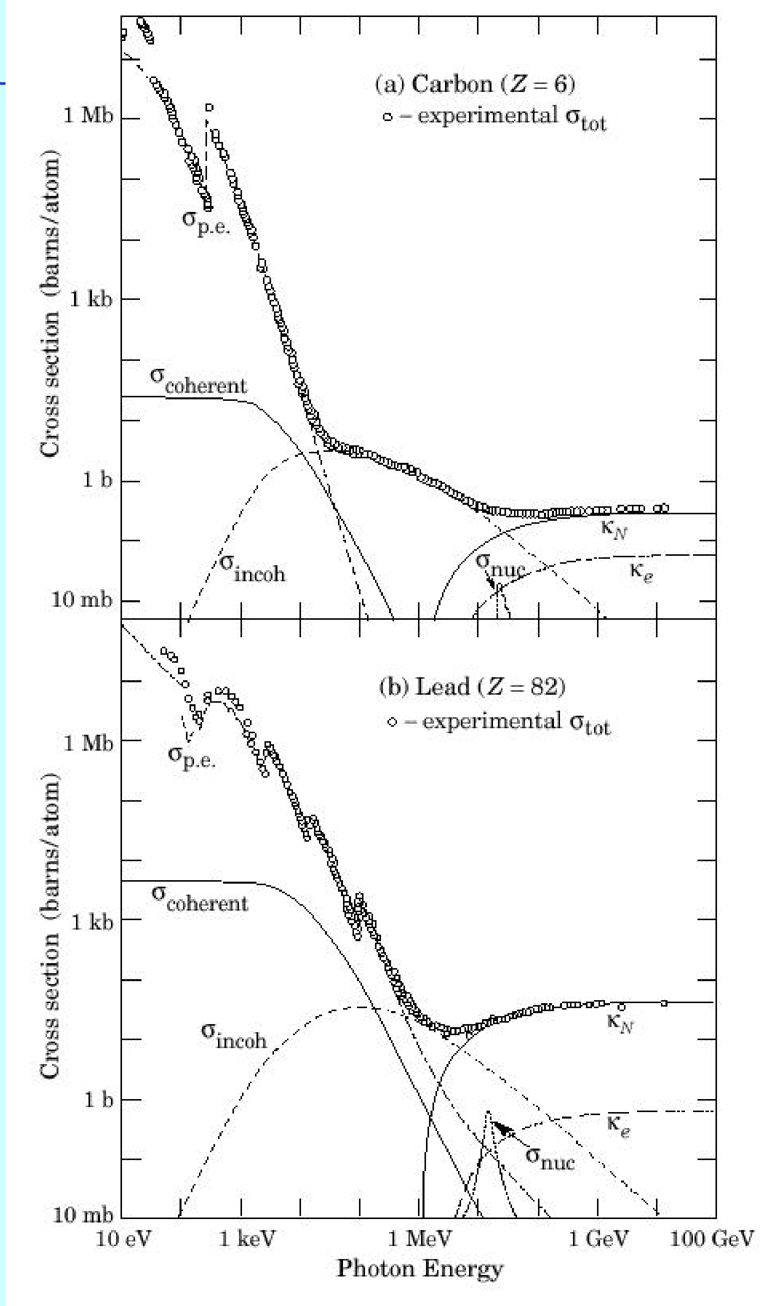
$\sigma = Zf(E_\gamma)$

pair production $E_\gamma > 2m_e$

contributions from nucleus (~Z^2)

and atomic electrons (~Z)

small contribution from nuclear interactions



Charged particles

•Ionisation dominates   Units: x = density x thickness = [g.cm^{-2}]

Stopping power = dE/dx   scales in similar way for all particles with p/m = βγ

dominated by interactions with atomic electrons

•low energies

slow particles lose energy rapidly

dE/dx increases with β to maximum

Bragg peak

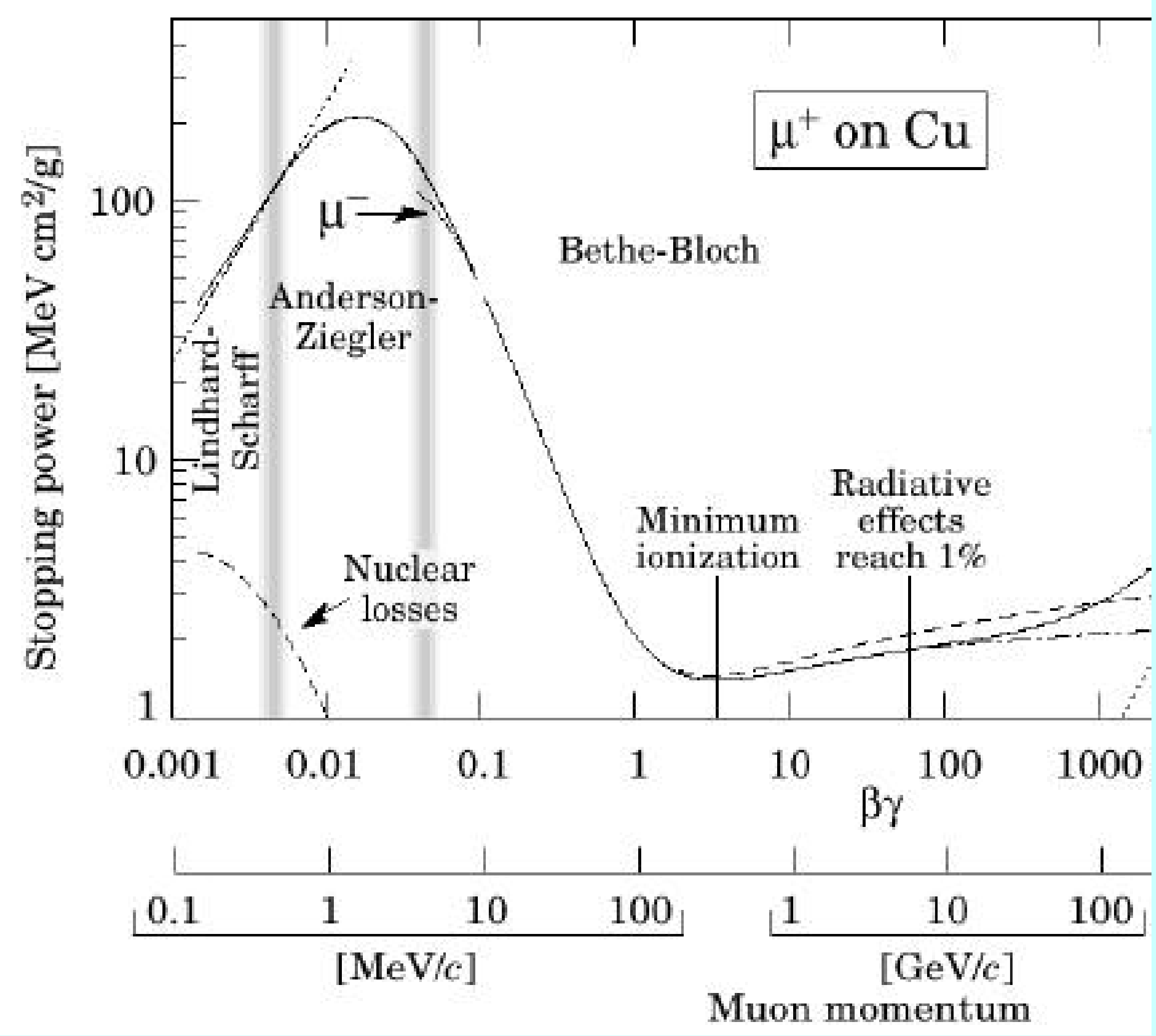
•relativistic energies

decline ~ 1/β^2

to minimum value

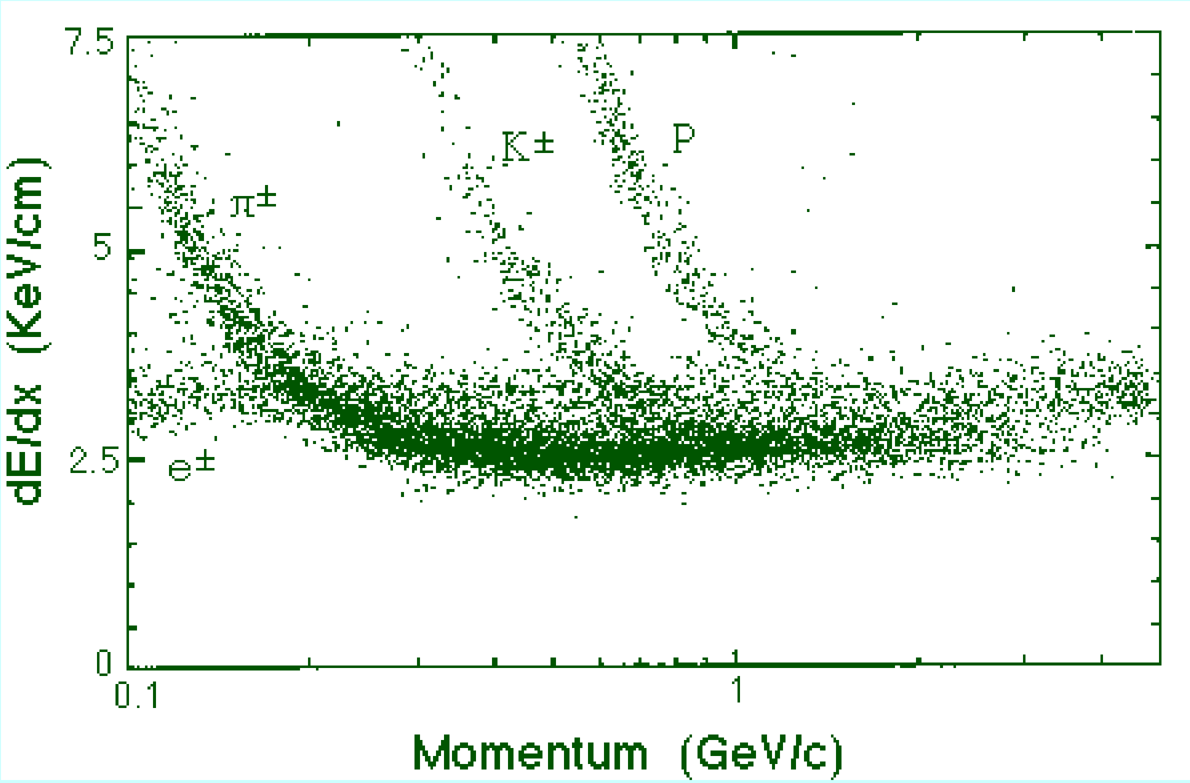
further slow rise ~ log(p/m)

•most cosmic rays and high energy particles approximately MIPs



dE/dx

- Measured energy loss can provide another way of identifying particles
  - gas detectors with multiple samples of ΔE from same particle
  - momentum measurement is needed - from bending in B field
  - accompanied by good calibration of p and dE/dx



Electrons

- are special because of their low mass

    classically accelerated charge radiates

- brehmstrahlung radiation in matter

    acceleration in nuclear field

- synchrotron radiation in accelerators

    generates beams of low energy x-rays

    typical E ~ 1-10keV

    widely used for studying atomic properties, eg protein crystallography

Other neutral particles

- neutrons

  do not generate ionisation directly so hard to measure

- at low energies

  mostly elastic collisions with atoms in material

  simple kinematics determines energy transfer

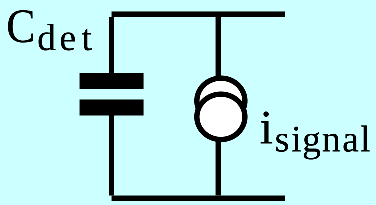
$$\Delta T_{max} = 4AT_{inc}/(1+A)^2$$

  low Z materials favoured to absorb neutron energy

  C, D_2O moderators in nuclear reactors

  hydrogenous or boron compounds used as detectors

Sensor equivalent circuits



- Many of the sensors considered so far can be modelled as

  current source + associated capacitance

  typical values ~ few pF

  but can range from

  ~100fF semiconductor pixel

  ~10-20pF gas or Si microstrip, PM anode

  ~100pF large area diode

  ~µF wire chamber

  usually there is some resistance associated with the sensor, eg leads or metallisation but this has little effect on signal formation or amplification

- Notable exception: microstrips - gas or silicon

  the capacitance is distributed, along with the strip resistance

  forms a dissipative transmission line