Semiconductor sensors

- Semiconductors widely used for charged particle and photon detection

  based on ionisation - same principles for all types of radiation

- What determines choice of material for sensor?

  Silicon and III-V materials widely used

  - physical properties
  - availability
  - ease of use
  - cost

- silicon technology is very mature

  high quality crystal material

  relatively low cost

  but physical properties do not permit it to be used for all applications

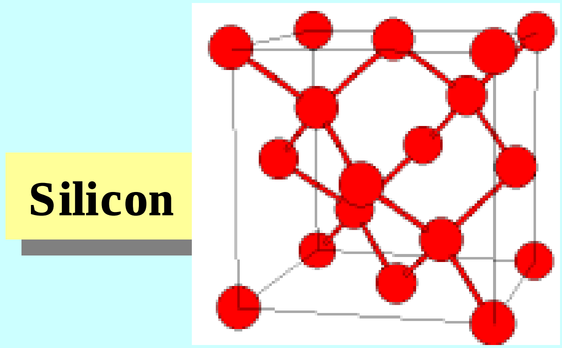
Semiconductor fundamentals reminder

•Crystalline

lattice symmetry is essential

atomic shells => electron energy bands

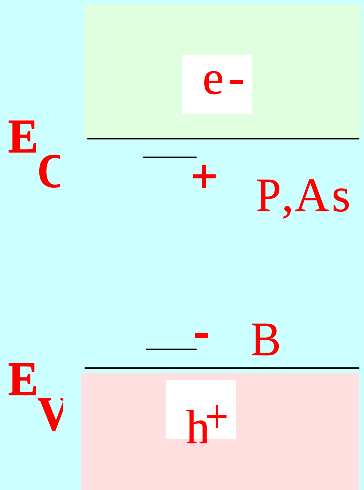
energy gap between valence and conduction bands



•Dope material with nearby valence atoms

donor atoms => n-type *excess mobile electrons*

acceptor atoms => p-type *holes*



•Dopants provide shallow doping levels

normally ionised at ~300K

conduction band occupied at room temp

NB strong T dependence

•Two basic devices

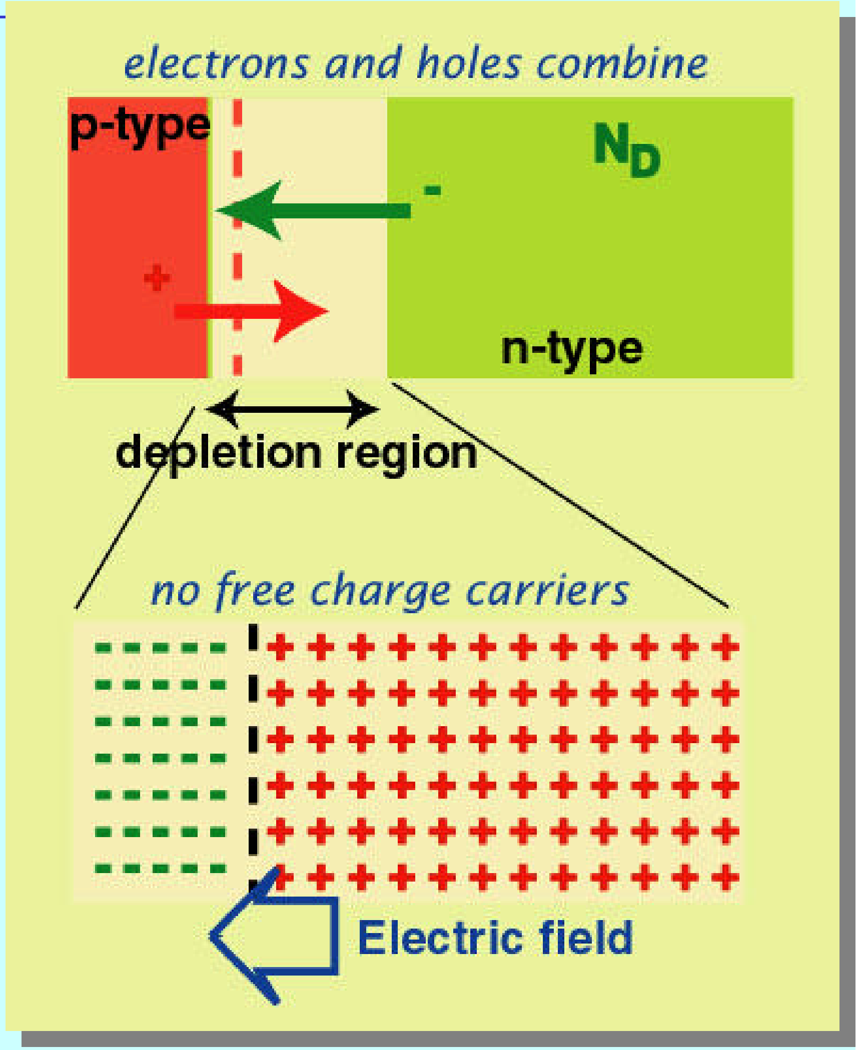
p-n diode

MOS capacitor

basis of most sensors and transistors

p-n diode operation

- imagine doped regions brought into contact
- establish region with no mobile carriers
  - built-in voltage
  - electric field
    - *maximum near junction*



- forward bias
  - overcome built-in voltage
  - current conduction

$$I \sim I_0[\exp(qV/kT) - 1]$$

- increase external reverse bias
  - increase field
  - increase depletion region size
  - reduce capacitance ≈ εA/d
  - small current flow

sensor operation

Requirements on diodes for sensors

- Operate with reverse bias

  should be able to sustain reasonable voltage

  larger E (V) = shorter charge collection time

- Dark (leakage) current should be low

  noise source

  ohmic current = power

- Capacitance should be small

  noise from amplification ~ C

  defined by geometry, permittivity and thickness

  circuit response time ~ [R] x C

- Photodetection

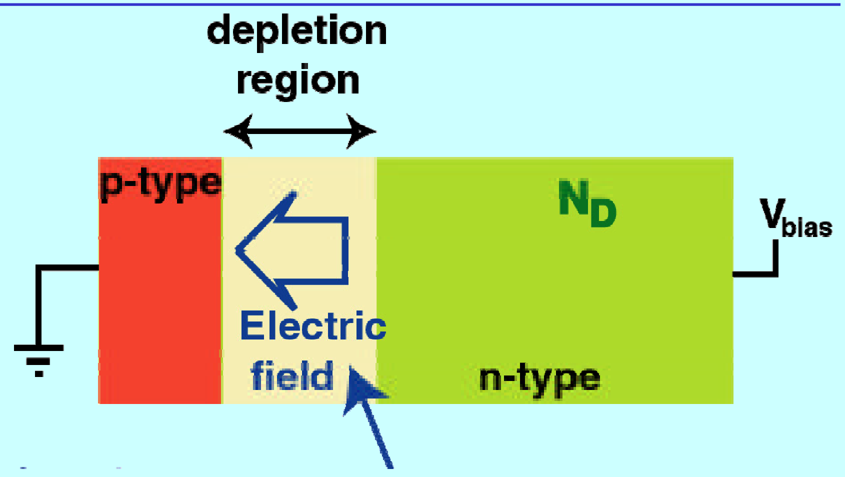
  thin detector: high E but high C unless small area

- X-ray and charged particle detection

  "thick" detectors required for many applications

  efficiency for x-rays

  larger signals for energetic charged particles



dielectric between conducting regions

commercial packaged photodiodes

Diode types

- Variety of manufacturing techniques

  depends on application & material

- Diffused & Ion implanted

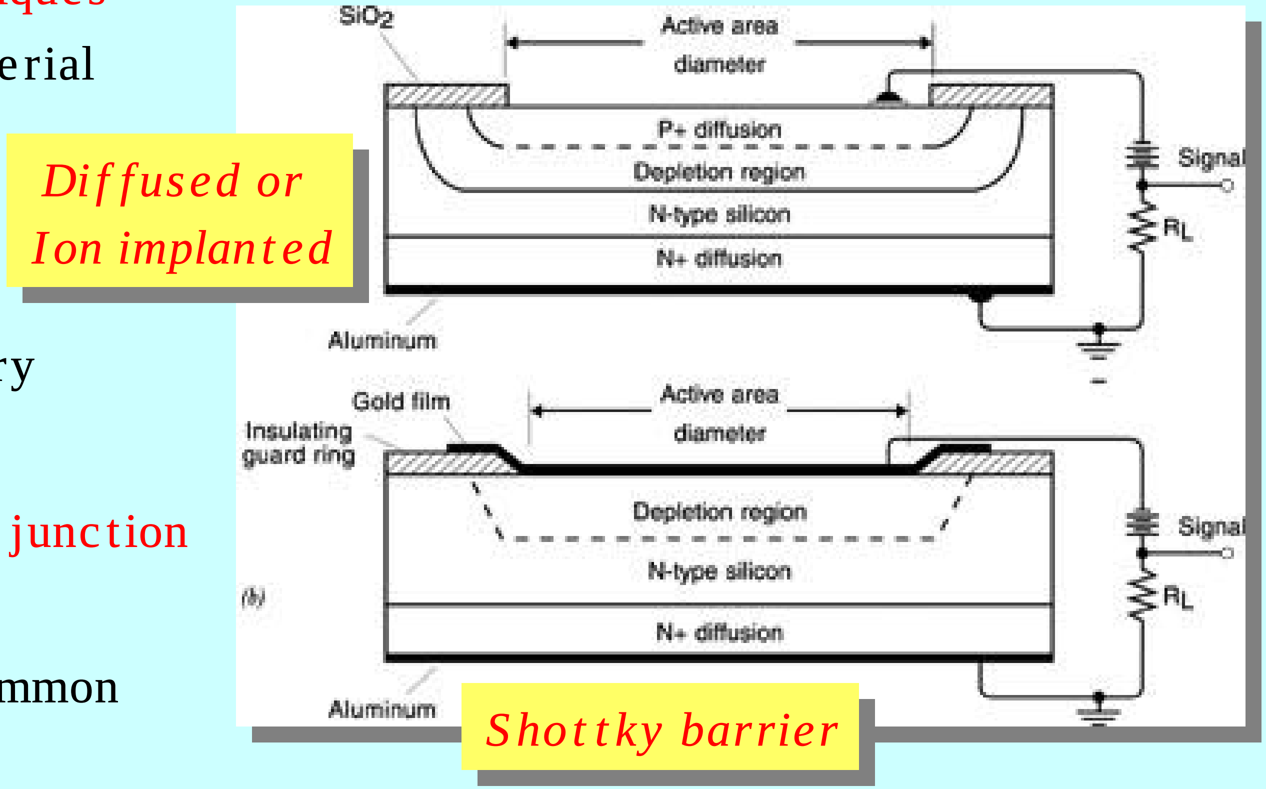
  oxide window

  robust, flexible geometry

- Shottky barrier - metal-silicon junction

  thin metal contact

  more fragile and less common



- III-V

  epitaxial = material grown layer by layer

  limits size, but essential for some modern applications

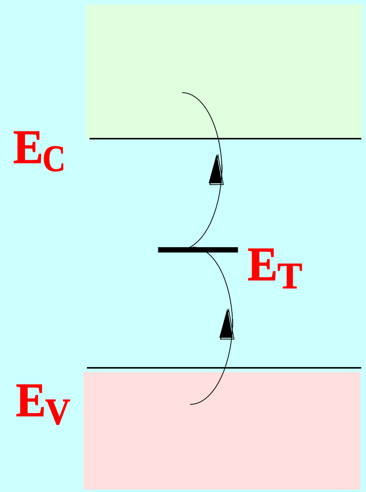
Real p-n diode under reverse bias

- Dark (leakage) current

  electrons & holes cross band-gap

  diffusion from undepleted region

  thermal generation--recombination



- Magnitude depends on...

  temperature (and energy gap) ~ $\exp(-\alpha E_{gap}/kT)$

  position of levels in band gap

  density of traps

  ease of emission and capture to bands

  availability of carriers & empty states

- Mid-gap states are worst

  avoid certain materials in processing

  structural defects may arise in crystal growth

Sensor materials

Property	Si	Ge	GaAs	SiO_2
Z	14	32	31/33	
Band gap [eV]	1.12	0.66	1.42	9
Energy to create e-h pair [eV]	3.55	2.85	4.1	17
Density [$g.cm^{-3}$]	2.33	5.33	5.32	2.2
Permittivity [pF/cm]	1.05	1.42	1.16	0.35
Electron mobility [$cm^2.V^{-1}.s^{-1}$]	1450	3900	8500	~20
Hole mobility [$cm^2.V^{-1}.s^{-1}$]	450	1900	400	10^{-4}-10^{-6}
Intrinsic resistivity [Ω.cm]	2.3 10^5	47	10^8	
Average MIP signal [e/µm]	110	260	173	20
Average MIP dE/dx [$MeV/g.cm^{-2}$]	1.66	1.40	1.45	1.72
MIP = minimum ionising particle				

- mobility $\underline{v} = \mu \underline{E}$

mobilities for linear region. At high E v saturates: ~ 10^5 $m.s^{-1}$

Silicon as a particle detector

- Signal sizes

  typical H.E. particle ~ 25000 e 300μm Si

  10keV x-ray photon ~ 2800e

- no in-built amplification

  E < field for impact ionisation

Ge	large crystals possible higher Z must cool for low noise
GaAs	less good material - electronic grade crystals less good charge collection

- Voltage required to deplete entire wafer thickness

  $V_{depletion} \approx (q/2\varepsilon)N_D d^2$ N_D = substrate doping concentration

  $N_D \approx 10^{12}$ cm^{-3} => $\rho = (q\mu N_D)^{-1} \approx 4.5$kΩ.cm

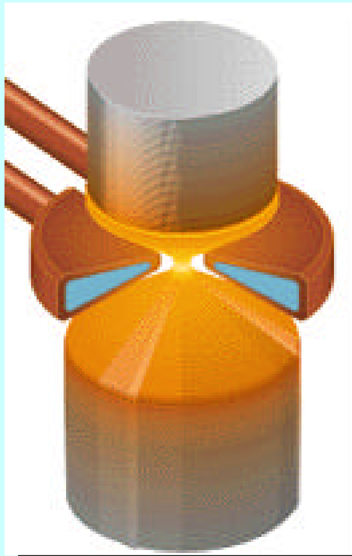
  $V_{depletion} \approx 70$V for 300μm

- electronic grade silicon $N_D > 10^{15}$ cm^{-3}

  $N_D = 10^{12} : N_{Si}$ ~ $1 : 10^{13}$ *ultra high purity !*

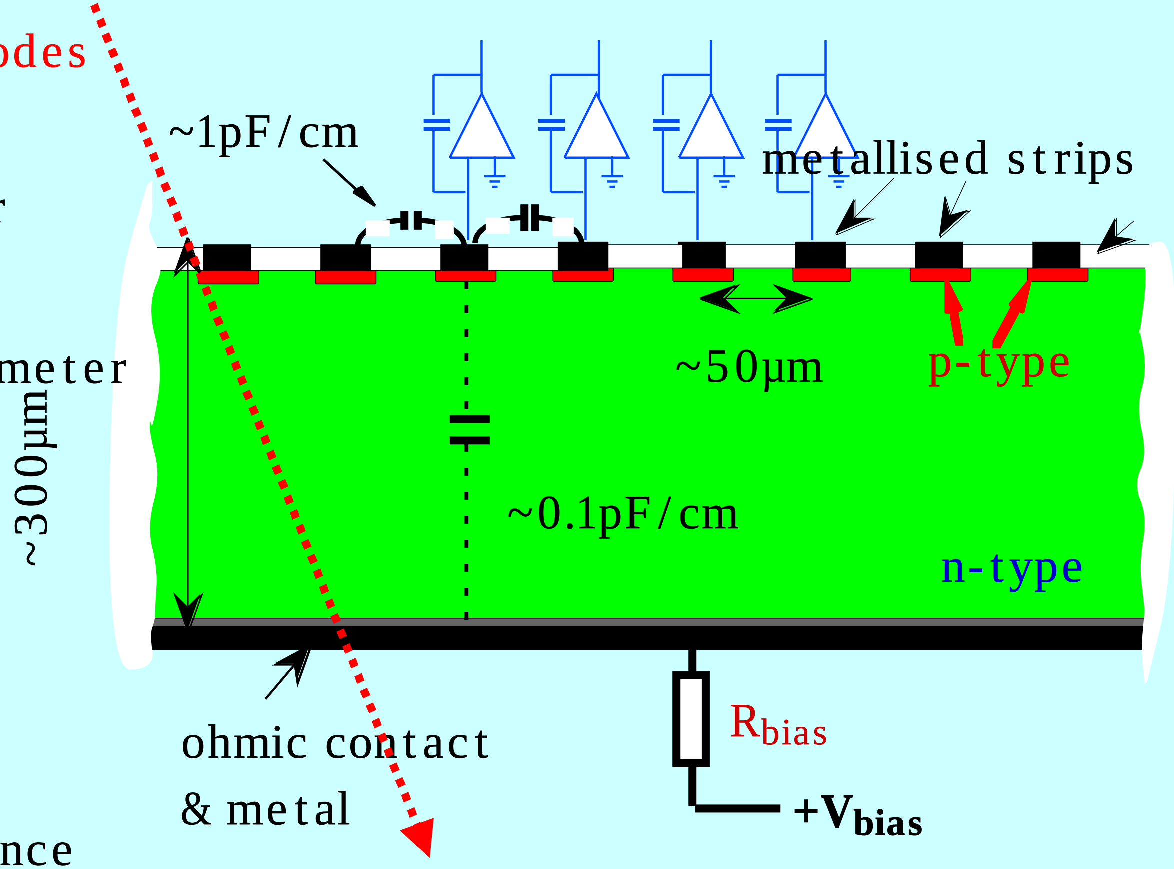
  further refining required

  Float Zone method: local crystal melting with RF heating coil



Silicon microstrip detectors

- Segment p-junction into narrow diodes
  - E field orthogonal to surface
  - each strip independent detector
- Detector size
  - limited by wafer size < 15cm diameter
- Signal speed
  - <E> ≥ 100V/300µm
  - p-type strips collect holes
  - $v_{hole} \approx 15$ µm/ns
- Connect amplifier to each strip
  - can also use inter-strip capacitance
  - & reduce number of amplifiers to share charge over strips
- Spatial measurement precision
  - defined by strip dimensions and readout method
  - ultimately limited by charge diffusion $\sigma \sim$ 5-10µm



Applications of silicon diodes

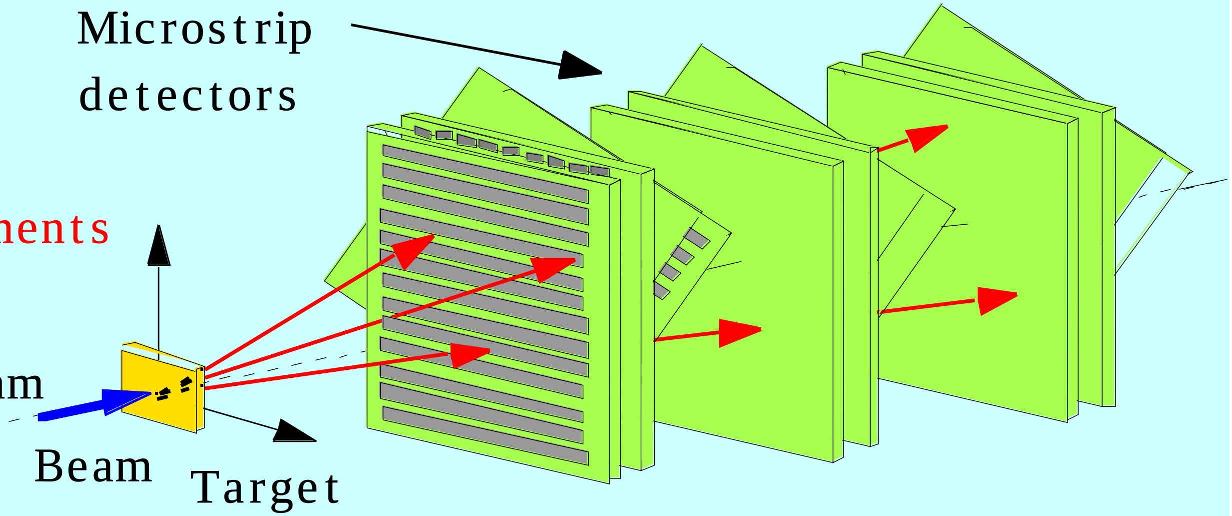
- Microstrips heavily used in particle physics experiments

    excellent spatial resolution

    high efficiency

    robust & affordable

    magnetic effects small



- Telescopes in fixed target experiments

    - or satellites

    cylindrical layers in colliding beam

- x-ray detection

    segmented arrays for synchrotron radiation

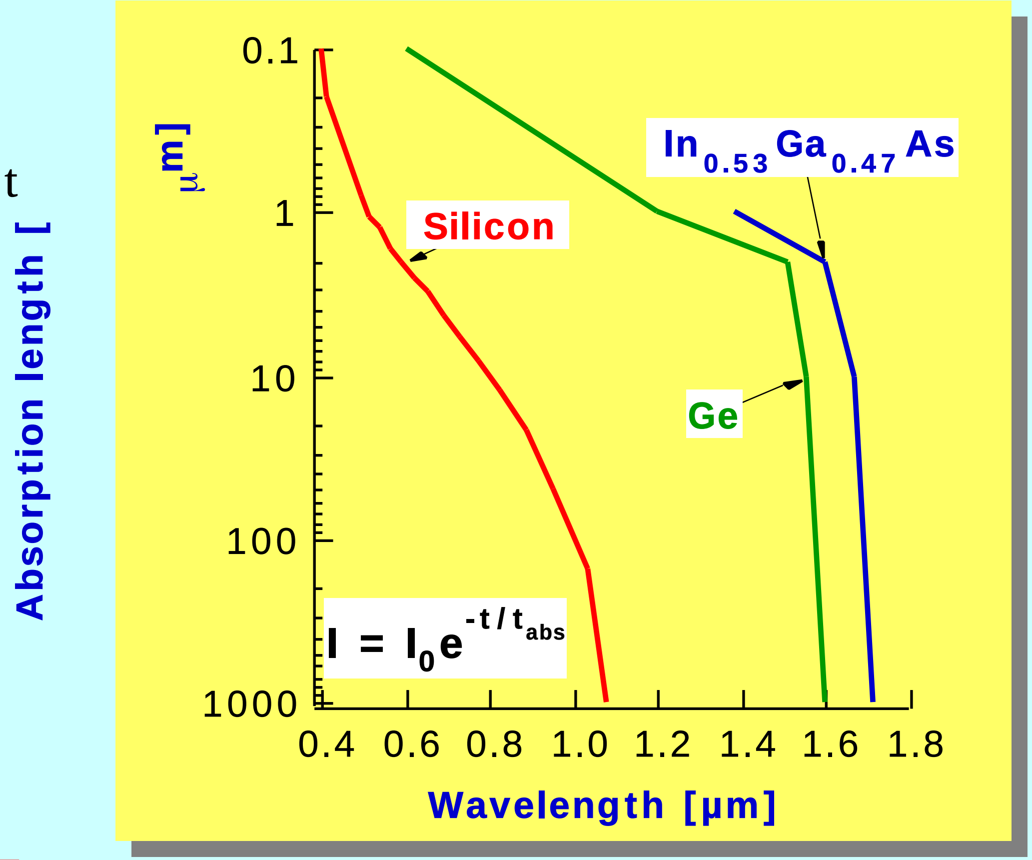
    pixellated sensors beginning to be used

- Photodiodes for scintillation light detection

    cheap, robust, compact size, insensitive to magnetic field

Photodetection in semiconductors

- For maximum sensitivity require
  - minimal inactive layer
  - short photo-absorption length
    - strongly λ and material dependent
- Silicon ($E_{gap} \approx 1.1eV$)
  - infra-red to x-ray wavelengths
    - other materials required for λ > 1μm
- III-V materials
  - GaAs, InP λ < 0.9μm
  - GaP λ < 0.6μm
- Engineered III-V materials, Ge - larger E_{gap}
  - telecommunications optical links at 1.3μm & 1.55μm
  - + short distance optical links ~0.85μm



Photodiode spectral response

- Units QE (η) or Responsivity (A/W)

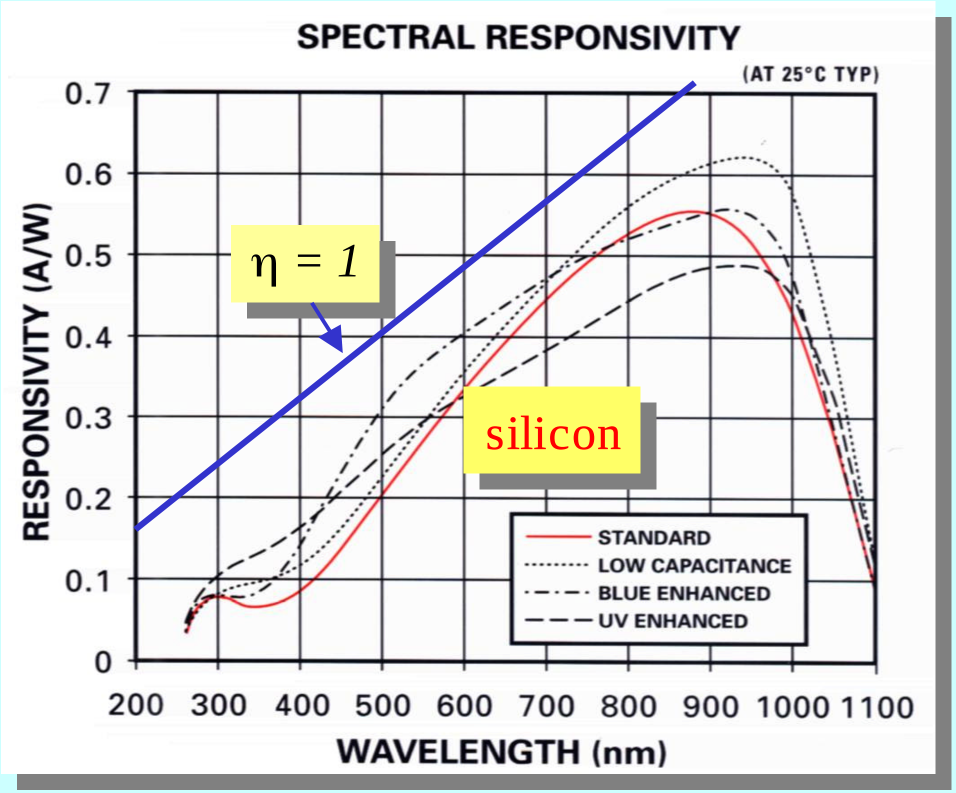
  $P = N_\gamma . E_\gamma / \Delta t$

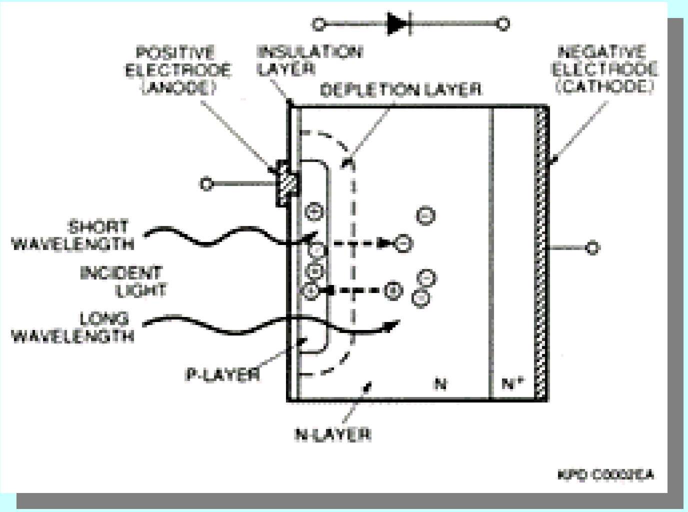
  $I = \eta . N_\gamma . q_e / \Delta t$

  $R = \eta . q_e . \lambda / hc \approx 0.8 \, \eta \, \lambda[\mu m]$

- silicon QE ~ 100% over broad spectral range

- windows and surface layers also absorb





Heterojunction photodiodes

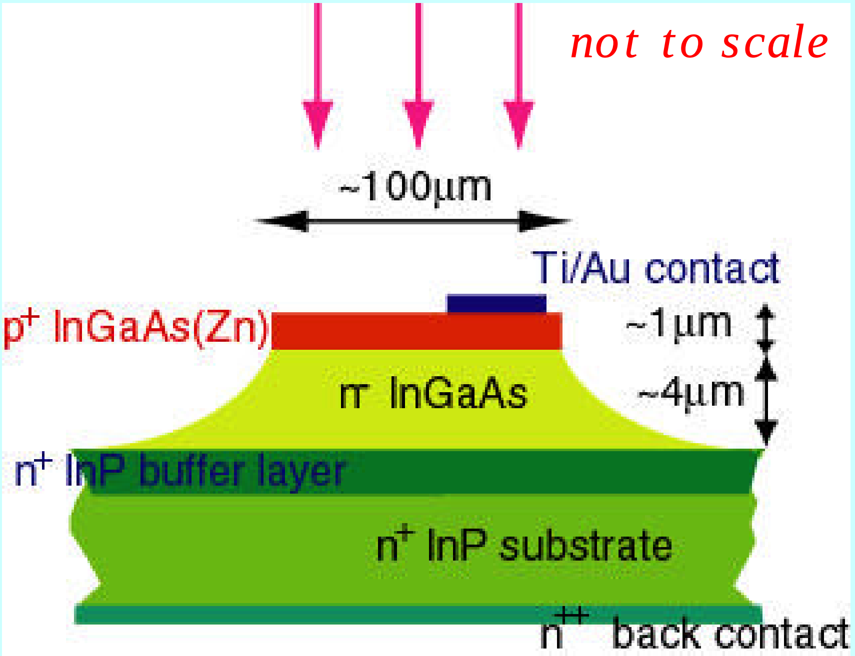
•For infra-red wavelengths, special materials developed

•drawbacks of p-n structure

thin, heavily doped surface layer

carrier recombination

=> *lower quantum efficiency*



•heterojunction

wider band gap in surface layer

minimise absorption

most absorption in sub-surface

narrower band-gap material

higher electric field

illumination through InP substrate also possible for long λ

mesa etching minimises area

Avalanche photodiodes

•p-n diode

Electric field is maximum at junction

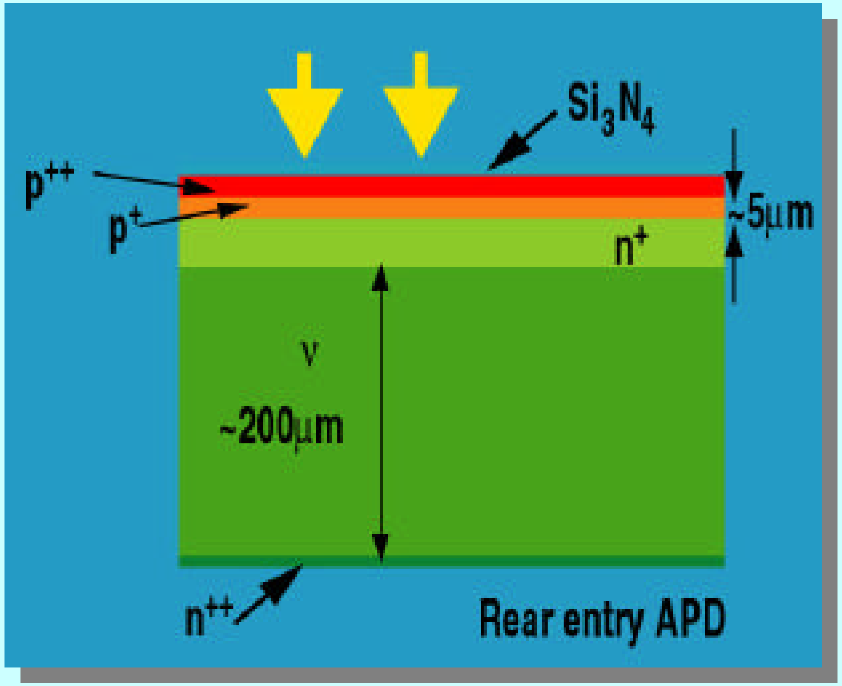
but below threshold for impact ionisation

$E_{max} \approx 2V/d \sim kV/cm$

•APD *tailor field profile by doping*

Detailed design depends on λ (*i.e. absorption)*

much higher E fields possible



•Pro

gain - valuable for small signals

fast response because high E field

•Con

Risk of instability

amplify dark current & noise

edge effects - breakdown in high field regions

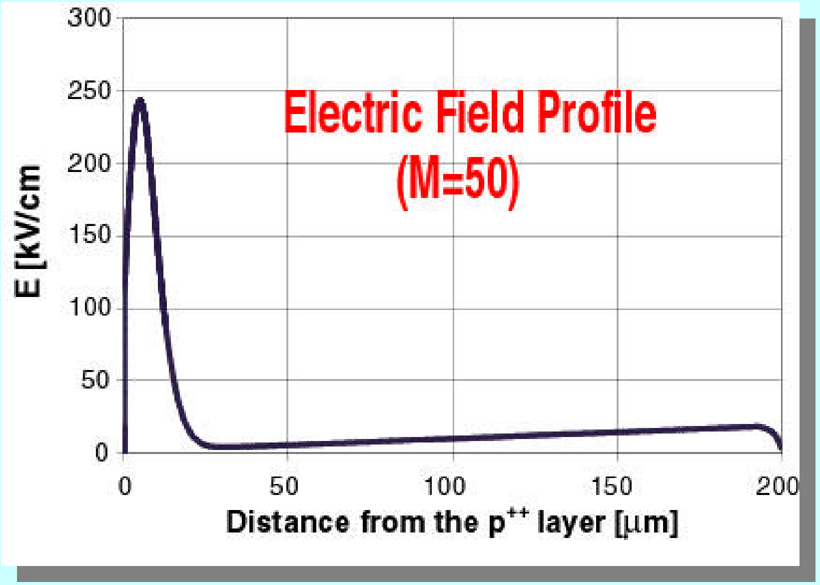
APD characteristics

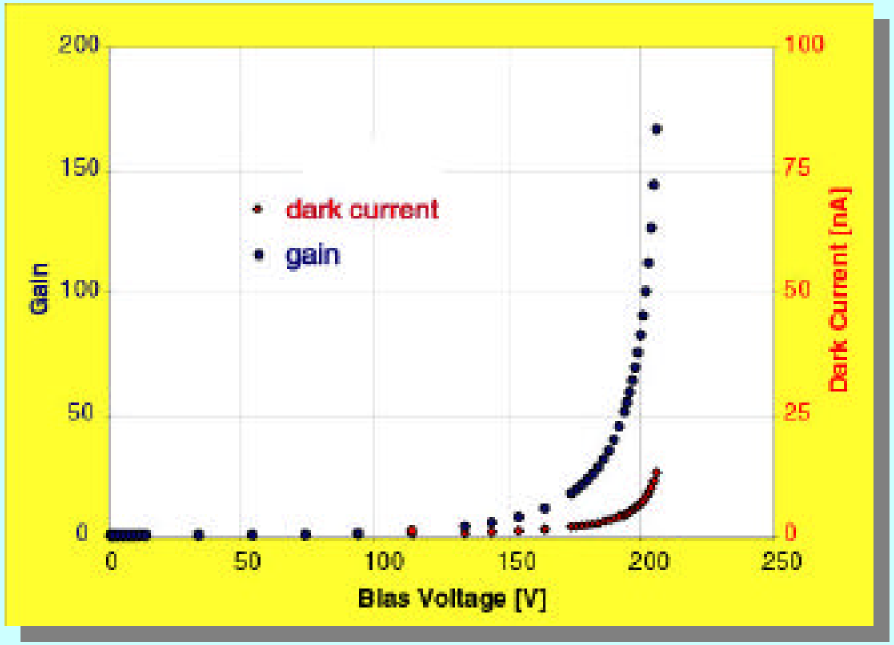
•This (example) design optimised for short wavelength

$\lambda \sim 400$nm *short absorption length*

for infra-ref wavelengths *-longer absorption length*

so entry from ohmic contact surface to maximise absorption





MIS capacitor

- Elementary device

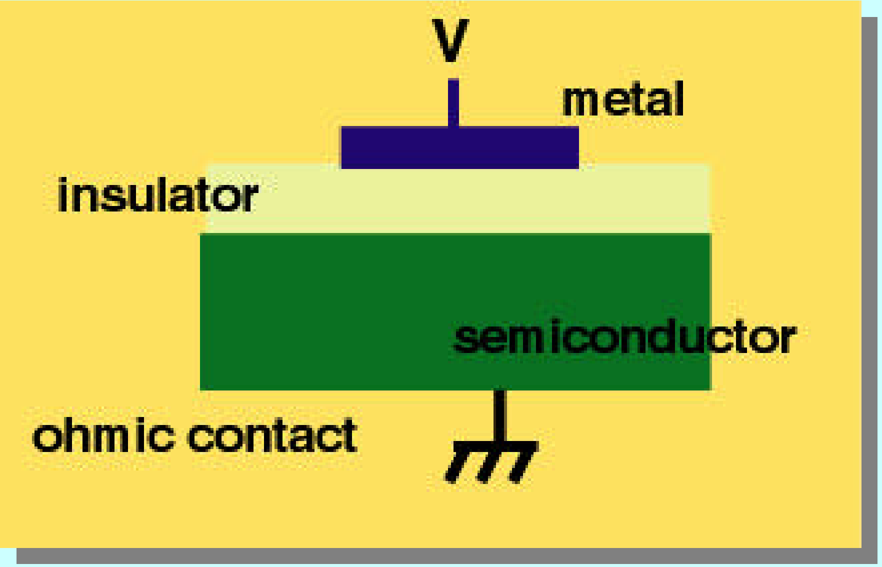
oxide well matched to silicon

transparent to wide λ range

excellent insulator

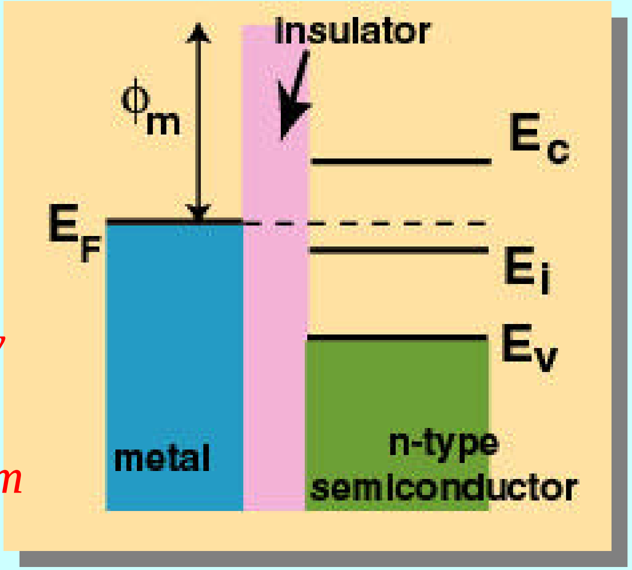
nitride frequently used in addition

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}

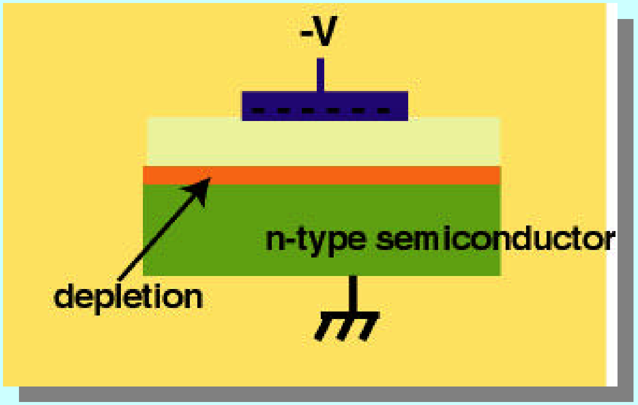
Energy band diagram

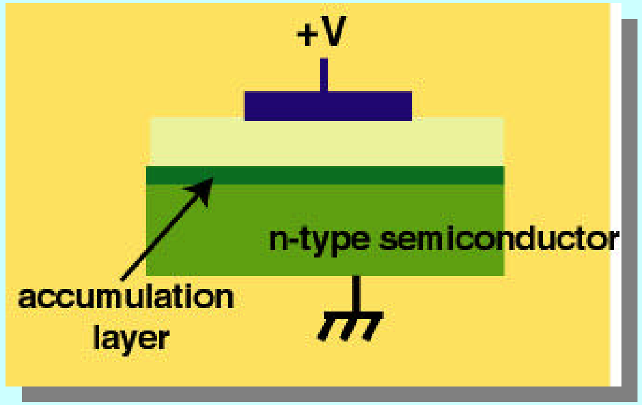


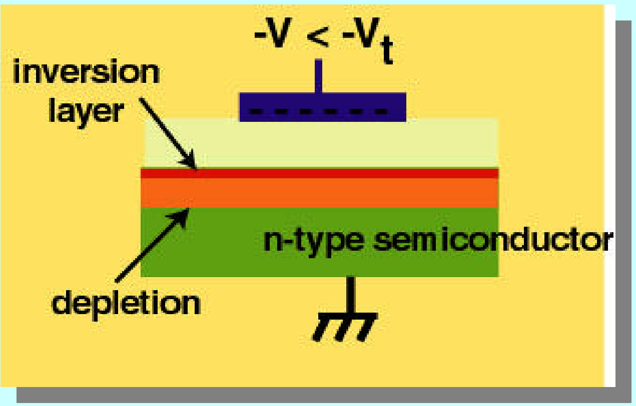
MOS capacitor characteristics

- 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

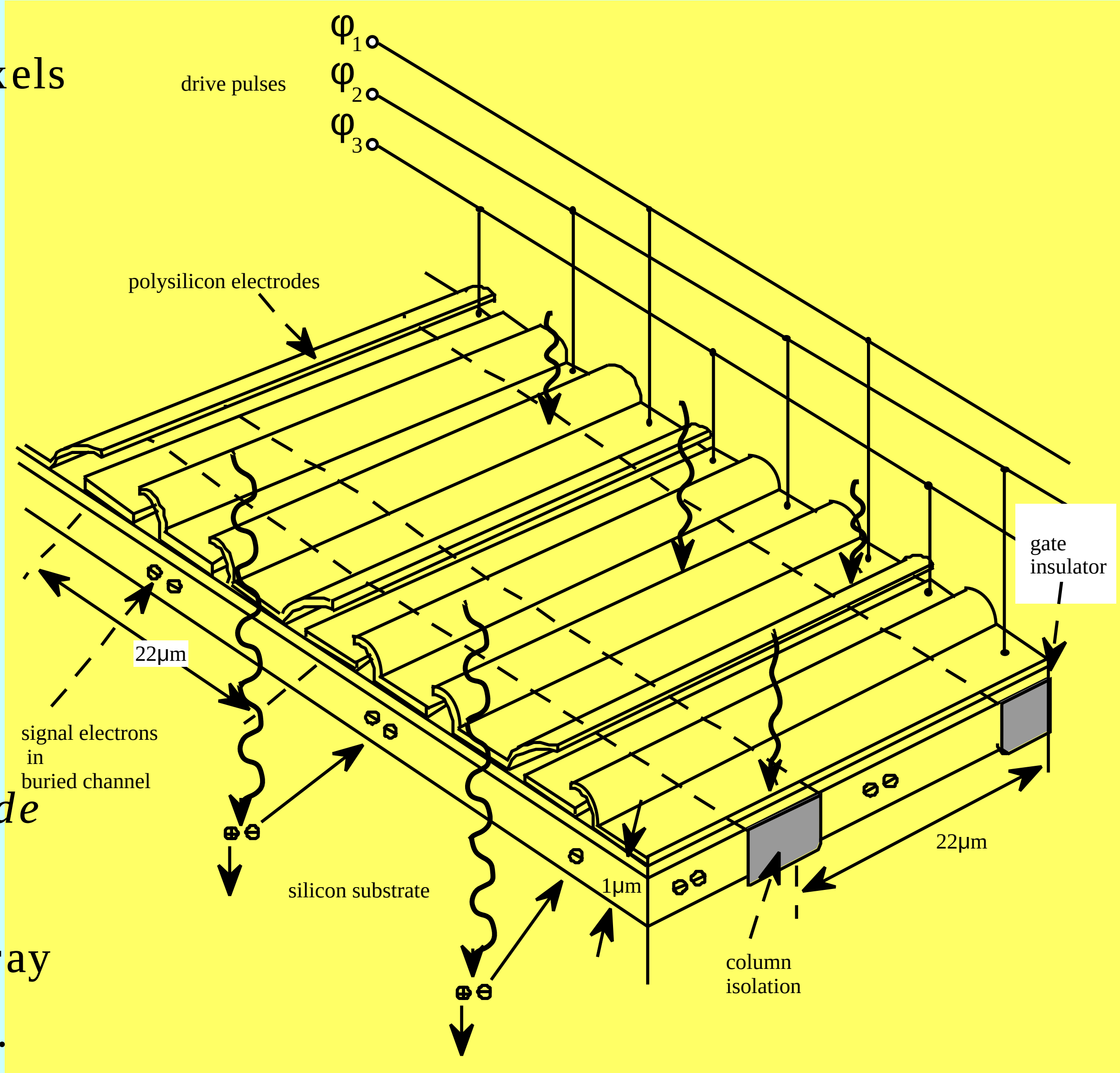






CCD - Charge Coupled Device

- 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")

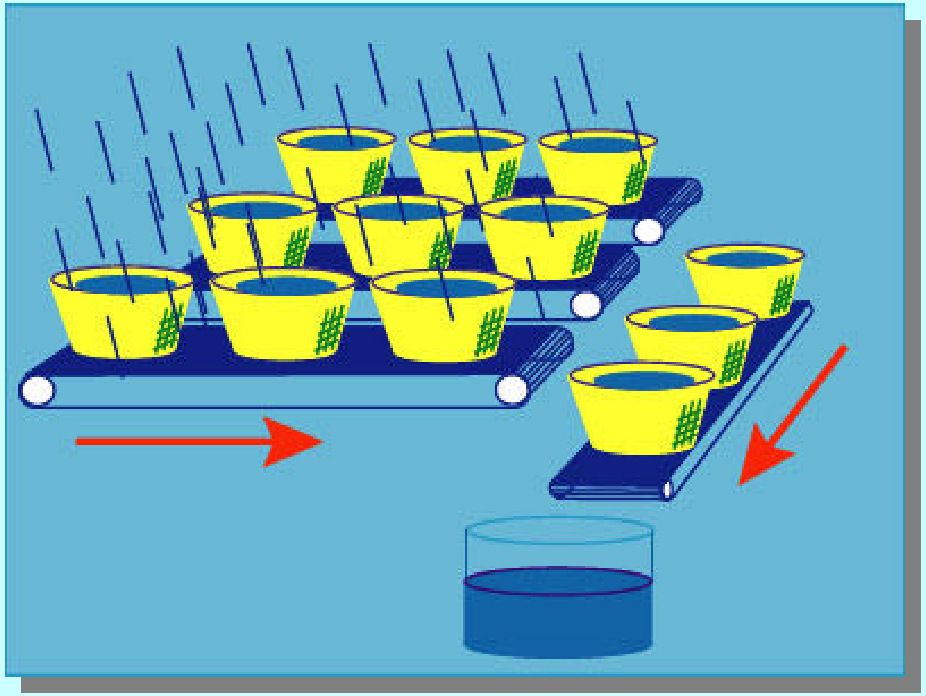
  3 gates per pixel

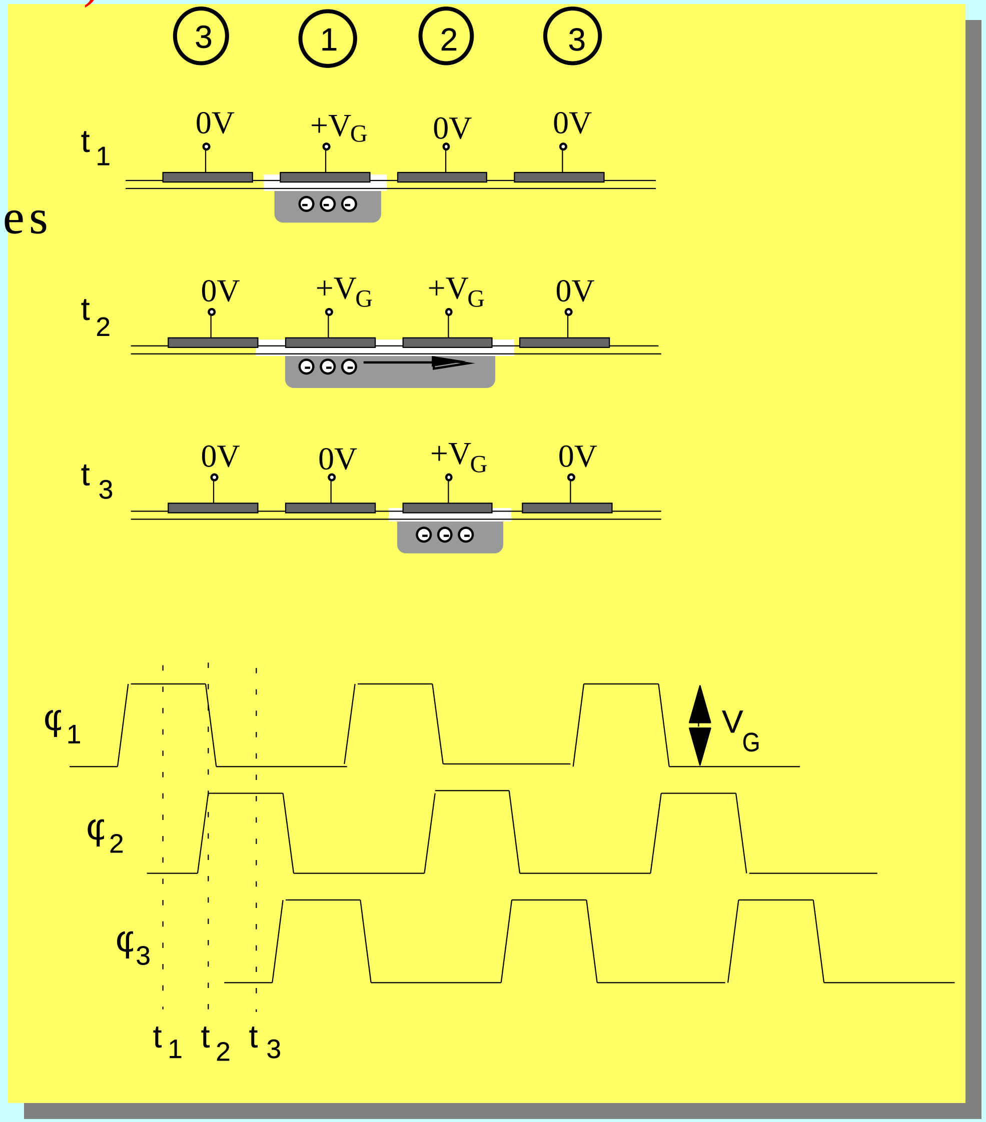
  3 phases per cycle

  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