Semiconductor sensors

These are now some of the most important detectors in particle physics, being widely used for tracking systems and for light sensing in calorimetry for example.

This is an introduction to the main properties and features only

Semiconductor sensors

- Semiconductors widely used for charged particle and photon detection

based on ionisation - same principles for all types of radiation

- Sensor material – silicon mainly - III-V materials also 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

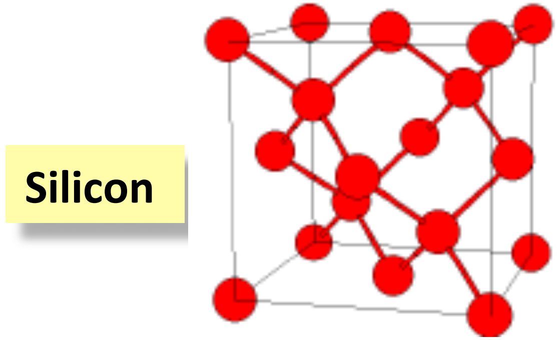
Semiconductor fundamentals reminder

- Crystalline

lattice symmetry is essential

atomic shells => electron energy bands

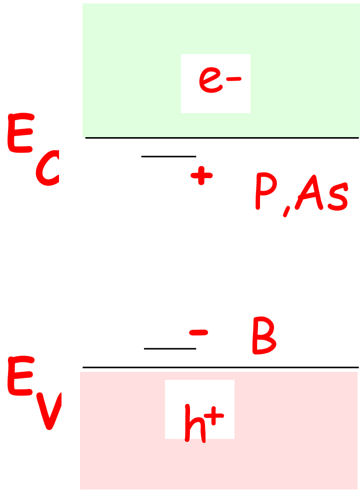
energy gap between valence and conduction bands



- 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

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

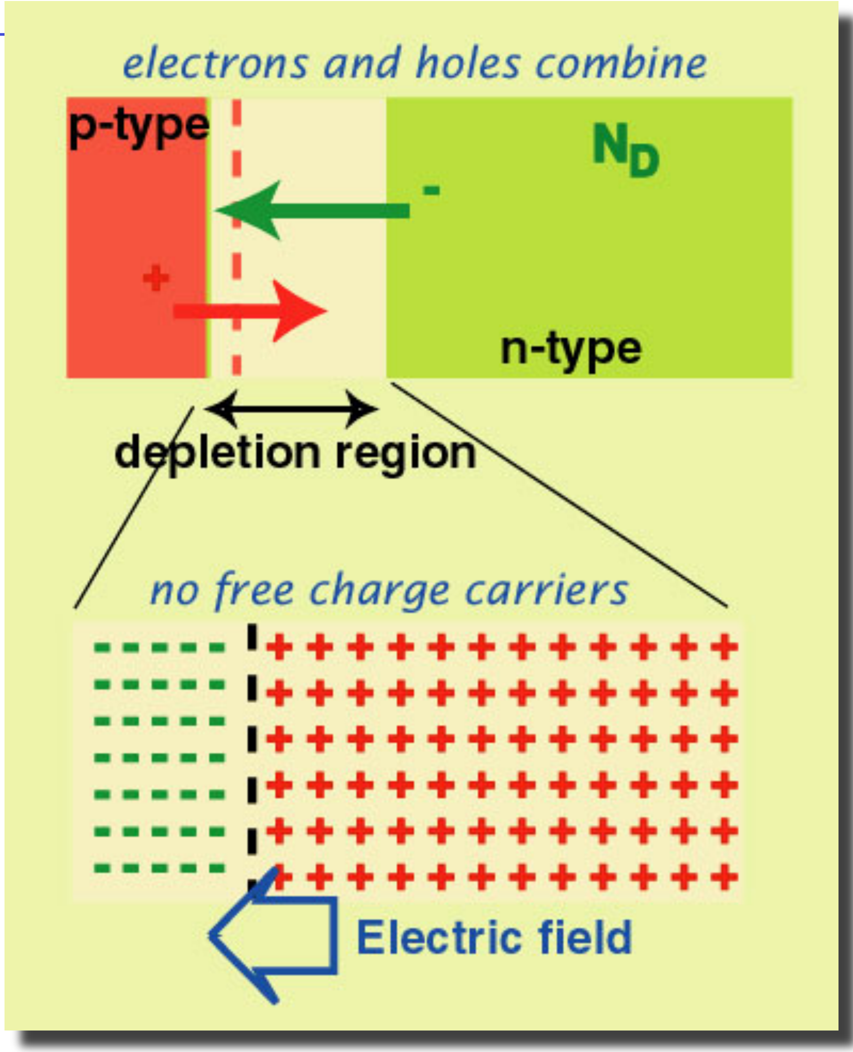
- increase external reverse bias

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

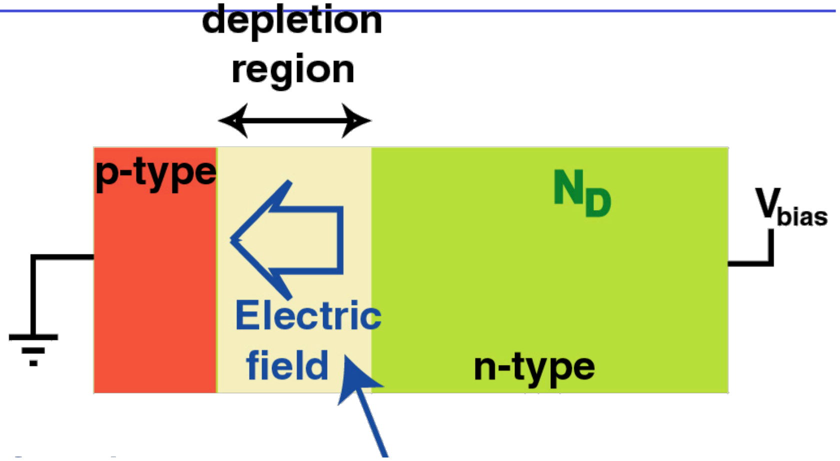
thin detector: high E but high C unless small area

- X-ray and charged particle detection

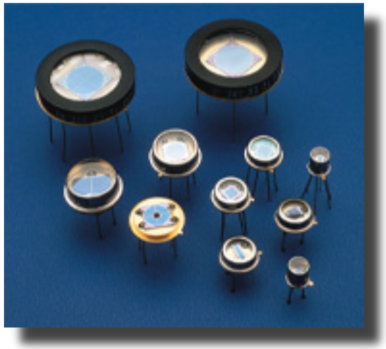
"thick" detectors required for many applications

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

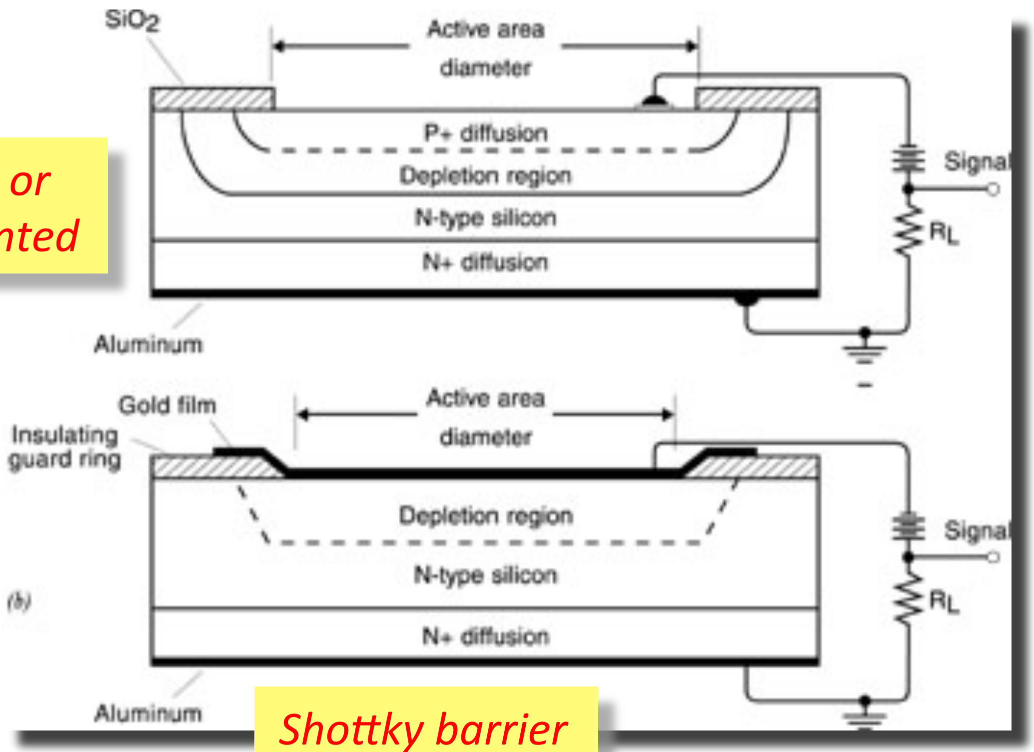
oxide window

robust, flexible geometry

- Schottky barrier - metal-silicon junction

thin metal contact

more fragile and less common



Diffused or Ion implanted

Shottky barrier

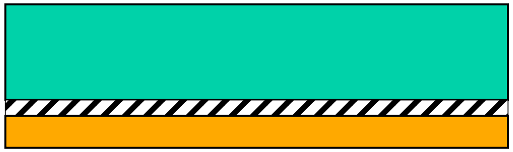
- III-V

epitaxial = material grown layer by layer

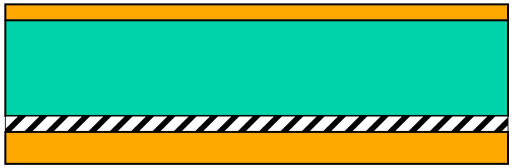
limits size, but essential for some modern applications

Main fabrication steps

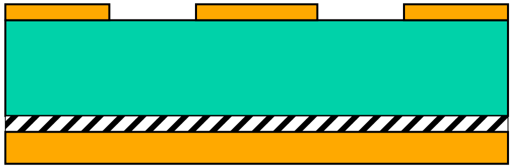
Simplest detector type based on p-on-n structure



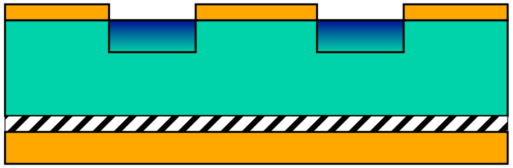
- Deposit SiO_2



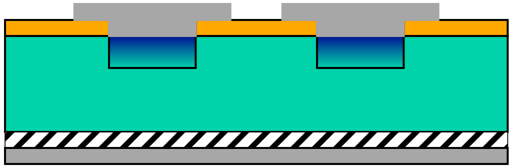
- Grow thermal oxide on top layer



- Photolithography + etching of SiO_2
  - Define electrode pattern



- Form p^+ implants
  - Boron doping
  - thermal anneal/activation



- Removal of back SiO_2
- Al metallisation + patterning to form contacts

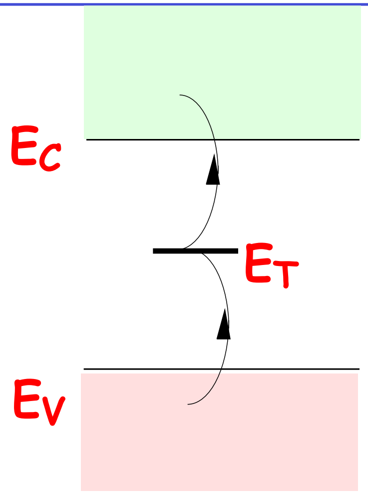
Real p-n diode under reverse bias

- 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**	**Diamond**	**SiO_2**
Z	14	32	31/33	6	
Band gap [eV]	1.12	0.66	1.42	5.47	9
Energy to create e-h pair [eV]	3.55	2.85	4.1	13	17
Density [g.cm^{-3}]	2.33	5.33	5.32	3.52	2.2
Permittivity [pF/cm]	1.05	1.42	1.16		0.35
Electron mobility [cm^{2}.V^{-1}.s^{-1}]	1450	3900	8500	1800	~20
Hole mobility [cm^{2}.V^{-1}.s^{-1}]	450	1900	400	1600	10^{-4}-10^{-6}
Radiation length [cm]	9.4	2.3	2.3	12	12.3
MP MIP signal [e/µm]	80		130	36	
Average MIP dE/dx [MeV/g.cm^{-2}]	1.66	1.40	1.45	1.75	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

- 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

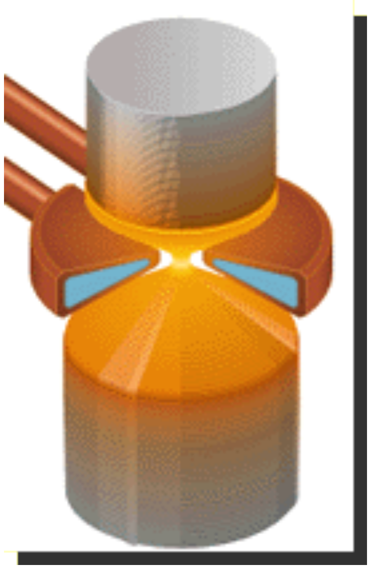
- electronic grade silicon $N_D > 10^{15}$ cm^{-3}

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

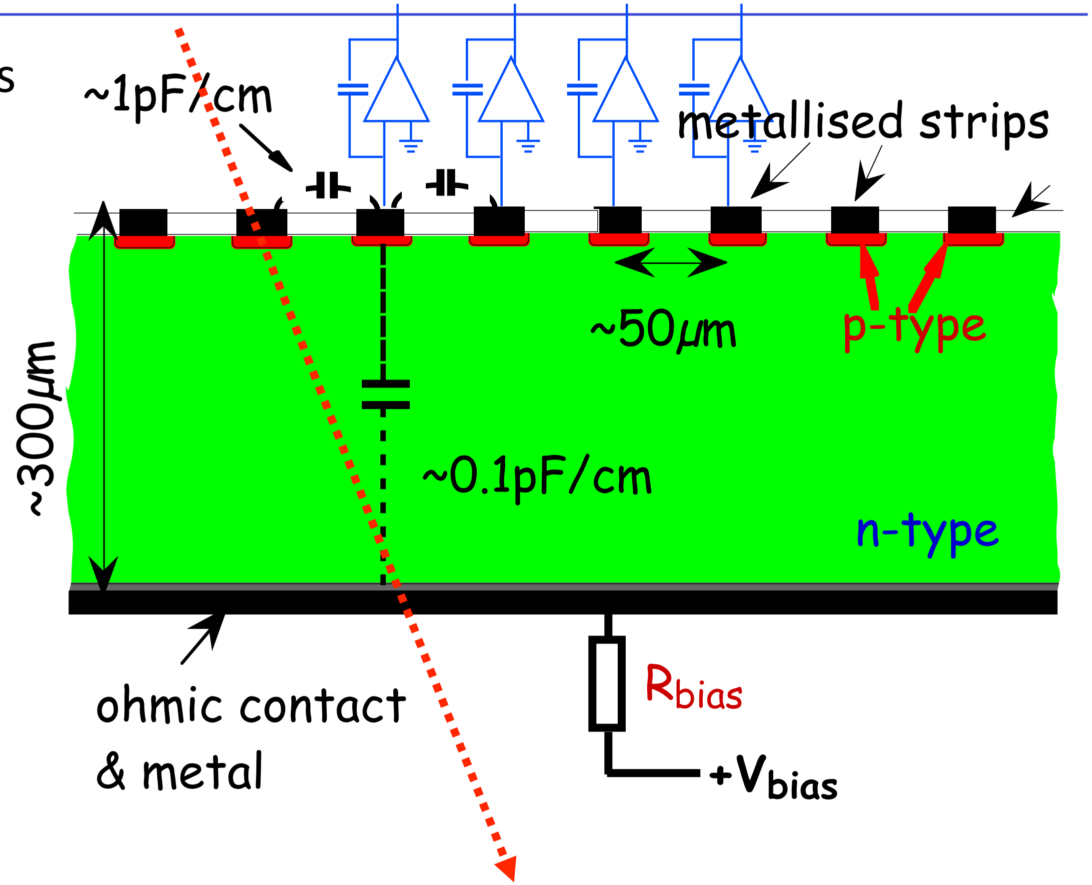
further refining required

Float Zone method: local crystal melting with RF heating coil

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



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

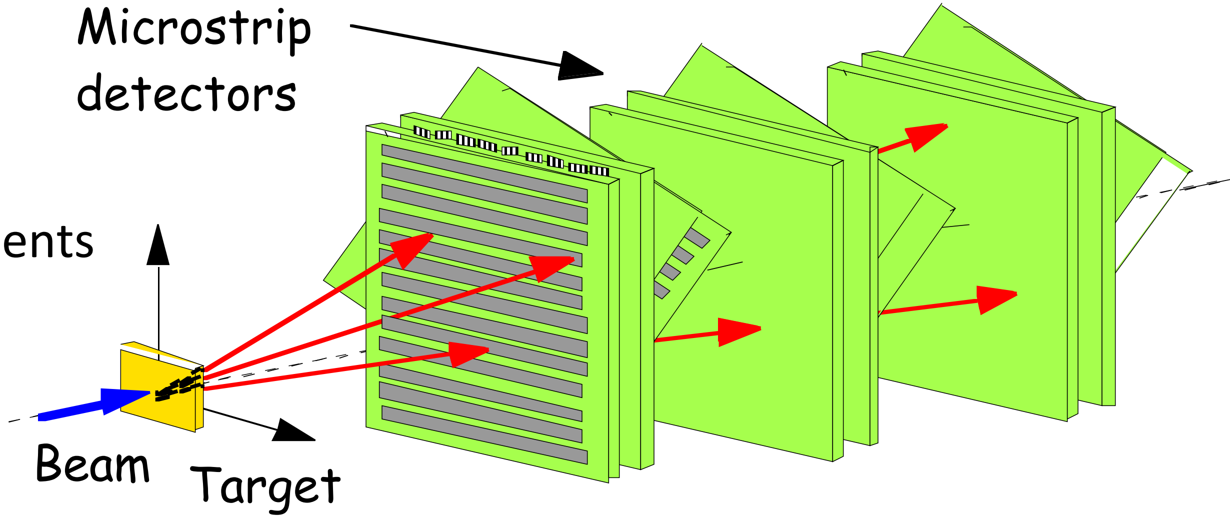
high efficiency

robust & affordable

magnetic effects small

- Telescopes in fixed target experiments

cylindrical layers in colliding beam



- x-ray detection

segmented arrays for synchrotron radiation

pixellated sensors now in use

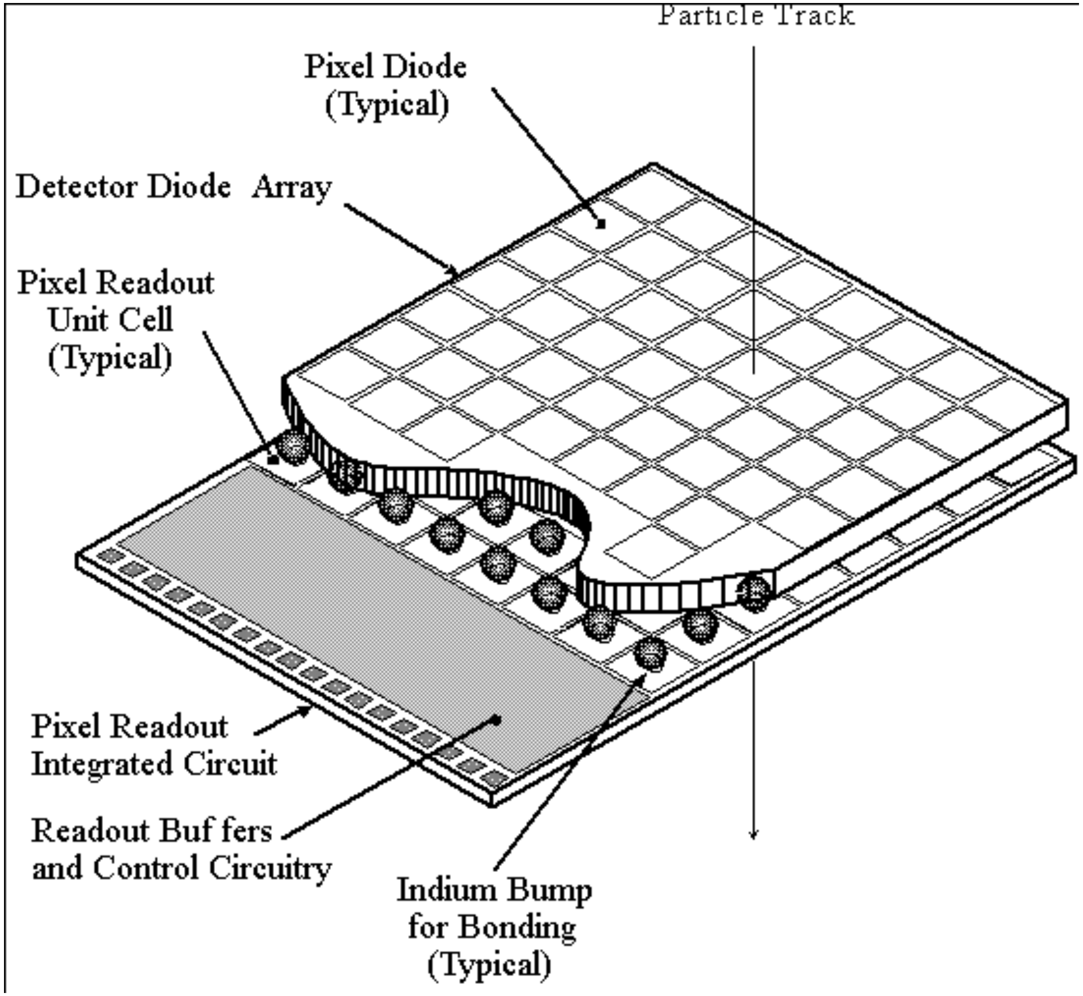
- Photodiodes for scintillation light detection

cheap, robust, compact size, insensitive to magnetic field

Pixel detectors

- Simplest case: p-type diodes on n-type substrate; 2-d array

Should be isolated by induced charge below oxide separating



- Features

Low element capacitance

Low leakage current

To connect readout electronics?

Bump bond with indium or solder

- For high radiation environments

n-type surface on n-type substrate

(reasons later)

Then need to isolate elements

Add surface p-type implants

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

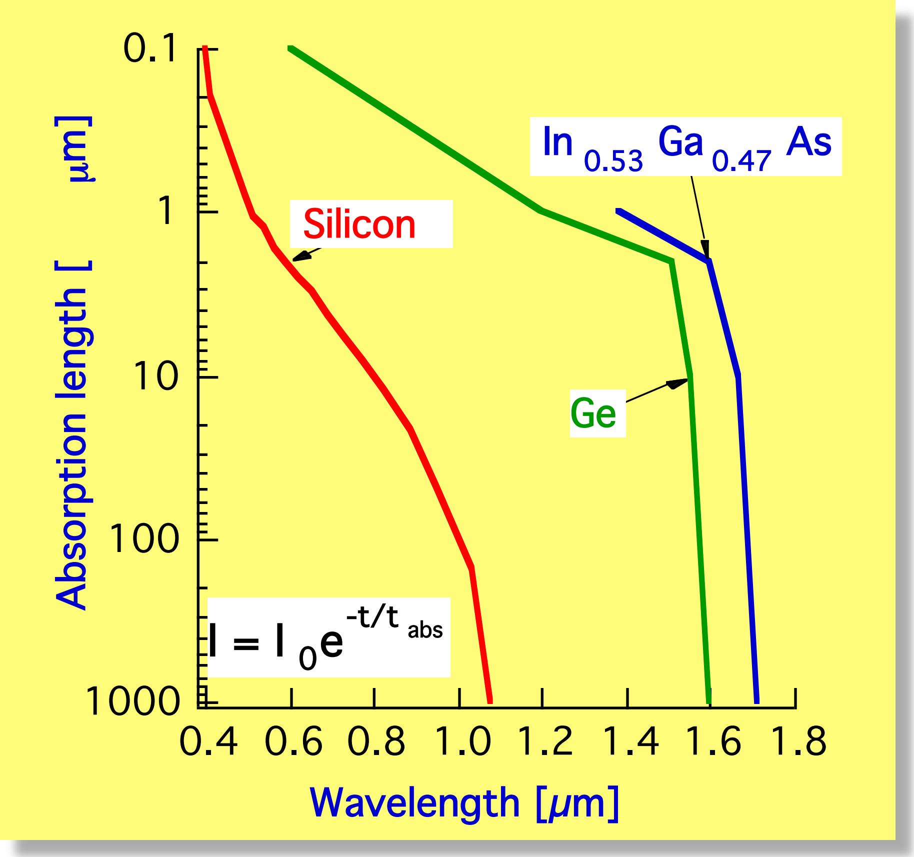
GaAs, InP λ < 0.9µm

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)

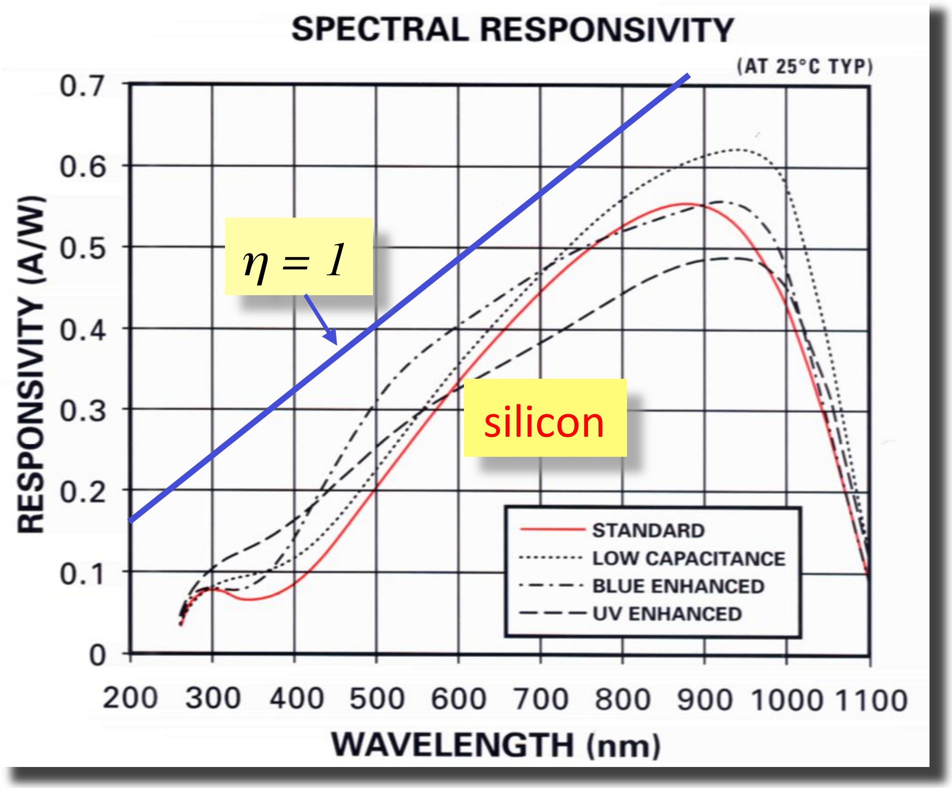
$P = N_{\gamma}.E_{\gamma} / \Delta t$

$I = \eta.N_{\gamma}.q_{e} / \Delta t$

$R = \eta.\ q_{e.}.\lambda/hc \approx 0.8\ \eta\ \lambda[\mu m]$

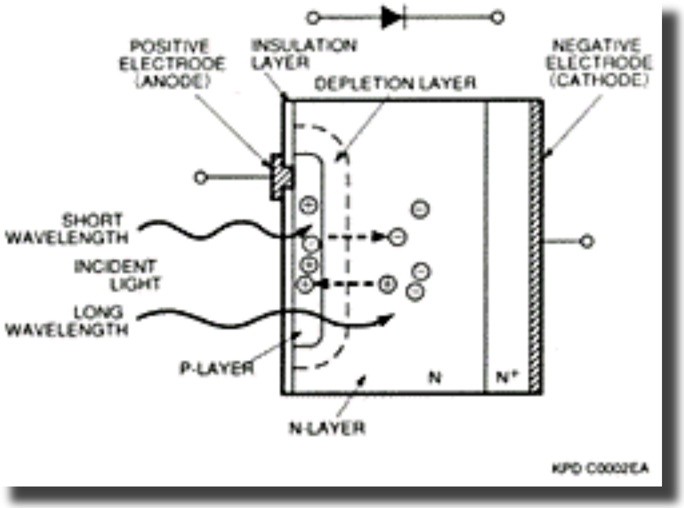
- silicon QE ~ 100% over broad spectral range

- windows and surface layers also absorb


SPECTRAL RESPONSIVITY

$\eta = 1$

silicon



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

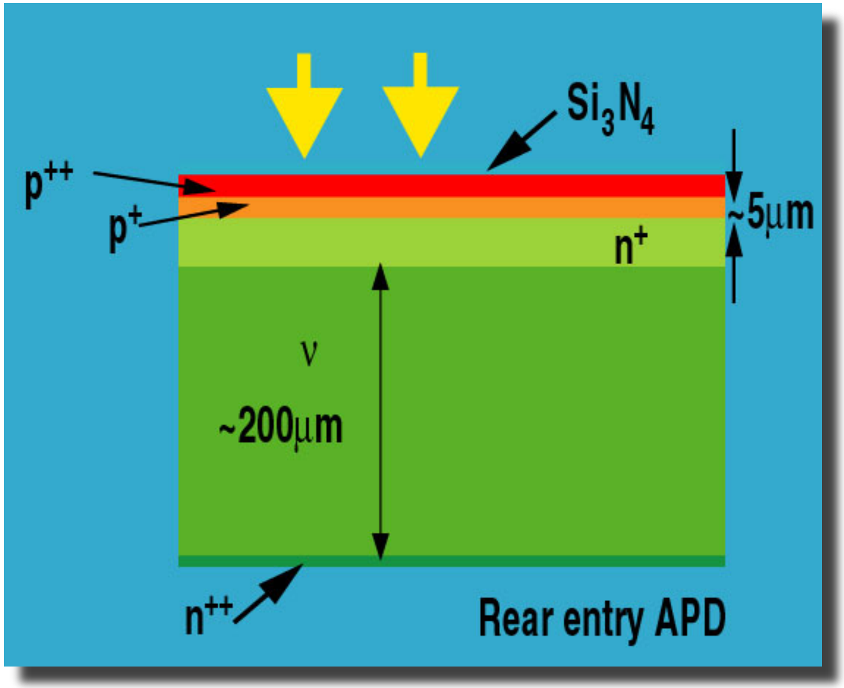
fast response because high E field

- Con

Risk of instability

amplify dark current & noise

edge effects - breakdown in high field regions



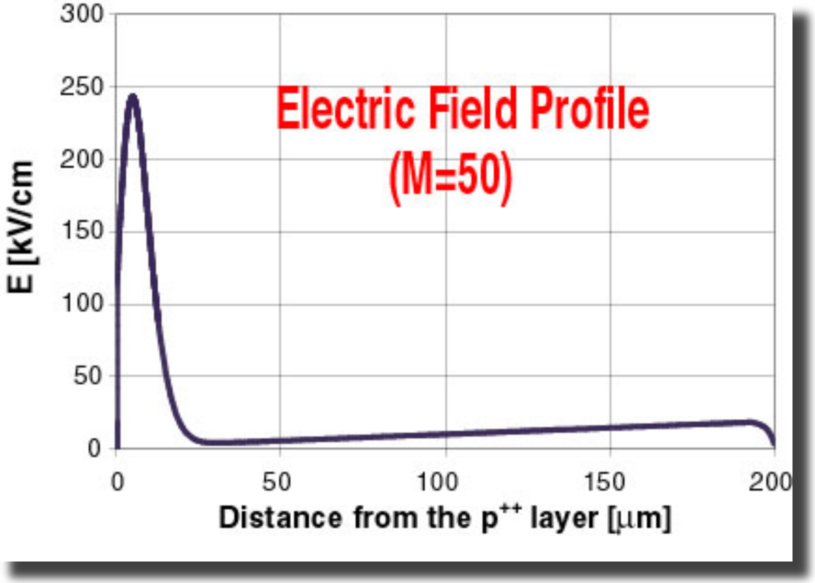
APD characteristics

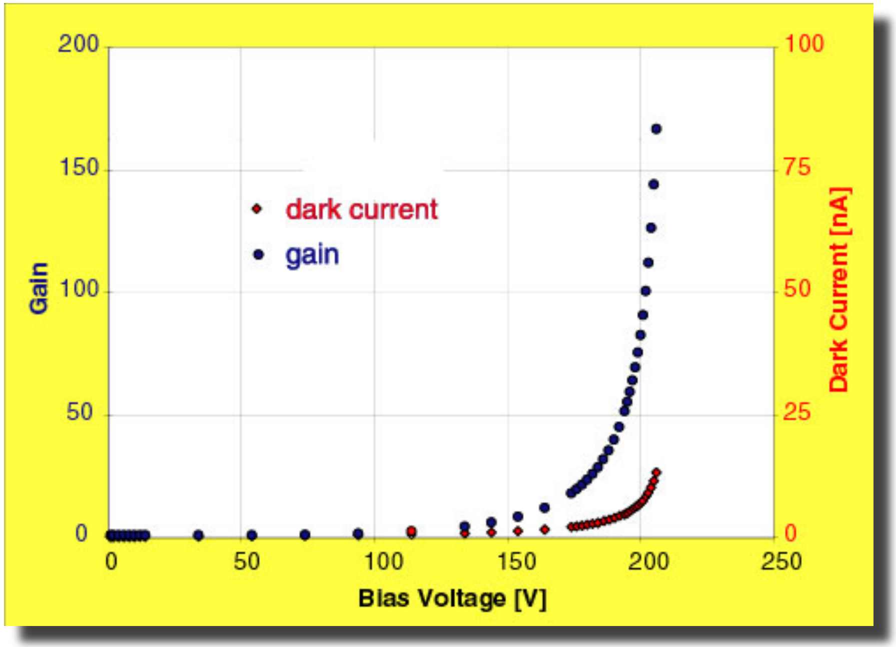
- This (example) design optimised for short wavelength

λ ~ 400nm *short absorption length*

for infra-ref wavelengths *-longer absorption length*

so entry from ohmic contact surface to maximise absorption





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

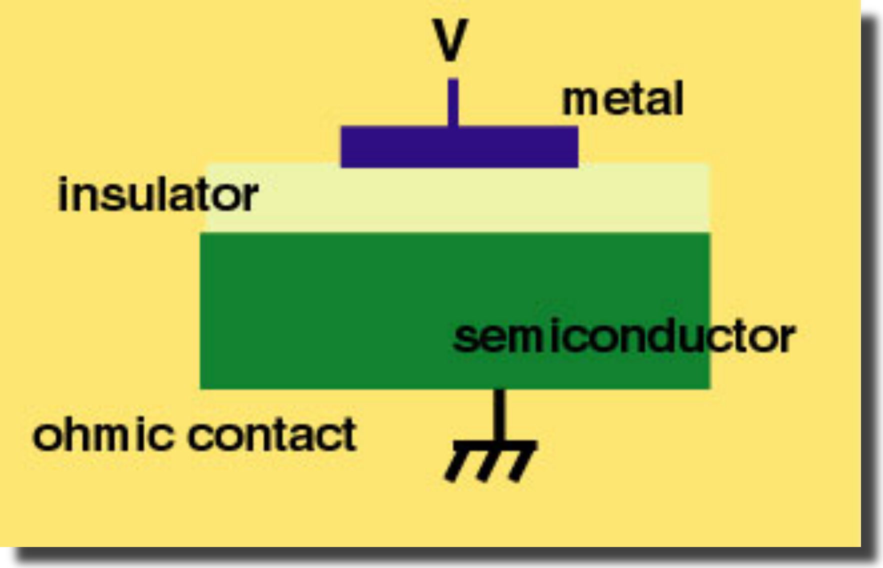
only heavy particles (p, n, π, …) cause significant damage

increased leakage currents - increased noise

changes in substrate doping

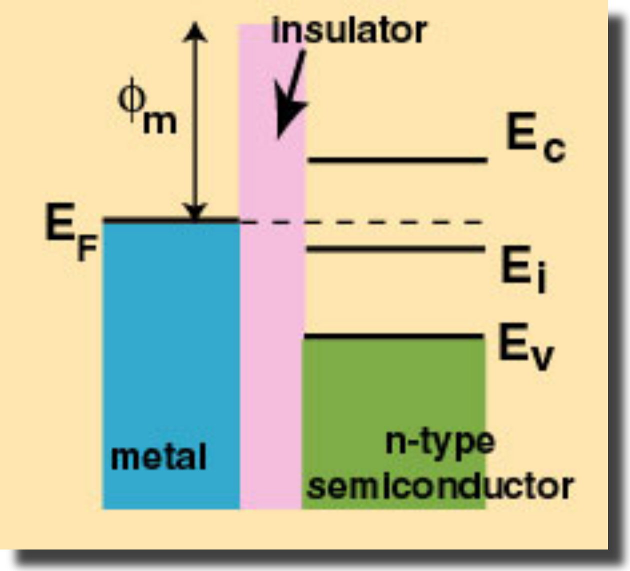
MIS capacitor

- Elementary device
  - oxide well matched to silicon
    - transparent to wide λ range
    - excellent insulator
  - nitride frequently used in addition
    - larger ε



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

Energy band diagram



MOS capacitor characteristics

- Apply bias voltage to influence charge under oxide

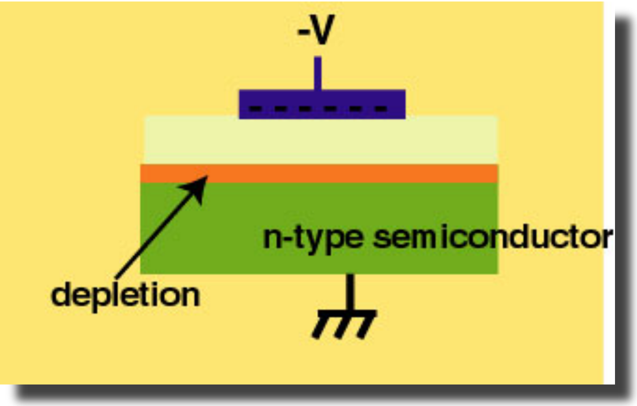
depletion - potential well which can store charge

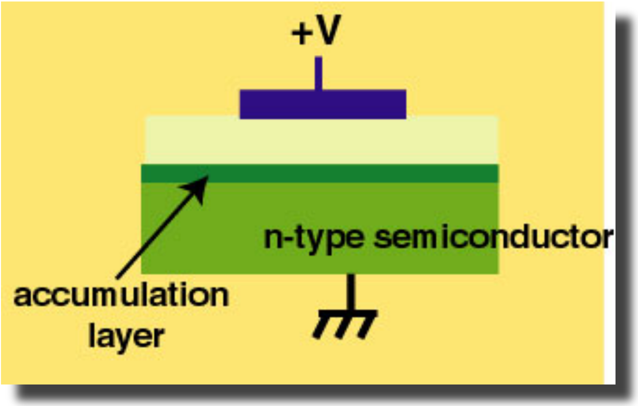
inversion - thin sheet of charge with high density

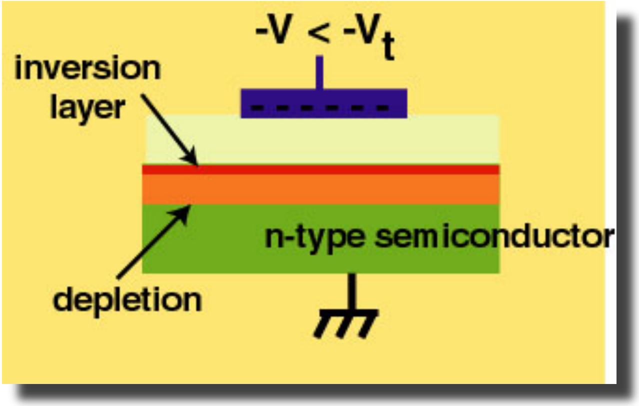
allows conduction in transistor

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

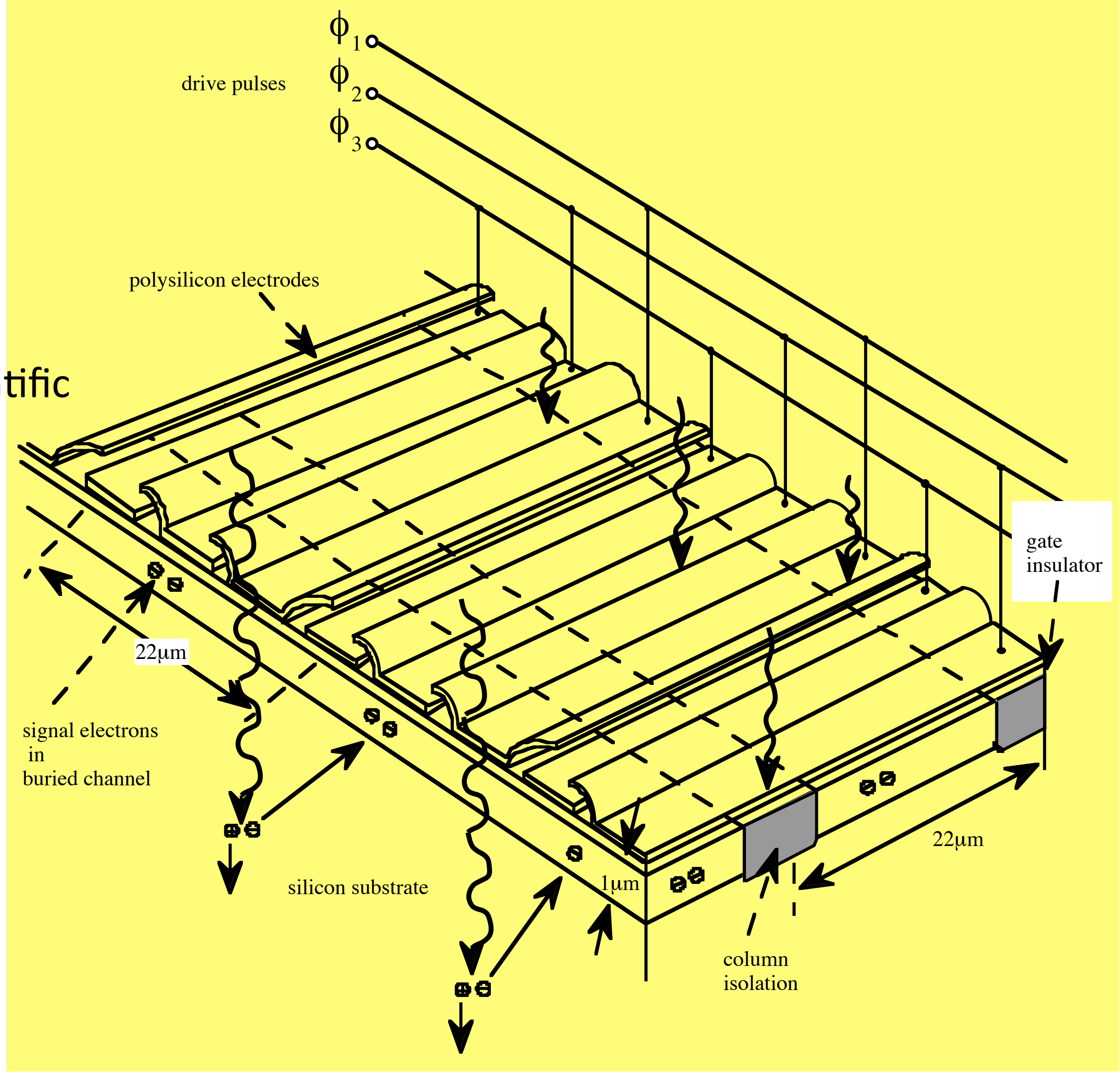
  smaller area & pixels

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")

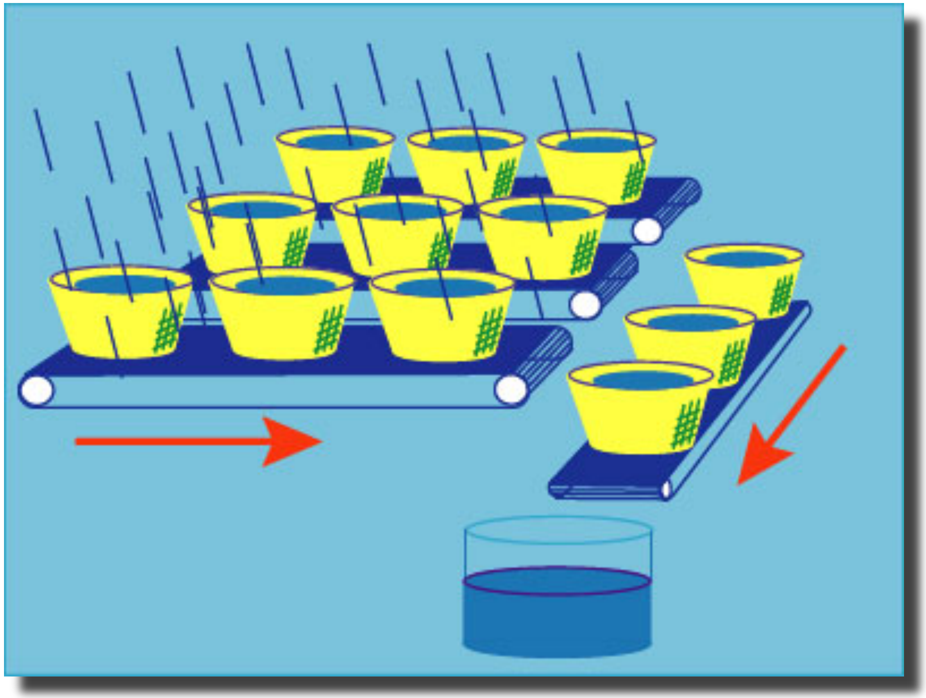
3 gates per pixel

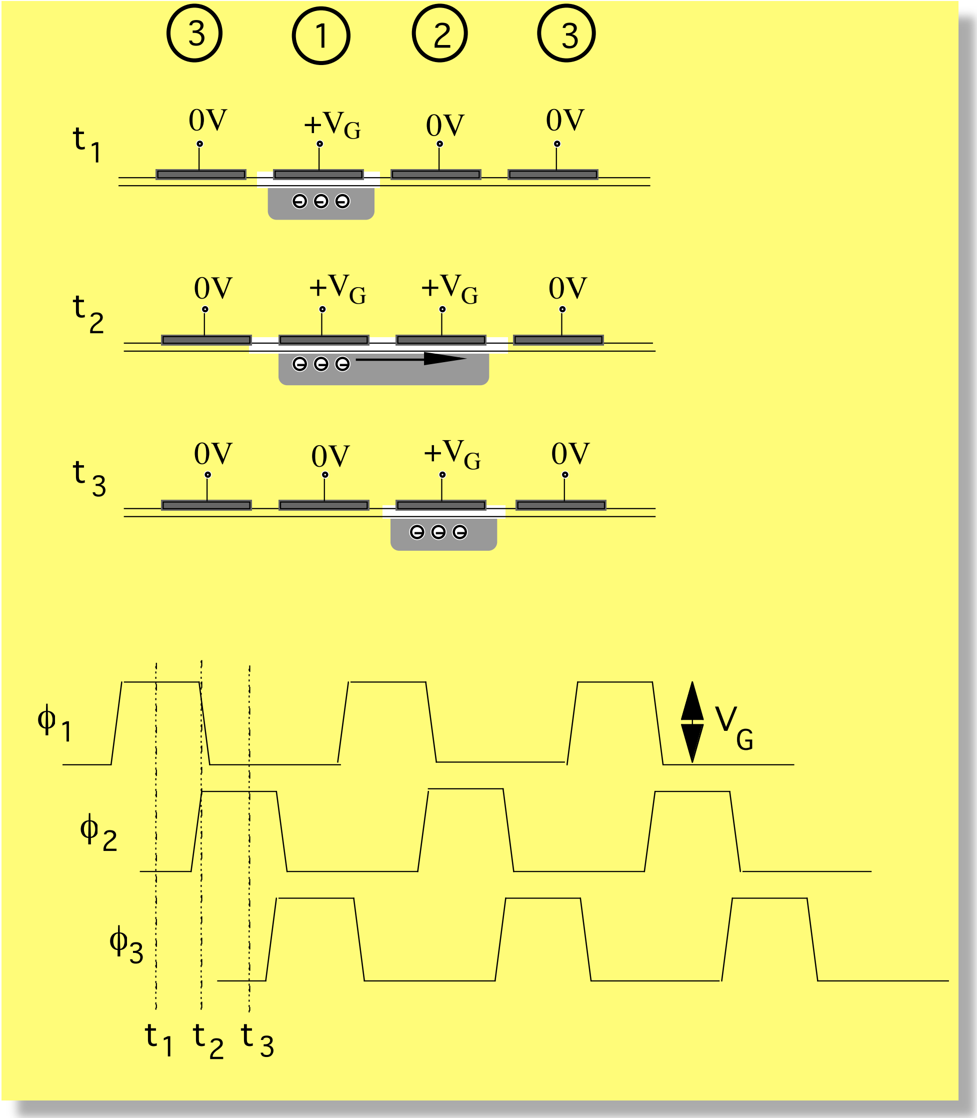
3 phases per cycle

depletion depth in adjacent regions changes

E field transfers charge to next pixel

- finally to output register





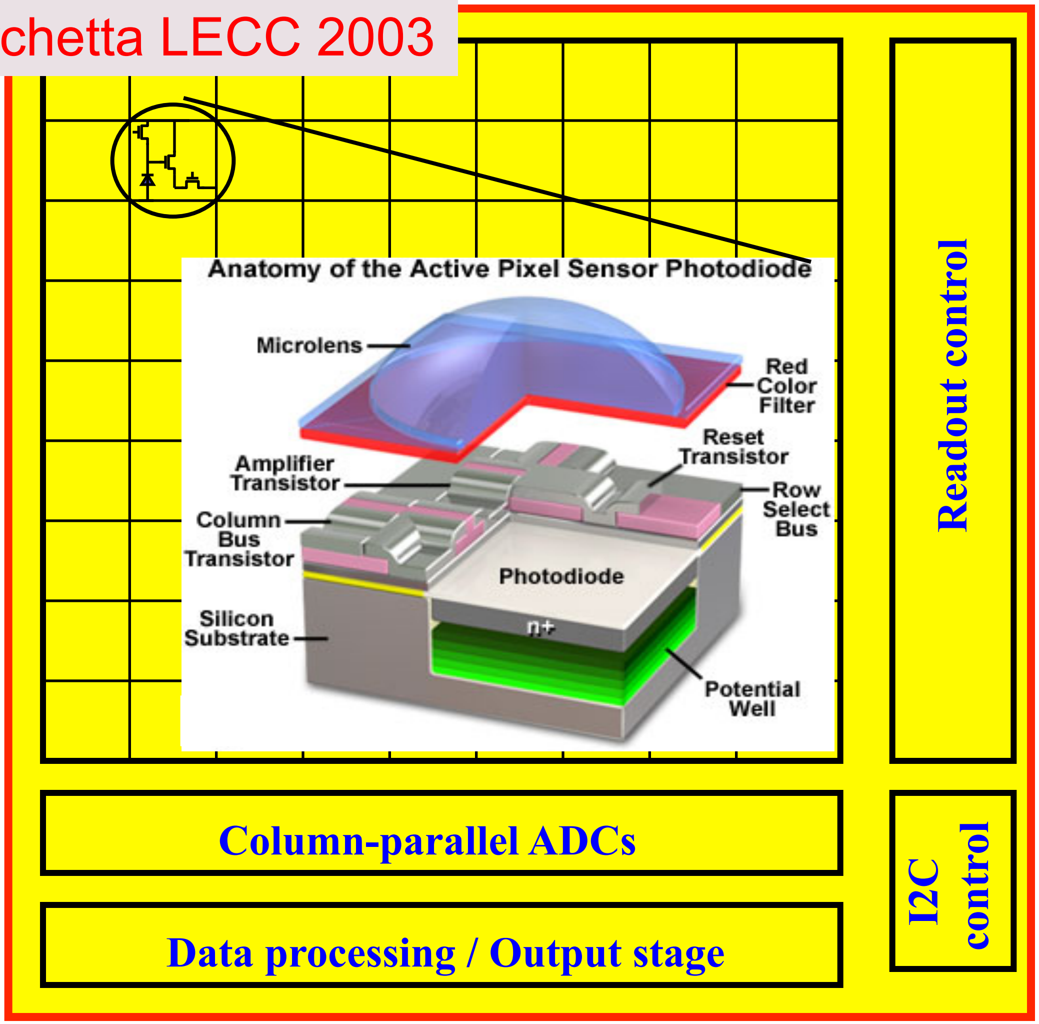
Example of monolithic sensors

- Active pixel sensors

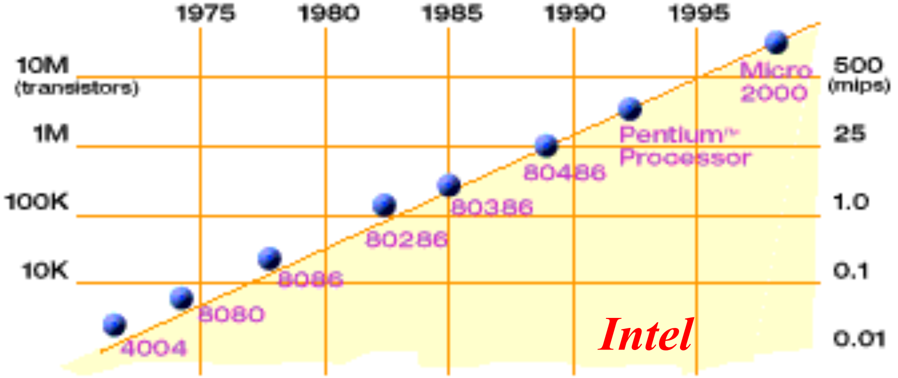
✓ Standard CMOS technology
✓ all-in-one detector-connection-readout
✓ small size / greater integration
✓ low power consumption
✓ radiation resistance
✓ system-level cost / Increased functionality
✓ random access
✓ increased speed (column- or pixel- parallel processing)
✓ ease of use for end users

Ideal for linear collider but LHC??

R. Turchetta LECC 2003



Technology trends - circuits

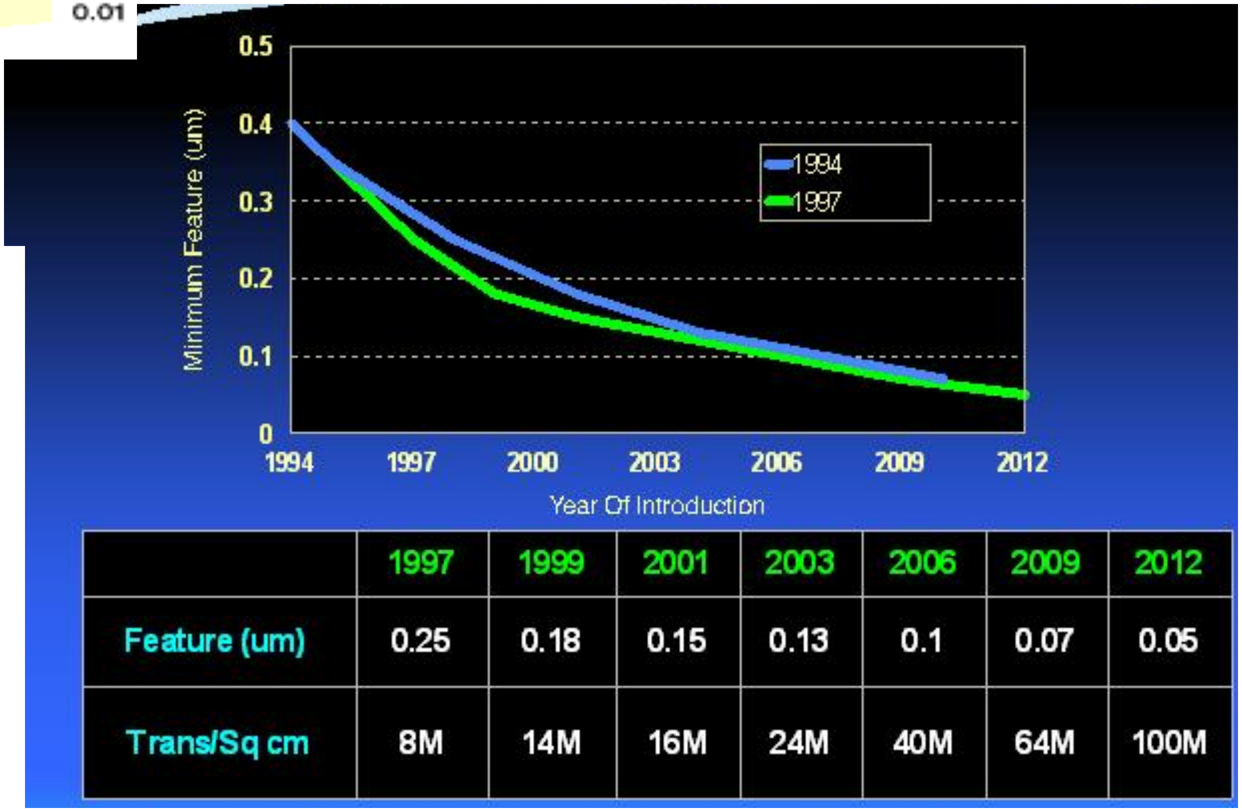


- Moore's law (1965)

  circuit density doubles every ~year

  "self-fulfilling prophecy"

Semiconductor Industry Association Roadmap data



	1997	1999	2001	2003	2006	2009	2012
Feature (um)	0.25	0.18	0.15	0.13	0.1	0.07	0.05
Trans/Sq cm	8M	14M	16M	24M	40M	64M	100M

"Silicon CMOS >75% world's semiconductor consumption"