UNIVERSITY OF LIVERPOOL

Particle Detection Techniques in HEP

Lecture 3: Solid State Tracking Detectors

Post-graduate lecture series

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(incl. slides from Jaap Velthuis)

Lecture 3 “Solid-state tracking detectors”

- Why do we want solid-state detectors
- Semi-conductors and the reverse-bias *pn*-junction diode
- Strip detectors
- Position resolution
- Analogue versus binary readout
- Pixel detectors
- CCD detectors
- Radiation damage to semi-conductor detectors?

Why solid-state detectors

Limitations Gaseous detectors

- Need large cells to obtain enough charge
  - Limits the position resolution
  - Limits the segmentation (problem at high occupancy)
- Charge collection by electron/ion drift in gas relatively slow
- Typically long wires (problem at high occupancy)

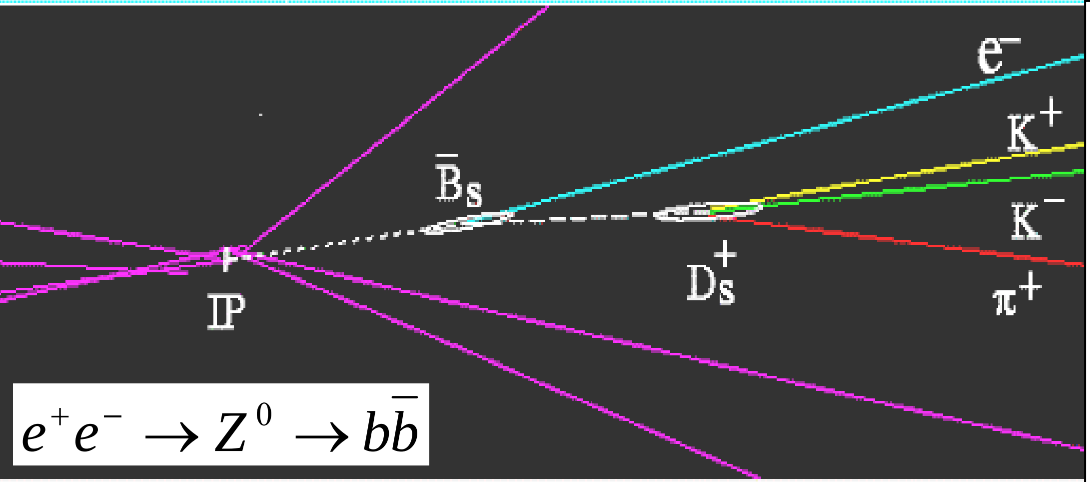
To induce more charge we need denser materials

- Denser hence more charge in a small area
  - Detectors can be very thin and have very small segments (pixels/strips)
- Charge travels much faster in a solid (electrical conduction)

Main applications solid-state detectors

- High precision tracking near IP (vertex detectors)
- Tracking in high occupancy environment (tracking at the LHC)
- Operation in high radiation environment (detectors near beam-line/LHC)

b/c quark flavour tagging from secondary decay vertices



Example:

Mean decay length B_s ($\tau \approx 1.5$ ps):

in B_s-frame: $c_\tau \approx 450\ \mu m$

in lab frame $\beta\gamma c_\tau$ = few mm!

D_s ($\tau \sim 0.5$ ps):

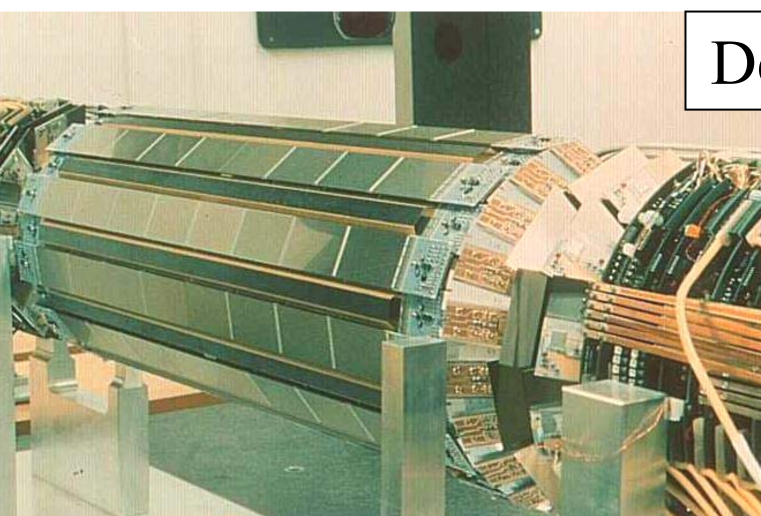
in D_s-frame: $c_\tau \approx 150\ \mu m$

in lab frame $\beta\gamma c_\tau$ = few mm!

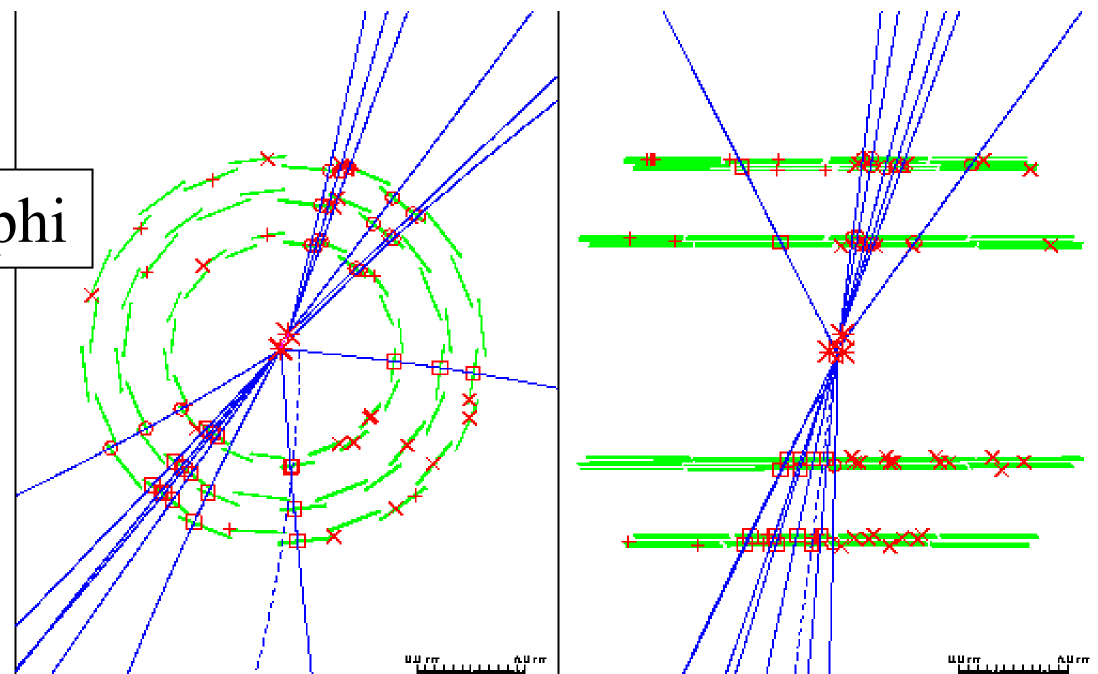
(lower mass $\Rightarrow$ more relativistic)

To find secondary vertex (measure decay length) need precise extrapolation of tracks to IP:

1. High precision points on trajectory
2. as close as possible to the IP



Delphi



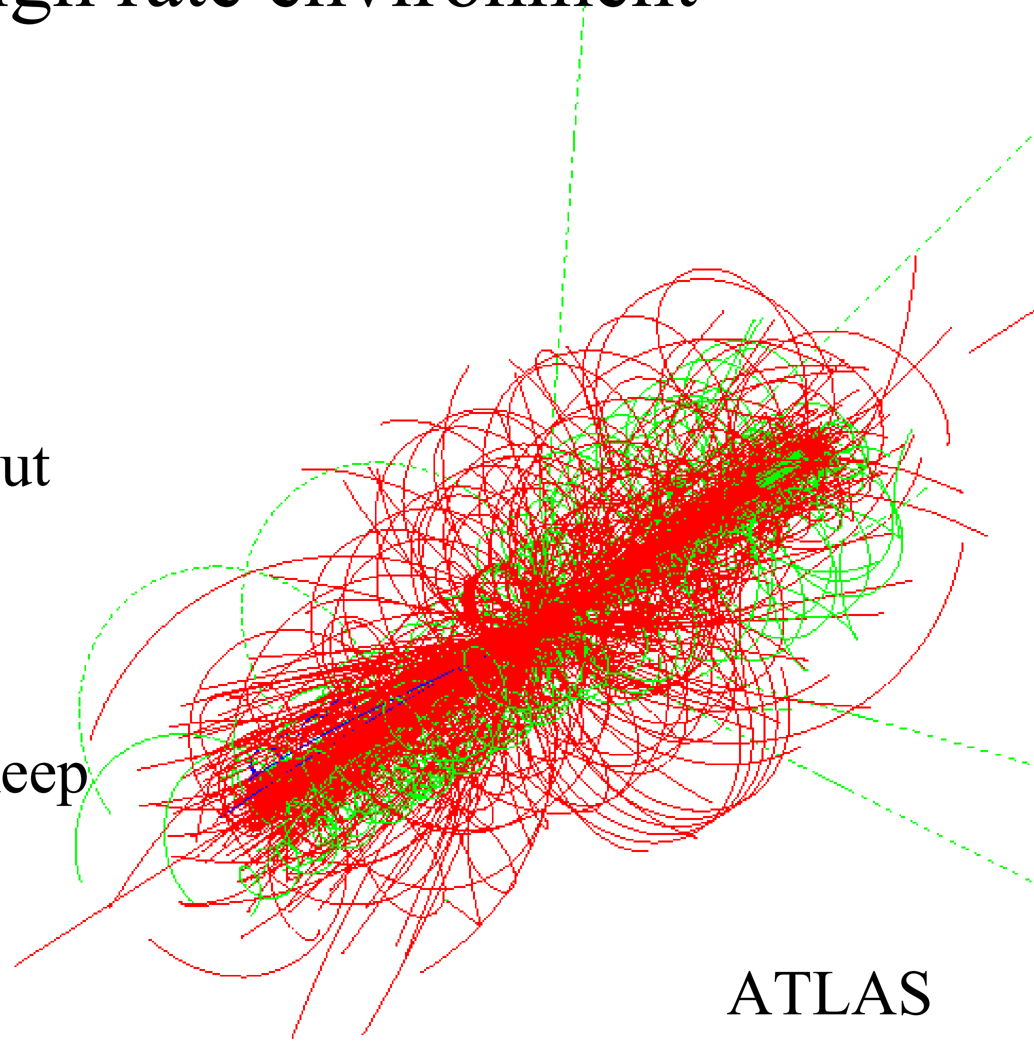
Tracking in a high rate environment

In high luminosity experiments (LHC) or for detectors near the beam-pipe we have to deal with:

• High event rate: need fast readout

• High particle density per event: need small detector elements to keep occupancy low

• High radiation dose: need radiation tolerant technology



ATLAS

Basic detection techniques: Electrical

From lecture 1

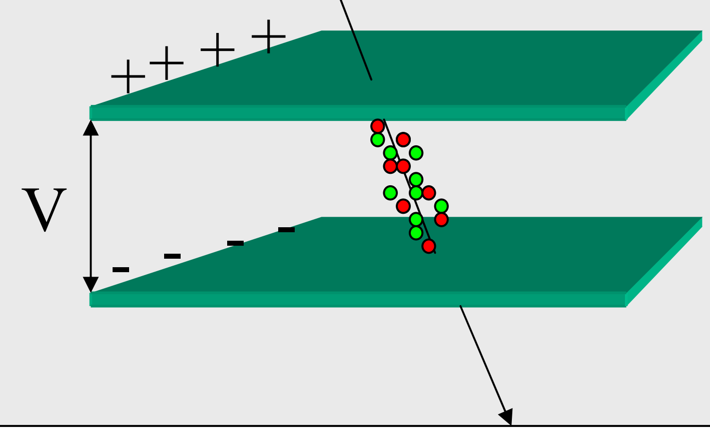
We can also electrically collect the charge produced by the ionisation

Particle causes ionisation in a material.

Charge is separated/collected by an electric field.

Requirement on material:

- no/few free charge carriers (non-conducting)
- mechanism for transport of charge



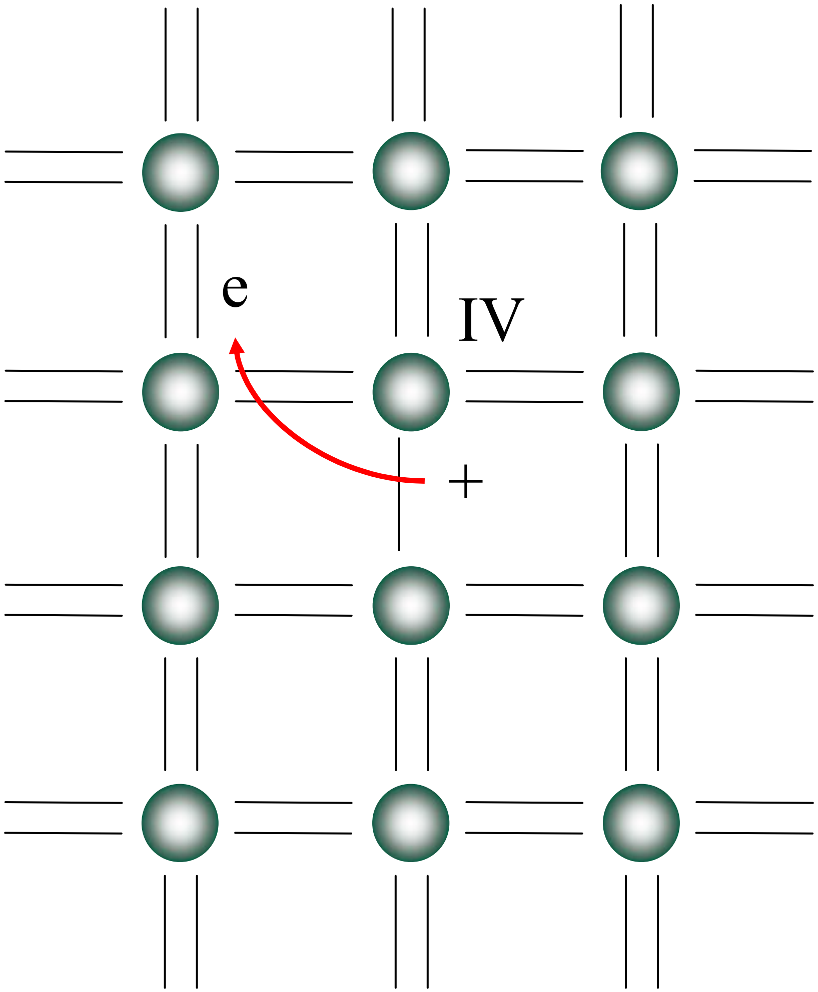
<u>Two options</u>:

- use insulating material, gas or liquid, charge transport through drift: lecture 2: gaseous tracking, lecture 4: liquid Argon calorimetry.
- use a solid-state, semi-conductor material, charge transport via conduction.

In HEP most semi-conductor detectors are made of Silicon:

- Widely available (many commercial applications), advanced photolithographic techniques allowing small feature sizes and hence high accuracy.
- High charge induction (~90 pairs/μm for a MIP) means detectors can be thin (100-300 μm) and hence low mass
- High mobility of charge in thin detectors means fast charge collection (~10 ns)

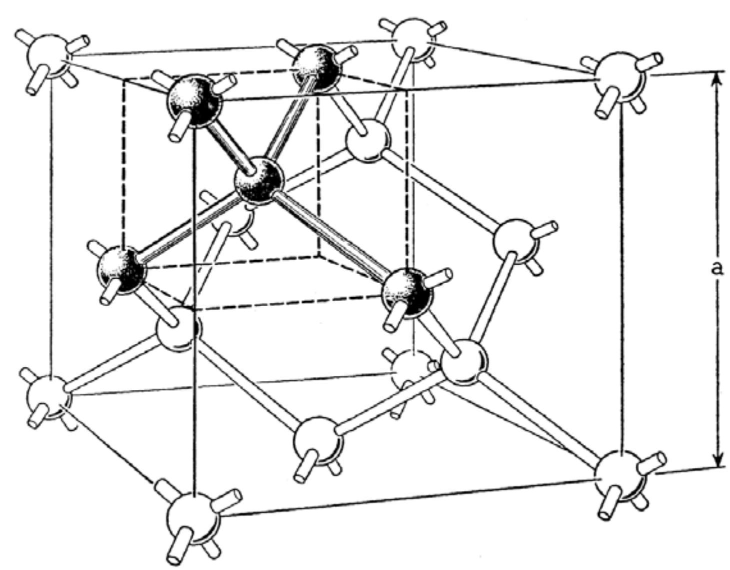
Intrinsic semiconductors (Silicon)



Atoms from group IV (4 valence electrons) which form covalent bonds with neighbours.

Electrons are weakly bound and can easily be "freed" to become conduction electrons, leaving behind a positively charged hole.

Both electrons and holes are mobile.



(from Schockley)

Energy band theory

In a solid (periodic potential) the electron energy levels of a single atom turn into energy bands!

Going from a gas to a solid:

• Levels filled by valence electrons ⇒ valence bands

• Vacant levels ⇒ conduction bands

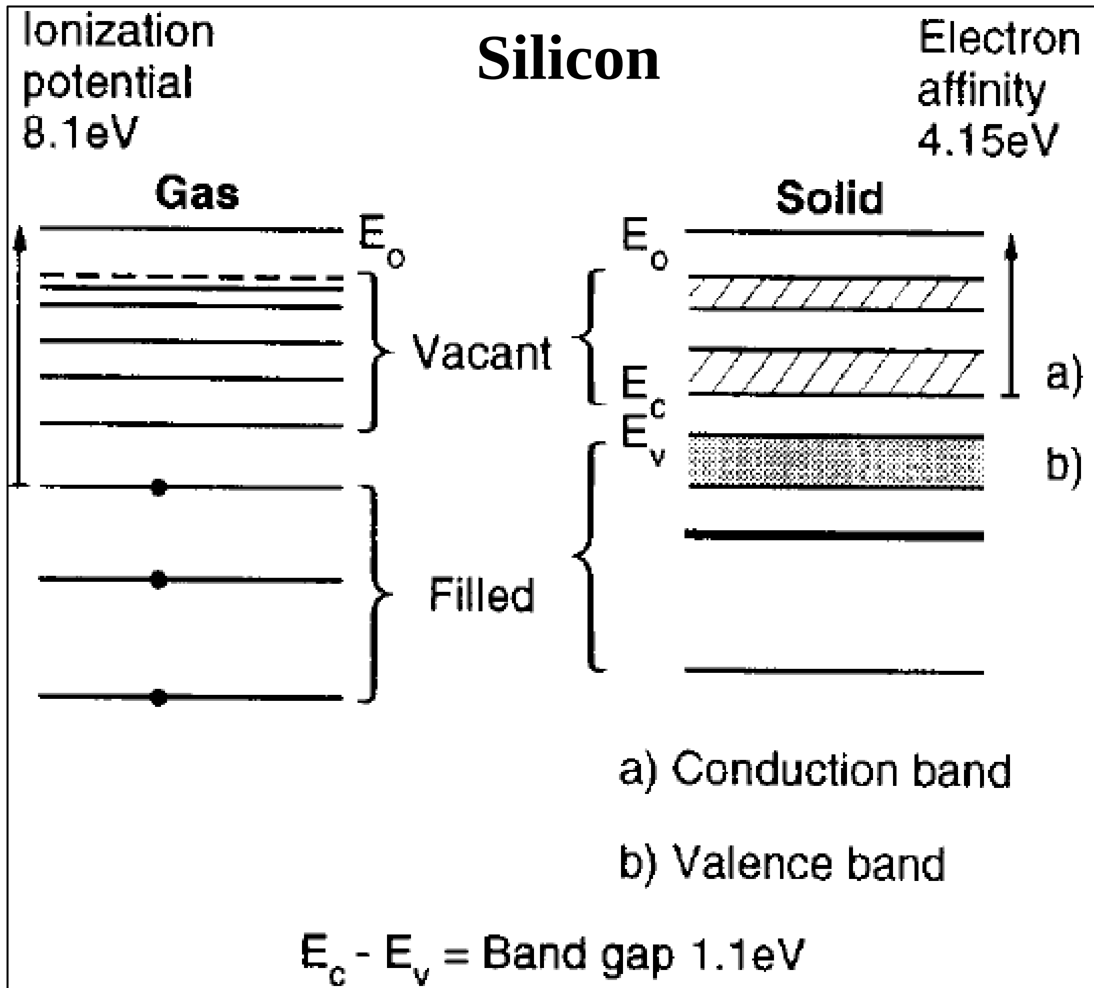
Conductor: overlap between valence and conduction bands.

Insulator: significant gap between valence and conduction bands.

Semi-conductor: small “band-gap”

e.g. Si band-gap 1.1 eV

Electrons can be moved from valence band to conduction band by e.g. thermal excitations.



Band level diagrams (Occupation of states)

At T=0 K all valence states are filled all higher states are empty!

At finite temperature occupation of state governed by Fermi-Dirac energy distribution:

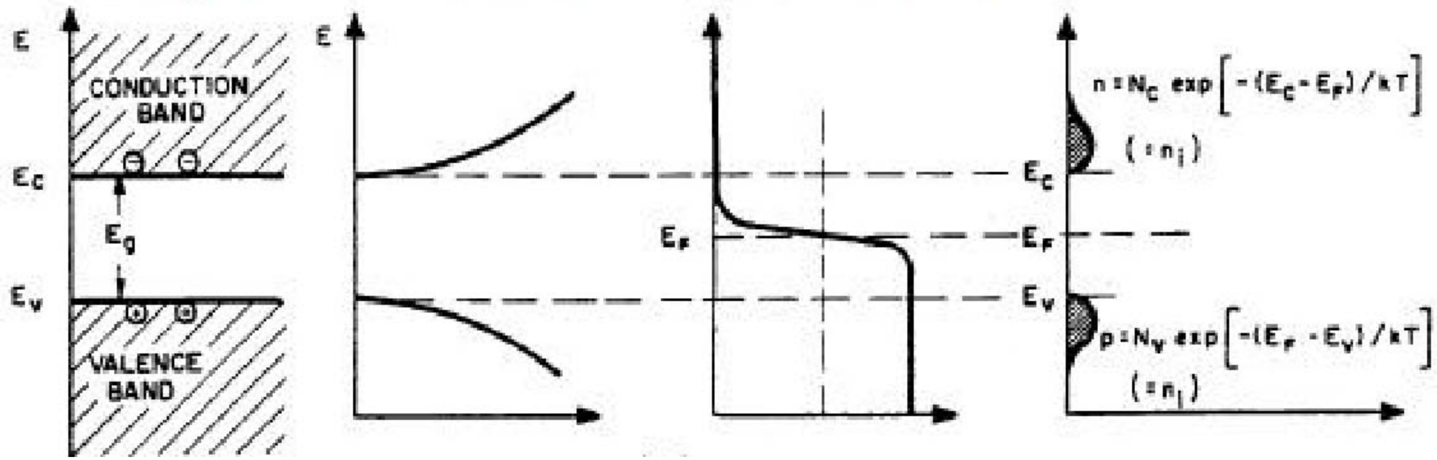
$$f_D(E) = \frac{1}{1+e^{(E-E_F)/kT}}$$

E_F: Fermi level, probability for state with energy E to be occupied. (50% at E_F)

<u>Intrinsic Silicon at finite temperature:</u>

Fermi level halfway between valence and conduction bands.

band diagram | **density of states** | **Fermi-dirac distribution** | **carrier concentrations**

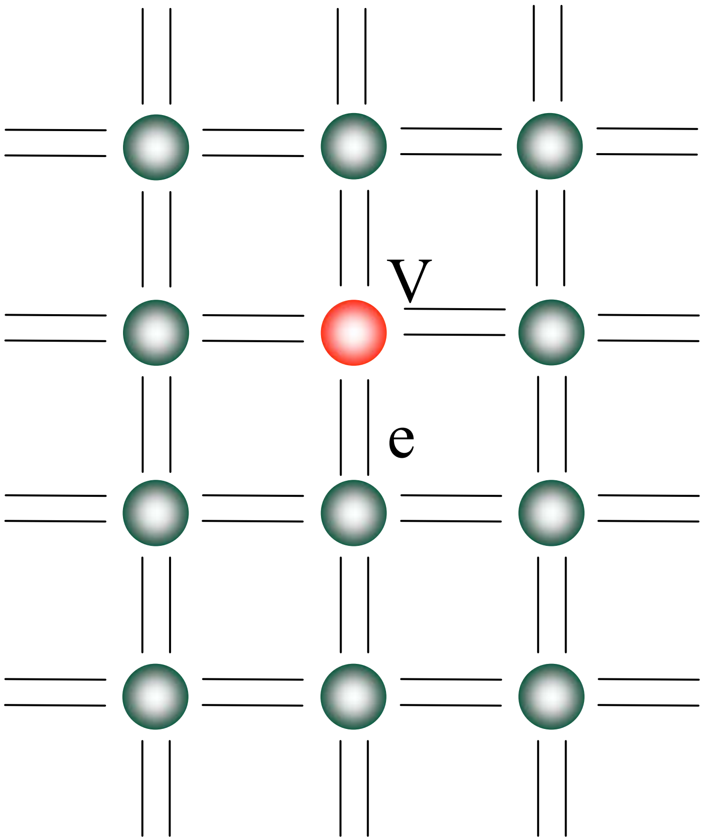


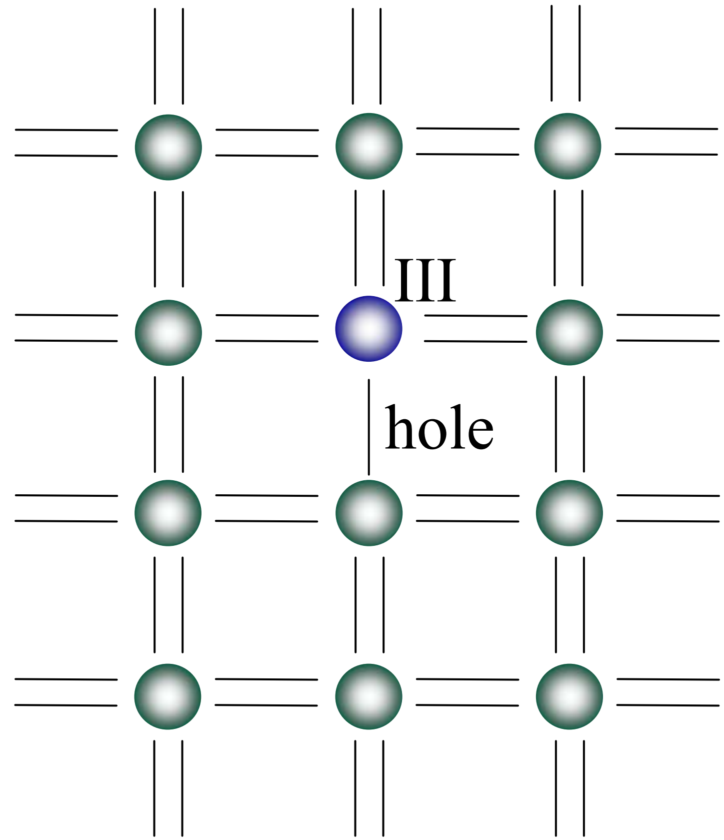
⇒ At room temperature intrinsic Silicon has ~1.45x10^{10} free pairs per cm^3!

⇒ Remember: from MIP we get ~ 9800 e/h pairs/100 µm.

⇒ Need a way to get rid of the free charge carriers ("reverse-biased *pn*-junction diode")

n-type and *p*-type doped semi-conductors





Group V: (5 valence electrons)

e.g. Phosphorus

Atoms contribute 1 (nearly) free electron. (“donor”)

n-type (*n*=negative)

(n^+, n^-: high/low doping level)

Group III: (3 valence electrons)

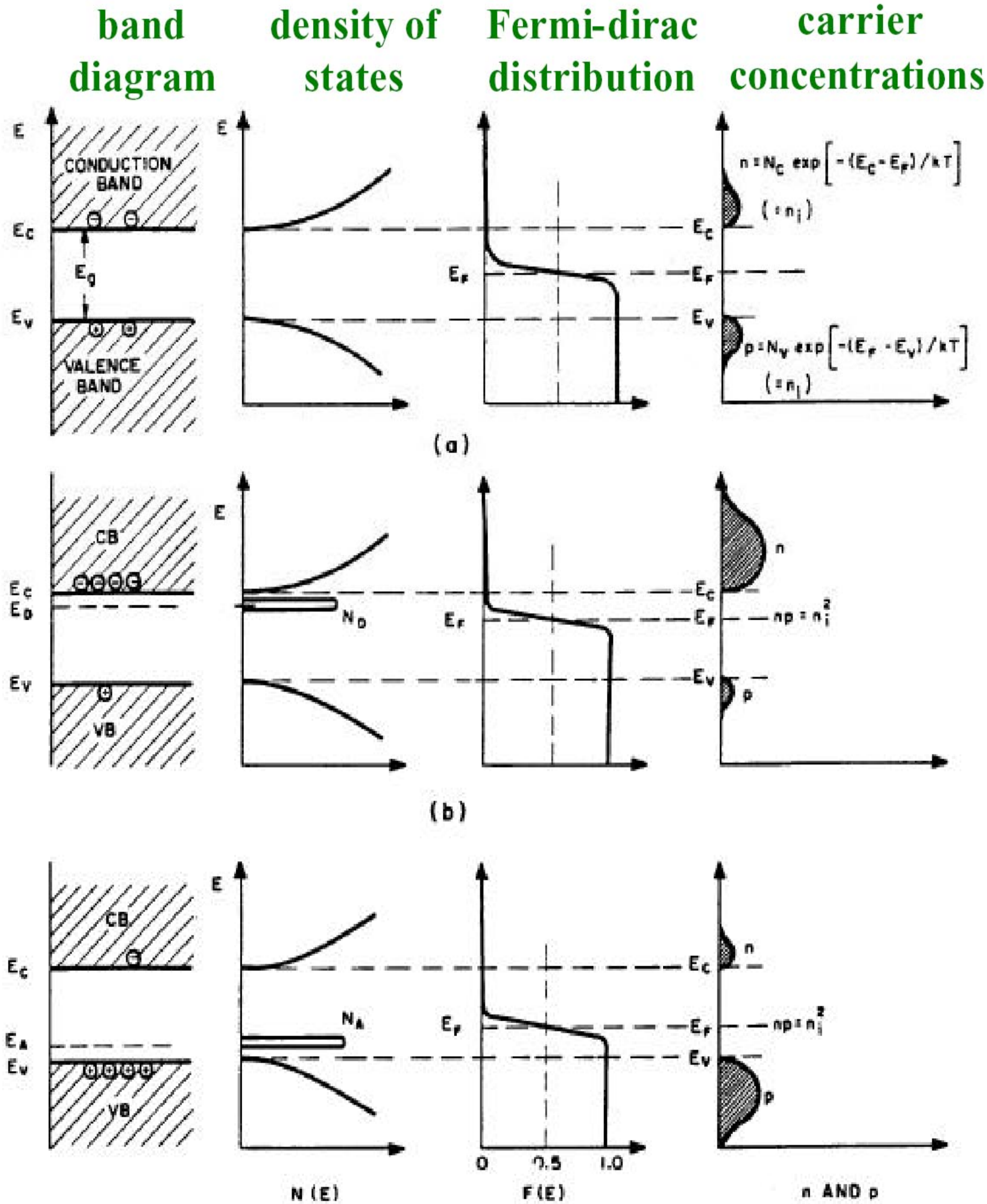
e.g. Boron

Each atom contributes (nearly) free 1 hole. (acceptor)

p-type (*p*=positive)

(p^+, p^-: high/low doping level)

Effects of doping:



Intrinsic Silicon: Fermi level

halfway between bands

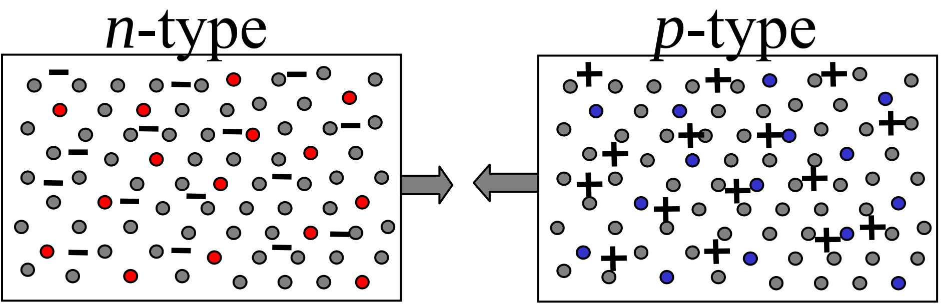
n-type doping: donor atoms (loosely bound electrons) form new (filled!) energy levels just near CB. These can easily donate electrons to CB

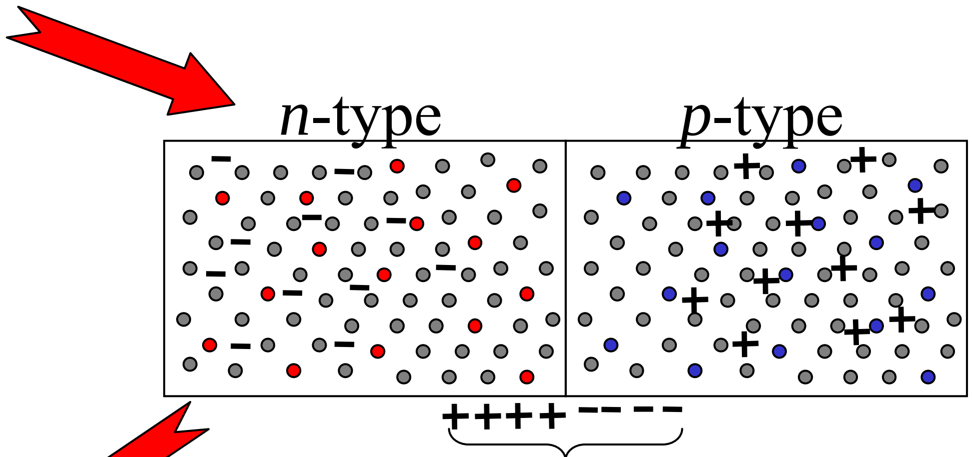
Fermi level moves closer to CB.

p-type doping: acceptor atoms form new (empty!) levels near valence band. These can easily accept an electron from the VB.

Fermi level moves closer to VB.

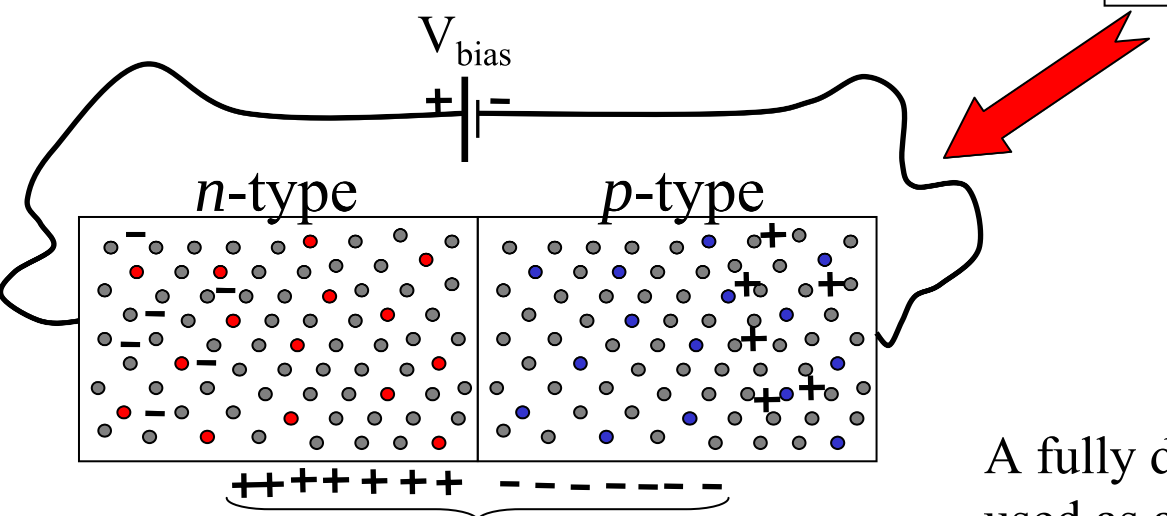
The reverse-biased *pn*-junction diode





Depletion zone:

no free charge carriers



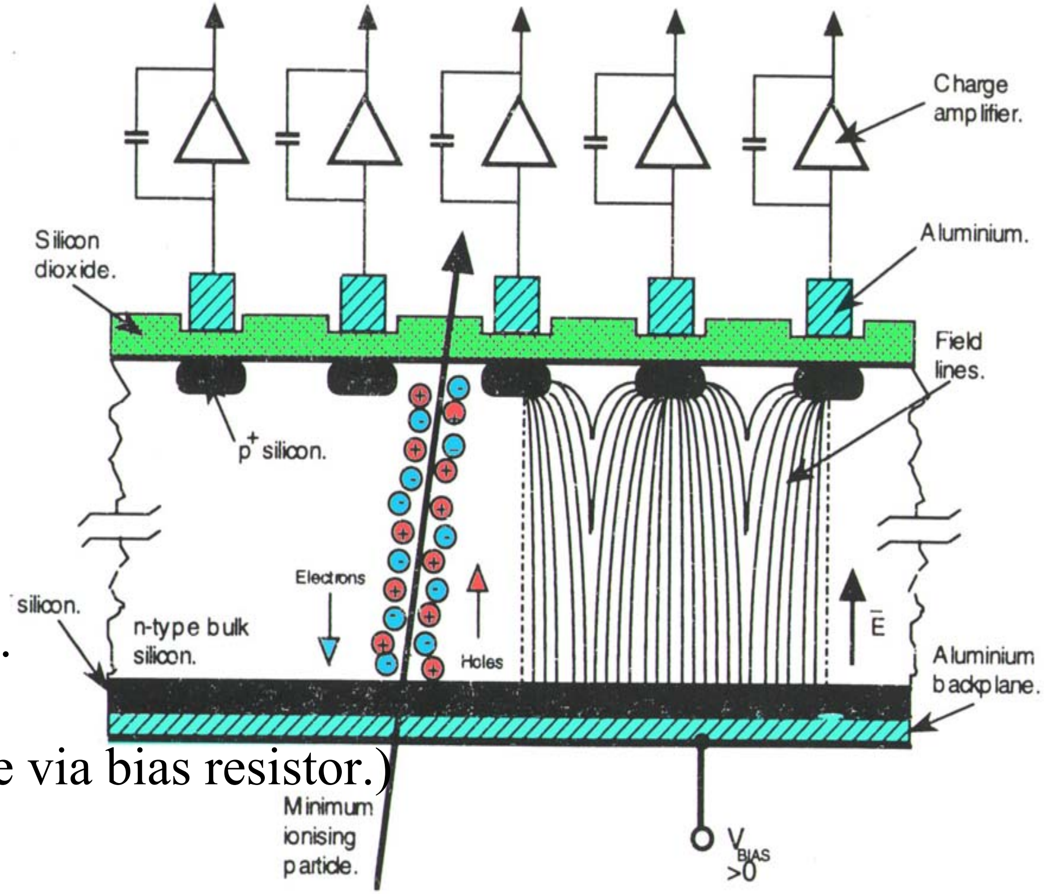
Reverse bias voltage increases the size of the depletion zone .

With high enough bias voltage the diode can be fully depleted!

A fully depleted *pn*-junction diode can be used as a particle detector!

Due to the strong *E*-field in the depletion region, e/hole pairs generated by a charged particle can collected on the *n* or *p* side.

Example silicon μ-strip detector (p-in-n)



Many diodes: p-strips in n-bulk

Positive (reverse-bias) voltage applied via conductive back-plane.

Depletes the detector and provides E-field for charge collection.

Deposited charge moves to nearest strip.

(strips connected back to ground voltage via bias resistor.)

Typical signal

- 8900 e/h pairs/100 μm
- typical size of the charge cloud ~10 μm

Here: signal readout via Al strip, capacitively coupled to p-strip (SiO_2 in between).

(prevents large currents flowing through amplifier, but reduces collected charge.)

Typical dimensions

Thickness: 200-500 μm

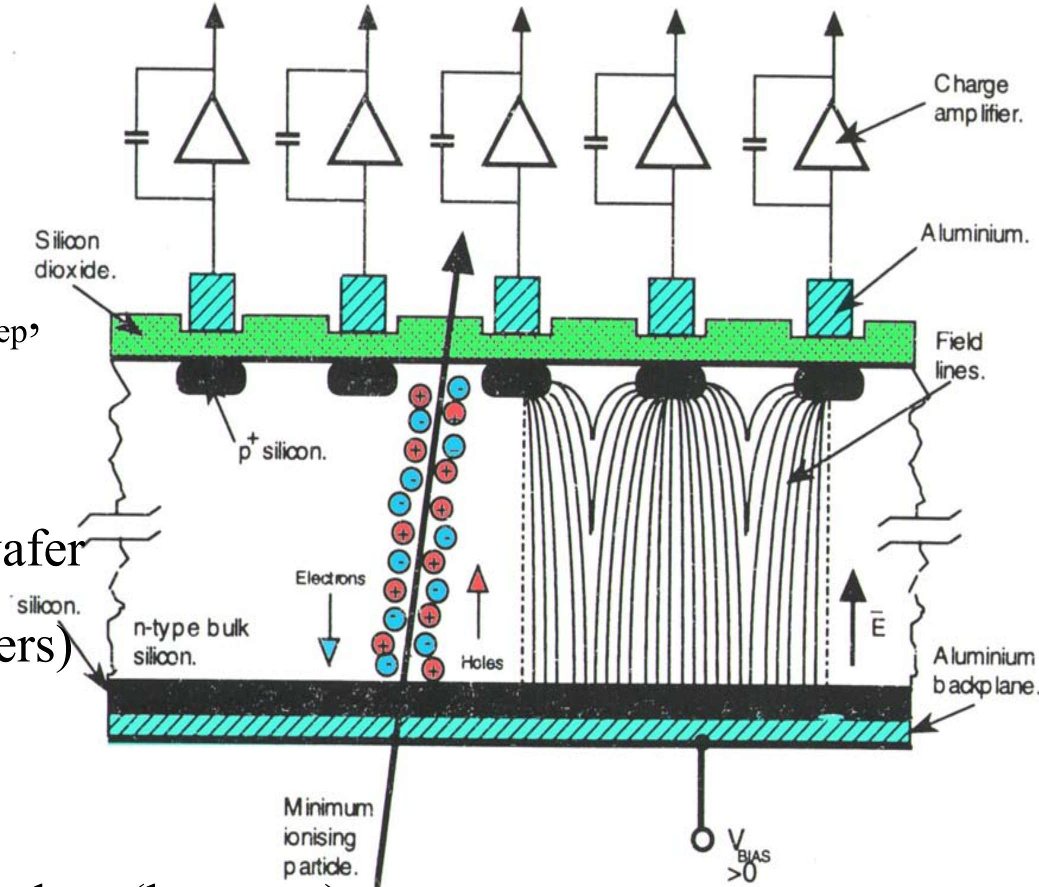
thicker ⇔ more signal

thinner ⇔ less scattering, lower V_{dep},
less leakage current

Size:

Often 6×6 cm or smaller. Made on 4” wafer

(In future up to more 9×9 cm on 6” wafers)



Strip pitch 50-200 μm

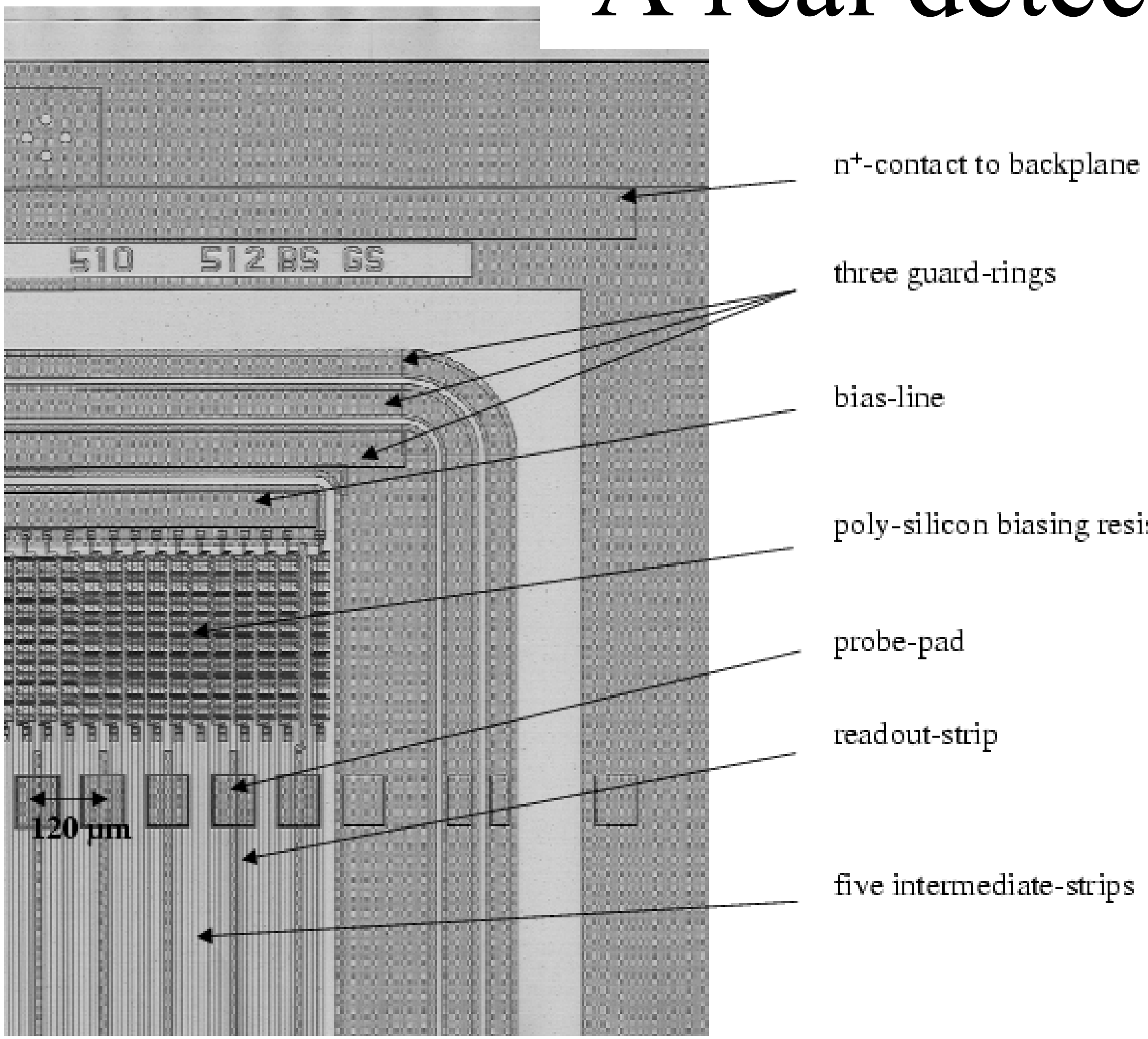
large pitch, fewer strips ⇔ less readout (less cost)

But detector noise scales with strip area (capacitive).

small pitch, more strips ⇔ better position resolution.

E.g. ATLAS SCT (barrel) 300 μm, 6×6 cm, 80 μm ⇒ 768 strips

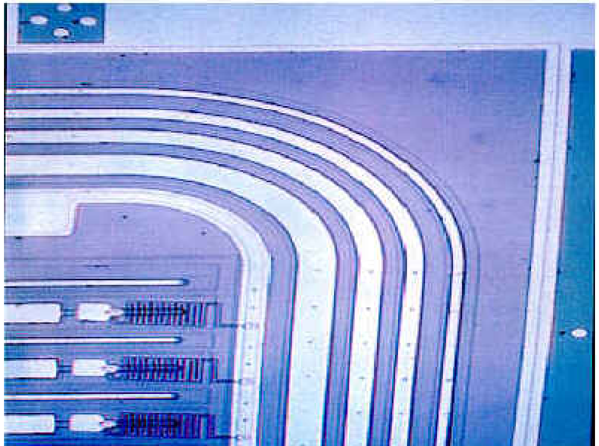
A real detector



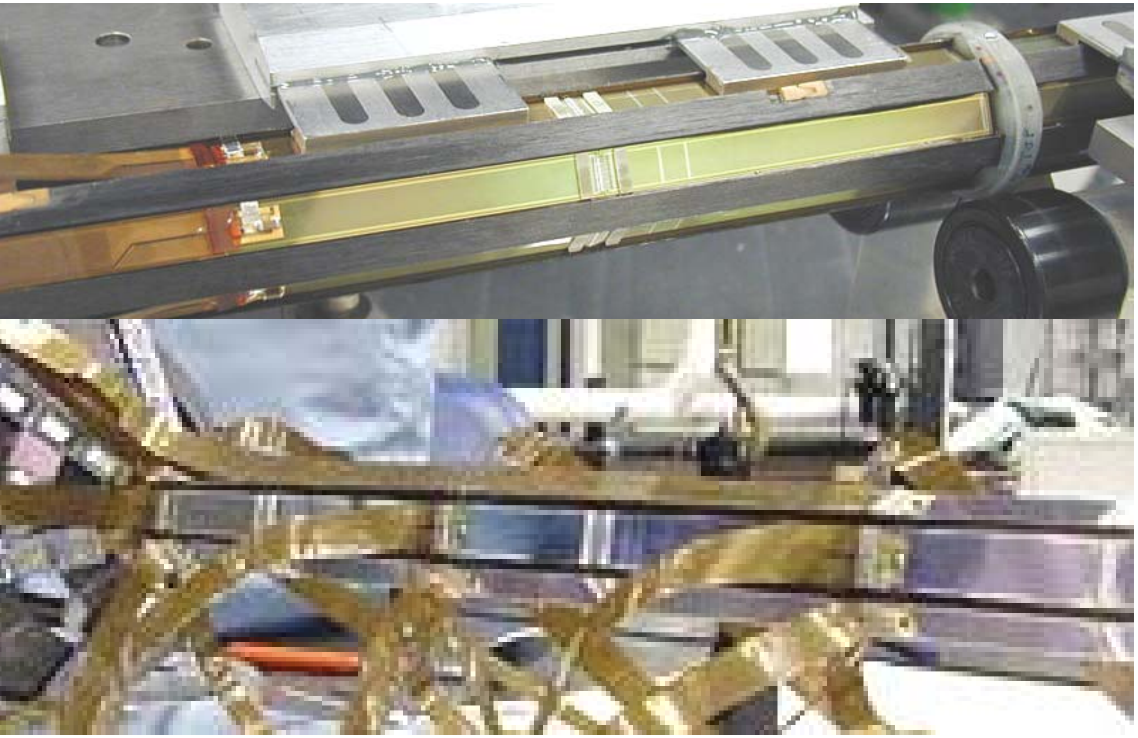
Real sensors have much more features:

- –**Backplane contacts**
- –**Guard rings**
- –**Bias resistors**
- –**P-strips**
- –**Al readout strips**
- –**Coupling capacitors**
- –**…**

Large potential difference at a sharp edge, gives high field, i.e. discharges.
Multiple (floating) guard-rings to between bias and ground (notice smooth corners)



CDF layer00



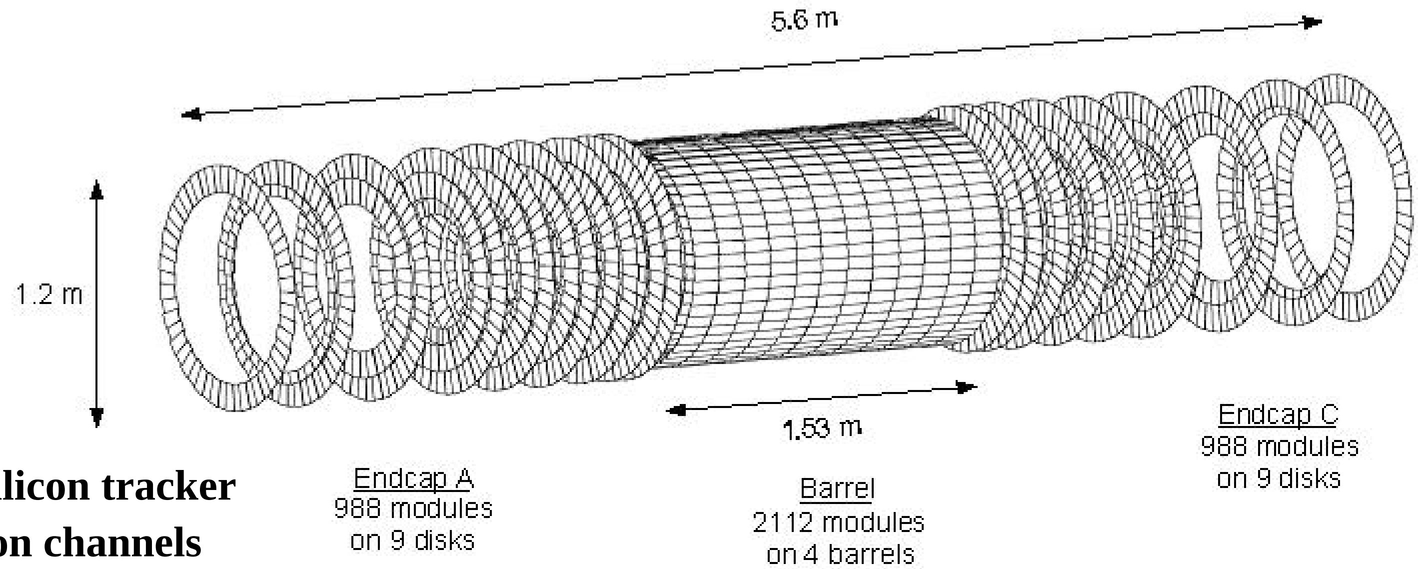
Innermost part of CDF vertex detector
Only ~1.5 cm away from IP!

Detectors:
- strip length: 7.84 cm (2 connected together: 15.7 cm)
- 300 μm thickness
- 25 μm strip pitch (read-out on every other strip)
- signals led out via kapton foils.

Position resolution ~ 6 μm

Role Liverpool: design silicon detectors & design and construction of carbon fibre support structure

ATLAS SCT

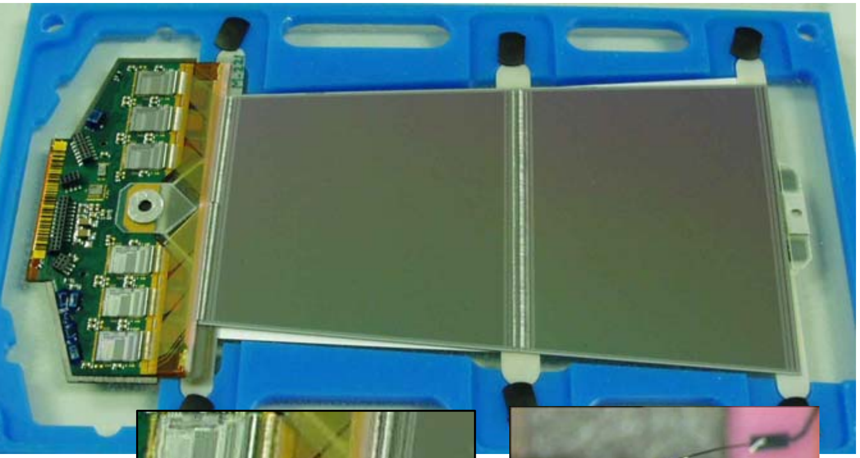


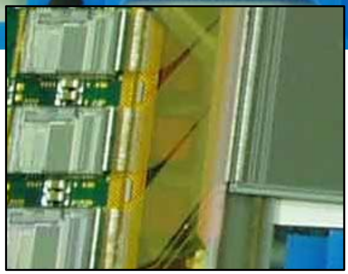
ATLAS SCT

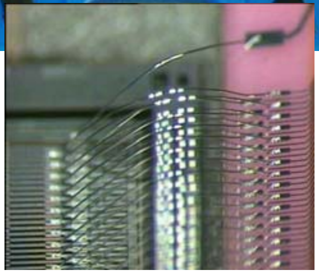
Large area (~60 m^2) of silicon tracker

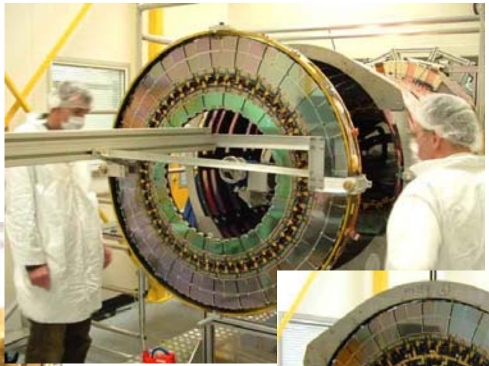
>4000 modules, ~6 Million channels

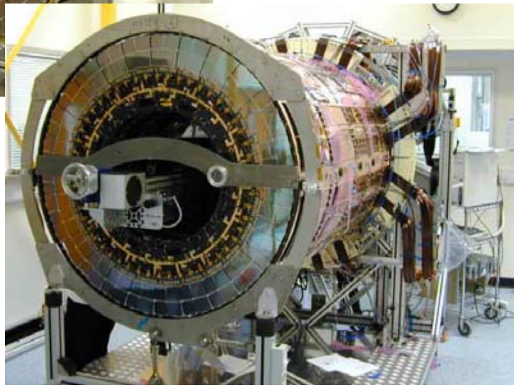
Resolution: rφ ~ 16μm





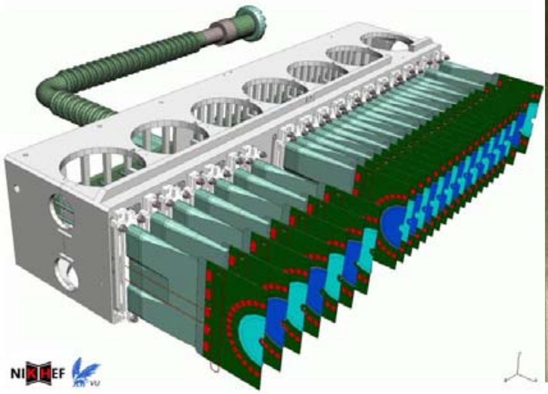


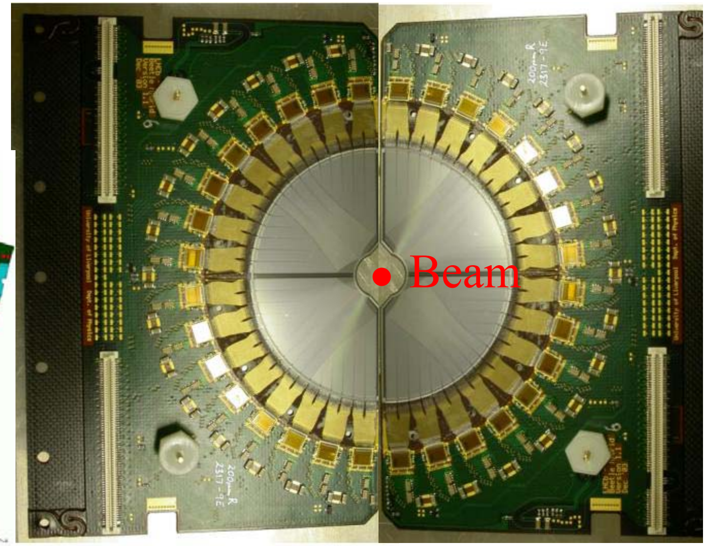


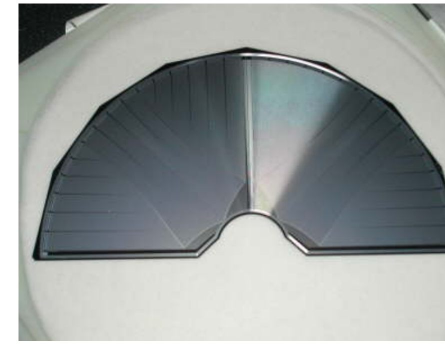


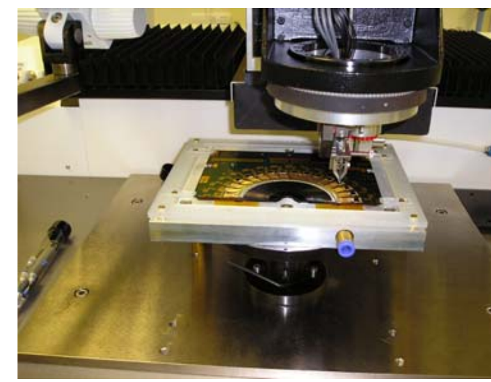
Role Liverpool: R&D silicon technology detector design, hybrid design and module production, disk assembly.

LHC-B Vertex Locator







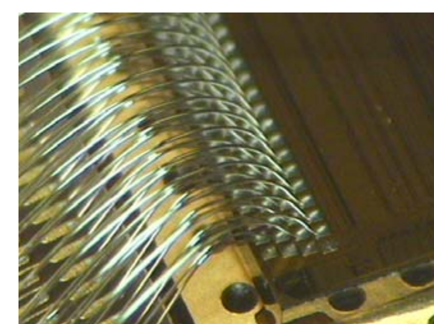


Trigger on b-decay vertices:

in high rate environment

inside secondary vacuum close to the beam .

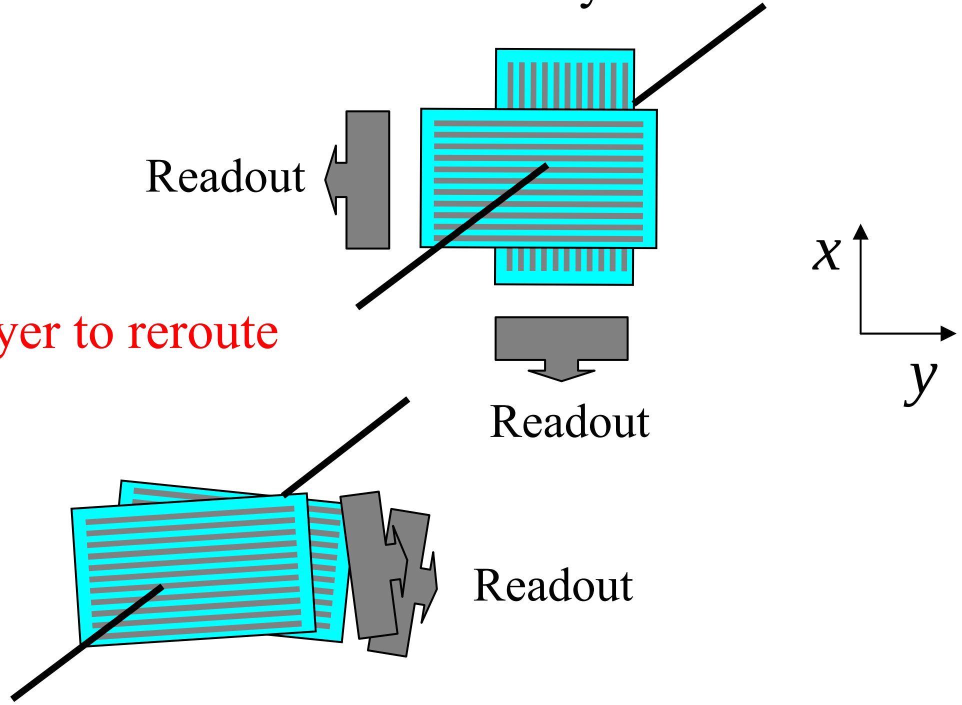
Silicon strip detector with 21 stations that move close to the beam.



Role Liverpool: R&D silicon technology, detector design & hybrid design and full module assembly

Silicon strip detectors: position reconstruction

x and y (or $r\varphi$ and z) reconstruction via combination of differently oriented detectors:



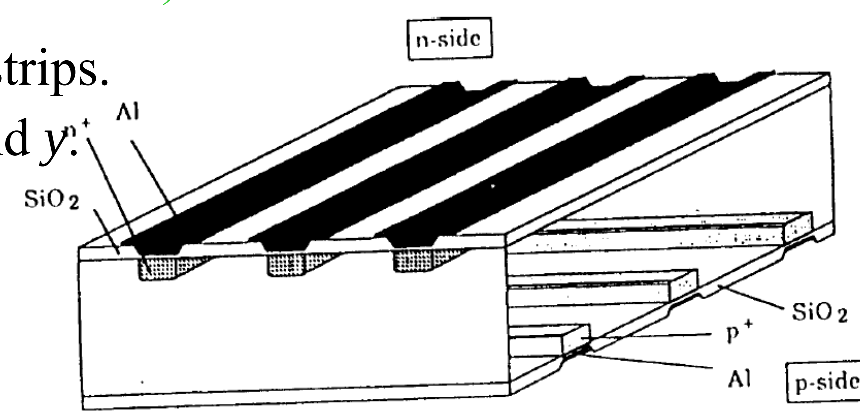
- perpendicular
  - readout from 2 sides or extra layer to reroute
  - more hit ambiguity
- stereo-angle:
  - poorer y resolution
  - + less hit ambiguity
  - + readout from one side (better for vertex detection)

<u>Double-sided detectors:</u> n-type bulk, p^+ and n^+ strips.

Collect both electrons and holes to measure x and y:

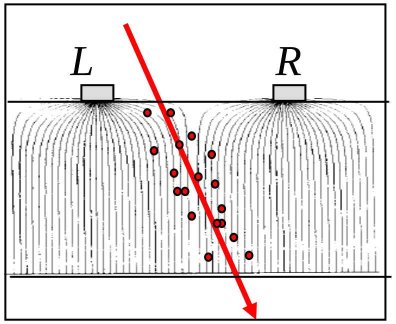
+ less material.

- double-sided processing wafers

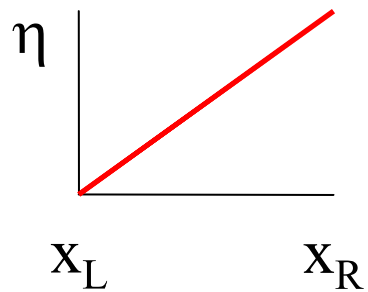


Position reconstruction:

If a particle passes between two strips the deposited charge flows to the nearest strip.
Due to transverse diffusion (~10 µm) and track angle the charge can be shared between strips.

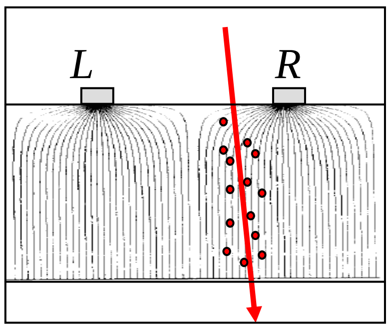


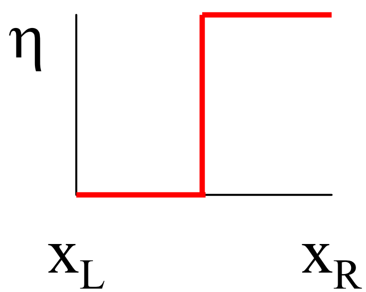
$$\eta = \frac{Q_R}{Q_R + Q_L}$$



Ideally: linear relation η and x

$$x = x_L + \eta\left(x_R - x_L\right)$$

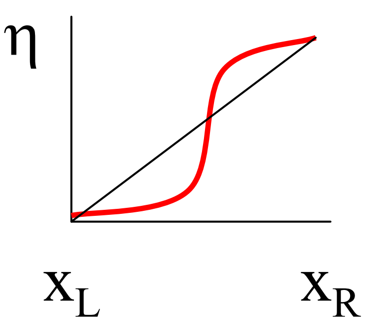




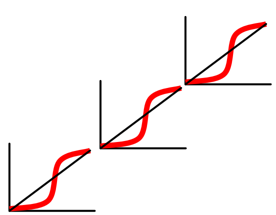
Worst case: no charge sharing, all charge on nearest strip

$$\sigma_x = \text{pitch}/\sqrt{12}$$

Typical situation

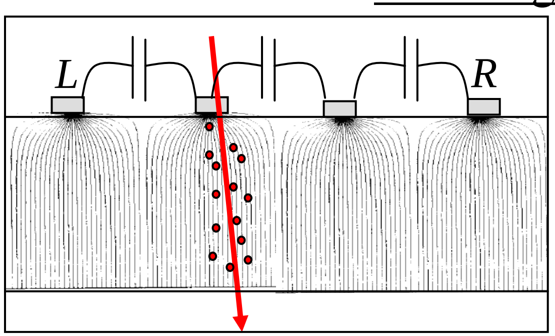


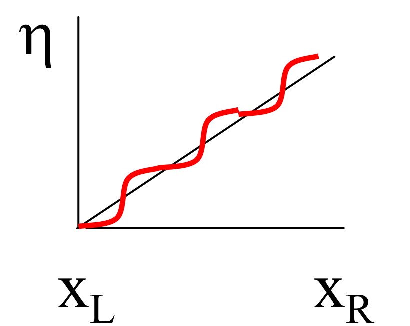
large strip pitch



small pitch
close to ideal situation

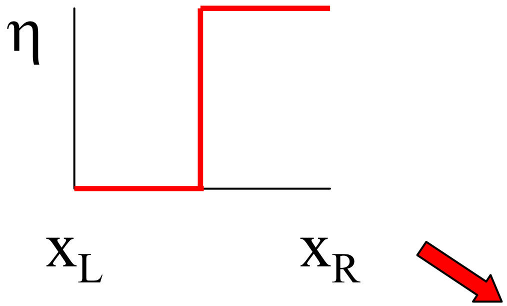
"Floating strips"





readout strips capacitively coupled to intermediate "floating" strips. (less charge collected)

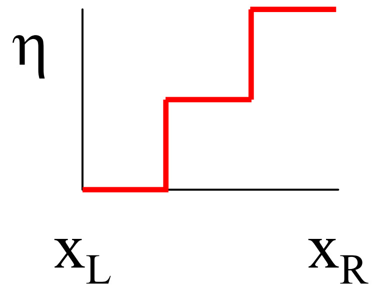
Position resolution



Binary readout:

If no charge sharing: $\dfrac{\text{pitch}}{\sqrt{12}}$

e.g. pitch 80 μm $\Rightarrow \sigma \approx 23$ μm



In practice slightly better as sometimes 2 strips are above threshold

Example: ATLAS SCT strip pitch 80 μm $\Rightarrow \sigma \approx 15$ μm

Analogue/digital readout:

Charge sharing greatly improves the resolution.

- transverse charge diffusion improves the position resolution!
- tracks under angle give better position resolution

Often floating strips can be used:

Example CDF-L00: 25 μm strip pitch (50 μm **read-out** pitch!) $\Rightarrow \sigma \approx 6$ μm

Factors limiting the resolution:

Occurrence of δ-electrons (see next page)

Electronics/detector noise

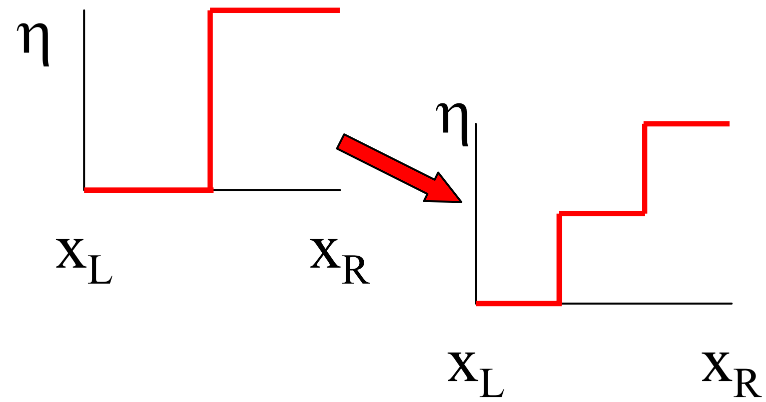
Precision of detector alignment

Position resolution

Binary readout: only work out if strip was above or below given threshold

I no charge sharing: $$\sigma \approx \frac{\text{pitch}}{\sqrt{12}}$$

(e.g. pitch 80 μm $\Rightarrow \sigma \approx 23$ μm)



In practice slightly better as often 2 strips above threshold

(e.g.: ATLAS SCT pitch 80 μm $\Rightarrow \sigma \approx 15$ μm)

Analogue/digital readout: record deposited signal on every strip

(much larger data volume and needs more power)

Measure charge sharing (e.g. due to transverse charge diffusion or tracks under angle)

Much better position resolution

(Can also use intermediate floating strips)

(e.g CDF-L00: 25 μm strip pitch, 50 μm **read-out** pitch $\Rightarrow \sigma \approx 6$ μm)

Other factors limiting the resolution:

Occurrence of δ-electrons (see next page)

Electronics/detector noise

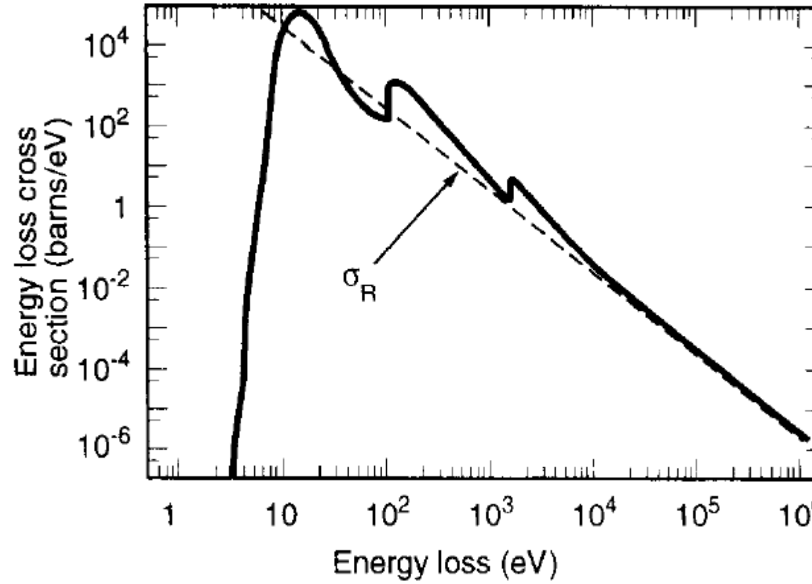
Precision of detector alignment

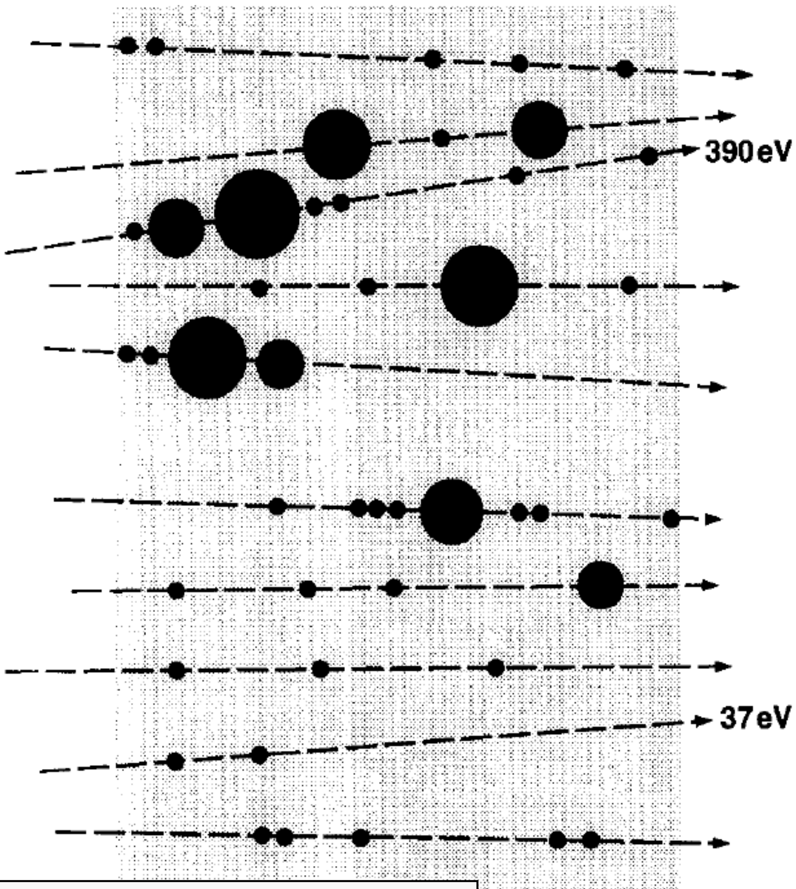
Effect of δ-electrons

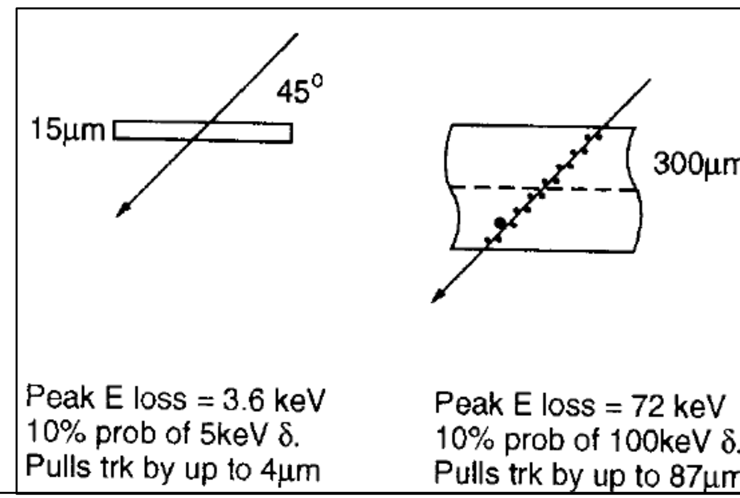
Energy loss in Silicon:

Predominantly collisions with valence electrons.

Tail to high energies due to collisions with electrons in deeper shells. The struck δ-electrons create large clusters of secondary e/hole pairs.





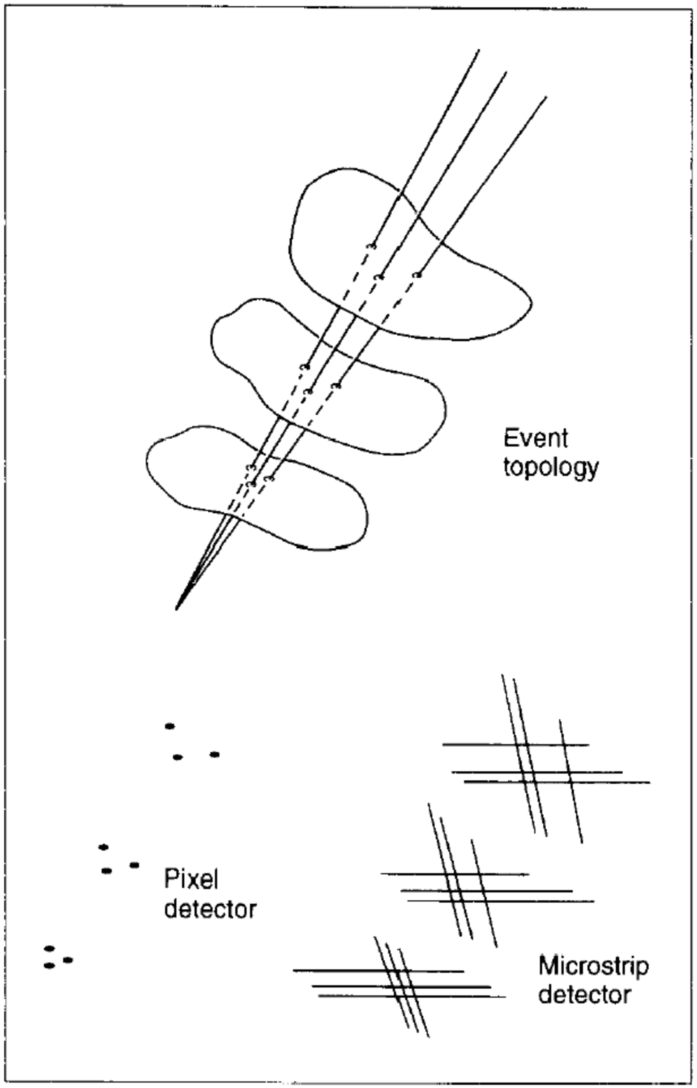


C. Damarell, SLAC Summer Institute on Particle Physics 1995.

In thick detectors δ-electrons spoil the position reconstruction for tracks for non-perpendicular tracks.

Solution: remove high energy hits (needs analogue/digital readout). Loss of efficiency.

Silicon pixel detectors



C. Damarell, SLAC Summer Institute on Particle Physics 1995.

Measure in pixels rather than strips:

Some advantages:

1. Less hit ambiguity
2. Higher granularity means less problems with high occupancy (1 strip ⇔ thousands CCD pixels)
3. More radiation tolerant (leakage current scales with area)
4. Lower capacitive coupling to electronics, less noise, thinner detectors.

Different technologies:

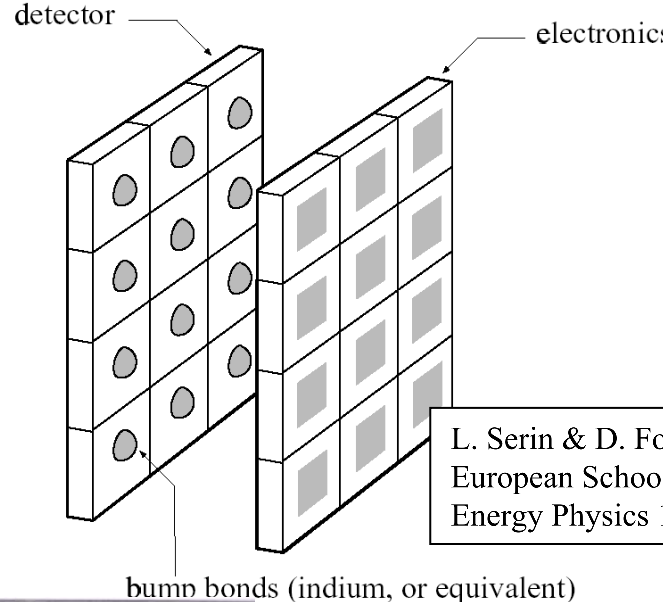
- Hybrid Active Pixel Sensors
- Monolithic Active Pixel Sensors
- Charge Coupled Devices (CCD)

Hybrid and Monolithic Active Pixel Sensors (HAPS/MAPS)

Hybrid technology:

1. strip-detector “cut” into pads
2. readout chip

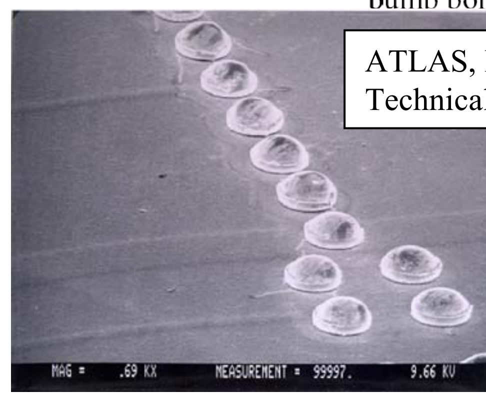
“Bump-bonded” together



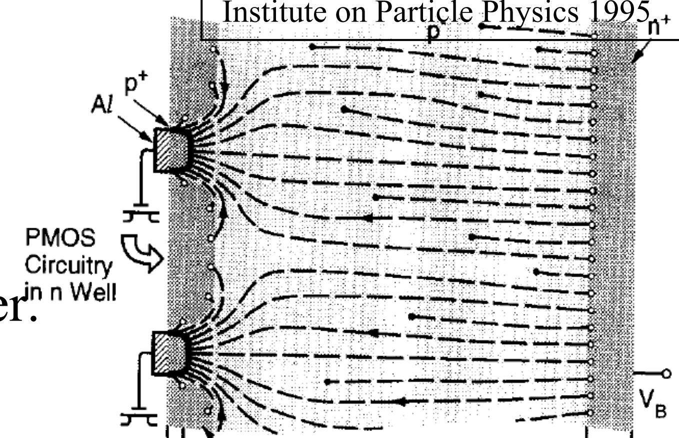
L. Serin & D. Fournier, European School of High Energy Physics 1995

Very short readout path:

- small capacitive coupling to electronics
  - ⇒ much lower noise
  - ⇒ much less signal needed
  - ⇒ thinner active depth detectors
- fast readout



ATLAS, Inner Detector Technical Design Report



C. Damarell, SLAC Summer Institute on Particle Physics 1995

For the future: Monolithic active pixels (MAPS)

Both detectors and readout integrated on one silicon wafer.

Ongoing investigations incl. in Liverpool (e.g. for ILC).

Silicon pixel detectors

ATLAS pixel detector

Hybrid Active Pixel Sensors

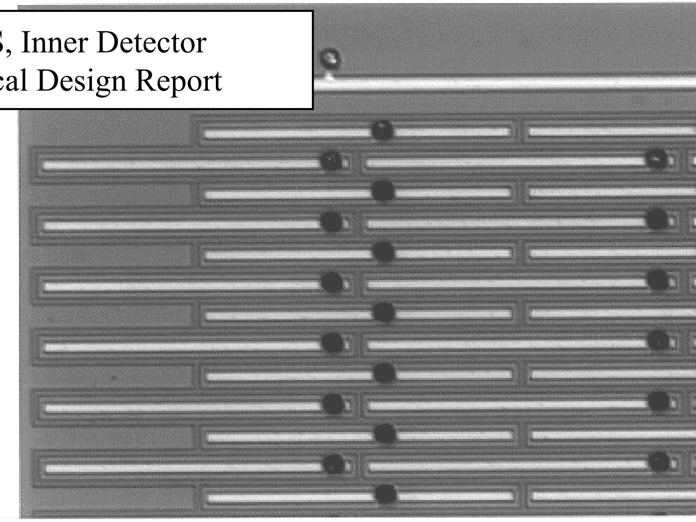
Pixels (as small as) 50 × 400 μm

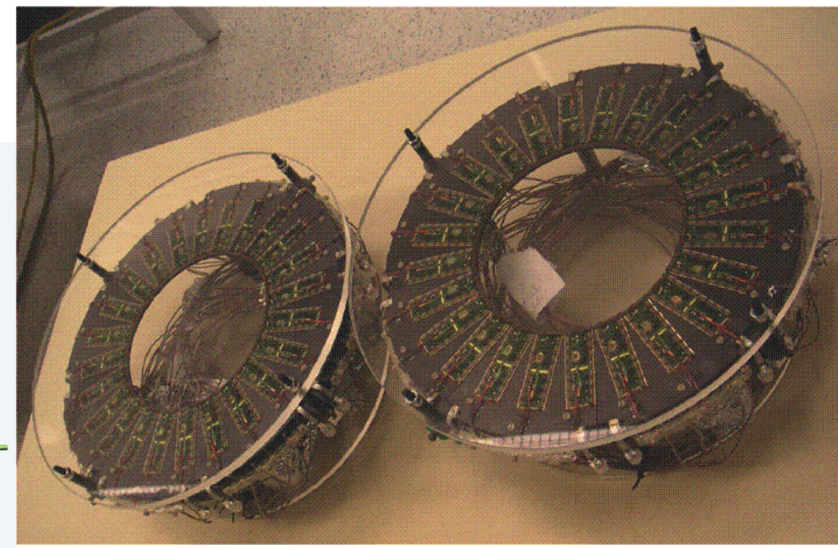
Inner barrel layer R=4.7 cm

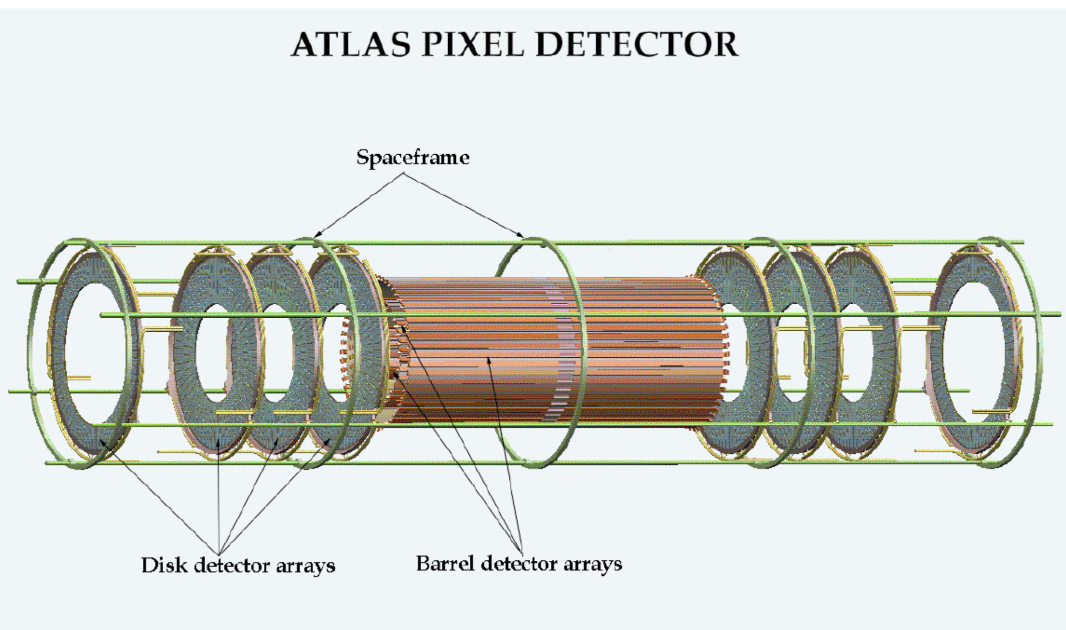
In total 140 million pixels!

Binary readout!

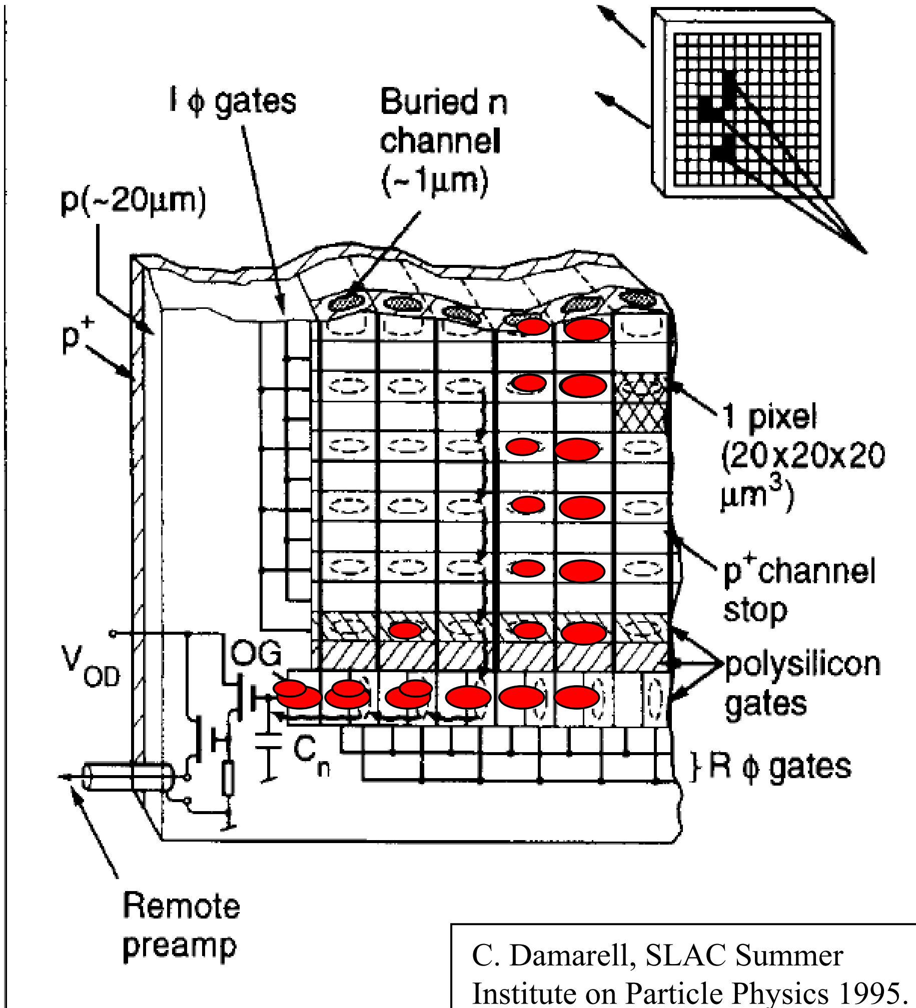
ATLAS, Inner Detector
Technical Design Report







Charge Coupled Devices (CCD)

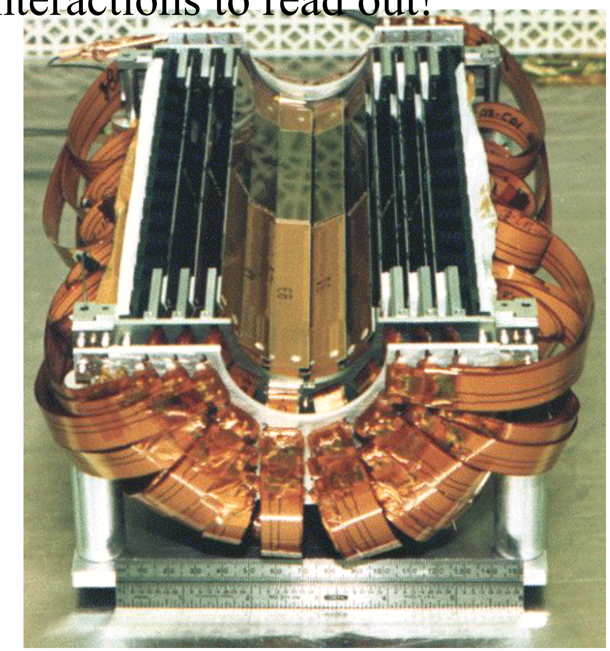


C. Damarell, SLAC Summer Institute on Particle Physics 1995.

Very small detection elements and very thin active layer.

Mainly used in optical applications. (All pixels read out via one amplifier, excellent uniformity)

Readout of CCD's is slow! Need time with no interactions to read out!



Successfully used in SLD vertex detector

Can they be made faster, to be used in a high rate environment?

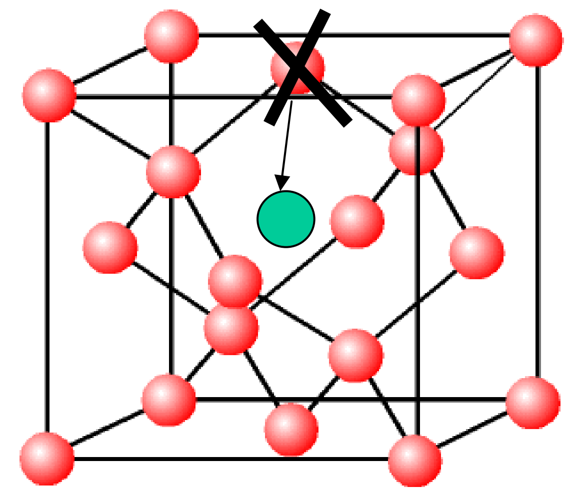
E.g. "Column parallel readout"

Ongoing research for ILC (also in Liverpool).

Radiation damage to silicon detectors

Silicon detectors are often operated in high particle density environment and very close to the interaction point.

Radiation with protons/neutrons



Surface damage: ion trapping in SiO_2, leading to charge on Si-SiO_2 interface. Sensor design must be robust against this (not discussed here).

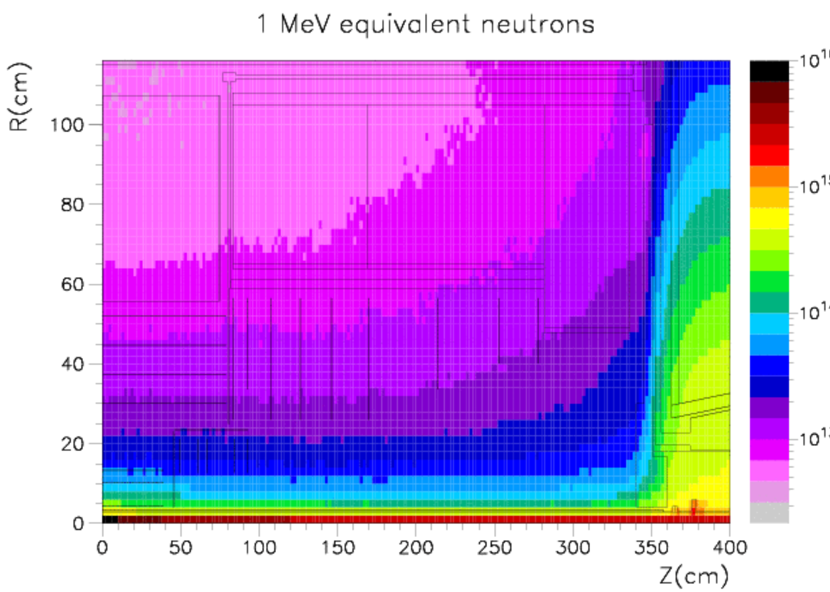
Bulk damage: displacement of Si atoms within the crystal leaves vacancies and interstitials (defects).

- Energy needed to displace atom from lattice=15eV
- Damage energy dependent
  - $<$ 2 keV $\Rightarrow$ isolated point defect
  - 2-12 keV $\Rightarrow$ defect cluster
  - $>$12 keV $\Rightarrow$ many defect clusters
- This damage is called:

  Non-Ionizing Energy Loss (NIEL)

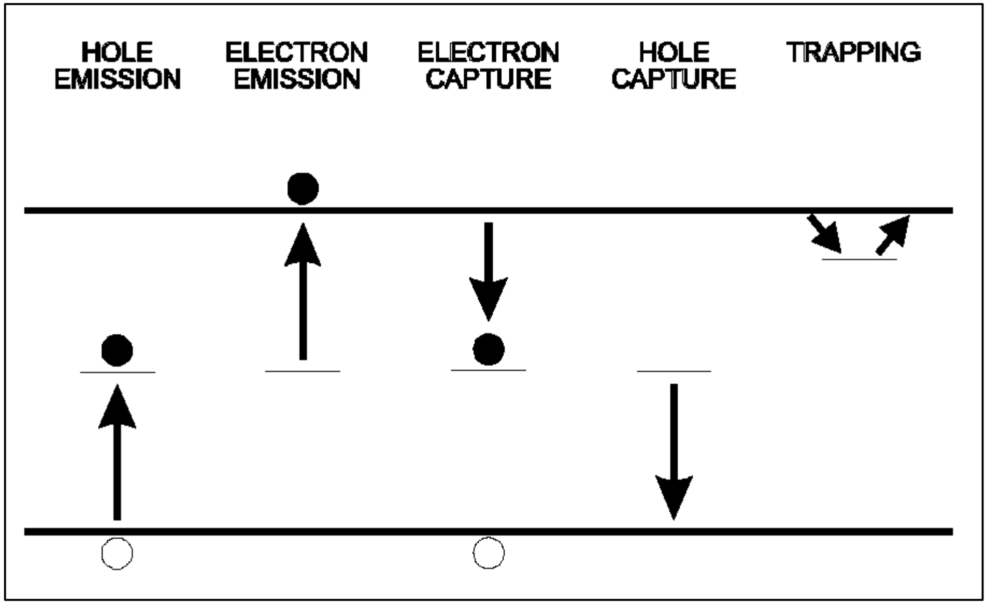
  – Results scaled to 1MeV neutrons

  (e.g. ATLAS ID up to ~2×10^{14} $n_{eq}cm^{-2}yr^{-1}$)
- Electrons and photons don't make defects!



Radiation damage to silicon detectors

Defects in the lattice leave extra energy levels in band-gap.



These can:

- donate electron/holes
- capture electron/holes (trapping)
- increase leakage current (two-step transitions valence to conduction band)
- act as recombination centres

Damaging effects on Silicon detectors:

- increased leakage currents
- type-inversion (change of effective doping type)
- reduced charge collection efficiency and charge carrier mobility

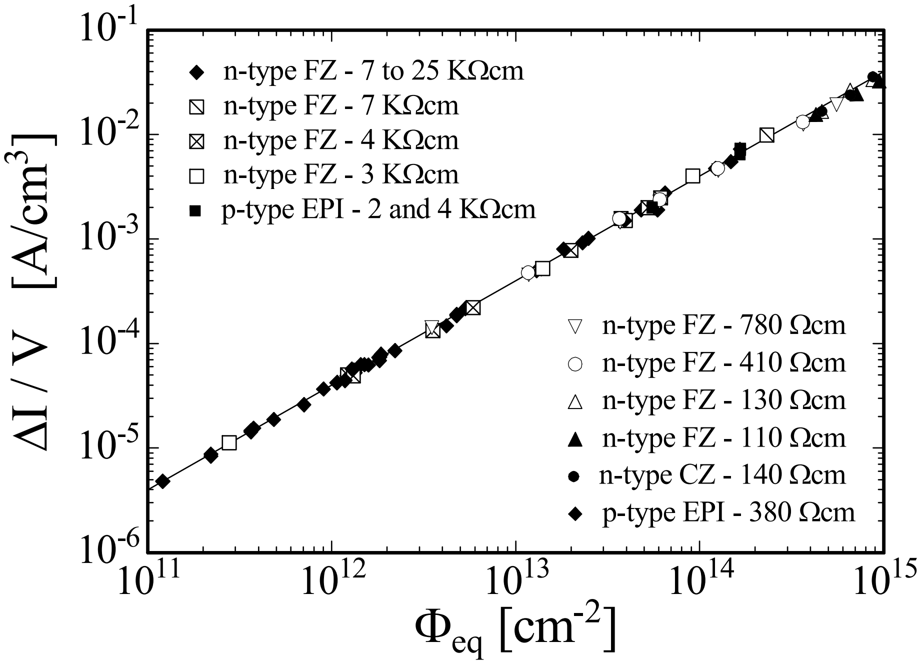
Detailed behaviour depends on many factors (e.g. other impurities present)

Annealing

Crystals can recover from radiation damage:

- Atoms (re)occupy vacancies
- Defect complexes can change into different complexes. (New defect complexes can also worsen damage, reverse annealing).
- highly temperature dependent
- Not very well understood
  - depends on which (unintentional) impurities present
  - which defects are formed

Leakage current



Independent of Silicon type (linked to defect clusters)

Same goes or annealing.

Scales with radiation dose $\quad I = \alpha \Phi V$

Strong temperature dependence

$$I(T) \propto T^2 \exp\left(-\frac{E_{gap}}{2kT}\right)$$

<u>Problems:</u>

- more current is more noise
- more current $\rightarrow$ more power $\rightarrow$ heating $\rightarrow$ more current $\rightarrow$ .. (thermal runaway)

<u>Solutions:</u>

- need efficient cooling to stop Silicon heating up
- run cold to reduce current (~ factor 10 less current per 20°)

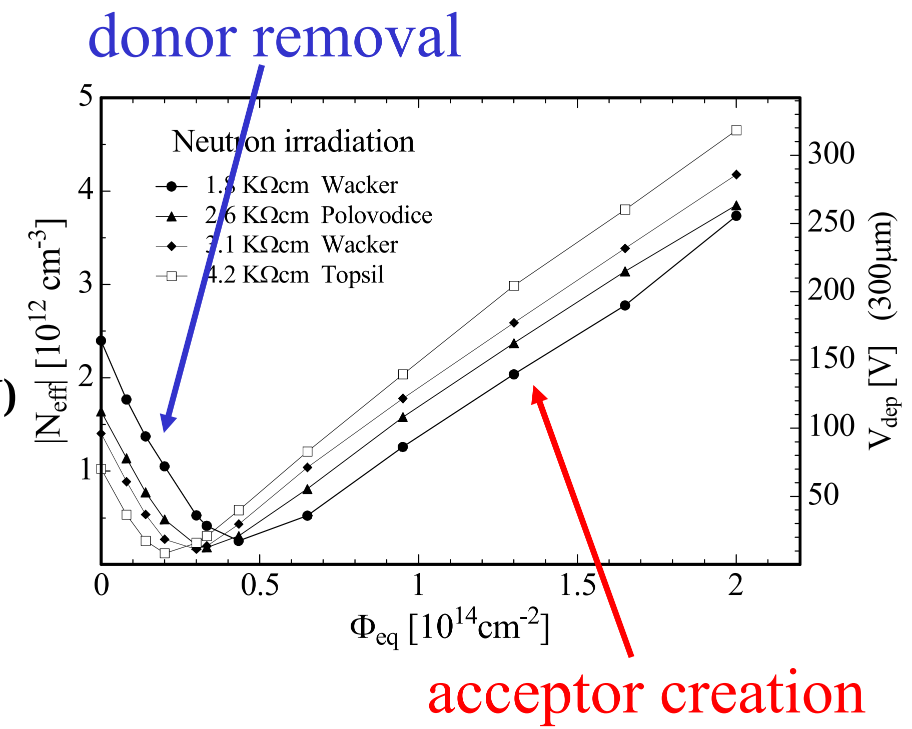
Type inversion

Type inversion:

Crystal defects act as electron acceptor

- Bulk: *n*-type ⇒ *p*-type
- After irradiation higher bias voltage needed

  (ATLAS-SCT: initially 150V, rising up to 500V)
- Damage continues to worsen when radiation has stopped (reverse annealing).



Solution (up to few times 10^{14} $n_{eq}cm^{-2}$)

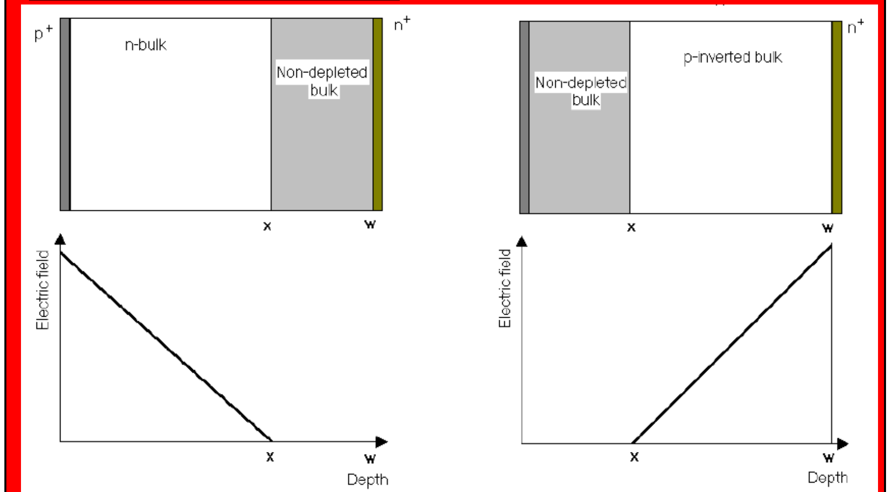
- keep detectors cold (stops reverse annealing effect)
- design detectors to allow operation with high V_{BIAS} (include guard-rings)

After very high irradiation when an adequate bias voltage can no longer be set detectors operate under-depleted.

Under-depleted detectors

<u>p-strips in n-bulk detector (p-in-n)</u>

<u>before irradiation</u> <u>after irradiation</u>

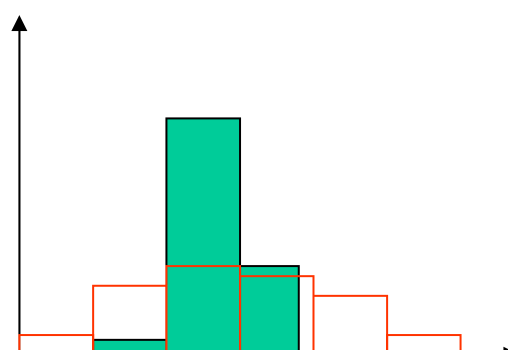


Undepleted region acts like an ohmic resistor.

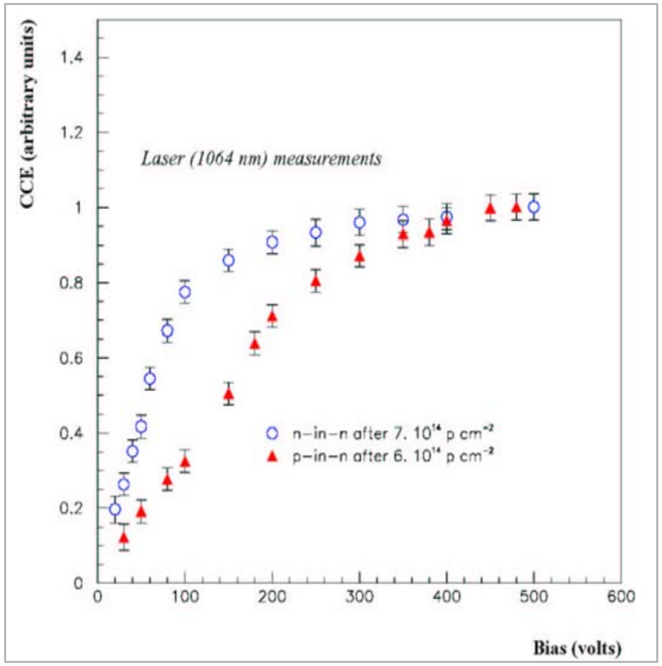
- no effective conduction
- no/weak field to collect charge to the nearest strip (relying on diffusion)

If detector is partially depleted:

- near the strip side
  - ⇒ only charge in depleted region contributes
  - ⇒ smaller signal, same spatial resolution
- near the backplane
  - ⇒ carriers travel towards strips, but don't reach it
  - ⇒ signal spread over many strips
  - ⇒ poor spatial resolution



At very high radiation levels



<u>Use shorter strips or pixels:</u>

Same signal

less noise (lower capacitance, less leakage current)

<u>n^+-in-n(LHC-b VeLo) or n-in-p:</u>

depletion region stays on the strip side of the detector

- higher charge collection when under-depleted

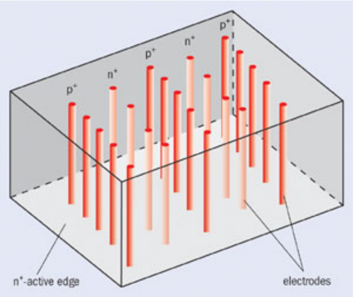
n-strips collect electrons (instead of holes):

- faster and less trapping

<u>material engineering</u> (e.g. oxygenation can slow down type inversion)

<u>operate cold</u> (different radiation effect less serious when running cold)

<u>different materials</u>: e.g. diamond, large E_{gap} → few free charge carriers → no need for reverse-biased diode



<u>3D-structures</u> ("bring the strip to the charge")

<u>Silicon-on-insulator</u>

<u>cryogenic operation</u> (trapping centres remain filled, "Lazarus effect")

Next Lecture

I Introduction

II Gaseous tracking detectors

III Semi-conductor trackers

IV Calorimetry

V Particle identification