European School of Instrumentation
in Particle & Astroparticle Physics

European Scientific Institute

DETECTOR TECHNOLOGIES

Lecture 2: Semi-conductors

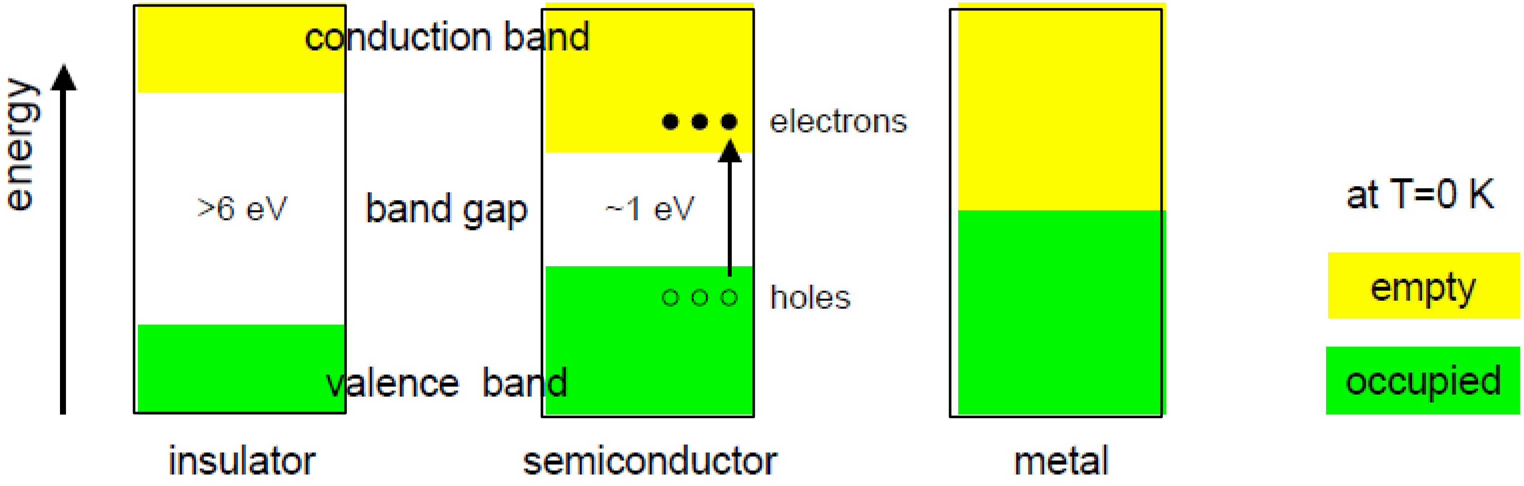
- Generalities
- Material and types
- Evolution

Semiconductors : generalities

Solid-States band structures :

Valence band : e⁻ bond atoms together

Conduction band : e⁻ can freely jump from an atom to another



At T ≠ 0 K

Electrons may acquire enough energy to pass the band gap…

Thermal condution

at T>0 K

$$n_i = p_i = \sqrt{N_c N_v}\, e^{-\frac{E_g}{2kT}} = A T^{3/2} e^{-\frac{E_g}{2kT}}$$

n_i: intrinsic density of electrons in conduction band

p_i: intrinsic density of hole in valence band

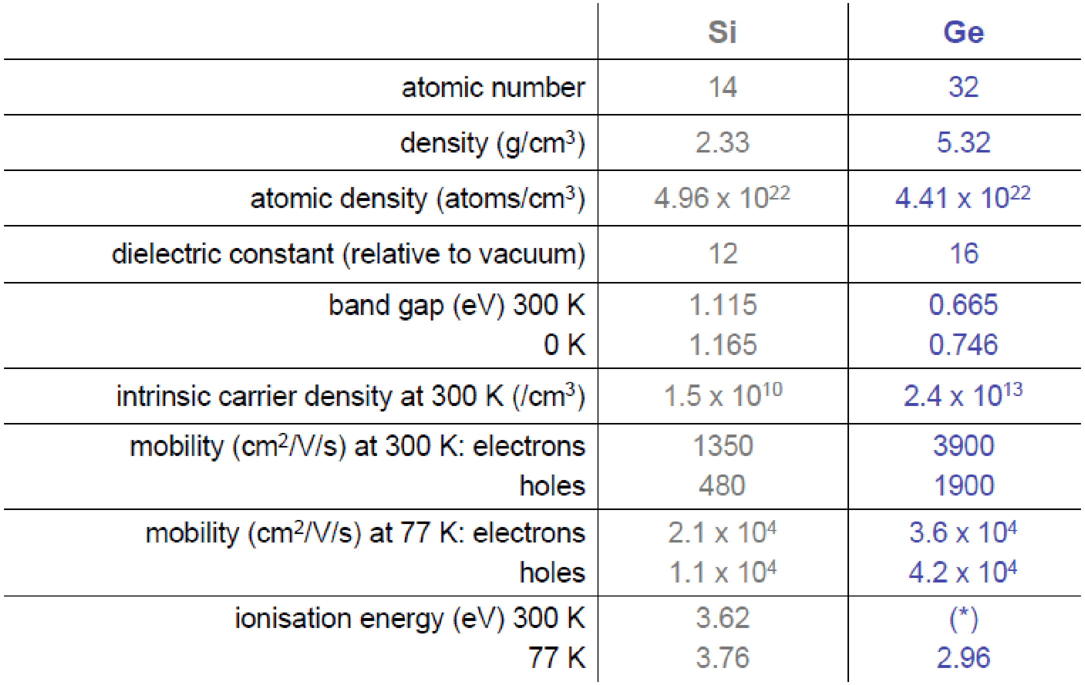
$N_{c,v}$: number of states in conduction, valence band

E_g: band gap at 0 K

A: temperature-independent constant

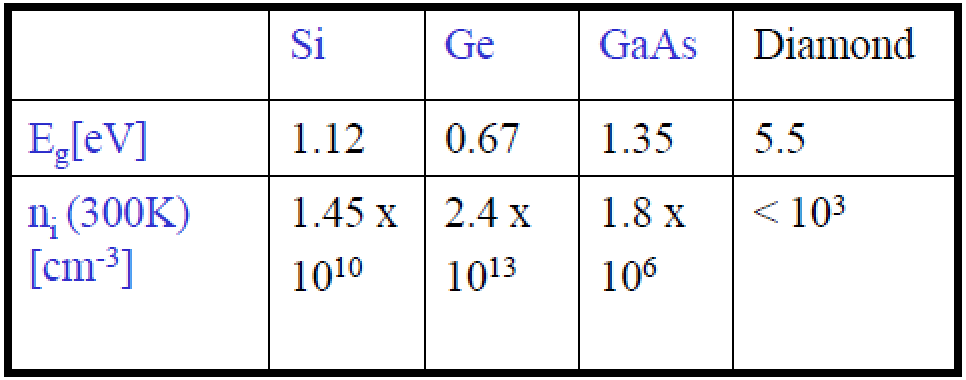
kT at 300 K = 0.025 eV

Semiconductors : generalities



	Si	Ge
atomic number	14	32
density (g/cm^3)	2.33	5.32
atomic density (atoms/cm^3)	4.96×10^{22}	4.41×10^{22}
dielectric constant (relative to vacuum)	12	16
band gap (eV) 300 K	1.115	0.665
0 K	1.165	0.746
intrinsic carrier density at 300 K (/cm^3)	1.5×10^{10}	2.4×10^{13}
mobility (cm^2/V/s) at 300 K: electrons	1350	3900
holes	480	1900
mobility (cm^2/V/s) at 77 K: electrons	2.1×10^4	3.6×10^4
holes	1.1×10^4	4.2×10^4
ionisation energy (eV) 300 K	3.62	(*)
77 K	3.76	2.96

Not the same !
(Thermal excitation + phonons)



	Si	Ge	GaAs	Diamond
E_g[eV]	1.12	0.67	1.35	5.5
n_i (300K) [cm^{-3}]	1.45×10^{10}	2.4×10^{13}	1.8×10^{6}	$< 10^3$

Semiconductors : generalities

Energy loss by a charged particle : Bethe-Bloch

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

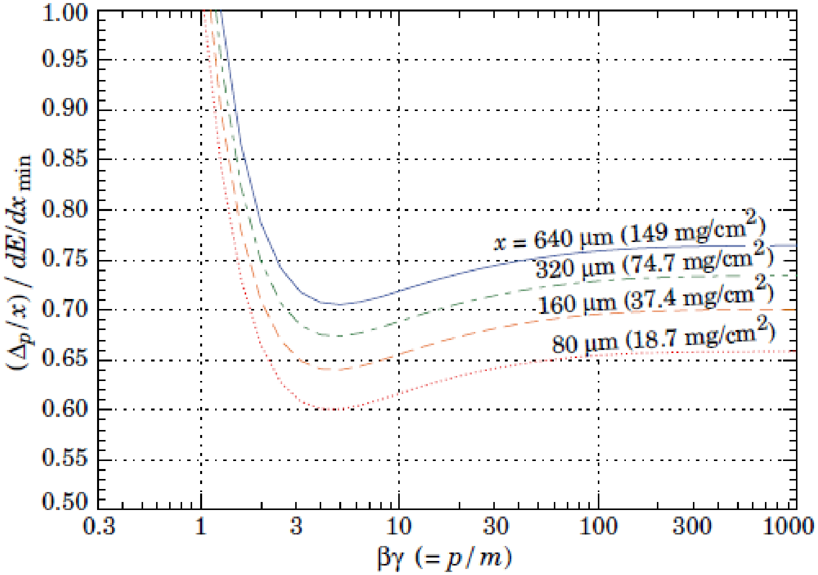


Figure 27.9: Most probable energy loss in silicon, scaled to the mean loss of a minimum ionizing particle, 388 eV/μm (1.66 MeV g^{-1}cm^2).

Standard :

Energy loss :

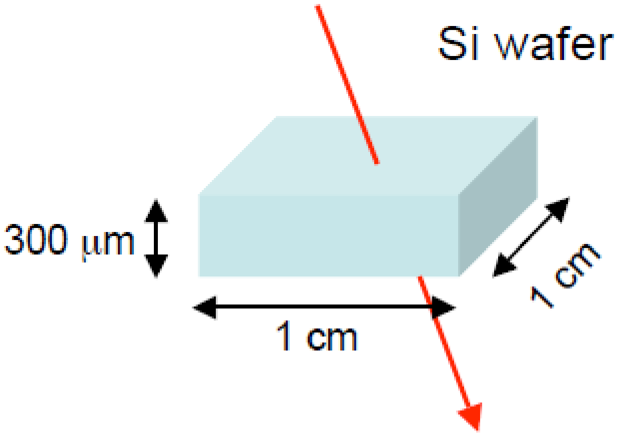
- electrons – holes pairs created
- (NOT electrons – ions…)

If Field (even natural)

- electrons migration
- Electrical pulse
- Information

Too simple !

Semiconductors : generalities



One MIP in Silicon at 300°K

Ionisation Energy : 3.62 eV
Energy loss : dE / dx ≈ 388 eV/µm

→ e – holes pairs created : 107/µm
For 300 µm : **3.2 10 ^{4}** pairs created

at T>0 K

$$n_i = p_i = \sqrt{N_c N_v}\, e^{-\frac{E_g}{2kT}} = AT^{3/2}\, e^{-\frac{E_g}{2kT}}$$

n_i: intrinsic density of electrons in conduction band
p_i: intrinsic density of hole in valence band
$N_{c,v}$: number of states in conduction, valence band
E_g: band gap at 0 K
A: temperature-independent constant

kT at 300 K = 0.025 eV

→ Free charge carriers in the same volume :
≈ **4.5 10 ^{9}**

Signal is lost !
Solution : Depletion of the detector
- Doping
- Blocking contacts

Depletion : removing the maximum possible thermally excitable electrons

Semiconductors : generalities

One of the most important parameter of a detector is the signal to noise ratio (SNR). A good detector should have a large SNR. However this leads to two contradictory requirements:

- ✘ Large signal
  → low ionisation energy → small band gap
- ✘ Low noise
  → very few intrinsic charge carriers → large band gap

An optimal material should have $E_g \approx 6$ eV.

In this case the conduction band is almost empty at room temperature and the band gap is small enough to create a large number of e^-h^+ pairs through ionisation.

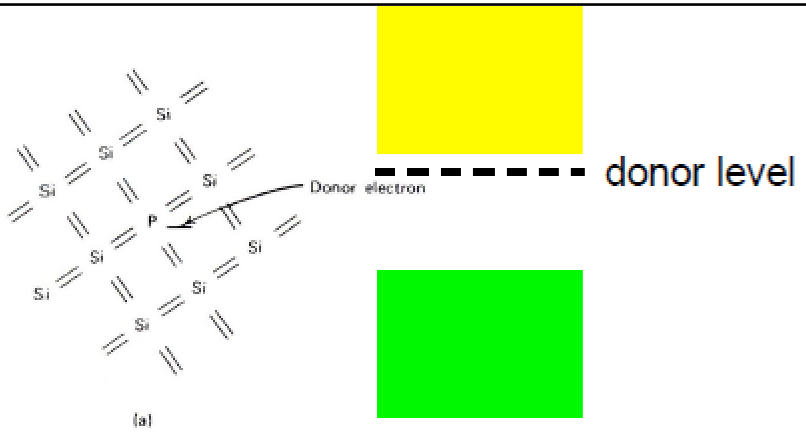
Such a material exist, it is Diamond. However even artificial diamonds (e.g. CVD diamonds) are too expensive for large area detectors.

Have to "modify" the semiconductor :

2 contradictory requirements : 2 contradictory remedies…

Semiconductors : generalities : p and n types

n - TYPE

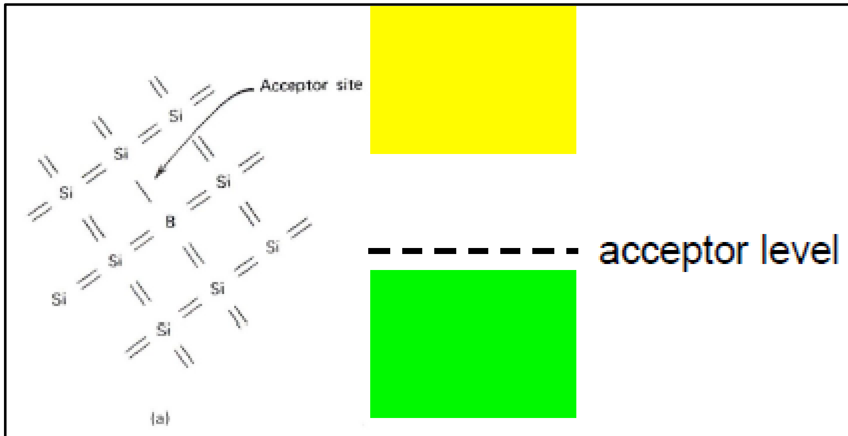


- pentavalent elements (group V/15, e.g. P, As, Sb) have one electron too much to fit in: "donor impurities"
- extra electrons are lightly bound
  - energy level close to the conduction band
  - thermally excited into the conduction band
  - recombination with holes: $n_e >> n_h$

→ n-type semiconductors
  - electrons are the majority charge carriers
  - holes are the minority charge carriers

dopants :
Arsenic, Phosphorous

p - TYPE



- trivalent elements (group III/13, e.g. Ga, B, In) have one electron too little to fit in: "acceptor impurities"
- electrons in missing bond slightly less bound
  - energy level close to the valence band
  - thermally excited electrons fill the acceptor level, creating holes
  - holes recombine with conduction band electrons: $n_h >> n_e$

→ p-type semiconductors
  - holes are the majority charge carriers
  - electrons are the minority charge carriers

dopants :
Boron, Gallium, Indium

Semiconductors : generalities : p and n types

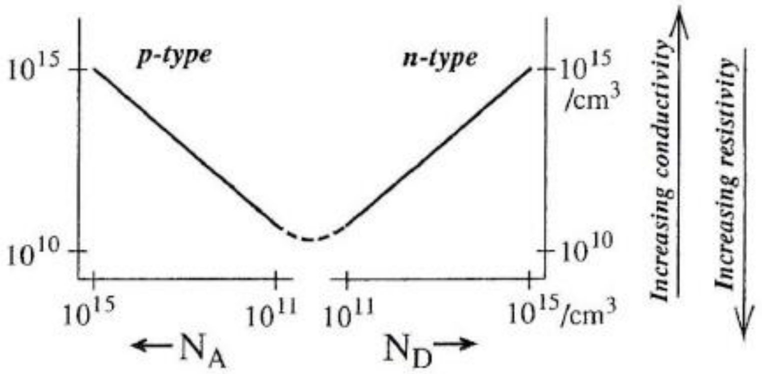


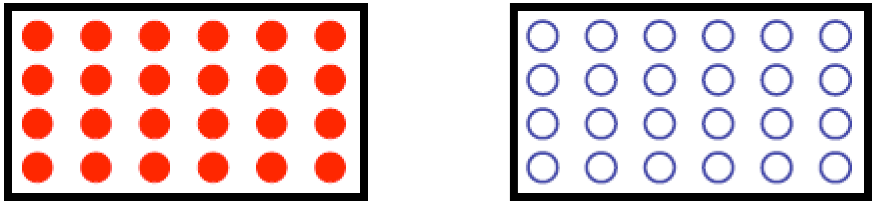
Figure 11.6 Plot using logarithmic scales of the conductivity of a semiconductor as a function of the net concentration of acceptors (N_A) or donors (N_D).

Typically : doping level for a Silicon Detector : 10 ^{12} atoms / cm ^{3}
Doping us usually done by ion implantation.

Semiconductors : generalities : junction detectors

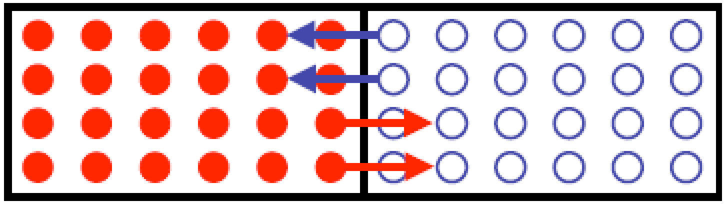
n-type
mobile electrons

p-type
mobile holes

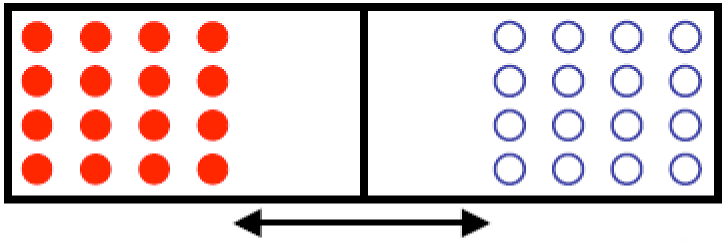


A p-n junction is formed when a single crystal of semiconductor is doped with acceptors on one side and donors on the other

diffusion: holes to n-region, electrons to p-region



uncompensated fixed charges build up
emerging “contact” potential stops diffusion



depletion region

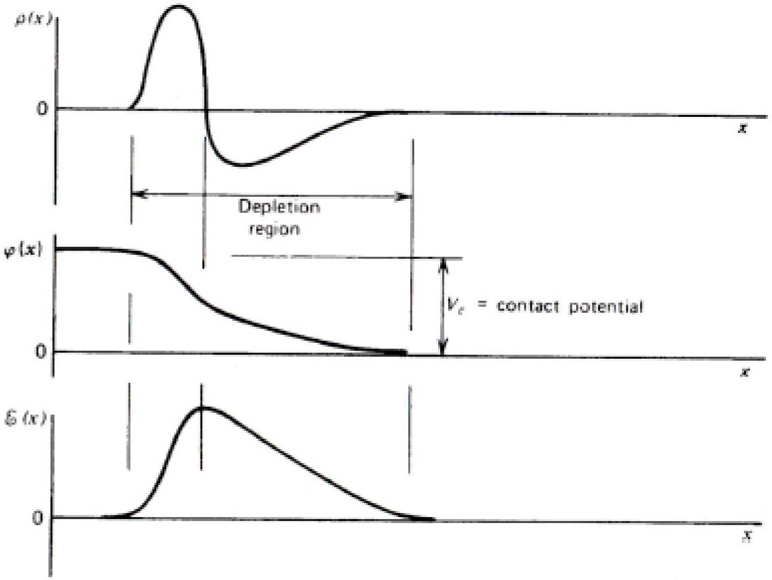
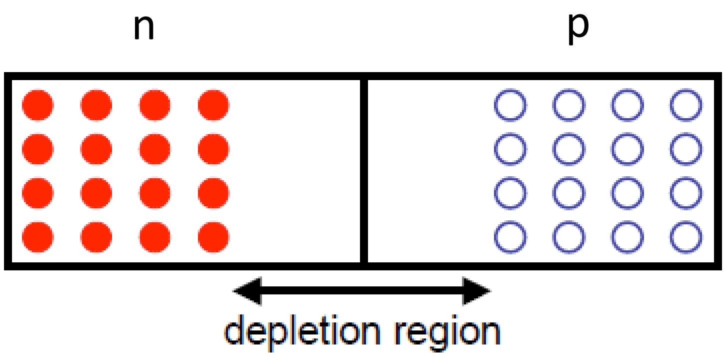


Figure 11.8 The assumed concentration profiles for the *n-p* junction shown at the top are explained in the text. The effects of carrier diffusion across the junction give rise to the illustrated profiles for space charge $\rho(x)$, electric potential $\varphi(x)$, and electric field $\mathscr{E}(x)$.

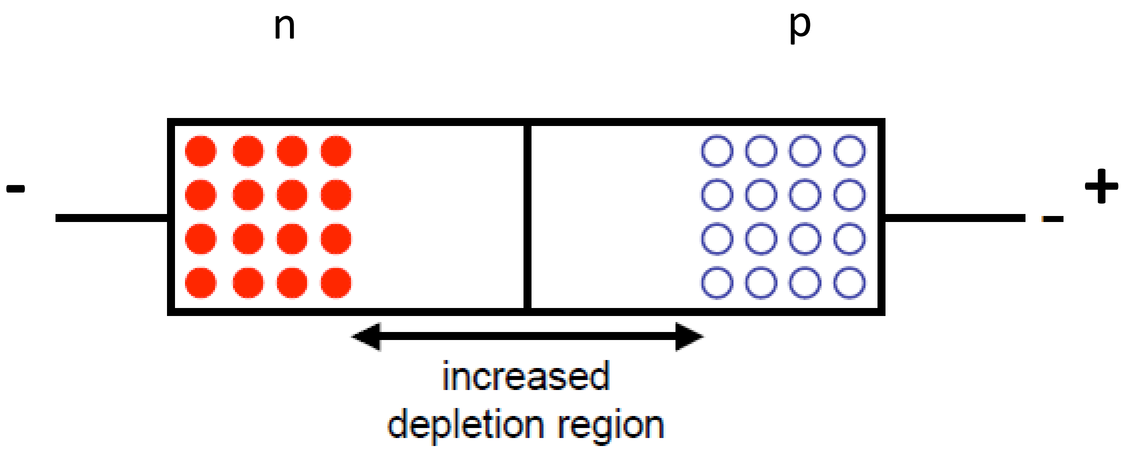
11

Semiconductors : generalities : junction detectors



- thermally generated charge carriers are quickly swept away due to the contact potential
  - → highly suppressed charge carrier density
  - → relatively small amount of charge carriers created by an ionising particle is easily detected
- poor performance because:
  - small contact potential (~1 V): slow-moving charges can be trapped, resulting in incomplete charge collection
  - depletion layer is thin:
    - high capacitance → large electronic noise
    - small sensitive volume cannot detect high-energy radiation

Semiconductors : generalities : forward biasing scheme

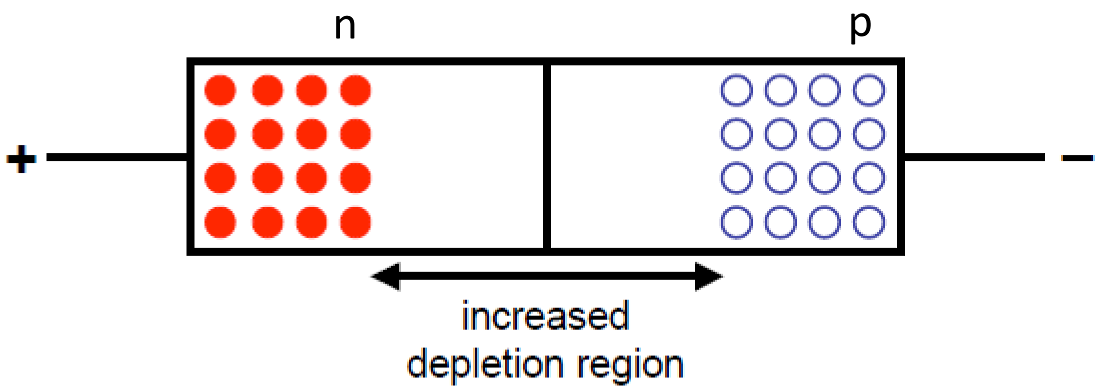


Holes are refilled in the depletion zone…
The depletion zone is narrower

The current across the Si (Leakage Current) increases

Not Good !

Semiconductors : generalities : reverse biasing scheme



- bias: 100 - 1000 V/cm
- V >> contact potential
- depletion region thickness increases
  - smaller capacitance, smaller electronic noise
  - quick and c

$$d = \left(\frac{2\,\varepsilon\,V}{e\,N}\right)^{1/2}$$

d: depletion region thickness
V: reverse bias voltage
ε: dielectric constant
e: electronic charge
N: net impurity concentration (atoms/cm^3)

Depletion zone becomes larger
Leakage Current decreases

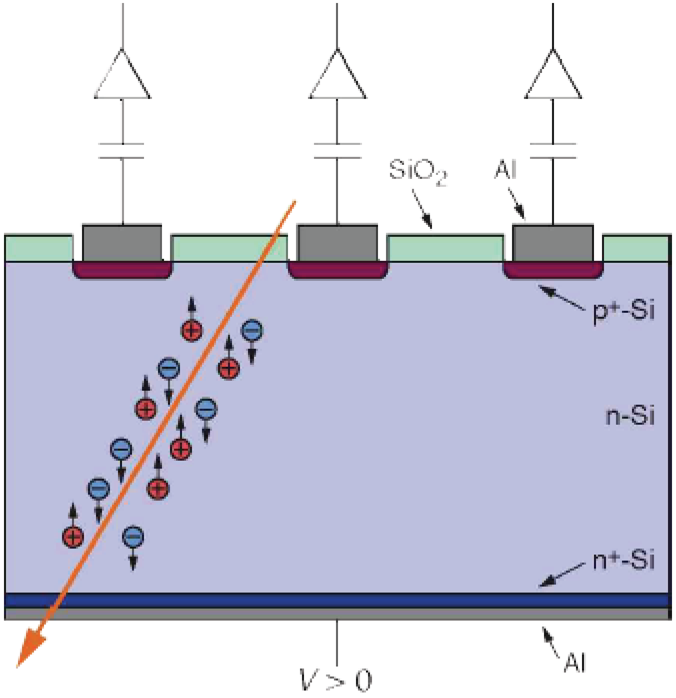
GOOD !

DC Coupling Silicon detector

Through going charged particles create e^-h^+ pairs in the depletion zone (about 30.000 pairs in standard detector thickness). These charges drift to the electrodes. The drift (current) creates the signal which is amplified by an amplifier connected to each strip. From the signals on the individual strips the position of the through going particle is deduced.

A typical n-type Si strip detector:

- ★ p^+n junction:
  $N_a \approx 10^{15}\ \mathrm{cm}^{-3}$, $N_d \approx 1\text{–}5 \cdot 10^{12}\ \mathrm{cm}^{-3}$
- ★ n-type bulk: $\rho > 2\ \mathrm{k\Omega cm}$
  ➔ thickness 300 μm
- ★ Operating voltage < 200 V.
- ★ n^+ layer on backplane to improve ohmic contact
- ★ Aluminum metallization

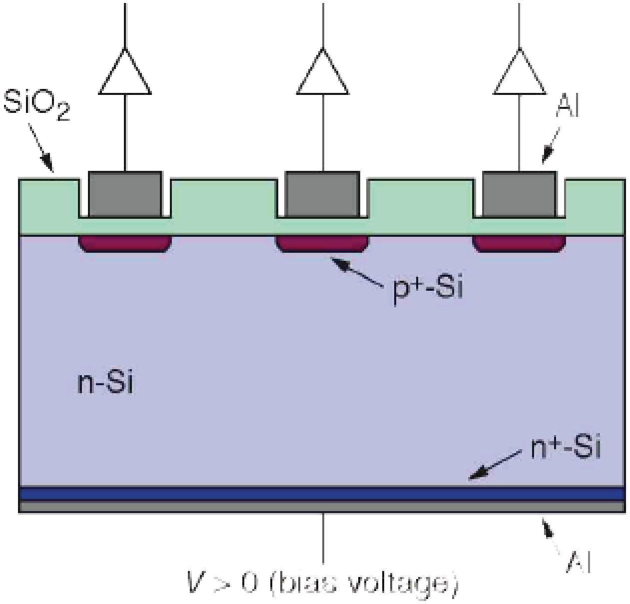


AC Coupling Silicon detector

AC coupling blocks leakage current from the amplifier.

- ★ Integration of coupling capacitances in standard planar process.
- ★ Deposition of SiO_2 with a thickness of 100–200 nm between p+ and aluminum strip
- ★ Depending on oxide thickness and strip width the capacitances are in the range of 8–32 pF/cm.
- ★ Problems are shorts through the dielectric (pinholes). Usually avoided by a second layer of Si_3N_4.

AC coupled strip detector:

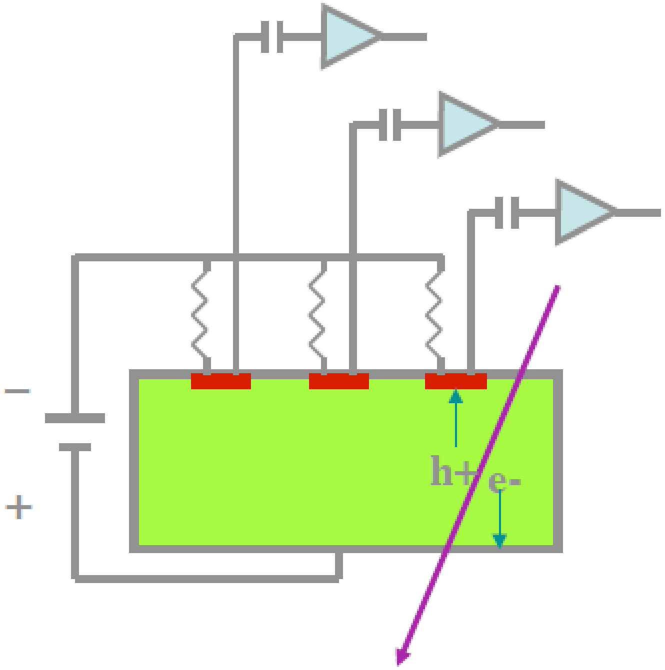


Several methods to connect the bias voltage: polysilicon resistor, punch through bias, FOXFET bias.

Semiconductors : generalities : building

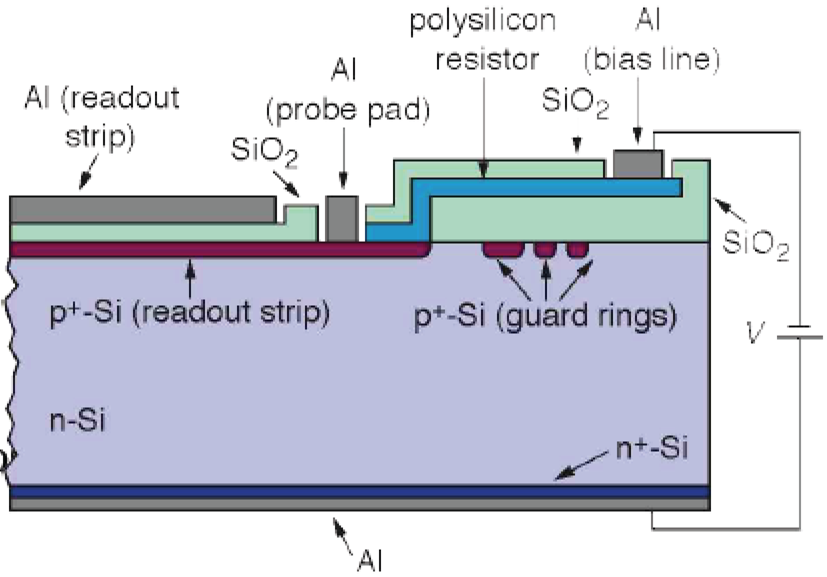
AC coupled Si detectors create 2 electrical circuits :

- Read-out circuit to the amplifier (AC current)
- Biasing circuit (DC current)



AC Coupling Silicon detector : bias voltage system

- Deposition of polycristalline silicon between p^+ implants and a common bias line.
- Sheet resistance of up to $R_s \approx 250\ \mathrm{k}\Omega/\square$. Depending on width and length a resistor of up to $R \approx 20\ \mathrm{M}\Omega$ is achieved ($R = R_s \cdot \mathit{length}/\mathit{width}$).
- To achieve high resistor values winding poly structures are deposited.
- Drawback: Additional production steps and photo lithograpic masks required.



Cut through an AC coupled strip detector with integrated poly resisto

Semiconductors : generalities : the Fano factor

Number of e – h pairs is a statistical process :

Number of e-h pairs : $N = E_{loss} / E_{ionization}$

If excitations are independants , they obey to a Poisson statistic with a standard deviation

$$\sigma_N = \sqrt{N} = \sqrt{\frac{E_{loss}}{E_{ionization}}}$$

variance : $\sigma^2{}_N = \frac{E_{loss}}{E_{ionization}}$

Fano factor :

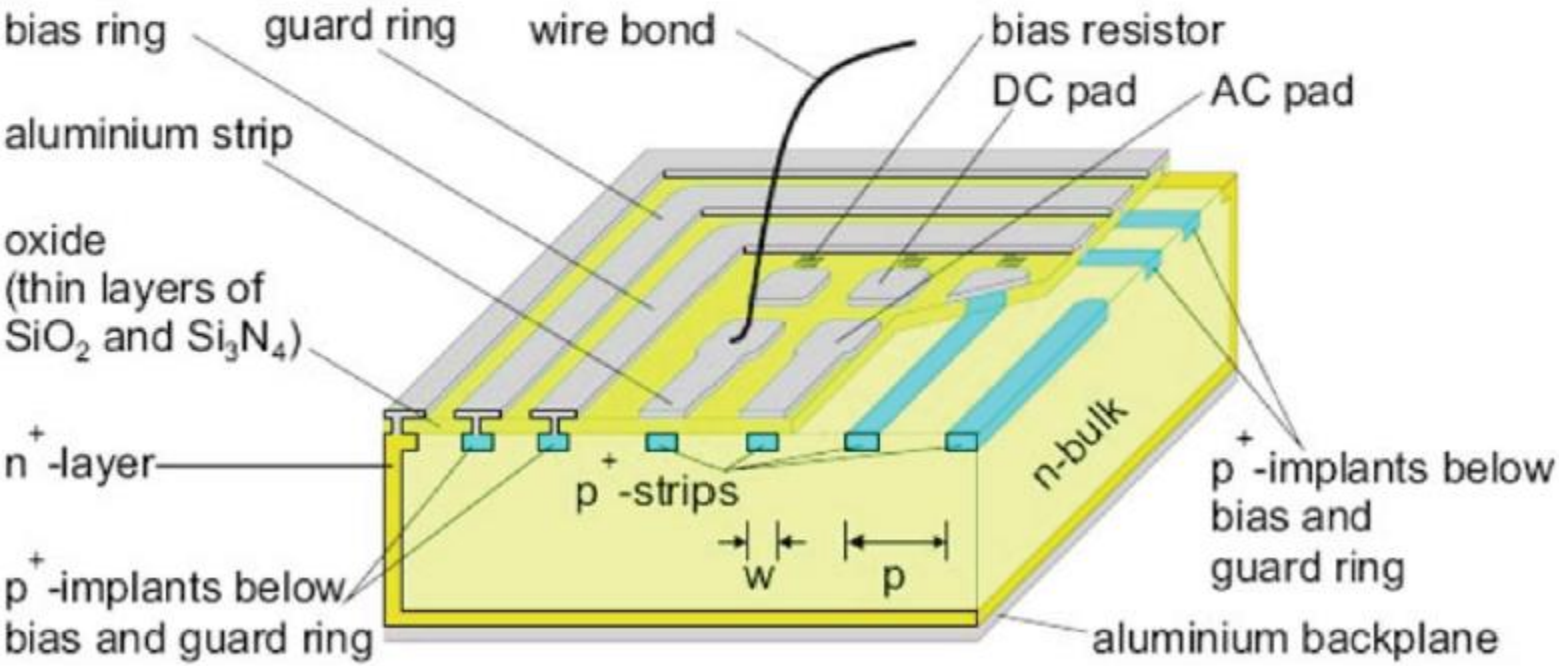
variance / mean of the process (should be 1 for a perfect Poisson distribution)

Si	0.115
Ge	0.13
GaAs	0.10
Diamond	0.08

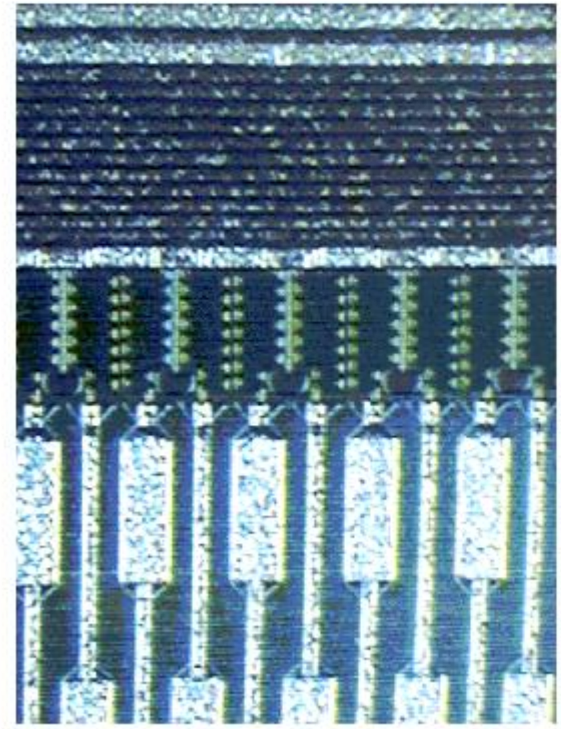
Fano factor related to energy resolution :
A Fano factor < 1 means that the energy resolution would be better than theoretically expected…

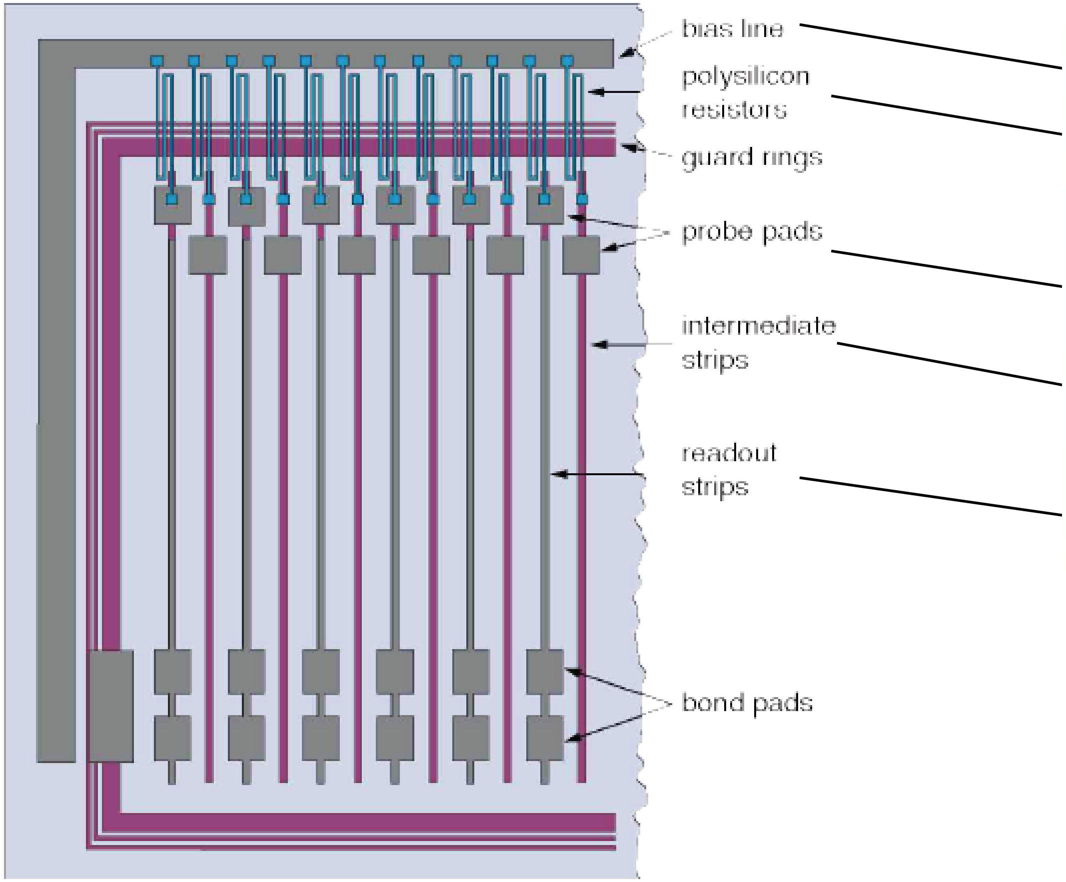
Semiconductors : Si detectors designs

Most commonly scheme AC + poly S-bias resistor

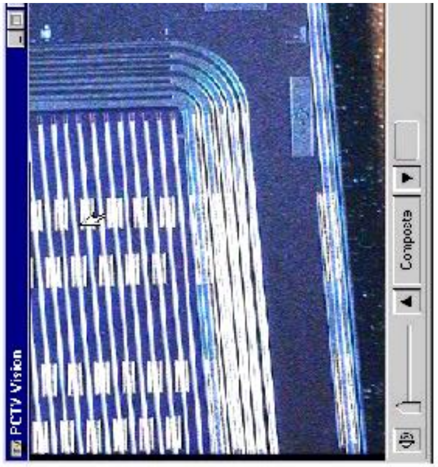


Semiconductors : Si detectors designs



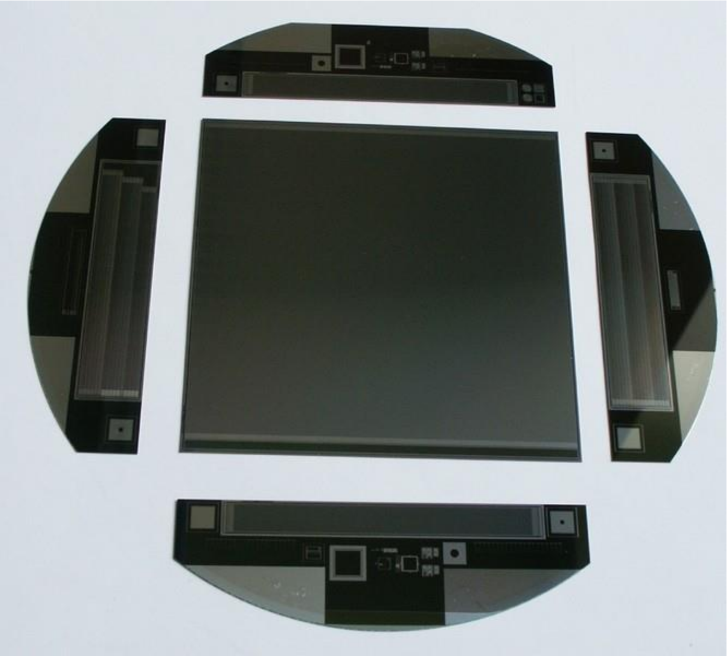


CMS design



ATLAS design

Semiconductors : Si detectors designs



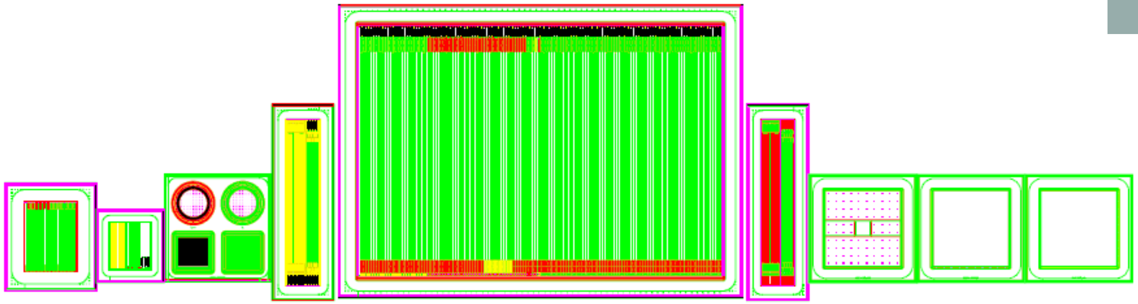


Figure 4.1: View of the Standard half-moon. The devices are (from left to right): TS-CAP, sheet, GCD, CAP-TS-AC, baby, CAP-TS-DC, diode, MOS1 and MOS2.

Two types of radiation damage :

- **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**

  - displacement damage, built up of crystal defects –

  Change of effective doping concentration (higher depletion voltage, under- depletion)
  Increase of leakage current (increase of noise, thermal runaway)
  Increase of charge carrier trapping (loss of charge)

- **Surface damage due to Ionizing Energy Loss (IEL)**

  - accumulation of positive in the oxide (SiO_2) and the Si/SiO_2 interface –
  affects: interstrip capacitance (noise factor), breakdown behavior, …

Impact on detector performance
(depending on detector type and geometry and readout electronics!)

Signal/noise ratio is the quantity to watch

$\Rightarrow$ **Sensors can fail from radiation damage !**

Loss of collected charges

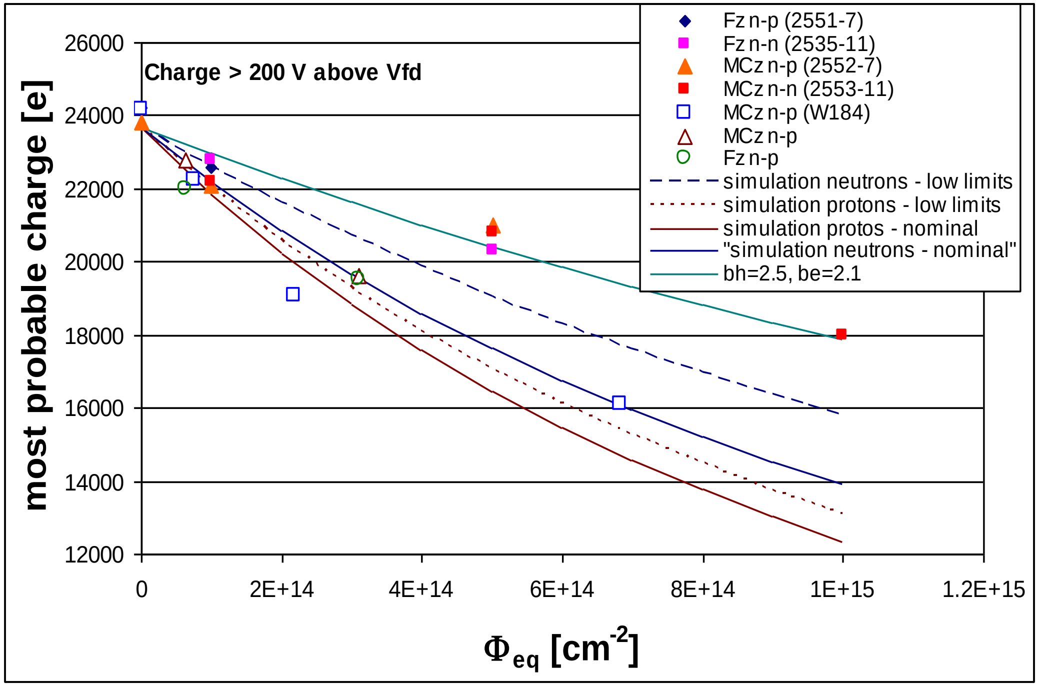
(new 300 µm Silicon ≈ 24 000 e- for 1 MIP)

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

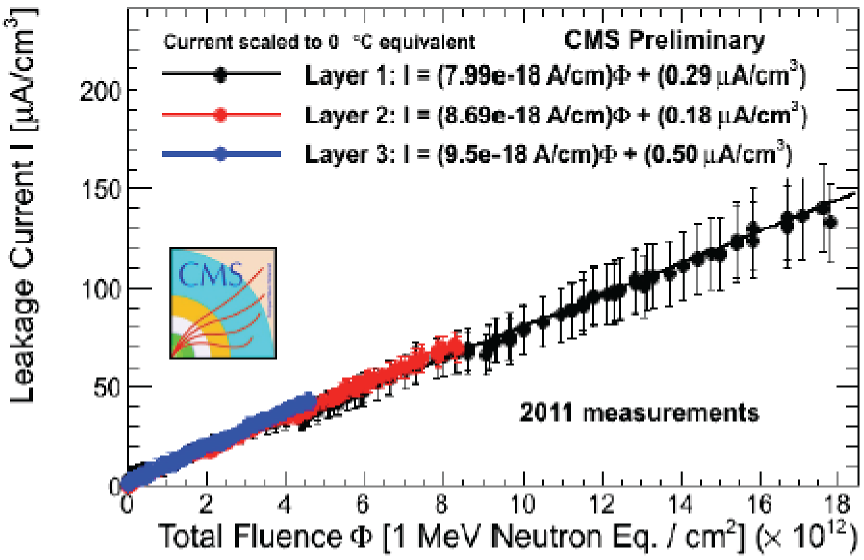
$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right)$$

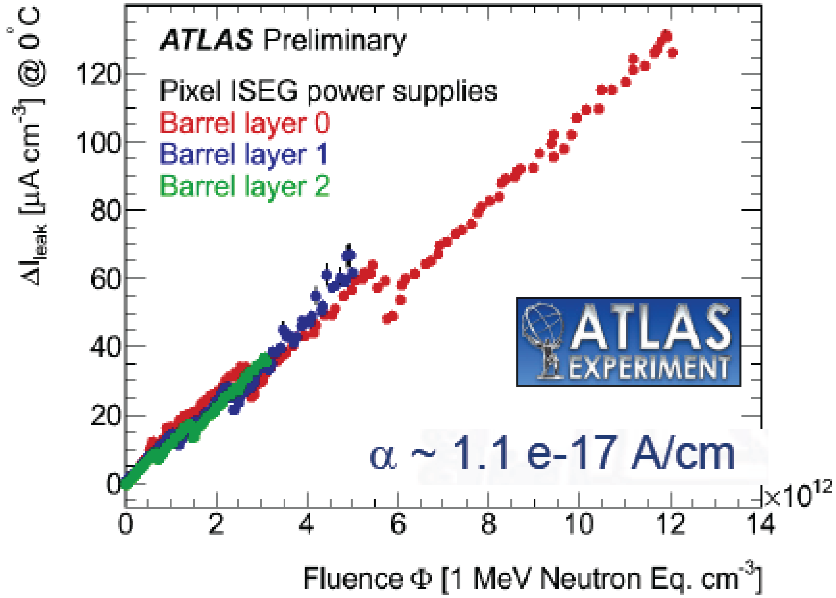
where

$$\frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$



Increase of Leakage current

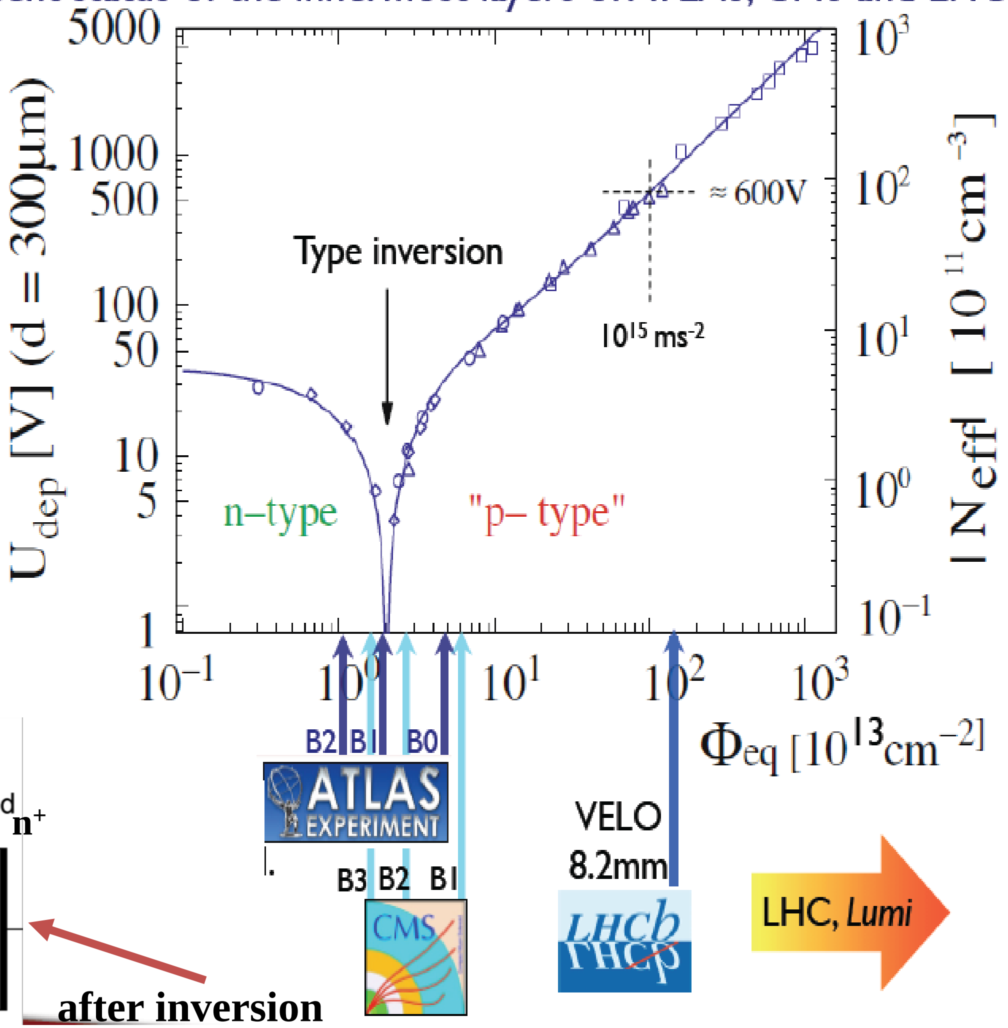




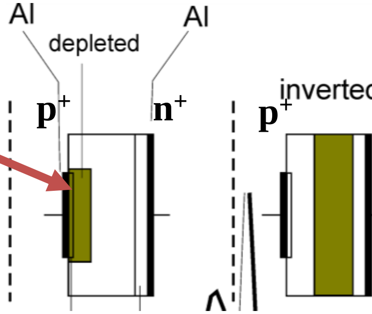
Change in depletion voltage and type inversion

- The present status of the innermost layers of ATLAS, CMS and LHCb:

Innermost layers should still work after $\Phi_{eq} \approx 10^{15}\, cm^{-2}$



before inversion



after inversion

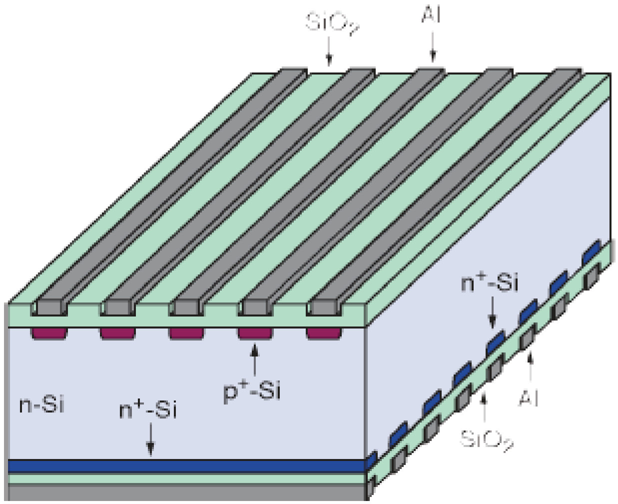
Double Sided Silicon Detectors (DSSD) Not much in use…

Advantages:

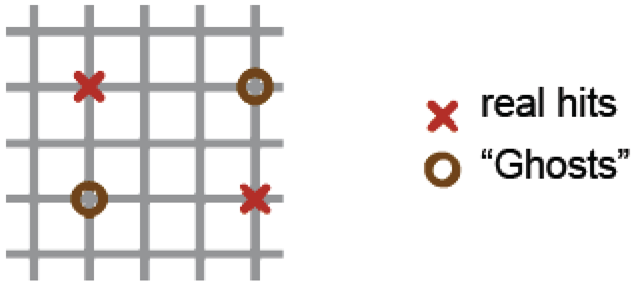
- More elegant way for measuring 2 coordinates
- Saves material

Disadvantages:

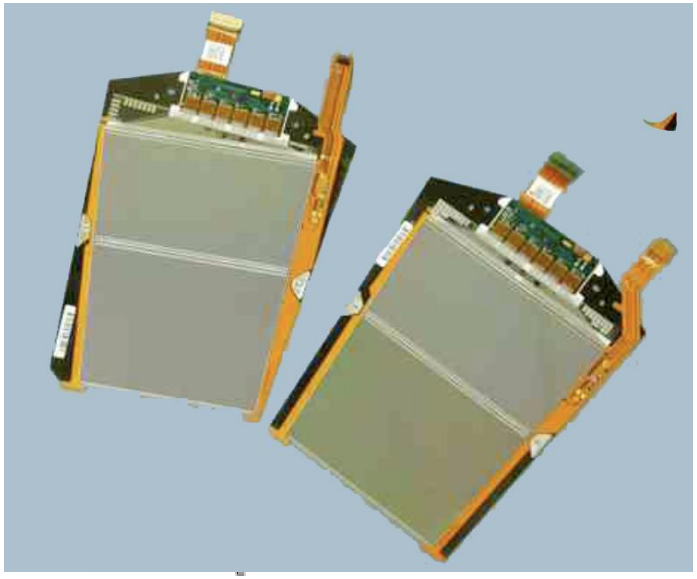
- Needs special strip insulation of n-side (p-stop, p-spray techniques)
- Very complicated manufacturing and handling procedures ⇒ expensive
- Ghost hits at high occupancy



Scheme of a double sided strip detector (biasing structures not shown)



Stereo Modules

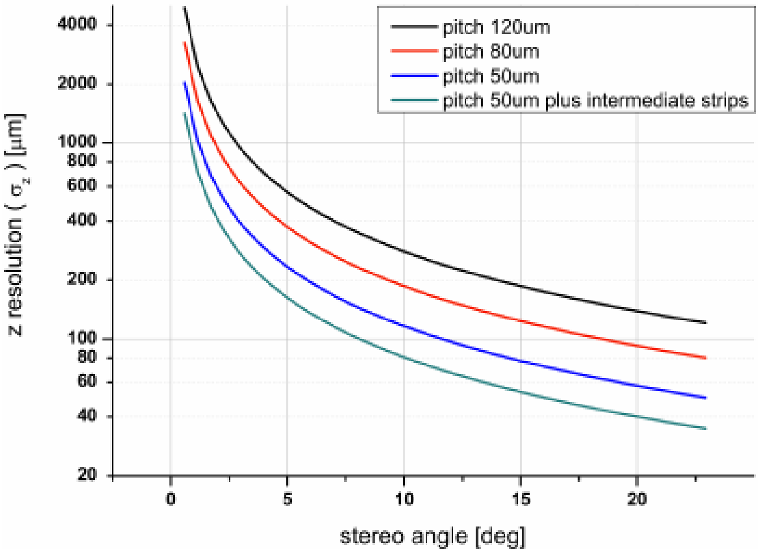


2nd coordinate requires second detector underneath
$\Rightarrow$ double the material

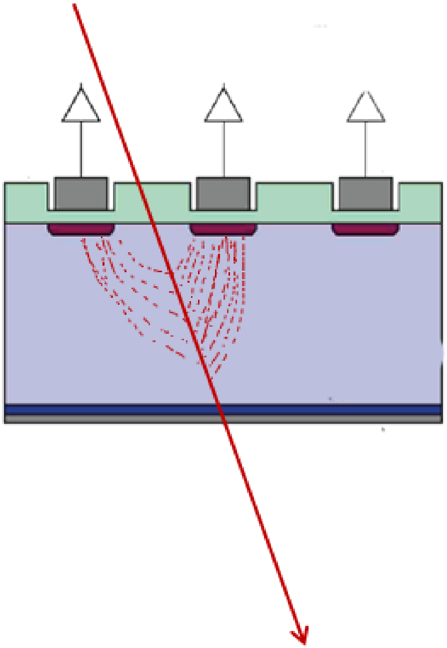
- Acceptable for hadron colliders like LHC
- Not acceptable for e+/e- colliders with tighter material budget

Tilt angle defines z-resolutions (usually along beam axis)

- CMS uses ~6 degrees



Semiconductors : Performance



- Threshold readout (one strip signal):
  - → position: $\boxed{x = \text{strip position}}$
  - → resolution: $\boxed{\sigma_x \approx \dfrac{p}{\sqrt{12}}}$

p … distance between strips (readout pitch)

x … position of particle track

- charge center of gravity (signal on two strips):
  - → position:

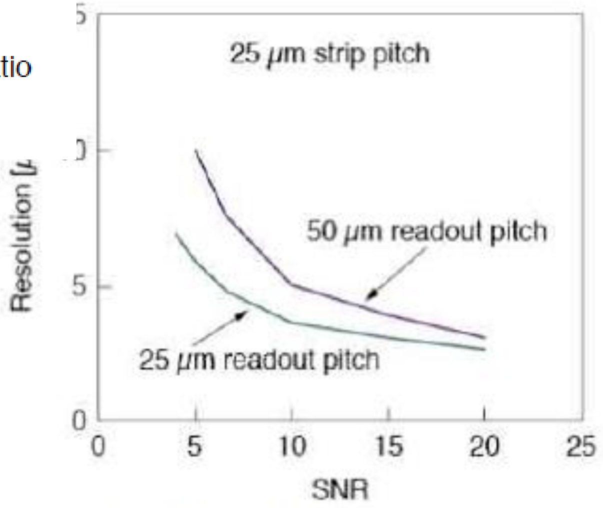
$$\boxed{x = x_1 + \frac{h_1^2}{h_1 + h_2}(x_2 - x_1) = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2}}$$

  - → resolution: $\boxed{\sigma_x \propto \dfrac{p}{SNR}}$

x_1, x_2 … position of 1st and 2nd strip

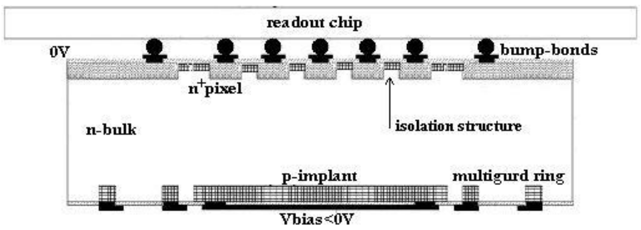
h_1, h_2 … signal on 1st and 2nd strip

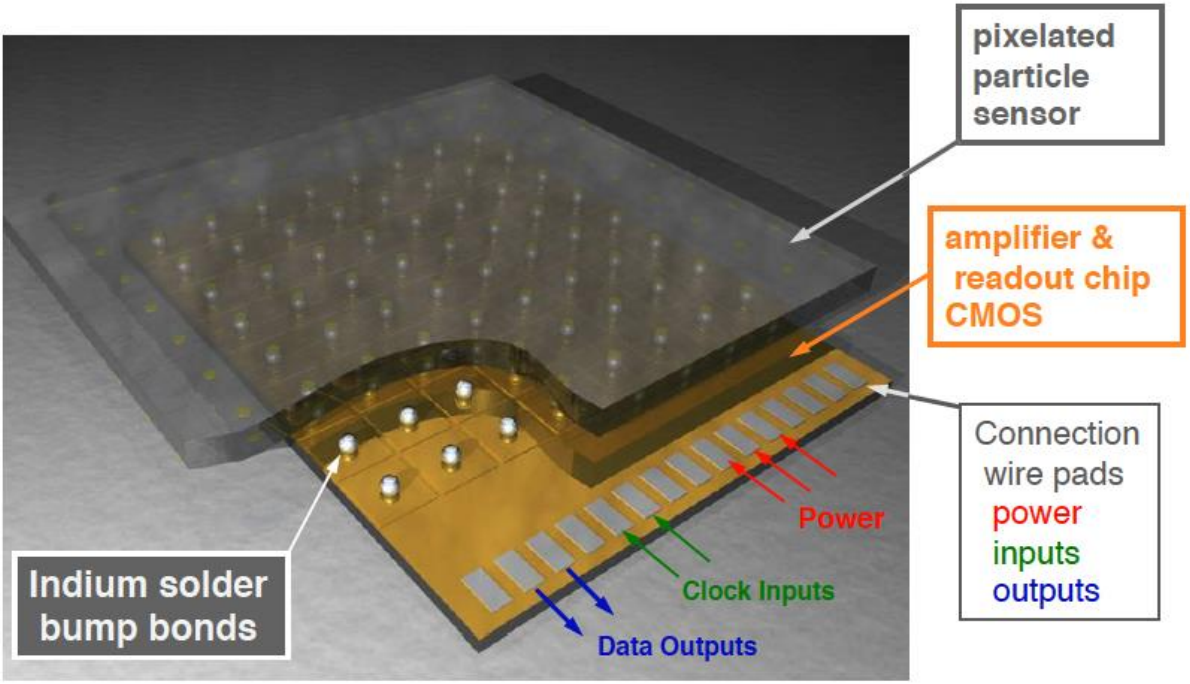
SNR … signal to noise ratio



A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992

Semiconductors : Pixels Detectors

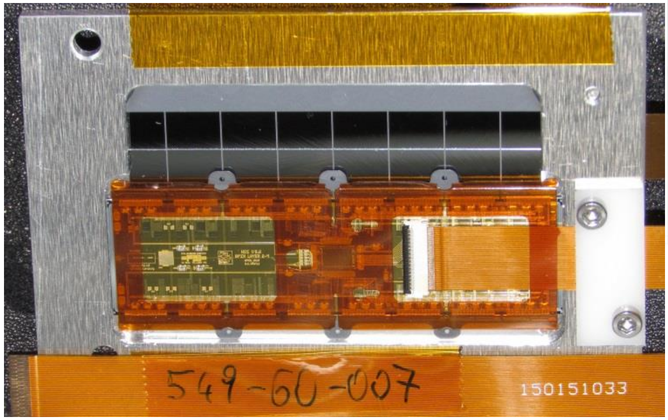


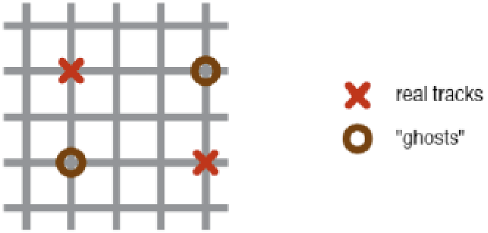

pixelated particle sensor

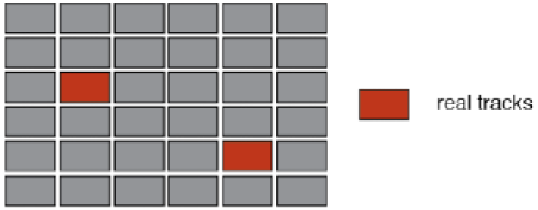
amplifier & readout chip CMOS

Connection wire pads
power
inputs
outputs

Indium solder bump bonds







Pixel sizes :

ATLAS : 50 µm x 400 µm

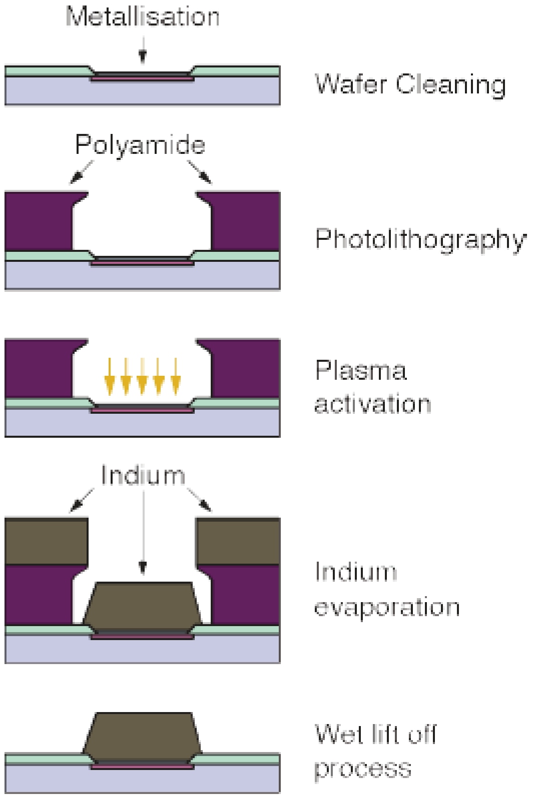
CMS : 100 µm x 150 µm

ALICE : 50 µm x 425 µm

CONNECTION BY BUMP BONDING

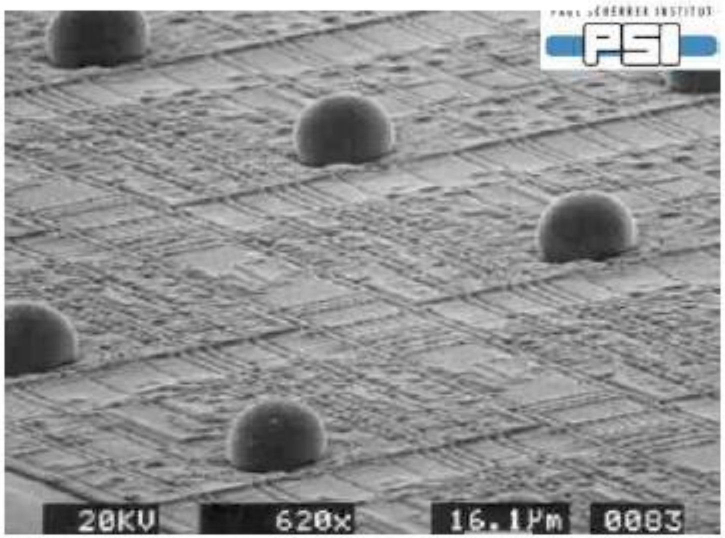
A typical bump bonding process (array bump bonding) is the following:

1. Deposition of an “under-bump metal layer”, plasma activated, for a better adhesion of the bump material.
2. Photolithography to precisely define areas for the deposition of the bond material.
3. Deposition, by evaporation, of the bond material (e.g. In or SnPb) producing little “bumps” (≈ 10 μm height).
4. Edging of photolithography mask leaves surplus of bump metal on pads.
5. Reflow to form balls.



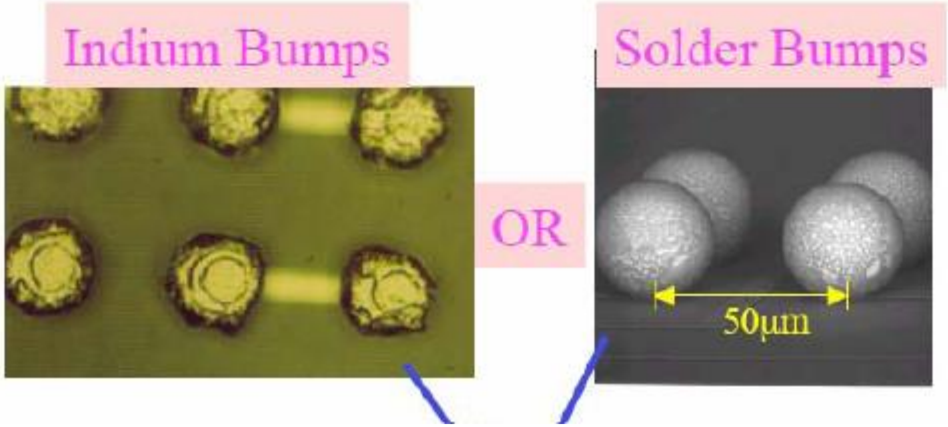
L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A 501, 239 (2003)

Semiconductors : Pixels Detectors

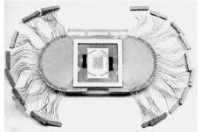


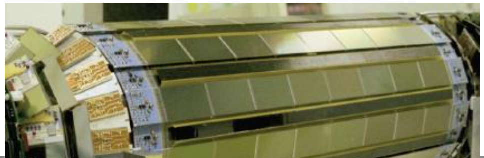
Pitch : 50 µm

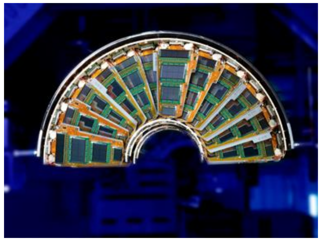
(wire bonding typically 200µm)

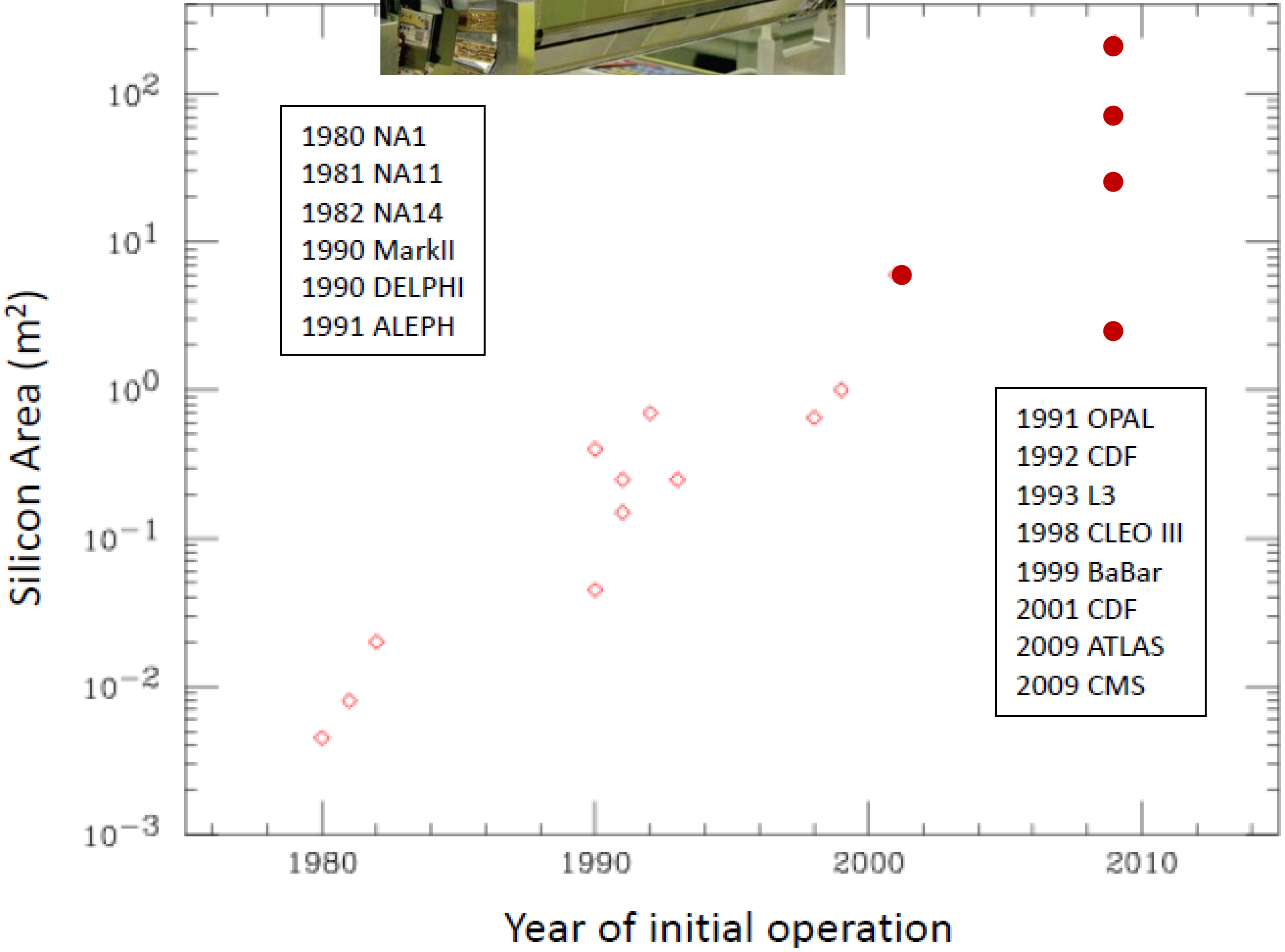


Semiconductors : Silicon history


NA 11


DELPHI


CDF



CMS ≈ 215 m^2

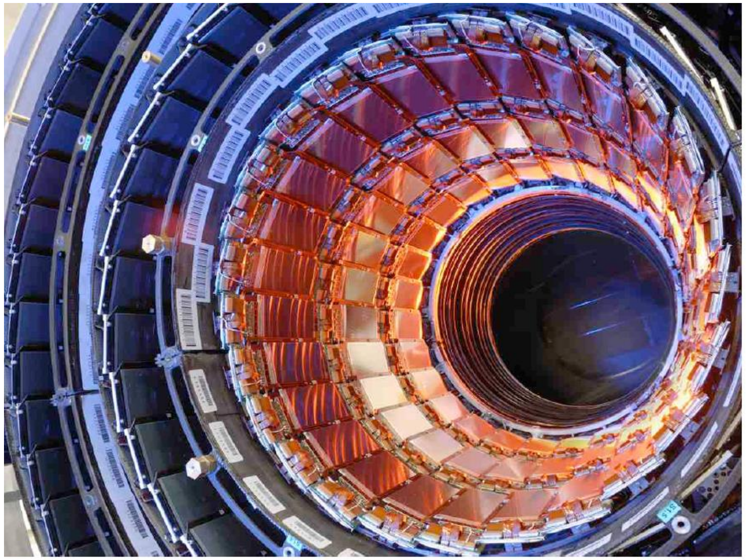
ATLAS ≈ 61 m^2

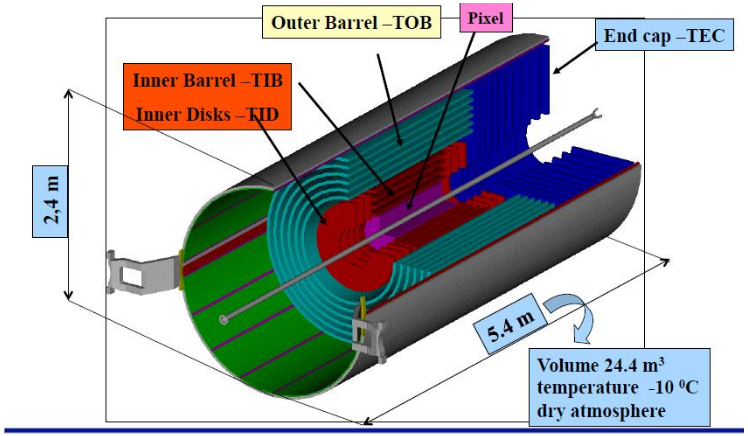
LHCb ≈ 12.5 m^2

CDF ≈ 3.5 m^2

ALICE ≈ 1.5 m^2

Semiconductors : CMS Silicon Detector



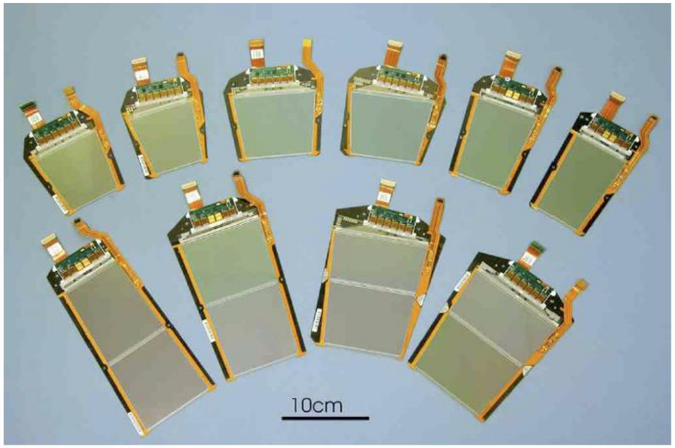


Strip detector:

~200 m^2 of silicon sensors
24,244 single silicon sensors
15,148 modules
9,600,000 strips ≡ electronics channels
75,000 read out chips (APV25)
25,000,000 Wire bonds

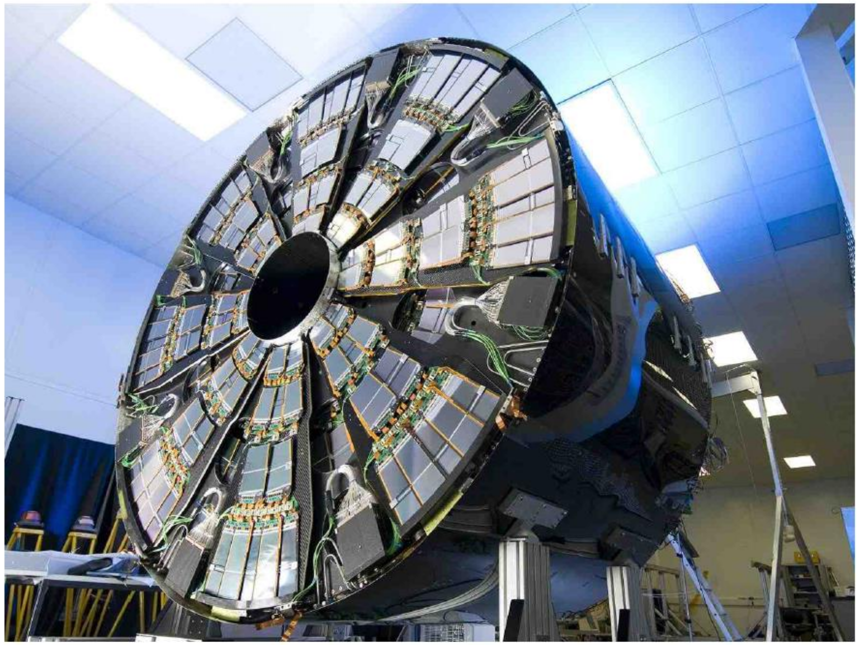
Pixel detector:

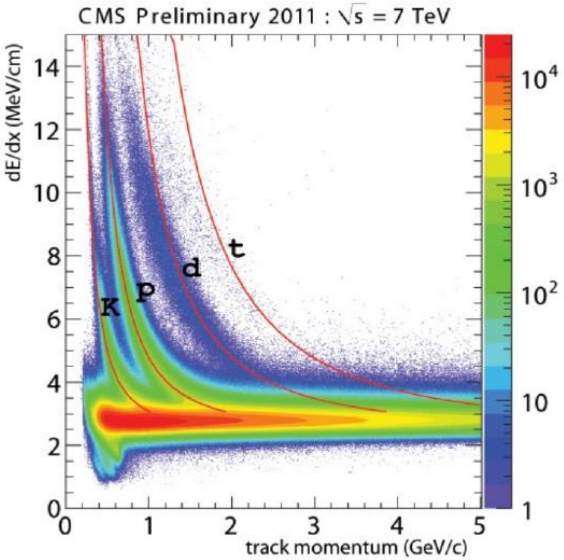
1 m^2 detector area
1440 pixel modules
66 million pixels

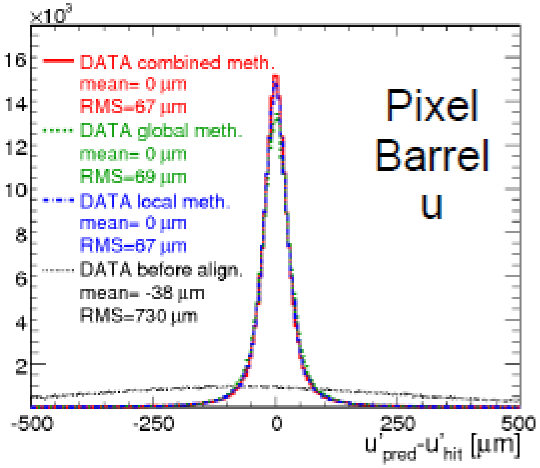


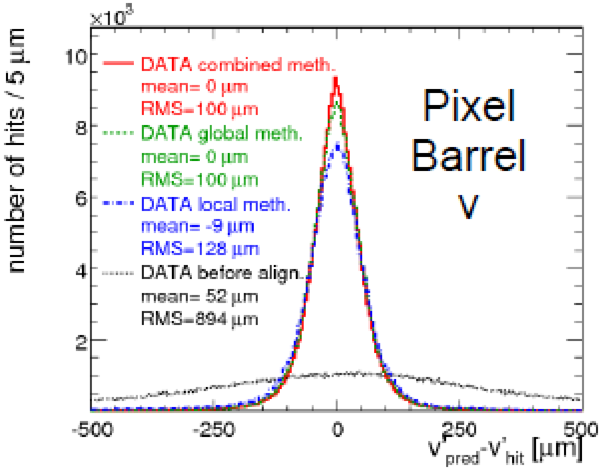
27 mechanical different modules + 2 types of alignment modules

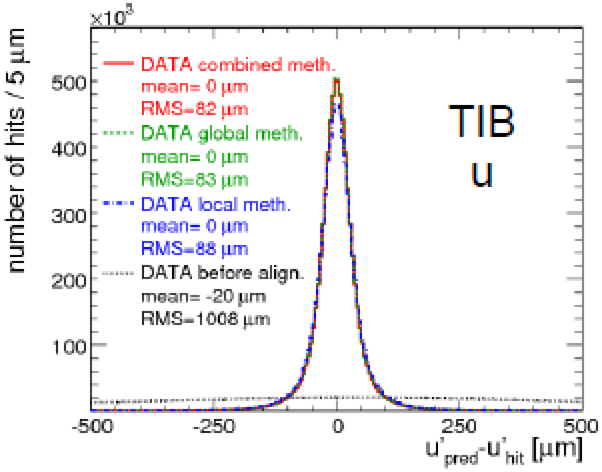
Semiconductors : CMS Silicon Detector



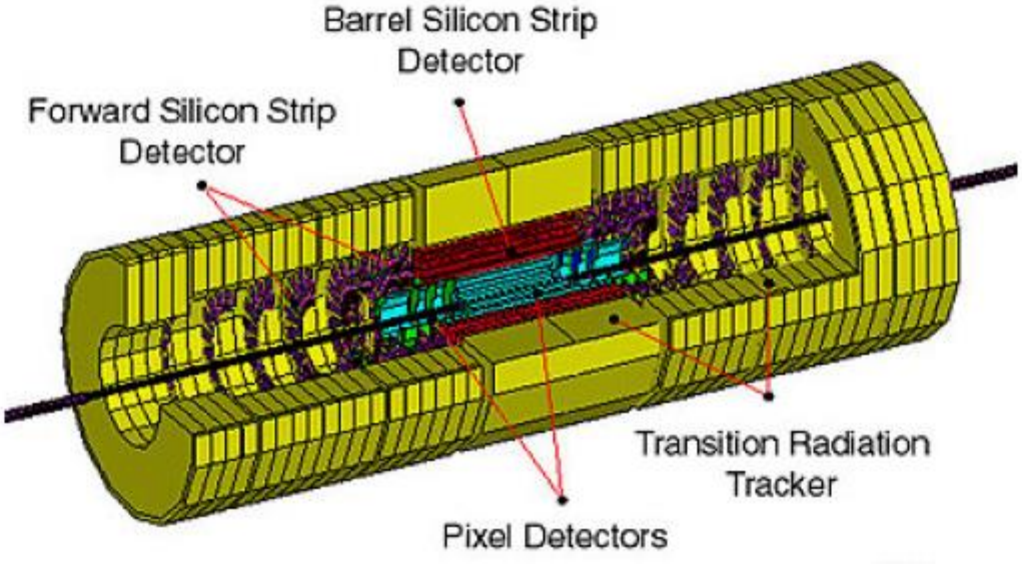


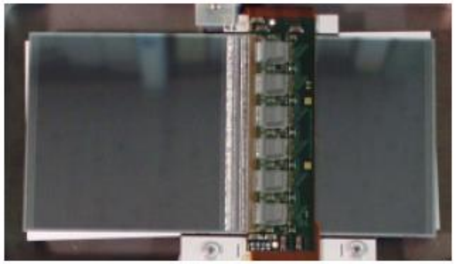


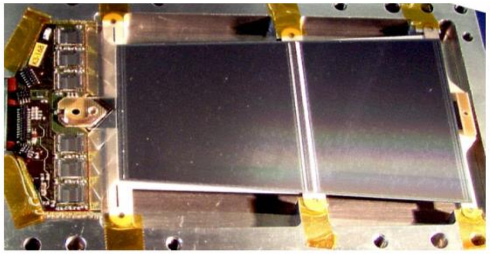




Semiconductors : ATLAS Silicon Detector

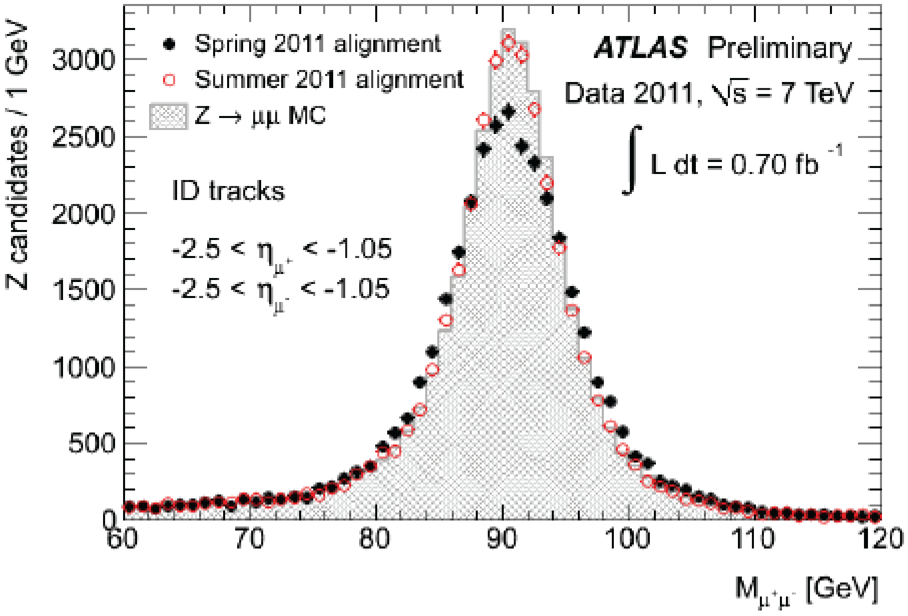


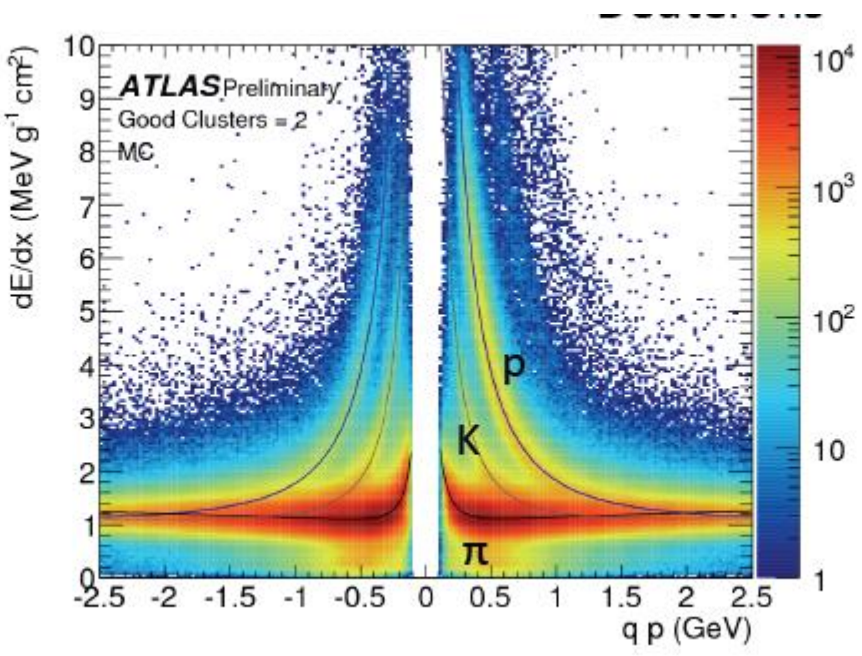


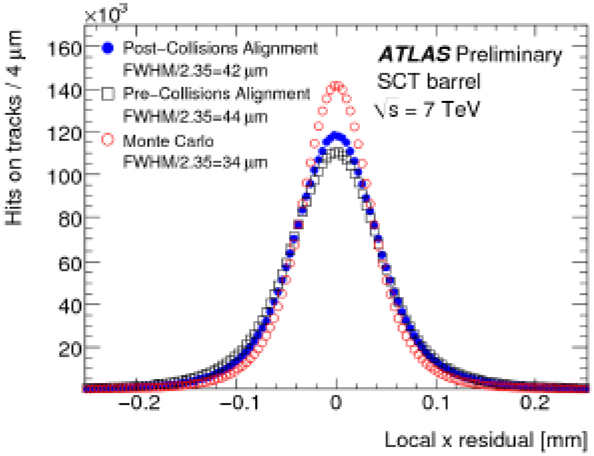


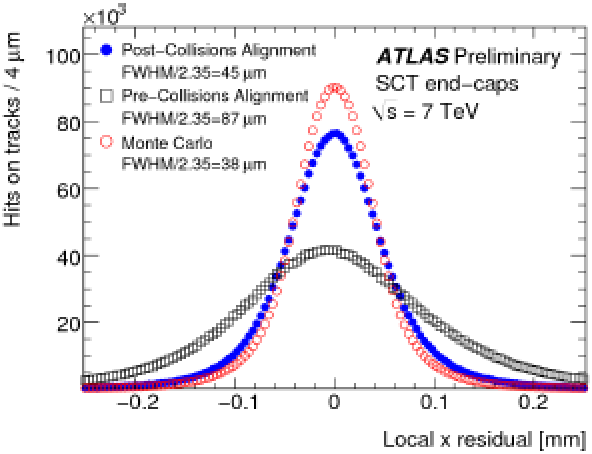
system		area (m^2)	resolution (µm)	channels (10^6)	|h | coverage
pixel	1 b layer	0.2	RF =12, z=66	16	2.5
	2 barrels	1.4	RF =12, z=66	81	1.7
	2x5 disks	0.7	zF =12, R=77	43	1.7-2.5
	total	**2.3**		**140**	**2.5**
SCT	4barrels	34.4	RF =16, z=580	3.2	1.4
	2x9 disks	26.7	zF =12, R=580	3.0	1.4-2.5
	total	**61.1**		**6.2**	**2.5**

Semiconductors : ATLAS Silicon Detector

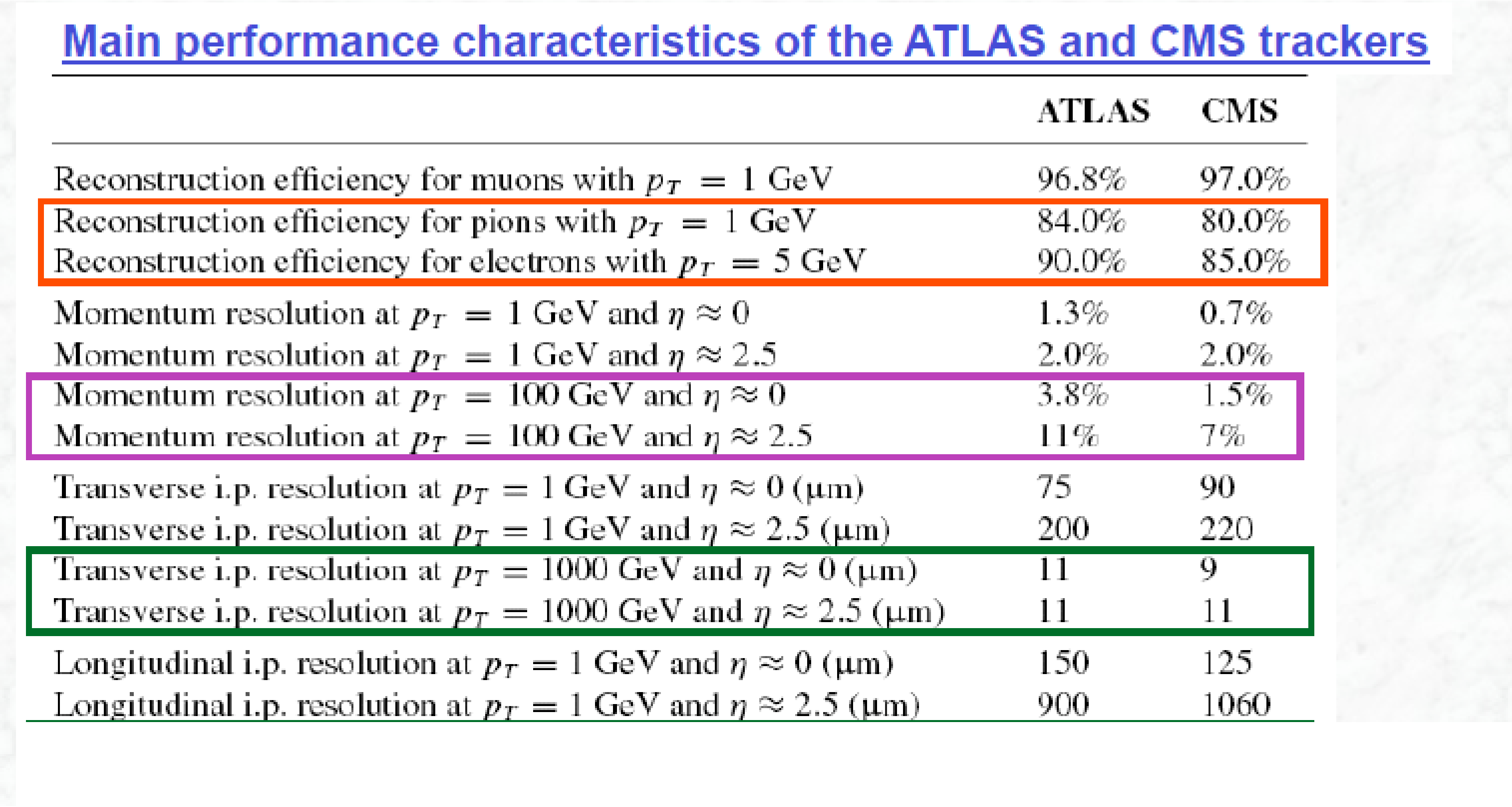








Semiconductors : CMS and ATLAS Silicon Detector



Main performance characteristics of the ATLAS and CMS trackers

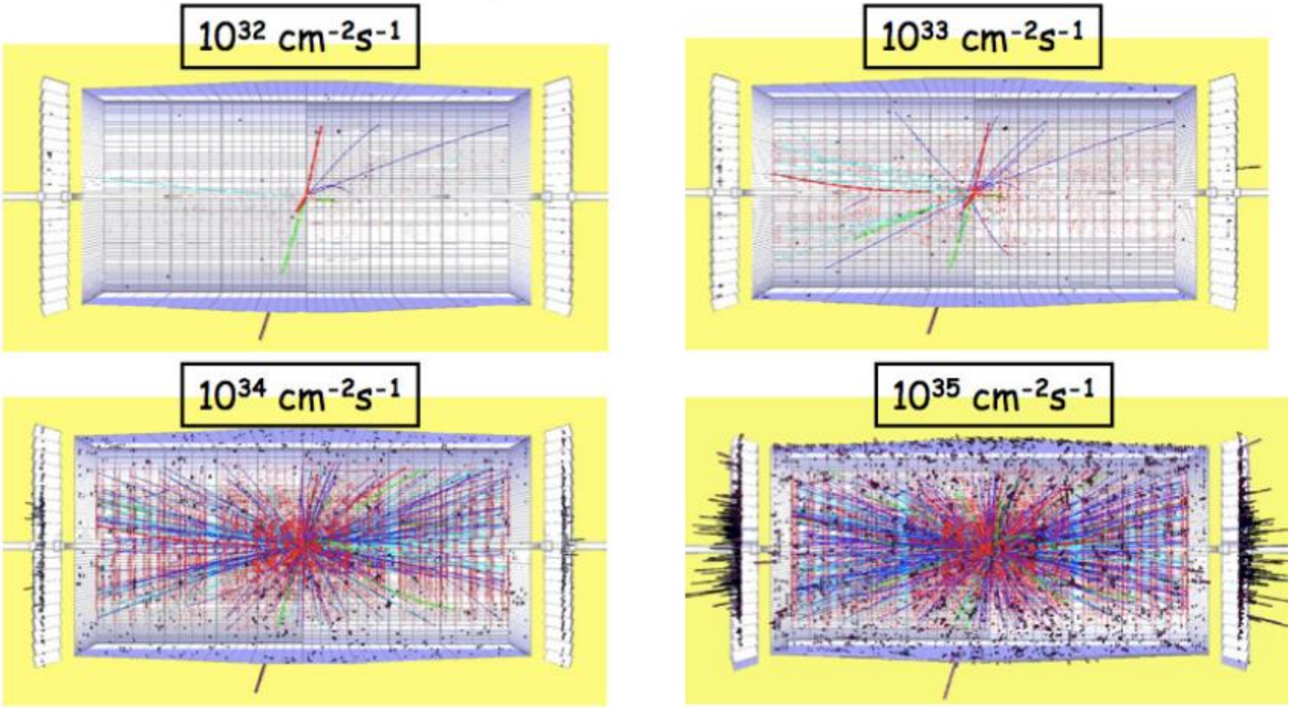
	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (µm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (µm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (µm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (µm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (µm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (µm)	900	1060

ATLAS : Si Pixels + Si Strips + Gas TRD

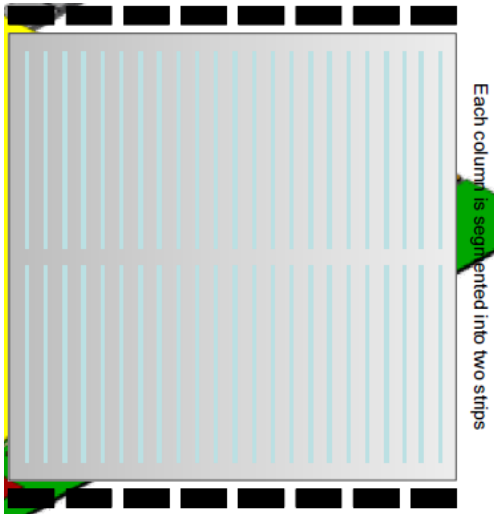
CMS : Si Pixels + Si Strips

Main Challenge : The LHC at High Luminosity (2024 ?)

$H \to ZZ \to \mu\mu ee$ event with M_H= 300 GeV for different luminosities



More tracks : Occupancy increases - Less resolution
More Flux : Radiation (bulk) damage



Read out on each side by 8 chips with 127 channel

Reduce the Occupancy : Increase the granularity

Mini-strips sensors (reduce lenght from 10 cm to 5 cm)

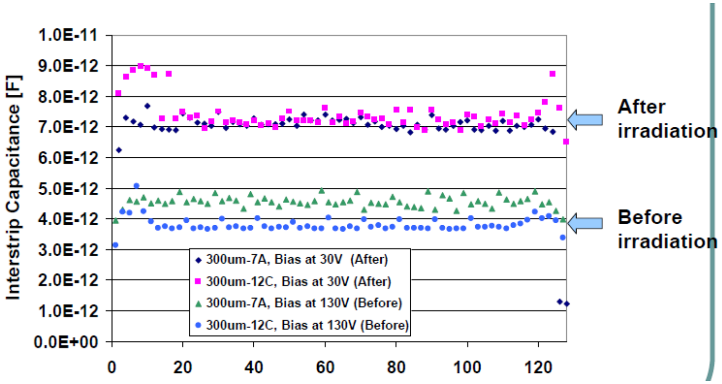
- Increases the number of channels
- Increases the cost
- Increases the power to be dissipated (already3kW in CMS, at -10°C)

Reduce the material : Thin Si sensors

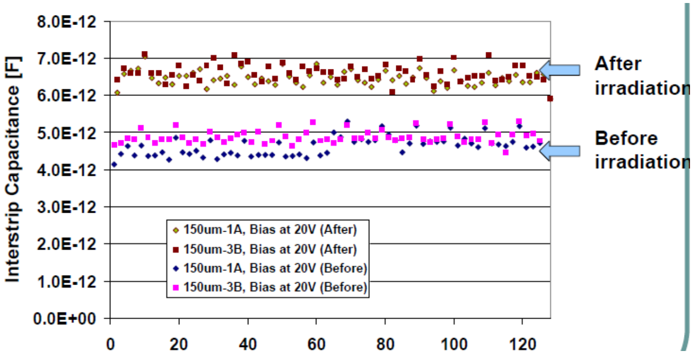
- Reduce the Charges Collected

Reduce the number of layers

- Reduce the overall Tracker efficiency



300 µm



150 µm

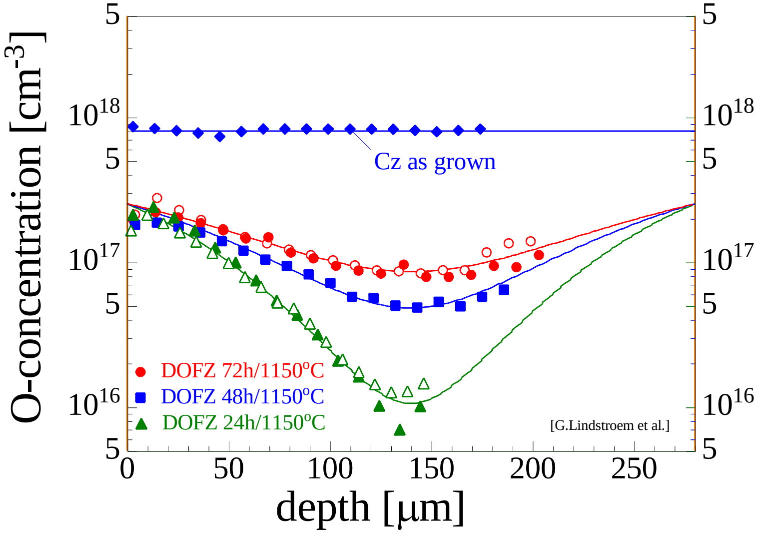
Change the material : Oxygenated Silicon

HE detectrors : **FZ** (Float Zone) Crystal - High resistivity > 3-4 kΩcm
- O2 contens < $50\ 10^{16}$

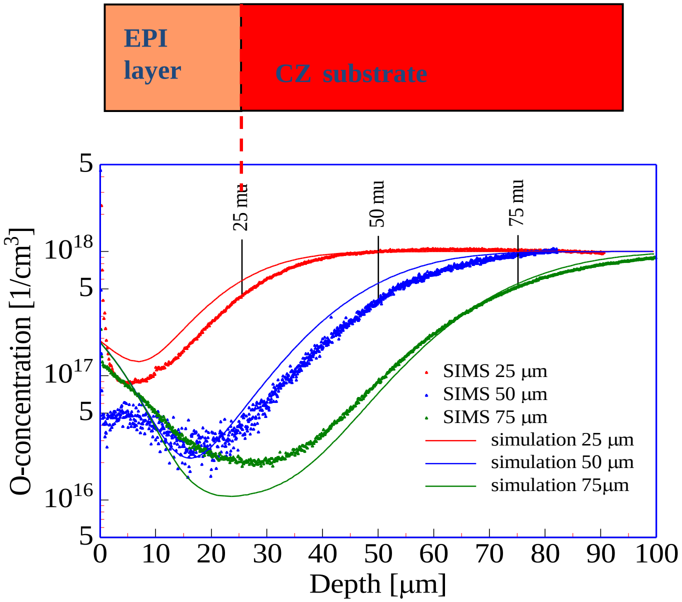
New Materials : **DOFZ** : O2 doped FZ Silicon (Oxydation of wafer at high temperature)

MCZ (Magnetic Czochralki) - Less resistivity ≈ 1.5 kΩcm
- O2 contens > $5\ 10^{17}$

EPITAXIAL growth : Chemical Vapor Deposition on CZ substrate

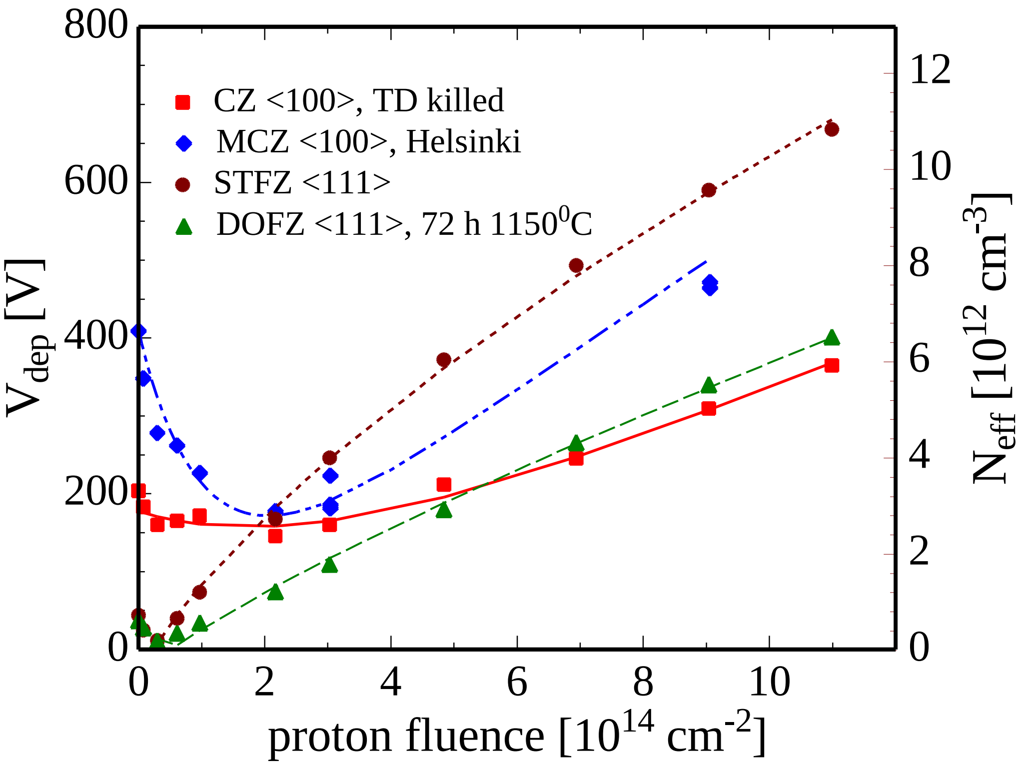


Oxygen concentration in DOFZ



Oxygen concentration in Epitaxial

24 GeV/c proton irradiation



- **Standard FZ silicon**
  - **type inversion at ~ 2×10^{13} p/cm^2**
  - **strong N_{eff} increase at high fluence**
- **Oxygenated FZ (DOFZ)**
  - **type inversion at ~ 2×10^{13} p/cm^2**
  - **reduced N_{eff} increase at high fluence**
- **CZ silicon and MCZ silicon**
  - **no type inversion in the overall fluence range (verified by TCT measurements)**

    (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)

    ⇒ **donor generation overcompensates acceptor generation in high fluence range**
- **Common to all materials (after hadron irradiation):**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

MAPS (Monolithic Active Sensor) or CMOS (Complementary Metal Oxide Semiconductor)

Pointing resolution	(12 ⊕ 19 GeV/p·c) µm
Layers	Layer 1 at 2.5 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 µm X 20.7 µm
Hit resolution	6 µm
Position stability	6 µm rms (20 µm envelope)
Radiation length per layer	$X/X_0 = 0.37\%$
Number of pixels	356 M
Integration time (affects pileup)	185.6 µs
Radiation environment	20 to 90 kRad / year $2*10^{11}$ to 10^{12} 1MeV n eq/cm^2
Rapid detector replacement	~ 1 day

Signal collection

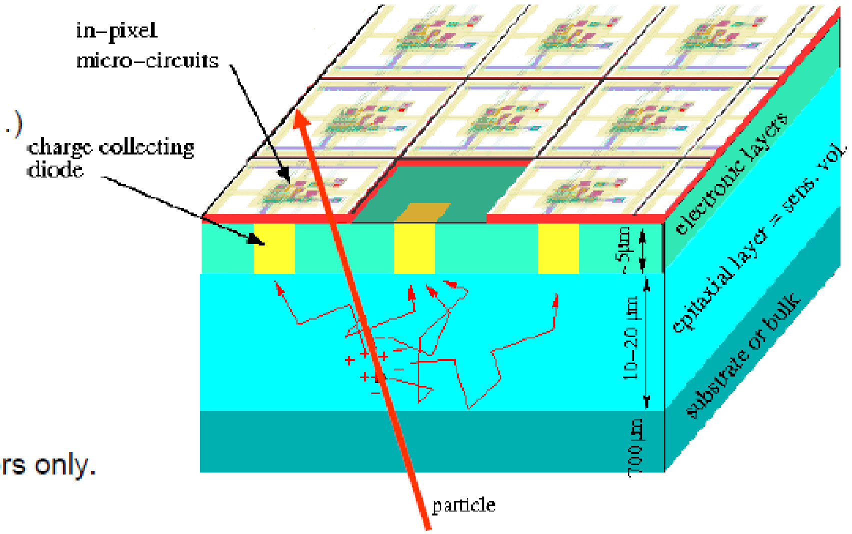
- Charges generated in epitaxial layer → ~1000 e^- for MIP.
- Charge carriers propagate thermally.
- In-pixel charge to signal conversion.

Advantages

- High granularity (< 10 µm pitch).
- Thickness (<50µm).
- Integrated signal processing.
- Standard process (cost, prototyping, …)

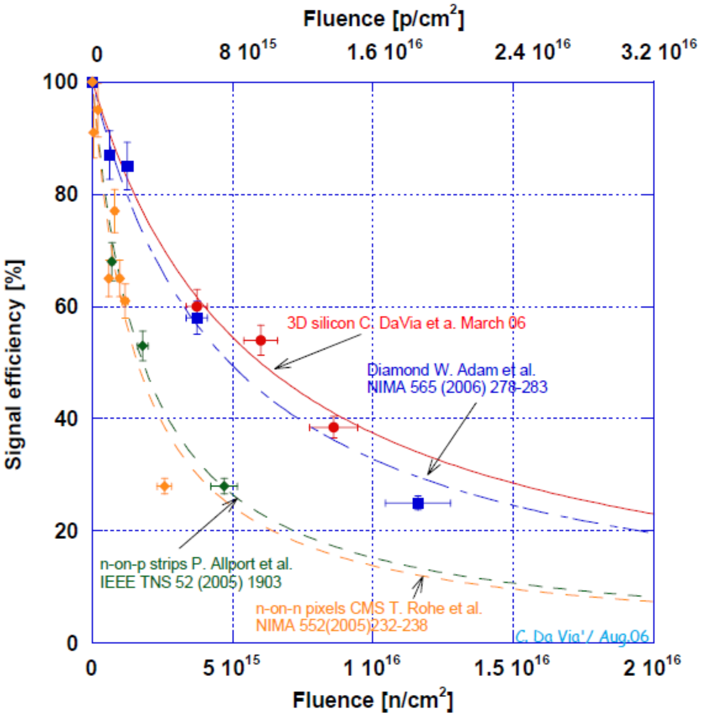
Issues

- Undepleted volume limitations .
  - radiation tolerance.
  - intrinsic speed.
- Small signal O(100e^-)/pixel.
- In-pixel µ-circuits with NMOS transistors only.



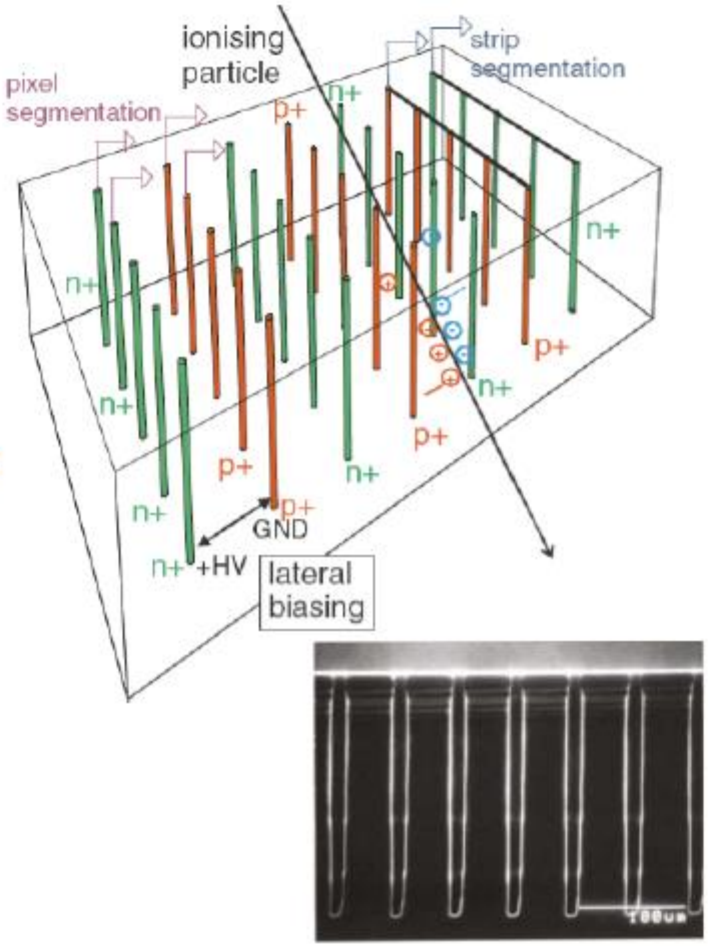
3D Silicon Detectors

Manufacturing challenge
Electrodes : dead zones



Efficiency vs fluence

S

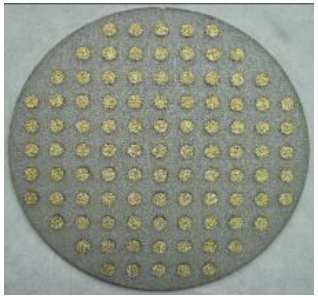


Diamond detectors

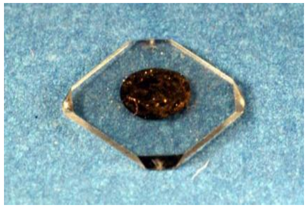
	CVD Diamond	Si
Z	6	14
Energy Gap	5,5 eV	1,21 to 1,1eV
Resistivity	10^{13} – 10^{16} Ωcm	10^{5} – 10^{6} Ωcm
Breakdown	10^{7} V/cm	3.10^{5} V/cm
Mobility (electrons)	2000 cm²/V/s	1350 cm²/V/s
Mobility (holes)	1600 cm²/V/s	480 cm²/V/s
Displacement Energy (e^-)	43 eV/atom	13 à 20 eV/atom
Pairs Creation	13 eV	3.6 eV
Charge Collection Distance	250 µm	100 m ?
Mean signal (MIP)	3600 e^- / µm	8900 e^- / µm
Dielectric Constant	5.5	10 à 12
Thermal Conductivity (W/m·K)	1600 - 2000	150

Diamond is better than Silicon
- Does not need any doping
- Better radiation hardness
- Better thermal conductivity
- Better speed (1psec vs 1 nsec)
- Light insensitive
- Multi-metalization possible (test and physics)

But :
- 3 times less signal for MIPs (3.6 / 13)
- Difficult to manufacture
- Expensive
- Diamond is not understood (at the moment)



2 forms :
Polycristalline
Wafer max.6 inches



Monocrystalline
max : 4 x 4 mm ^{2}