

# DETECTOR TECHNOLOGIES

## Lecture 2: Semi-conductors

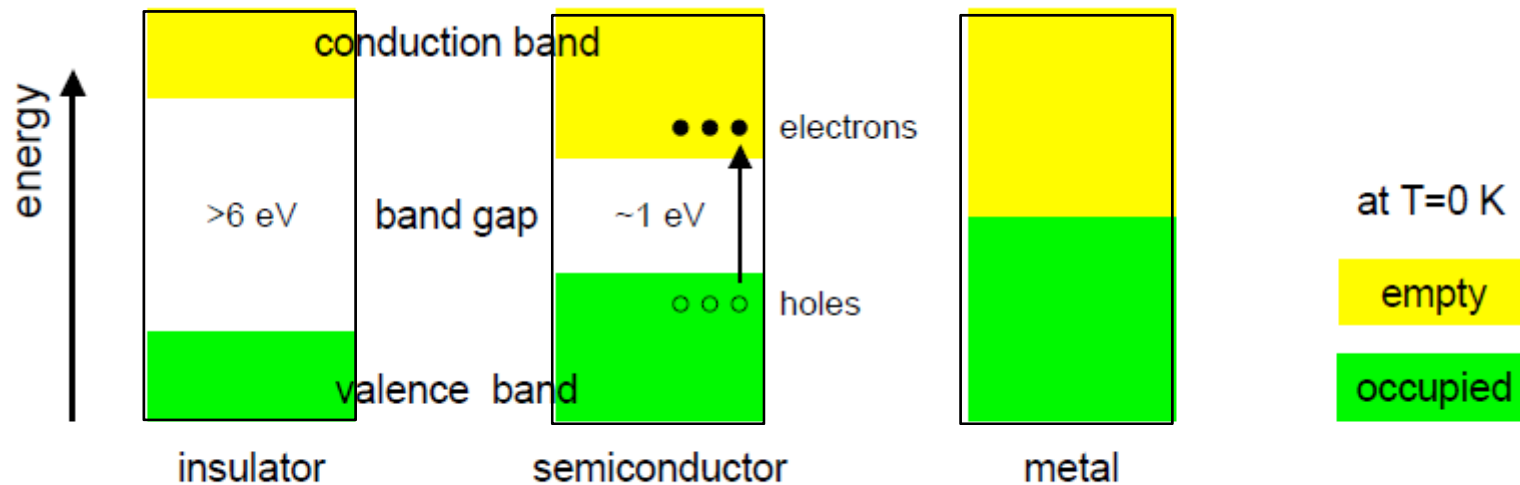
- Generalities
- Material and types
- Evolution

# Semiconductors : generalities

Solid-States band structures :

Valence band : e<sup>-</sup> bond atoms together

Conduction band : e<sup>-</sup> can freely jump from an atom to another



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<sub>i</sub>: intrinsic density of electrons in conduction band
- p<sub>i</sub>: intrinsic density of hole in valence band
- N<sub>c,v</sub>: number of states in conduction, valence band
- E<sub>g</sub>: band gap at 0 K
- A: temperature-independent constant

kT at 300 K = 0.025 eV

At T ≠ 0 K

Electrons may acquire enough energy to pass the band gap... Thermal conduction

## Semiconductors : generalities

	Si	Ge
atomic number	14	32
density (g/cm <sup>3</sup> )	2.33	5.32
atomic density (atoms/cm <sup>3</sup> )	4.96 x 10 <sup>22</sup>	4.41 x 10 <sup>22</sup>
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 <sup>3</sup> )	1.5 x 10 <sup>10</sup>	2.4 x 10 <sup>13</sup>
mobility (cm <sup>2</sup> /V/s) at 300 K: electrons	1350	3900
holes	480	1900
mobility (cm <sup>2</sup> /V/s) at 77 K: electrons	2.1 x 10 <sup>4</sup>	3.6 x 10 <sup>4</sup>
holes	1.1 x 10 <sup>4</sup>	4.2 x 10 <sup>4</sup>
ionisation energy (eV) 300 K	3.62	(*)
77 K	3.76	2.96

Not the same !  
(Thermal excitation + phonons)

	Si	Ge	GaAs	Diamond
E <sub>g</sub> [eV]	1.12	0.67	1.35	5.5
n <sub>i</sub> (300K) [cm <sup>-3</sup> ]	1.45 x 10 <sup>10</sup>	2.4 x 10 <sup>13</sup>	1.8 x 10 <sup>6</sup>	< 10 <sup>3</sup>

Energy loss by a charged particle : Bethe-Bloch

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

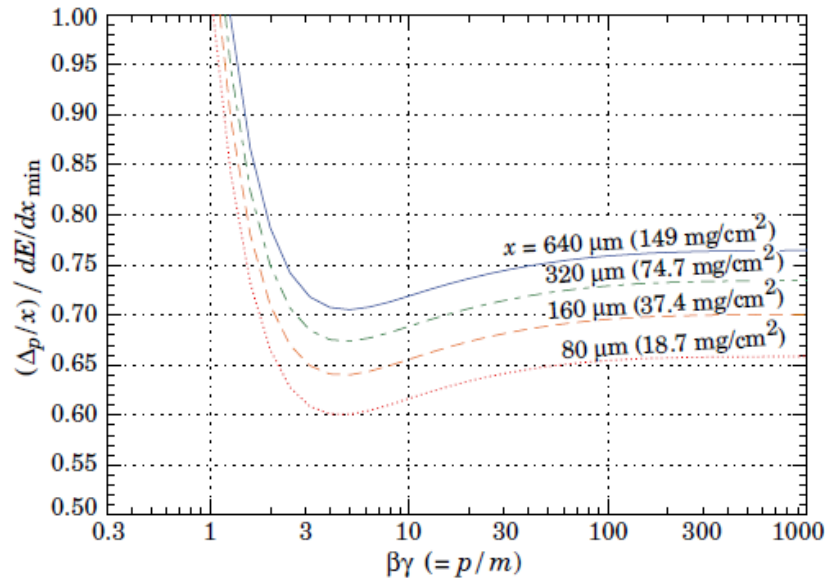
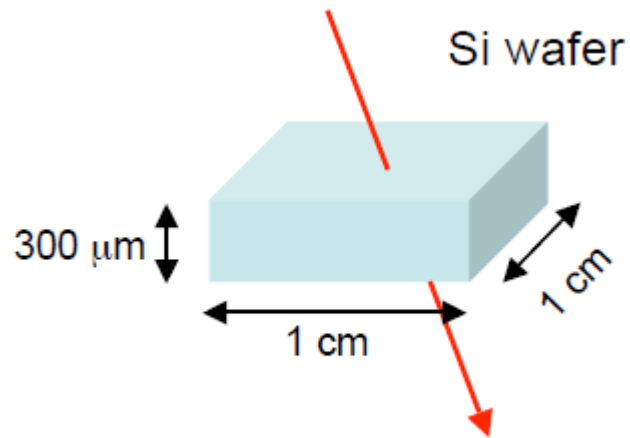


Figure 27.9: Most probable energy loss in silicon, scaled to the mean loss of a minimum ionizing particle, 388 eV/μm (1.66 MeV g<sup>-1</sup>cm<sup>2</sup>).

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 :  $dE / dx \approx 388 \text{ eV}/\mu\text{m}$

→ e – holes pairs created : 107/ $\mu\text{m}$

For 300  $\mu\text{m}$  :  **$3.2 \cdot 10^4$**  pairs created

at  $T > 0 \text{ K}$

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

$n_i$ : 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 :  
 **$\approx 4.5 \cdot 10^9$**

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  $E_g \approx 6 \text{ eV}$ .

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.

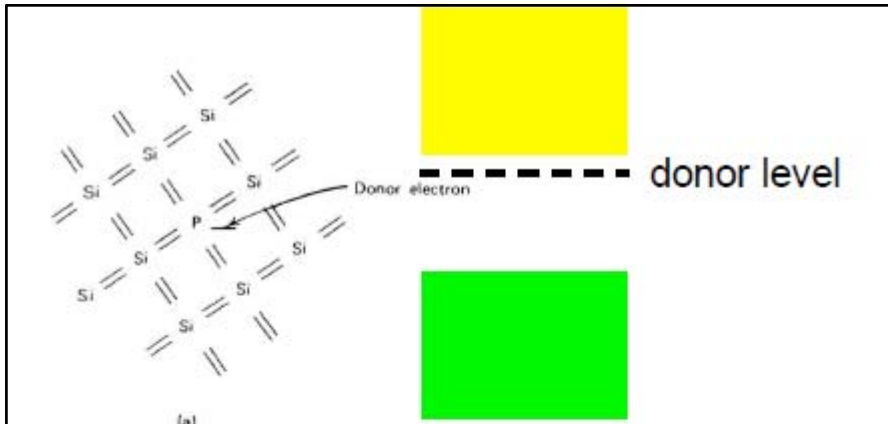
Such a material exist, it is **Diamond**. However even artificial diamonds (e.g. CVD diamonds) are too expensive for large area detectors.

**Have to "modify" the semiconductor :**

**2 contradictory requirements : 2 contradictory remedies...**

## Semiconductors : generalities : p and n types

### n - TYPE



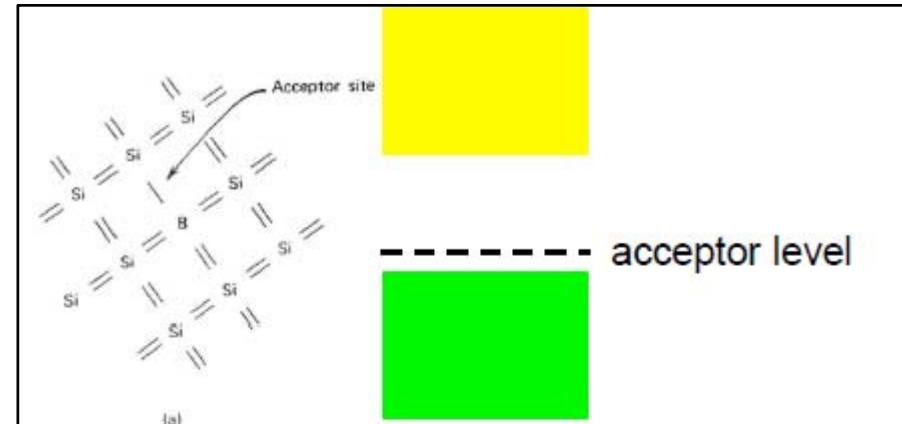
- pentavalent elements (group V/15, e.g. P, As, Sb) have one electron too much to fit in: “donor impurities”
- extra electrons are lightly bound
  - energy level close to the conduction band
  - thermally excited into the conduction band
  - recombination with holes:  $n_e \gg n_h$

→ n-type semiconductors

- electrons are the majority charge carriers
- holes are the minority charge carriers

dopants :  
Arsenic, Phosphorous

### p - TYPE



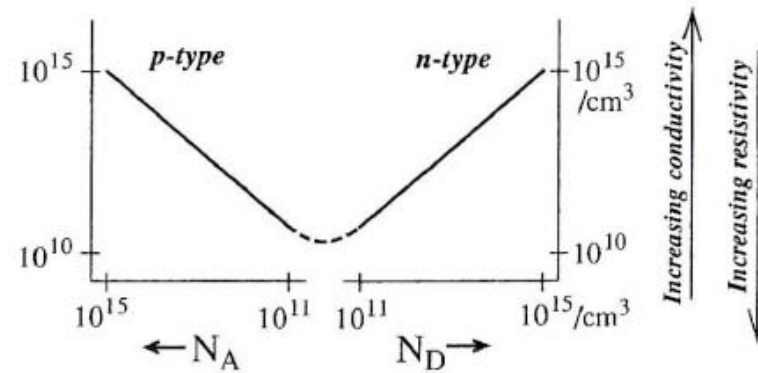
- trivalent elements (group III/13, e.g. Ga, B, In) have one electron too little to fit in: “acceptor impurities”
- electrons in missing bond slightly less bound
  - energy level close to the valence band
  - thermally excited electrons fill the acceptor level, creating holes
  - holes recombine with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

→ 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

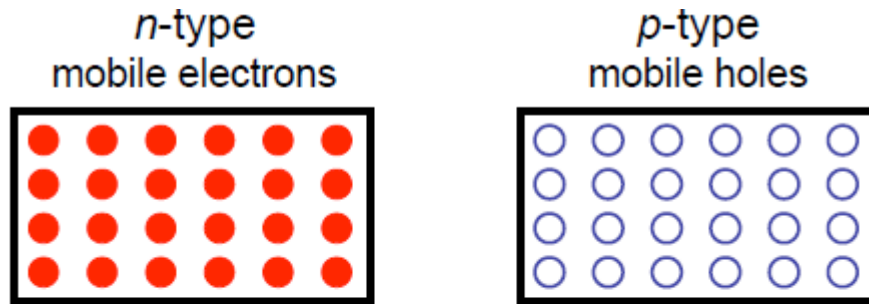


**Figure 11.6** Plot using logarithmic scales of the conductivity of a semiconductor as a function of the net concentration of acceptors ( $N_A$ ) or donors ( $N_D$ ).

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

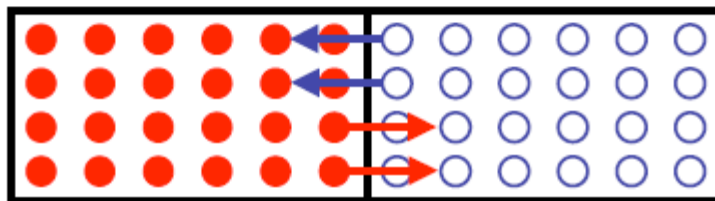


# Semiconductors : generalities : junction detectors



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

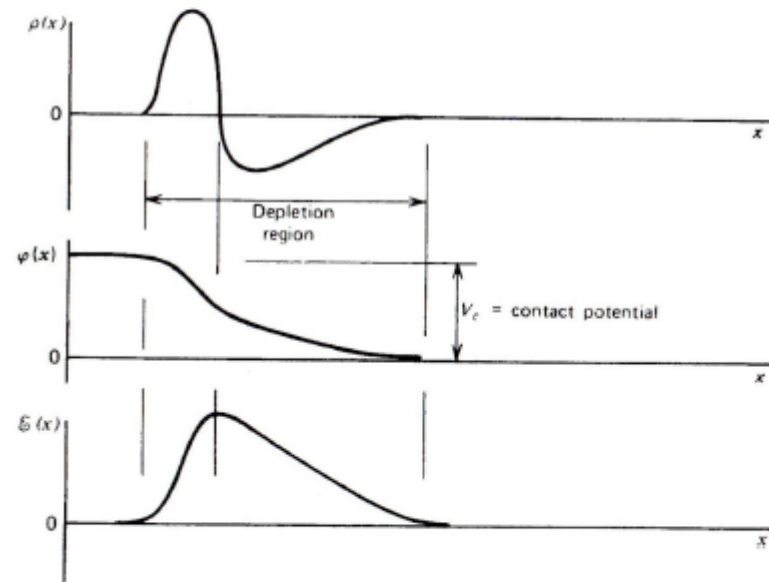
diffusion: holes to n-region, electrons to p-region



uncompensated fixed charges build up emerging "contact" potential stops diffusion



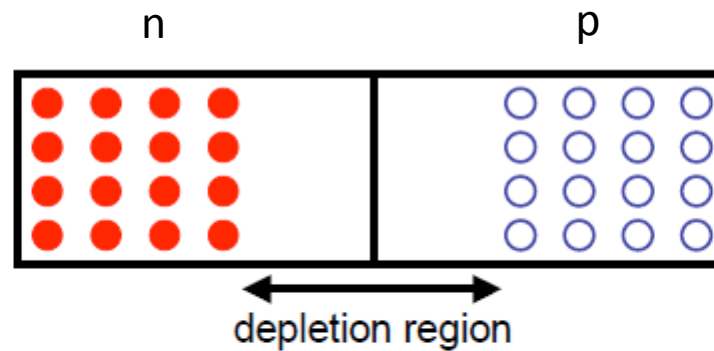
depletion region



**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  $\phi(x)$ , and electric field  $\mathcal{E}(x)$ .

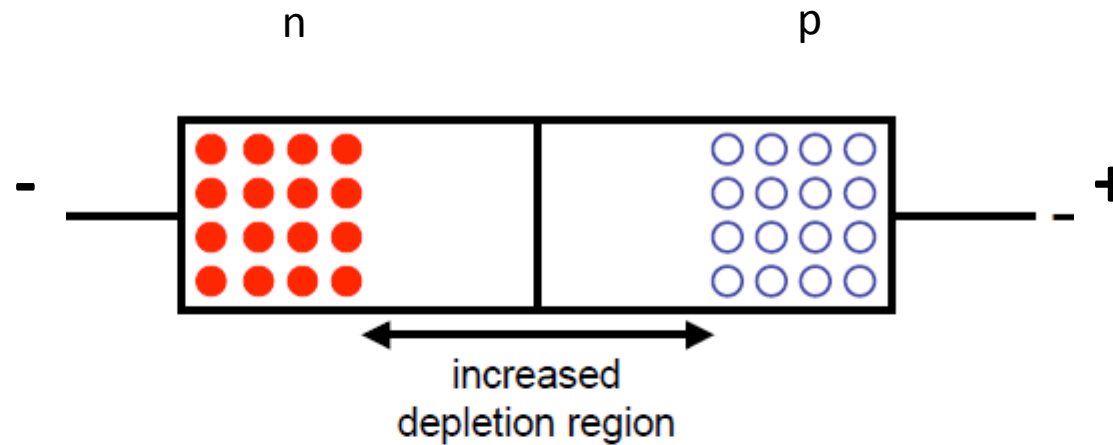
11

## 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 ( $\sim 1$  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

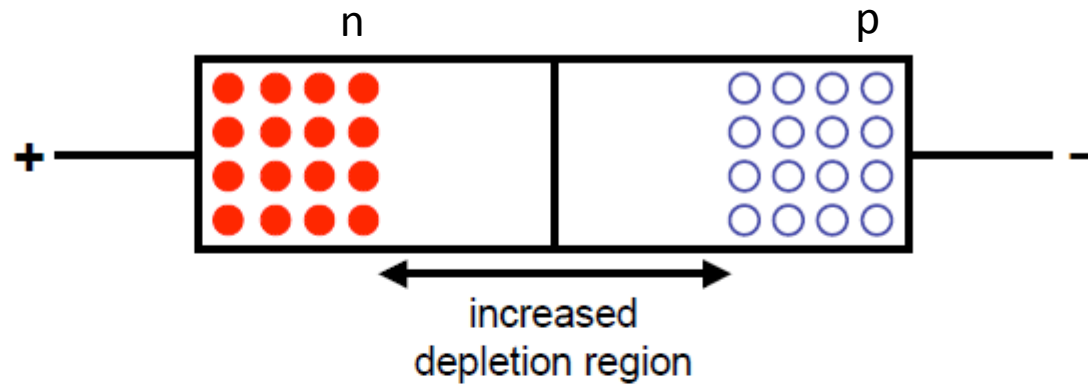


Holes are refilled in the depletion zone...  
The depletion zone is narrower

**The current across the Si (Leakage Current) increases**

**Not Good !**

## Semiconductors : generalities : reverse biasing scheme



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

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

d: depletion region thickness

V: reverse bias voltage

$\epsilon$ : dielectric constant

e: electronic charge

N: net impurity concentration (atoms/cm<sup>3</sup>)

**Depletion zone becomes larger**  
**Leakage Current decreases**

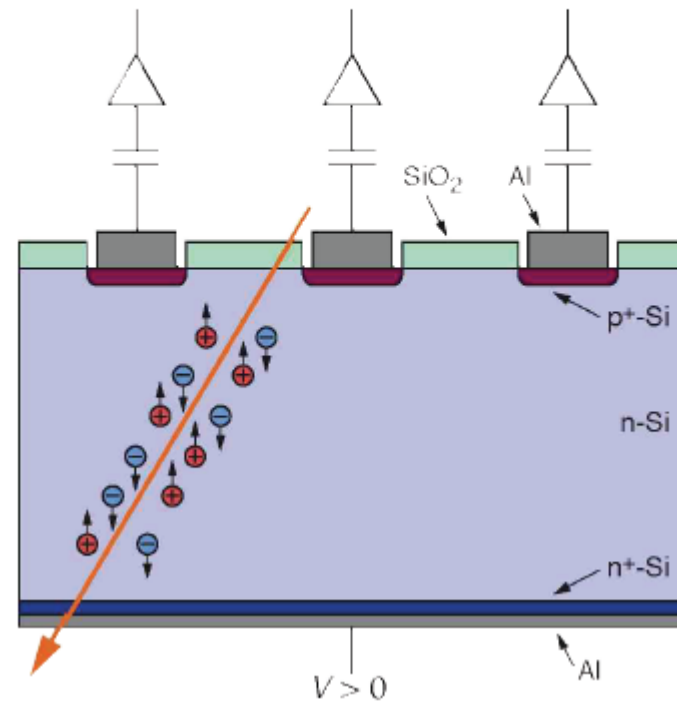
**GOOD !**

## 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:

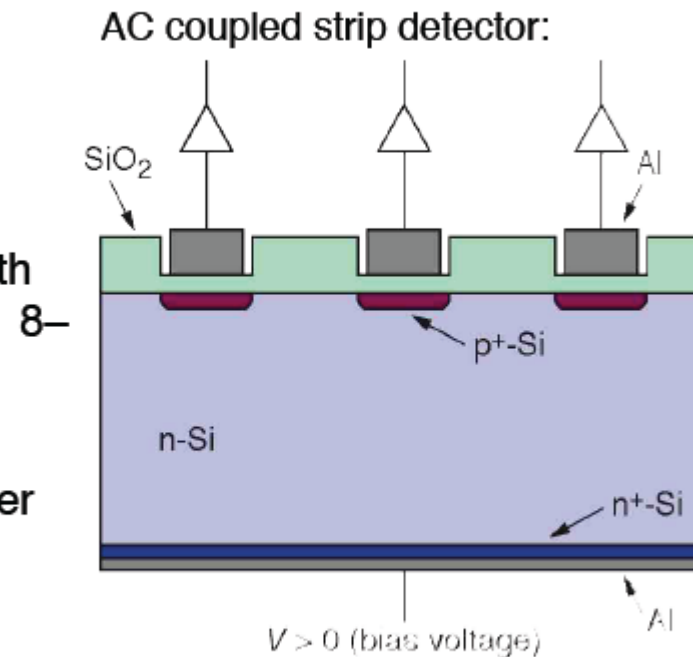
- ★  $p^+n$  junction:  
 $N_a \approx 10^{15} \text{ cm}^{-3}$ ,  $N_d \approx 1-5 \cdot 10^{12} \text{ cm}^{-3}$
- ★ n-type bulk:  $\rho > 2 \text{ k}\Omega\text{cm}$   
→ thickness  $300 \mu\text{m}$
- ★ Operating voltage  $< 200 \text{ V}$ .
- ★  $n^+$  layer on backplane to improve ohmic contact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



## AC Coupling Silicon detector

AC coupling blocks leakage current from the amplifier.

- ★ Integration of coupling capacitances in standard planar process.
- ★ Deposition of  $\text{SiO}_2$  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 32 pF/cm.
- ★ Problems are shorts through the dielectric (pinholes). Usually avoided by a second layer of  $\text{Si}_3\text{N}_4$ .

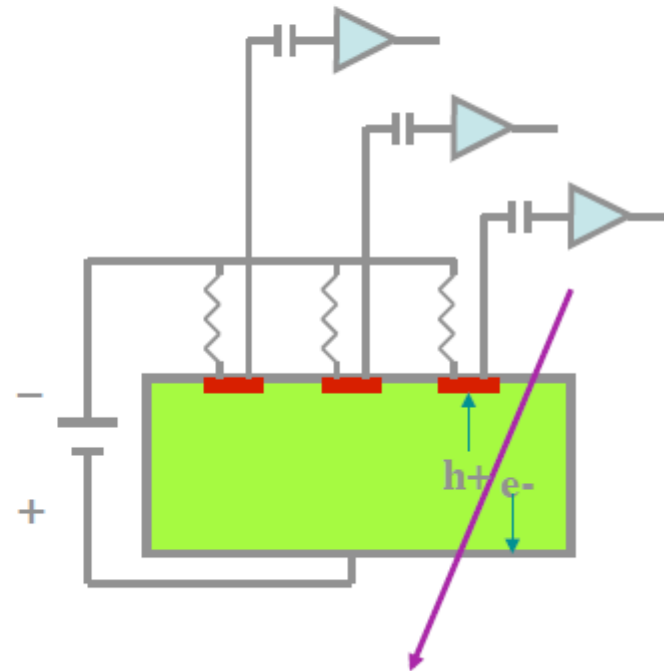


Several methods to connect the bias voltage: polysilicon resistor, punch through bias, FOXFET bias.

## Semiconductors : generalities : building

AC coupled Si detectors create 2 electrical circuits :

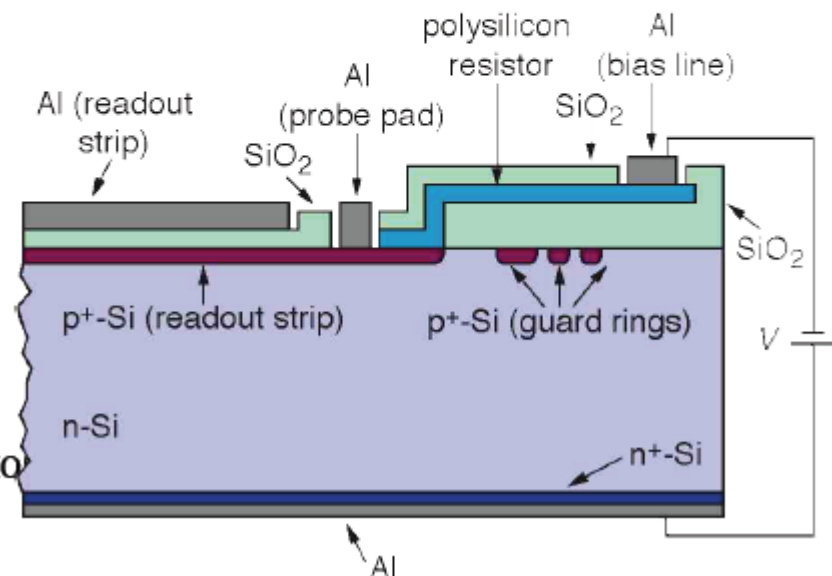
- Read-out circuit to the amplifier (AC current)
- Biasing circuit (DC current)



## AC Coupling Silicon detector : bias voltage system

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

Cut through an AC coupled strip detector with integrated poly resistor





## Semiconductors : generalities : the Fano factor

Number of e – h pairs is a statistical process :

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

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

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

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

Fano factor :

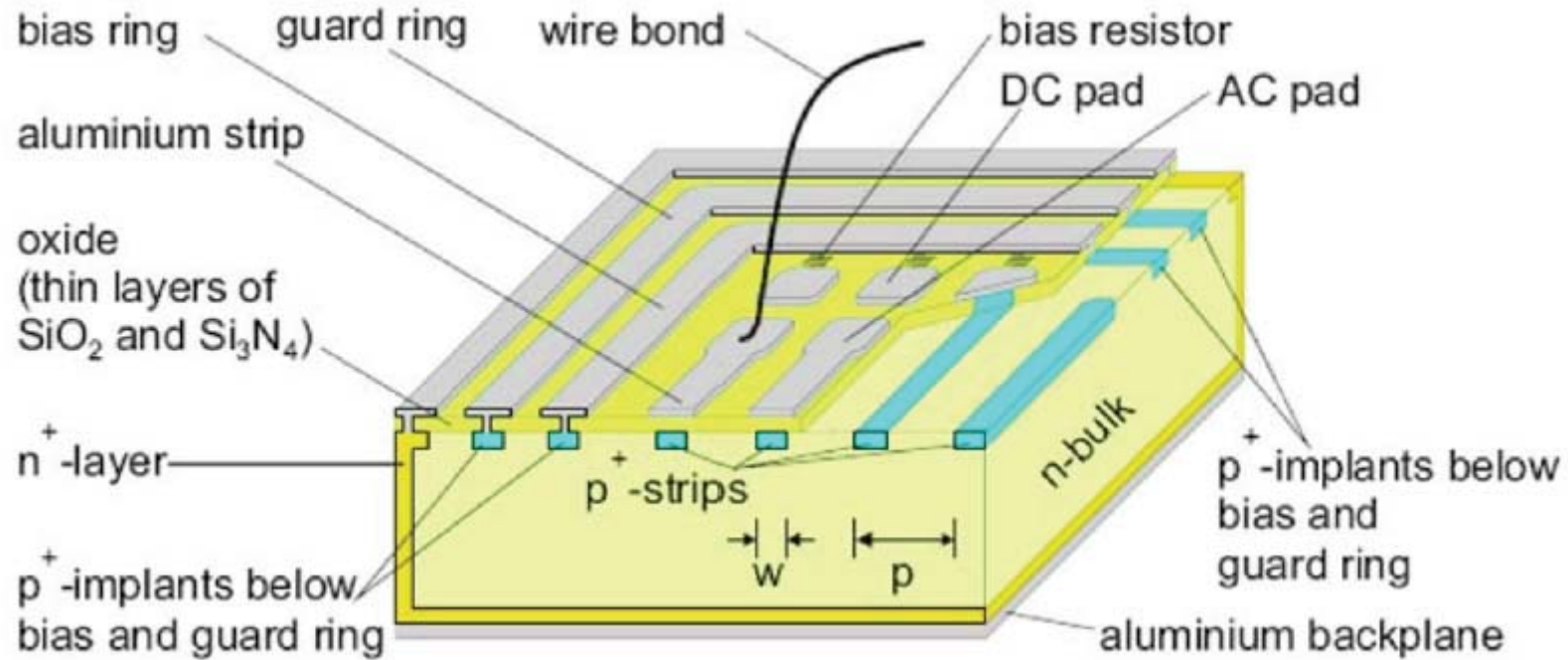
variance / mean of the process (should be 1 for a perfect Poisson distribution)

Si	0.115
Ge	0.13
GaAs	0.10
Diamond	0.08

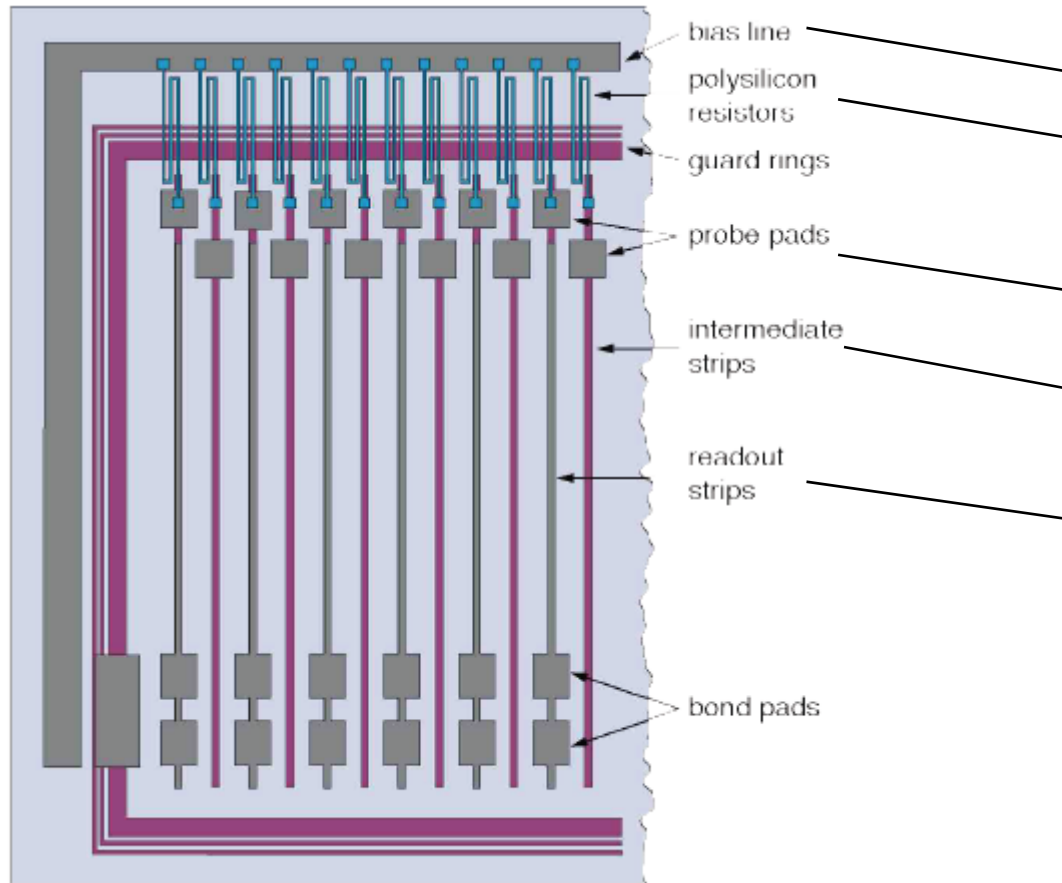
Fano factor related to energy resolution :

A Fano factor < 1 means that the energy resolution would be better than theoretically expected...

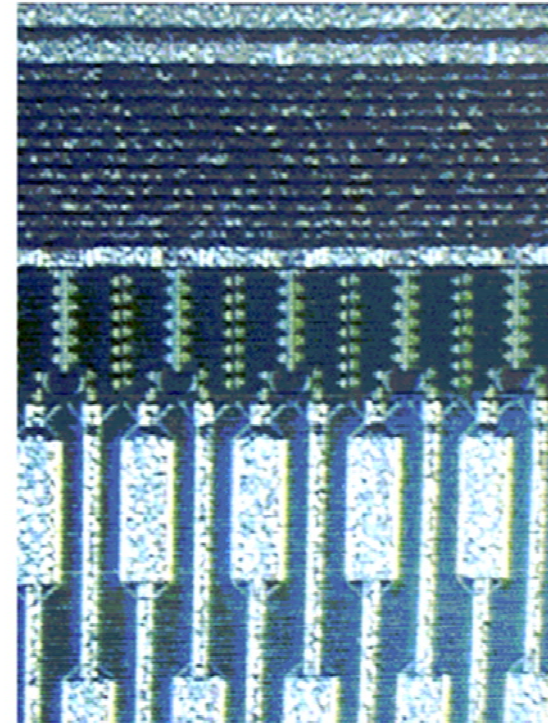
Most commonly scheme AC + poly S-bias resistor



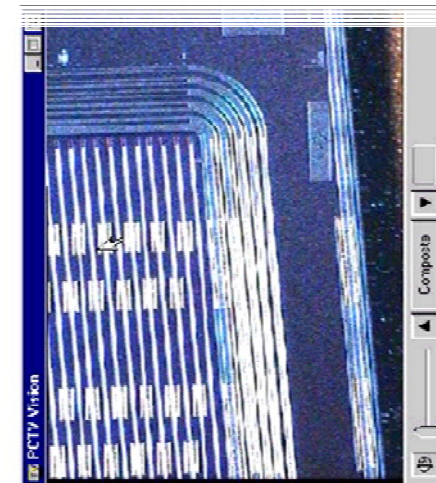
# Semiconductors : Si detectors designs



CMS design



ATLAS design



## Semiconductors : Si detectors designs

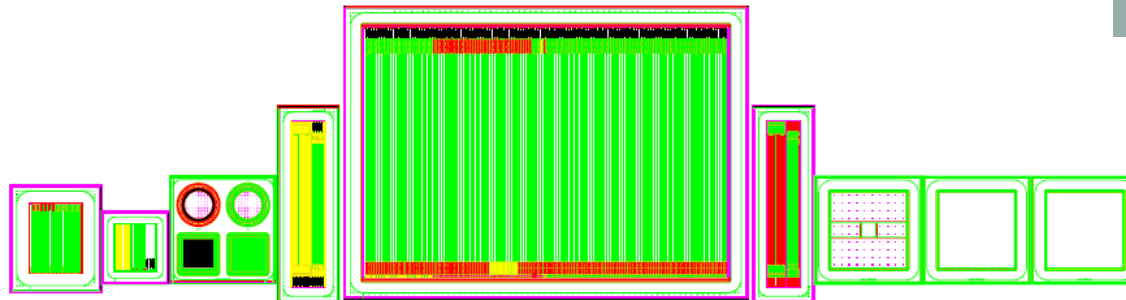
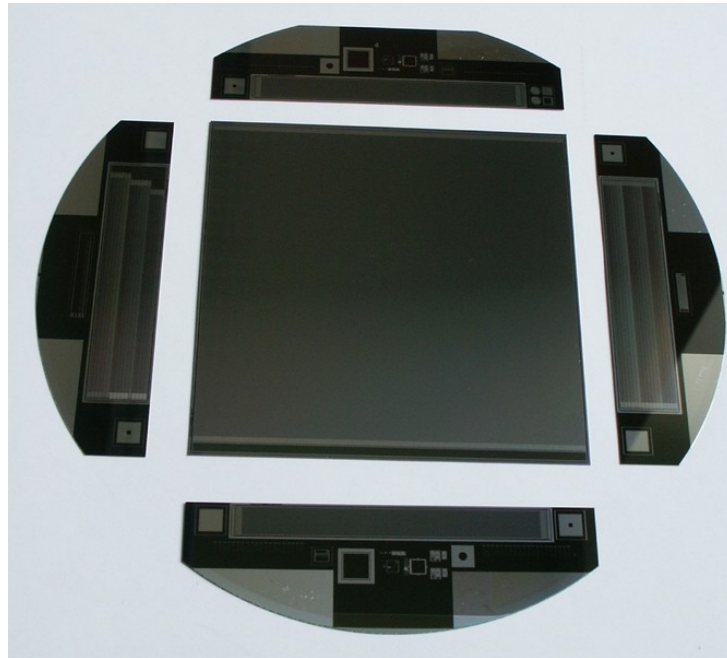


Figure 4.1: View of the Standard half-moon. The devices are (from left to right): TS-CAP, sheet, GCD, CAP-TS-AC, baby, CAP-TS-DC, diode, MOS1 and MOS2.

## 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 ( $\text{SiO}_2$ ) and the Si/ $\text{SiO}_2$  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**

⇒ **Sensors can fail from radiation damage !**

## Loss of collected charges

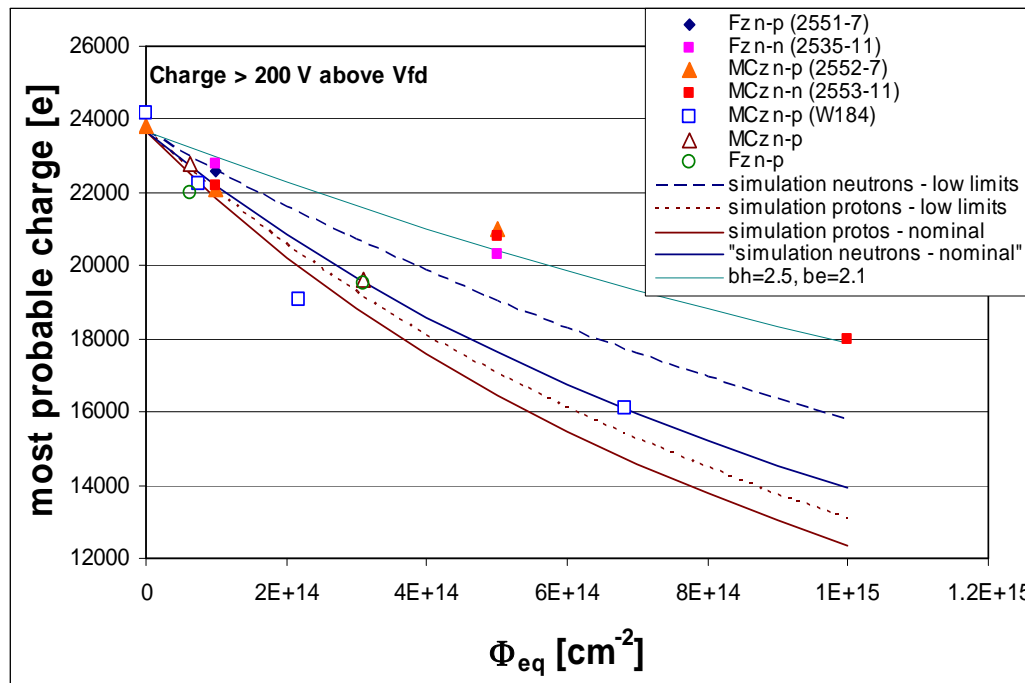
(new 300 μm Silicon ≈ 24 000 e- for 1 MIP)

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

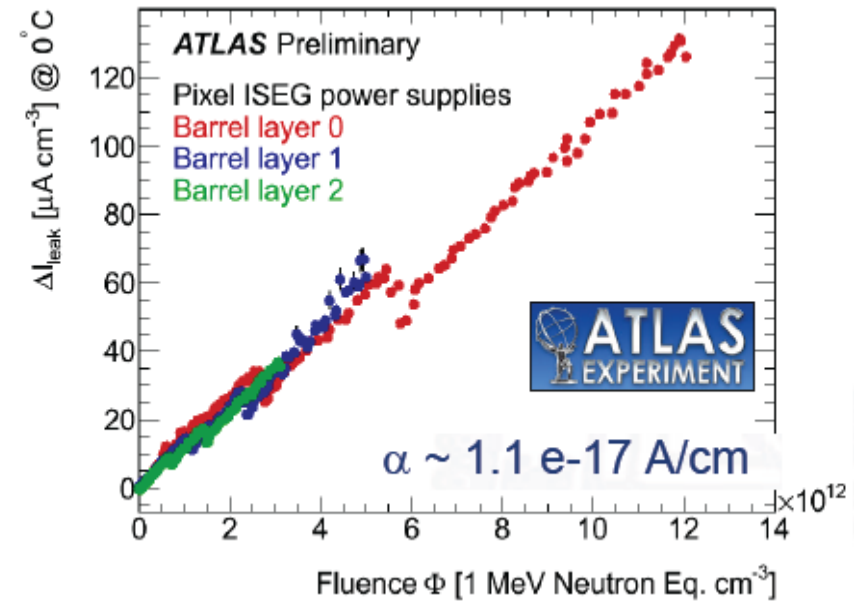
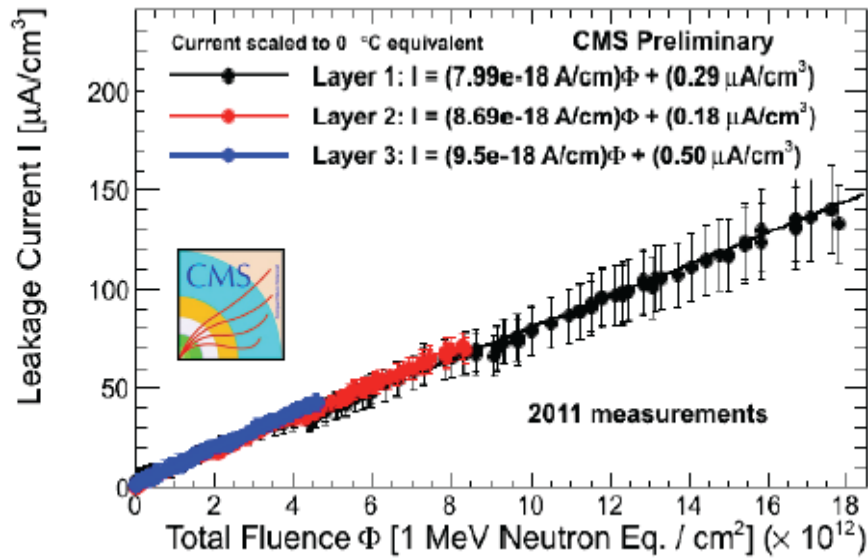
$$Q_{e,h}(t) = Q_{0,e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right)$$

where

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



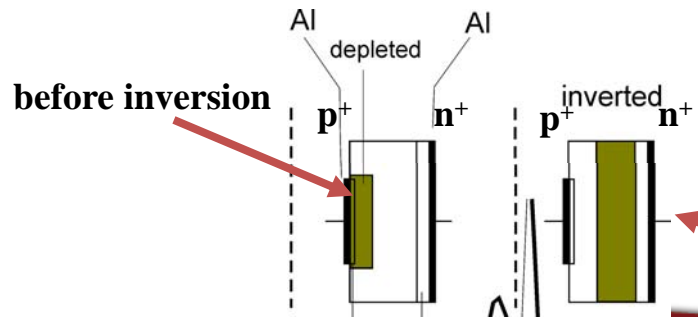
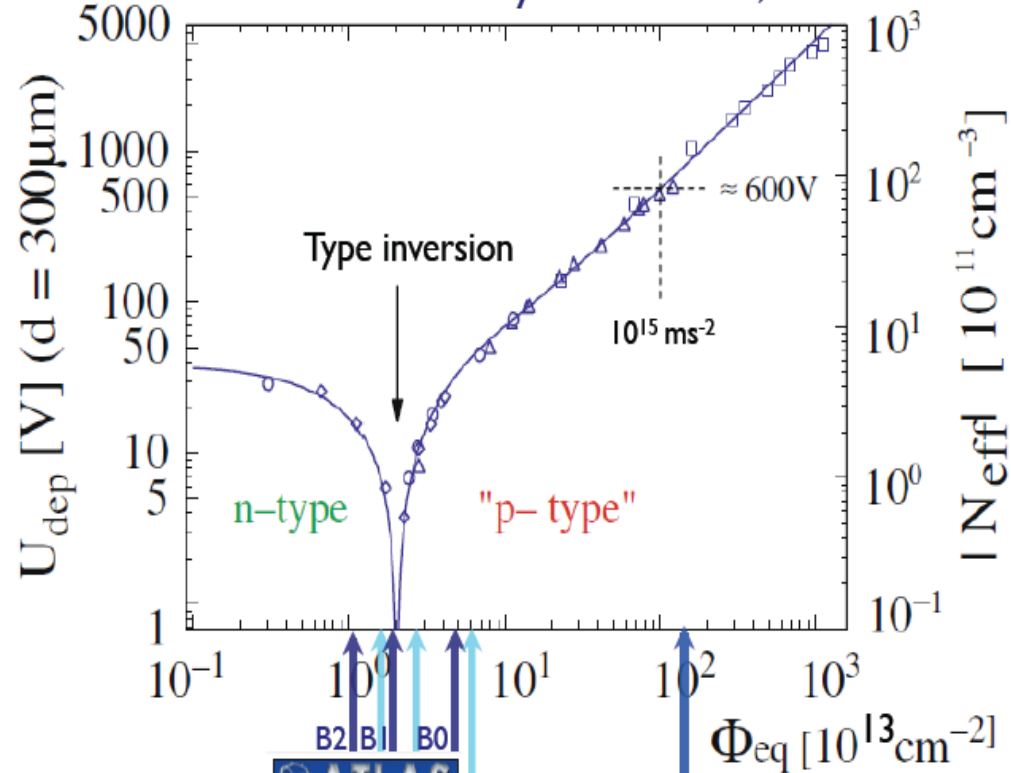
## Increase of Leakage current



## 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  $\Phi_{eq} \approx 10^{15} \text{ cm}^{-2}$





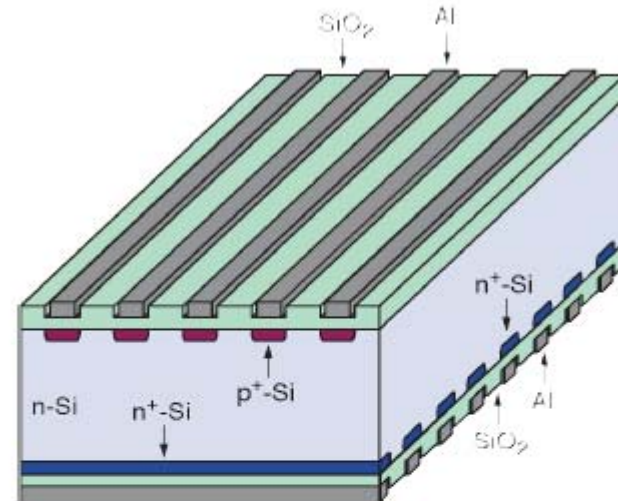
## Double Sided Silicon Detectors (DSSD) Not much in use...

### Advantages:

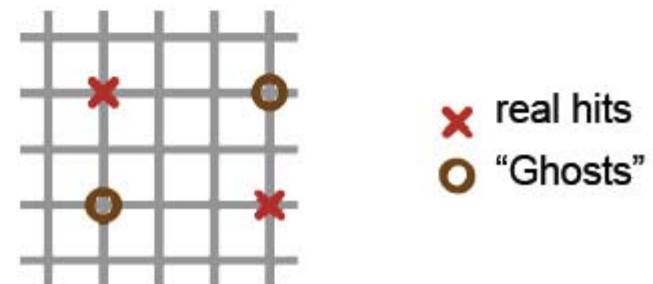
- More elegant way for measuring 2 coordinates
- Saves material

### Disadvantages:

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



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



## Stereo Modules

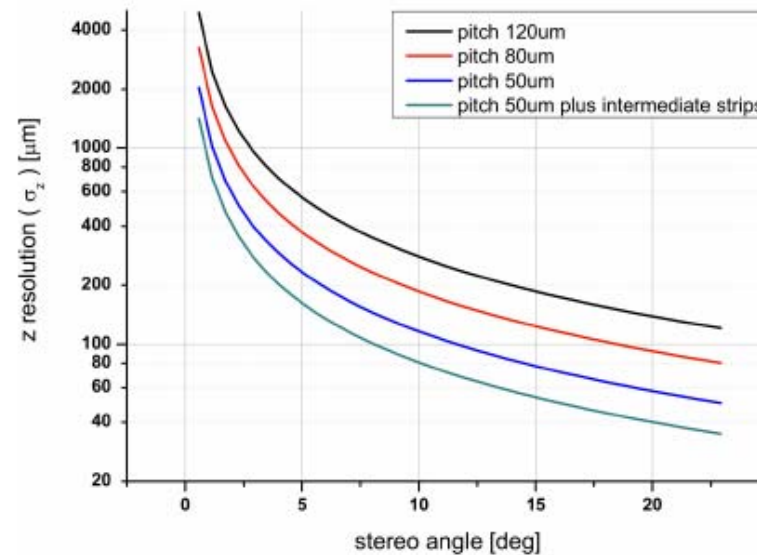
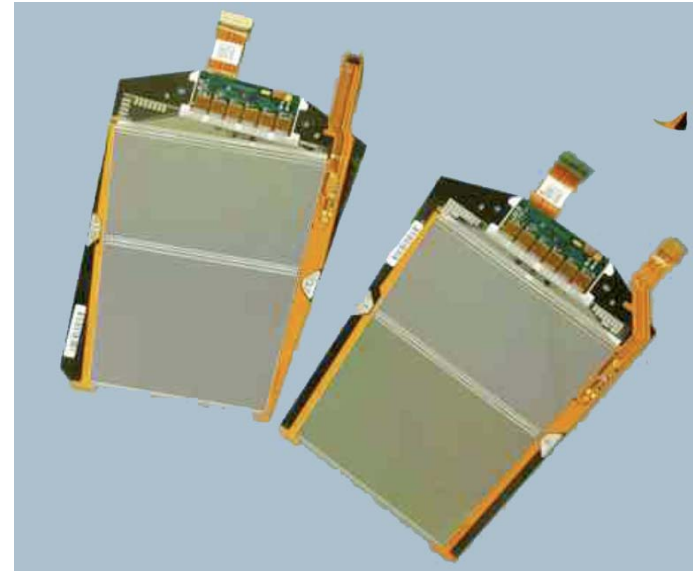
2<sup>nd</sup> coordinate requires second detector underneath

⇒ double the material

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

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

- CMS uses ~6 degrees



# Semiconductors : Performance

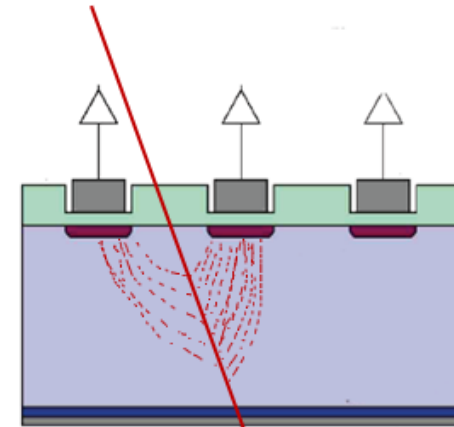
★ Threshold readout (one strip signal):

→ position:  $x = \text{strip position}$

→ resolution:  $\sigma_x \approx \frac{p}{\sqrt{12}}$

$p$  ... distance between strips (readout pitch)

$x$  ... position of particle track



★ charge center of gravity (signal on two strips):

→ position:

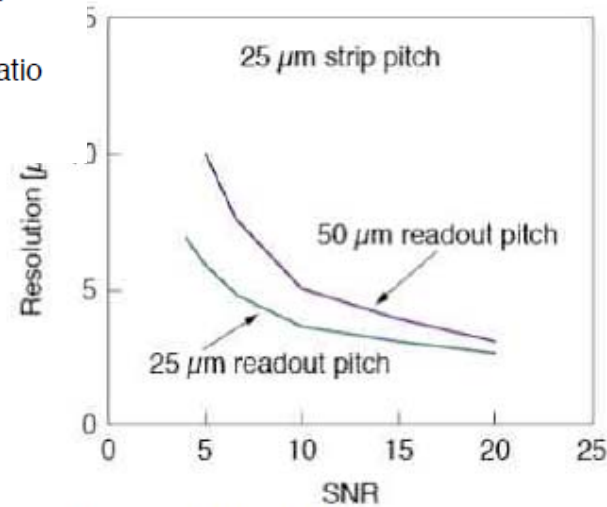
$$x = x_1 + \frac{h_1^2}{h_1 + h_2} (x_2 - x_1) = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2}$$

$x_1, x_2$  ... position of 1<sup>st</sup> and 2<sup>nd</sup> strip

$h_1, h_2$  ... signal on 1<sup>st</sup> and 2<sup>nd</sup> strip

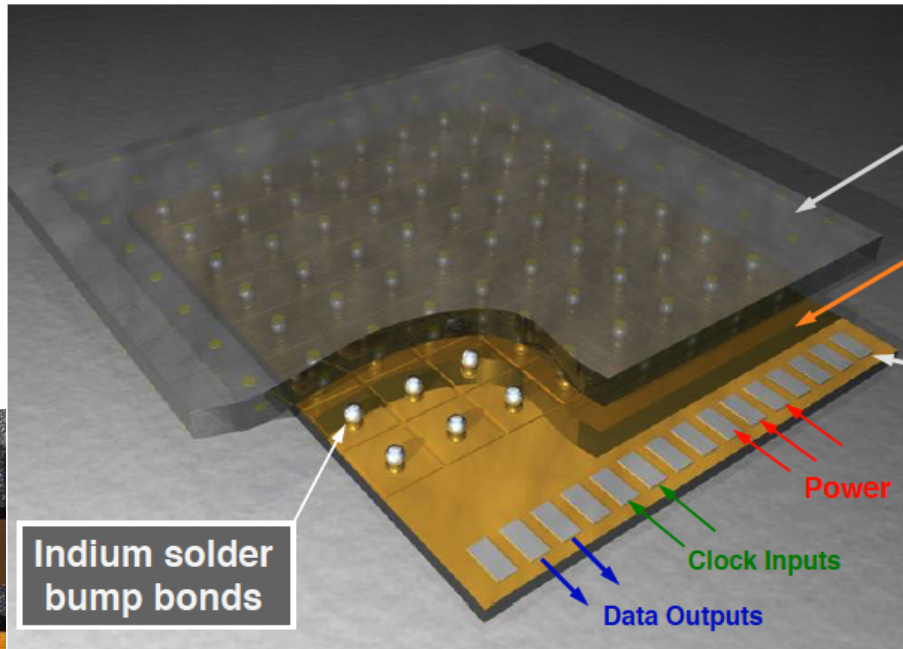
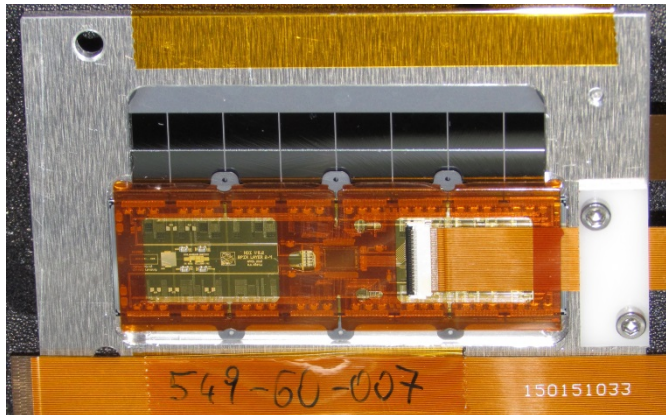
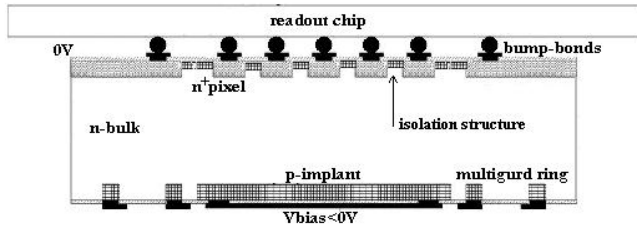
$SNR$  ... signal to noise ratio

→ resolution:  $\sigma_x \propto \frac{p}{SNR}$



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

# Semiconductors : Pixels Detectors



pixelated particle sensor

amplifier & readout chip CMOS

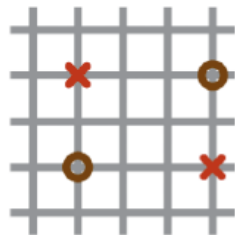
Connection wire pads  
power inputs  
outputs

Indium solder bump bonds

Power

Clock Inputs

Data Outputs



X real tracks  
O "ghosts"



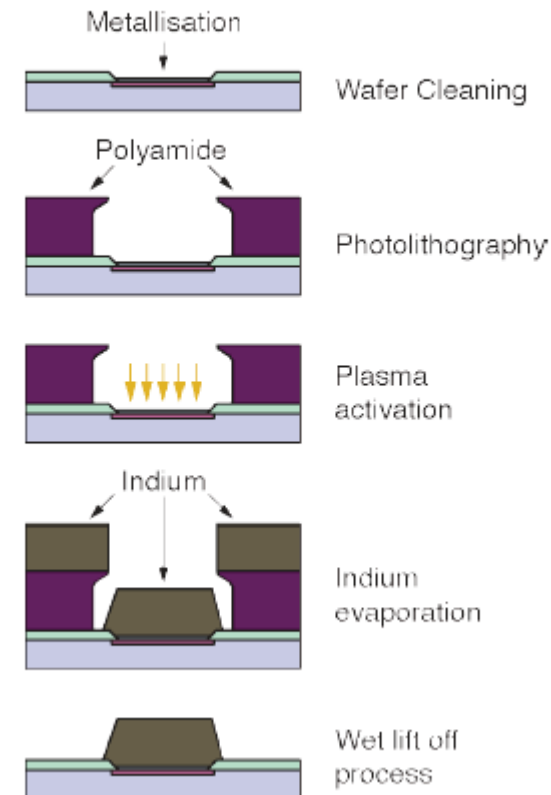
real tracks

Pixel sizes :  
ATLAS : 50  $\mu\text{m}$  x 400  $\mu\text{m}$   
CMS : 100  $\mu\text{m}$  x 150  $\mu\text{m}$   
ALICE : 50  $\mu\text{m}$  x 425  $\mu\text{m}$

## CONNECTION BY BUMP BONDING

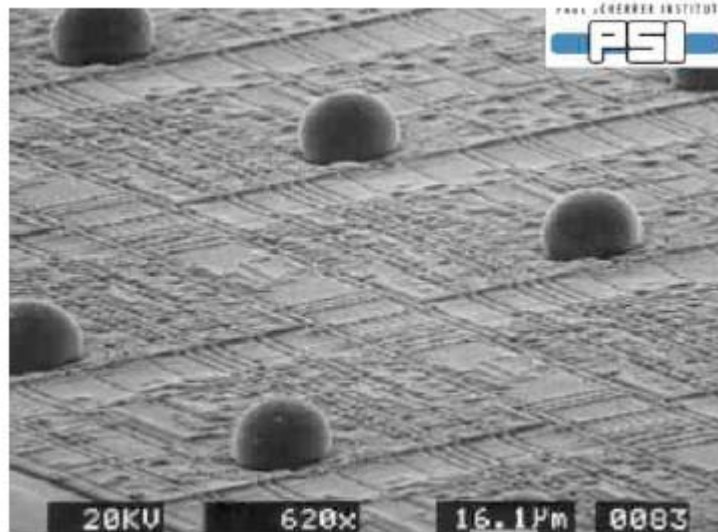
A typical bump bonding process (array bump bonding) is the following:

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” ( $\approx 10 \mu\text{m}$  height).
4. Edging of photolithography mask leaves surplus of bump metal on pads.
5. Reflow to form balls.



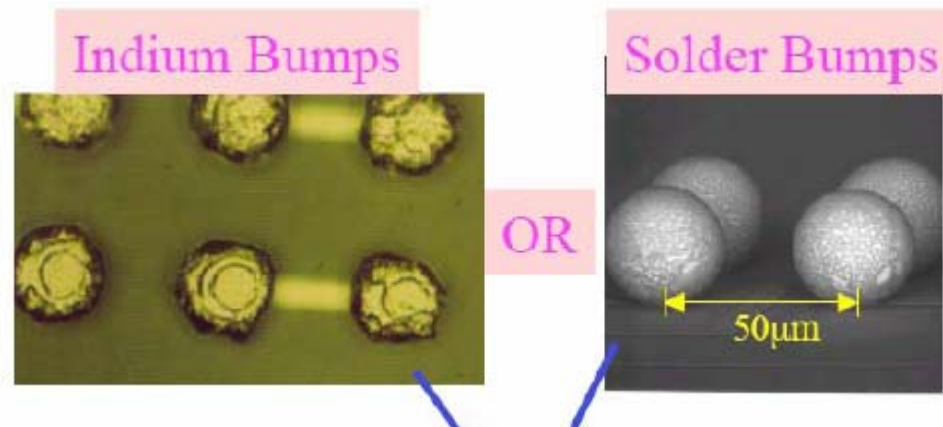
L. Rossi, Pixel Detectors Hybridisation, Nucl. Instr. Meth. A 501, 239 (2003)

## Semiconductors : Pixels Detectors

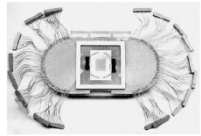


Pitch : 50 µm

(wire bonding typically 200µm)



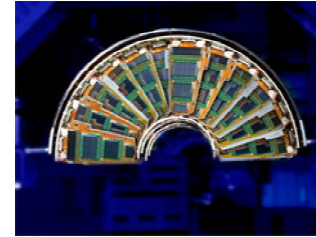
# Semiconductors : Silicon history



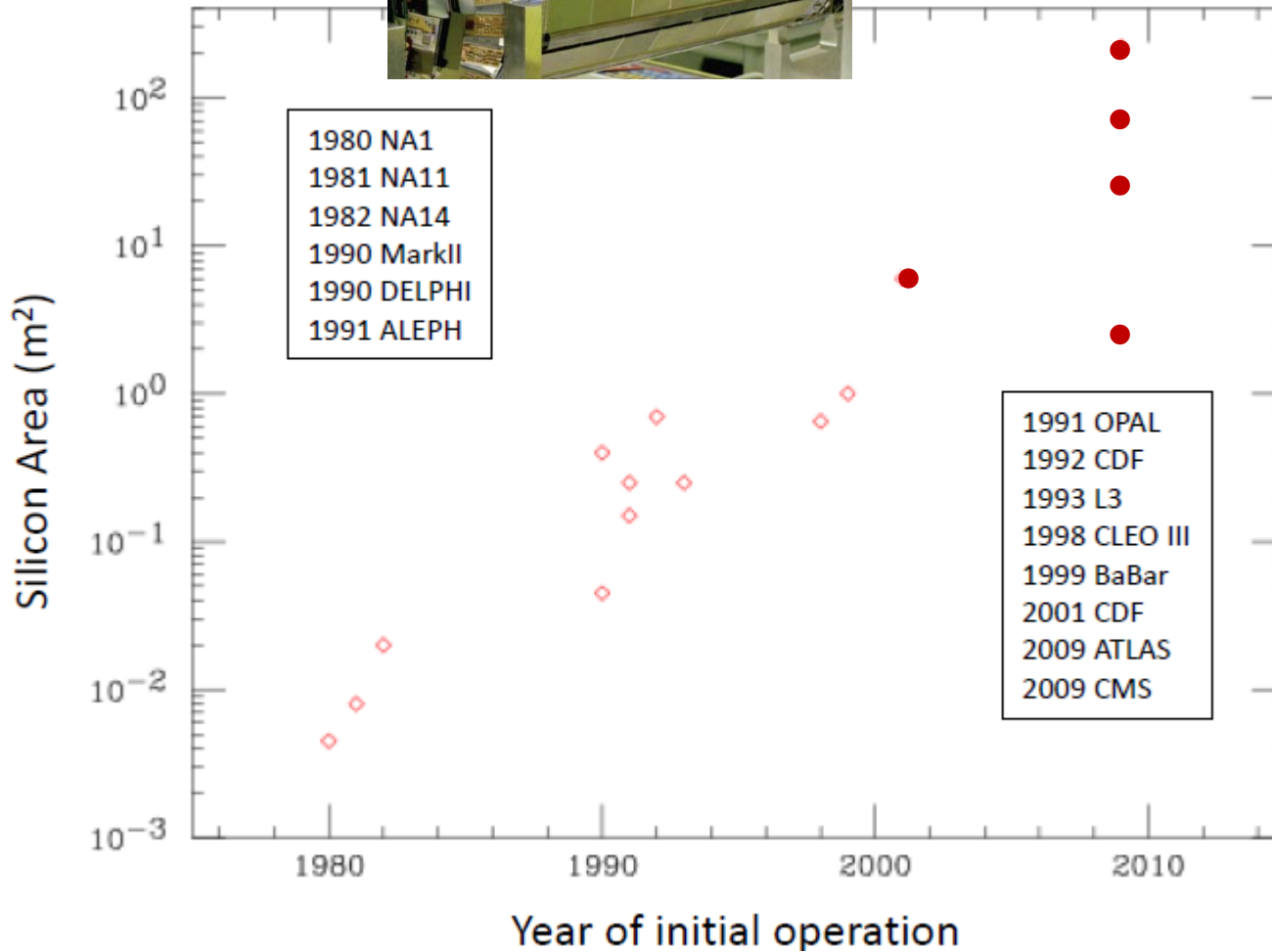
NA 11



DELPHI

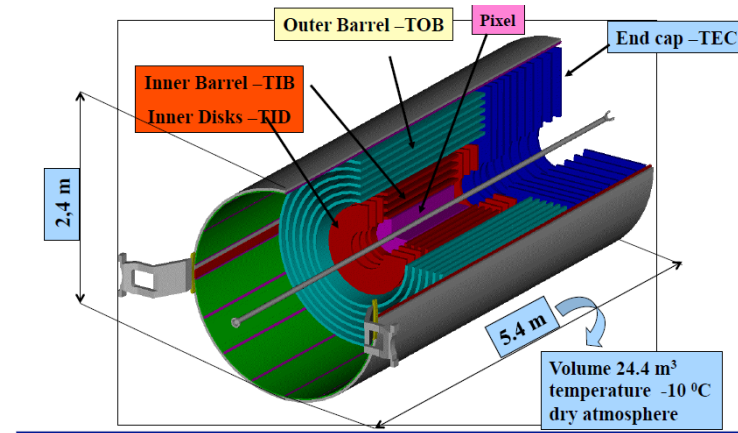
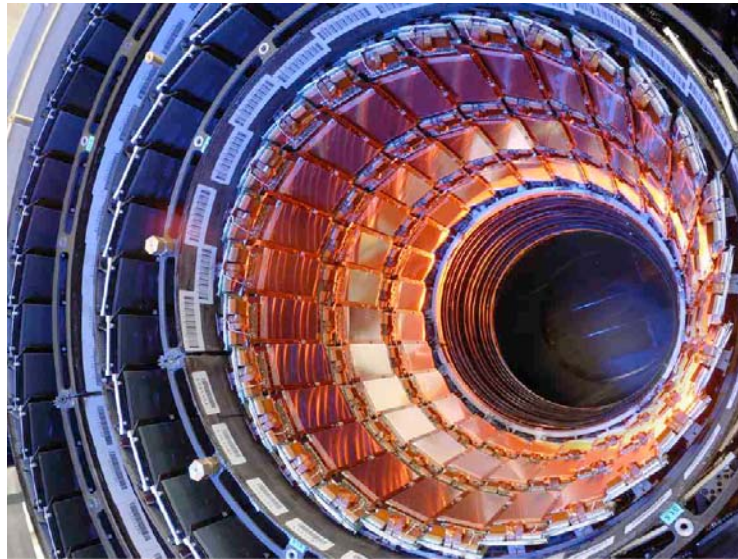


CDF



- CMS  $\approx 215 \text{ m}^2$
- ATLAS  $\approx 61 \text{ m}^2$
- LHCb  $\approx 12.5 \text{ m}^2$
- CDF  $\approx 3.5 \text{ m}^2$
- ALICE  $\approx 1.5 \text{ m}^2$

## Semiconductors : CMS Silicon Detector

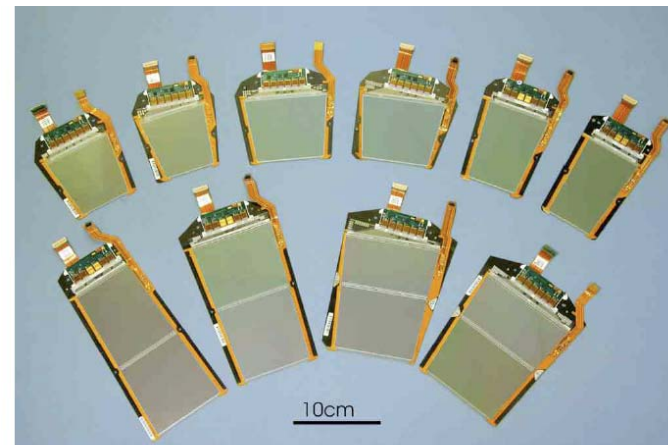


### Strip detector:

- ~200 m<sup>2</sup> 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:

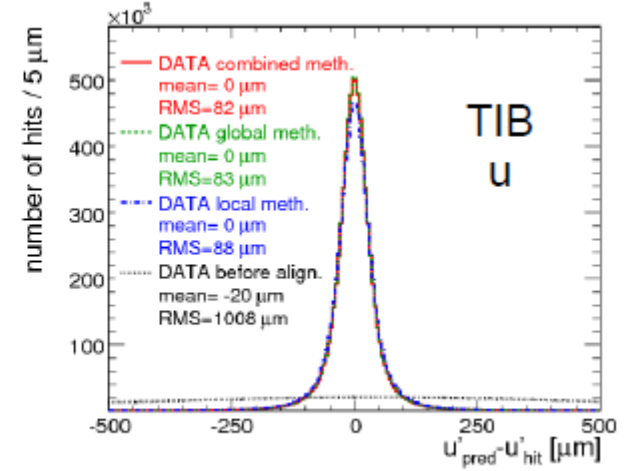
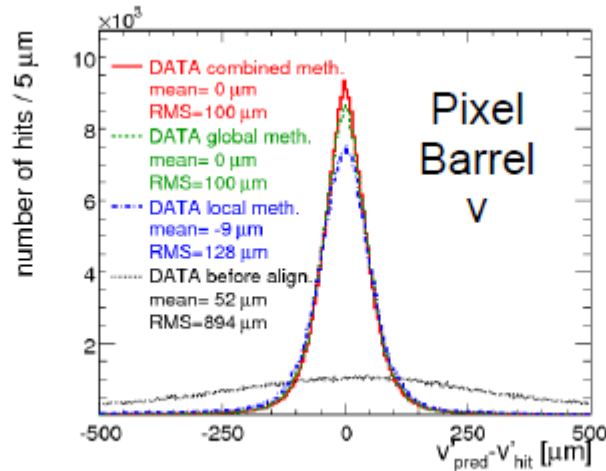
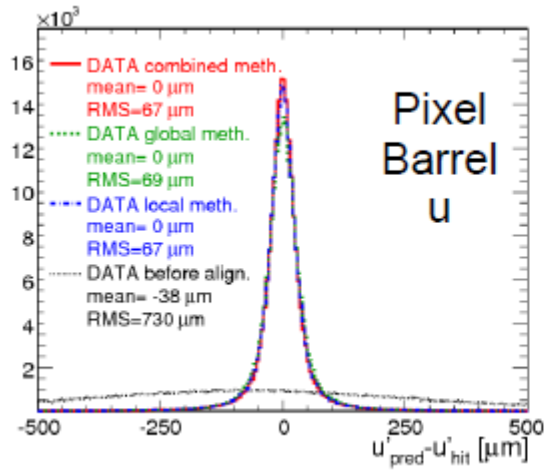
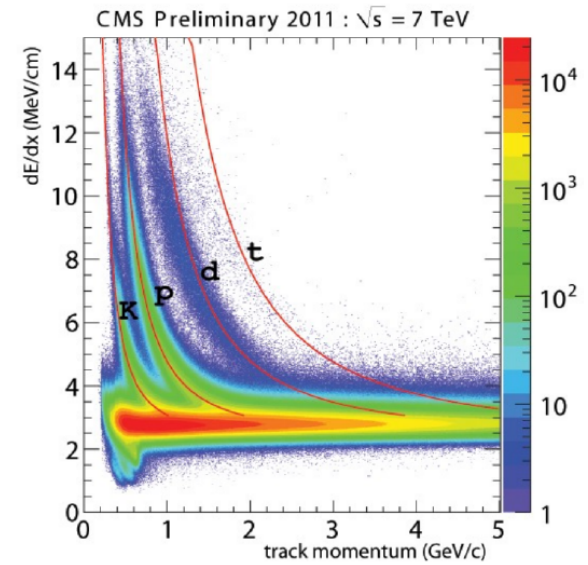
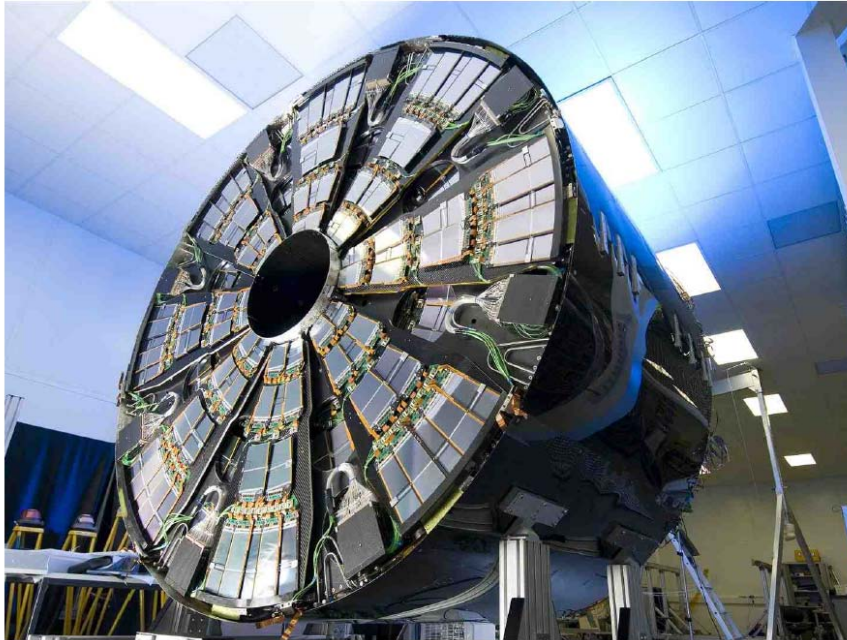
- 1 m<sup>2</sup> detector area
- 1440 pixel modules
- 66 million pixels



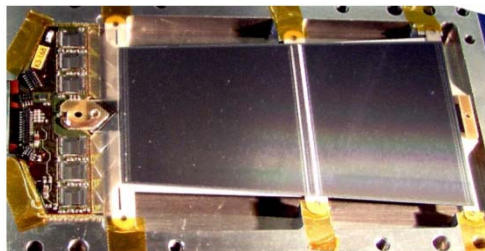
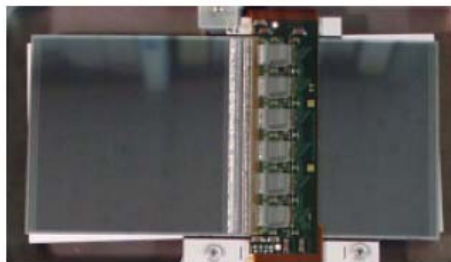
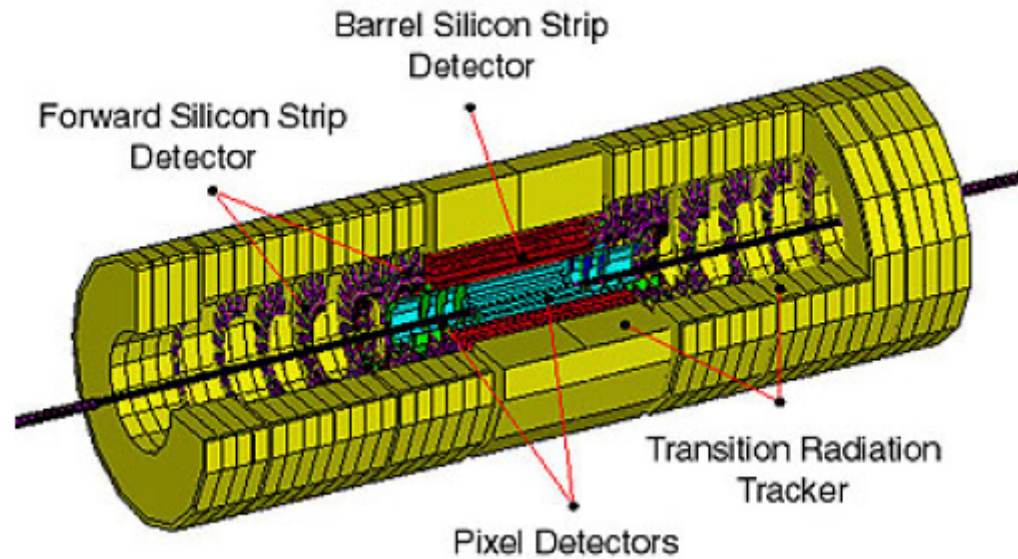
27 mechanical different modules + 2 types of alignment modules



# Semiconductors : CMS Silicon Detector

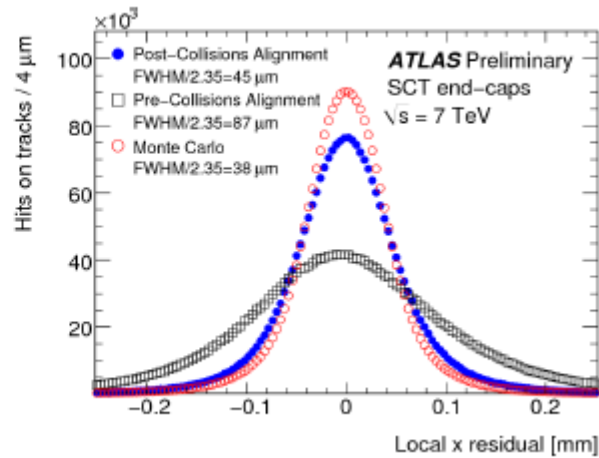
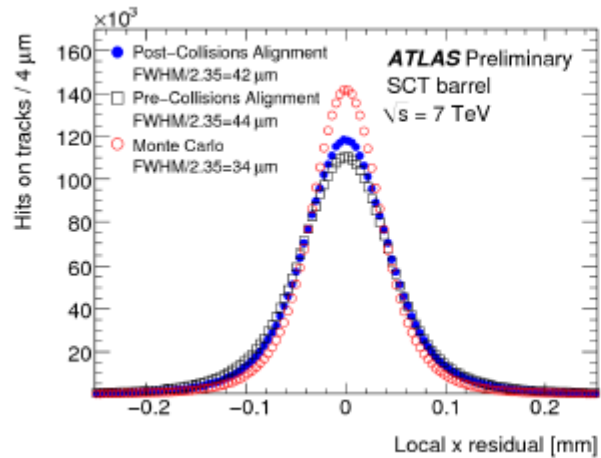
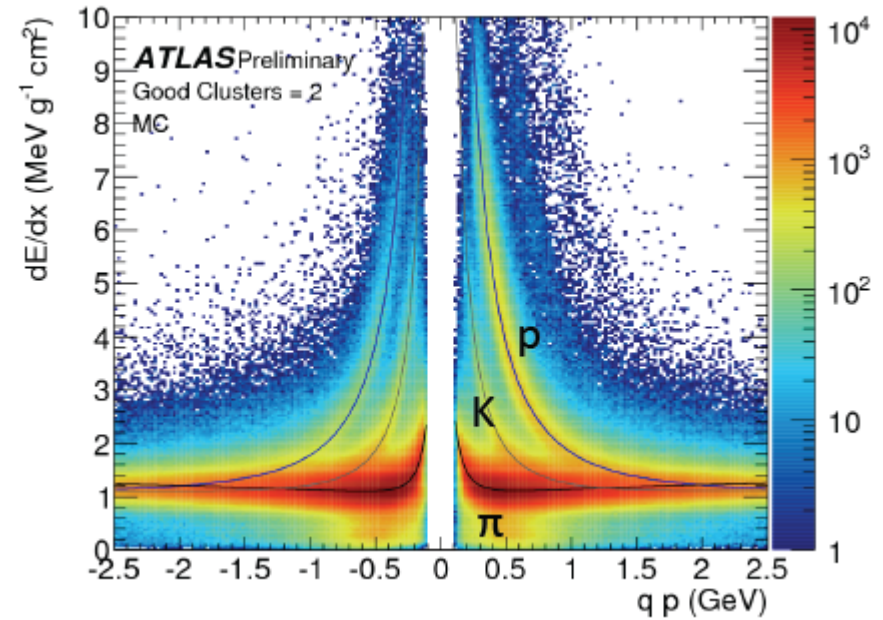
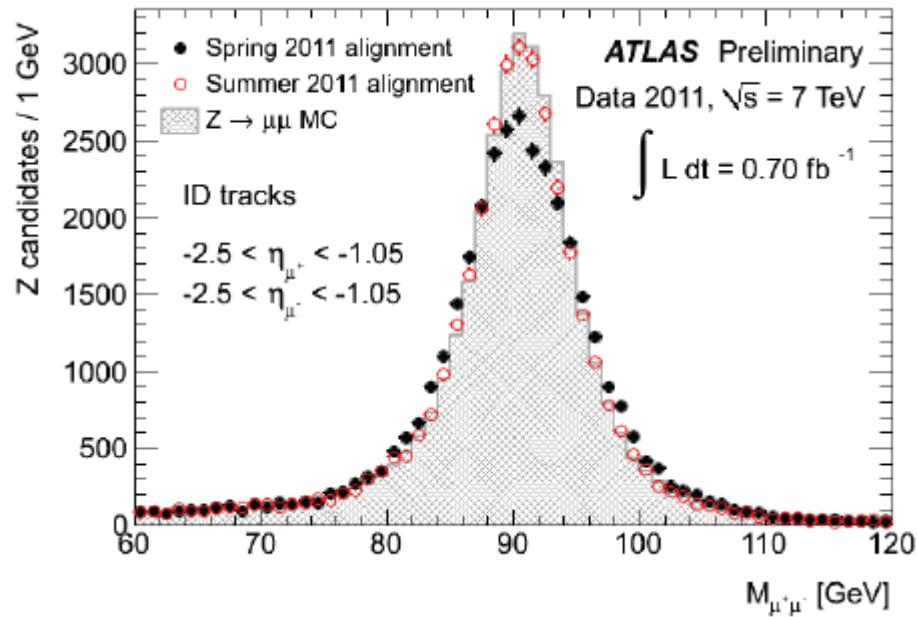


# Semiconductors : ATLAS Silicon Detector



system		area (m <sup>2</sup> )	resolution (μm)	channels (10 <sup>6</sup> )	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
	<b>total</b>	<b>2.3</b>		<b>140</b>	<b>2.5</b>
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
	<b>total</b>	<b>61.1</b>		<b>6.2</b>	<b>2.5</b>

# Semiconductors : ATLAS Silicon Detector



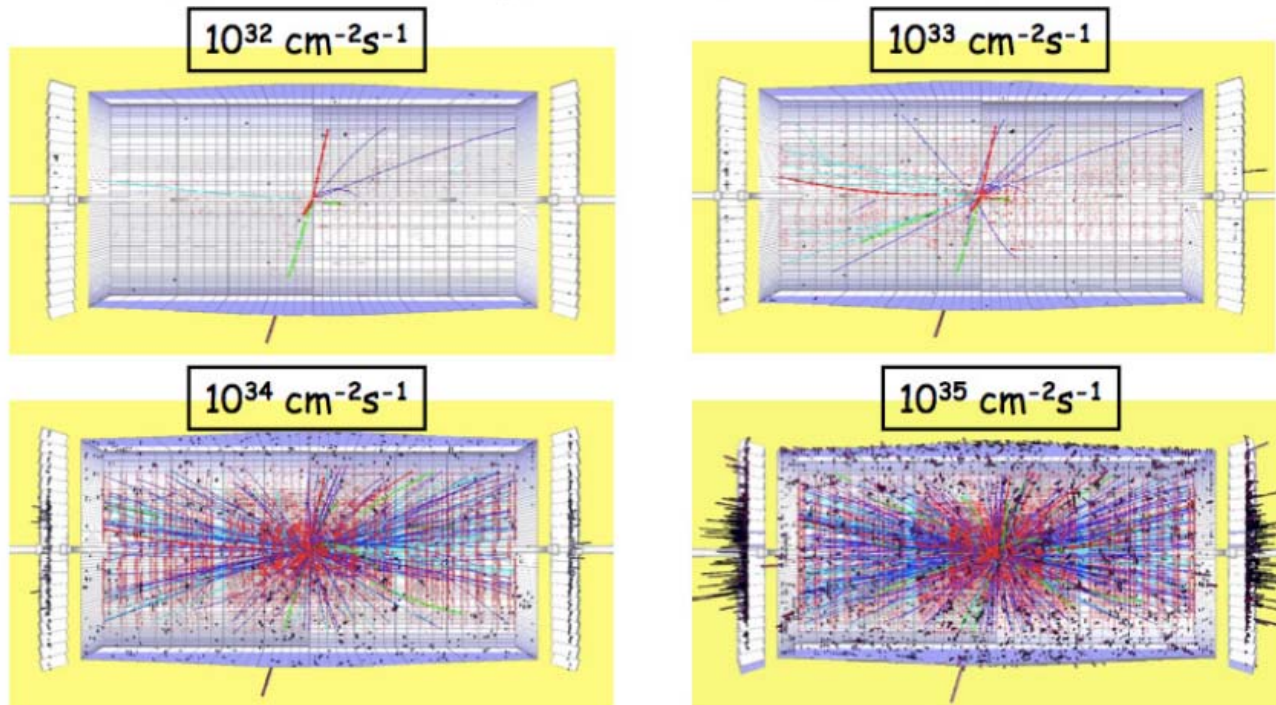
Main performance characteristics of the ATLAS and CMS trackers

	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 $\eta \approx 0$ ( $\mu\text{m}$ )	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ ( $\mu\text{m}$ )	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ ( $\mu\text{m}$ )	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ ( $\mu\text{m}$ )	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ ( $\mu\text{m}$ )	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ ( $\mu\text{m}$ )	900	1060

**ATLAS : Si Pixels + Si Strips + Gas TRD**  
**CMS : Si Pixels + Si Strips**

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

$H \rightarrow ZZ \rightarrow \mu\mu ee$  event with  $M_H = 300 \text{ GeV}$  for different luminosities



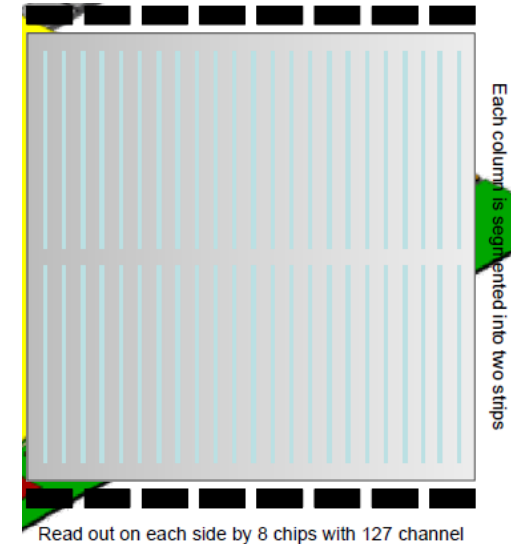
More tracks : Occupancy increases - Less resolution

More Flux : Radiation (bulk) damage

**Reduce the Occupancy** : Increase the granularity

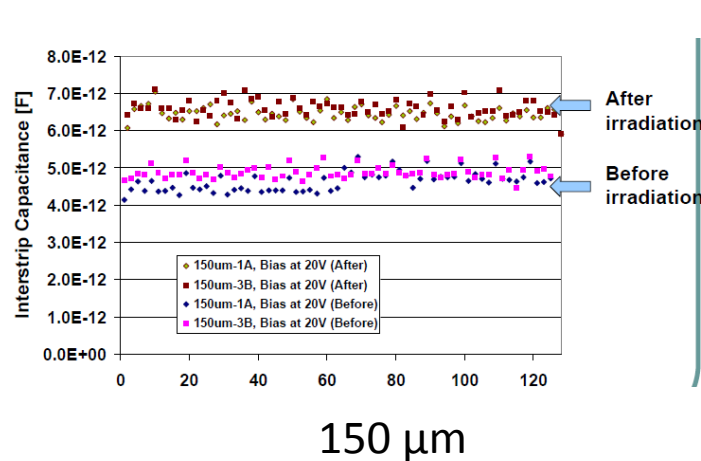
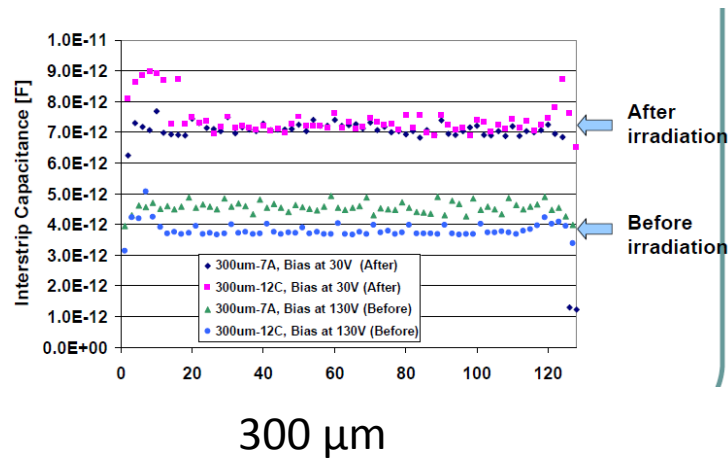
Mini-strips sensors (reduce length from 10 cm to 5 cm)

- Increases the number of channels
- Increases the cost
- Increases the power to be dissipated (already 3kW 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



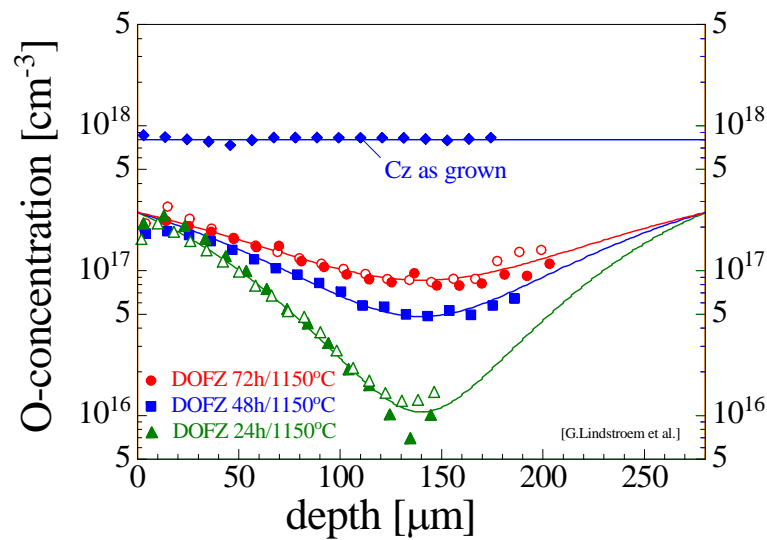
Change the material : Oxygenated Silicon

HE detectors : **FZ** (Float Zone) Crystal - High resistivity > 3-4 kΩcm  
 - O2 contents < 50 10<sup>16</sup>

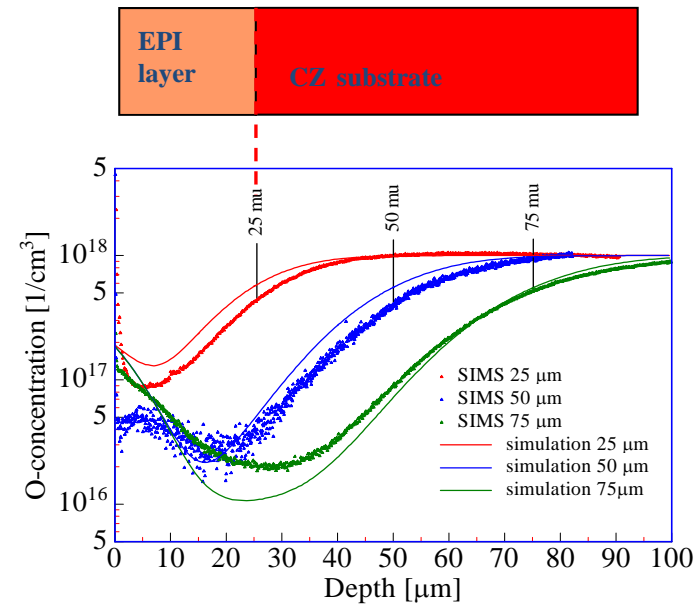
New Materials : **DOFZ** : O2 doped FZ Silicon (Oxydation of wafer at high temperature)

**MCZ** (Magnetic Czochralki) - Less resistivity ≈ 1.5 kΩcm  
 - O2 contents > 5 10<sup>17</sup>

**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  $\sim 2 \times 10^{13}$  p/cm<sup>2</sup>
- strong  $N_{\text{eff}}$  increase at high fluence

- **Oxygenated FZ (DOFZ)**

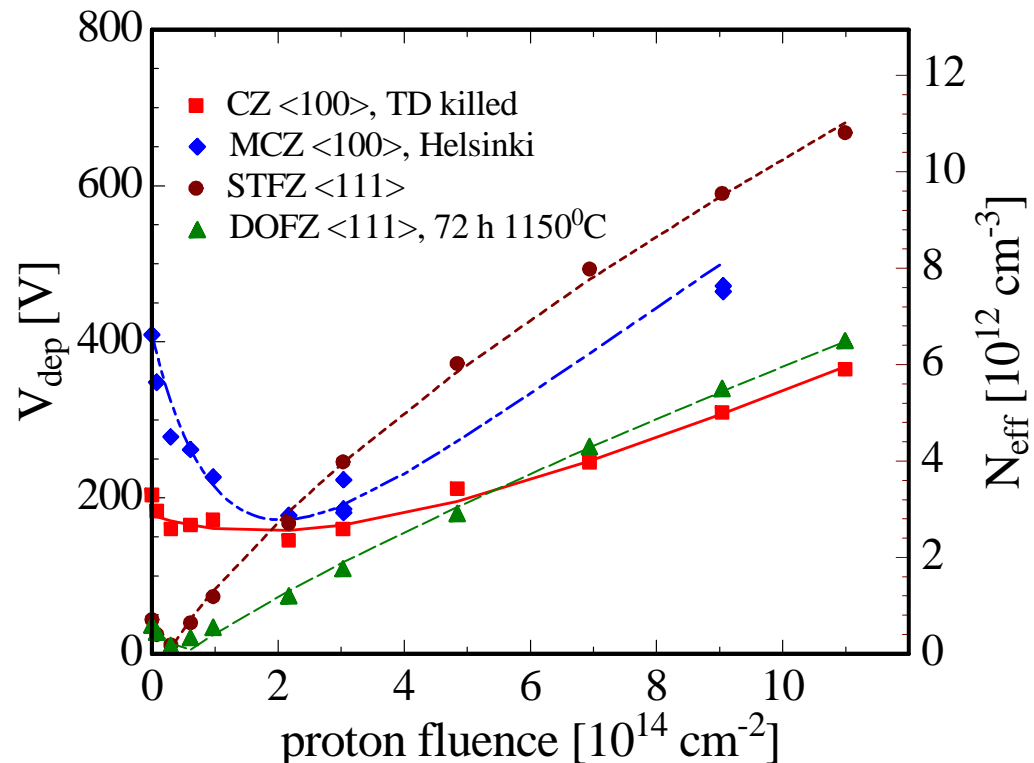
- type inversion at  $\sim 2 \times 10^{13}$  p/cm<sup>2</sup>
- reduced  $N_{\text{eff}}$  increase at high fluence

- **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  $\sim 20\%$





## 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 <sub>0</sub> = 0.37%
Number of pixels	356 M
Integration time (affects pileup)	185.6 μs
Radiation environment	20 to 90 kRad / year 2*10 <sup>11</sup> to 10 <sup>12</sup> 1MeV n eq/cm <sup>2</sup>
Rapid detector replacement	~ 1 day

### Signal collection

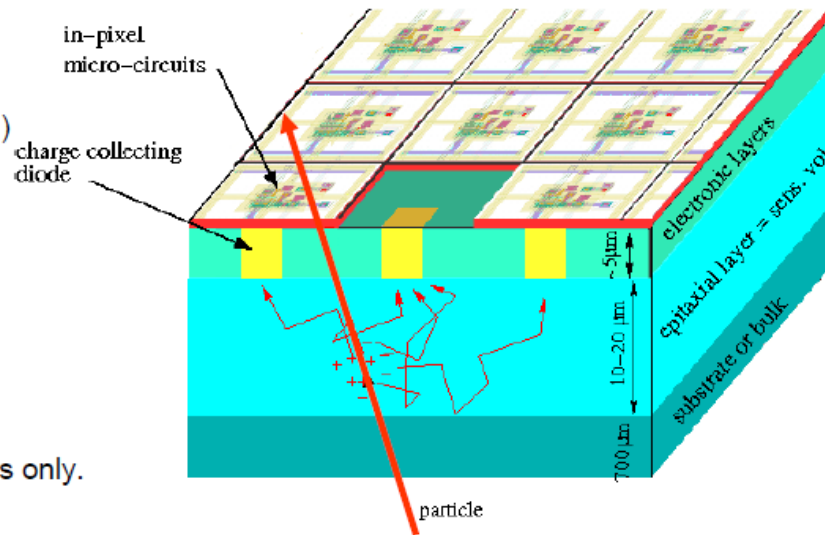
- Charges generated in epitaxial layer → ~1000 e<sup>-</sup> for MIP.
- Charge carriers propagate thermally.
- In-pixel charge to signal conversion.

### Advantages

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

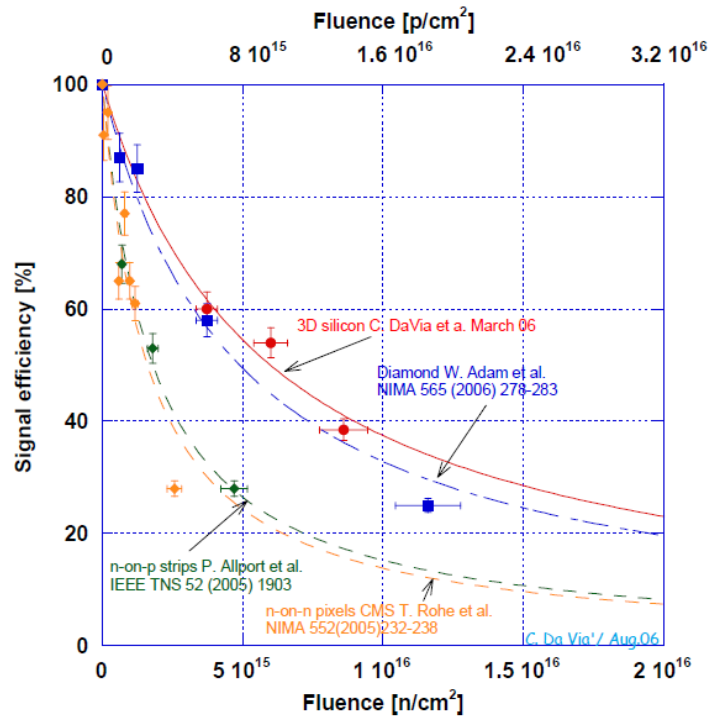
### Issues

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

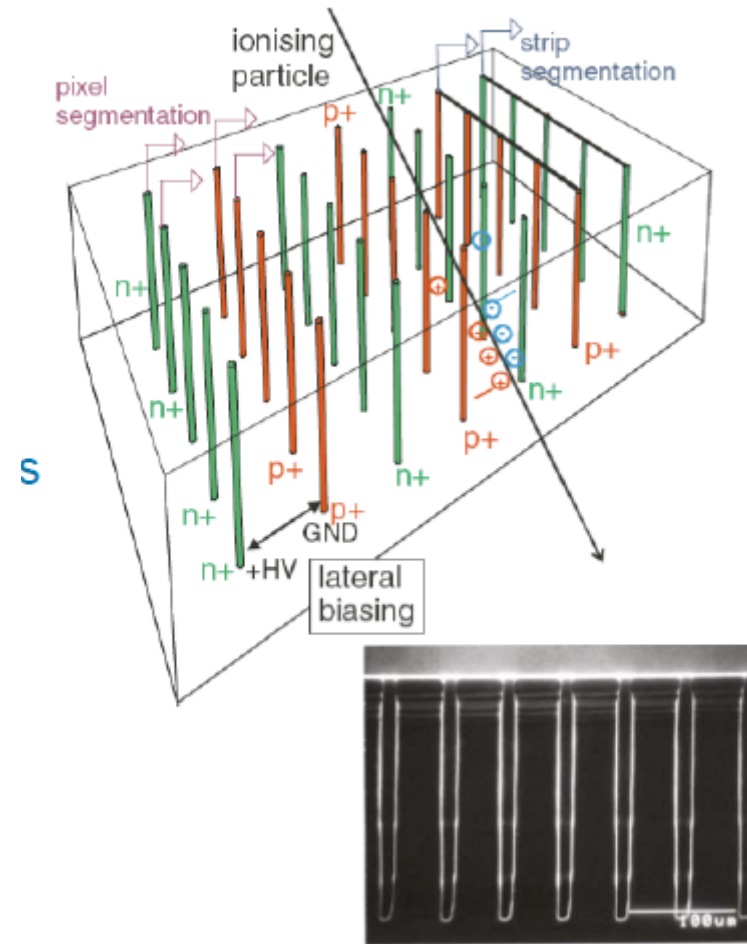


### 3D Silicon Detectors

Manufacturing challenge  
Electrodes : dead zones



Efficiency vs fluence



### Diamond detectors

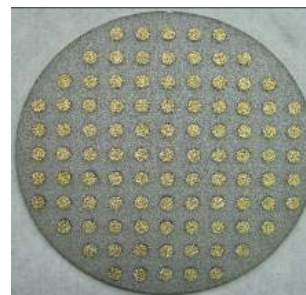
	CVD Diamond	Si
Z	6	14
Energy Gap	5,5 eV	1,21 to 1,1eV
Resistivity	$10^{13} - 10^{16}$ Ωcm	$10^5 - 10^6$ Ωcm
Breakdown	$10^7$ V/cm	$3.10^5$ V/cm
Mobility (electrons)	2000 $cm^2/V/s$	1350 $cm^2/V/s$
Mobility (holes)	1600 $cm^2/V/s$	480 $cm^2/V/s$
Displacement Energy (e <sup>-</sup> )	43 eV/atom	13 à 20 eV/atom
Pairs Creation	13 eV	3.6 eV
Charge Collection Distance	250 μm	100 m ?
Mean signal (MIP)	3600 e <sup>-</sup> / μm	8900 e <sup>-</sup> / μm
Dielectric Constant	5.5	10 à 12
Thermal Conductivity (W/m·K)	1600 - 2000	150

Diamond is better than Silicon

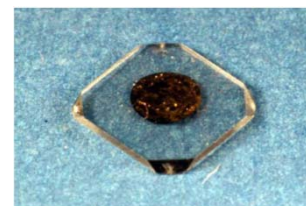
- Does not need any doping
- Better radiation hardness
- Better thermal conductivity
- Better speed (1psec vs 1 nsec)
- Light insensitive
- Multi-metalization possible  
(test and physics)

But :

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



2 forms :  
Polycrystalline  
Wafer max.6 inches



Monocrystalline  
max : 4 x 4 mm<sup>2</sup>