European School of Instrumentation in Particle & Astroparticle Physics

European Scientific Institute

DETECTOR TECHNOLOGIES

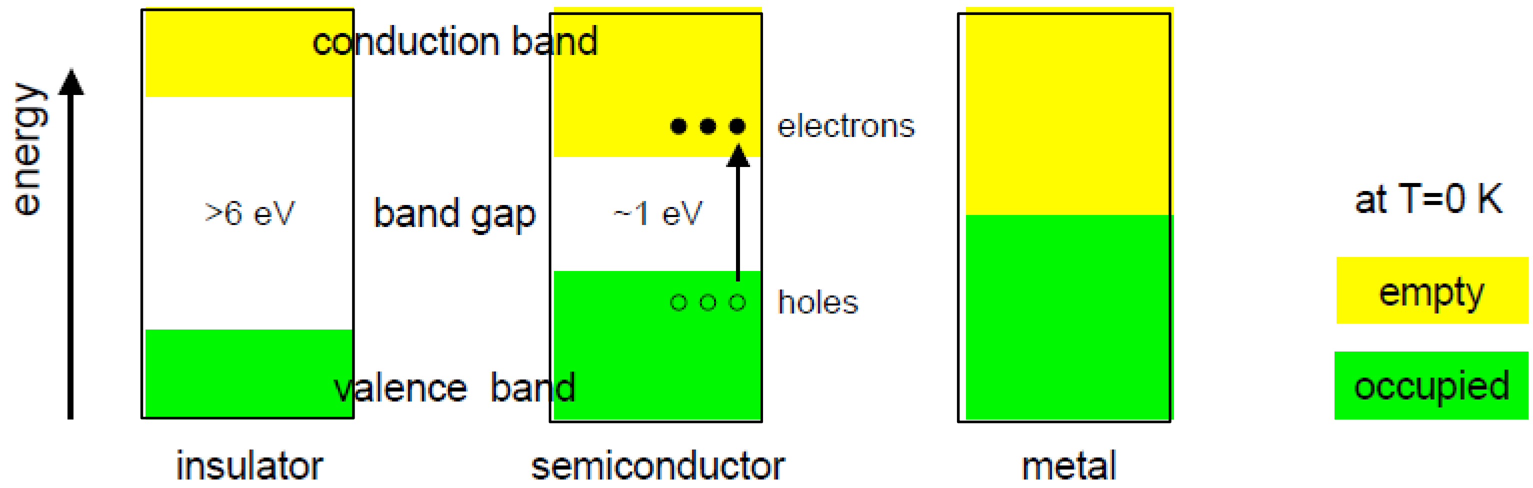
Lecture 3: Semi-conductors

- Generalities
- Material and types
- Evolution

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

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

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

At T ≠ 0 K

Electrons may acquire enough energy to pass the band gap… Thermal condution

Semiconductors : generalities

	Si	Ge
atomic number	14	32
density (g/cm^3)	2.33	5.32
atomic density (atoms/cm^3)	4.96 x 10^{22}	4.41 x 10^{22}
dielectric constant (relative to vacuum)	12	16
band gap (eV) 300 K 0 K	1.115 1.165	0.665 0.746
intrinsic carrier density at 300 K (/cm^3)	1.5 x 10^{10}	2.4 x 10^{13}
mobility (cm^2/V/s) at 300 K: electrons holes	1350 480	3900 1900
mobility (cm^2/V/s) at 77 K: electrons holes	2.1 x 10^4 1.1 x 10^4	3.6 x 10^4 4.2 x 10^4
ionisation energy (eV) 300 K 77 K	3.62 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 x 10^{10}	2.4 x 10^{13}	1.8 x 10^6	< 10^3

Energy loss by a charged particle : Bethe-Bloch

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

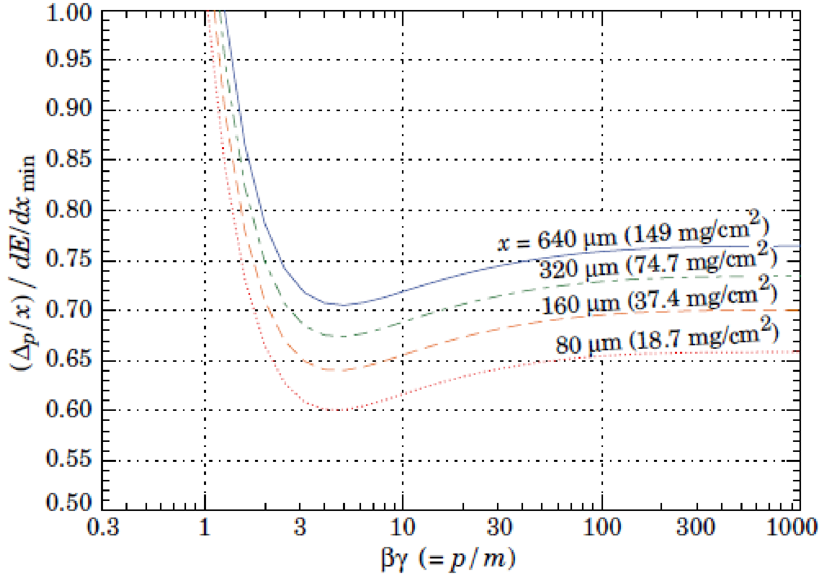


Figure 27.9: Most probable energy loss in silicon, scaled to the mean loss of a minimum ionizing particle, 388 eV/μm (1.66 MeV $g^{-1}cm^2$).

Standard :

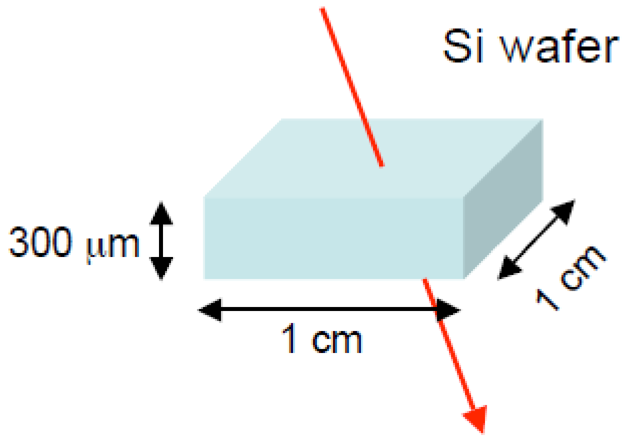
Energy loss :

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

If Field (even natural)

- electrons migration
- Electrical pulse
- Information

Too simple !



One MIP in Silicon at 300°K

Energy loss : dE / dx ≈ 388 Ev/µm

Ionisation Energy : 3.62 eV

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

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

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

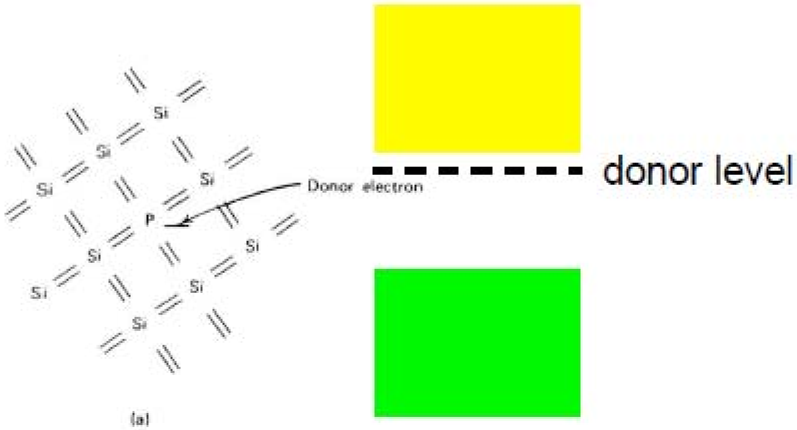
$$\text{variance : } \sigma^2{}_N = \frac{E_{loss}}{E_{ionization}}$$

Fano factor :

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

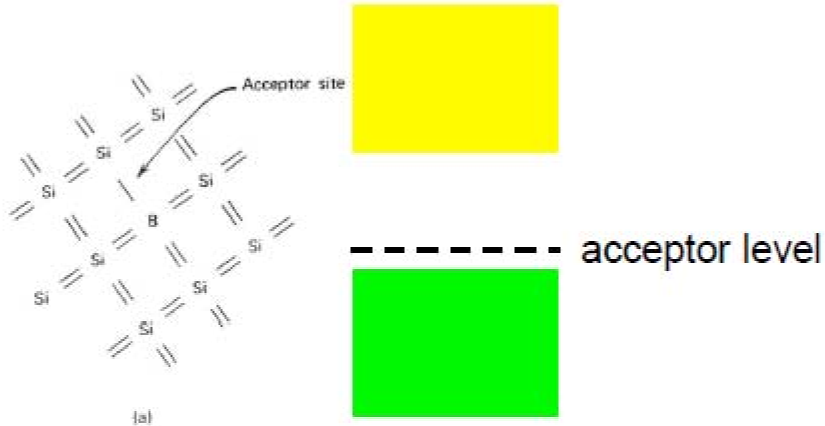
Si	0.115
Ge	0.13
GaAs	0.10
Diamond	0.08

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



- 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



- 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 :
Arsenic, Phosphorous

dopants :
Boron, Gallium, Indium

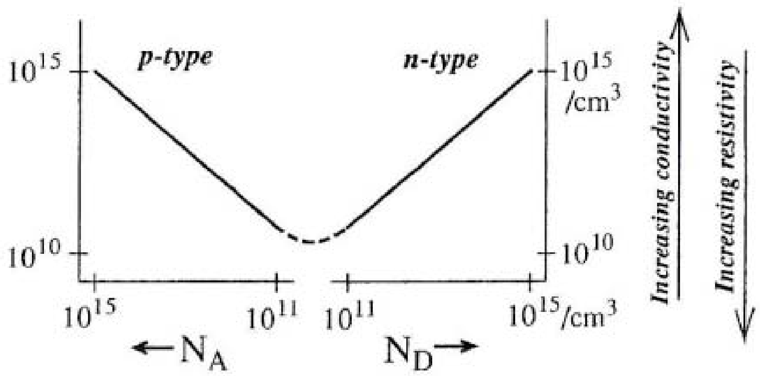
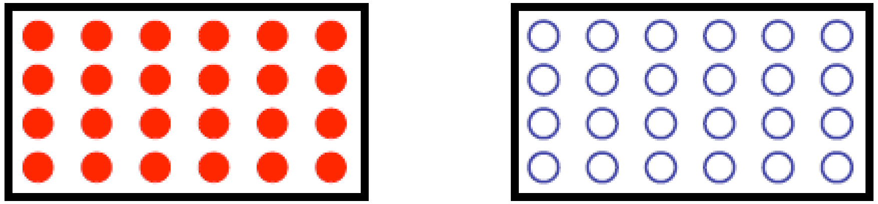


Figure 11.6 Plot using logarithmic scales of the conductivity of a semiconductor as a function of the net concentration of acceptors (N_A) or donors (N_D).

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

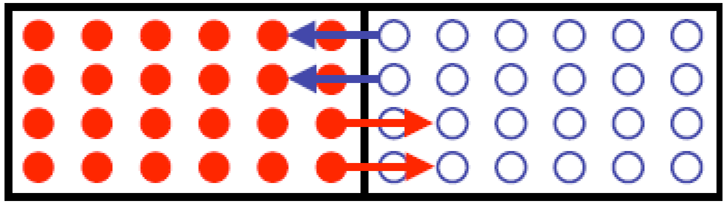
n-type
mobile electrons

p-type
mobile holes

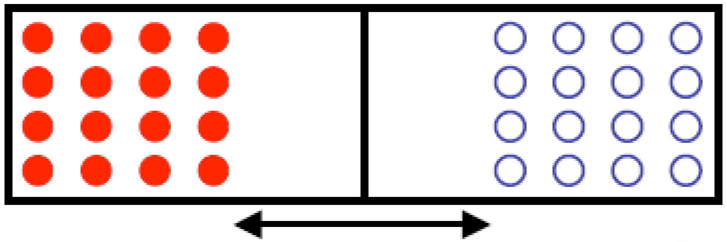


A p-n junction is formed when a single crystal of semiconductor is doped with acceptors on one side and donors on the other

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



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



depletion region

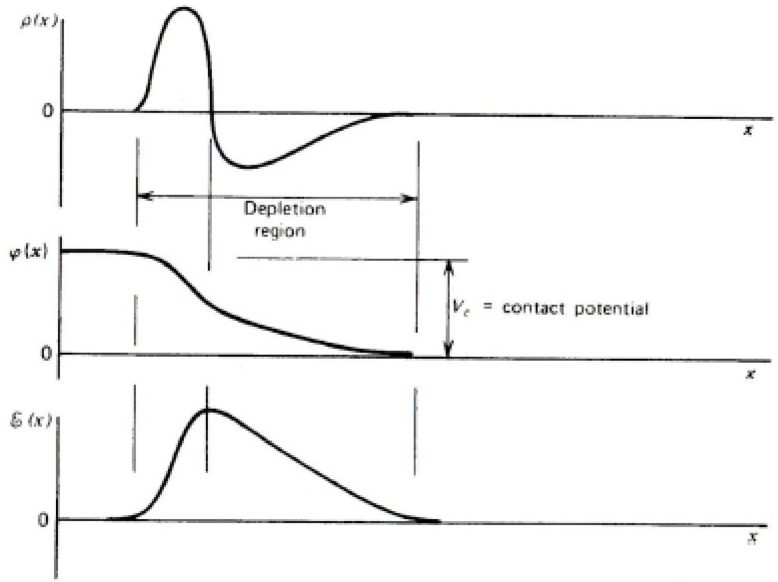


Figure 11.8 The assumed concentration profiles for the *n*-*p* junction shown at the top are explained in the text. The effects of carrier diffusion across the junction give rise to the illustrated profiles for space charge $\rho(x)$, electric potential $\varphi(x)$, and electric field $\mathscr{E}(x)$.

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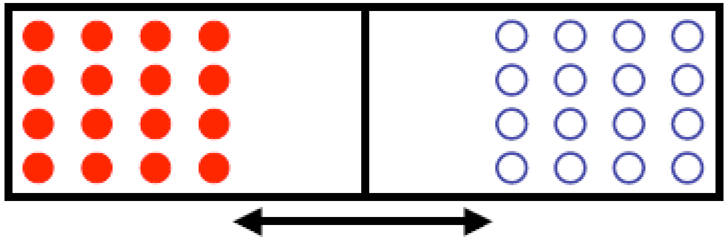
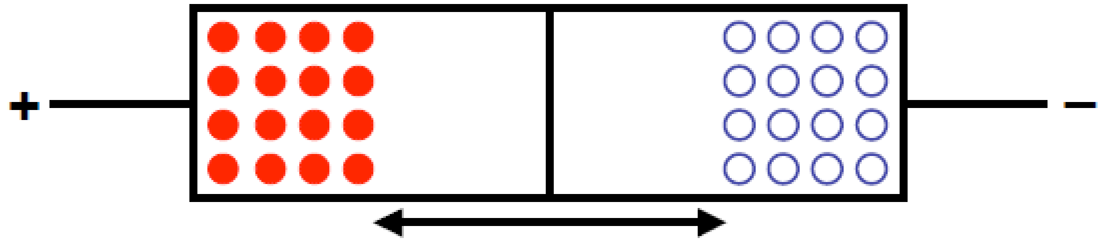


- thermally generated charge carriers are quickly swept away due to the contact potential
  - → highly suppressed charge carrier density
  - → relatively small amount of charge carriers created by an ionising particle is easily detected
- poor performance because:
  - small contact potential (~1 V): 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



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

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

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

The p – n zones will be used for contact
and to block (Blocking Contacts) the undesired noise

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:

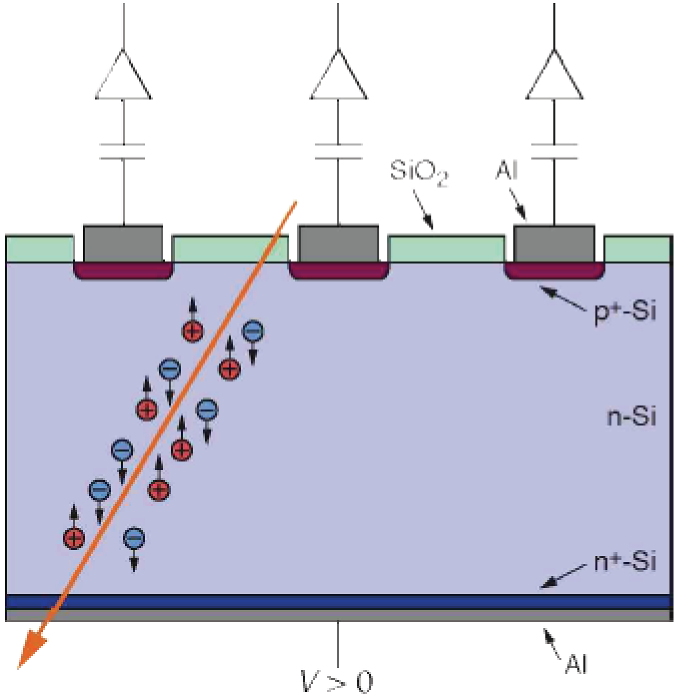
★ p^+n junction:
$N_a \approx 10^{15}$ cm^{-3}, $N_d \approx 1$–$5 \cdot 10^{12}$ cm^{-3}

★ n-type bulk: $\rho > 2$ kΩcm
➔ thickness 300 μm

★ Operating voltage < 200 V.

★ n^+ layer on backplane to improve ohmic contact

★ Aluminum metallization

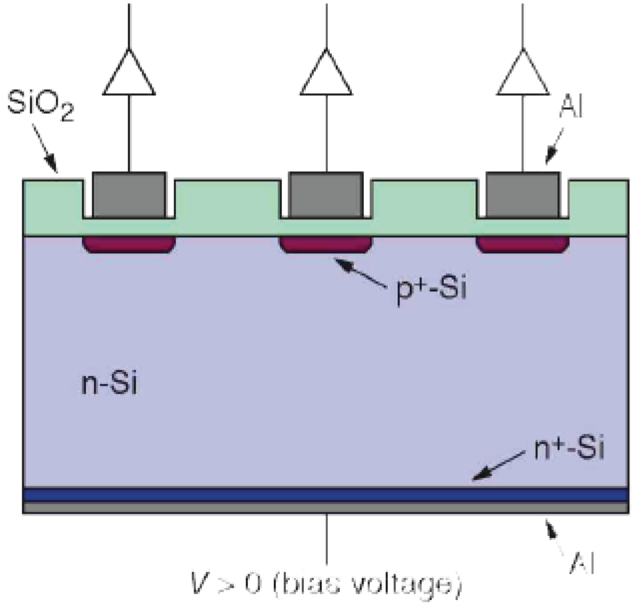


AC Coupling Silicon detector

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:

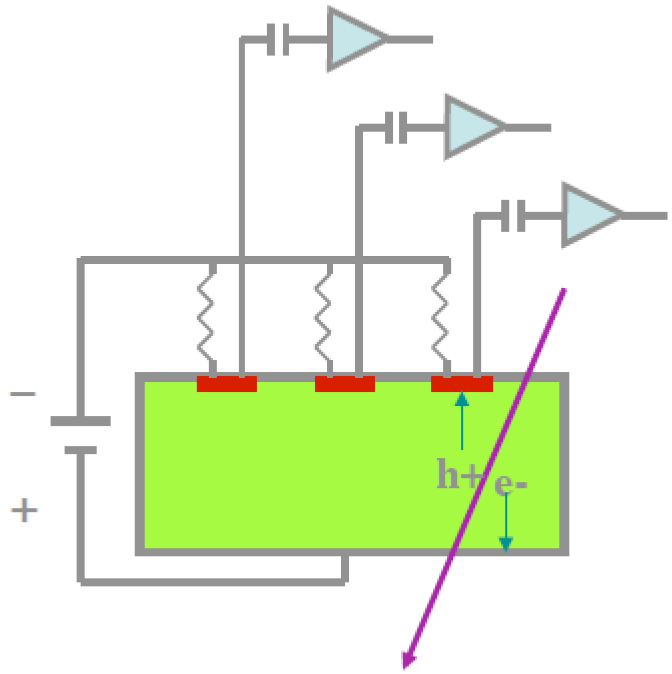


Several methods to connect the bias voltage: polysilicon resistor, punch through bias, FOXFET bias.

AC coupled Si detectors create 2 electrical circuits :

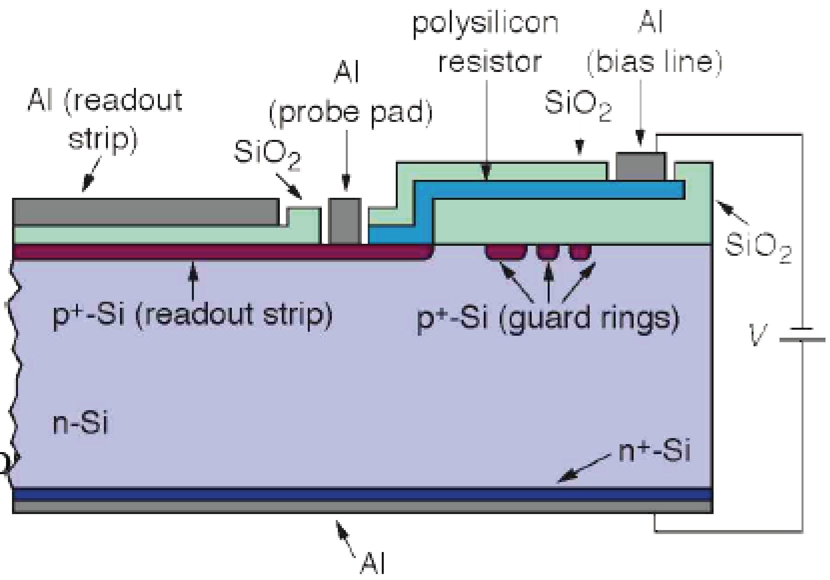
- Read-out circuit to the amplifier (AC current)

- Biasing circuit (DC current)



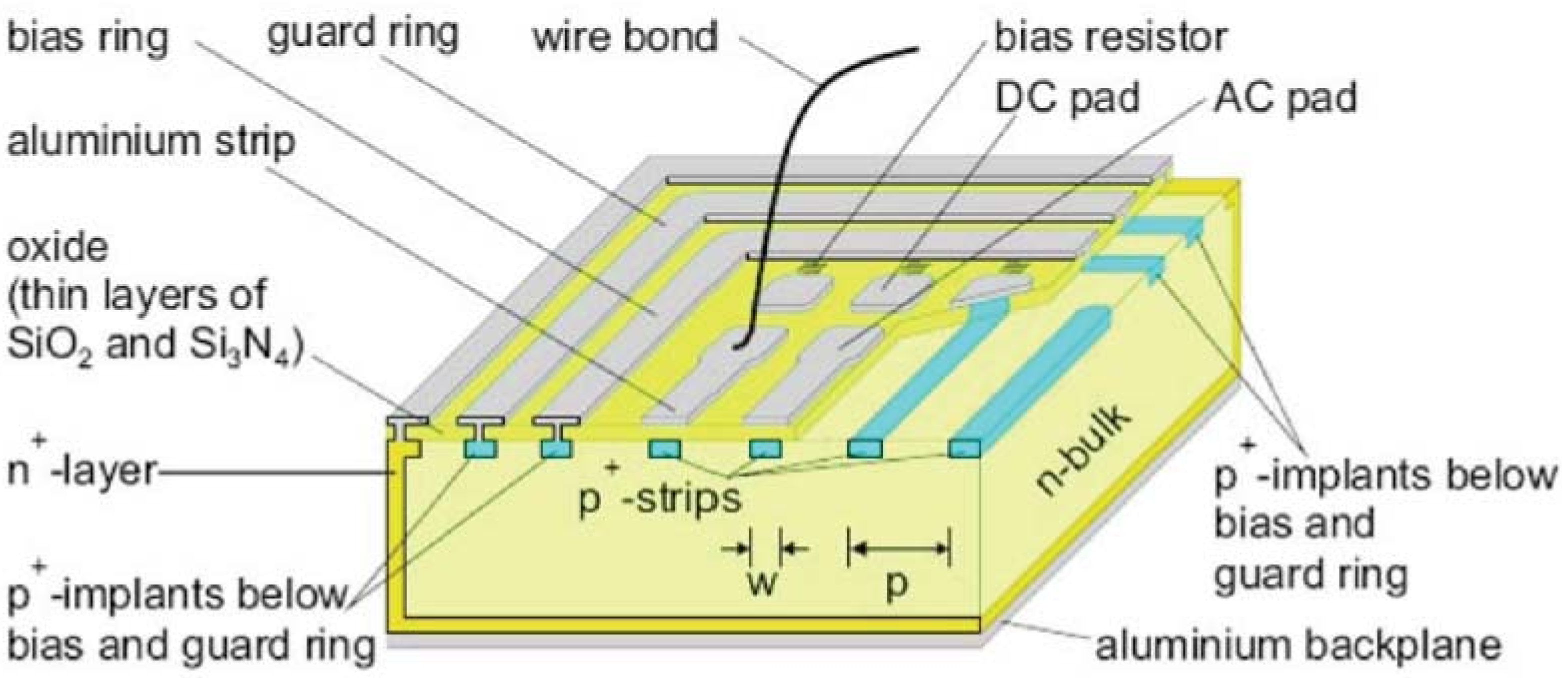
AC Coupling Silicon detector : bias voltage system

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

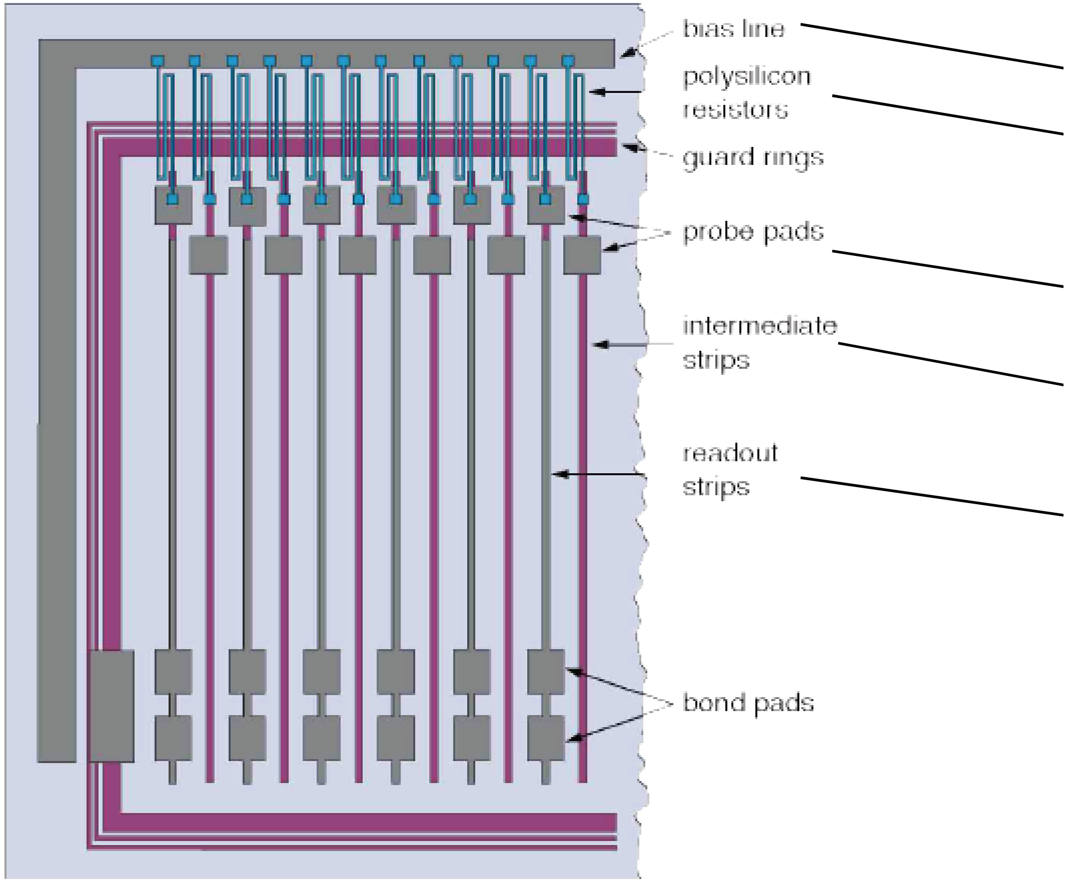


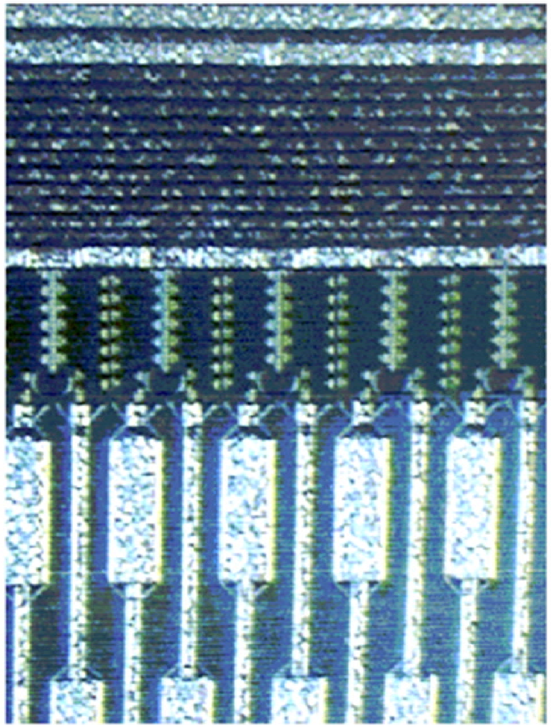
Cut through an AC coupled strip detector with integrated poly resisto

Most commonly scheme AC + poly S-bias resistor

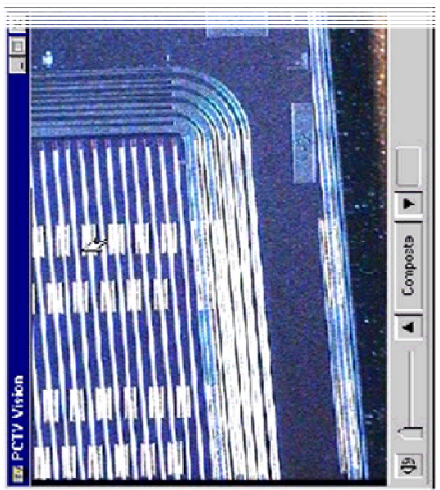


Semiconductors : Si detectors designs



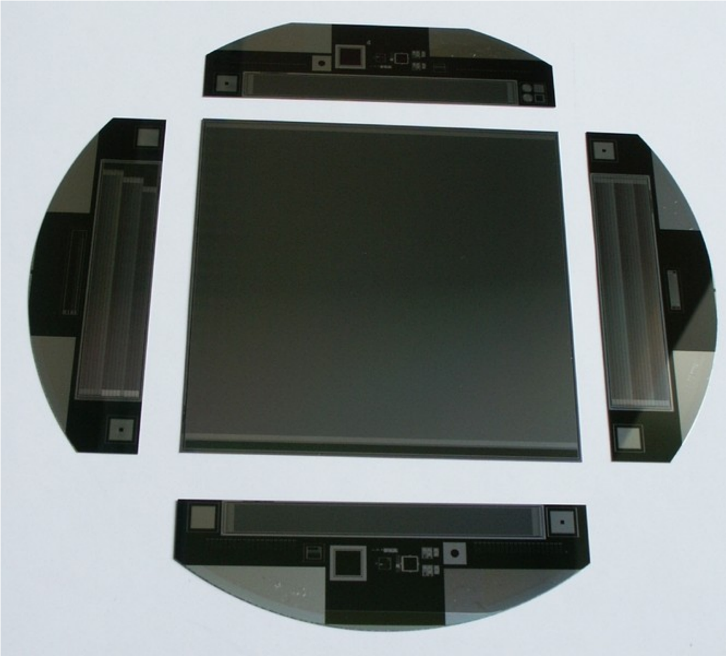


CMS design



ATLAS design

Semiconductors : Si detectors designs



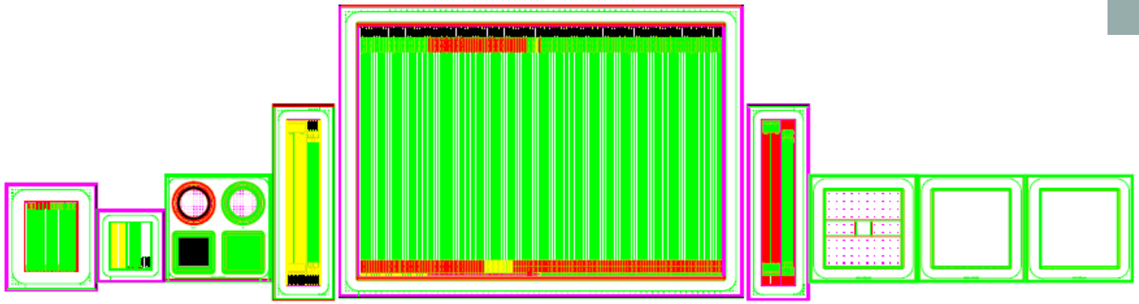


Figure 4.1: View of the Standard half-moon. The devices are (from left to right): TS-CAP, sheet, GCD, CAP-TS-AC, baby, CAP-TS-DC, diode, MOS1 and MOS2.

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

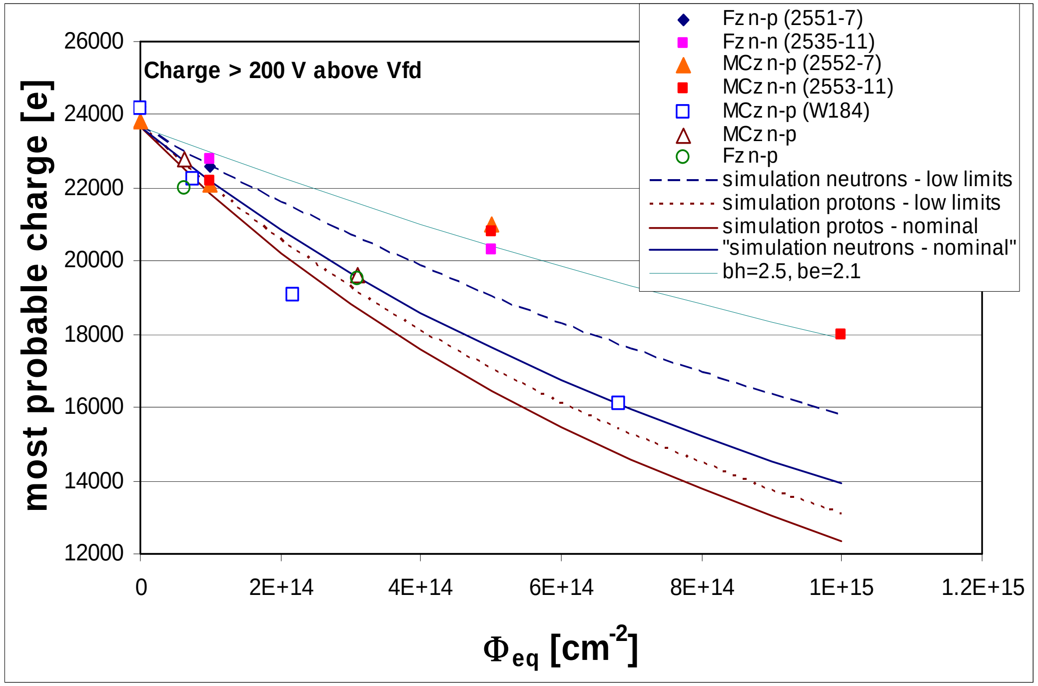
(new 300 µm Silicon ≈ 24 000 e- for 1 MIP)

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

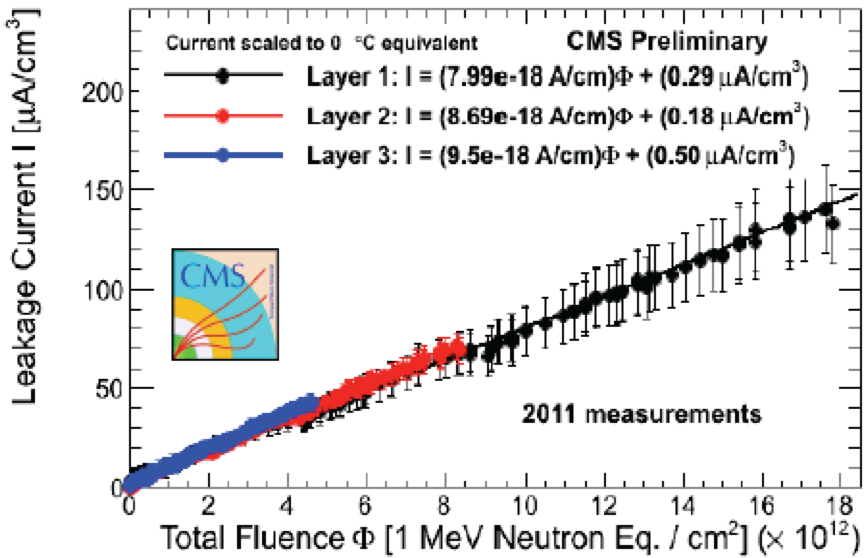
$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right)$$

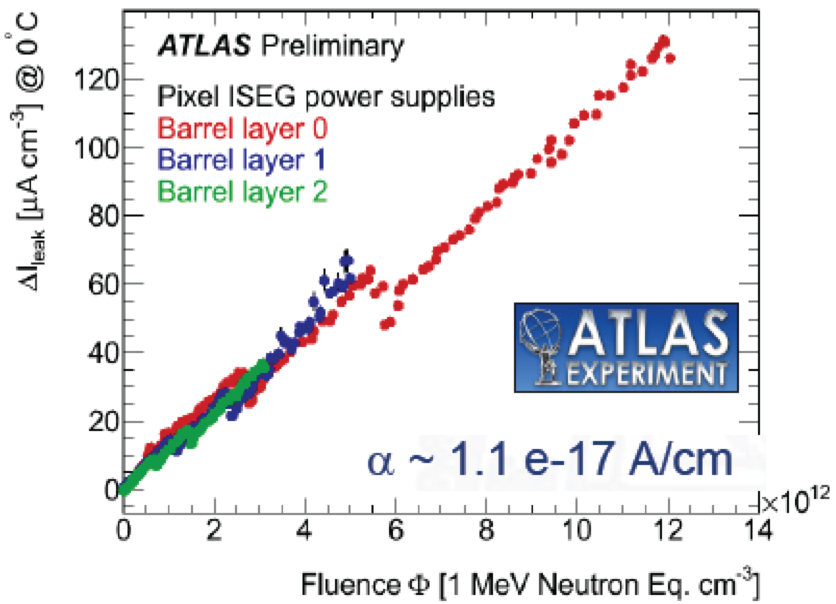
where

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



Increase of Leakage current

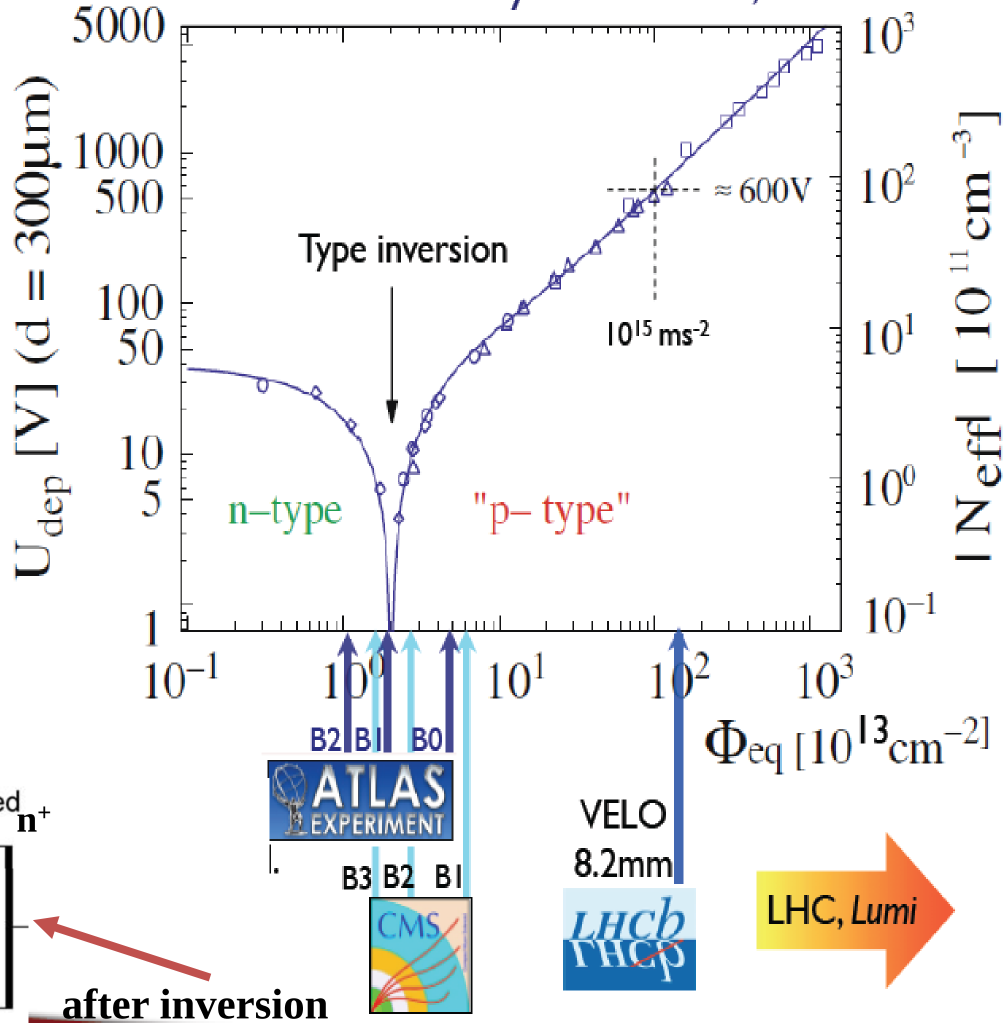


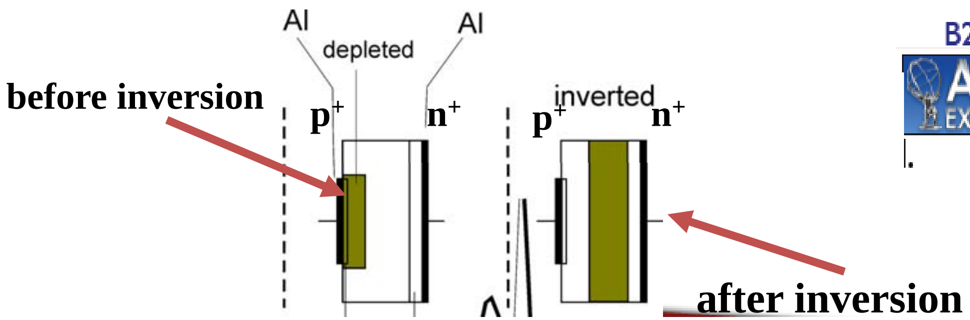


Change in depletion voltage and type inversion

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

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





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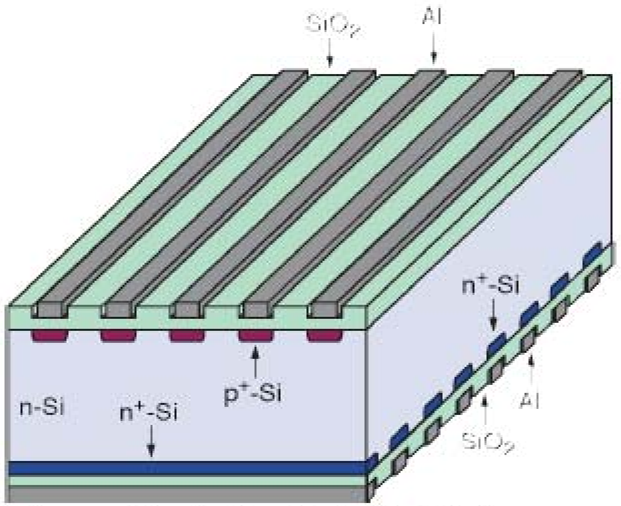
Double Sided Silicon Detectors (DSSD) Not much in use…

Advantages:

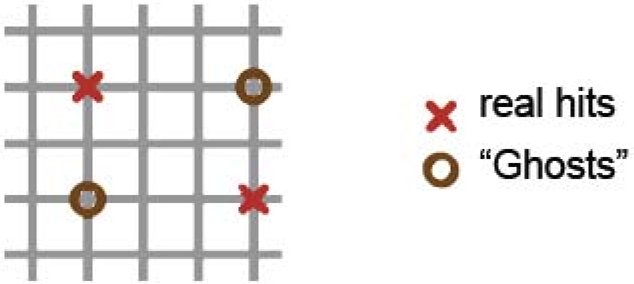
- More elegant way for measuring 2 coordinates
- Saves material

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)



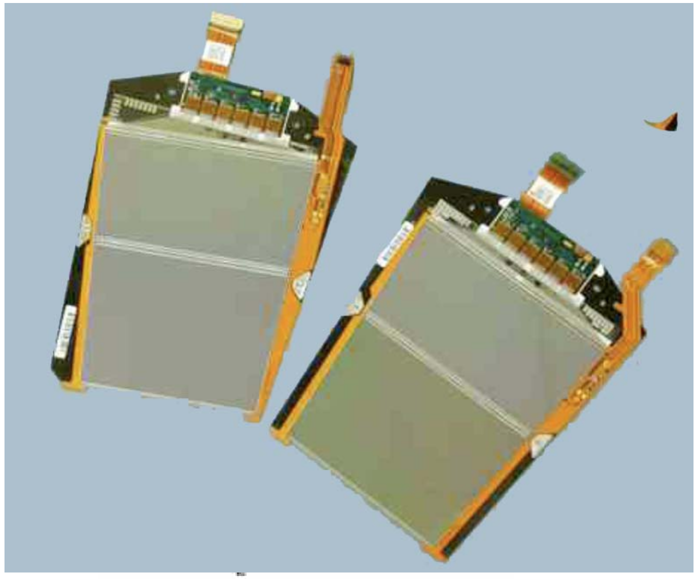
Stereo Modules

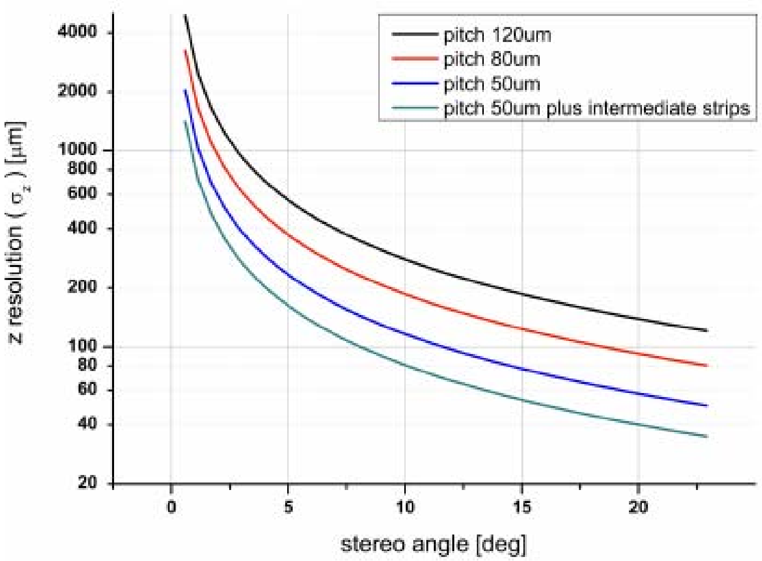
2^{nd} coordinate requires second detector underneath
⇒ double the material

- 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





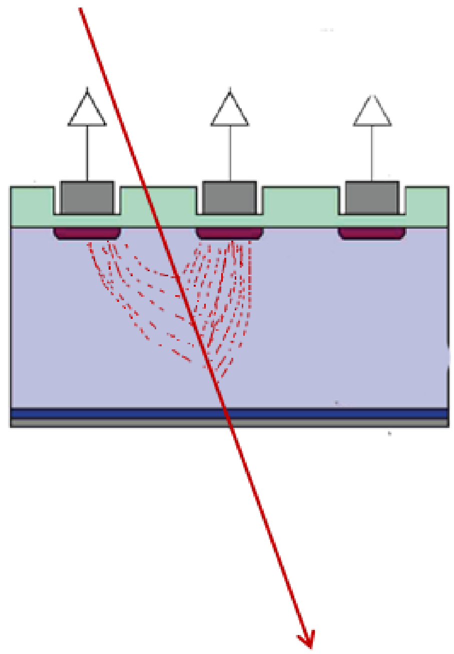
★ Threshold readout (one strip signal):

→ 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:

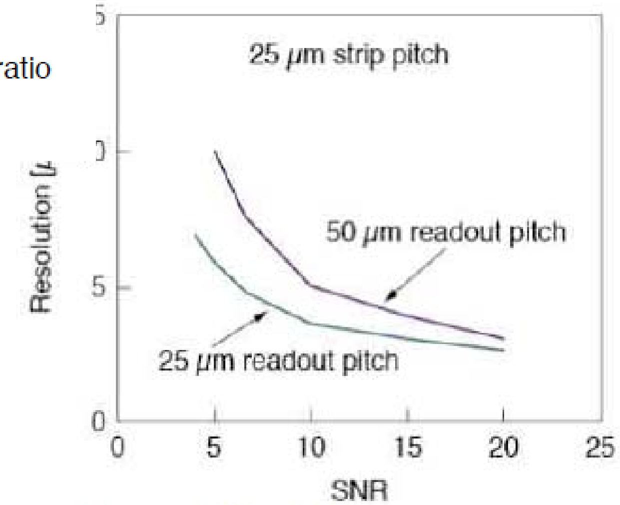
$$x = x_1 + \frac{h_1^2}{h_1 + h_2}(x_2 - x_1) = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2}$$

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

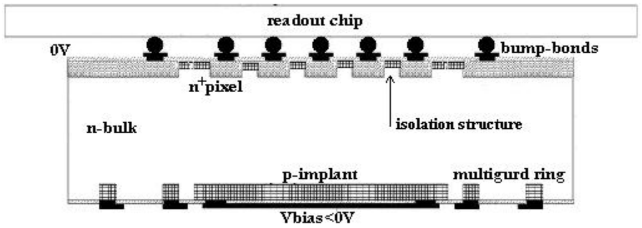
x_1, x_2 … position of 1st and 2nd strip

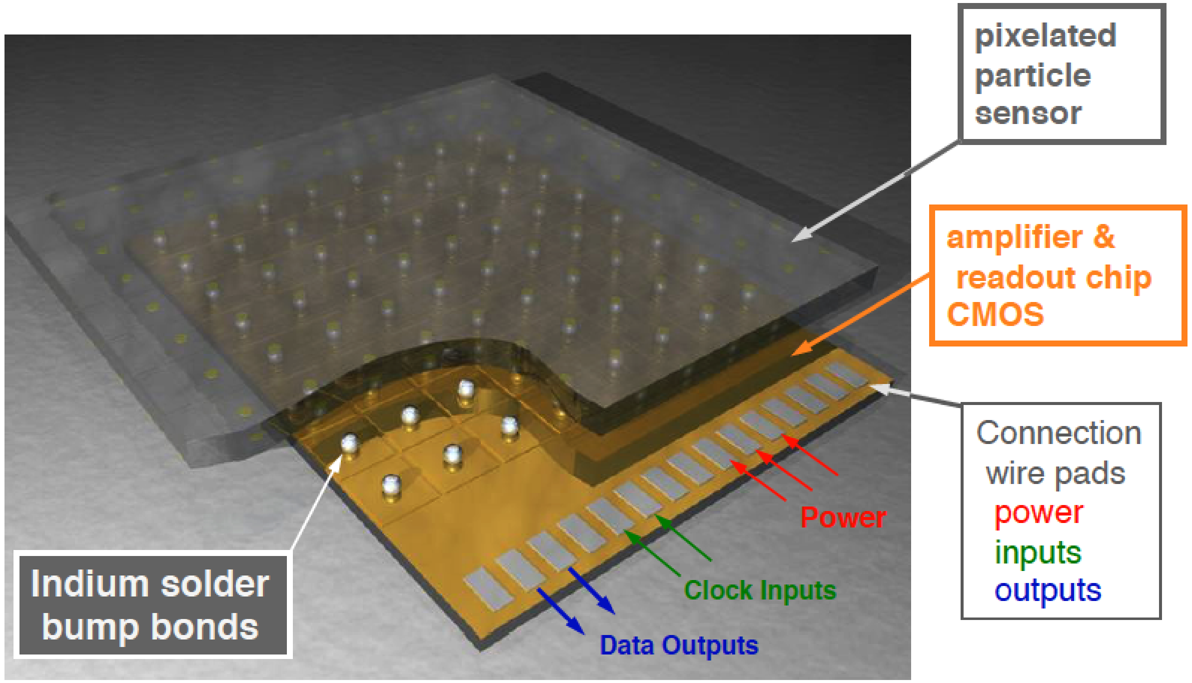
h_1, h_2 … signal on 1st and 2nd strip

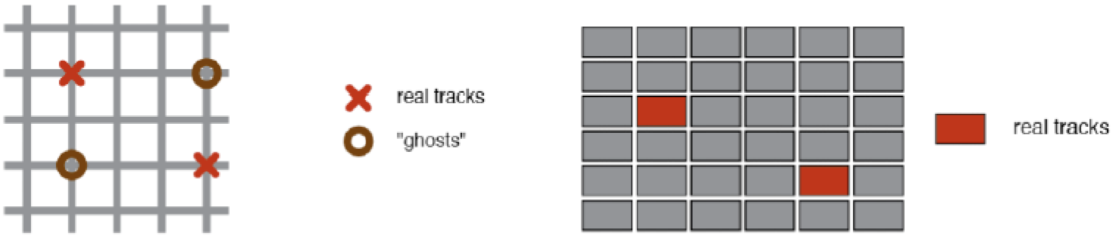
SNR … signal to noise ratio



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







Pixel sizes :

ATLAS : 50 µm x 400 µm

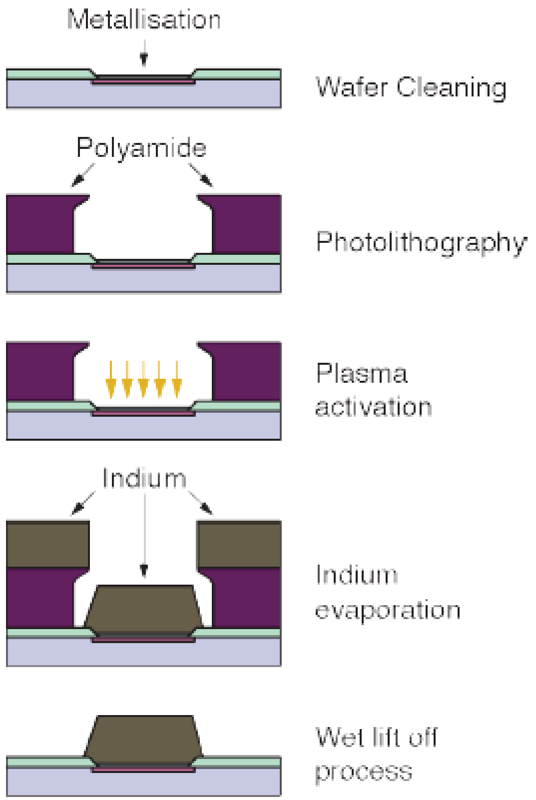
CMS : 100 µm x 150 µm

ALICE : 50 µm x 425 µm

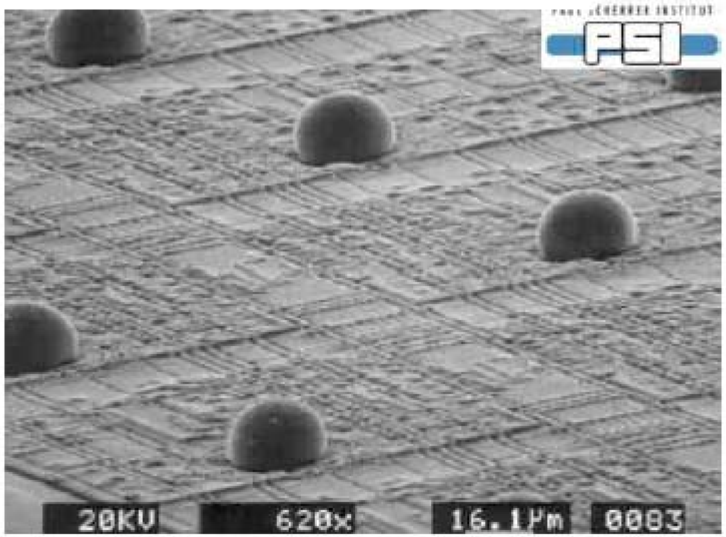
CONNECTION BY BUMP BONDING

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.

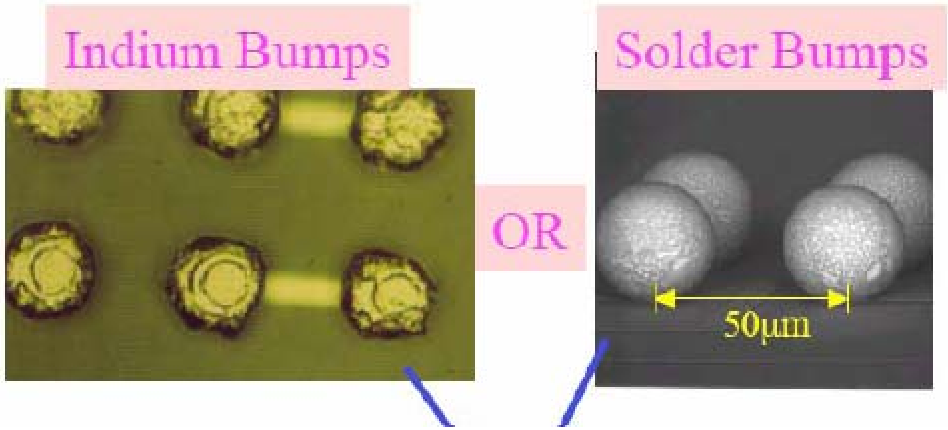


L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

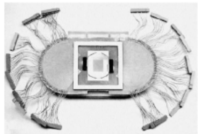


Pitch : 50 µm

(wire bonding typically 200µm)



Semiconductors : Silicon history



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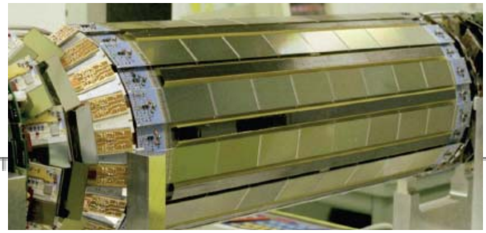
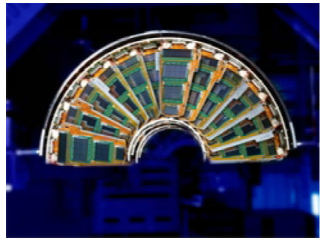
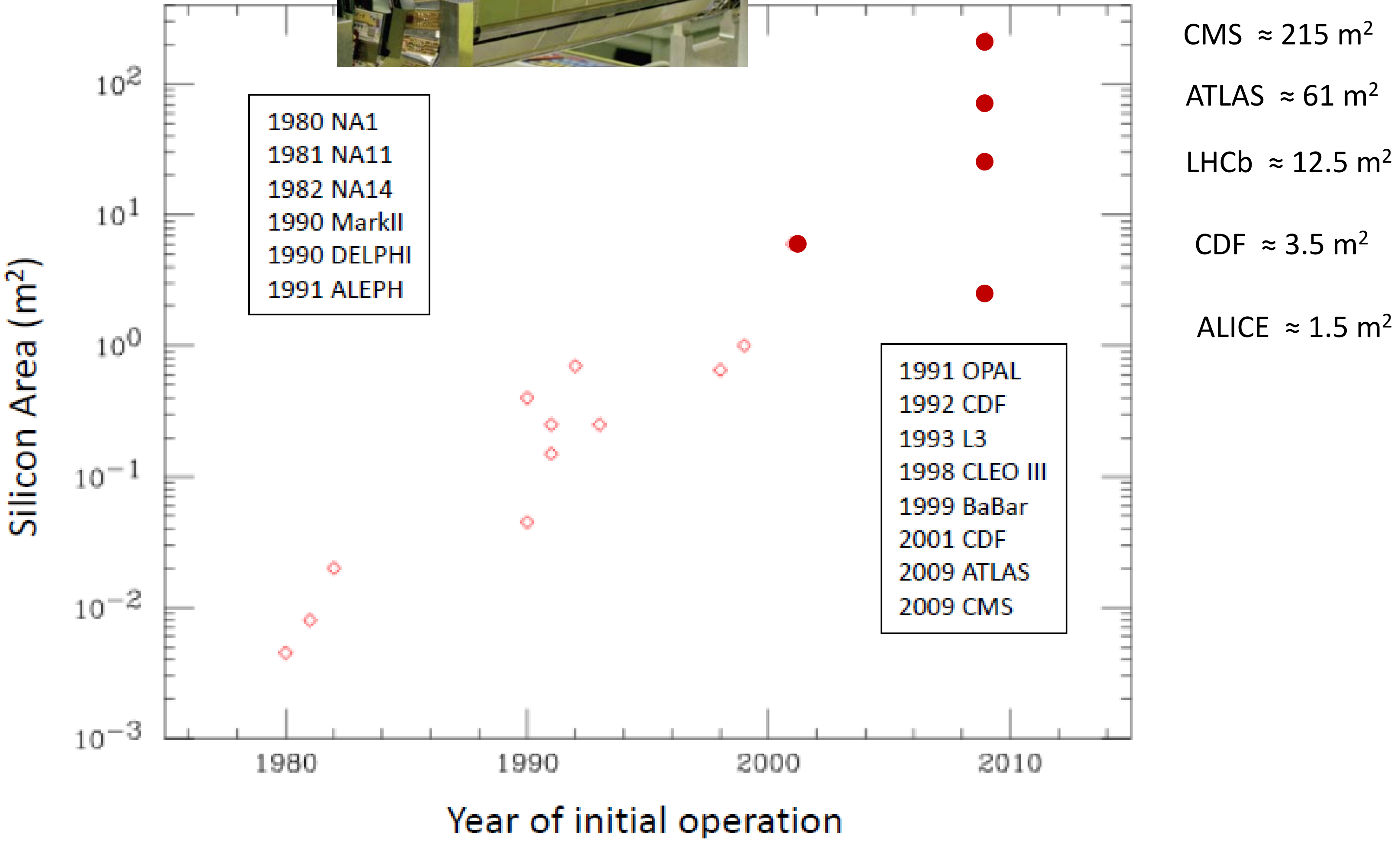


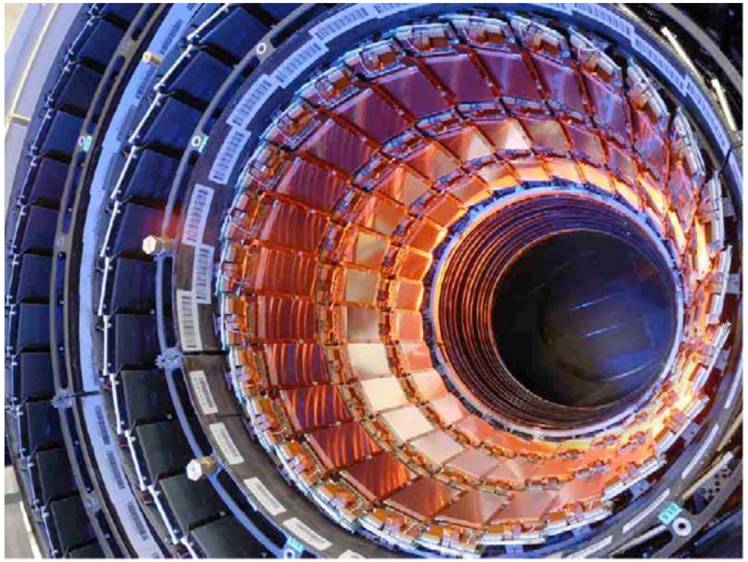
DELPHI

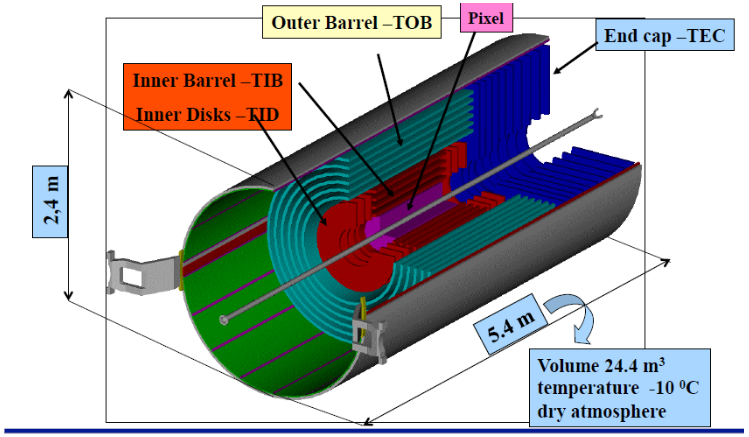


CDF



Semiconductors : CMS Silicon Detector



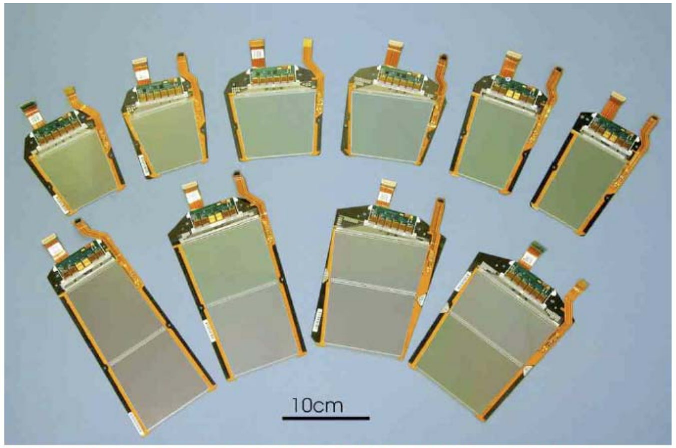


Strip detector:

- ~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

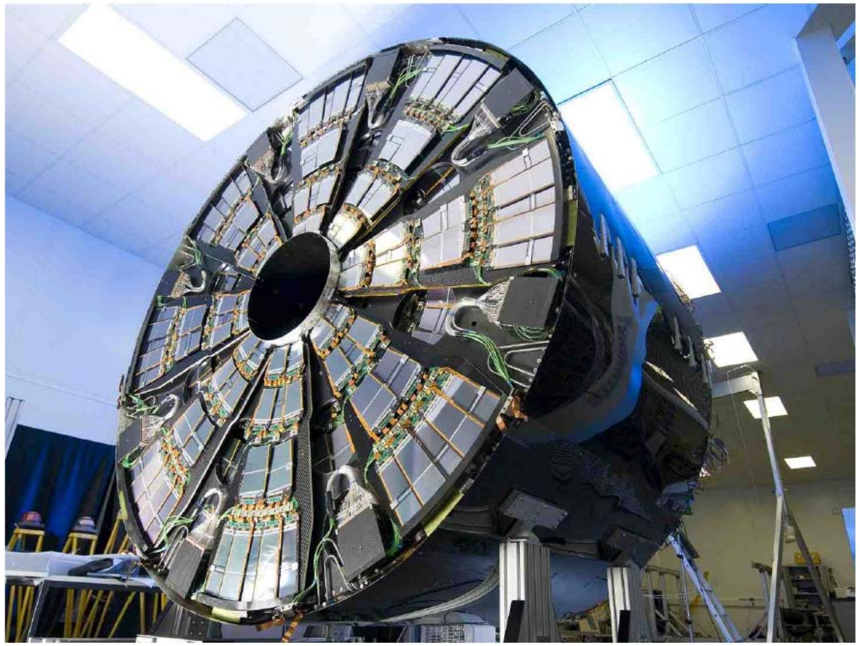
Pixel detector:

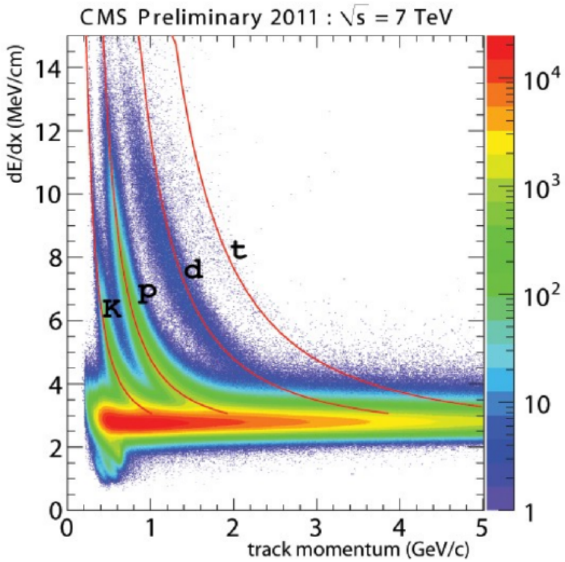
- 1 m^2 detector area
- 1440 pixel modules
- 66 million pixels

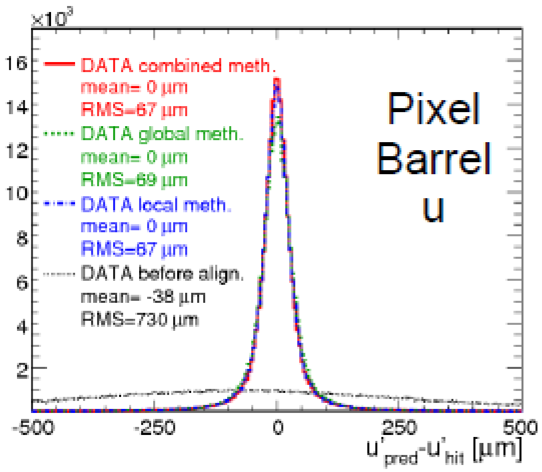


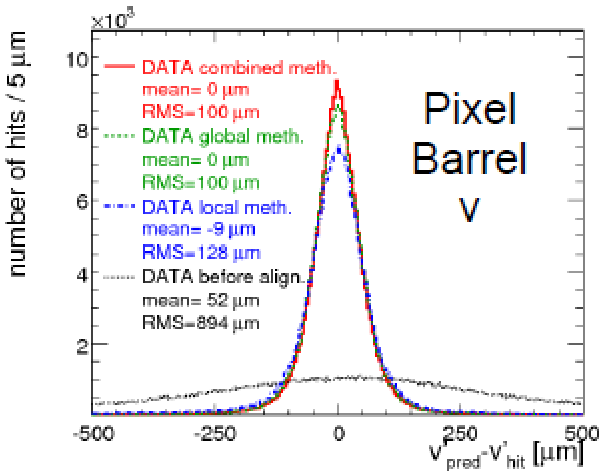
27 mechanical different modules + 2 types of alignment modules

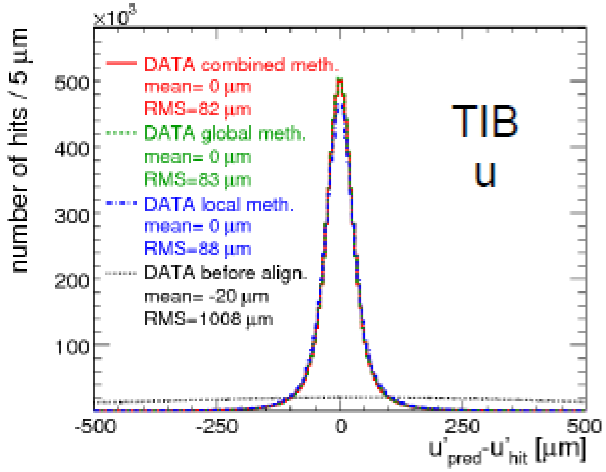
Semiconductors : CMS Silicon Detector



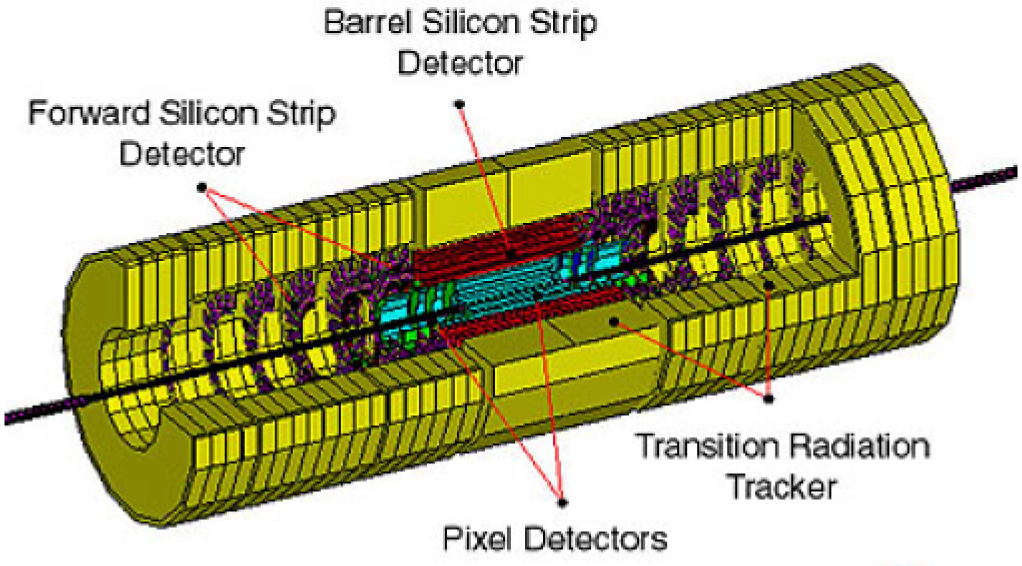


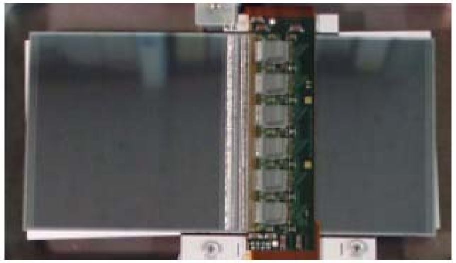


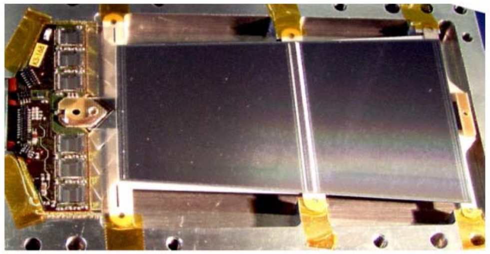




Semiconductors : ATLAS Silicon Detector

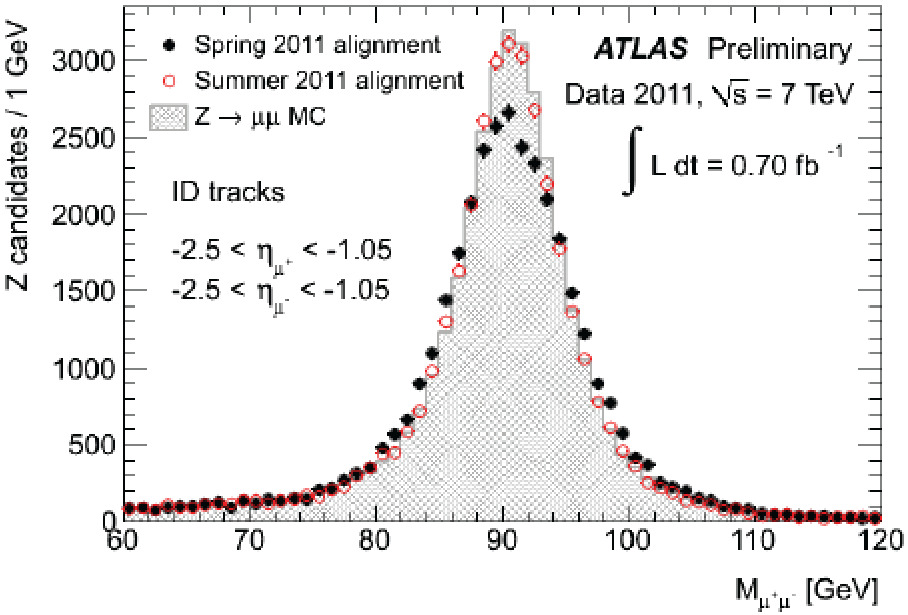


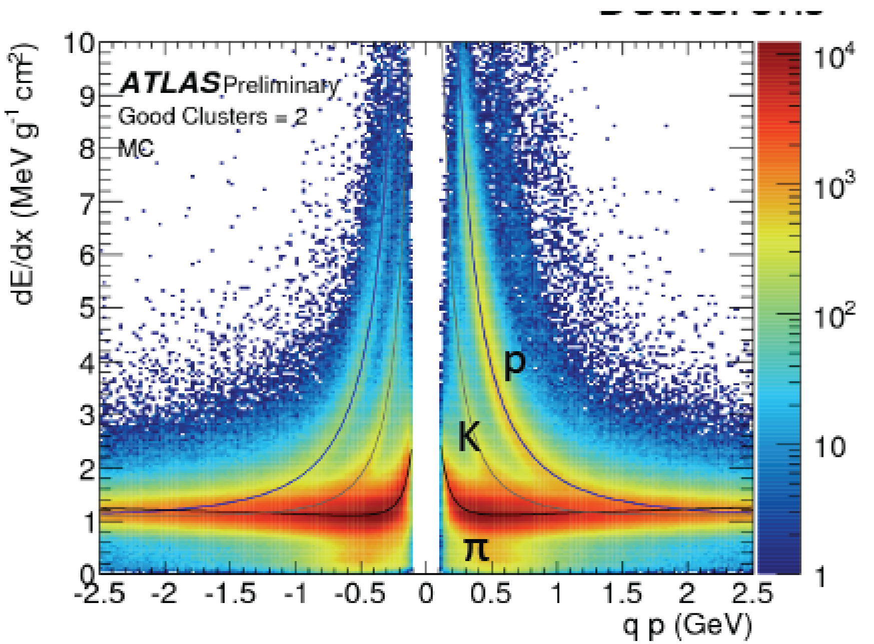


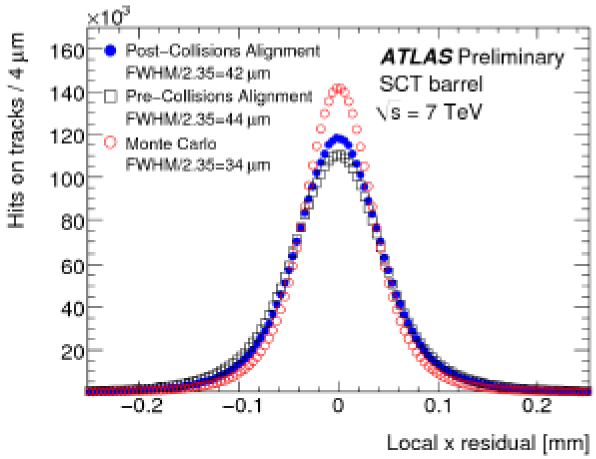


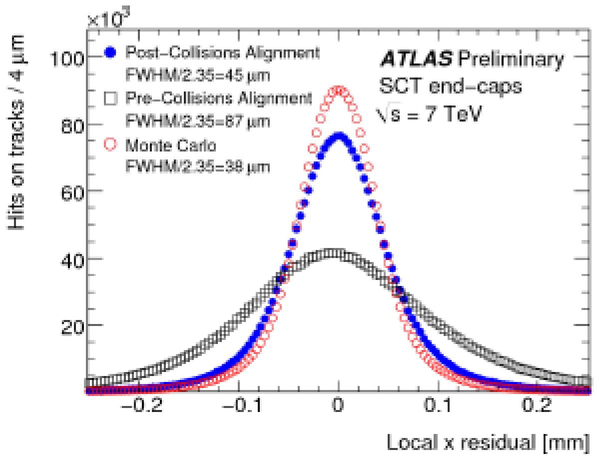
system		area (m²)	resolution (µm)	channels (10^6)	|h | coverage
pixel	1 b layer	0.2	RF =12, z=66	16	2.5
	2 barrels	1.4	RF =12, z=66	81	1.7
	2x5 disks	0.7	zF =12, R=77	43	1.7-2.5
	total	**2.3**		**140**	**2.5**
SCT	4barrels	34.4	RF =16, z=580	3.2	1.4
	2x9 disks	26.7	zF =12, R=580	3.0	1.4-2.5
	total	**61.1**		**6.2**	**2.5**

Semiconductors : ATLAS Silicon Detector









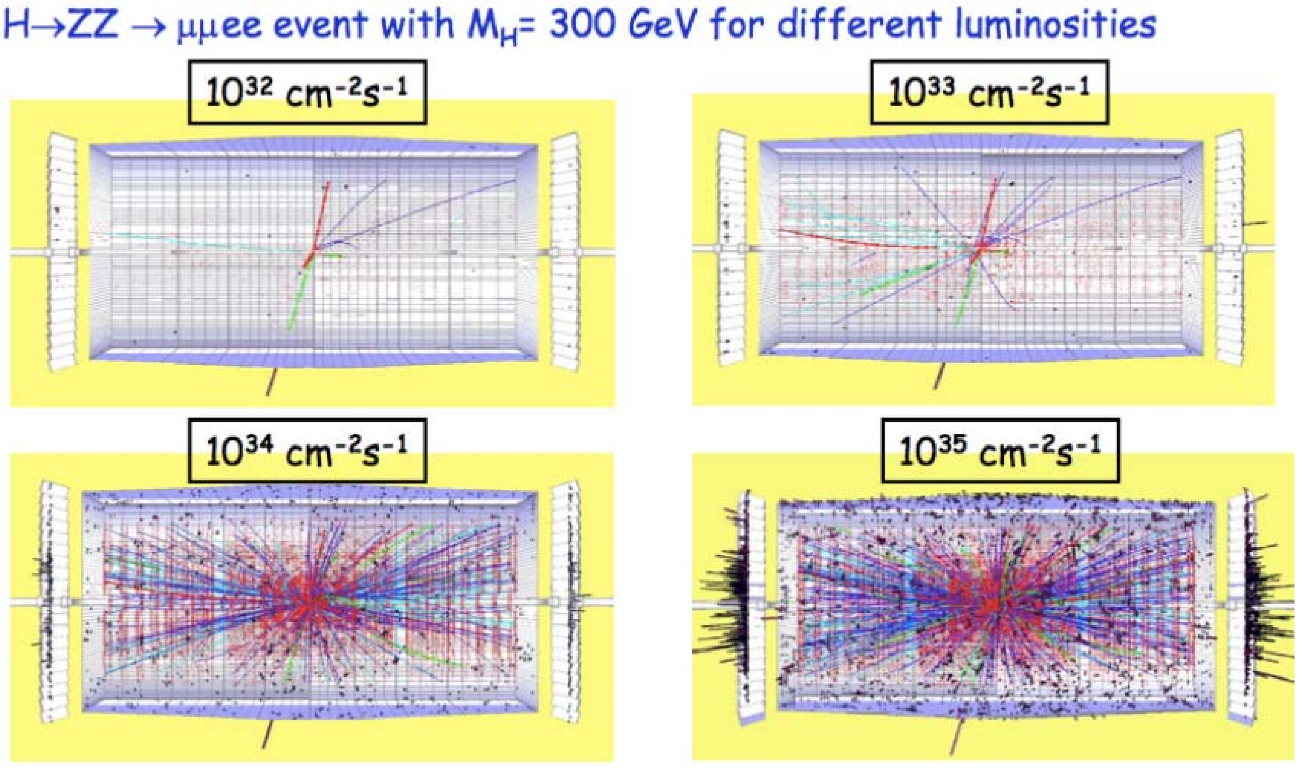
Main performance characteristics of the ATLAS and CMS trackers

	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 ?)

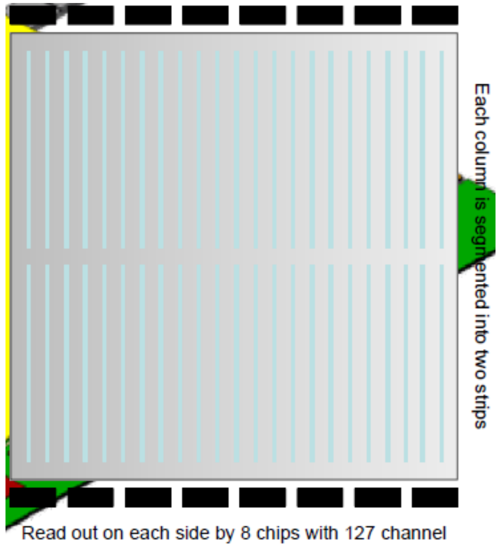


More tracks : Occupancy increases - Less resolution
More Flux : Radiation (bulk) damage

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)

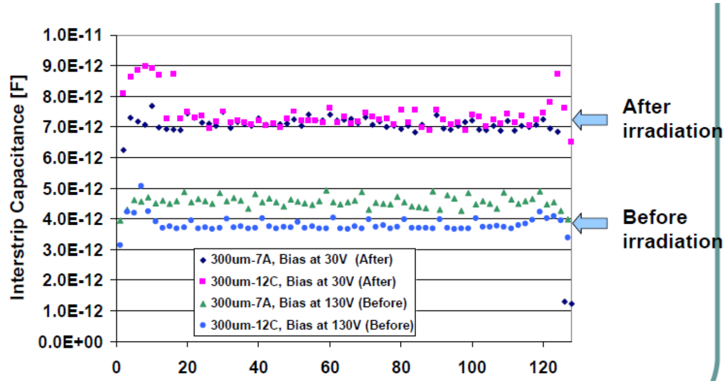


Reduce the material : Thin Si sensors

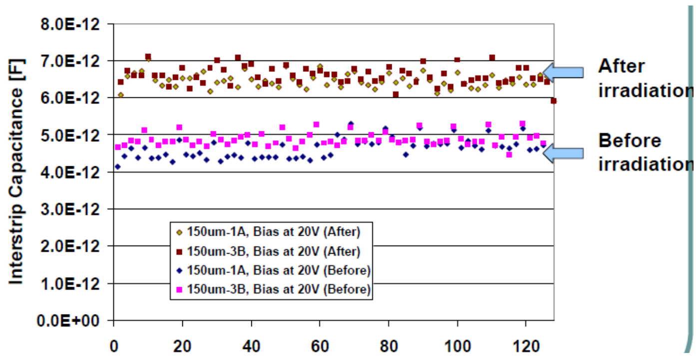
- Reduce the Charges Collected

Reduce the number of layers

- Reduce the overall Tracker efficiency



300 µm



150 µm

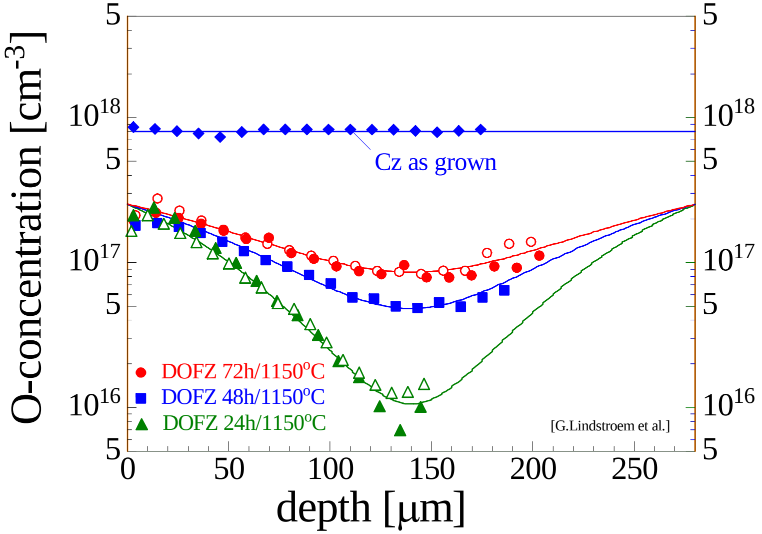
Change the material : Oxygenated Silicon

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

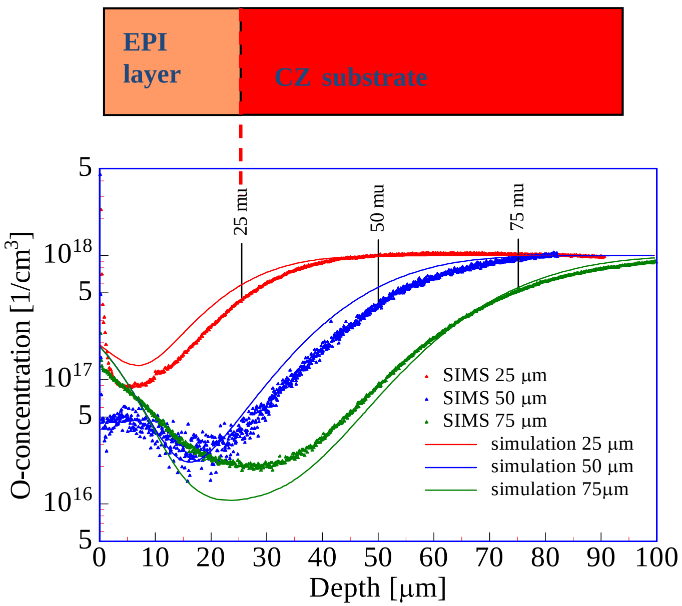
New Materials : **DOFZ** : O2 doped FZ Silicon (Oxydation of wafer at high temperature)

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

EPITAXIAL growth : Chemical Vapor Deposition on CZ substrate



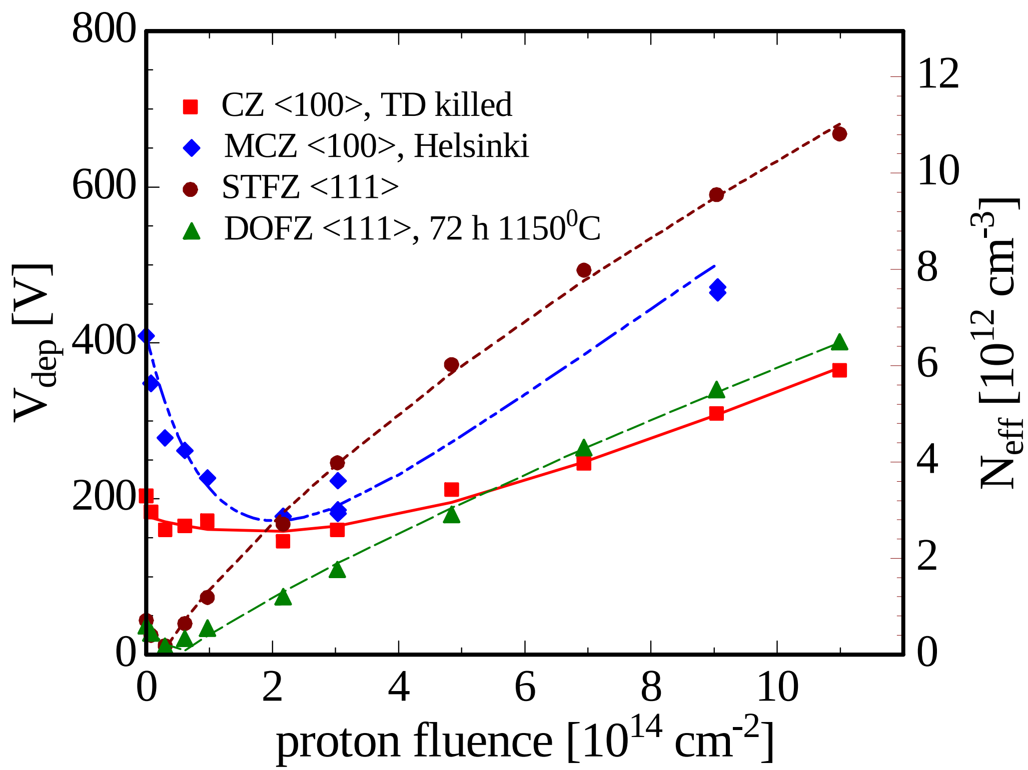
Oxygen concentration in DOFZ



Oxygen concentration in Epitaxial

24 GeV/c proton irradiation

- **Standard FZ silicon**
  - **type inversion at ~ 2×10^{13} p/cm²**
  - **strong N_{eff} increase at high fluence**
- **Oxygenated FZ (DOFZ)**
  - **type inversion at ~ 2×10^{13} p/cm²**
  - **reduced N_{eff} increase at high fluence**



- **CZ silicon and MCZ silicon**
  - **<u>no type inversion</u> 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)

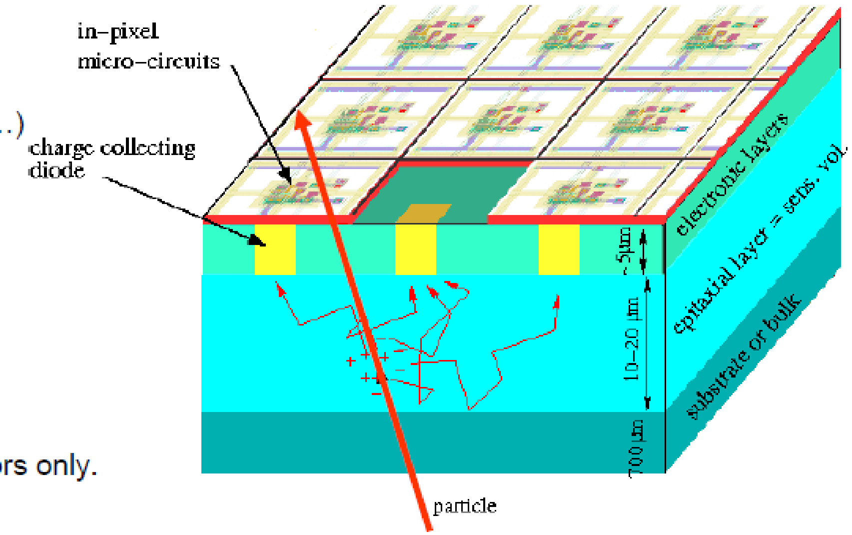
Pointing resolution	(12 ⊕ 19 GeV/p·c) µm
Layers	Layer 1 at 2.5 cm radius Layer 2 at 8 cm radius
Pixel size	20.7 µm X 20.7 µm
Hit resolution	6 µm
Position stability	6 µm rms (20 µm envelope)
Radiation length per layer	X/X_0 = 0.37%
Number of pixels	356 M
Integration time (affects pileup)	185.6 µs
Radiation 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, …)

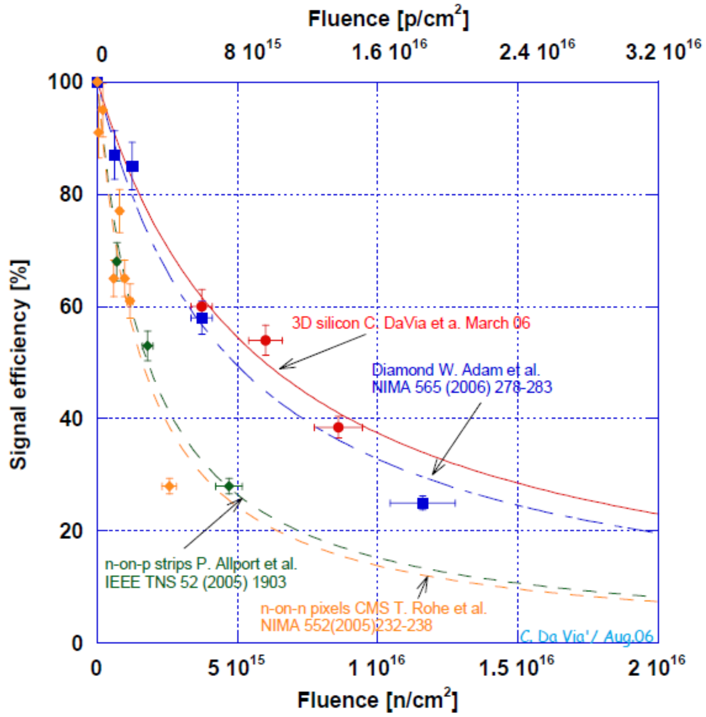


Issues

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

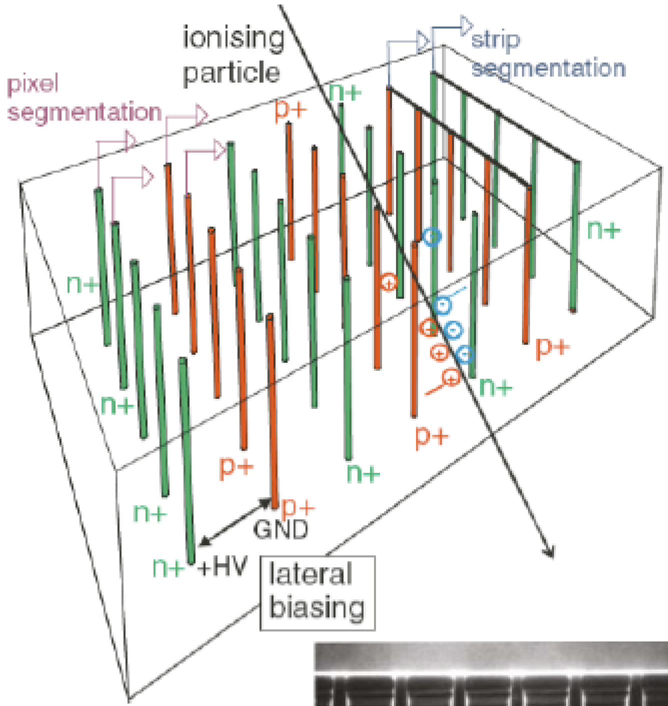
3D Silicon Detectors

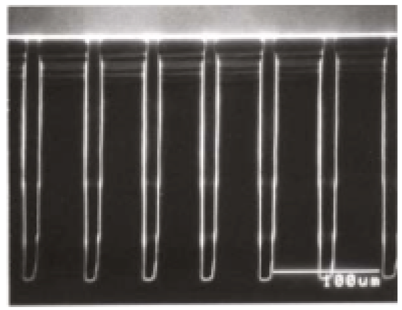
Manufacturing challenge
Electrodes : dead zones



Efficiency vs fluence

S



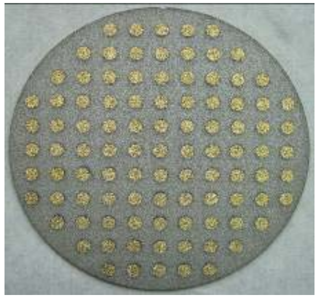


Diamond detectors

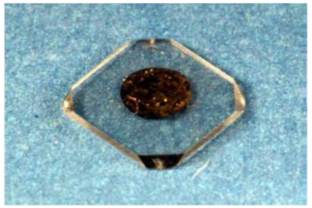
	CVD Diamond	Si
Z	6	14
Energy Gap	5,5 eV	1,21 to 1,1eV
Resistivity	$10^{13} – 10^{16}$ Ωcm	$10^5 – 10^6$ Ωcm
Breakdown	10^7 V/cm	3.10^5 V/cm
Mobility (electrons)	2000 cm²/V/s	1350 cm²/V/s
Mobility (holes)	1600 cm²/V/s	480 cm²/V/s
Displacement Energy (e⁻)	43 eV/atom	13 à 20 eV/atom
Pairs Creation	13 eV	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}

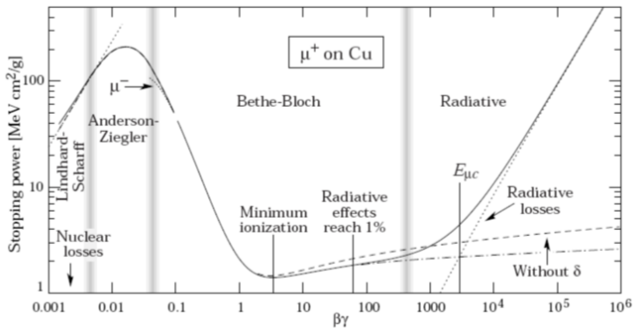
CCD : CHARGE COLLECTION DISTANCE

Energy loss (Bethe-Bloch 1932)

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$$

Charge transportation (Hecht 1932)

$$CCE = \frac{Q}{Q_o} = \frac{\lambda_e}{L}\left[1-\exp\left(-\frac{(L-x_o)}{\lambda_e}\right)\right] + \frac{\lambda_h}{L}\left[1-\exp\left(-\frac{x_o}{\lambda_h}\right)\right]$$



CHARGE COLLECTION DISTANCE :

$$\delta = \lambda_e + \lambda_h = (\mu_e\,\tau_e + \mu_h\,\tau_h)\,E$$

λ : mean drift distance (mean free path of the carrier)
μ : mobility
τ : lifetime
E : applied electric field

Si (mono) = 100m

Si (amorphe) =10 μm

Diam = 0(100μm)

CCD : MEASUREMENT

Charge Collection Distance : $d = (\mu_e \cdot \tau_e + \mu_h \cdot \tau_h).E$

Collected charge: $Q = \frac{d}{L} Q_0$

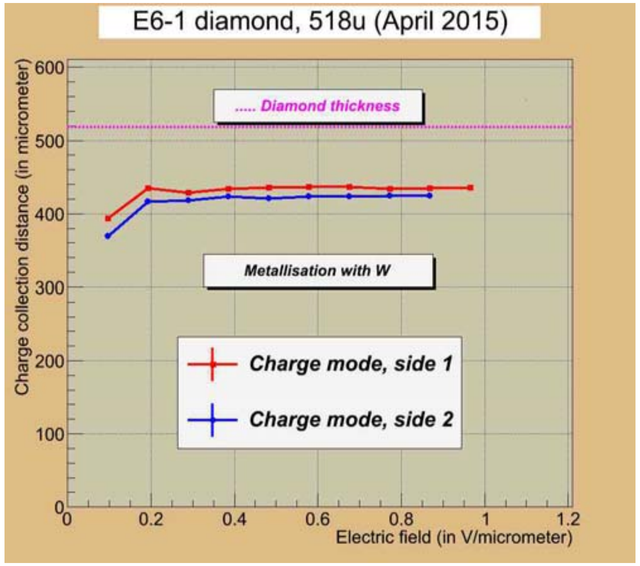
$$d = \frac{N_{électrons}}{36}$$

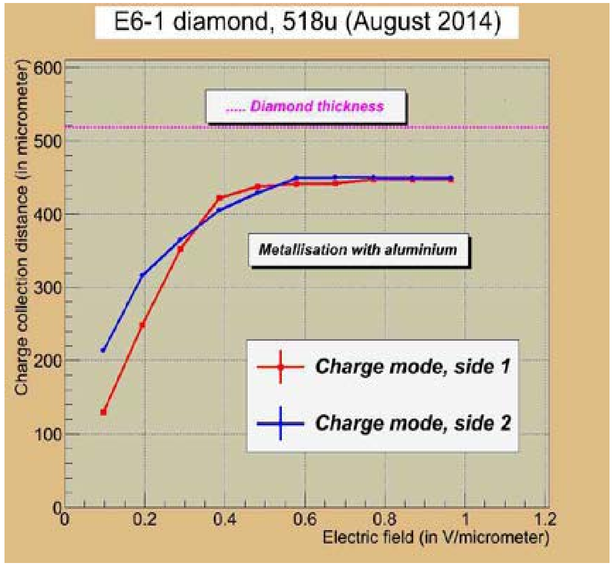
Pairs / MIP : 3600 / 100 µ diamant)

CCD : Measurement of diamond quality (pCVD ou sCVD)

For particle detection :
$N_{électrons}$ (MIP) ~ 10 000
Thickness (Xo…) ~ 300 µm

CCD ~ 280 µm





CCD OK, but different shapes ?

Diamant ?

<u>Natural diamond:</u> Lots of impurities
Lots of defects

<u>Diamant HPHT (High Pressure – High Temperature) 1940</u>

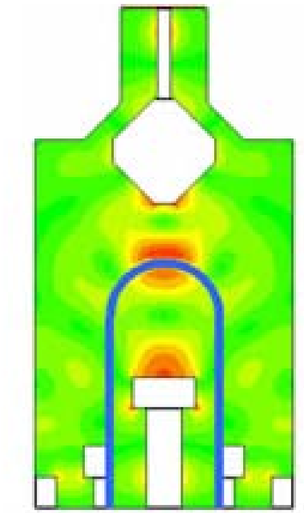
P > 50 000 bars

T > 2000 °C

Monocrystal

Dimension (few mm^2)

Impurities



<u>Diamant CVD (Carbon Vapor Deposition) 1980</u>

Plasma CH_4 – H_2 (+X…)

P ≈ 0,1 bar

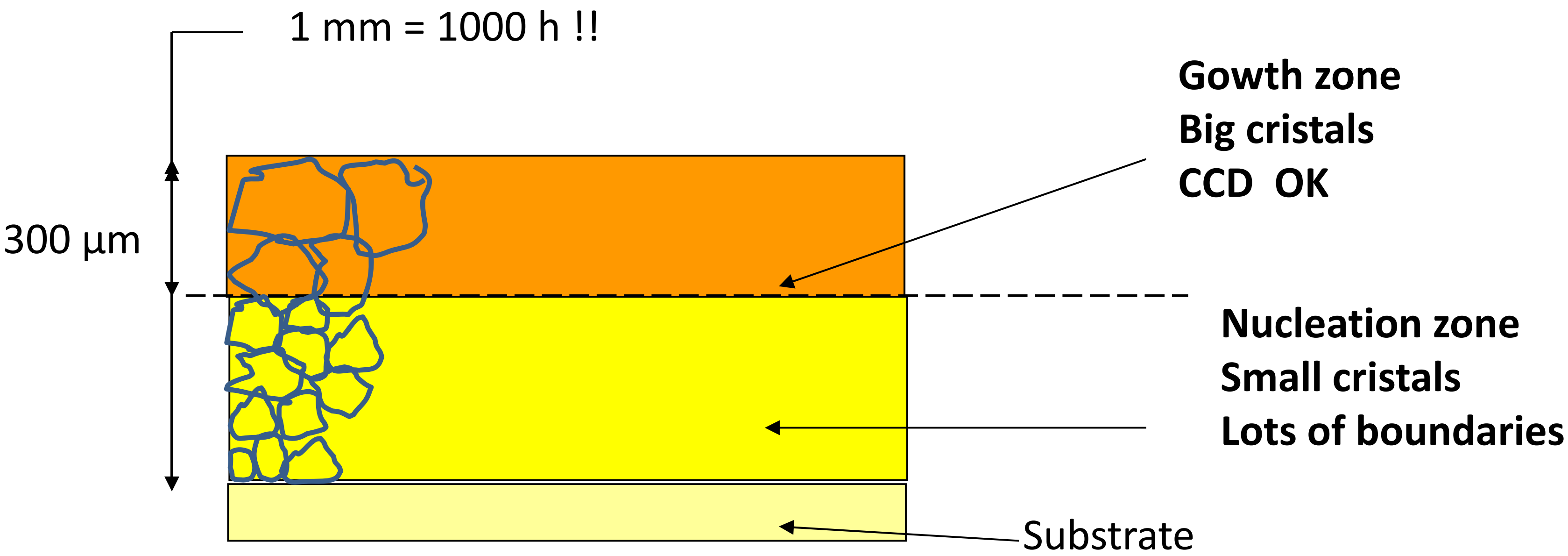
T ≈ 1000 °K

Slow deposition on substrate

1 – 50 µm / heure

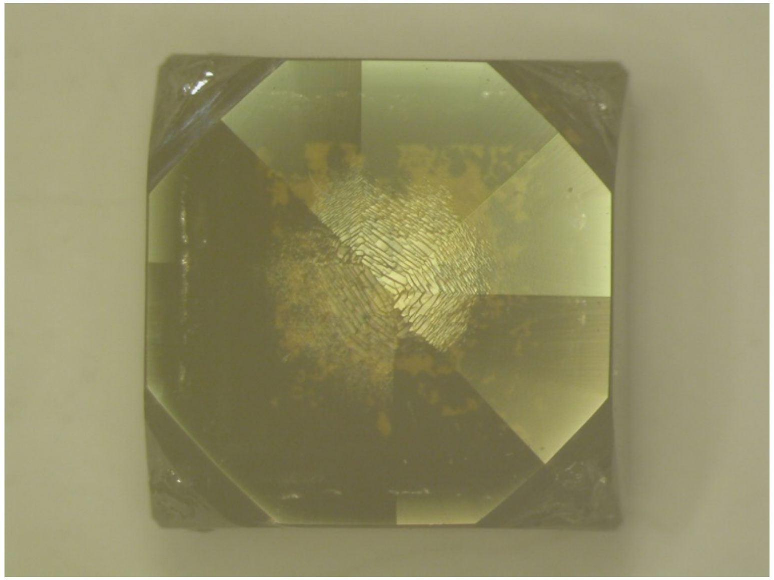
Polycristalline CVD (pCVD)

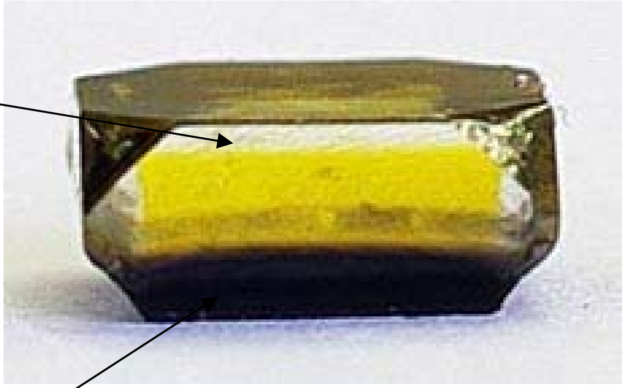
Grows on any substrate (Si)
Slow process (around 1µm / h)
Cristal bigger along the process
Industrial well controlled process



Monocrystalline CVD (sCVD)

Grows only on another monocrystal (HPTHT seed)
small dimensions (typical 4 x 4 mm^2)
faster processus : 25 µm /h)
Very few industrial manufacturers





Finishing :

pCVD : Nucleation (small grains) supppression)

sCVD : Seed suppression

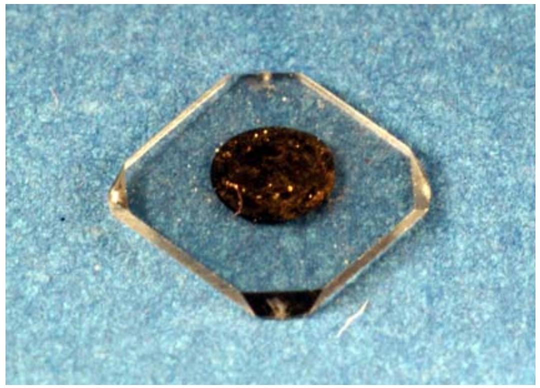
Monocristal CVD

seed HPHT

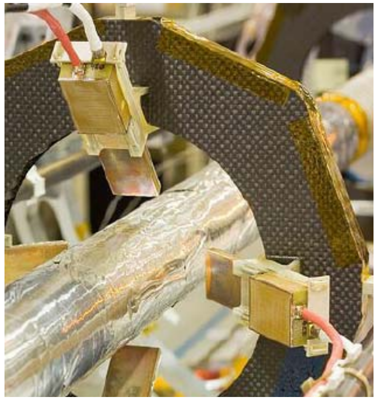
Métalisation (cf bonding)

Cleaning
Re- métalisation

charactérisation (CCD…)



APPLICATIONS IN HEP EXPERIMENTS



Beam Conditions Monitors
Beam Loss Monitors
- BaBar
- CDF
- ATLAS – CMS - LHCb

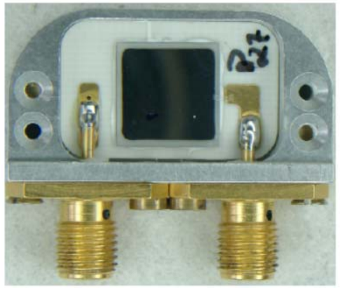
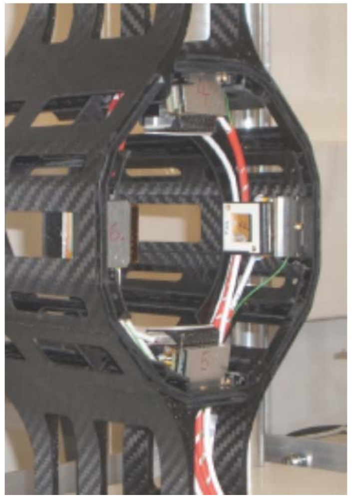
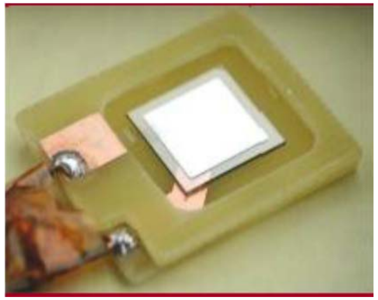


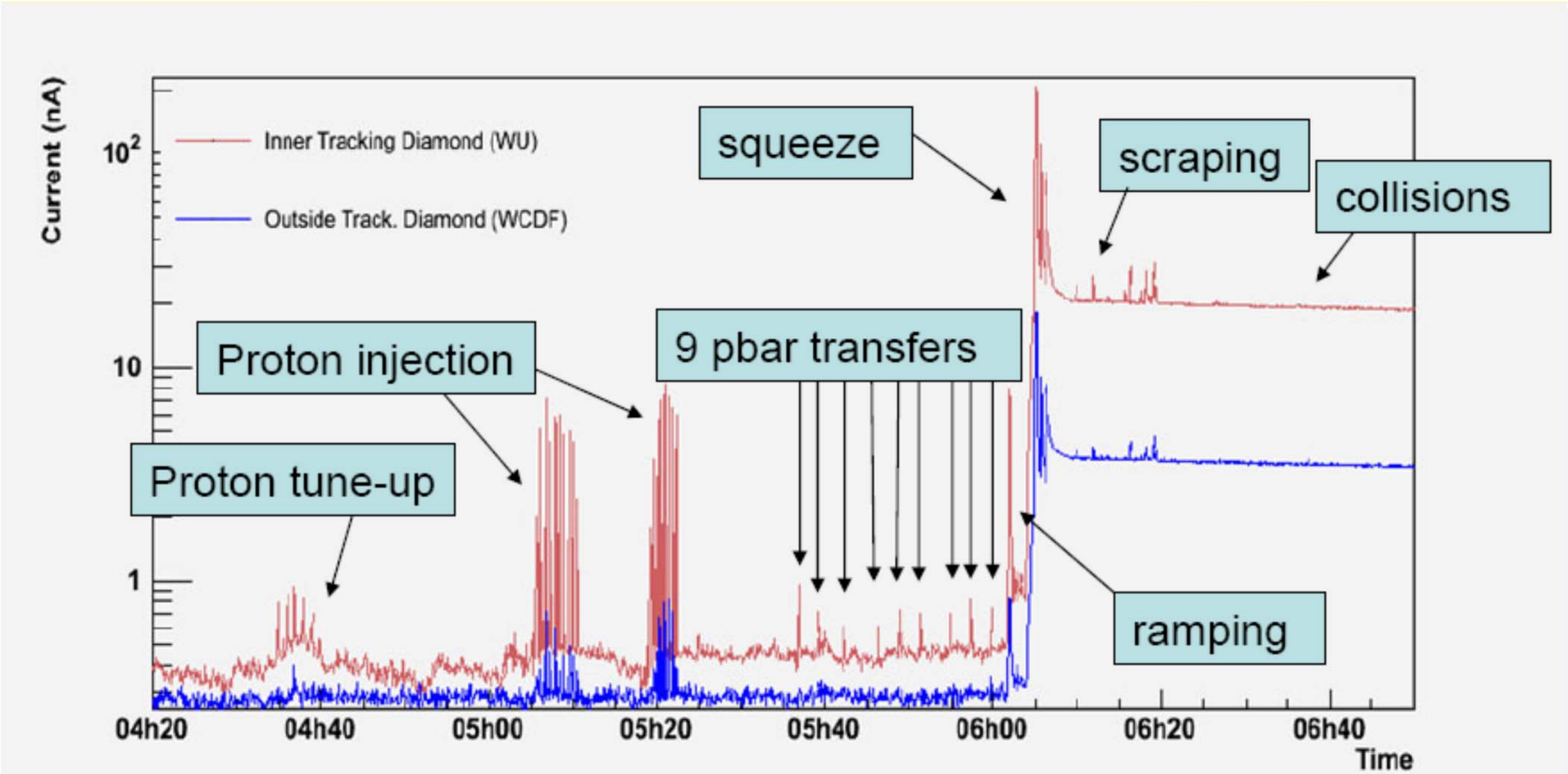
Figure 20: A photograph of the final module used by CMS for its BLM system.



Principe :
Continuous current measurement with field E ~ 1 V / μ



MAPS vertical integration
(Heat Dissipation)
Since 2007



CDF at Fermilab

Conclusion : Diamond is OK for beam condition monitor

Idea in 1995 : Diamond is more resistant than Silicon
can it be used for tracking in very difficult conditions ?

LHC Phase II : Φ at 4 cm ~1.4 ÷ 1.6 10^{16} n_{eq}/cm^2 mainly charged
Φ at r> 60cm ~1 ÷ 3 10^{14} n_{eq}/cm^2 mainly neutral

Present Tracker Layers radii

L= 8 x 10^{34}

High fluence regime Charged particles predominant

Medium fluence regime Combined Charged and neutral particles

Low fluence regime Neutral particles predominant

r (cm)	ϕ X 10^{13} cm^{-2}	% charged	% neutral
4,30	1509,97	84,5	15,5
7,10	622,76	82,0	18,0
11,00	297,74	78,7	21,3
22,00	117,71	69,2	30,8
32,00	72,39	63,6	36,4
41,00	54,55	59,1	40,9
49,00	43,40	55,8	44,2
58,00	35,47	51,8	48,2
74,50	19,35	26,0	74,0
82,50	17,27	21,9	78,1
90,50	15,78	18,5	81,5
98,50	14,33	13,9	86,1
114,50	12,79	8,4	91,6

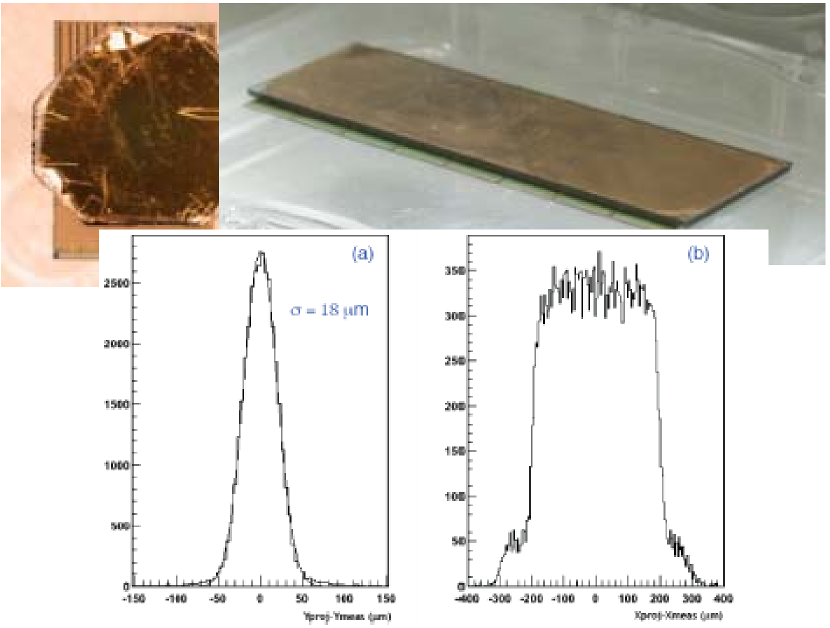
Not a clear picture

Data and simulations agree

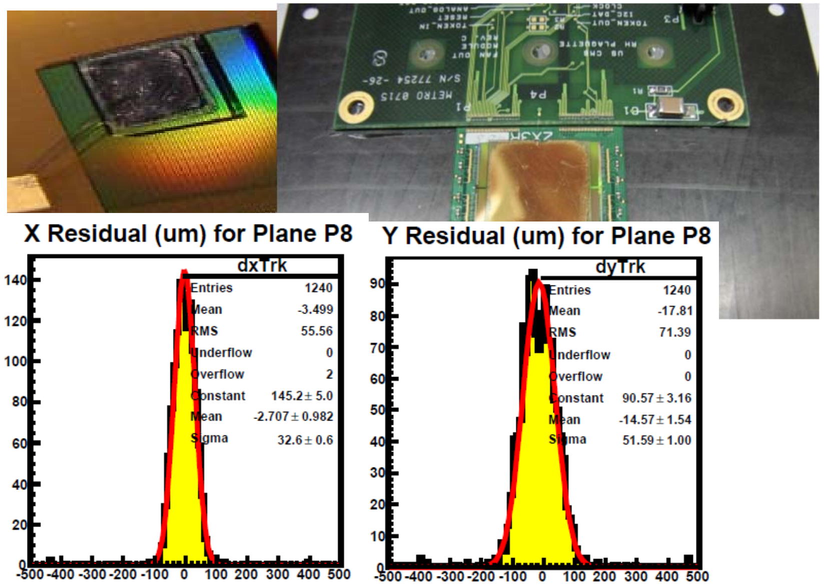
Mixed irradiation new options/scenario

CVD diamond already tested as pixel sensors

By ATLAS (pCVD)



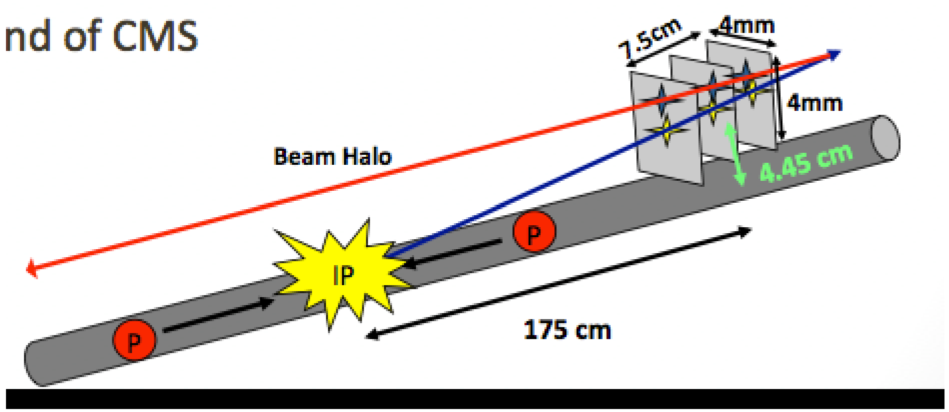
By CMS (sCVD)

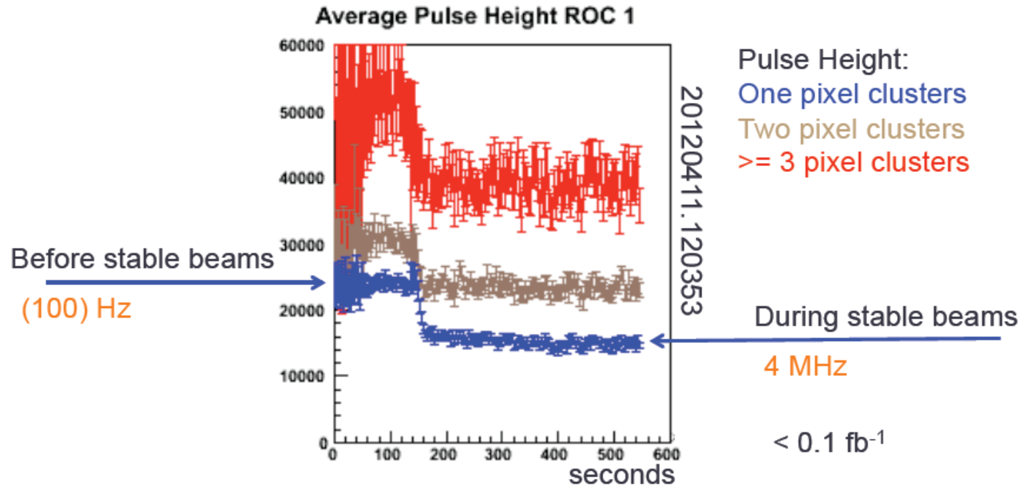


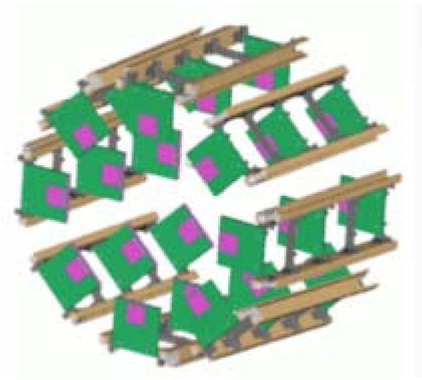
Correct…

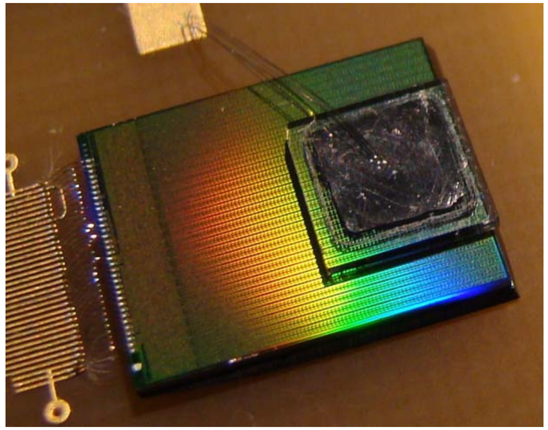
But only once…

THE CMS PLT









Failure …

Why ? - Industrial manufacturers (industrial secrets)
- Characterisation test : CCD measuremen t for a short time.
- lack of information within the community.
- Particle physicists are NOT solid state physicists.

The fundamental problems is : Understanding what makes a ''good'' diamond

MONODIAM-HE Project (ANR-12-BS05-0014)

Work with a laboratory expert in growing diamonds (LSPM – Paris)
- growing **sCVD** and comparison with industrial sCVDs
- Understanding the important parameters
- Improving the quality (for tracking at HE)

Answering some questions :

- Important parameters for growing diamond (the recipe)
- Important parameters for preparing the diamond
- Important parameters to watch

- **Nitrogen contens**
- **Surface finishing**
- **Metallisation**
- **Long term**

1. Growing conditions : Nitrogen impurities

Adding Nitrogen :

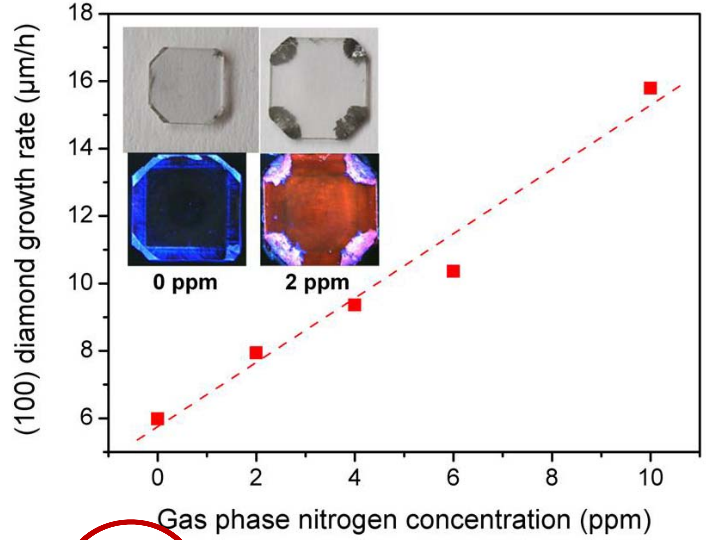
Strong effect on growth rates (up to 100 µ/h)

Twinning at the edges

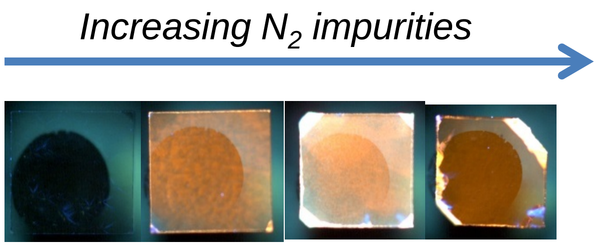
Limitation of twinning at the surface

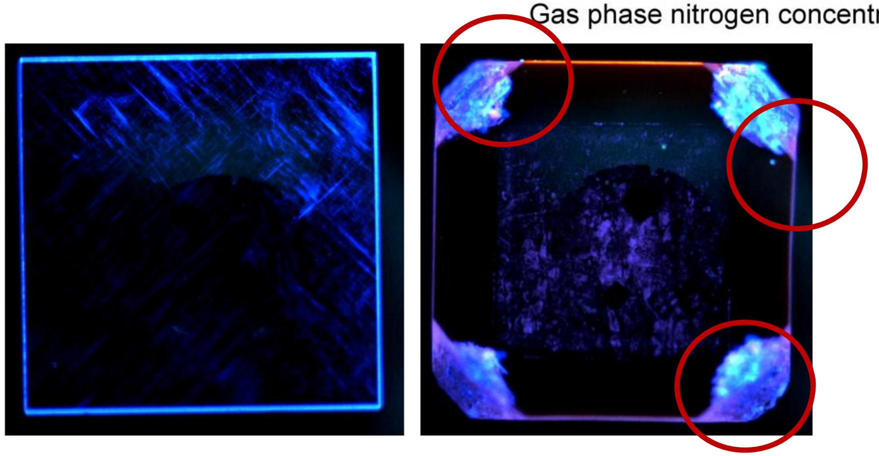
Effect on CCD

(incorporation of N2 in the crystal)



Prototypes made at LSPM with variable N2 contents

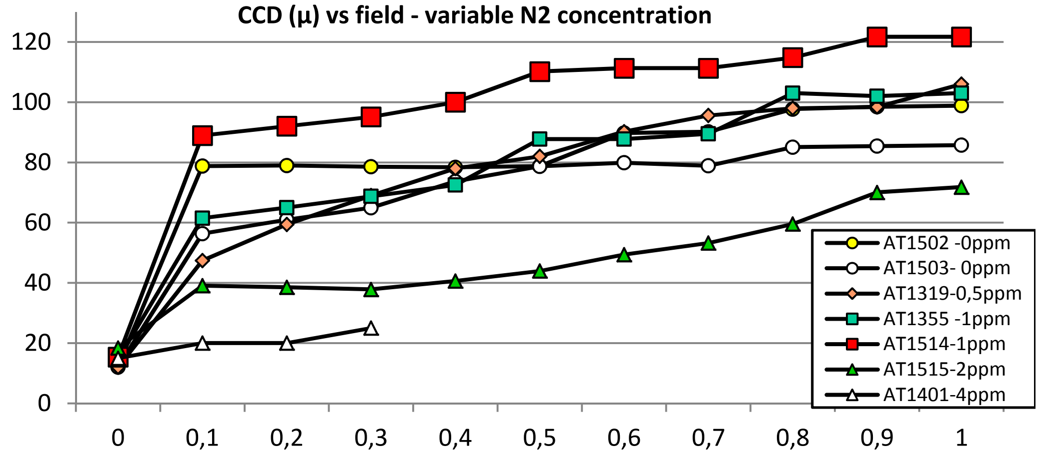


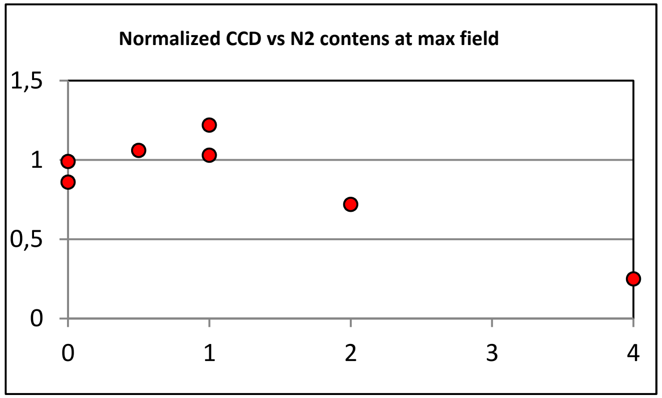


Industrial sCVD
(no N2 ?)

Laboratory sCVD
(2 ppm N2)

thickness	N2 cont.	CCD max.	CCD Norm.	HT Lim
518	0	512	99	500
582	0	499	86	500
500	0,5	530	106	500
430	1	412	103	400
452	1	550	122	500
571	2	410	72	500
518	4	130	25	150





Study made on several prototypes

- same laboratory (LSPM)
- same growing protocol
- same finishing
- same metallisation
- **variable N2 contents**

Optimal : 0 to 1 ppm

2. Surface finishing

Observation :

2 possible problems :

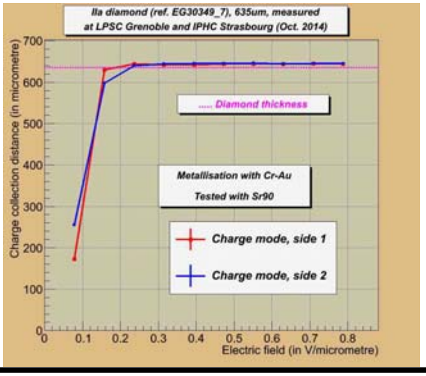
- CCD not correct (less than 10000 e^-)
- High voltage limitation (less than 1V/µ)

Possibility ?

CCD related to defects (traps) in the bulk

HV limitation due to surface problems

Evaluation of the quality of a diamond detector :
Measurement of the CCD using MIP (^{90}Sr)
Need : 10 000 e^- : CCD ≈ 280 – 300µ
≈ 100% for a 300µ sCVD



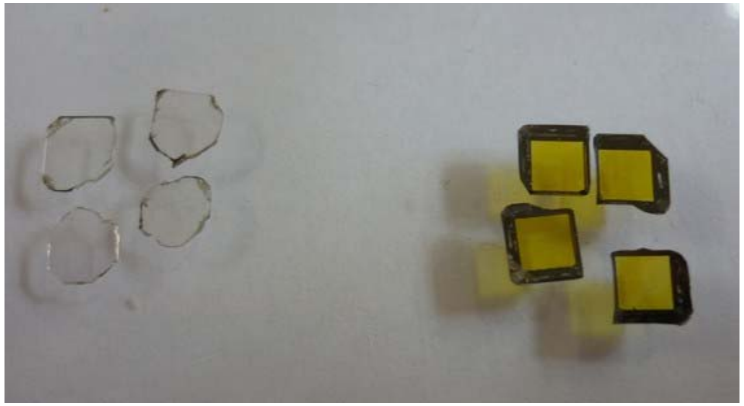
Example :
Industrial sCVD
Thickness : 635 µ
CCD about 600 µ

Use 4 LSPM prototypes sCVD (MM7- 1 to 4)

grown under the same conditions
in the same reactor
at the same time
prepared the same way (same company)
- laser cut to separate the HPHT seed
- precise polishing

Cleaned
metallised (Cr-Au) in laboratory
Measured (CCD and HV limts)

Use 1 industrial (good) sCVD (IND-1)



Reprocessing :

MM7-1 : precise re-polishing by another company (specialized in pCVD)
MM7- 2 : re-etched by RIE at laboratory
MM7- 3 : Terminated by VUV (172nm) in O2 flux
MM7- 4 : untouched . For calibration
IND - 1 : badly re-polished (on purpose)

And metallisation Cr-Au

On HV Limits

	Before reprocessing		**After reprocessing**		**Observation**
sCVD	Side 1	Side 2	Side 1	Side 2	
IND - 1	500V	600V	500V	300V	degradation
MM7-1	600V	400V	600V	400V	same
MM7-2	200V	400V	400V	500V	**Improvement**
MM7-3	100V	100V	300V	100V	**Little improvement**
MM7-4	500V	350V	500V	400V	same

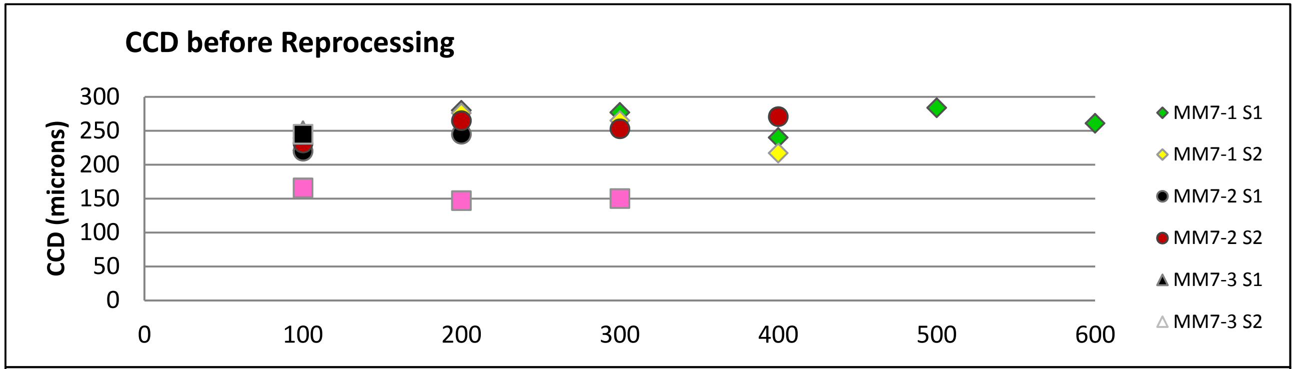
As good as it is , polishing may not be enough…

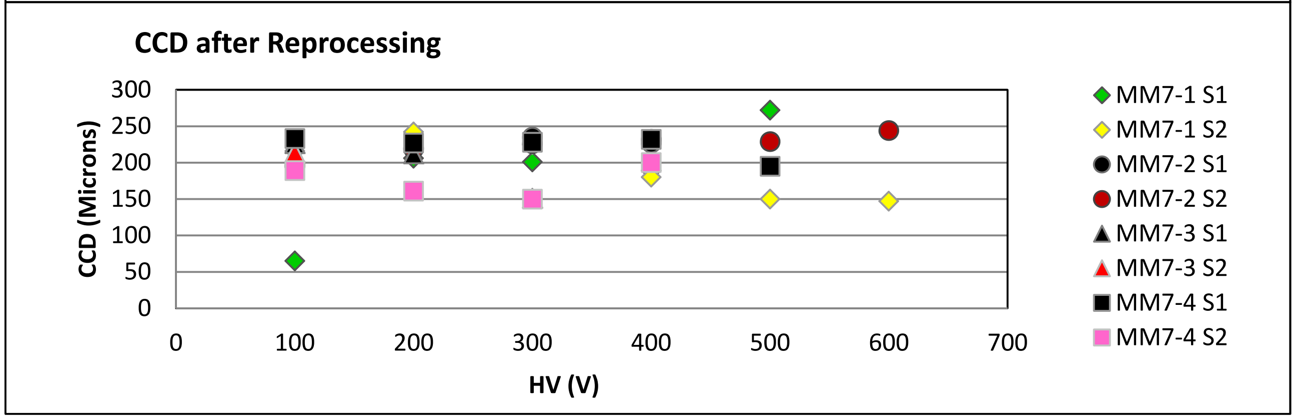
Reactive Ion etching

Ozonization

(and probably very agressive cleaning)

Seems to be having an effect on the HV limitation





Reprocessing
has a little effect on CCD
(given the measuerment
uncertainties)

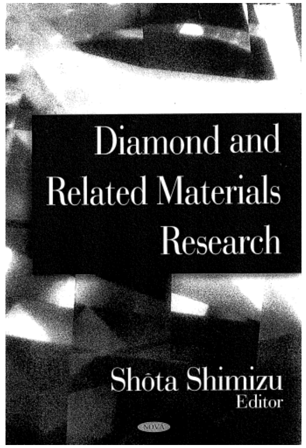
Conclusion :

- CCD is related to Bulk quality
- HV limitation is related to surface quality
  and **may be improved.**

3. Metallisation

Metallisation needed for contacts (wire bonding or bump-bonding)
Early prototypes showed a Schottky Diode Behaviour
Extensive researches on diamond contacts
see, for example «

> Though there are numerous reports of rectifying Schottky contacts and low resistance Ohmic contacts to diamond, currently there is no standardised process for fabrication of Schottky or Ohmic contacts to diamond.



Use Two (industrial) reference detectors

metalised Cr-Au
Tested on different benches

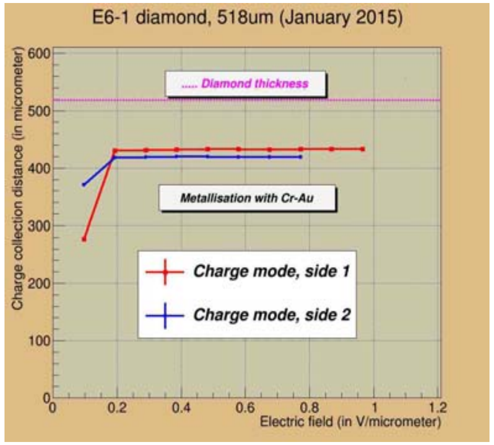
Cleaned
Metallisation (pulverisation)
Tests : **Cr- Au**
W
Cu
Al
In (Cu-In)

At LSPC-Grenoble

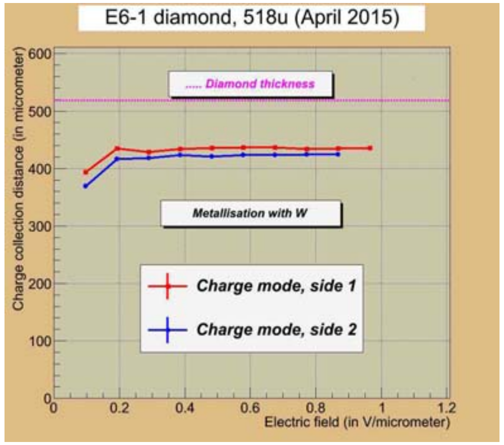
Metal deposition by
by microwave plasma-assisted sputtering
Cleaning by
2 steps of plasma-assisted cleaning

At Icube - Strasbourg

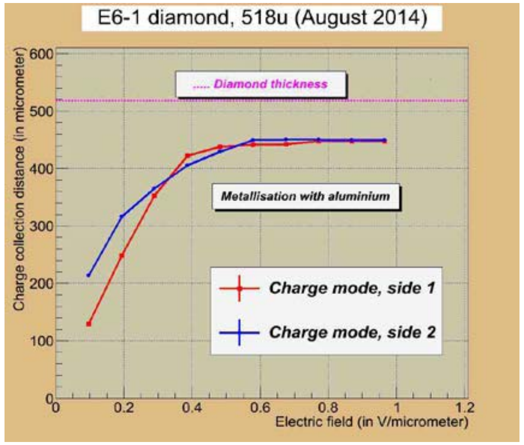
Metal deposition by
Vacuum evaporation
Cleaning by
Hot H_2S0_4 – KNO_3



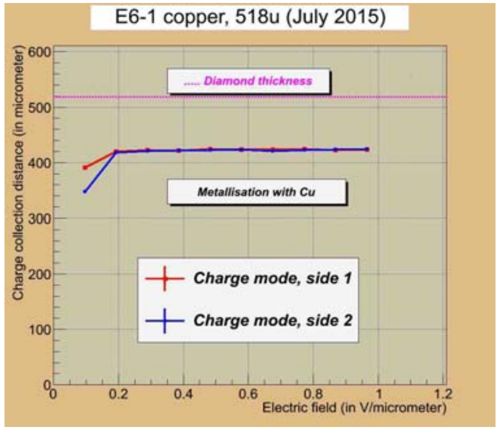
Cr-Au



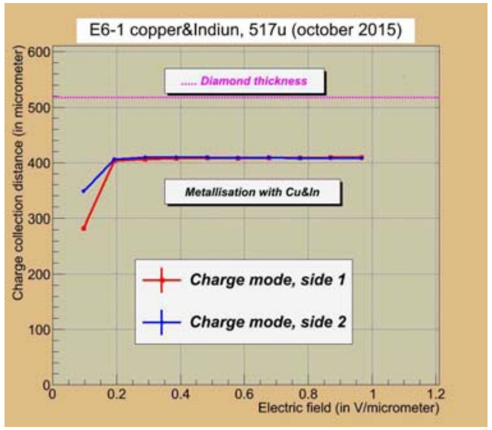
W



Al

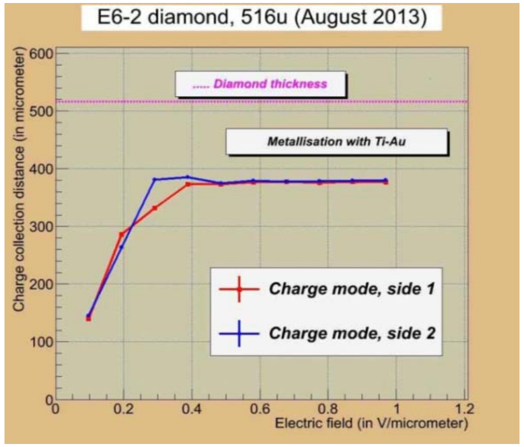


Cu

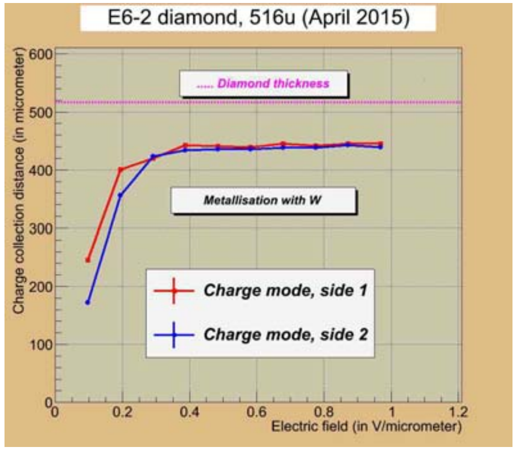


Cu-In

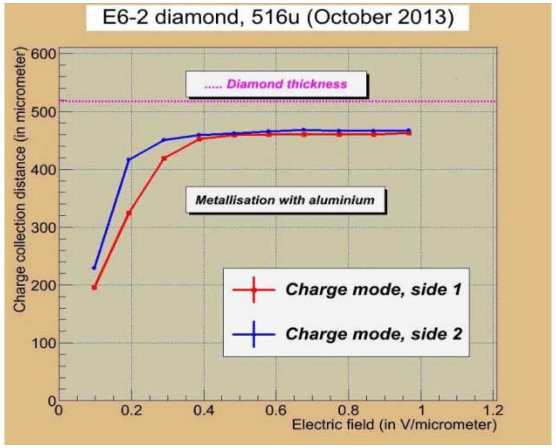
Cr-Au :	HT limits 500V	/ 400V
	CCD 440 µm / 420 µm	
W :	HT limits 500V	/ 450V
	CCD 440 µm / 420 µm	
Al :	HT limits 500V	/ 500V
	CCD 440 µm / 440 µm	
Cu :	HT limits 500V	/ 500V
	CCD 425 µm / 425 µm	
Cu-In :	HT limits 500V	/ 500V
	CCD 410 µm / 410 µm	



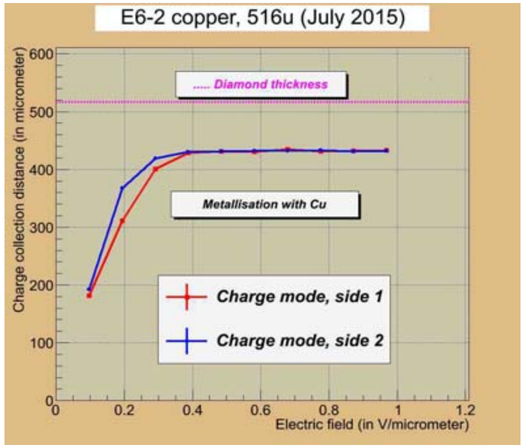
Ti-Au



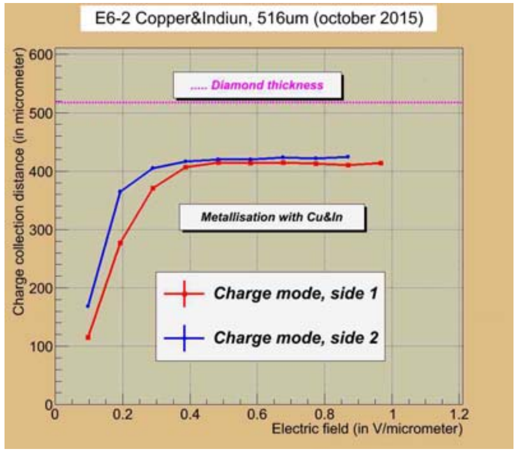
W



Al



Cu



Cu-In

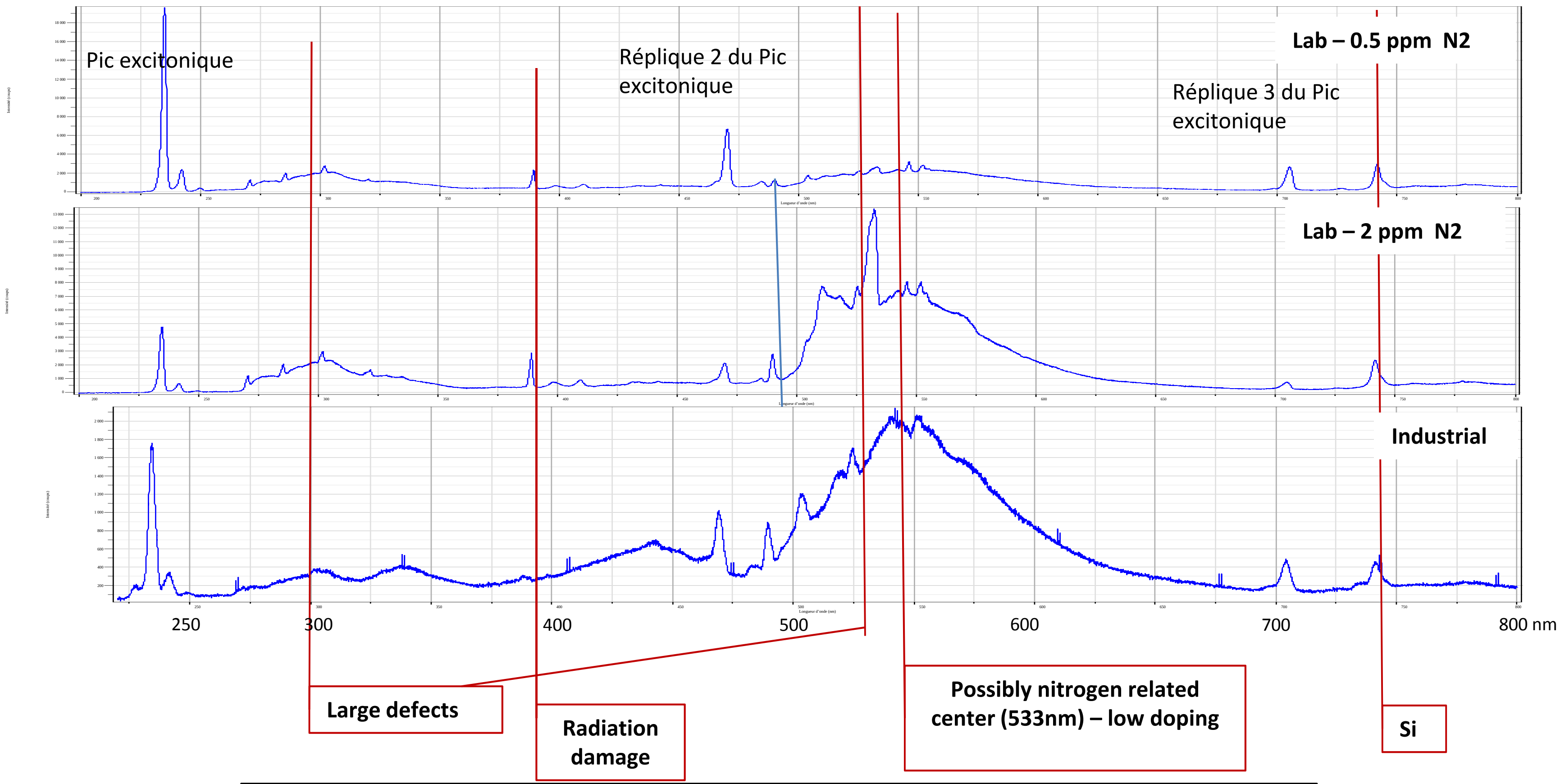
Ti-Au :	HT limit	500V	/ 500V
	CCD	380 µm	/ 380 µm
W :	HT limit	500V	/ 500V
	CCD	425 µm	/ 425 µm
Al :	HT limit	500V	/ 500V
	CCD	460 µm	/ 460 µm
Cu :	HT limit	500V	/ 500V
	CCD	410 µm	/ 410 µm
Cu-In :	HT limit	500V	/ 450V
	CCD	410 µm	/ 420 µm

Various metallisations have **very little effect** on CCD
(Schottky element already stabilized by cleaning ?)
HT limit related to **surface quality**

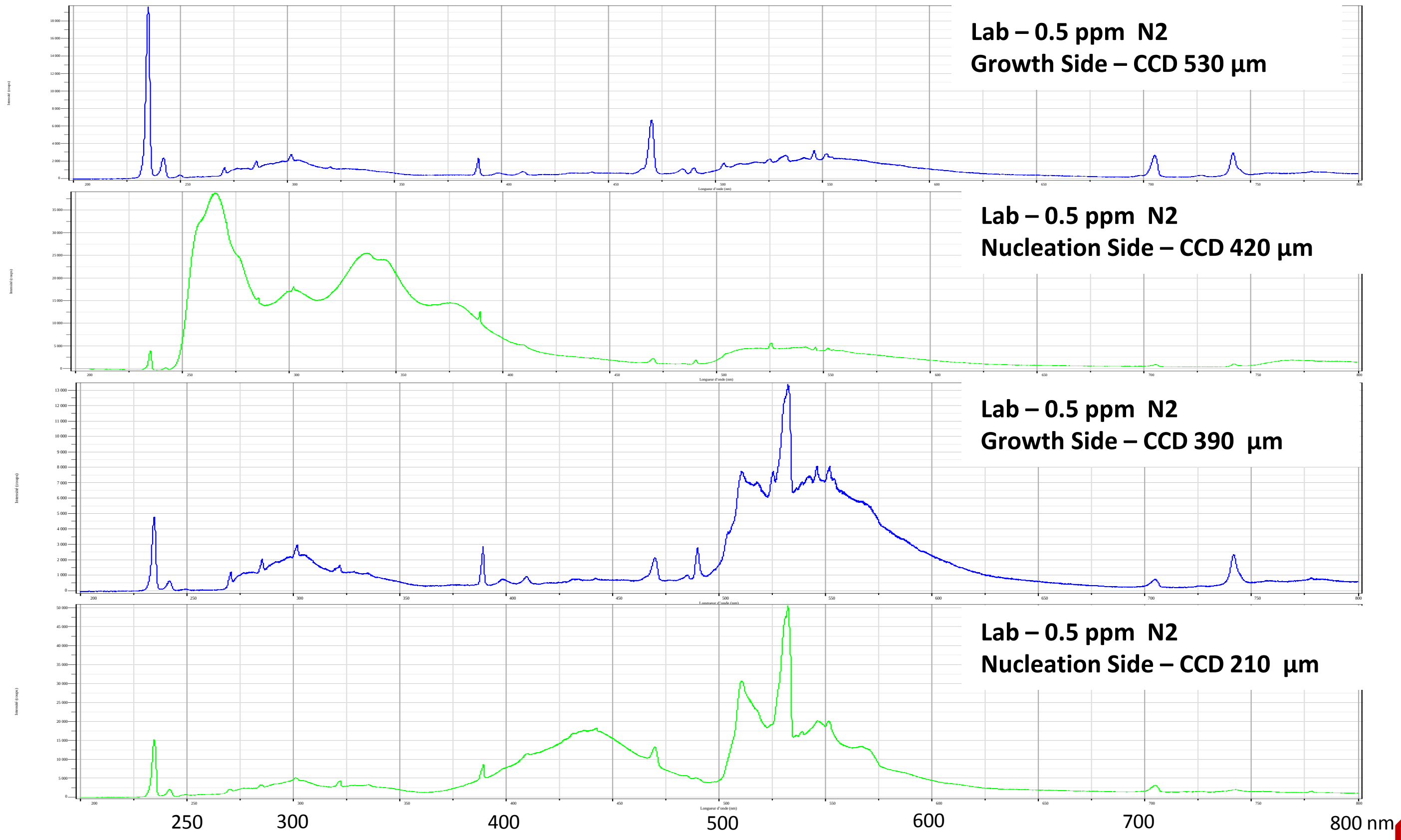
4. Bulk Studies

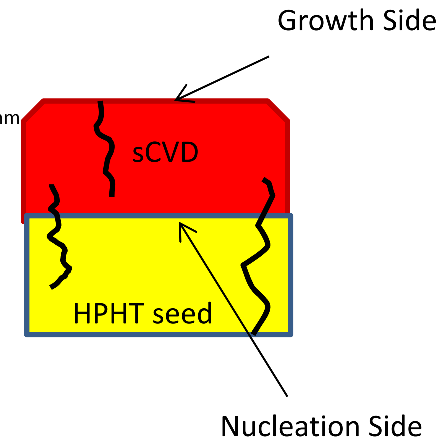
By Cathodo-luminescence at low temperature
(electron beam 10kV, 7nA – T=110°K)

Lab – 0.5 ppm N2 : Limit HT, limited CCD
Lab – 2 ppm N2 : HT OK, CCD OK
Ind - ? : HT OK, CCD OK



One can see clearly the presence of Nitrogen
There are extended defects in all diamonds
Test under source (74 MBq) induces damages: Radiation hardness ?

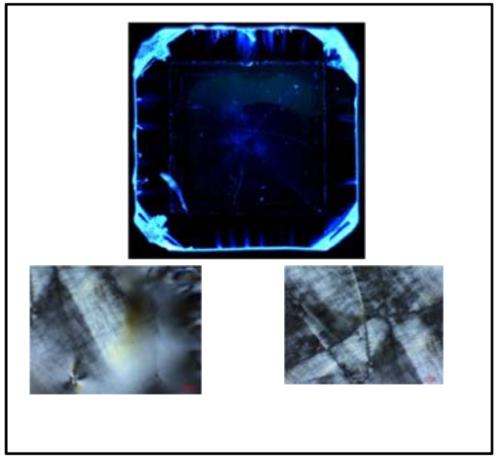




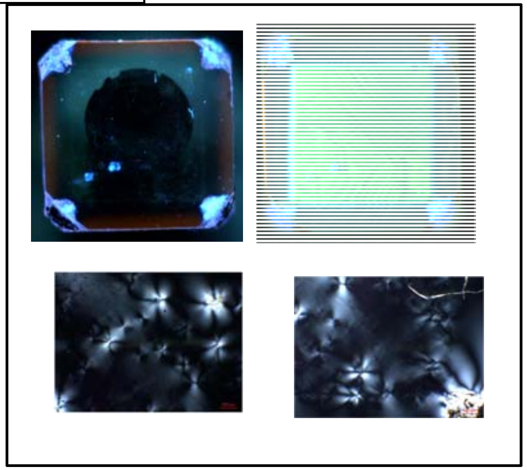
More extended defects on the nucleation side (HPHT mirror effect)
Even the sCVD are asymetrics (known for the pCVDs)
(with consequences on the CCD)

5. Bulk and surface Studies

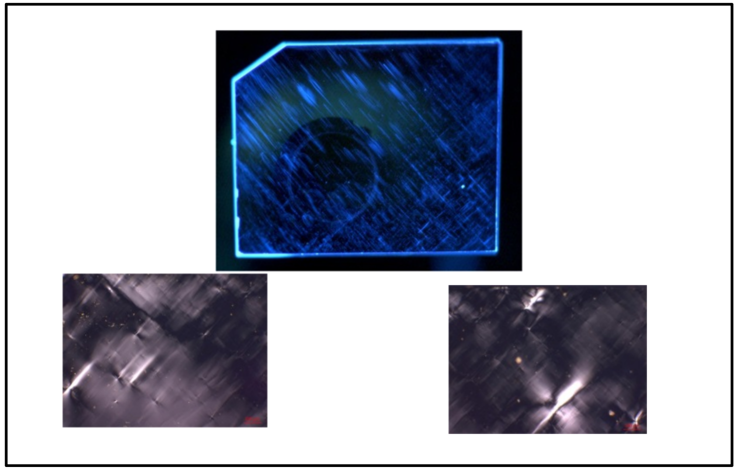
By Images (Fluorescence / polarised light / X-ray Tomography)



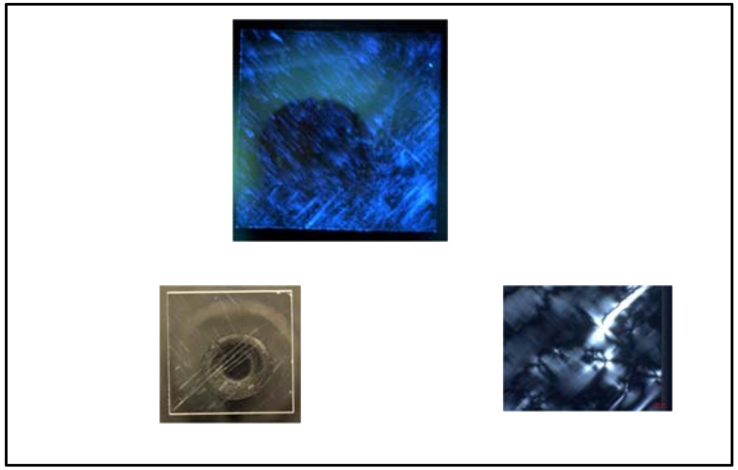
LSPM – 0 ppm N2
results on CCD OK



LSPM – 1 ppm N2
results on CCD OK



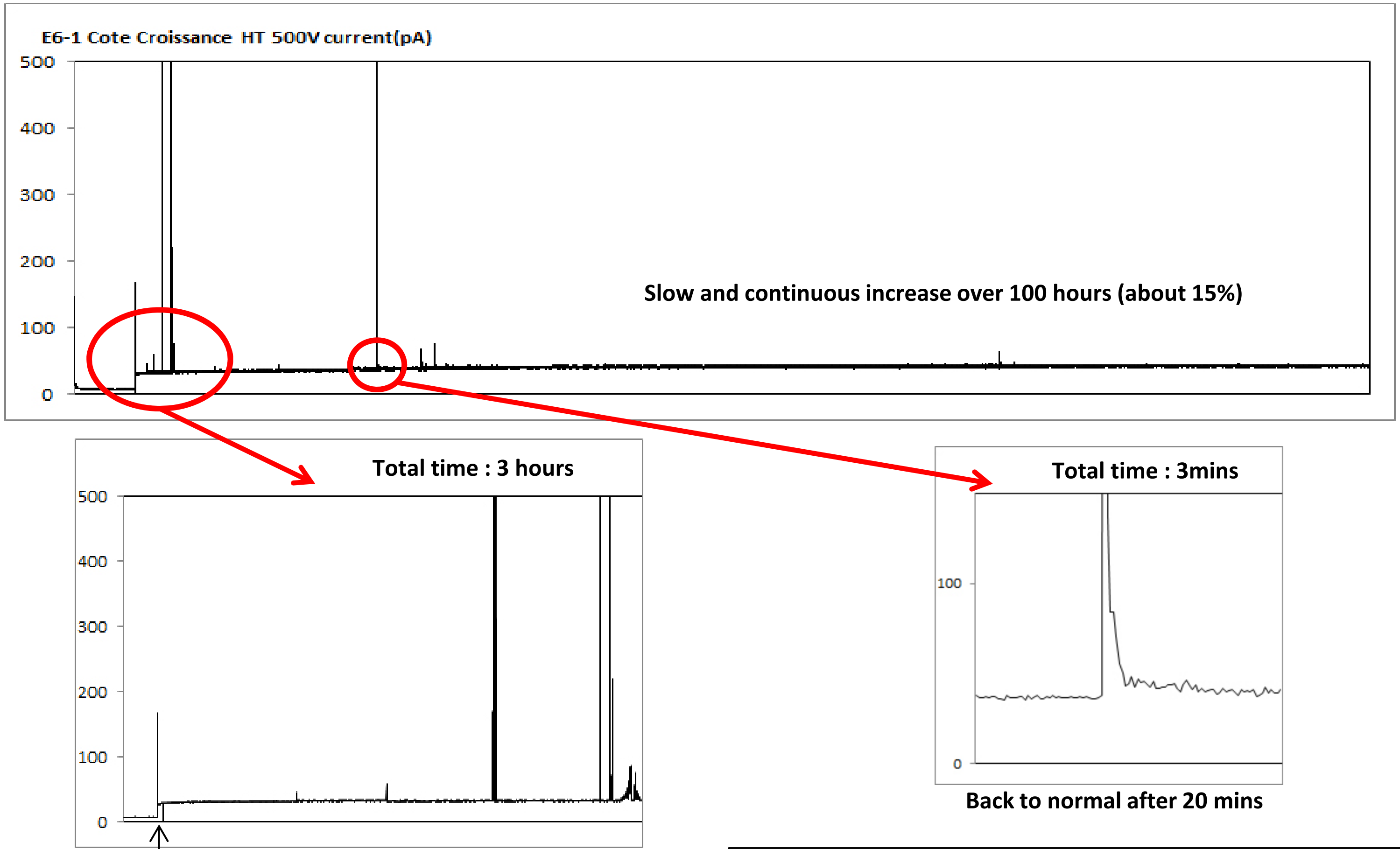
Industry
results on CCD very good



All sCVD show defects
- deep dislocations
- bad polishing
- N2 incorporation
- …

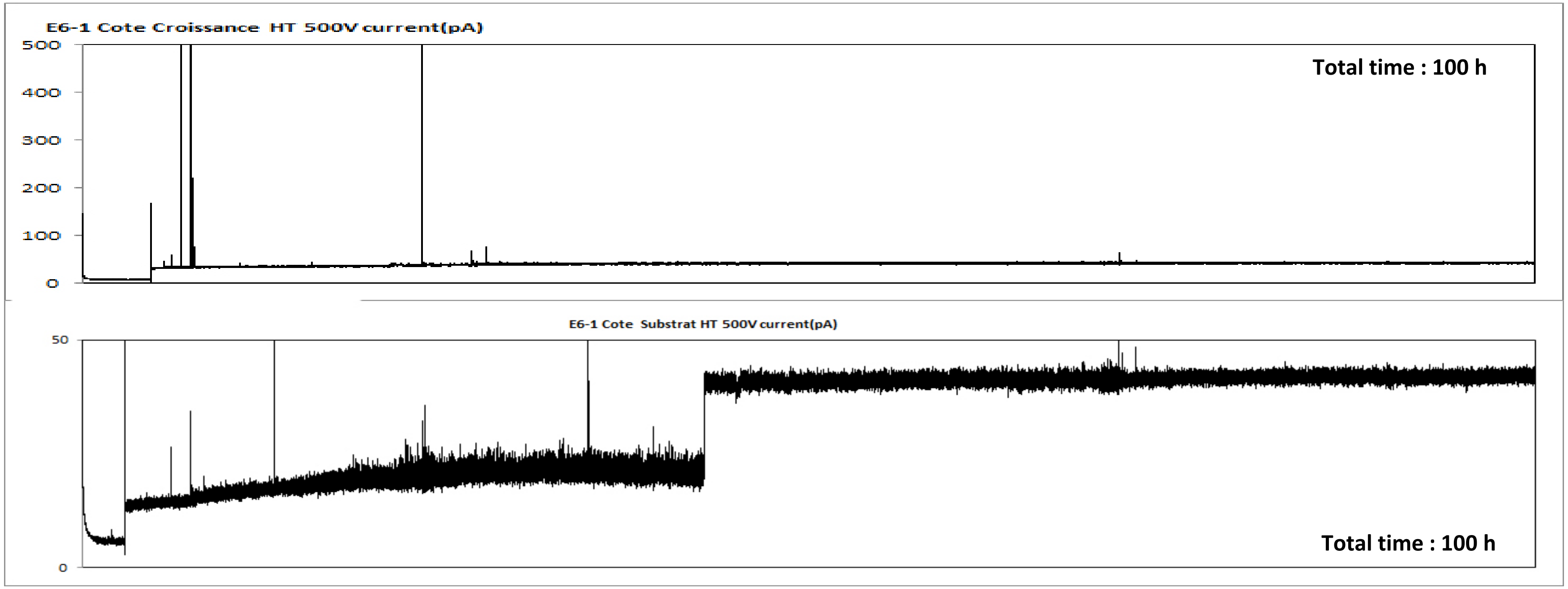
6. Long term effects – ''Polarisation'' ?

Long term measurement leakage current at max field (≈1 V/µm)

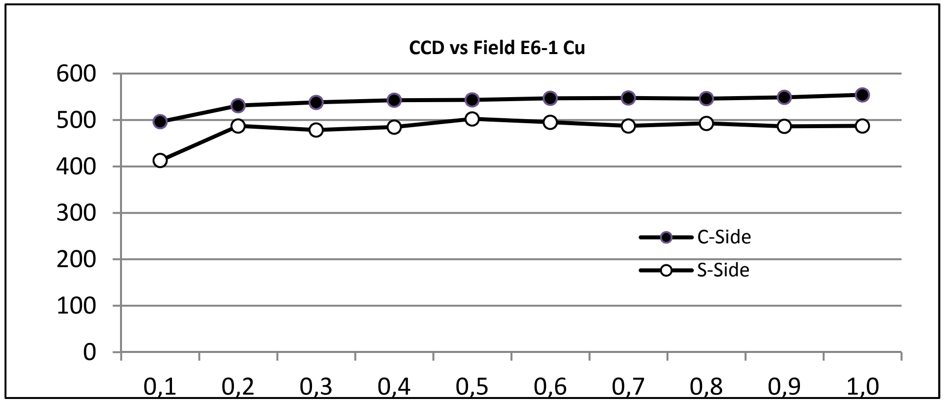


74 MBq source

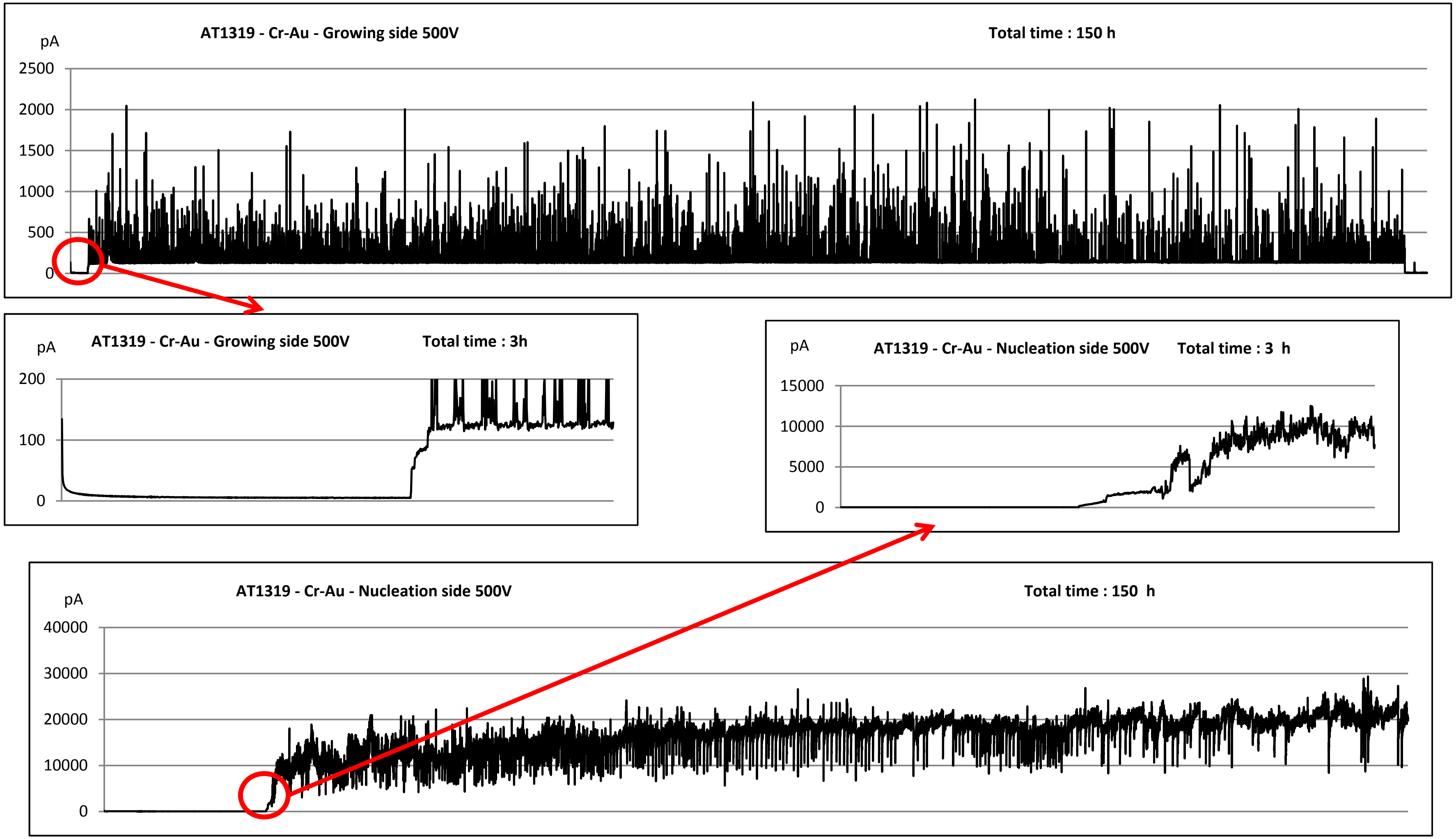
Clear source effect
'' slow '' discharges (charging – discharging of traps)



For a ‘’good’’ (industrial) sCVD



Difference between sides
Lower CCD on the nucleation side
More defects (traps) on the nucleation side



Strong difference between sides
More defects (traps) on the nucleation side
Could be a way to evaluate the defects rate ??

Conclusion and prospectives (?)

We have started to adress fundamental problems :

Diamond bulk effects

impurities (Nitrogen – Boron)

bulk defects importance

defects rate have to be understood, and under control

some ideas exist :

differential growing, immediate anealing, disorientation)

Diamond surface effects

surface finishing

metallisation

problem considered as solved (?)

The main lesson :

True :

Developpements in the Research Community may lead to Industrial Developpements.

Wrong :

Objects developped in the Industrial World can be easily used in the Research Community.