Tracking Detectors at LHC

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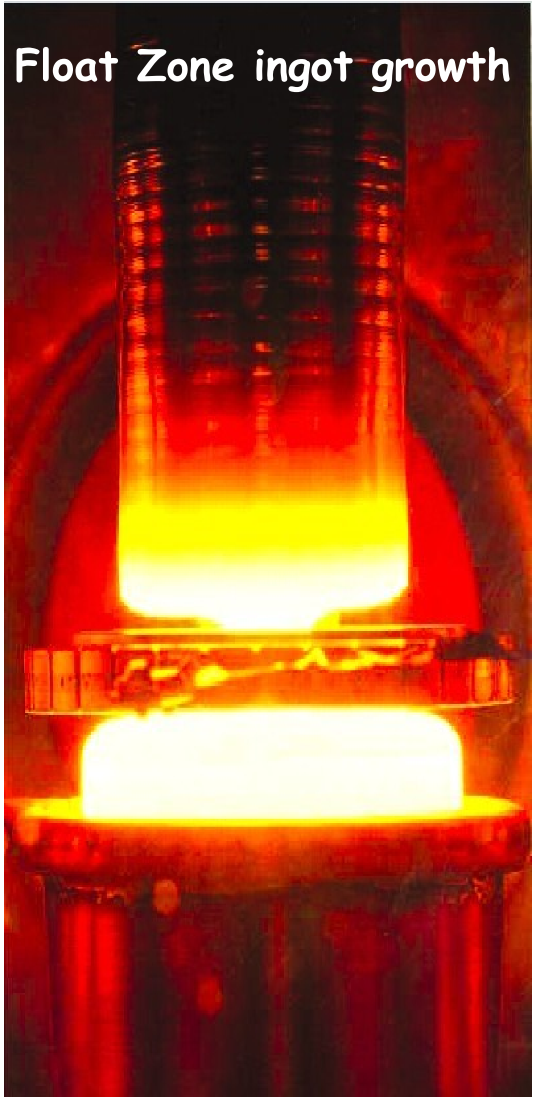
Outline

- Detector Requirements at LHC
- Semiconducting Detectors
  - Semiconductors for tracking
  - Solutions at LHC
  - Improvements for the future
- Gas Detectors
  - Gas detection technique & issues
  - Gas detectors at LHC

LHC Requirements

- High granularity for high track density
- Low material budget
- Speed : bunch crossings every 25ns, detectors and their electronics need to be fast.
- Radiation hardness :
  - Expected accumulated dose =2 10^6 Gy / r^2 / year (r in cm),
  - 70kGy of ionizing radiation
- Magnetic Field for high momentum precision



Silicon Detectors for tracking

Some characteristics of Silicon crystals

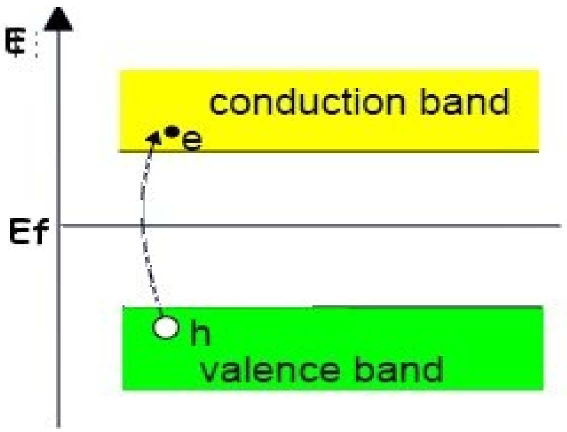
- Small band gap Eg = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
- High specific density 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/µm (average)
- High carrier mobility μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
- Very pure < 1ppm impurities and < 0.1ppb electrical active impurities
- Rigidity of silicon allows thin self supporting structures
- Detector production by microelectronic techniques ⇒ well known industrial technology, relatively low price, small structures easily possible

Alternative semiconductors

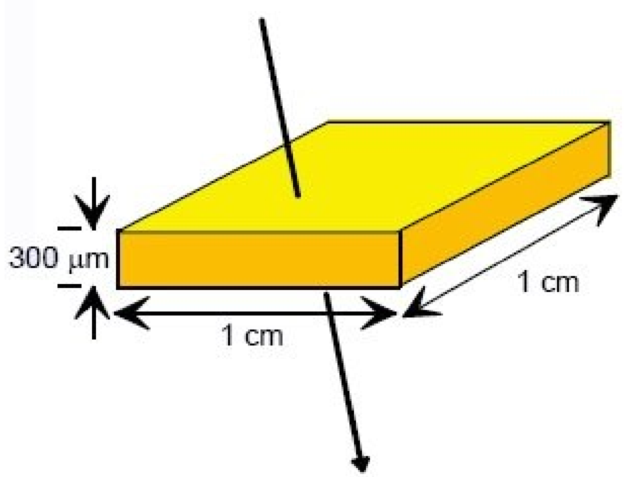
- Diamond
- GaAs
- Silicon Carbide
- Germanium

	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

Signal of a charged track

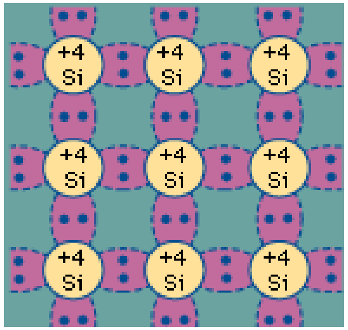


- In an undoped (intrinsic) semiconductor the the carrier densities $p=n=n_i$ For Si: $n \approx 1.45\ 10^{10} cm^{-3}$.



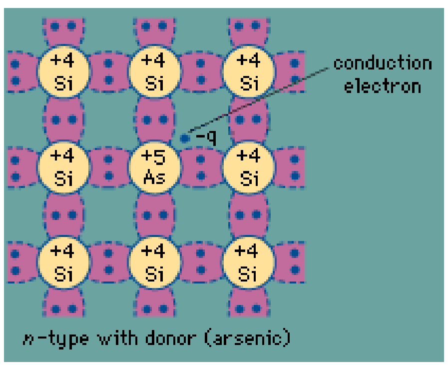
- $4.5 \cdot 10^8$ free charge carriers in this volume, but only $3.2 \cdot 10^4$ e-h pairs produced by a M.I.P.
- We need to “remove” the initial charges, to deplete the silicon

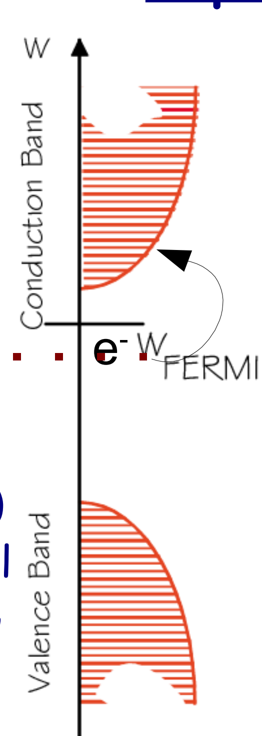
Doping



- Si is in group IV
- E_g=1.11 eV

Doping





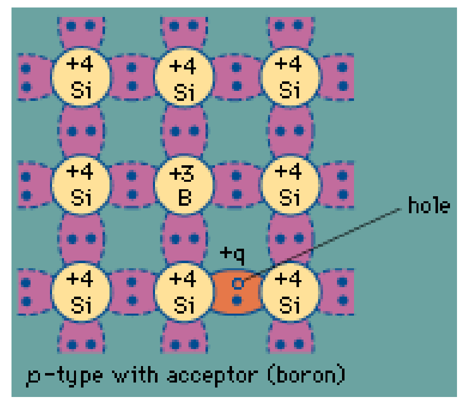
n-Type

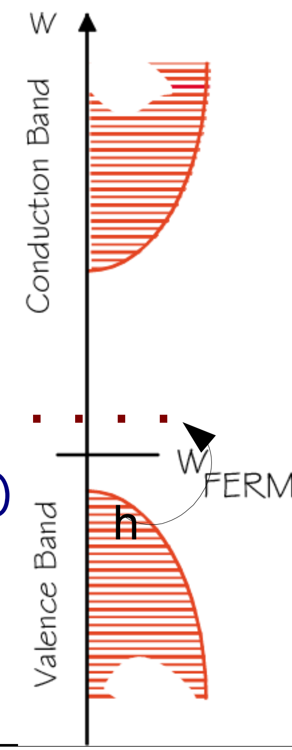
P, As, Sb (Group V)

5 electrons in the M-shel

→1 electron with binding energy 10-50 meV

donors





P-Type (Group III)

B, Al, Ga

3 electrons in the M-shell

→1 electron missing

acceptors

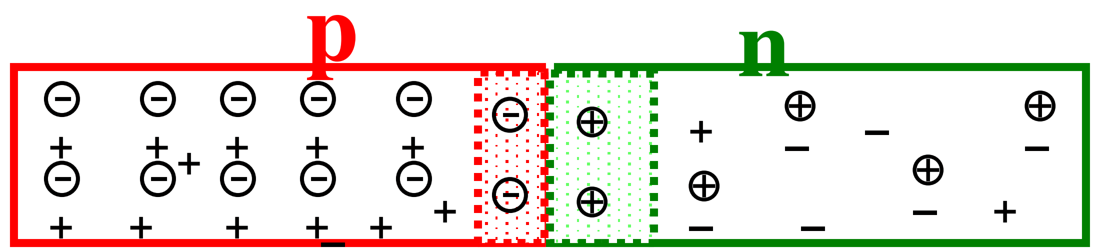
p-n junction

- Resistivity

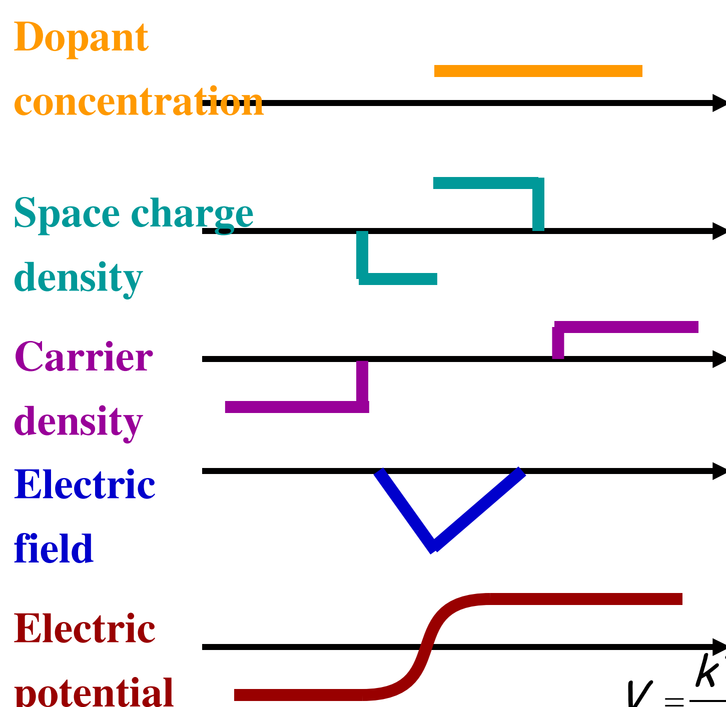
  carrier concentrations n, p

  carrier mobility μ_n, μ_p

$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$



- Detectors: doping: $10^{12}\,cm^{-3}$
  - ρ= 5kΩcm
- After migration of majority carriers across the junction, an E field due to immobile ions prevents further migration
- $V_d \approx$ few 100 mV



$$V_d = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

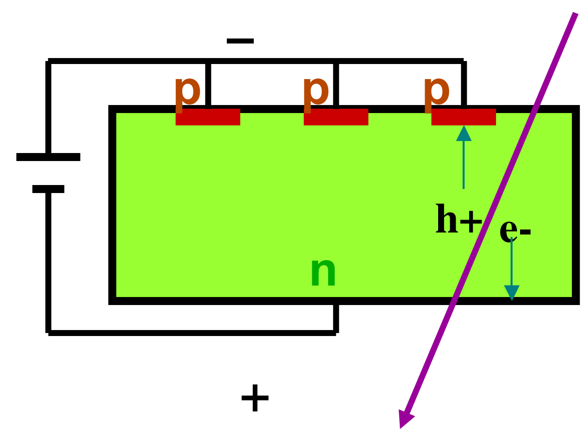
Depletion Voltage

- The crystal is neutral: $N_a W_1 = N_d W_2$
- Poisson equation on each side of the junction $\frac{d^2V}{dx^2} = -\frac{\rho}{\epsilon} = \frac{qN_a}{\epsilon}$
- Imposing the boundary condition V=0 at -W1
  - $V = \frac{qN_a}{\epsilon} \cdot \left(\frac{x^2}{2} + W_1 x + \frac{W_1^2}{2}\right)$ $\qquad V_1 = \frac{qN_a W_1^2}{2\epsilon}$
- Similarly $V_2 = \frac{qN_d W_2^2}{2\epsilon}$
  - $V_B = V_1 + V_2 = \frac{Q}{2\epsilon}(N_a W^2{}_1 + N_d W^2{}_2)$

$$W_1 = \sqrt{\frac{2\epsilon V_B}{qN_a(1+N_a/N_d)}} \qquad W_2 = \sqrt{\frac{2\epsilon V_B}{qN_d(1+N_d/N_a)}}$$

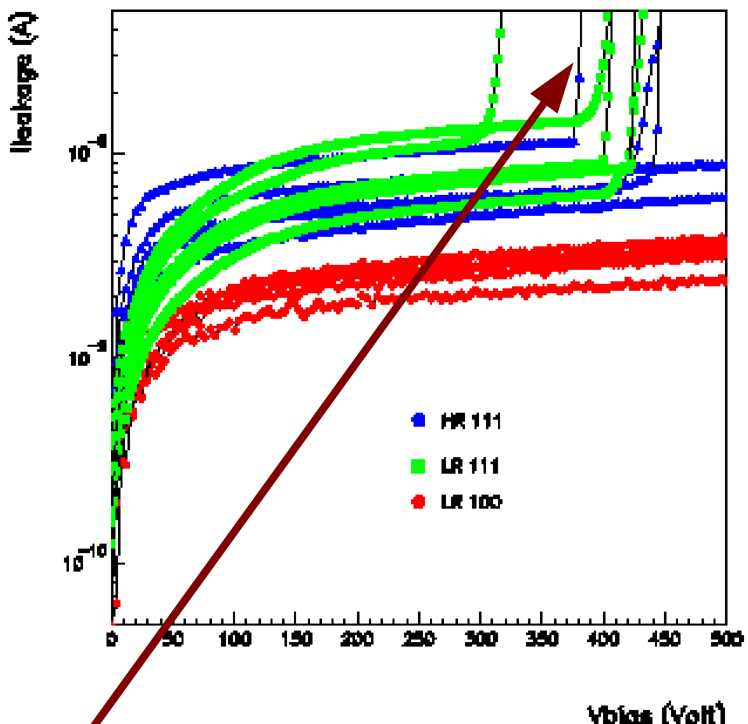
- The 2 depletion regions extend in inverse proportion of the impurity concentration ! If $N_a \gg N_d \implies W_1 \ll W_2$
- For p^+n type: $N_a \sim 10^{15} cm^{-3}$ and $N_d \sim 5\ 10^{12}$ cm-3 $W_1 = 0.4\mu m$, $W_2 = 300\mu m$ for $V_B = 100V$: the p^+ layer is there to allow depletion of the n-type active volume

$^+$ = highly doped



Leakage current

- Thermal generation of carrier pairs in depletion zone: $j_{gen} = \frac{1}{2} a \frac{n_i}{\tau_0} W$
  - n_i depends on T $n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$ so one needs to keep T low
  - W depends on √V until fully depleted
  - τ_0 is the lifetime of minority carriers : regulated by impurities
    - Need a pure, clean crystal !



- Local defect can locally ↑E to give enough energy for e-h creation (E~30V/μm) Breakdown by avalanche creation.

Junction capacitance

- In the bulk region of p^+n junction $N_a \gg N_d$ and $\rho = \frac{1}{q\mu_n N_d}$

$$W = \sqrt{\frac{2\epsilon V_B}{qN_d(1+N_d/N_a)}} \approx \sqrt{\frac{2\epsilon V_B}{qN_d}} = \sqrt{2\epsilon\rho\mu V_B}$$

(note for the same thickness if p bulk, μ_h is lower -> V_B must be higher)

- The higher the resistivity, the lower the bias voltage to apply to reach full depletion !
- Junction capacitance linked to the charges appearing on either side of the junction when V_B is applied

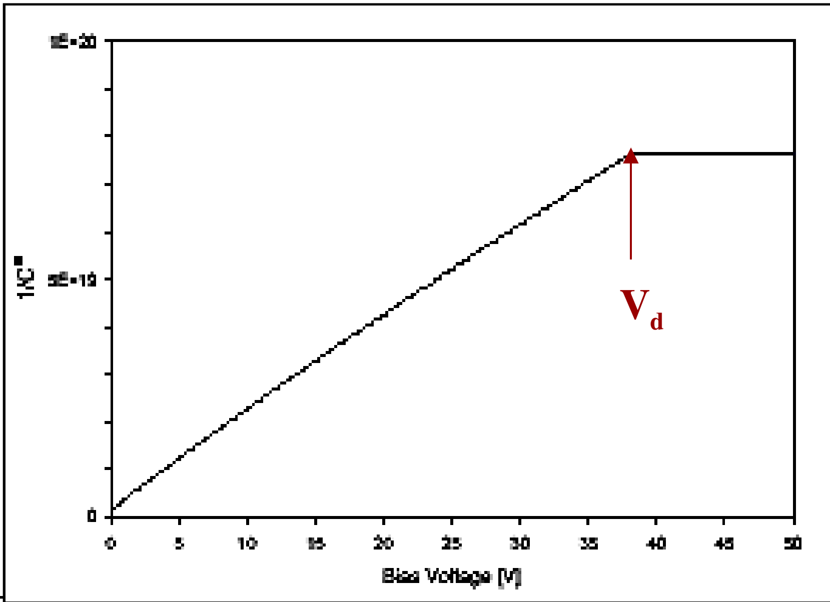
$$C_j = \frac{dQ}{dV_B} = \frac{dQ}{QW}\frac{dW}{dV_B}$$

with $dQ = qN_d dW = \frac{dW}{\rho\mu}$

and $\frac{dW}{dV_B} = \sqrt{\frac{\epsilon\rho\mu}{2V_B}}$

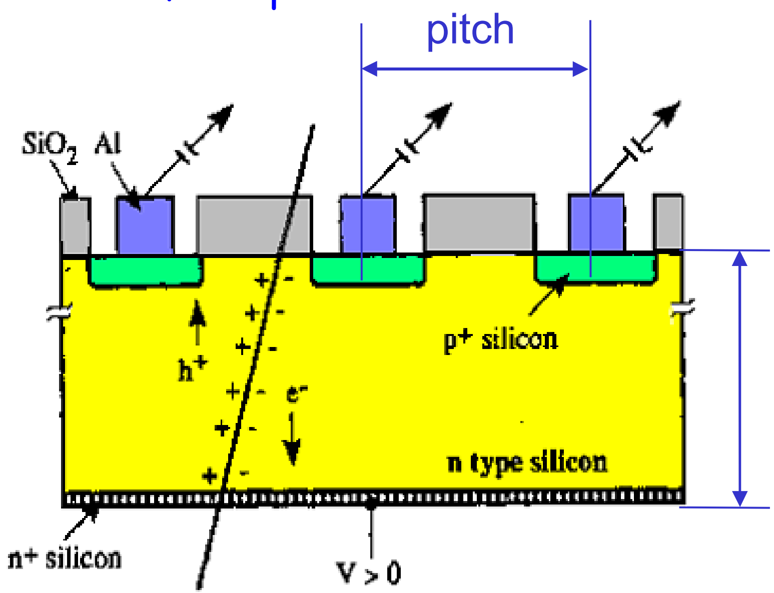
$$C_j = \sqrt{\frac{\epsilon}{2\rho\mu V_B}}$$

One measures the capacitance as a function of the voltage to find the depletion voltage.



Single sided strip detector

- Segmentation of the p^+ layer into strips (Diode Strip Detector) and connection of strips to individual read-out channels gives spatial information



typical thickness: 300μm (150μm - 500μm used)

- using n-type silicon with a resistivity of ρ = 2 KΩcm (N_D ~$2.2 \cdot 10^{12}$cm^{-3})

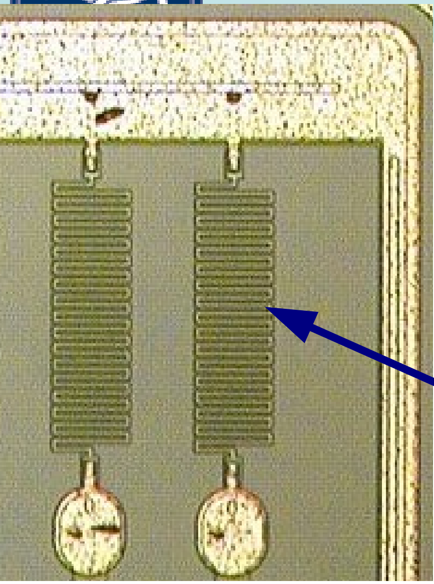
  results in a depletion voltage ~ 150 V

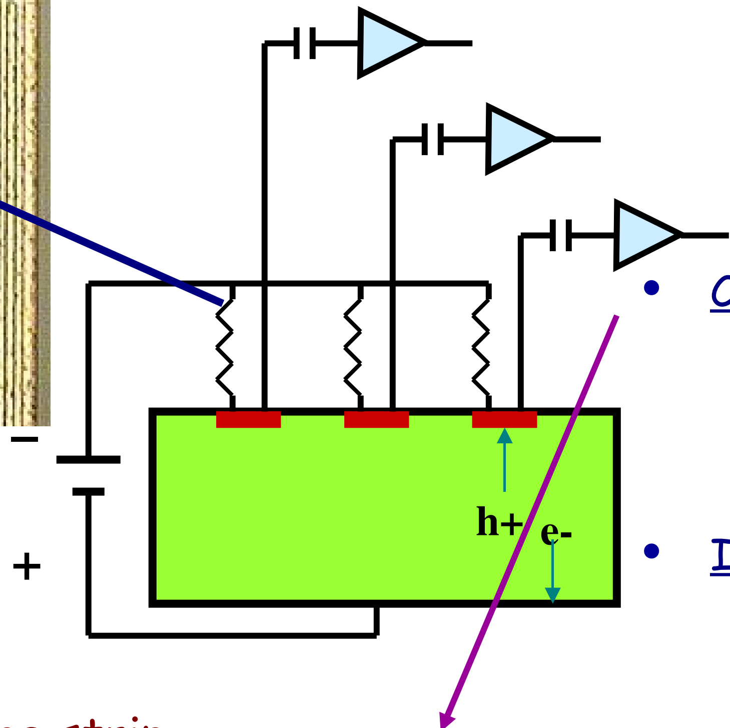
- Resolution σ depends on the pitch p (distance from strip to strip) $\sigma = \frac{p}{\sqrt{12}}$

- - e.g. detection of charge in binary way (threshold discrimination) and using center of strip as measured coordinate results in:

- typical pitch values are 20 μm– 150 μm $\Rightarrow$ 50 μm pitch results in 14.4 μm resolution

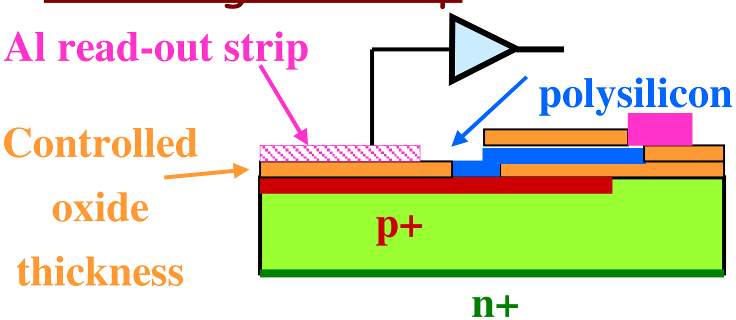
Operation





- Bias Resistor
  - Need to isolate strips from each other and collect/measure charge on each strip ⇒ high impedance bias connection (1MΩ resistor)
- Coupling capacitor
  - Usually want to AC couple input amplifier to avoid large DC input currents
- Integration on sensor
  - Bias resistors via doped polysilicon deposition
  - capacitors via metal readout lines over the implants but separated by an insulating dielectric layer (SiO_2, Si_3N_4 d=.1-0.2μm for C≥ 100pF).

Cut along the strip



Collected signal

- Collected Charge for a Minimum Ionizing Particle (MIP)

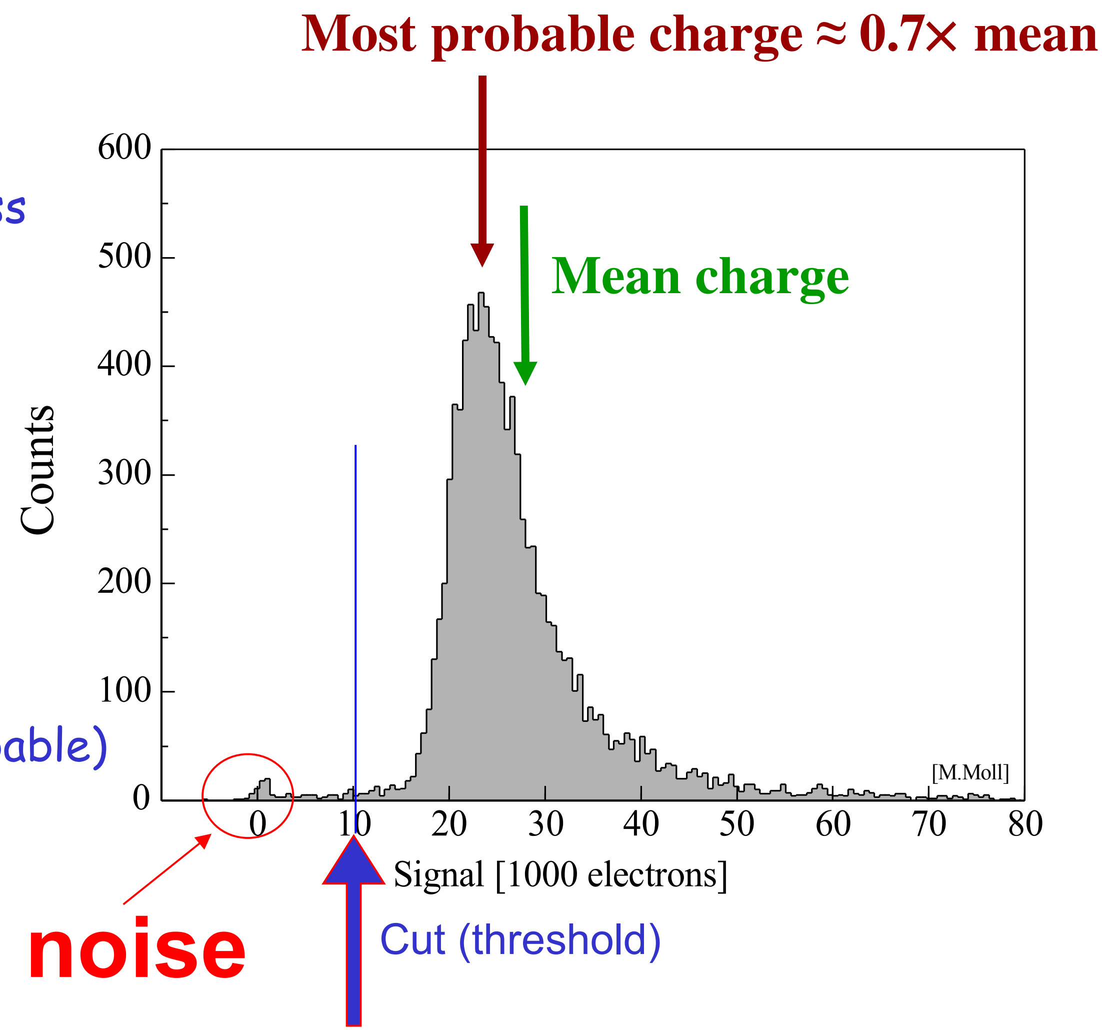
- Mean energy loss
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness

- Most probable energy loss
  ≈ 0.7 ×mean
  ⇒ 81 keV

- 3.6 eV to create an e-h pair
  ⇒ 72 e-h / μm (mean)
  ⇒ 108 e-h / μm (most probable)

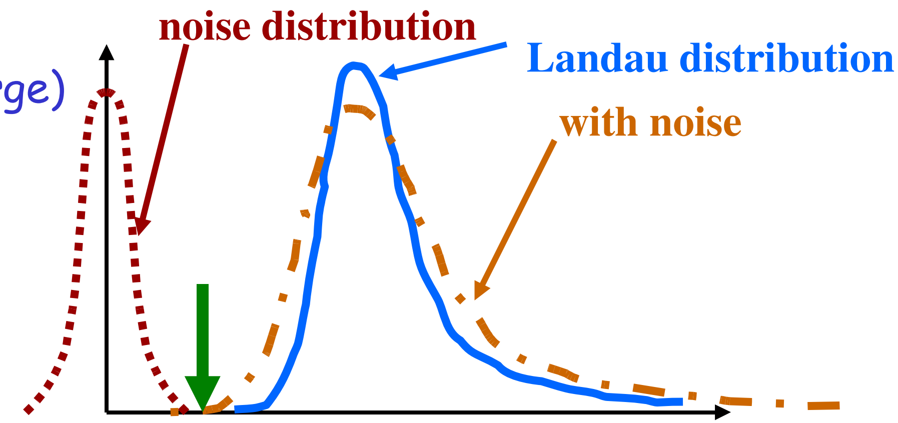
- Most probable charge (300 μm)

  ≈ 22500 e ≈ 3.6 fC

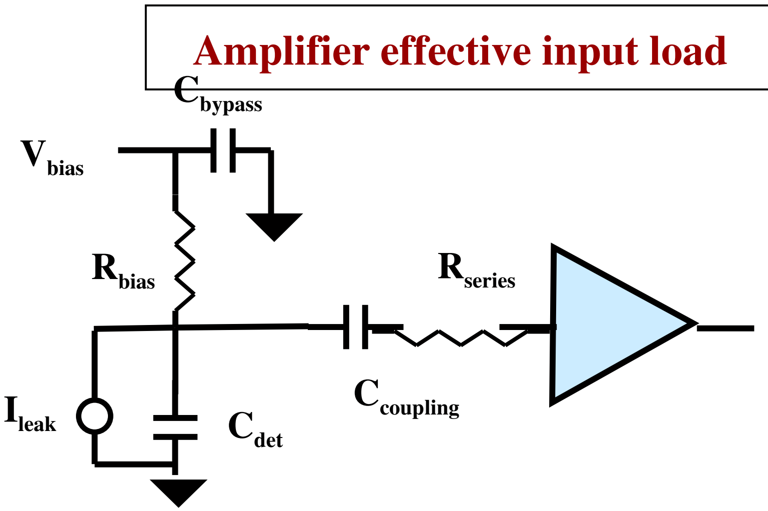


Signal to Noise ratio

- Landau distribution has a low energy tail
  - becomes even lower by noise broadening



- Noise sources: (ENC = Equivalent Noise Charge)
  - Capacitance $ENC \propto C_d$
  - Leakage Current $ENC \propto \sqrt{I}$
  - Thermal Noise (bias resistor) $ENC \propto \sqrt{k_B T / R}$



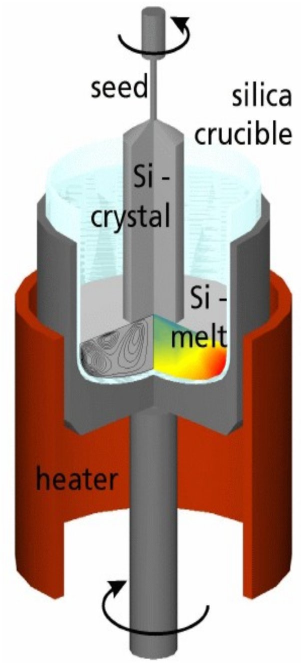
- Good hits selected by requiring N_{ADC} > noise tail
  If cut too high ⇒ efficiency loss
  If cut too low ⇒ noise occupancy

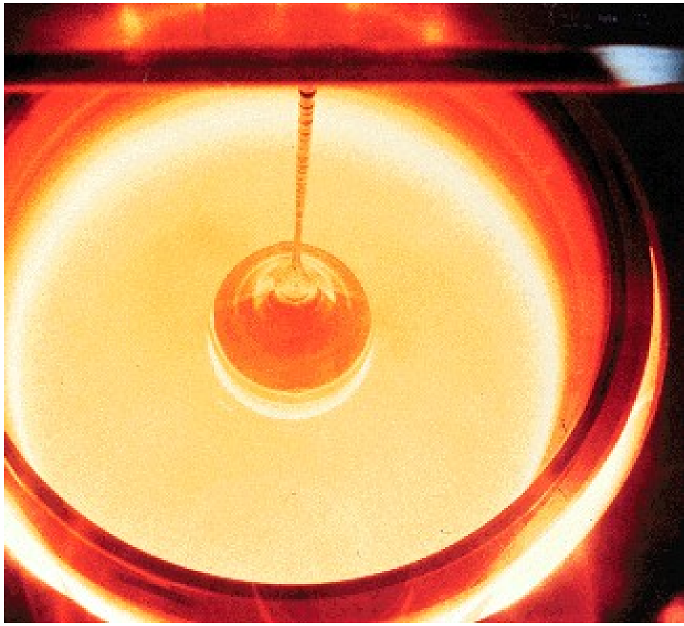
- Figure of Merit: Signal-to-Noise Ratio S/N

- Typical values >10-15, Radiation damage severely degrades the S/N.

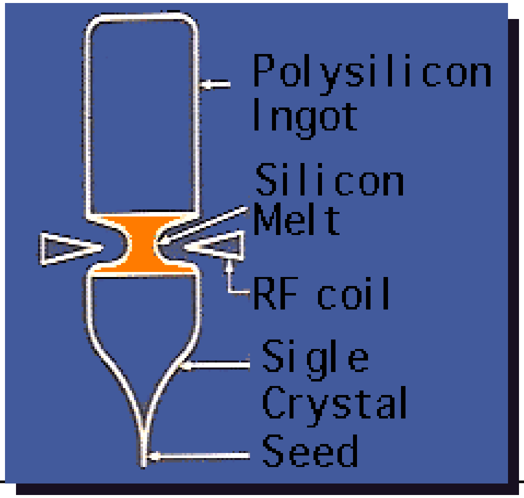
Mono-crystillaline Ingot fabrication

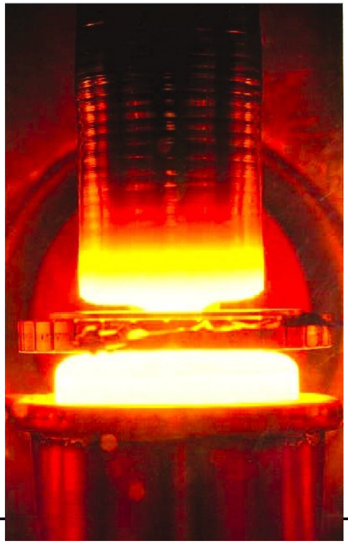
- Czochralski (or magnetic Cz)
- Silicon melt into quartz crucible
  - High Oxygen content into the crystal
- "pull crystal out" while rotating
- Magnetic field allows better crystal quality (homogeneity of melt)





- Float Zone : very pure crystal, from single-crystal seed
- The polycrystalline ingot is melted via rf power the impurities stay into the melt





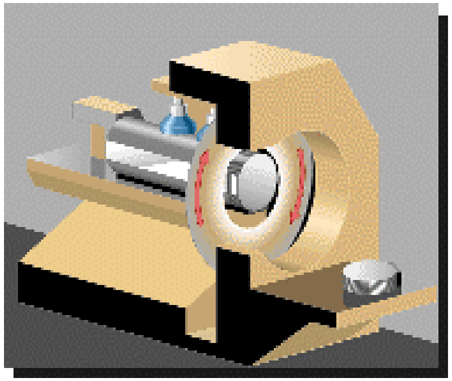
wafer fabrication

- Slicing, lapping, etching and polishing

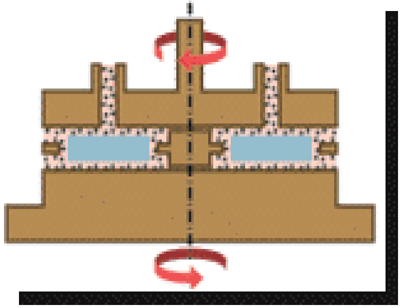
Ingot is sliced into wafers of thickness 300-500μm with diamond encrusted wire or disc saws.

Lapping (grinding away large imperfections), etching (more removal of impurities and imperfections), and polishing are needed to attain the desired wafer thickness and to ensure a surface with minimal defects.

diamond disc saw



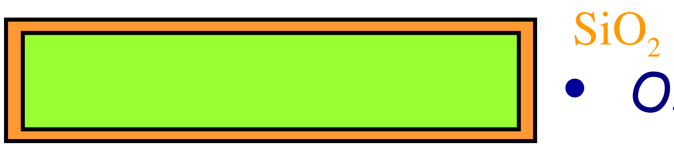
lapping machine



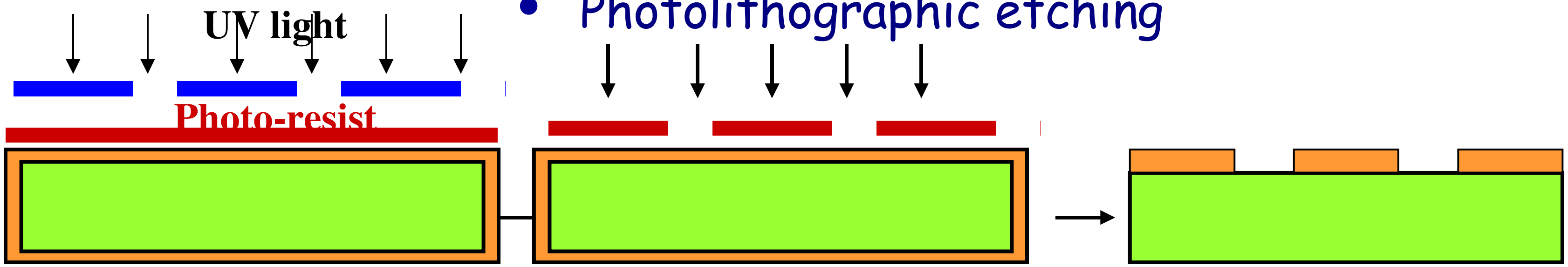
polishing machines

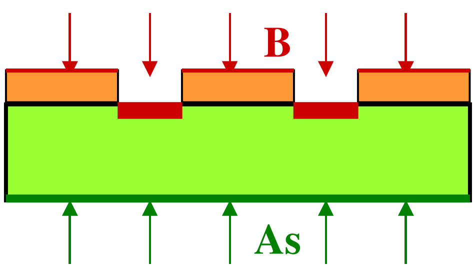
Sensor fabrication

- Start with n-doped Si Wafer ρ≈1-10k'Ωcm

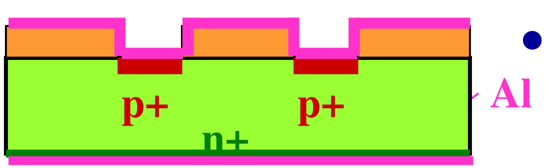


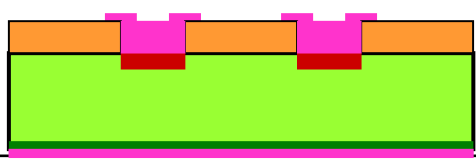
- Oxidation by baking @ 800-1200°C
- Photolithographic etching





- Doping by ion implantation or diffusion
- + Annealing 600°C (repair silicon lattice)
- Metallisation (Al)



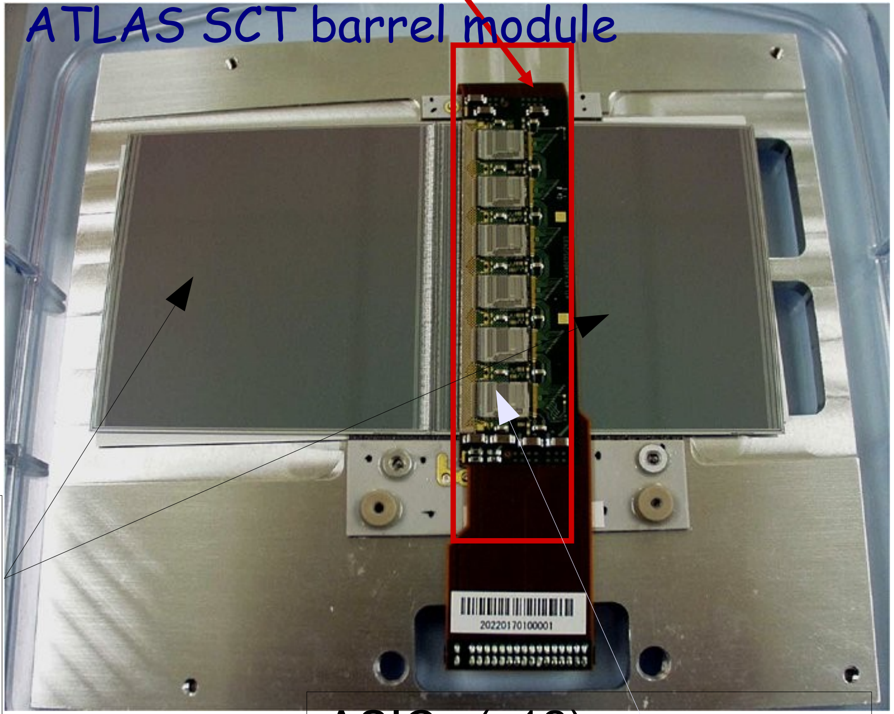


- Photolithographic contact for strips

Construction of detector modules

- Detector Modules - "Basic building block of tracking detectors"
  - Silicon Sensors
  - Mechanical support (cooling)
  - Front end electronics and signal routing (connectivity)
- ATLAS-SCT
  - 15552 sensors
  - 61m² silicon

ATLAS flexible kapton hybrid circuit. Note also that hybrid is mounted directly over one of the two chained silicon sensors. A thermal challenge!

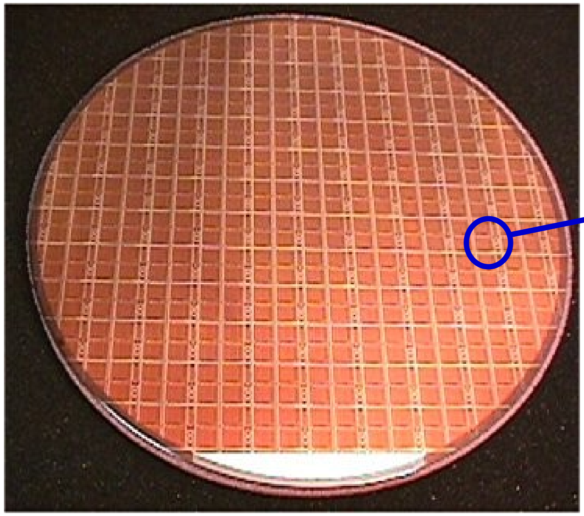


Silicon sensors (x4)
- 64 x 64 mm2
- p-in-n, single sided
- AC-coupled
- 768 strips
- 80μm pitch/12μm width

ASICs (x12)
-ABCD chip binary R/O
-DMILL technology
-128 channels

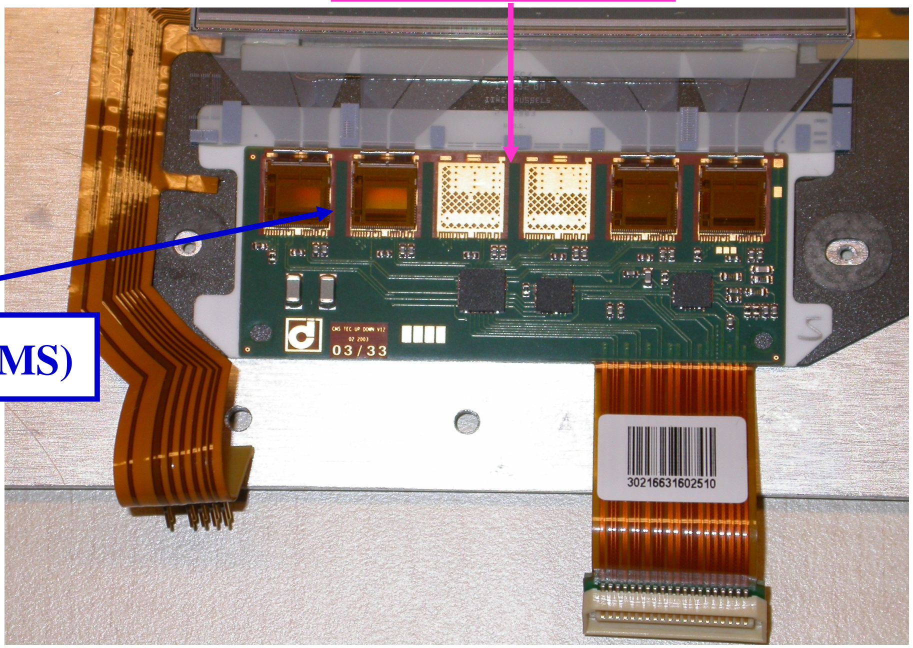
- Hybrids…
  - Front-end read-out electronics are usually in the form of ASIC (application specific integrated circuits) chips mounted on a hybrid circuit that provides power lines, control signals and read-out connectivity. This hybrid circuit has often been made on a ceramic substrate with thick-film gold deposition techniques.

400 front-end ASICs on 8" wafer (IBM)



APV25 (CMS)

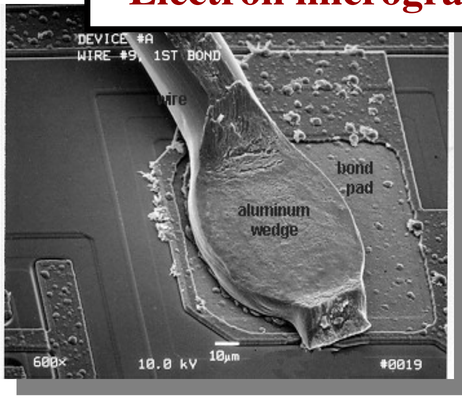
Ceramic hybrid

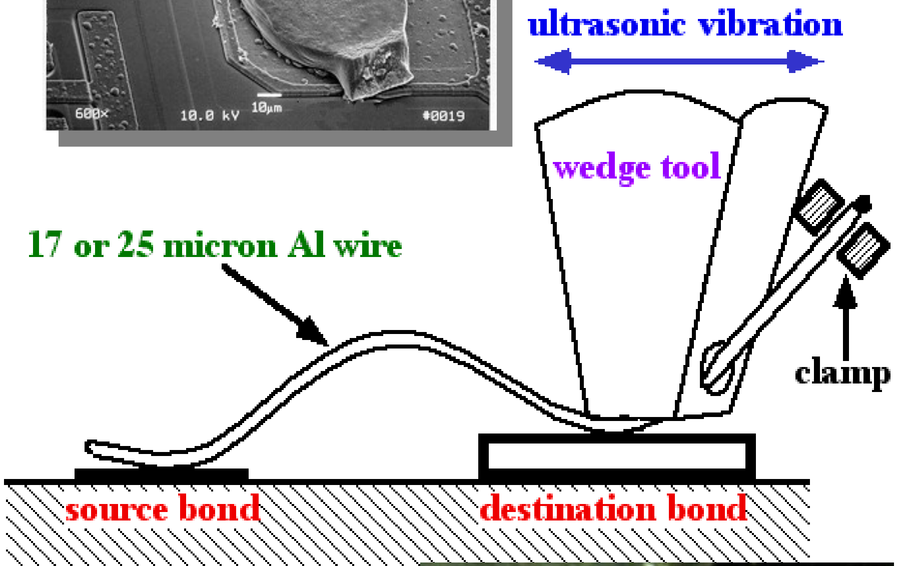


Bonding

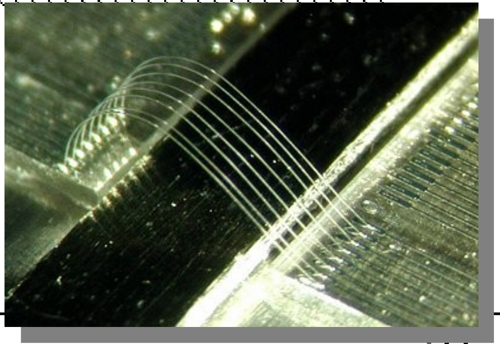
- Wire bonding
  - Uses ultrasonic power to vibrate needle-like tool on top of wire. Friction welds wire to metallized substrate underneath.
  - Can easily handle 80µm pitch in a single row and 40µm in two staggered rows (typical FE chip input pitch is 44µm).
  - 25µm diameter aluminium wire and bond to aluminium pads (chips) or gold pads (hybrid substrates).

Electron micrograph of bond "foot"

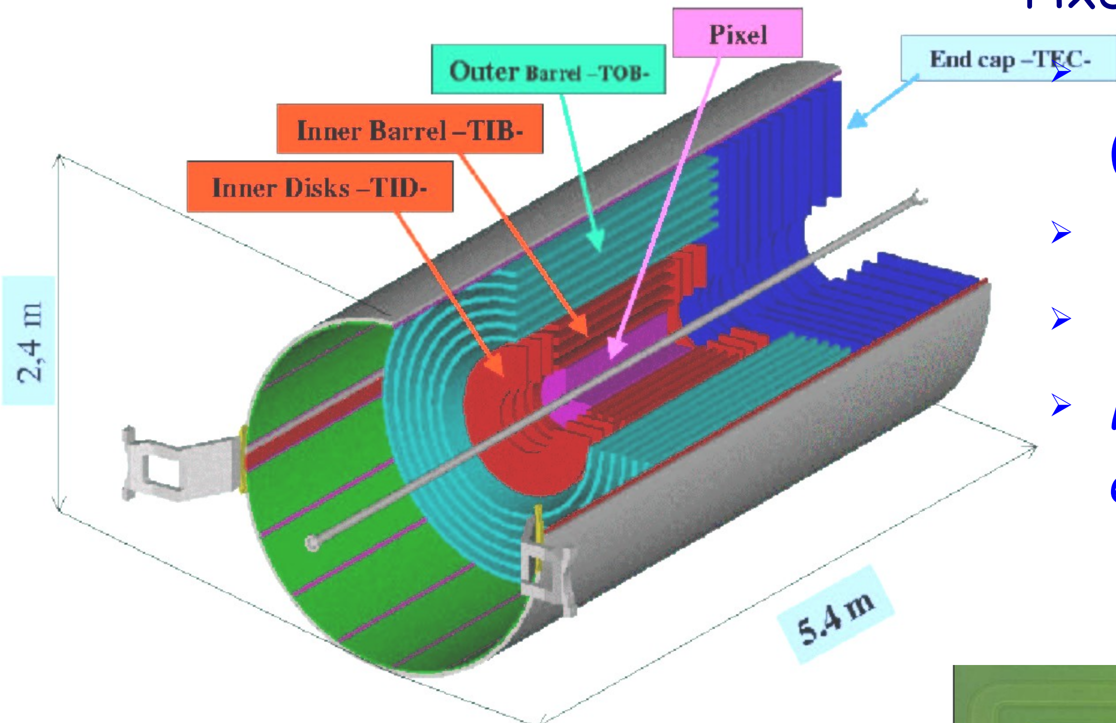




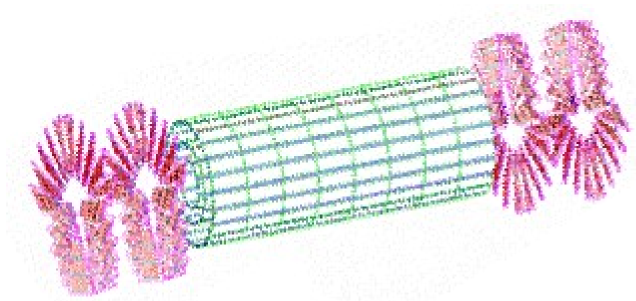
View through microscope of wire bonds connecting sensor to fan-out circuit

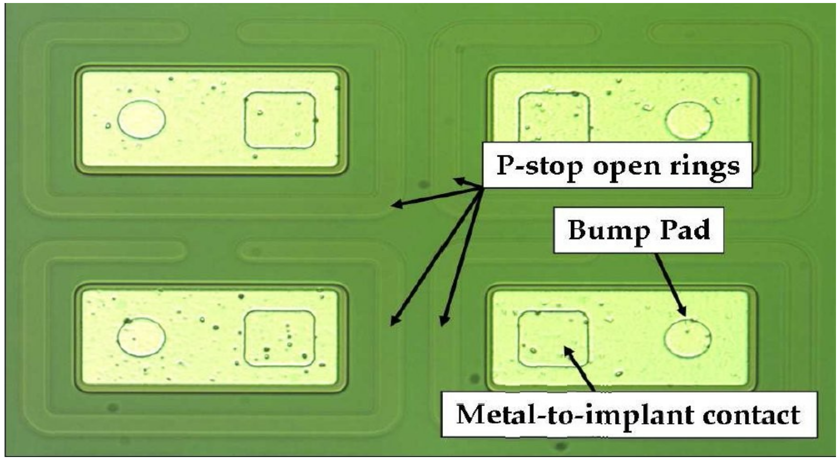


CMS pixel

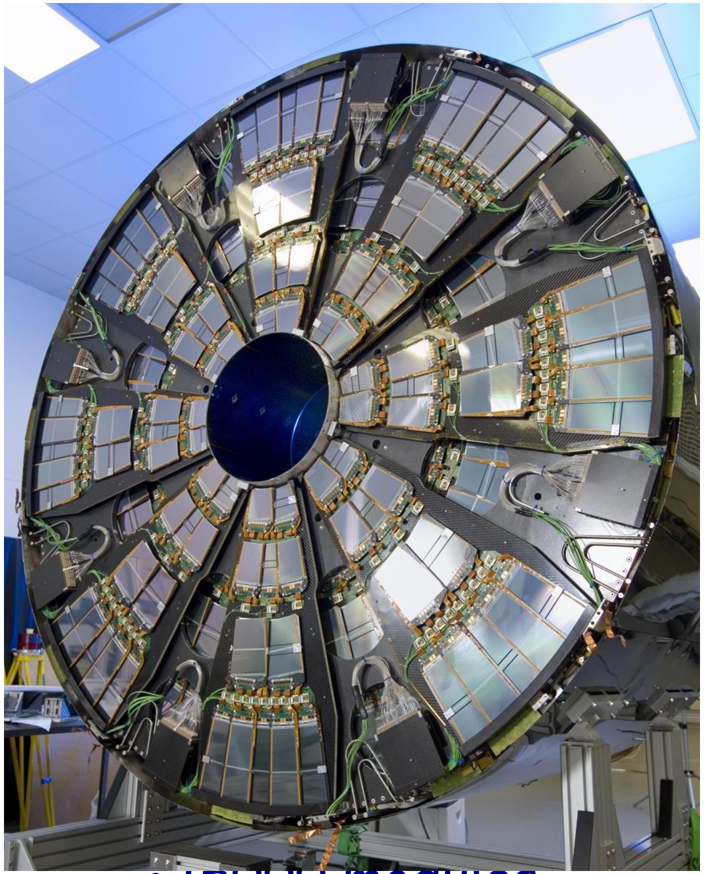


- Pixel: n+ on n , electron collection
  - Inner 3 layers: silicon pixels (~ 1m^2)
  - 66 million pixels (100x150µm)
  - Precision: σ(rφ) ~ σ(z) ~ 15µm
  - Most challenging operating environments (LHC)





CMS Silicon Strip Tracker

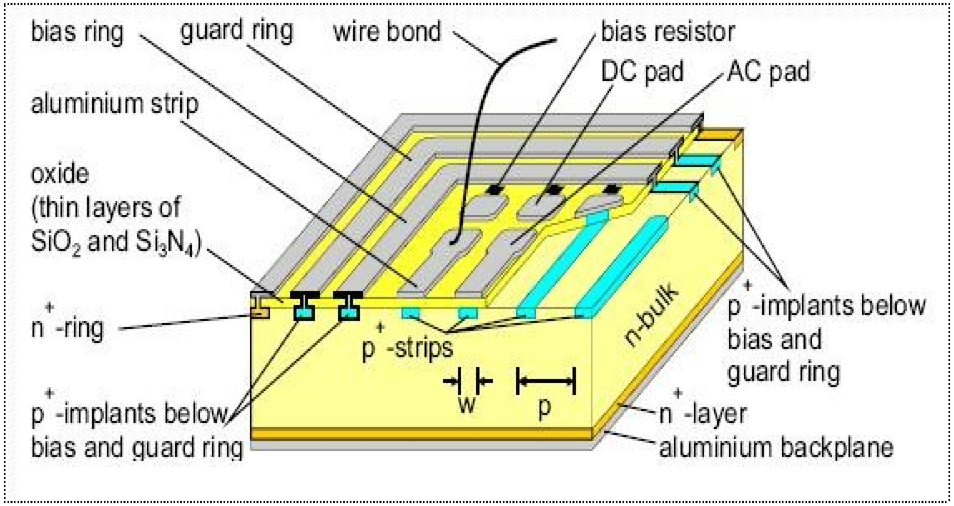


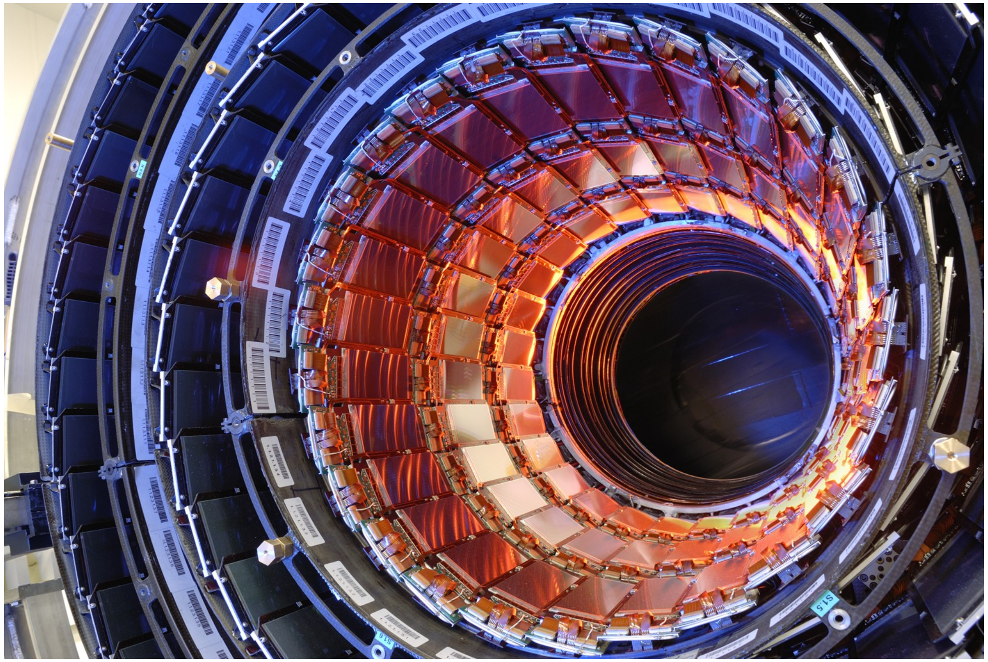
~15000 modules

~9600000 strips

dp/p=1.5% @ 100GeV/c

p in n





A CMS module

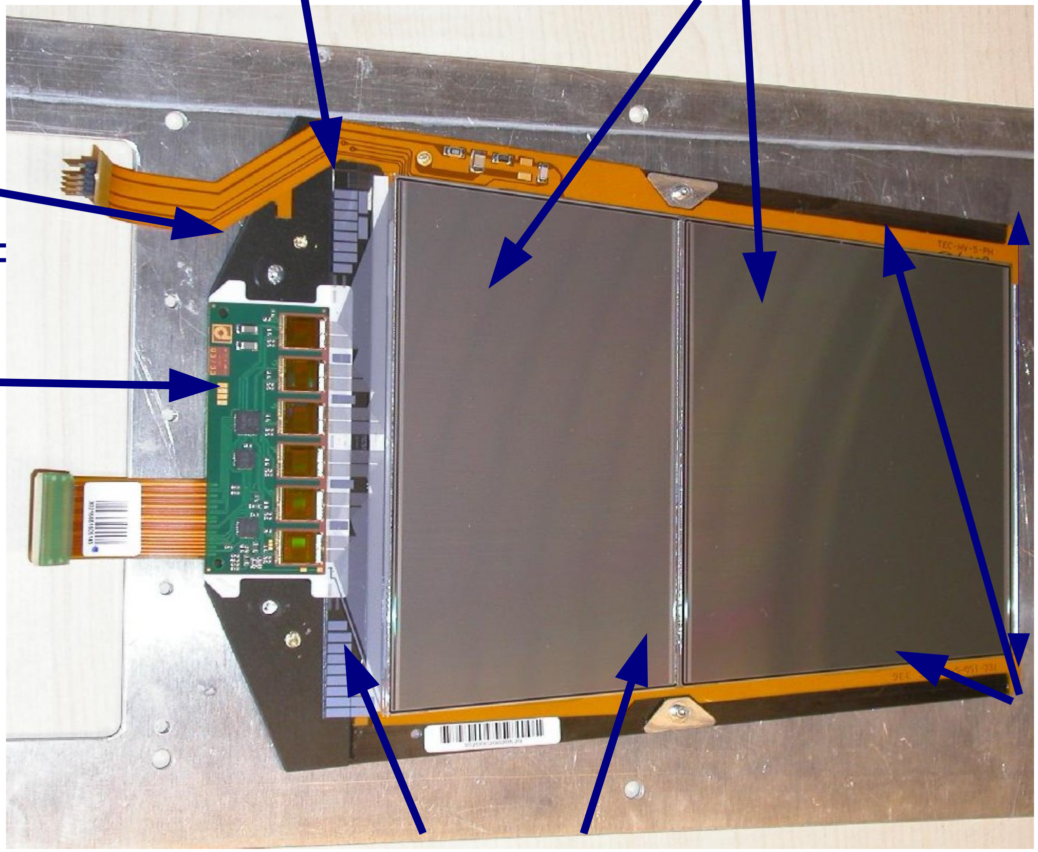
A TEC ring 5 module:

1 or 2 silicon sensors
- p-type strips on n-type bulk
- pitch 80-205μm, width/pitch = 0.25

pitch adapter

support frame
- graphite and carbon fibre (CF

front-end (FE) hybrid



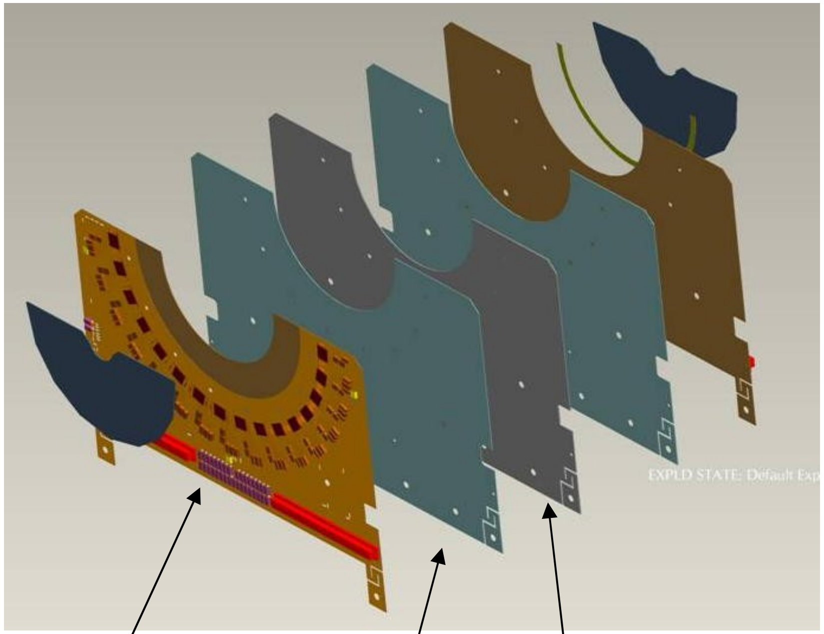
$\approx$**10cm**

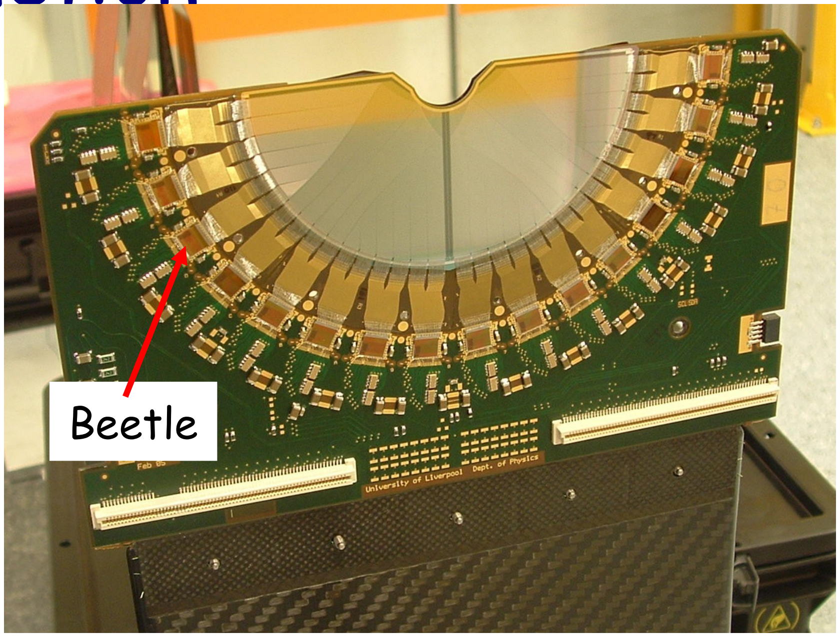
Kapton circuit
- bias voltage
- back plane isolatior
- temperature sensor

micro bonds

15 module types: 512 or 768 strips, 1 or 2 sensors, wedge-shaped sensors, geometry, coating.....

LHCb-VELO - Module construction



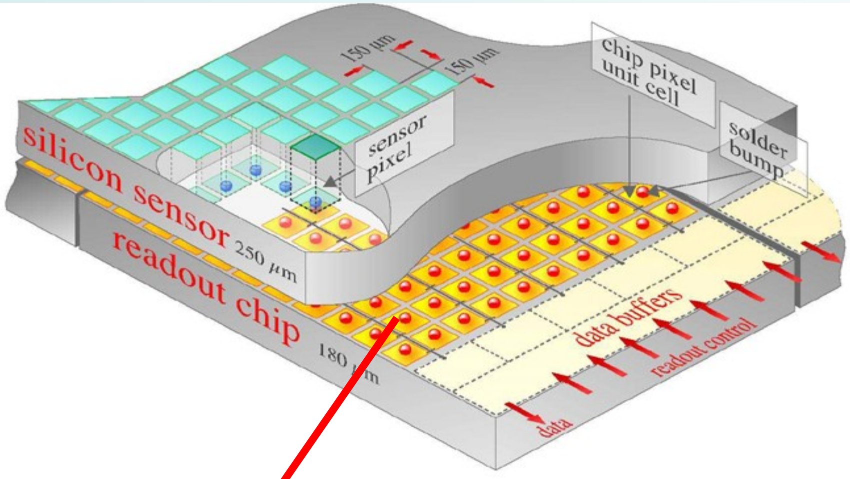


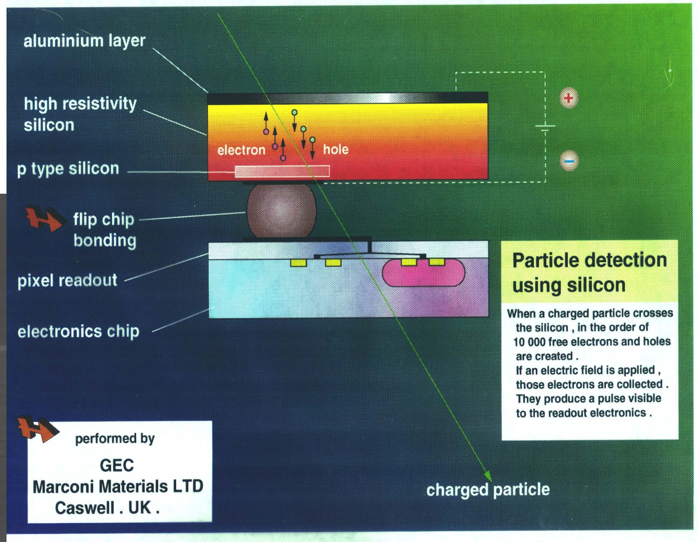
- 4 layer kapton circuit
- Heat transport with TPG
- Readout with 16 Beetle chips
  - 128 channels, 25 ns shaping time, analog pipeline
  - 0.25 μm CMOS
  - no performance loss up to 40 Mrad
  - Yield > 80 %

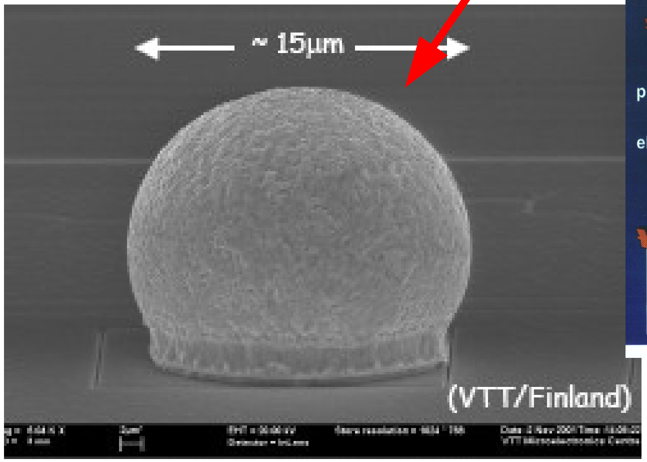
[Martin van Beuzekom, STD6, September 2006]

Hybrid pixel detectors

- HAPS – Hybrid Active Pixel Sensors
  - segment silicon to diode matrix with high granularity (⇒ true 2D, no reconstruction ambiguity)
- readout electronic with same geometry (every cell connected to its own processing electronics)
- connection by "bump bonding" requires sophisticated readout architecture
- Hybrid pixel detectors will be used in the 4 LHC experiments: ATLAS, ALICE, CMS and LHCb



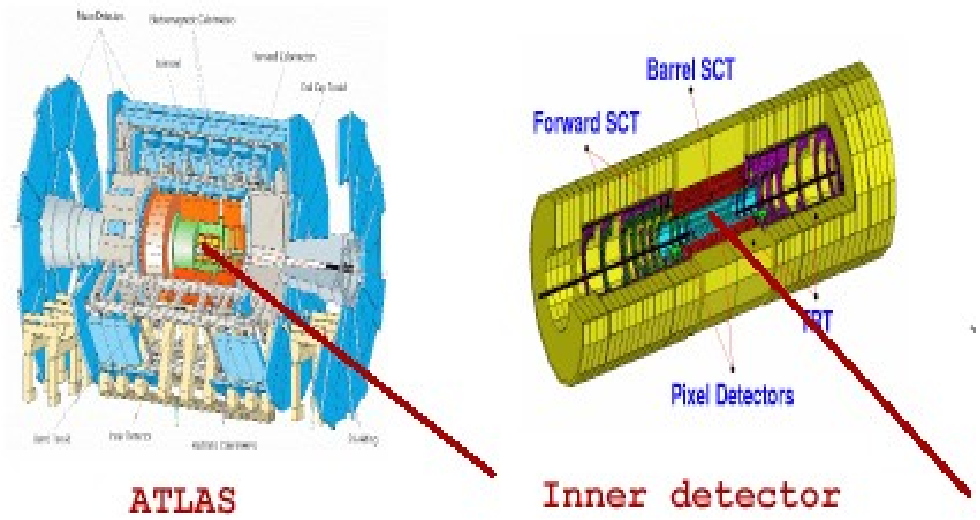


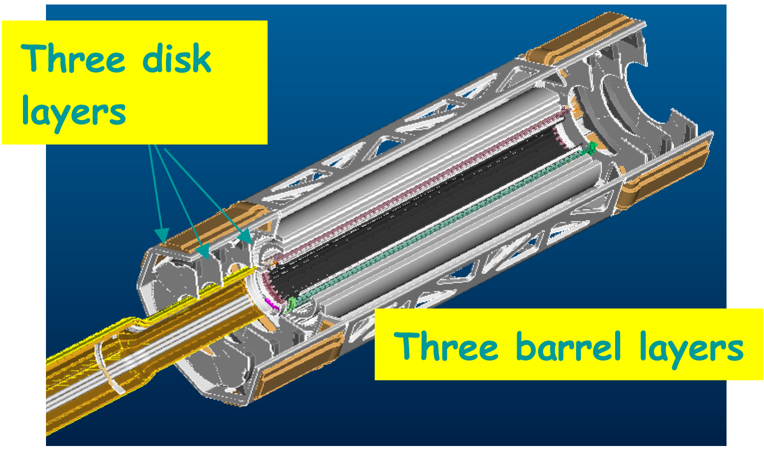


ATLAS Pixel

- An example of a HAPS: ATLAS

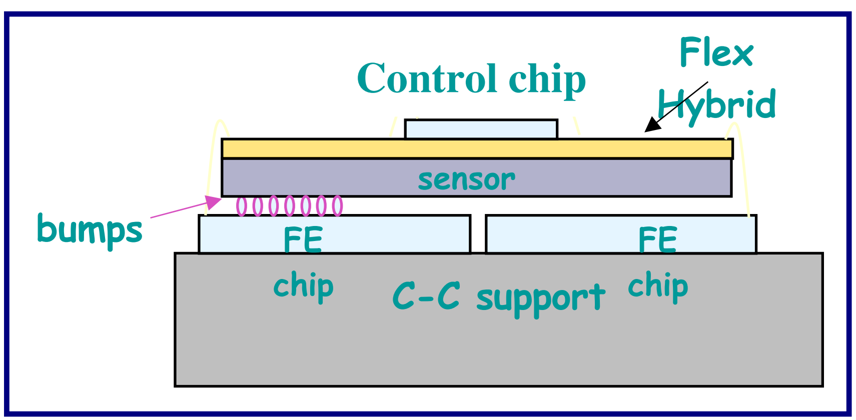
s=8->10μm

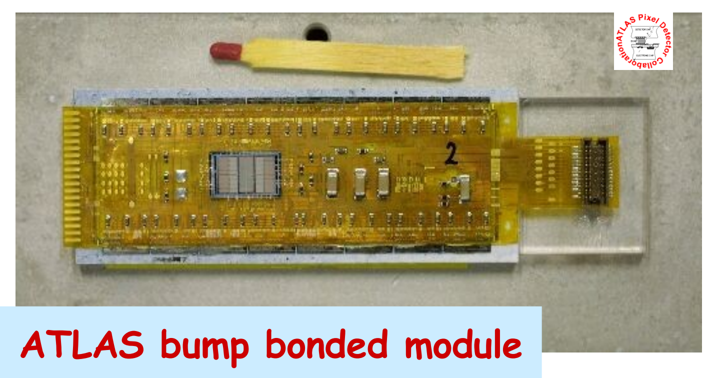




The ATLAS Pixel Vertex

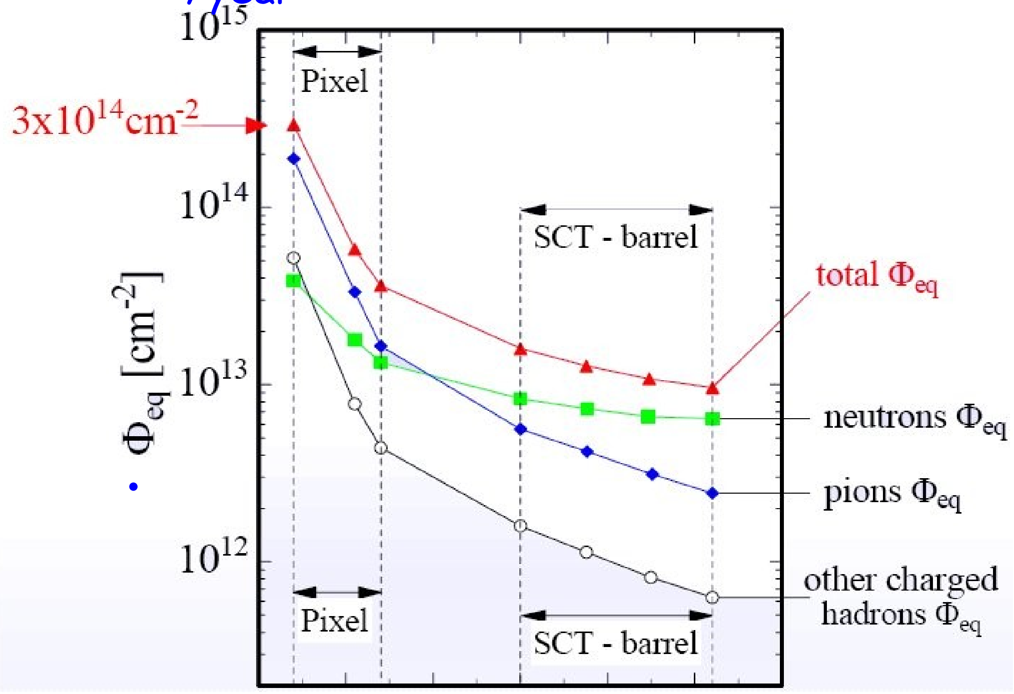
$2m^2 \cdot 8\ 10^7$ pixels





Radiation Damage

- Example: ATLAS
  - Fluences per year at full Luminosity
  - Pixel detector: up to $\Phi_e q \approx 3.5.10^{14}$ cm^{-2} /year



  - Dominating type of particle is different for pixel (pions) and strip detectors (neutrons)

- LHC silicon detectors:
  - All detectors have been extensively tested and developed for radiation tolerance and are expected to survive the LHC radiation environment.
- Some experiments have already foreseen upgrades (e.g. LHCb Velo after 3 years).
- Super LHC

- upgrade of LHC to 10 x higher Luminosity

⇒ 10 x higher radiation levels

⇒ Radiation damage will become a critical issue!

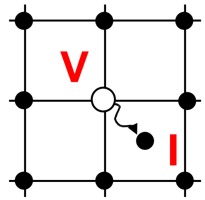
⇒ New, radiation tolerant detectors needed!

- What is radiation damage ?
- How to cope with it ?

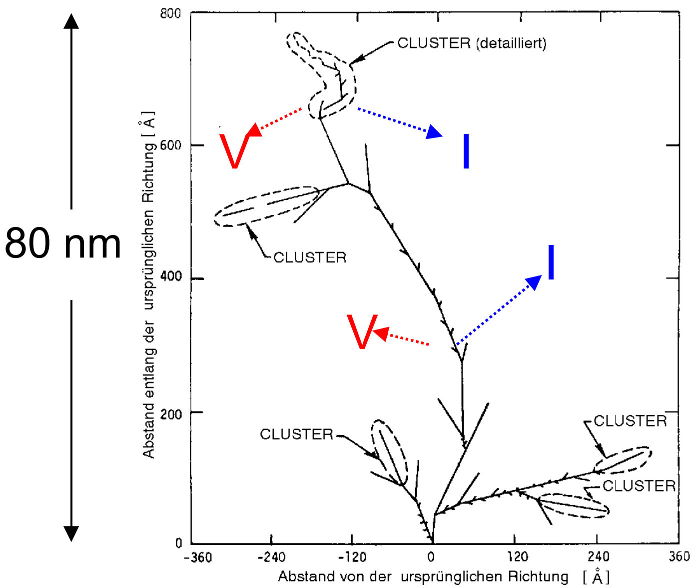
Microscopic defects

- **Damage to the silicon crystal:** Displacement of lattice atoms

- particle → Si_S — E_K>25 eV → **V**acancy + **I**nterstitial ⟺ "point defects", mobile in silicon, can react with impurities (O,C,..)



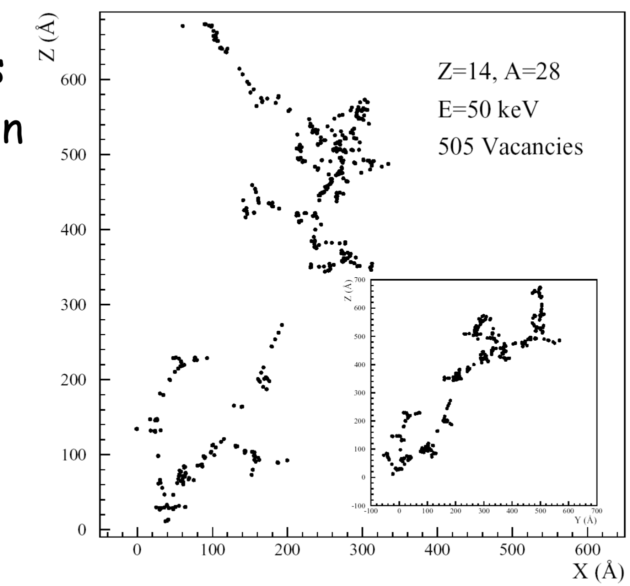
E_K > 5 keV → **point defects and clusters of defects**



Distribution of vacancies created by a 50 keV Si-ion in silicon (typical recoil energy for 1 MeV neutrons):

Schematic [Van Lint 1980]

Simulation [M.Huhtinen 2001]



- **Defects can be electrically active (levels in the band gap)**
  - capture and release electrons and holes from conduction and valence band

  ⇒ can be charged - can be generation/recombination centers - can be trapping centers

Radiation damage consequences

- Two general types of radiation damage:
  - Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)

    I. Change of depletion voltage (higher operation voltage, underdepletion)

    ⇒ constant cooling needed to avoid reverse annealing

    II. Increase of leakage current (increase of shot noise, thermal runaway) ⇒ needs cooling of sensors during operation

    III. Decrease of charge collection efficiencydue to underdepletion and increased trapping
  - Surface damage due to Ionizing Energy Loss (IEL)

    accumulation of positive in the oxide (SiO_2) and the Si/SiO_2 interface

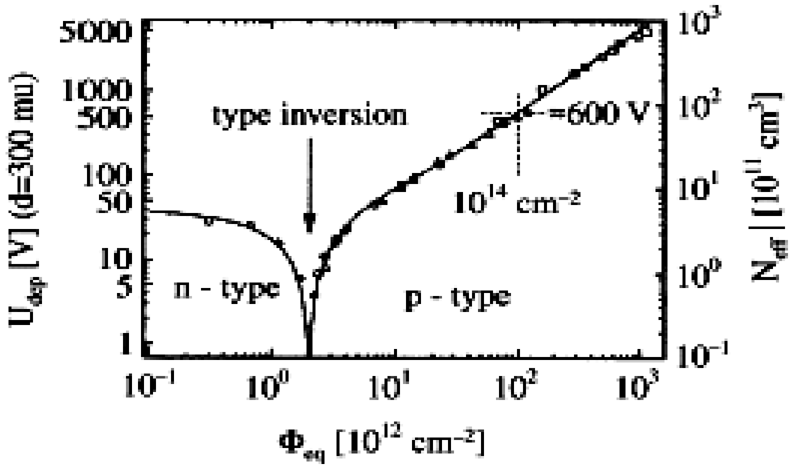
    affects: interstrip capacitance (noise factor), breakdown behaviour

    and other structures depending on near-surface effects
- Signal/noise ratio is the quantity to watch

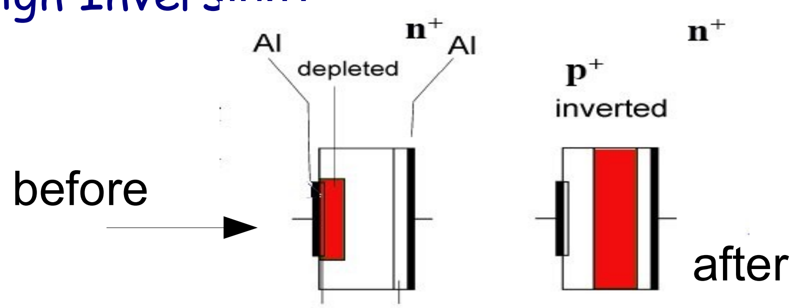
⇒ Sensors can fail from radiation damage !

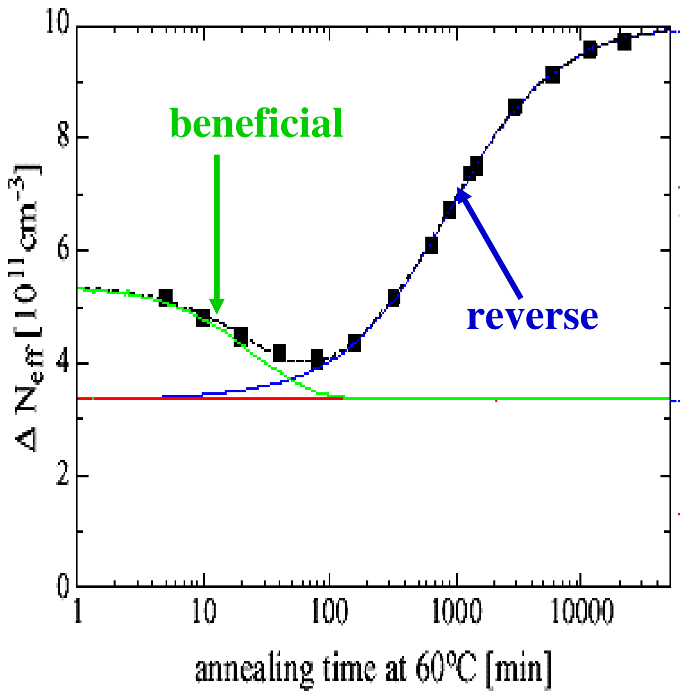
Depletion Voltage

- Change of Depletion Voltage Vdep (Neff)…. with particle fluence:



- "Type inversion": N_{eff} changes from positive to negative (Space Charge Sign Inversion)





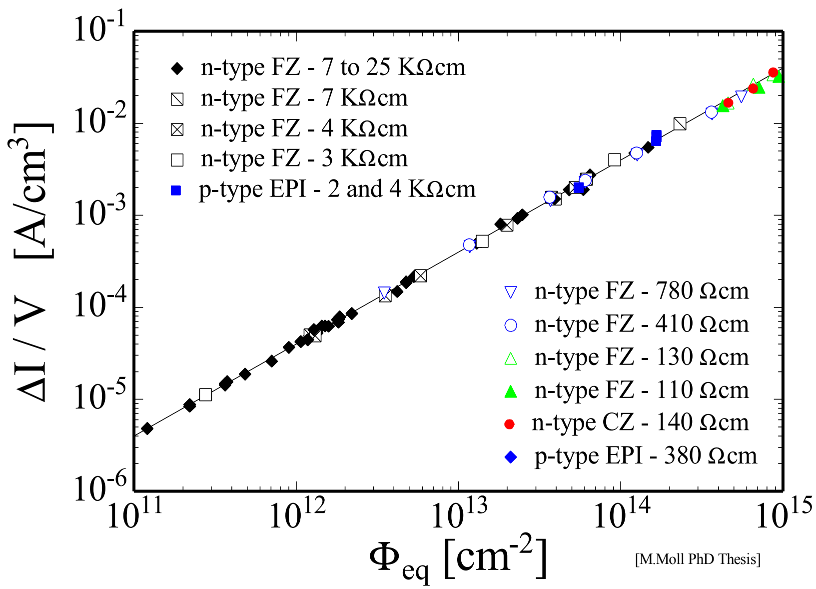
- Time constant depends on T
- Detectors must be kept cold even when the experiments are not running

Effect on I_{leak} and CCE

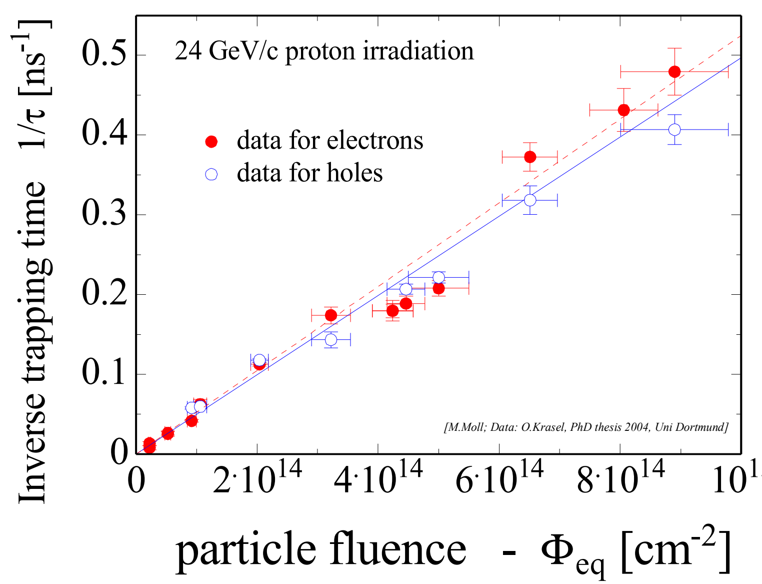
- **Effects on leakage current**
  - Leakage current as function of fluence:

    $\Delta I_{leak} = \alpha\Phi$, α is known as the damage constant
  - For I_{leak} there is only beneficial and no reverse annealing effect.
  - Thermal runaway risk

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$



- **Effects on charge collection**
  - The increased number of trapping states in the depletion region leads to a decrease of CCE (signal). The magnitude of the effect is about a 10% loss of signal for $\Phi = 2\times10^{14}$ n/cm².



Approaches to develop radiation harder tracking detectors

Scientific strategies:

- Material engineering
- Device engineering
- Change of detector operational conditions

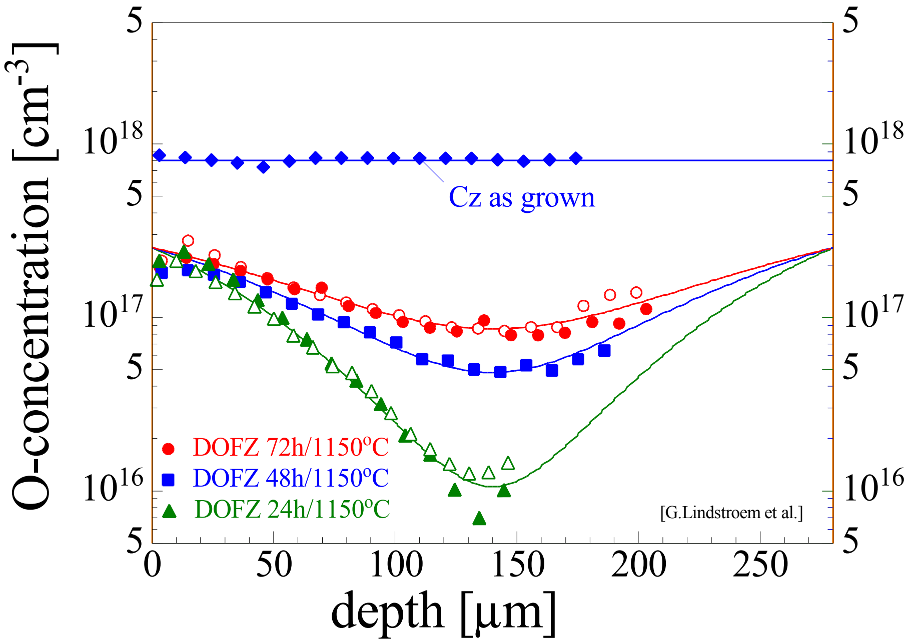
- Defect Engineering of Silicon
  - Understanding radiation damage
    - Macroscopic effects and Microscopic defects
    - Simulation of defect properties & kinetics
    - Irradiation with different particles & energies
  - Oxygen rich Silicon
    - DOFZ, Cz, MCZ, EPI
  - Oxygen dimer & hydrogen enriched Si
  - Pre-irradiated Si
  - Influence of processing technology
- New Materials
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond: CERN RD42 Collaboration
  - Amorphous silicon

- Device Engineering (New Detector Designs)
  - p-type silicon detectors (n-in-p)
  - thin detectors
  - 3D and Semi 3D detectors
  - Stripixels
  - Cost effective detectors
  - Simulation of highly irradiated detectors
  - Monolithic devices

Oxygen concentration in FZ, CZ and EPI

Cz and DOFZ silicon

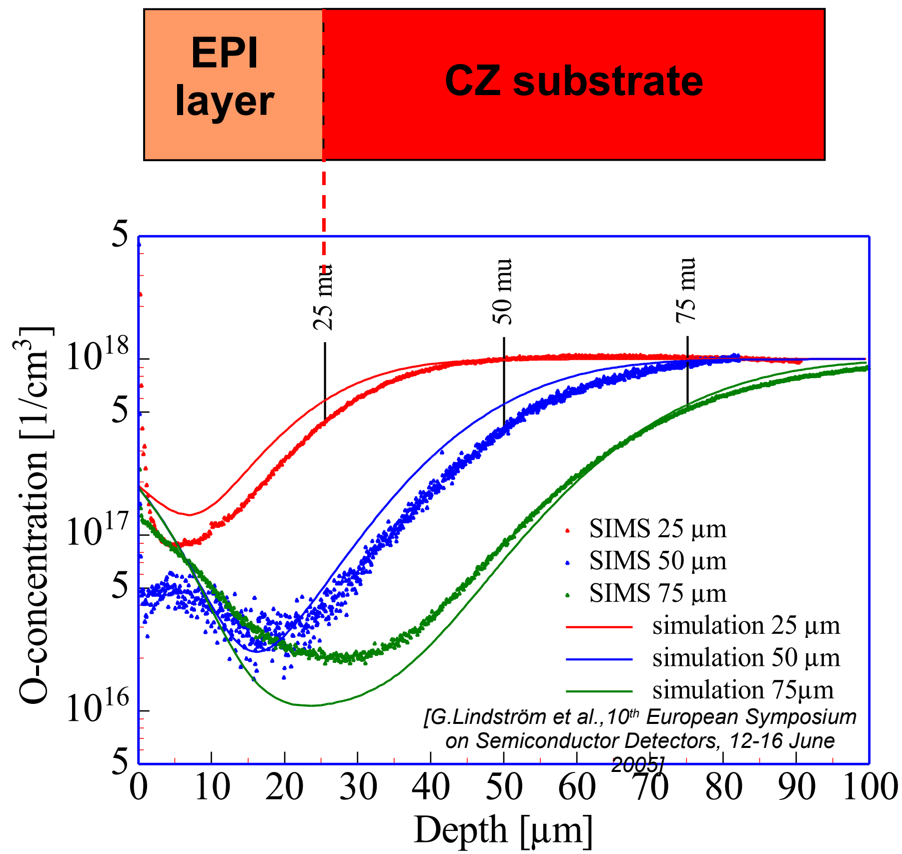
- CZ: high O_i (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)
- CZ: formation of Thermal Donors possible !



- DOFZ: inhomogeneous oxygen distribution
- DOFZ: oxygen content increasing with time at high temperature

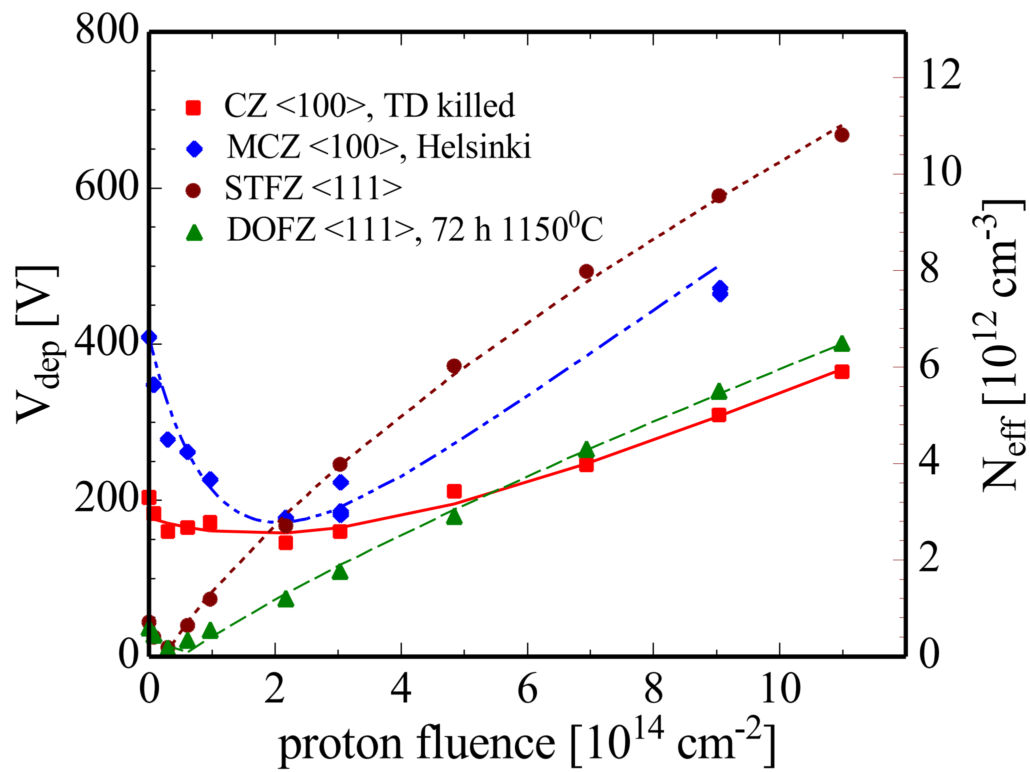
DOFZ Used by CMS & ATLAS for pixels

Epitaxial silicon



- EPI: O_i and O_{2i} (?) diffusion from substrate into epi-layer during production
- EPI: in-homogeneous oxygen distribution

Standard FZ, DOFZ, Cz and MCz Silicon



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

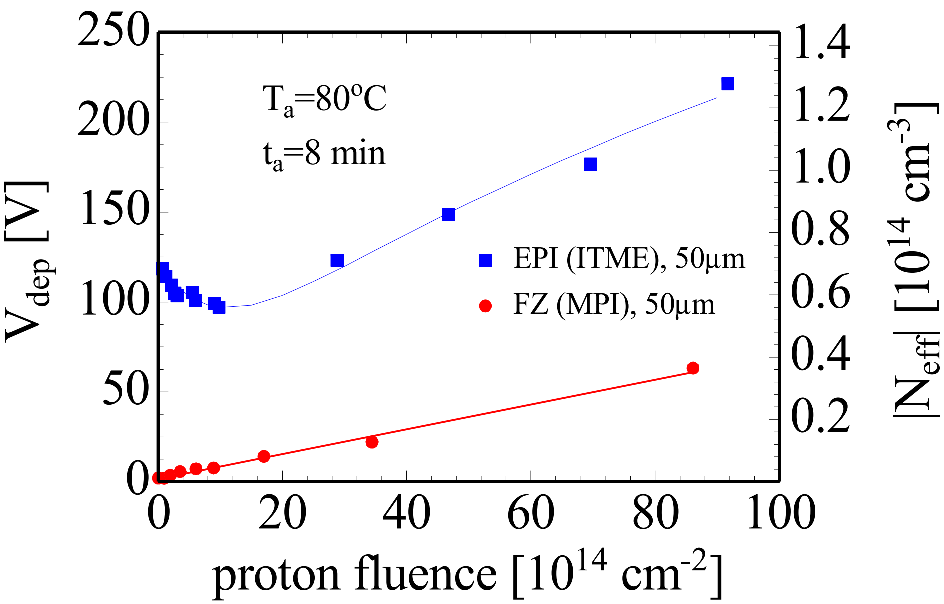
no type inversion in the overall fluence range (verified by TCT measurements)
(verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
⇒ donor generation overcompensates acceptor generation in high fluence range

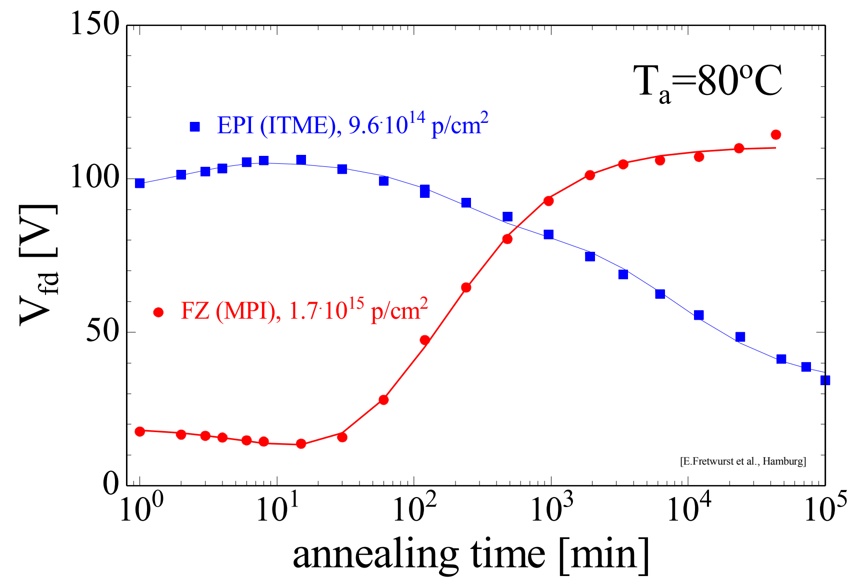
Common to all materials (after hadron irradiation):

- reverse current increase
- increase of trapping (electrons and holes) within ~ 20%

Epitaxial silicon - Annealing

- 50 μm thick silicon detectors:
  - Epitaxial silicon (50Ωcm on CZ substrate, ITME & CiS)
  - Thin FZ silicon (4KΩcm, MPI Munich, wafer bonding technique)





[E.Fretwurst et al.,RESMDD - October 2004]

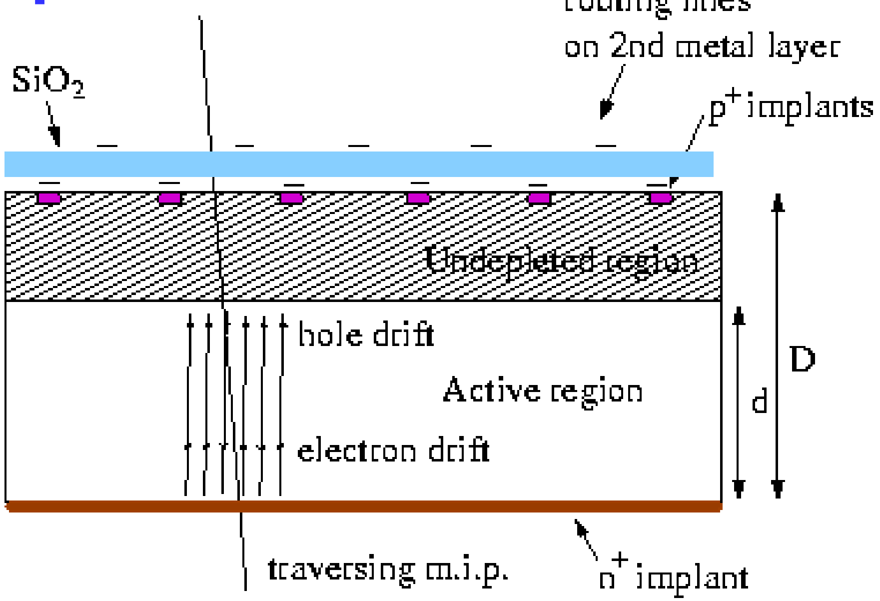
- Thin FZ silicon: Type inverted, increase of depletion voltage with time
- Epitaxial silicon: No type inversion, decrease of depletion voltage with time ⇒ No need for low temperature during maintenance of SLHC detectors!

Device engineering

p-in-n versus n-in-n detectors

n-type silicon after type inversion:

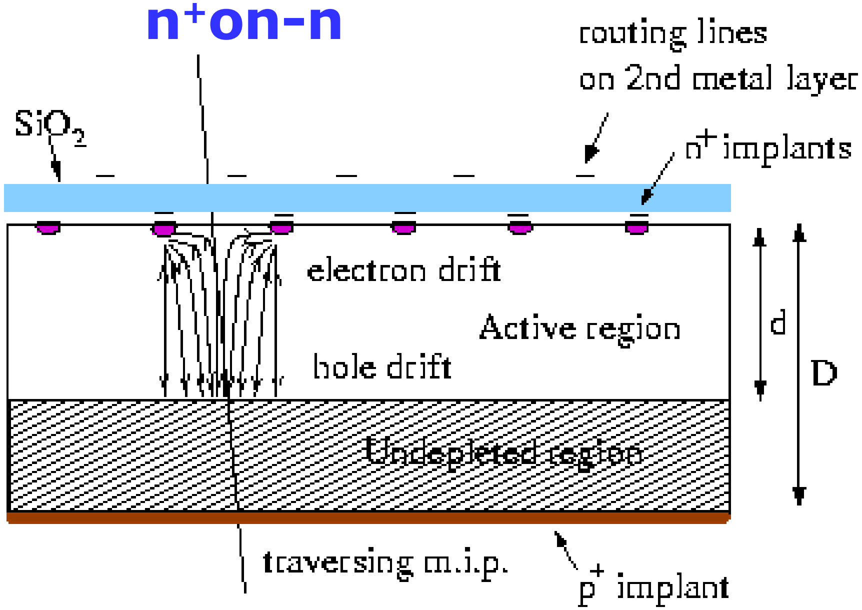
p^+on-n



p-on-n silicon, under-depleted:

- Charge spread – degraded resolution
- Charge loss – reduced CCE
- Atlas and CMS strips

n^+on-n



n-on-n silicon, under-depleted:

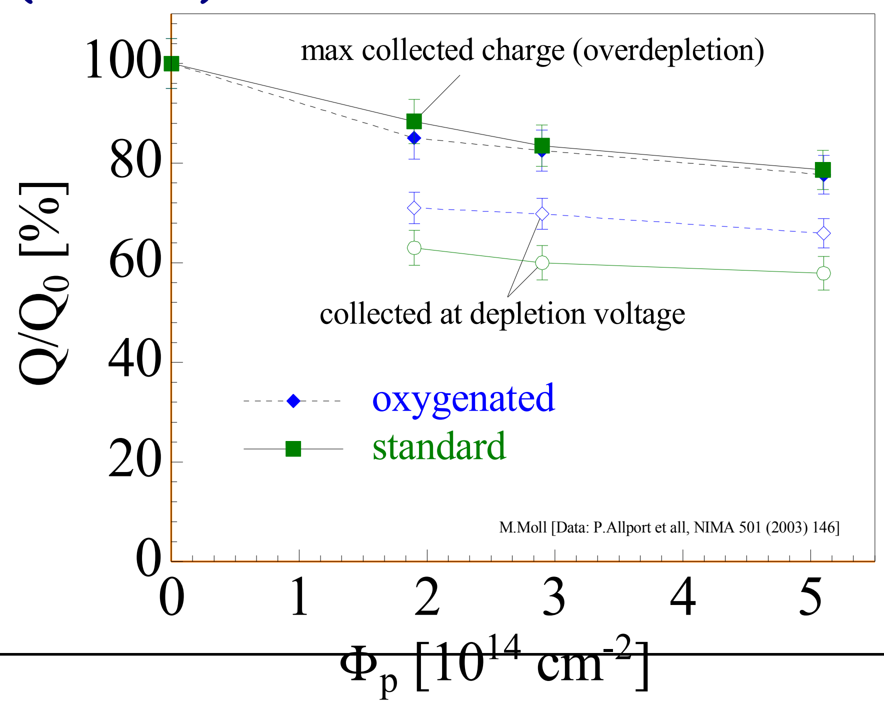
- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (fast)
- ATLAS and CMS pixels

Impact on Detector: Decrease of CCE
- Loss of signal and increase of noise -

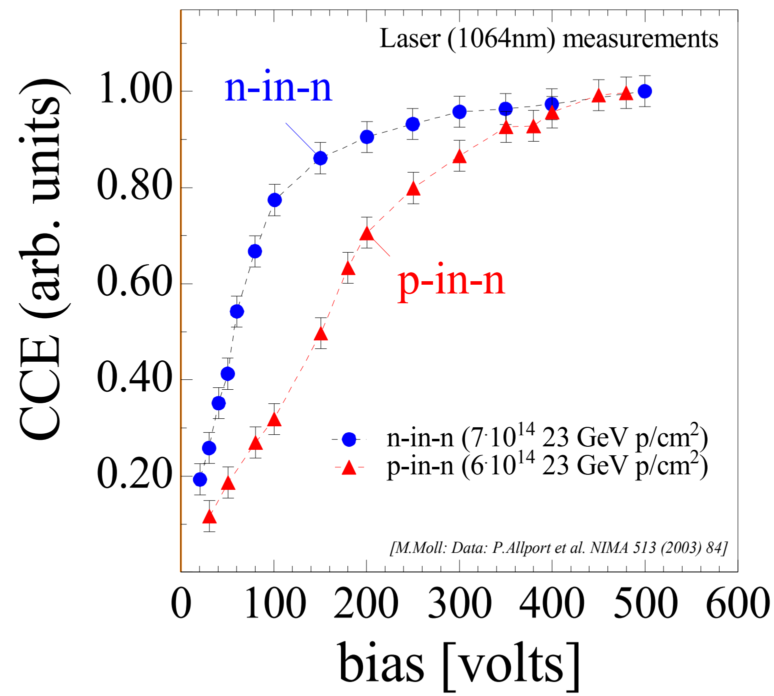
- Two basic mechanisms reduce collectable charge:
  - trapping of electrons and holes (depending on drift and shaping time !)
  - under-depletion (depending on detector design and geometry !)

- Example: ATLAS microstrip detectors + fast electronics (25ns)

- p-in-n : oxygenated versus standard FZ
  - beta source
  - 20% charge loss after $5x10^{14}$ p/cm^2 (23 GeV)



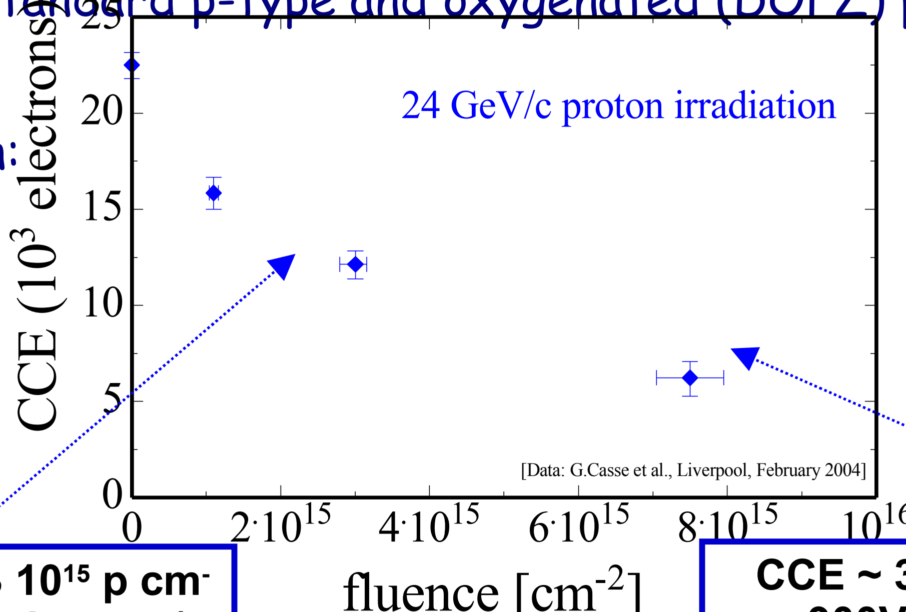
- n-in-n versus p-in-n
  - same material, ~ same fluence
  - over-depletion needed



n-in-p microstrip detectors

n-in-p: - no type inversion, high electric field stays on structured side
- collection of electrons

- Miniature n-in-p microstrip detectors (280μm)
- Detectors read-out with LHC speed (40MHz) chip (SCT128A)
- Material: standard p-type and oxygenated (DOFZ) p-type
- Irradiation:



G. Casse et al., NIMA535(2004) 362

At the highest fluence Q~6500e at V_{bias}=900V

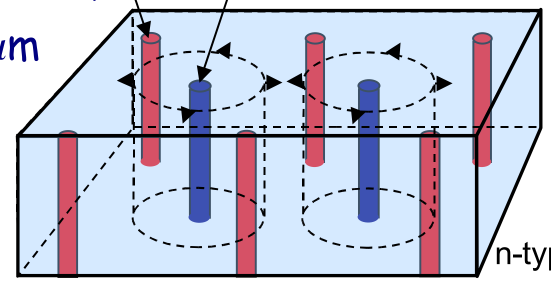
CCE ~ 60% after 3 10^{15} p cm^{-2} at 900V(standard p-type)

CCE ~ 30% after 7.5 10^{15} p cm^{-2} 900V (oxygenated p-type)

3D detector - concepts

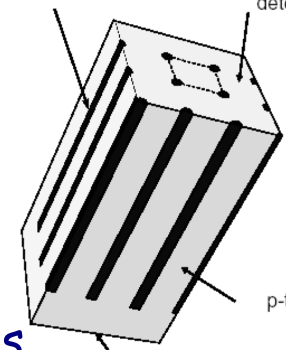
Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

- "3D" electrodes: - narrow columns along detector thickness,
  - diameter: 10μm, distance: 50 - 100μm
- Lateral depletion: - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard



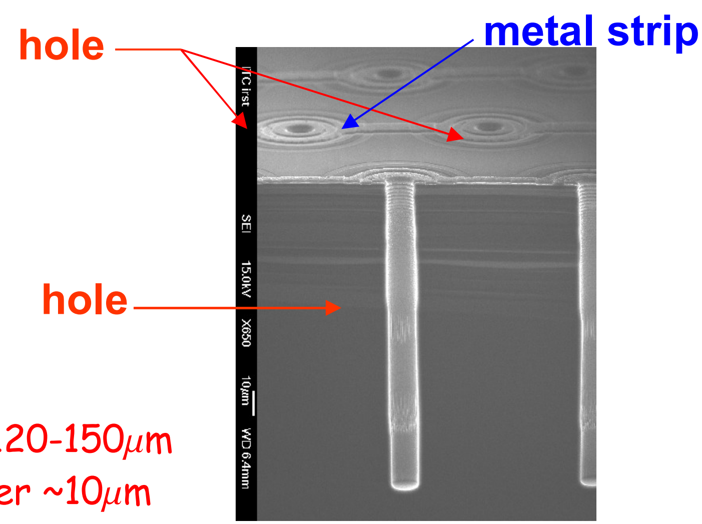
- Simplified 3D architecture
  - n^+ columns in p-type substrate, p^+ backplane
  - operation similar to standard 3D detector

[C. Piemonte et al., NIM A541 (2005) 441]



- Simplified process
  - hole etching and doping only done once
  - no wafer bonding technology needed

- Simulations performed
- Fabrication:
  - IRST(Italy), CNM Barcelona



Hole depth 120-150μm
Hole diameter ~10μm

C.Piemonte et al., STD06, September 2006

- First CCE tests under way

Summary

•At fluences up to $10^{15}cm^{-2}$ (Outer layers of a SLHC detector) the change of depletion voltage and the large area to be covered by detectors is the major problem.

- CZ silicon detectors could be a cost-effective radiation hard solution (no type inversion, use p-in-n technology)
- p-type silicon microstrip detectors show very encouraging results: CCE $\approx$ 6500 e; Φ_{eq}= 4×10^{15} cm^{-2}, 300μm, collection of electrons, no reverse annealing observed in CCE measurement!

•At the fluence of $10^{16}cm^{-2}$ (Innermost layer of a SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping.

The promising new options are:

Thin/EPI detectors : drawback: radiation hard electronics for low signals needed
e.g. 2300e at Φ_{eq} $8x10^{15}cm^{-2}$, 50μm EPI,

3D detectors : drawback: technology has to be optimized
….. steady progress within RD50

•New Materials like SiC and GaN (not shown) have been characterized .
CCE tests show that these materials are not radiation harder than silicon

Further information:
http://cern.ch/rd50/

References

- " Silicon Microstrip Detectors ", A.Peisert, in " Instrumentation in High Energy Physics ", F.Sauli (ed), World Scientific, (1992).

Many plots (and slides) from

- M. Moll, CERN Summer Student Lectures, 2005 and Pixel2005 presentation, RD50 presentations http://rd50.web.cern.ch/rd50/
- O. Ullaland, CERN Summer Student Lectures, 2006
- Alan Honma, “Silicon Detectors”, Nato Advanced Study Institute, Virgin Islands, 06/2002, http://cern.ch/honma/