Towards sensors for the HL-LHC phase

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Research Techniques Seminar

Fermilab

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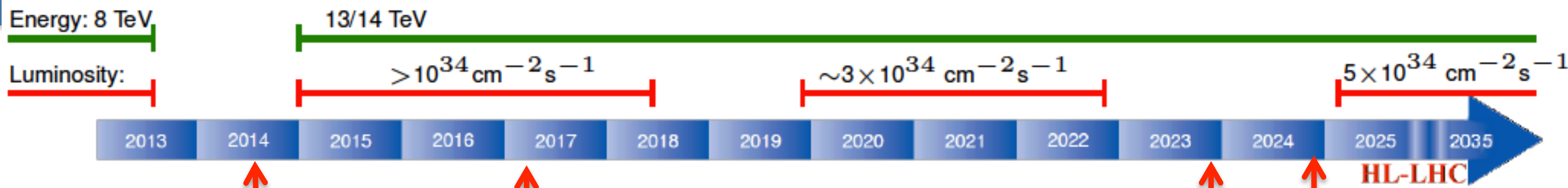
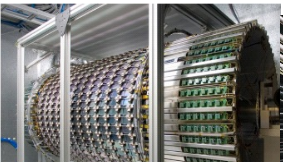
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

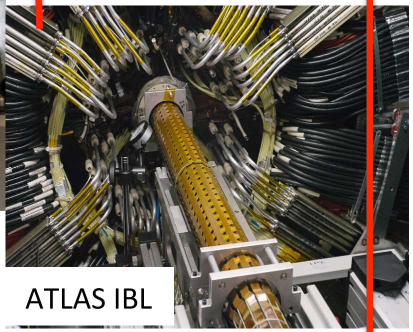
CMS
Compact Muon Solenoid

LHC timeline

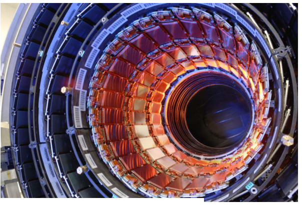




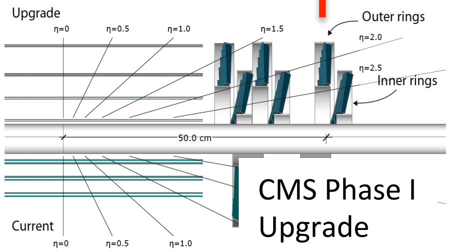
ATLAS Tracker



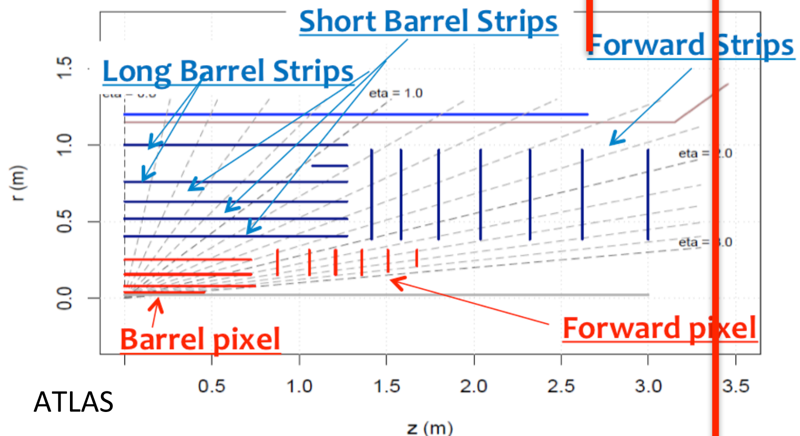
ATLAS IBL



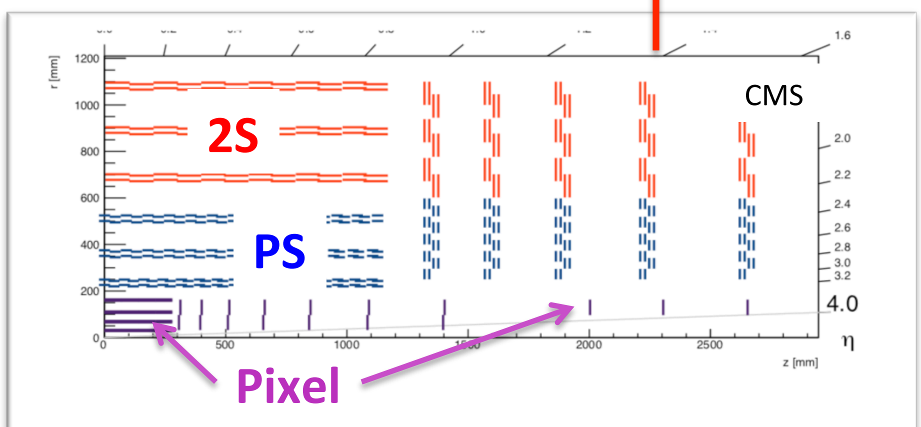
CMS Tracker



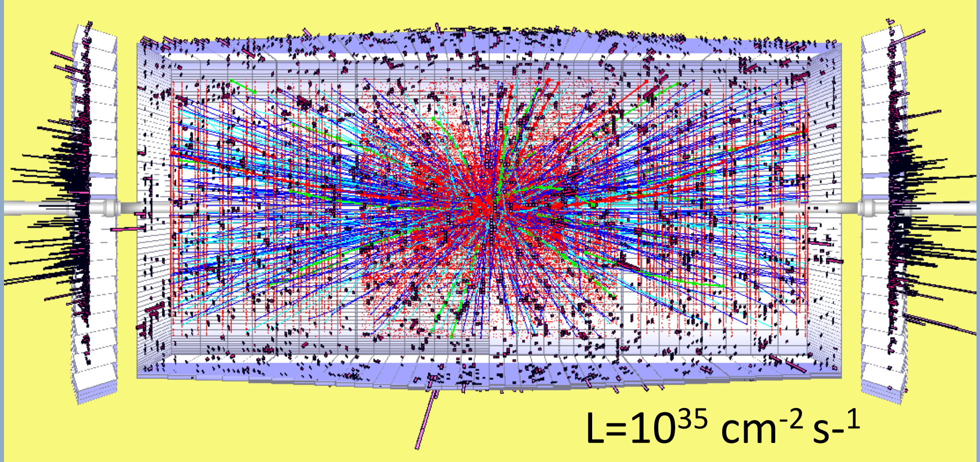
CMS Phase I Upgrade



ATLAS



High Luminosity LHC Challenges



2022	LS3	Installation of a new CMS tracker • Phase-2 pixel detector (Pixel) • Phase-2 outer tracker (OT) • Level 1 Track trigger
2023		
2024	Data taking "phase II"	
↓		

Challenging environment for
- Precision tracking
- Primary and secondary vertex reconstruction

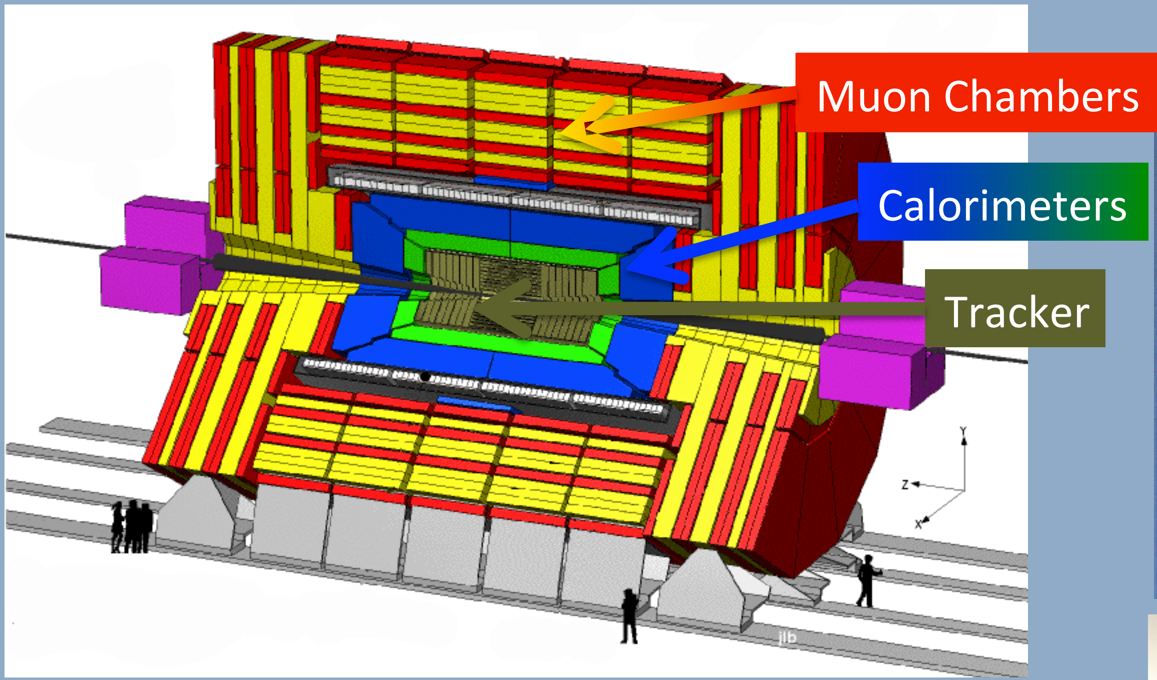
Requirements:
- Operate in 140 collisions per bunch crossing at $5\mathbf{x}10^{34}\ cm^{-2}\ s^{-1}$ and 40 MHz
- Maintain occupancy at ≈ % level

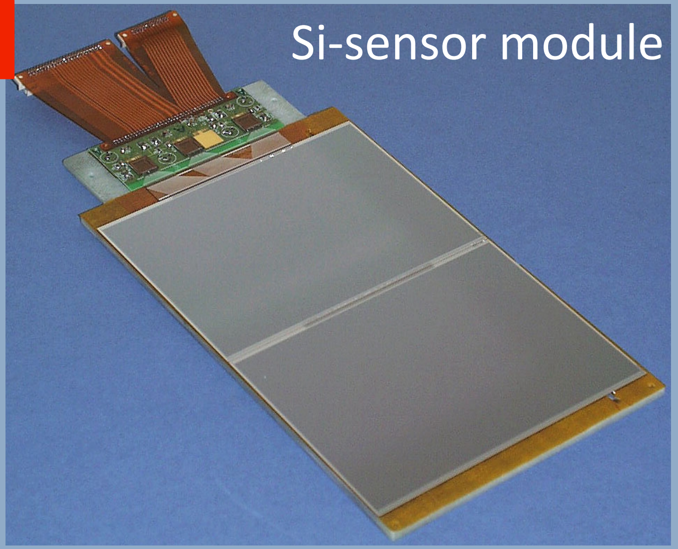
→More granularity and smaller pixel
→More radiation hard sensors

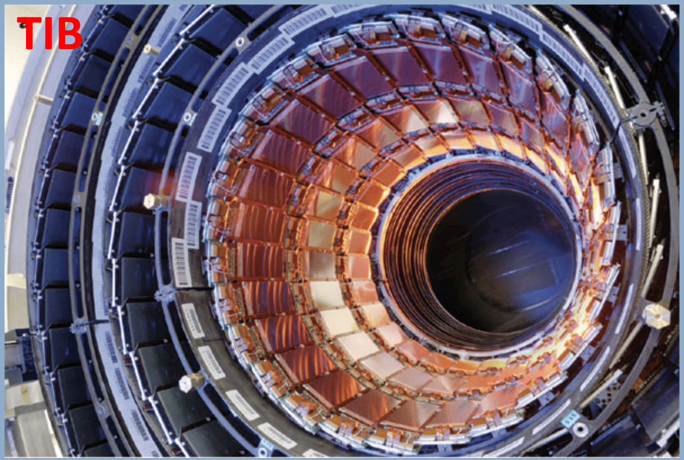
Reducing material in the tracking volume
- Improves performance at low p_T
- Reduce rates of nuclear interaction, γ conversions, bremsstrahlung…

Reducing the pixel size
- Improves performance at high p_T and two track separation

The CMS experiment





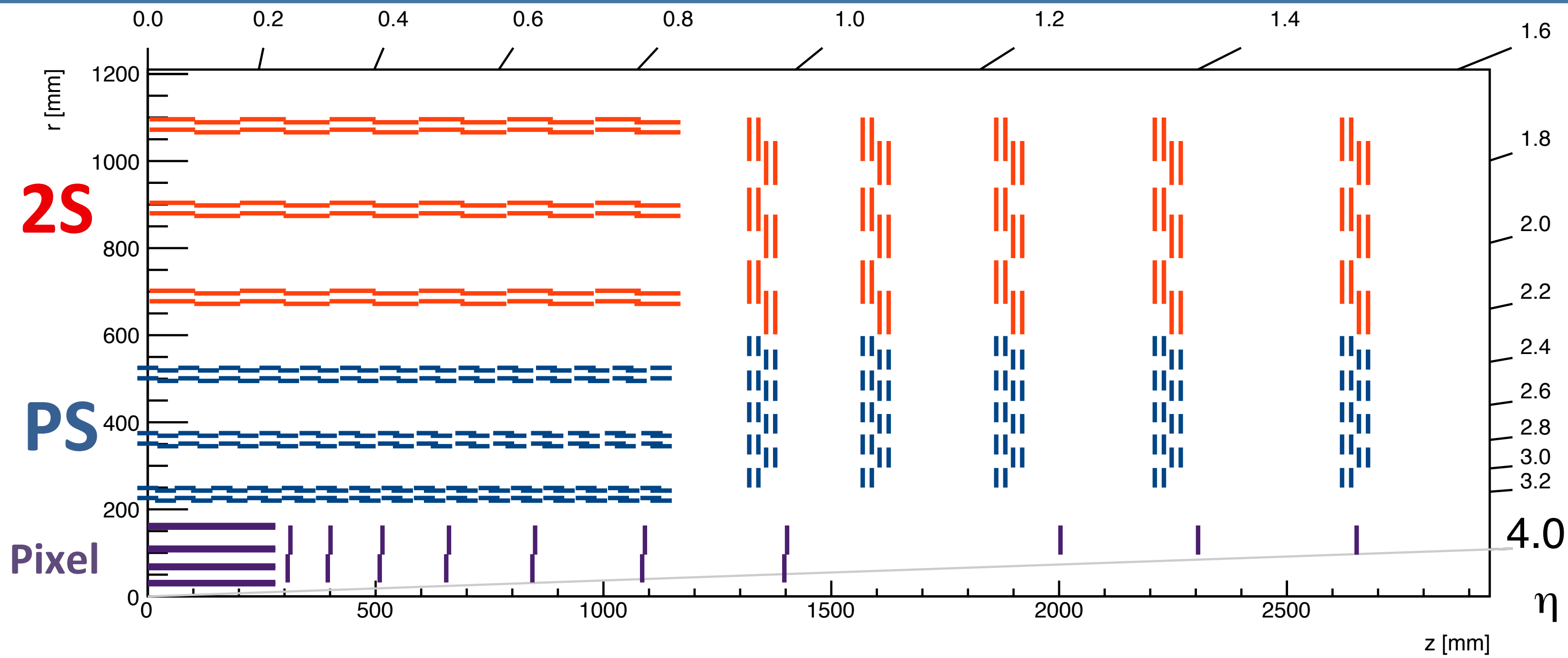


Tracking very important for physics programme

Micro Strip
- ~214 m^2 of silicon strip sensors, 11.4 million strips

Pixel
- Inner 3 layers: silicon pixels (~1 m^2)
- 66 million pixels (100 x 150 µm)

Layout for the CMS Phase II Tracker



Baseline layout:

R > 20 cm: Outer Tracker with 6 barrel layers and 5 endcap disks (with 2S and PS modules)

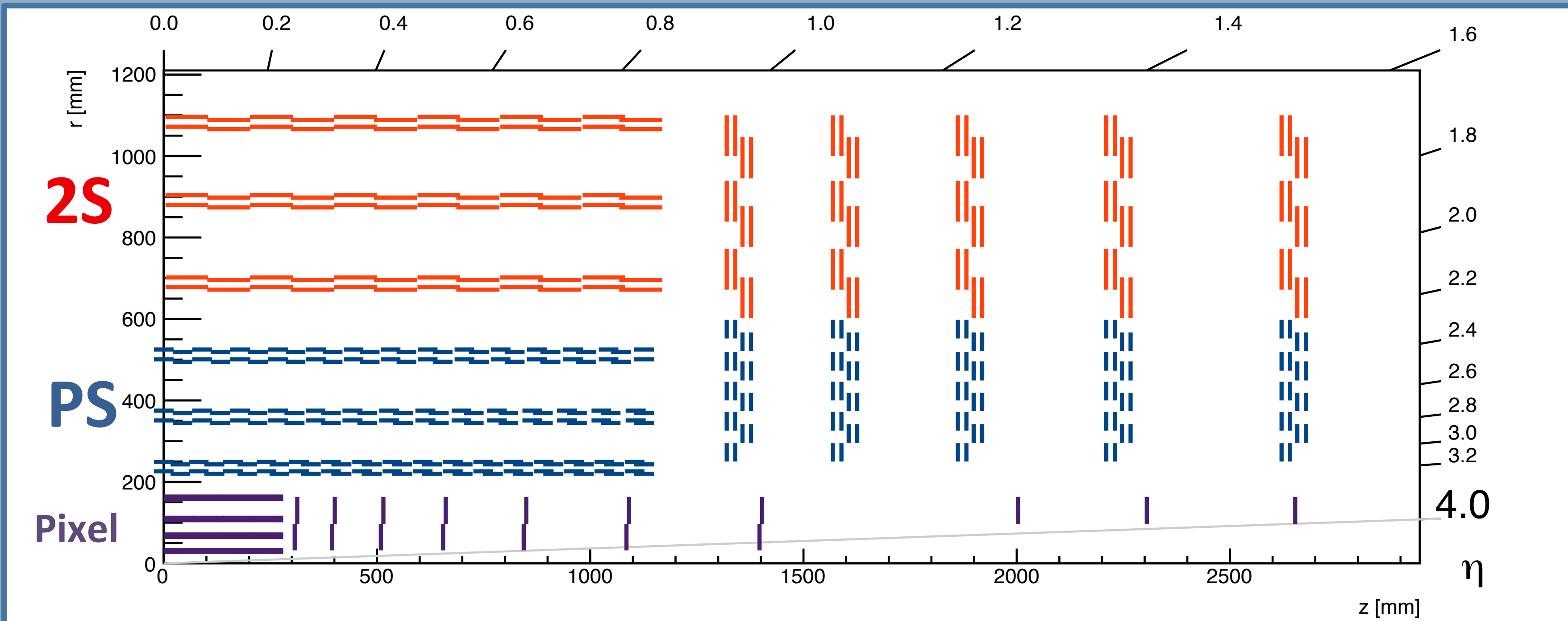
20 cm > R > 4 cm: Inner Tracker with 4 barrel layers and 10 disks (with pixel modules)

Pixel detector layout:

- "Similar" to Phase I Pixel
- Extends to η=4 in the forward region

Requires most R&D work

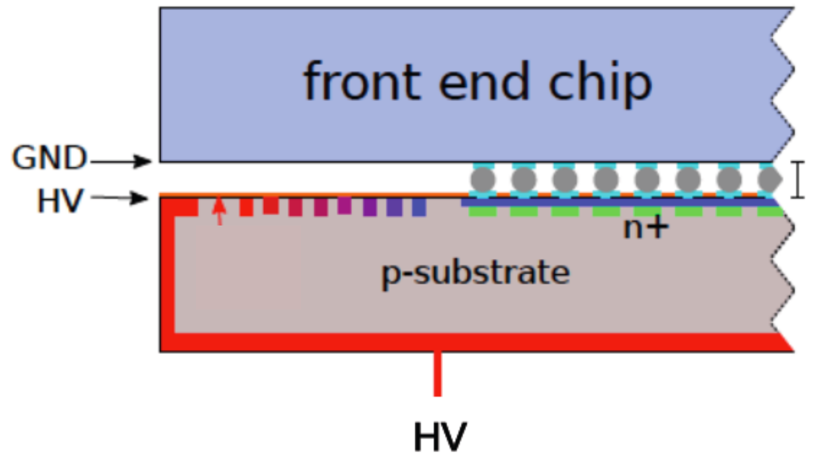
Layout for the CMS Phase II Tracker



Pixel Issues:

- How to manufacture and bump bond very fine pitch pixel (25 μm x 100 μm).
- Radiation damage up to $\Phi = 2 \times 10^{16}\ cm^{-2}$.

Pixel Design Challenges



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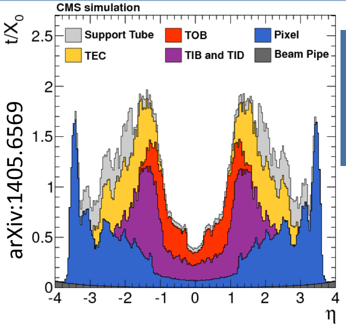
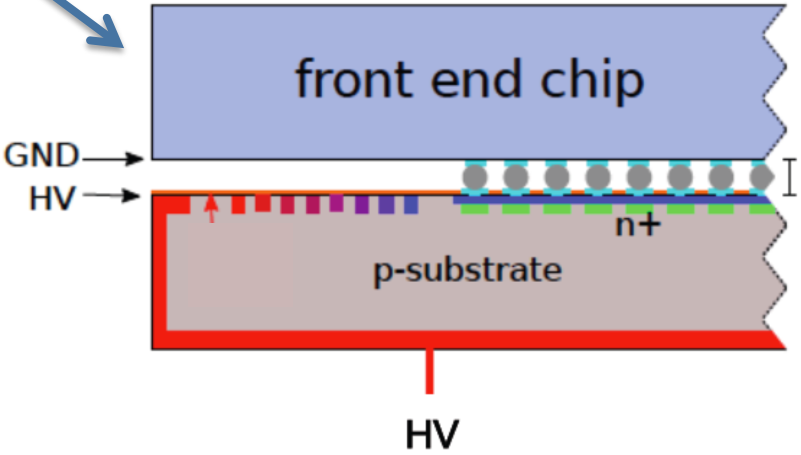


Reduce material budget



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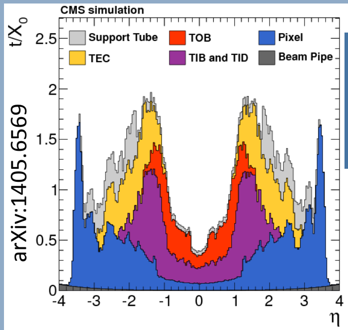
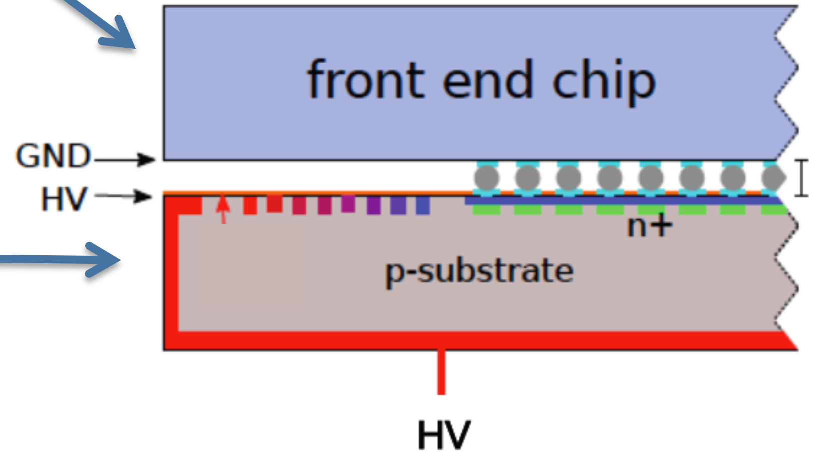
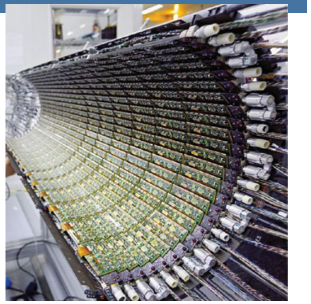


Reduce material budget

Each experiment has to cover
8 + ? m^2
with silicon
→ Be cheap and reliable





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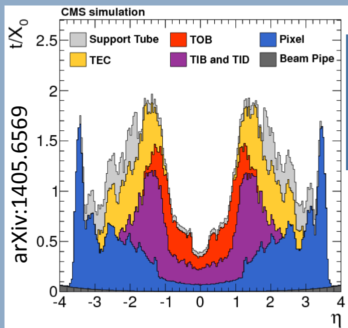

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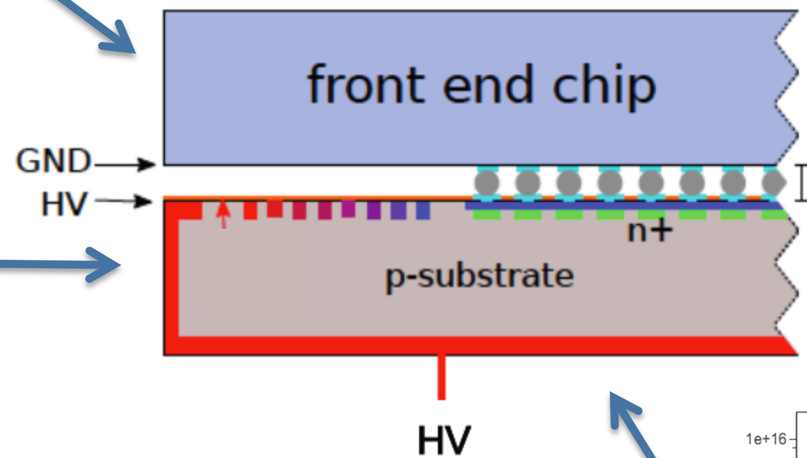

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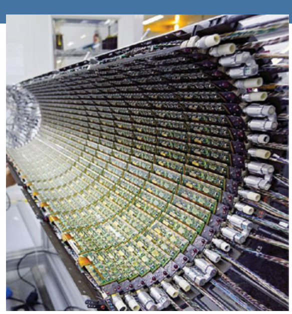
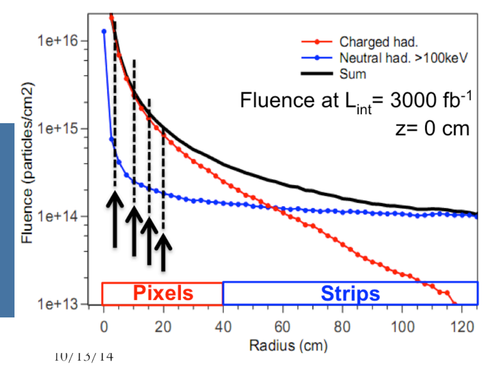


Improve radiation tolerance
→ Maximize efficiency and minimize noise hits



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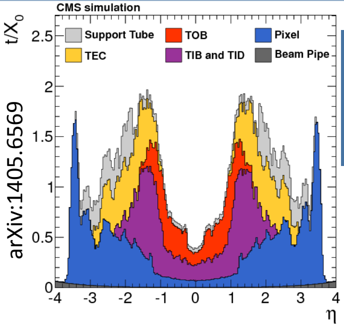

Reduce material budget

Each experiment has to cover
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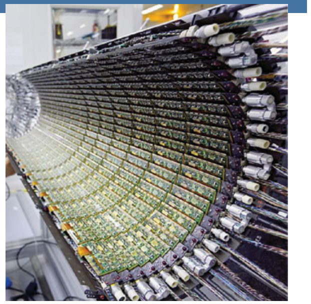
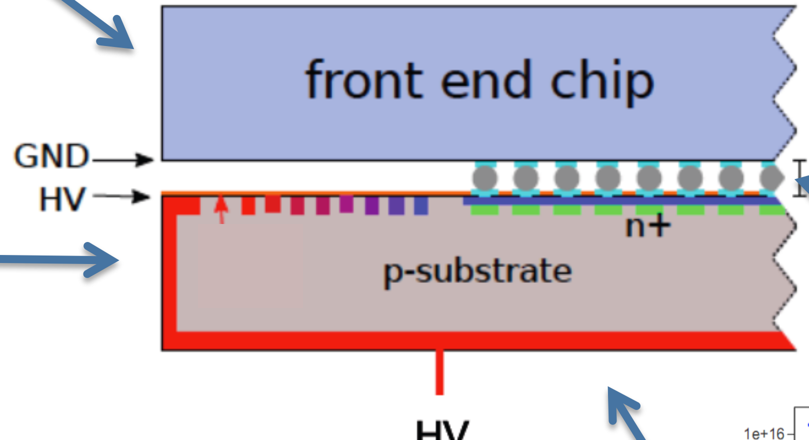
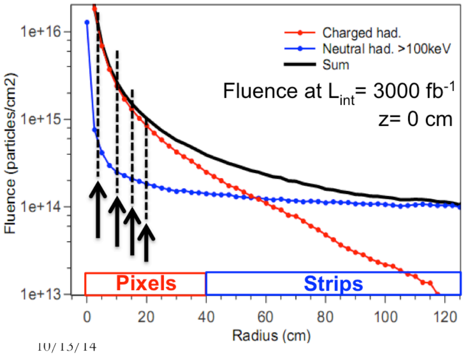




Improve inter-connection techniques

Improve radiation tolerance
→ Maximize efficiency and minimize noise hits



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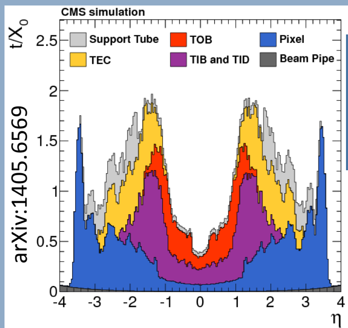
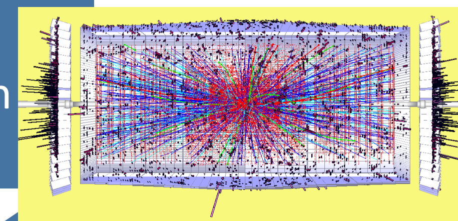
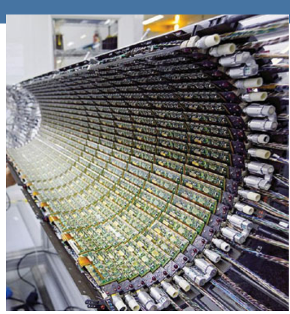


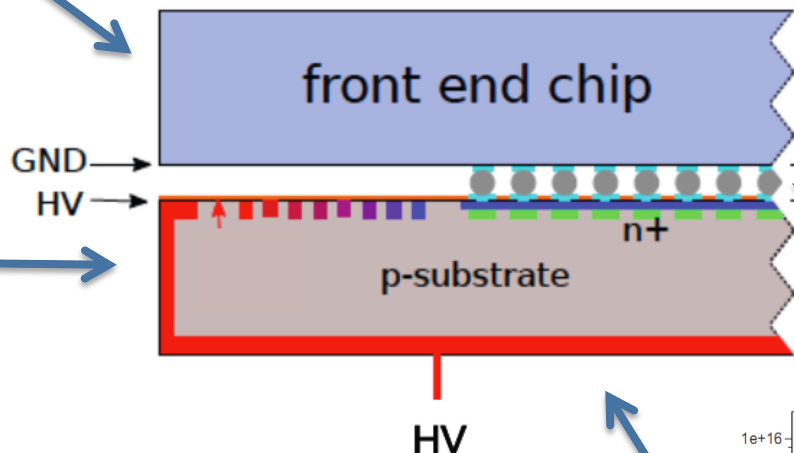
Reduce material budget

Luminosity: 5x10^{34} cm^{-2} s^{-1}
→ Improve spatial resolution and maintain occupancy at ≈ % level



Each experiment has to cover 8 + ? m^2 with silicon
→ Be cheap and reliable





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Improve radiation tolerance
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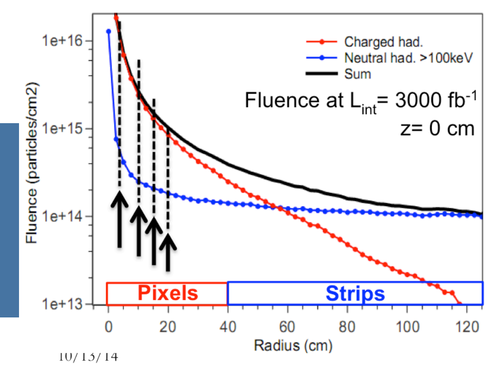
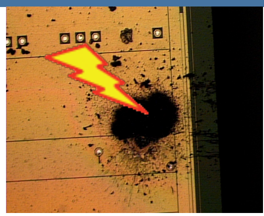


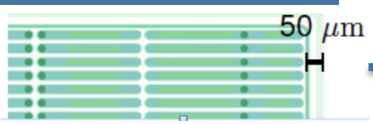
Pixel Design Goals

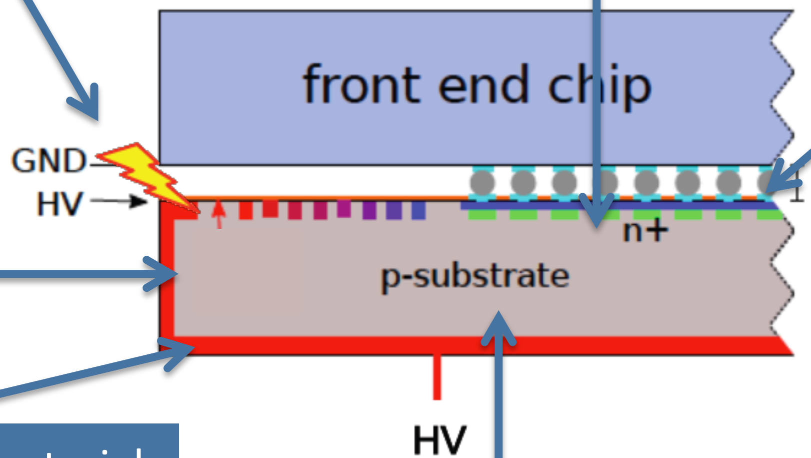
Sparking at sensor edge



Optimize pixel geometries (small pitches)

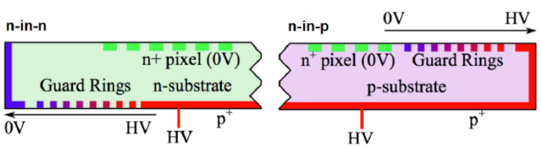
Decrease inactive edges



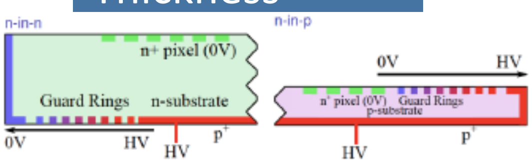


Bump bonding (small pitches, thin sensor / ROC)

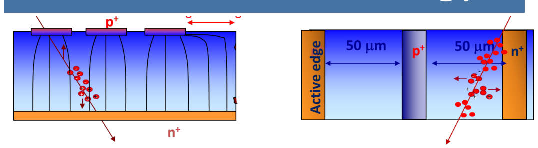
Choose sensor bulk material
- n-in-p 6” wafers



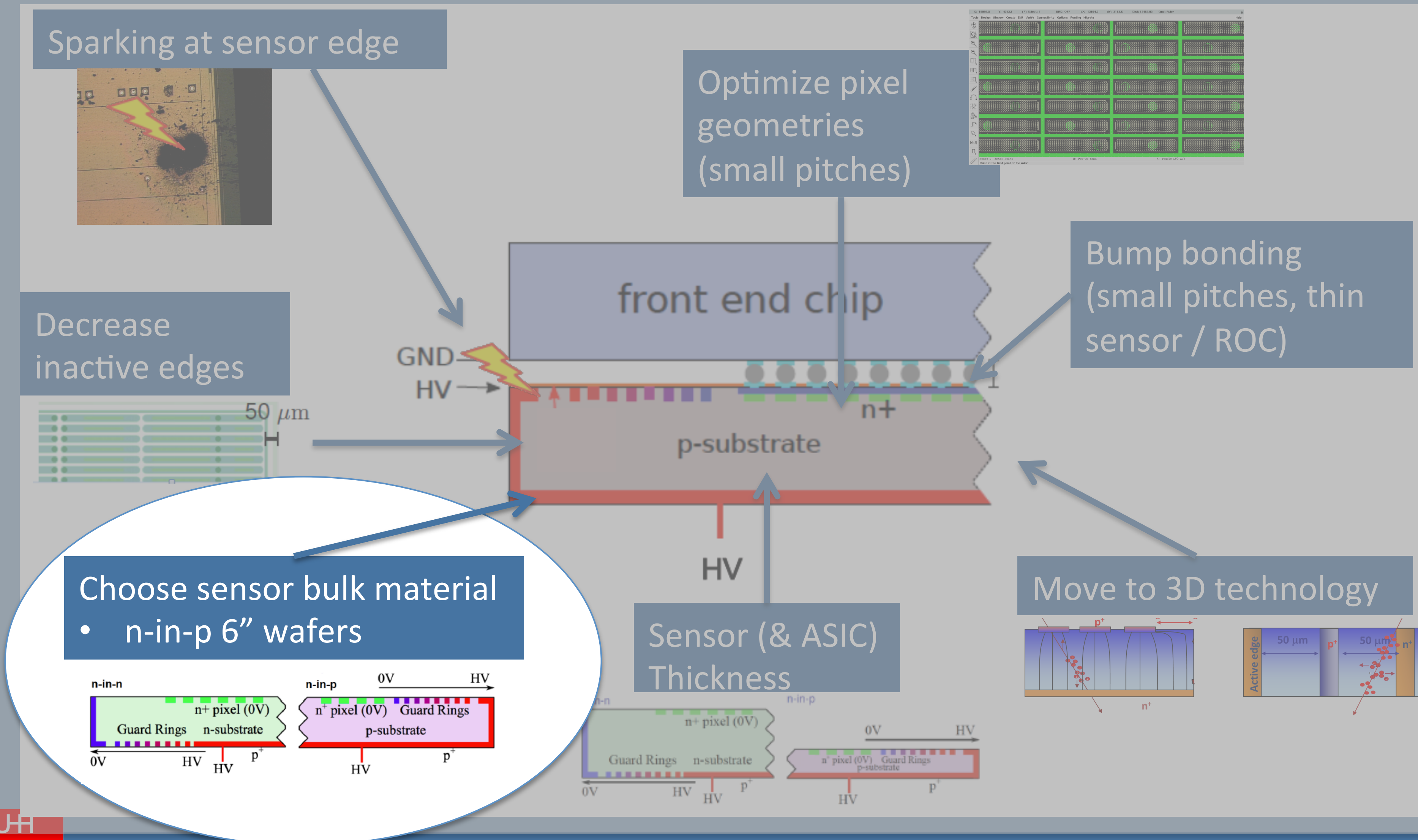
Sensor (& ASIC) Thickness



Move to 3D technology



Pixel Design Goals

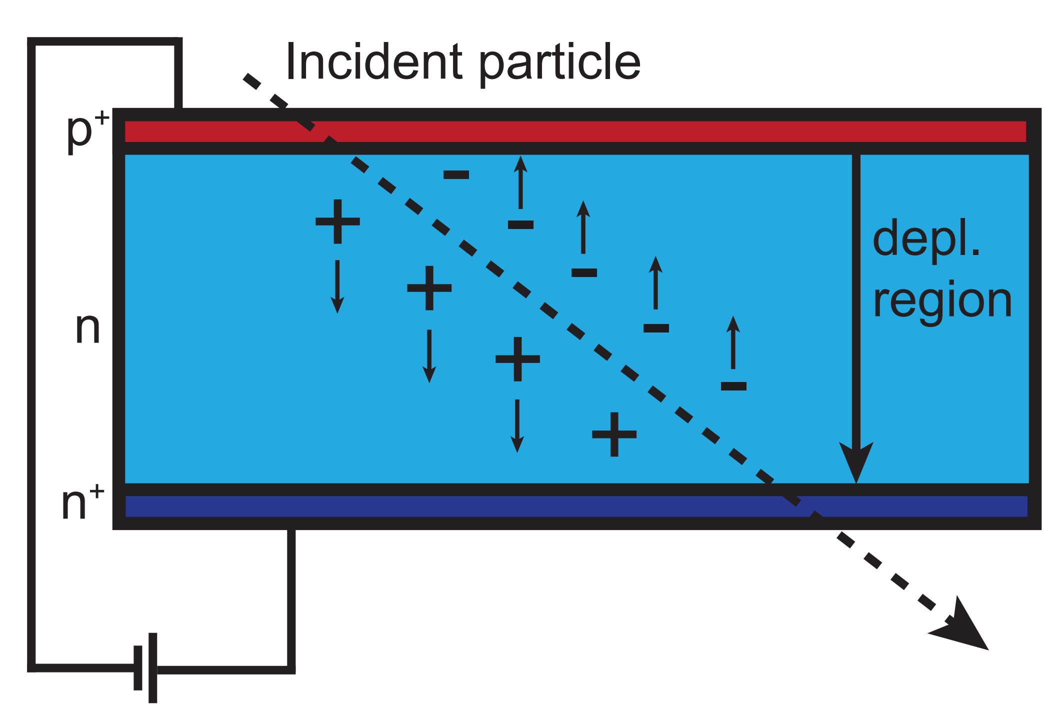


Silicon sensor principle

Operation:
- pn diode in reverse-bias
- Depletion layer starts from junction
- Particle ionises Si, producing e/h-pairs
- e/h-pairs drift in E-field to electrodes

Properties:
- Thickness currently 300 μm

➔ Signal ∼25000 e/h-pairs
- Segmented in strips or pixels

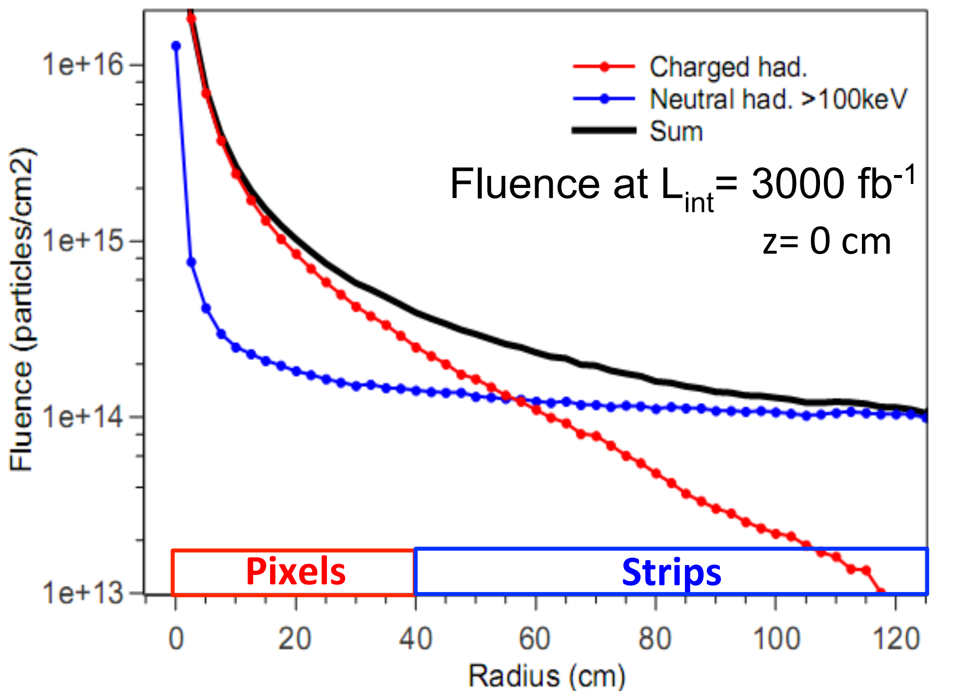


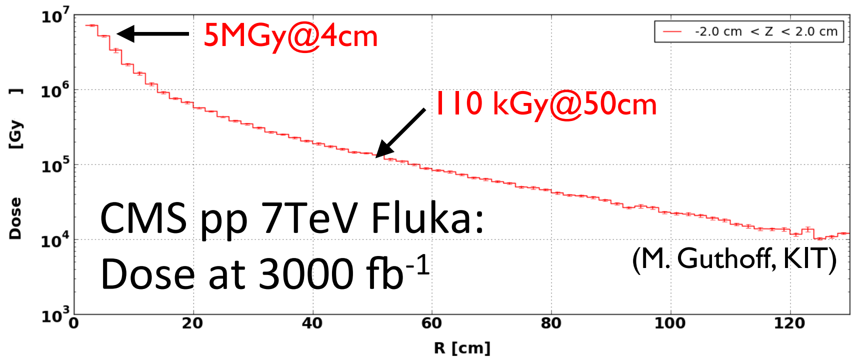
Advantage of silicon:
- Low ionisation energy
- Fast signal collection

Relevant parameters for performance
- Leakage current (I_{dep})
- Depletion voltage (V_{dep}) → operational voltage

→ Power consumption (P = U*I) & heat load
- Collected charge

Radiation damage in the tracker





Fluence up to $\Phi \approx 2E16\ cm^{-2}$ for innermost pixel layer

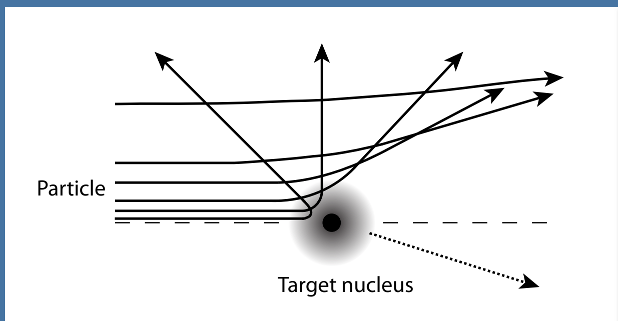
- Phase 2 will yield 3,000 fb^{-1} and about 300 fb^{-1}/year.
- Radiation damage of the previous 10 years in only one year!

Surface damage not negligible for pixel region:

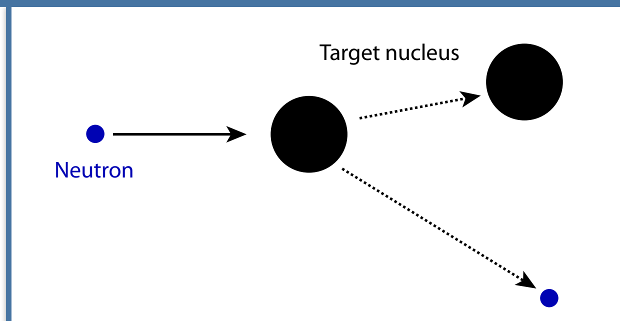
- Dose at 4 cm: 5 MGy
- Dose at 50 cm: 110 kGy

Generation of bulk damage

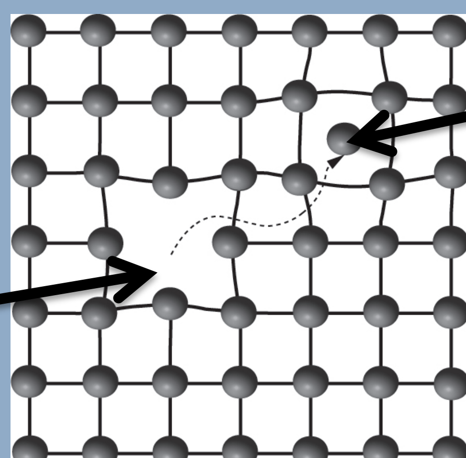
Coulomb scattering



Elastic nuclear scattering

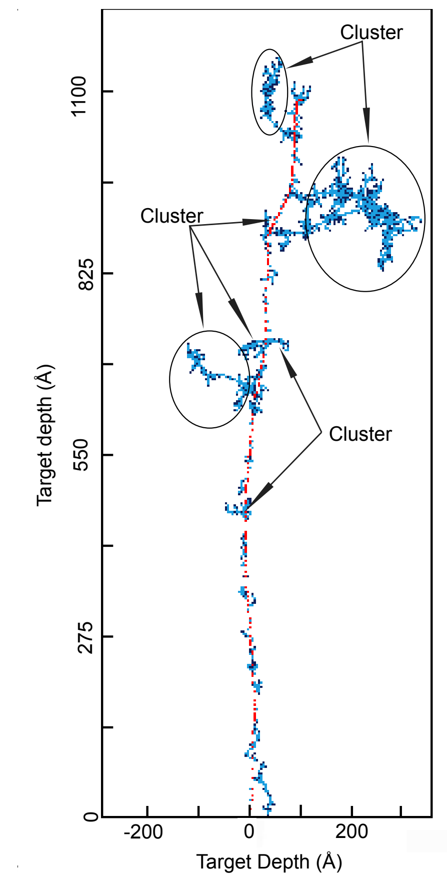


PKA E_{PKA}>25 eV



Interstitial
additional Si atom

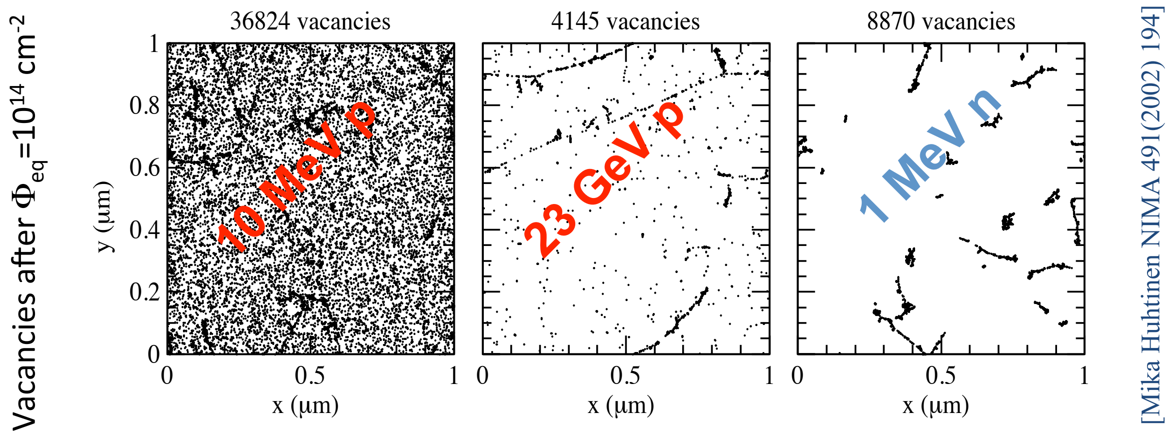
Vacancy
missing Si atom



Simulation of 50 keV PKA damage cascade (1 MeV n)

Generation of bulk damage

Depending on particle charge and mass



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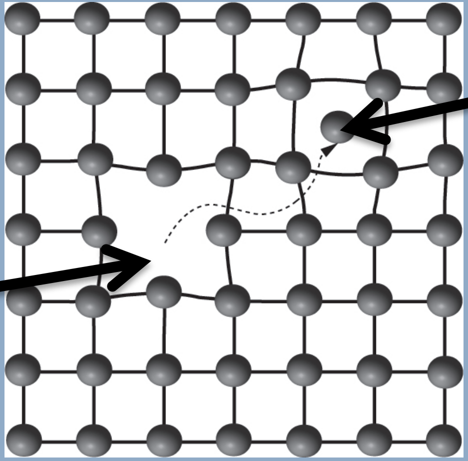
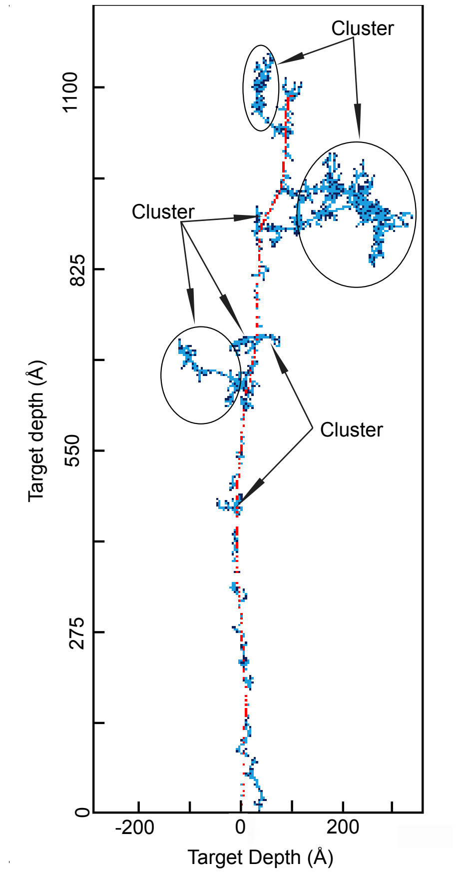


Interstitial
additional Si atom

Vacancy
missing Si atom

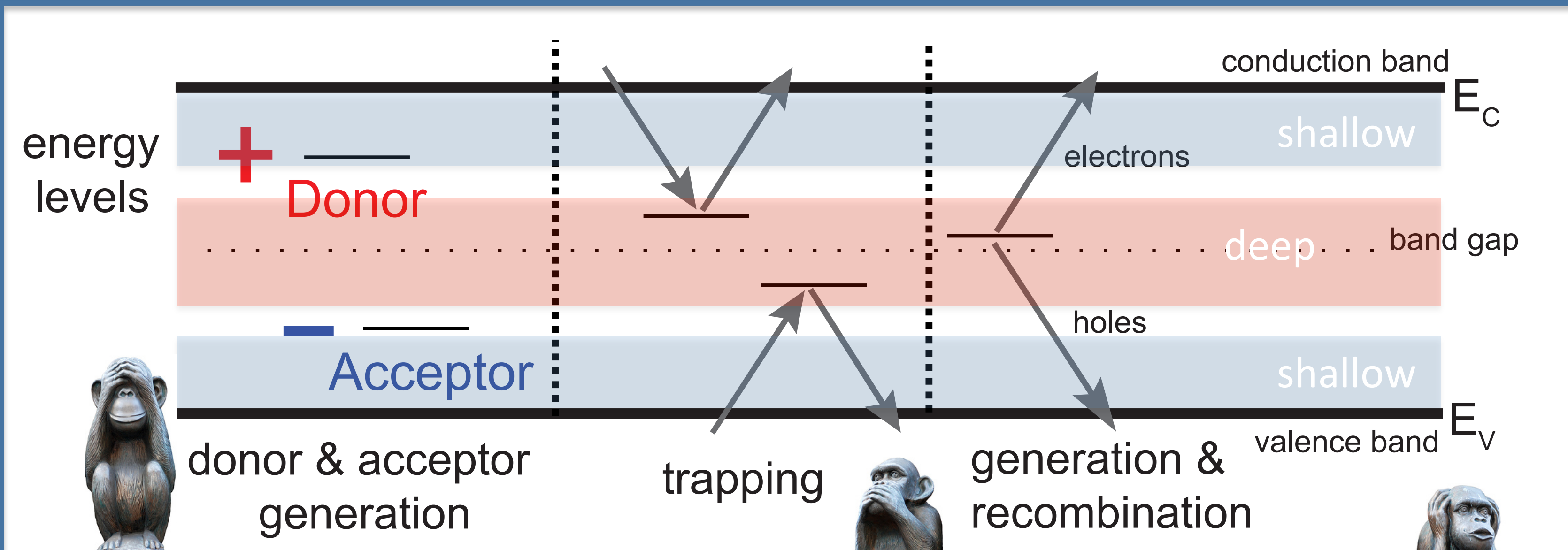
+ Impurities



Simulation of 50 keV PKA damage cascade (1 MeV n)

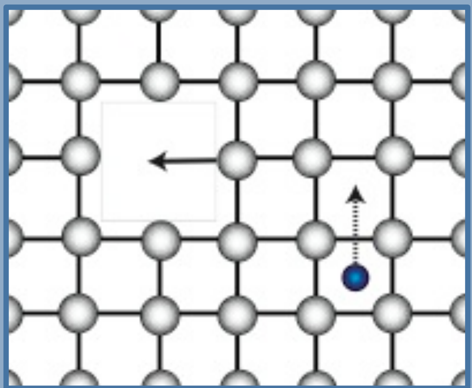
Impact of defects on detector properties

Determined by Shockley-Read-Hall statistics



Charged defects (at RT)	Deep defects	Levels close to midgap
→ Change of space charge (Acceptors in the lower half and donors in the upper half of the band gap)	→ CCE (Shallow defects do not contribute due to de-trapping)	→ I_{leak} (Noise) → Polarisation effects → Power consumption / heat dissipation

Approach: Defect engineering



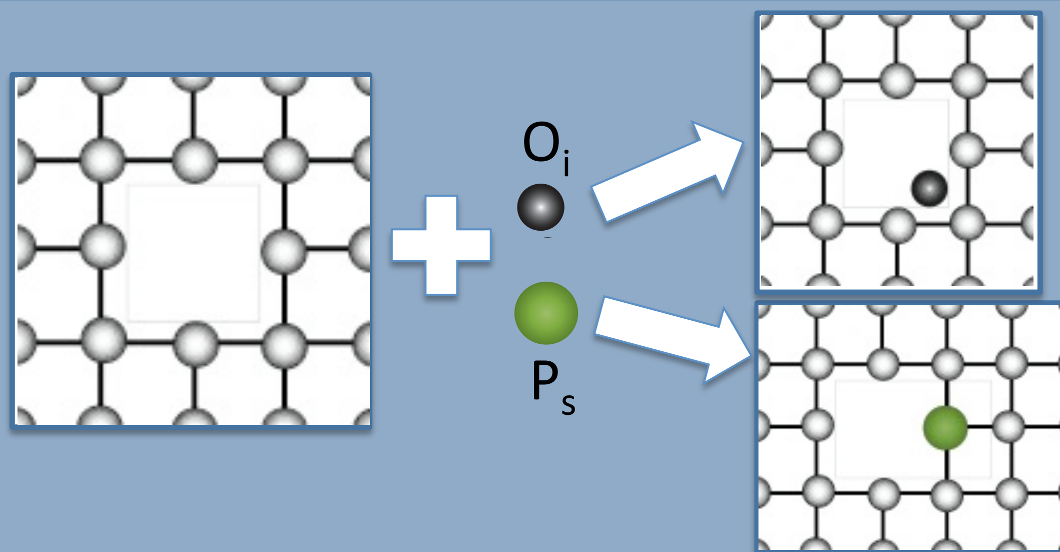
- Frenkel pairs are created due to irradiation
- Defect complexes form due to migration
  - ➔ Migration depends on thermal energy
  - ➔ Kinetics like in chemical reactions

Example: Benefit of oxygen rich silicon: VO_i generation high – VP (donor removal) suppressed

$V+O_i \rightarrow VO_i$

or

$V+P_s \rightarrow VP$

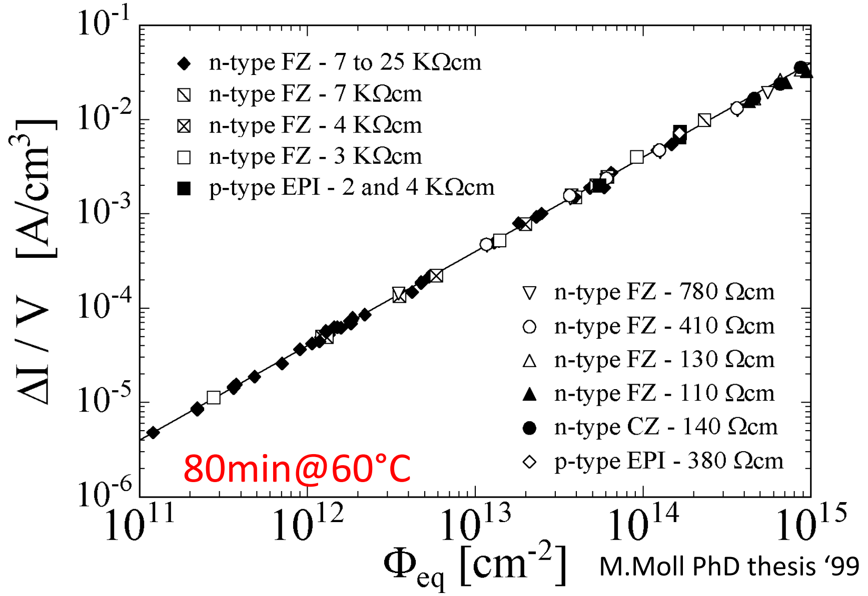


No influence!

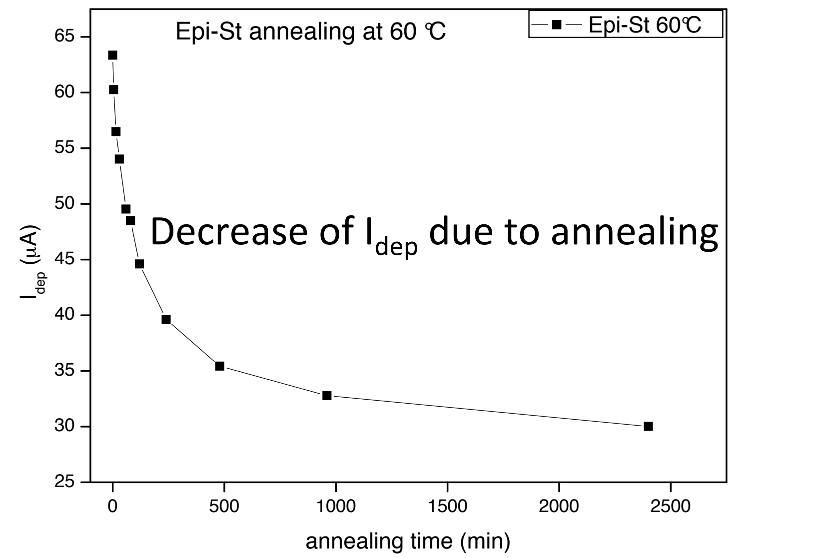
Donor removal

Change of leakage current…

… depending on the fluence…



… and on annealing



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

- Damage parameter α not depending on material or particle type

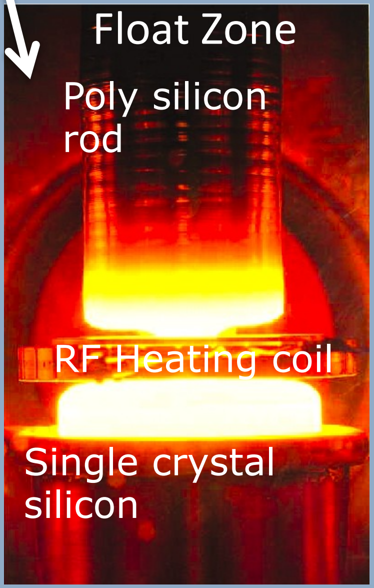
➔ Oxygen does not influence behaviour

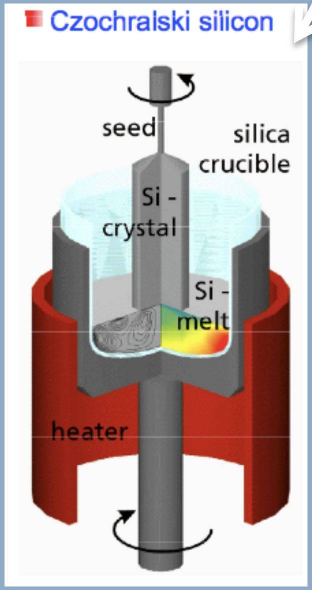
- Constant over orders of magnitude

➔Noise increase (cooling helps due to T-dep of I_{leak})

Silicon "Materials"

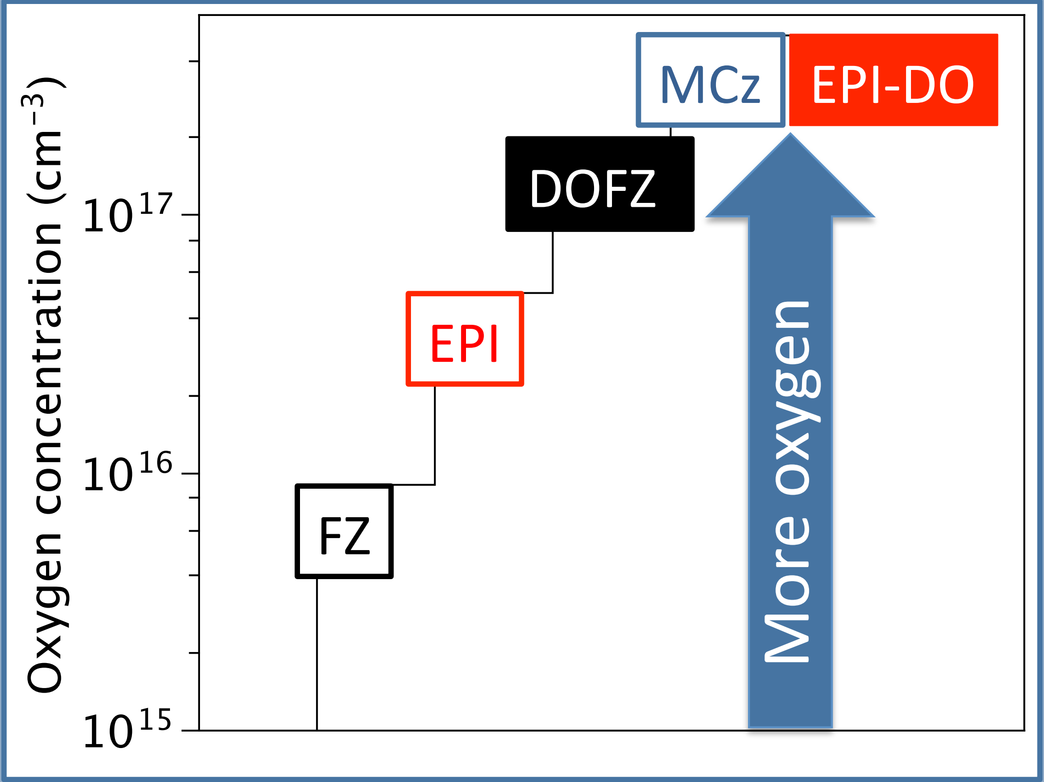
- Float zone (FZ)
- Magnetic Czochralski (MCz)
- Epitaxial silicon (EPI)
- Oxygen enriched FZ (DOFZ)
- Oxygen enriched EPI (EPI-DO)





Si-growth process determines

Impurity concentration, mainly oxygen



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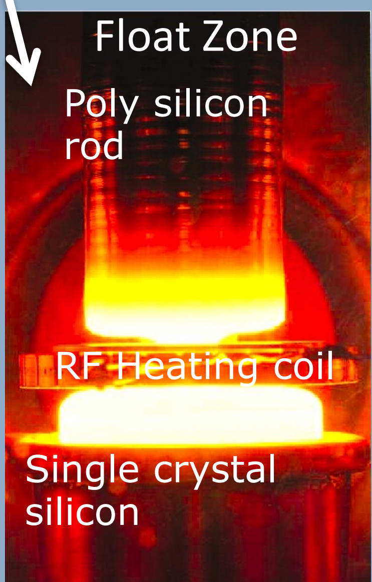

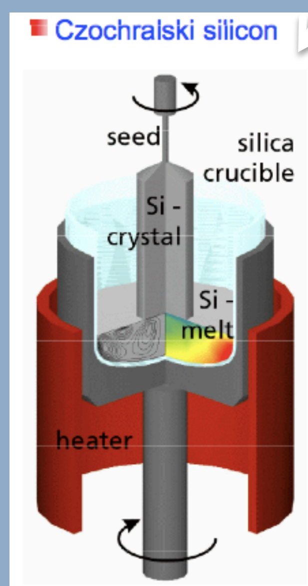

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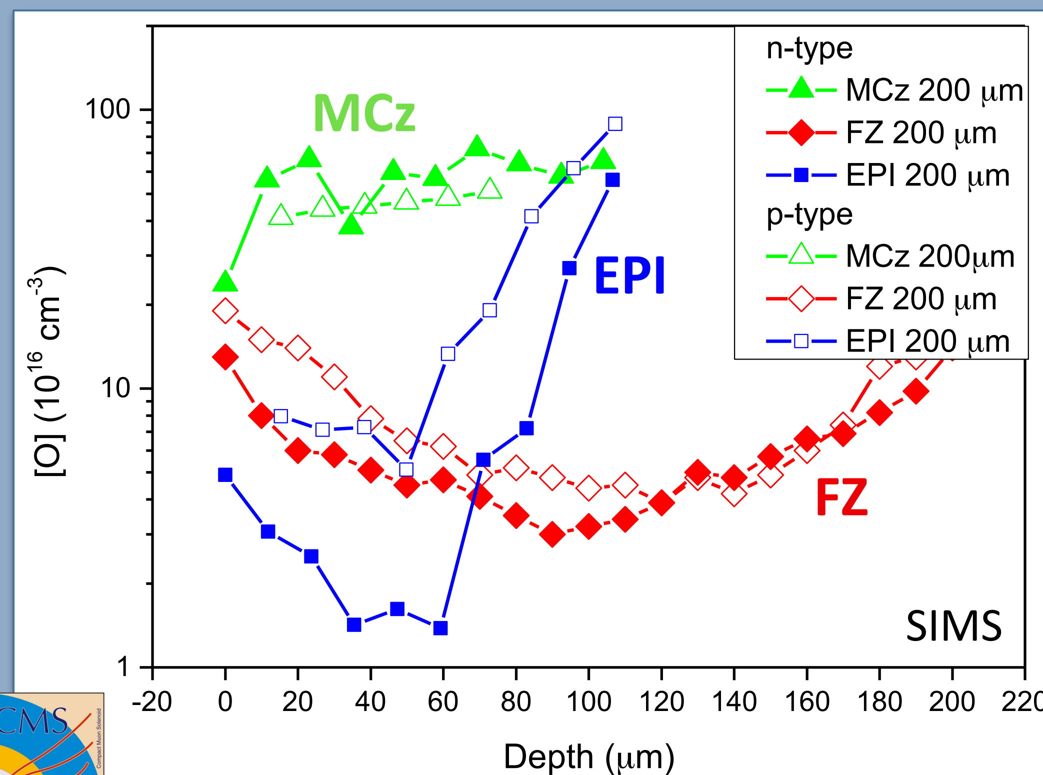
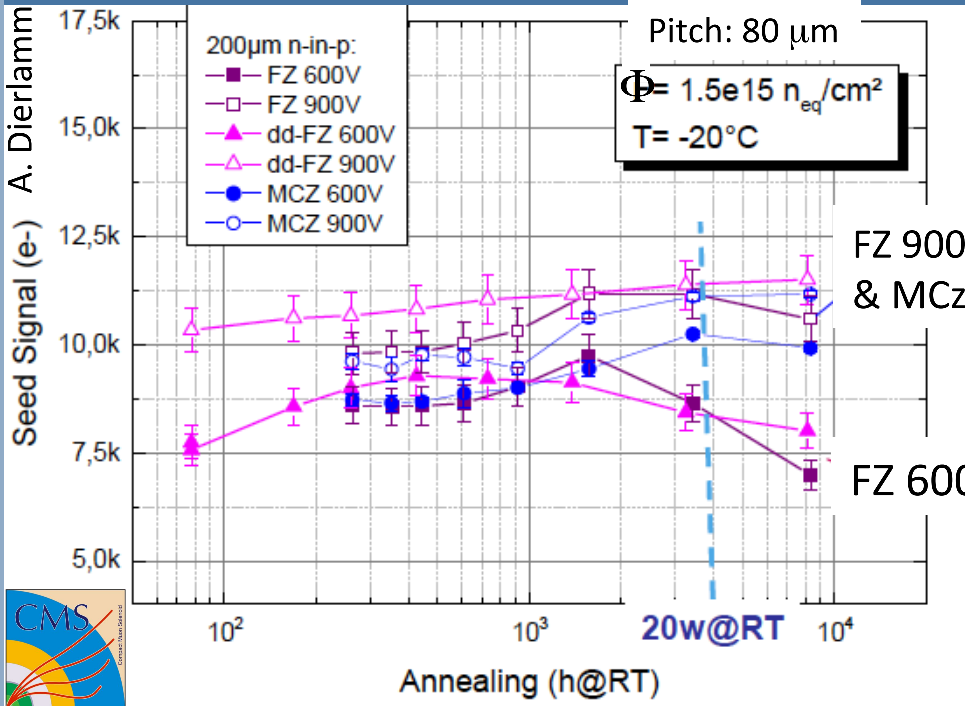
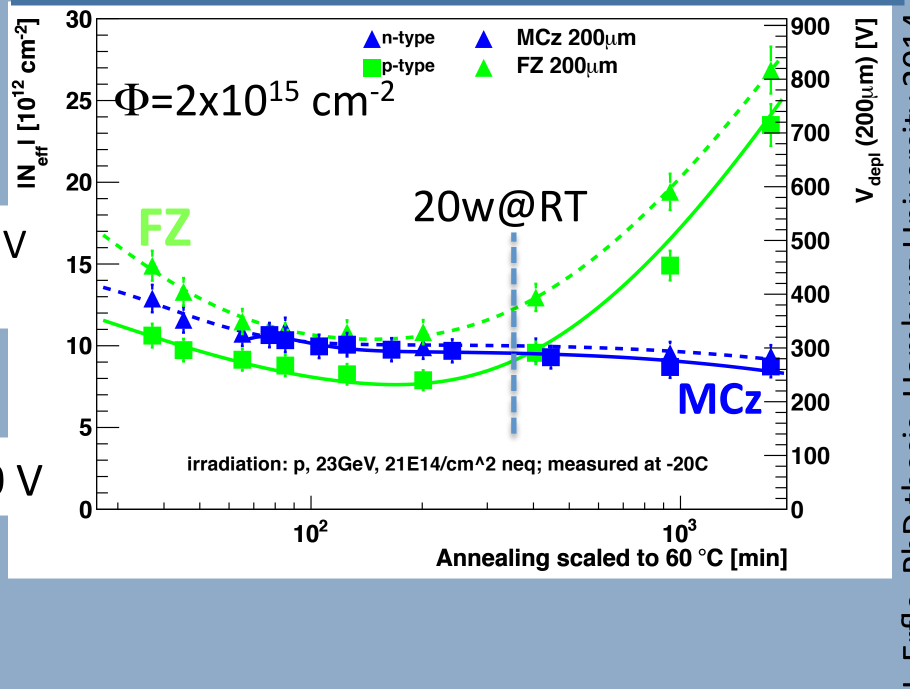


Advantageous Annealing Behavior of p-MCz

Proton & neutron irradiated strip sensors



Proton & neutron irradiated pad diodes



- P-type MCz demonstrates advantageous "long term annealing"
- Operation voltage does not increase in MCz at long annealing times

→ Longer warm up or controlled annealing periods possible

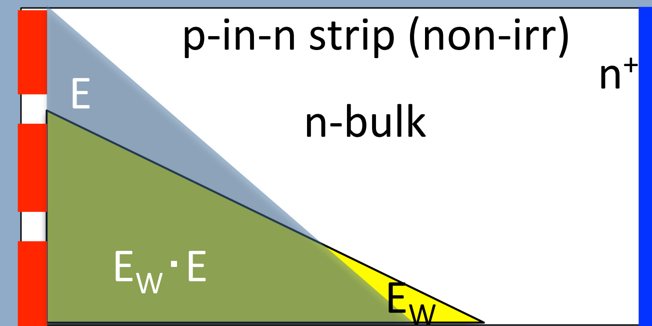
→ Potentially good for power dissipation

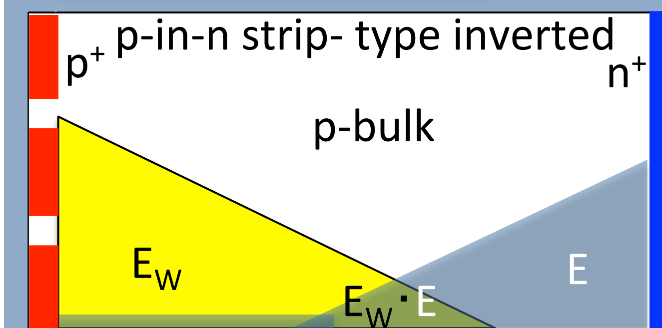
From n-in-n to n-in-p

- Be cost effective → N-in-p is a single sided process
- Thin → very costly with a double-sided process

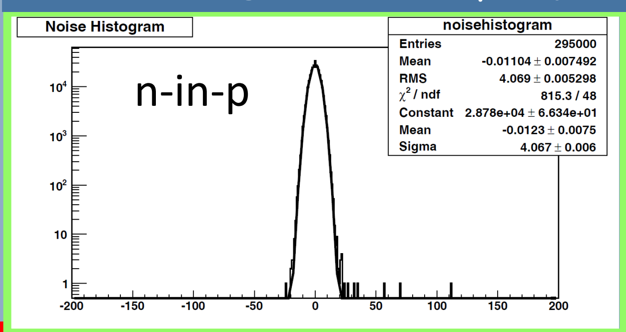
N-side read out is preferred:

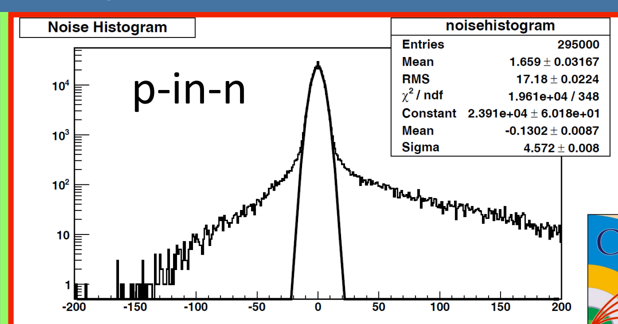
- Favourable combination of weighting and electric field in heavily irradiated detector
- CMS results show potential noise effects at doses > $1x10^{15}$ n_{eq}/cm^2
- T-CAD simulations confirm the tendency of p-in-n strip sensors to exhibit higher electric fields at the strips for increasing oxide charge





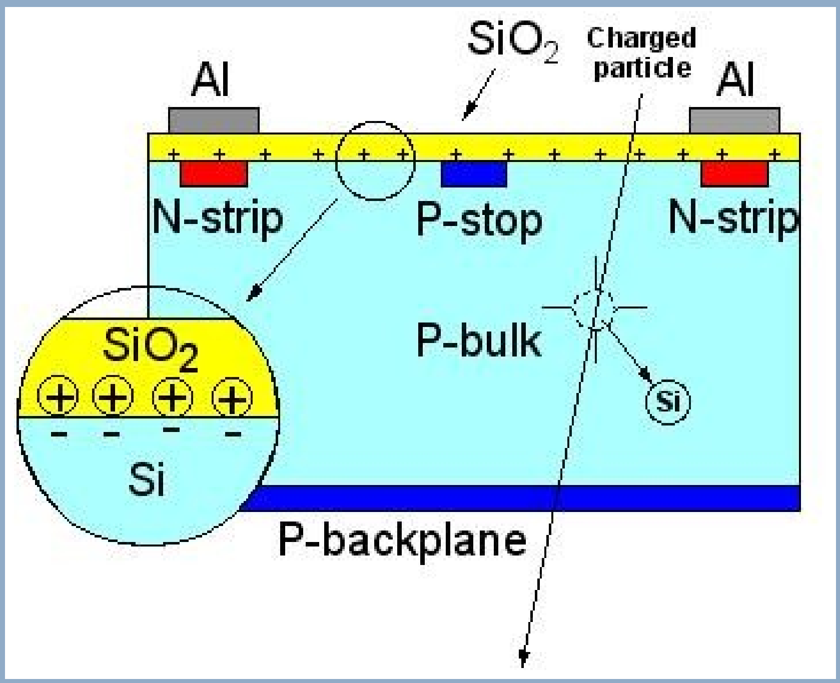
Noise histograms in 80 μm pitch strip sensor





A. Nürnberg

N-in-p sensors require isolation layer



Oxide charge in SiO_2

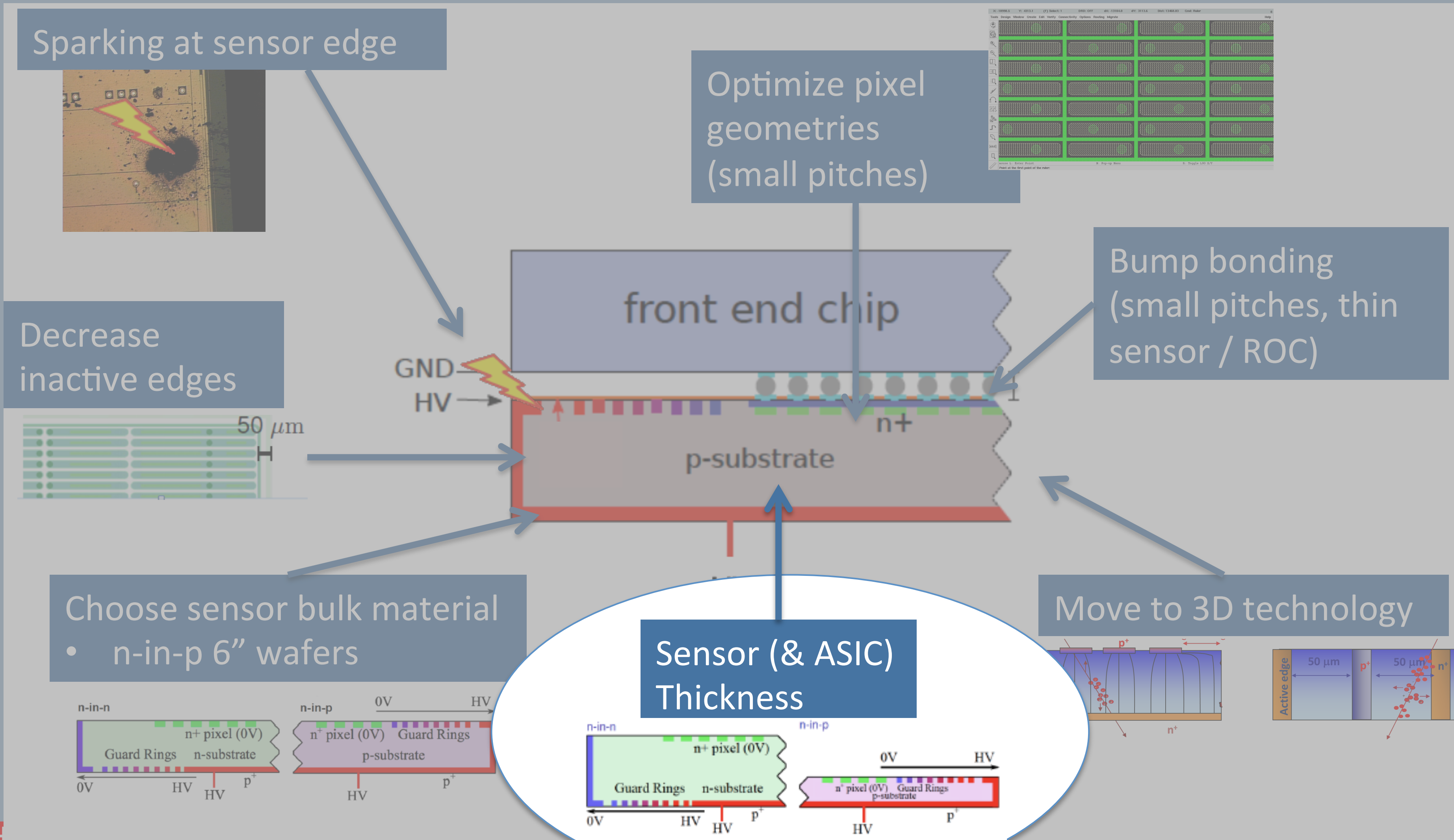
- Positive oxide charges
- Attract negative charges (electron accumulation at Si-SiO_2 interface)
- Bad/no strip or pixels isolation

→ Additional p implant layer (p-spray)
→ Additional p implant trench or ring (p-stop)

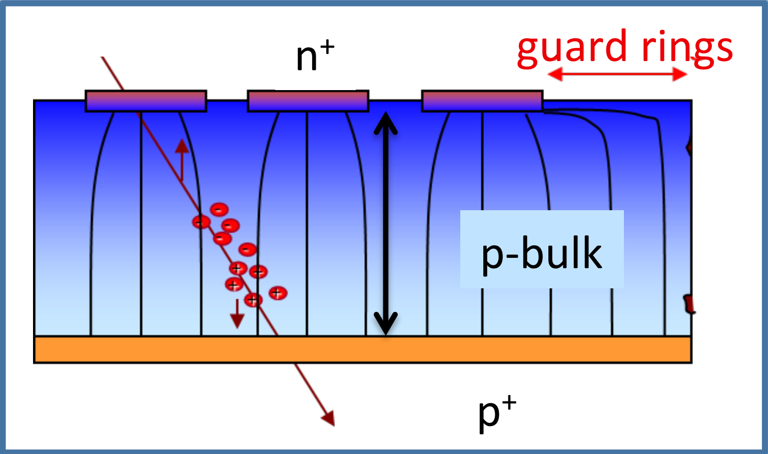
Problems of p-spray and p-stop:

- Noise due to high fields or bad breakdown behavior
- Instability due to radiation damage
- Critical design point for fine pitches
  → Sets limits on inter pixel distances and so on

Pixel Design Goals



Going thin



Thinning technologies:

- Deep diffusion
- Handling wafer
- Epitaxial growth
- Etching
- Grinding

Advantage:

- Lower total leakage current after irradiation
- Lower operational voltage

→ less power consumption

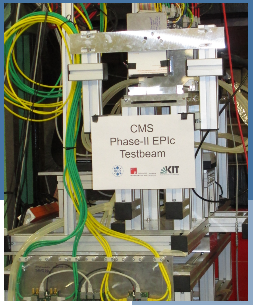
- Short drift path → less trapping
- Higher electric fields at low V_{bias} (faster collection time)
- Less material (multiple scattering)
- Lower occupancy at high eta

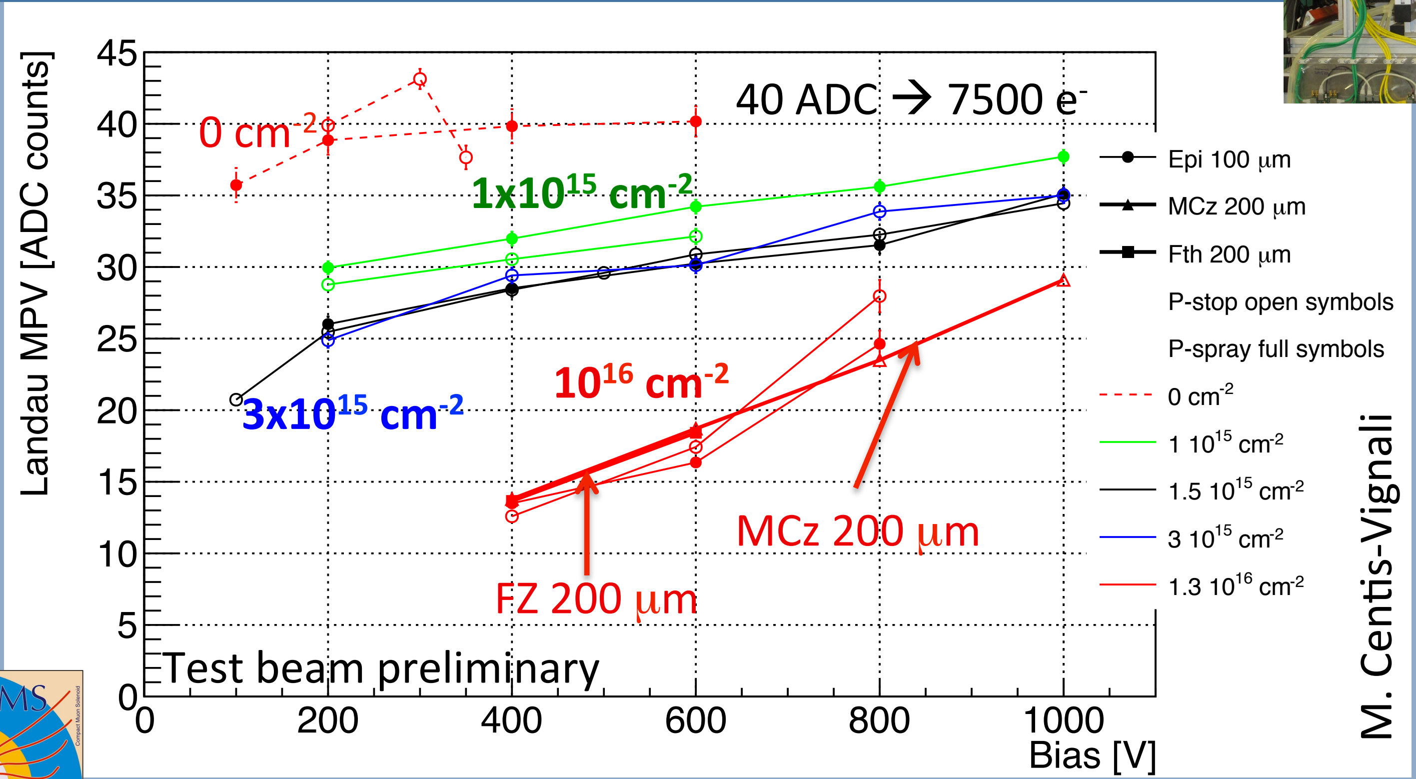
Drawback:

- Smaller initial signal (76 e^-/µm)
- Thinning technologies increase price
- Thin sensors (and ROCs) "bow"

Comparison between 100 μm & 200 μm sensor thickness

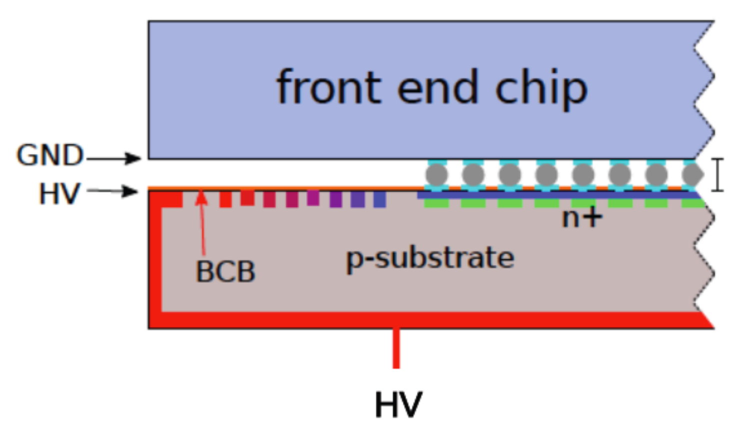
- Strip sensors with 80 μm pitch, mainly EPI with 100 μm active + 200 μm substrate
- @10^{16} cm^{-2}: MCz and FZ with 200 μm physical thickness
  - 100 μm → faster signal recovery
  - 200 μm → higher breakdown voltage
  - Similar signal height for both thicknesses at highest bias

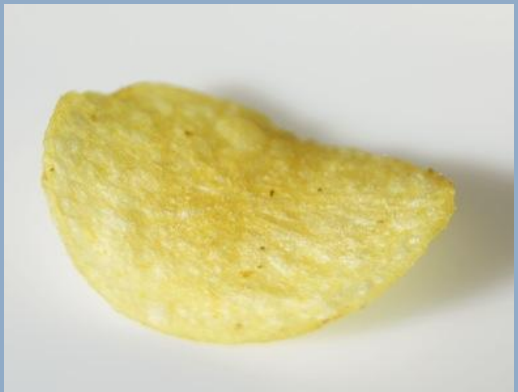




Flatness of sensor and read out chip

Normally bump bonding is done with flat chip and flat sensor





If sensor and roc are shaped like potato chips, bump bonding will not work well

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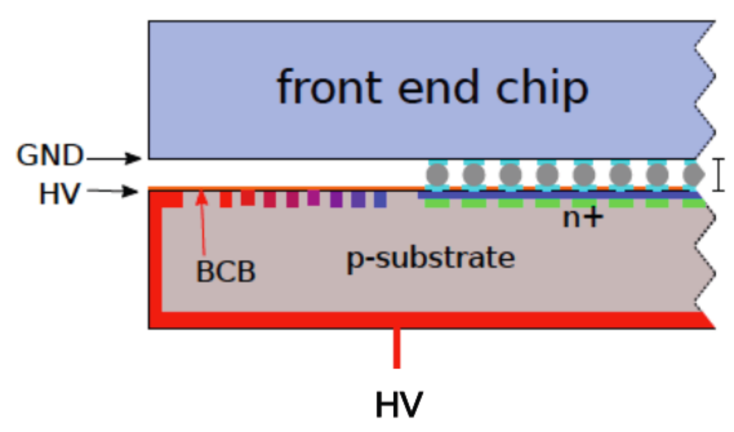

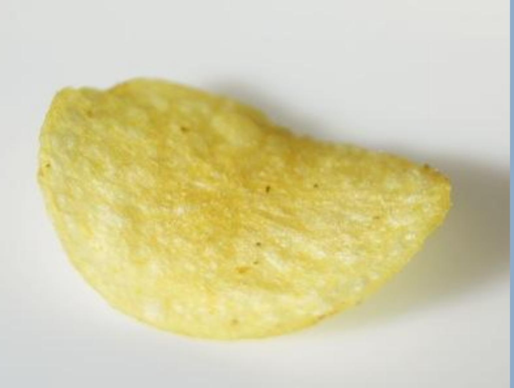

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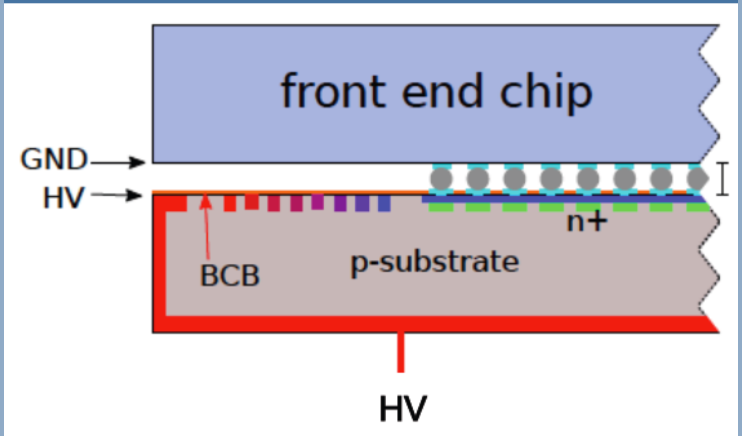


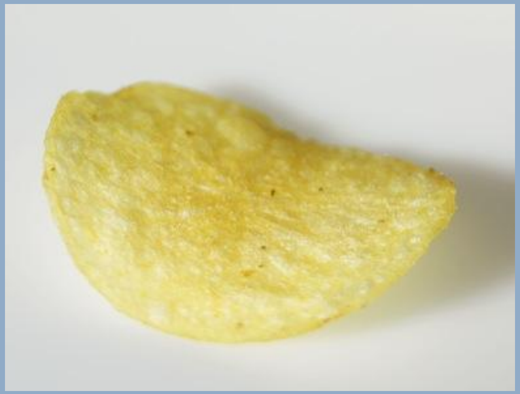
ASICs: Multiple metal stacks and large ROC sizes can lead to internal stresses

Sensors: thinning, UBM, sensor size

- Bow during processing leads to alignment inaccuracies
- Bow during reflow can lead to disconnected bumps

Community and vendors are working on:

- Compensation layers
- Stress release
- Staves
- Temporary support



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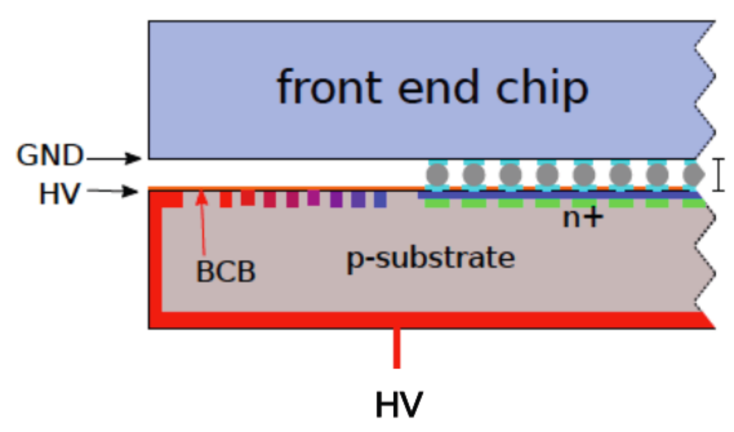

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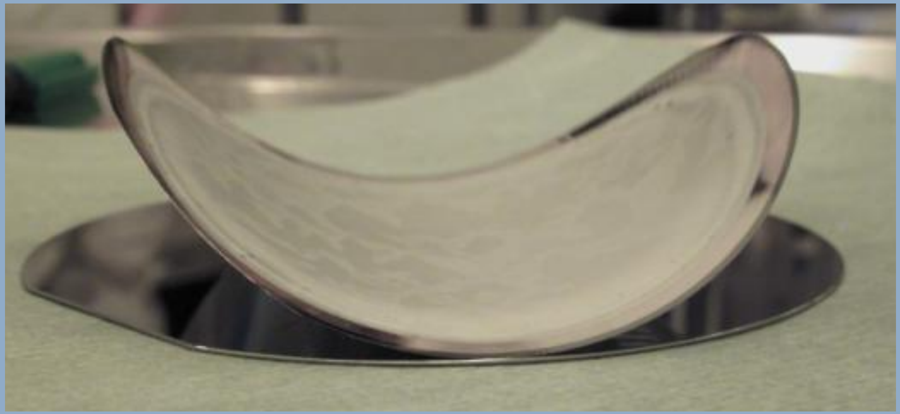
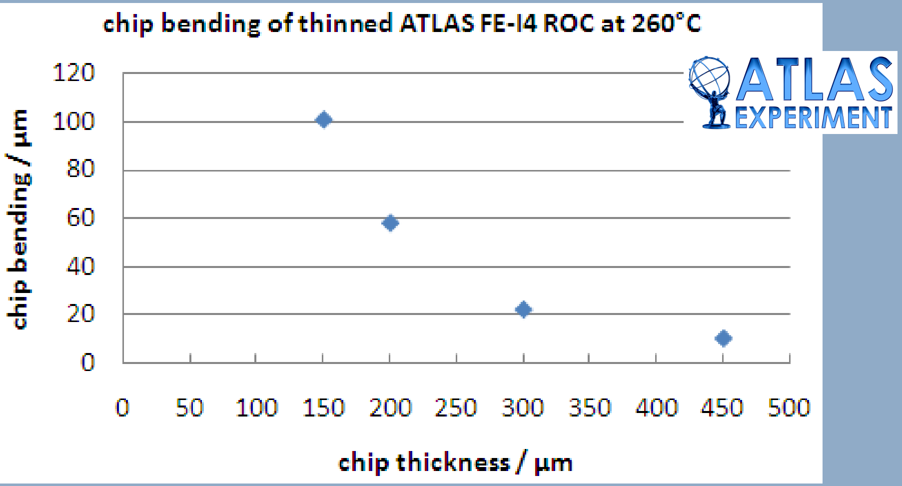


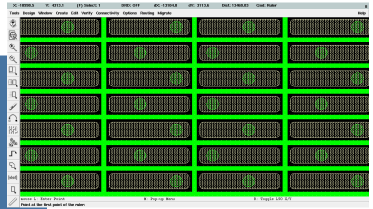
T. Fritzsch, TALENT Summer School, CERN 2013



Pixel Design Goals

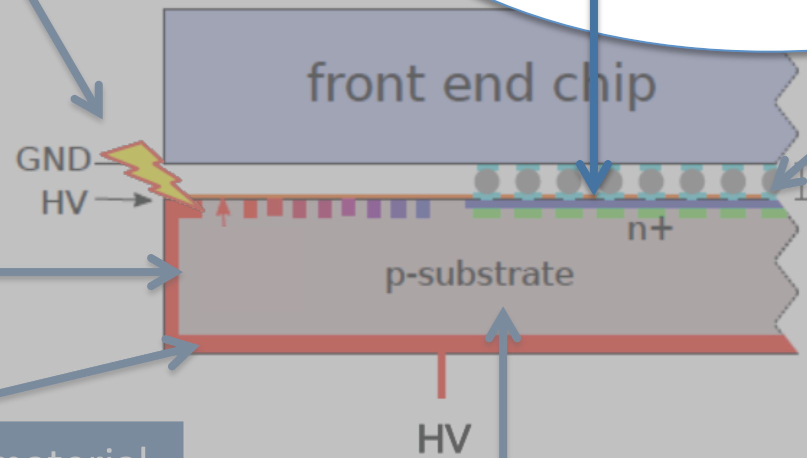
Sparking at sensor edge

Optimize pixel geometries (small pitches)



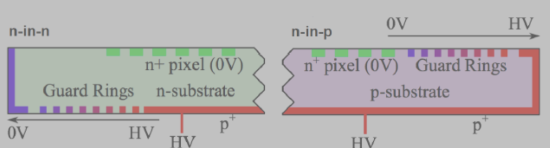
mp bonding (small pitches, thin sensor / ROC)

Decrease inactive edges

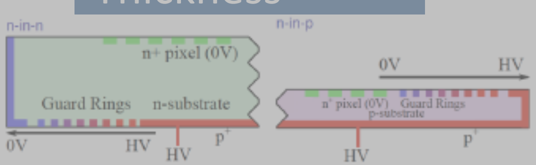


Choose sensor bulk material

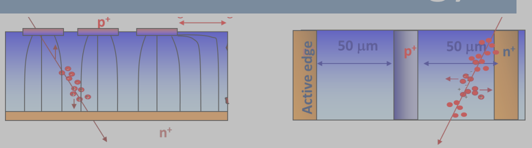
- n-in-p 6” wafers



Sensor (& ASIC) Thickness



Move to 3D technology



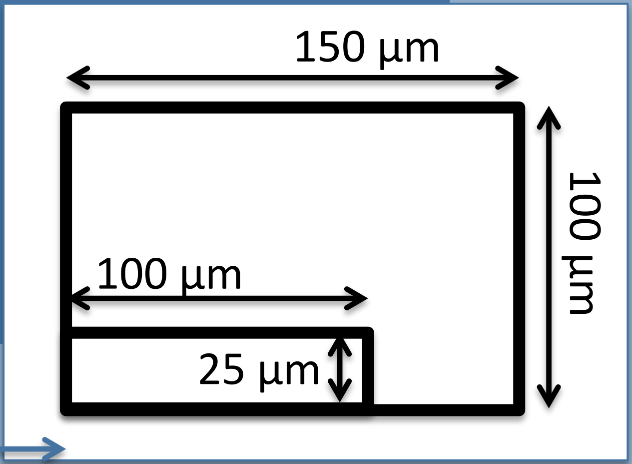
Investigate Fine-Pitch Pixel Sensors

Motivation
- Improve spatial resolution (depending on rϕ, rz)
- Keep occupancy below %-level

→ Investigate 25 µm x 100 µm (and 50 µm x 50 µm)

Problems for fine pitches
- Not enough space for p-stop for each pixel cell
- Not enough space for conventional bias scheme (for sensor tests)
- Not much experience with bias scheme at very high Φ

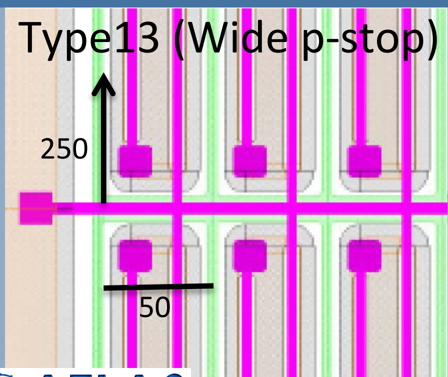
→ Investigate alternatives
  - Common p-stop
  - Common punch through
  - Poly-Si resistors
  - No biasing scheme



Comparison of current CMS pixel cell size to foreseen size

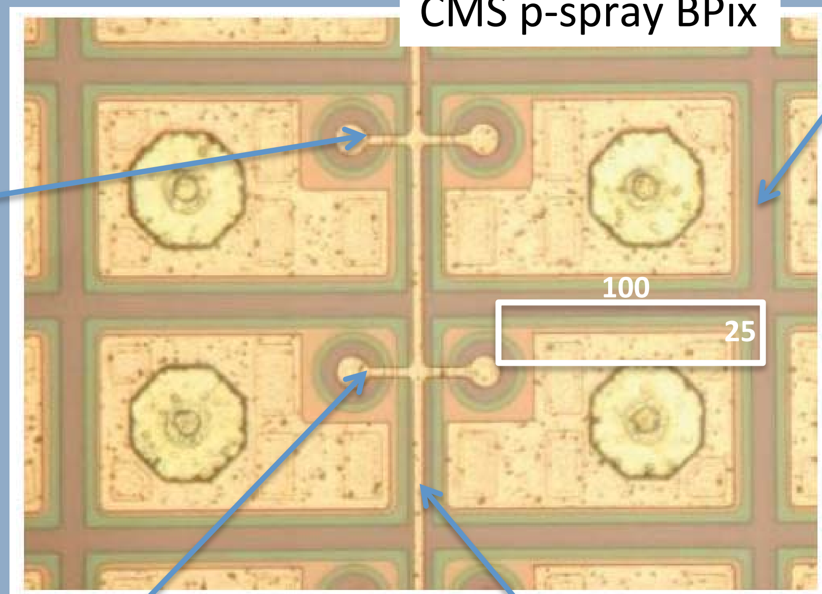
Investigate Alternatives

Poly-Si resistor

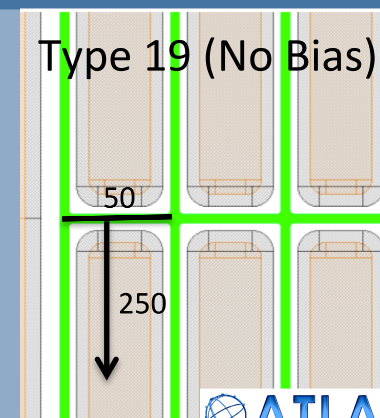


ATLAS EXPERIMENT

CMS p-spray BPix

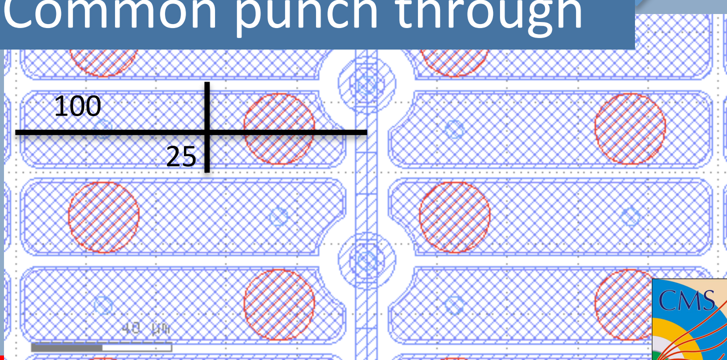


Common p-stop

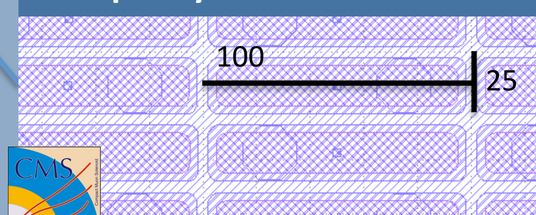


ATLAS EXPERIMENT

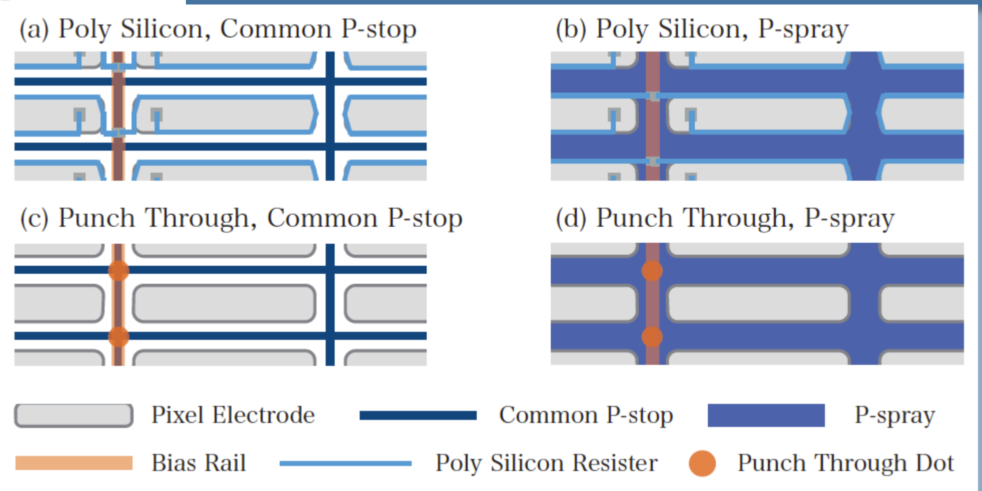
Common punch through

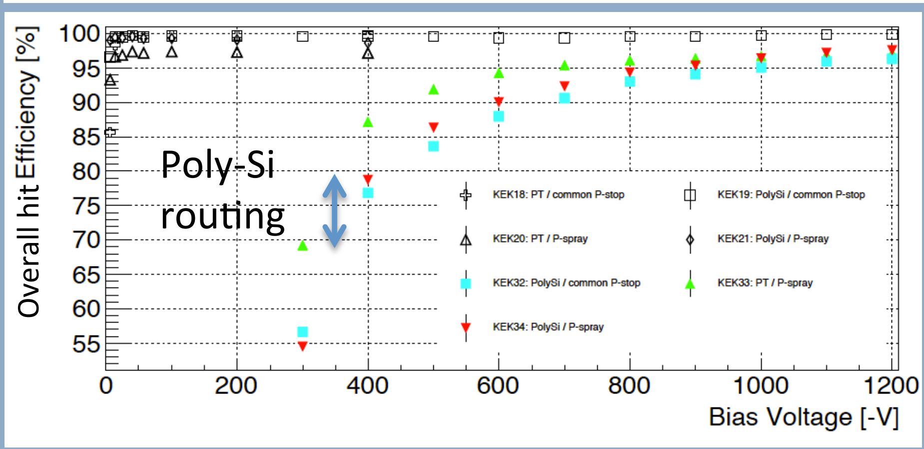


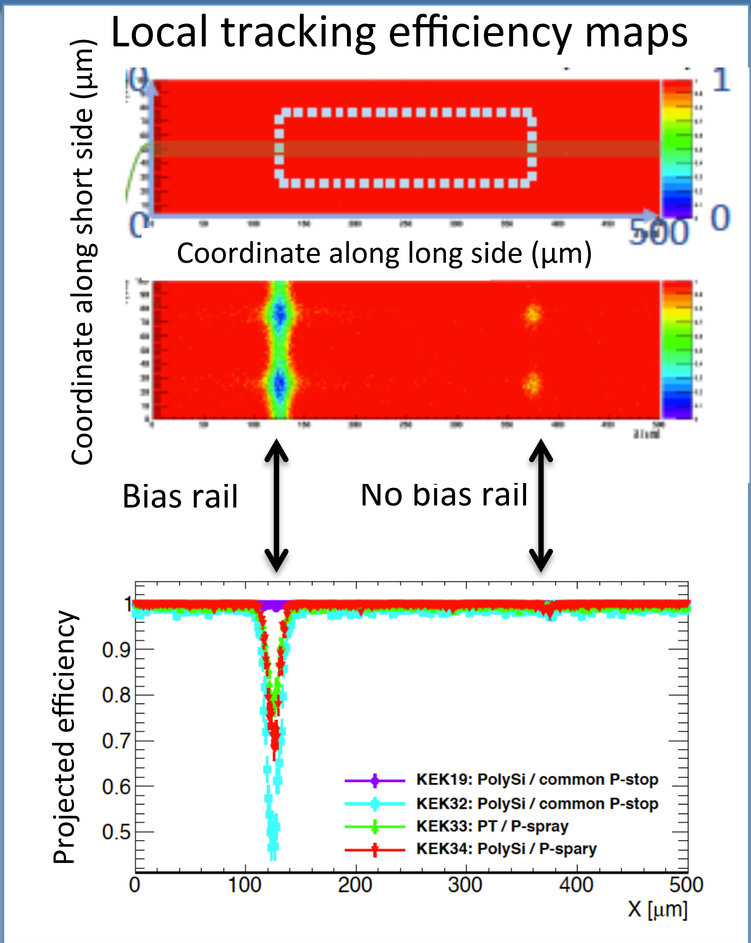
No biasing scheme P-spray



Effect of the Bias Rail at 1×10^{16} cm^{-2}



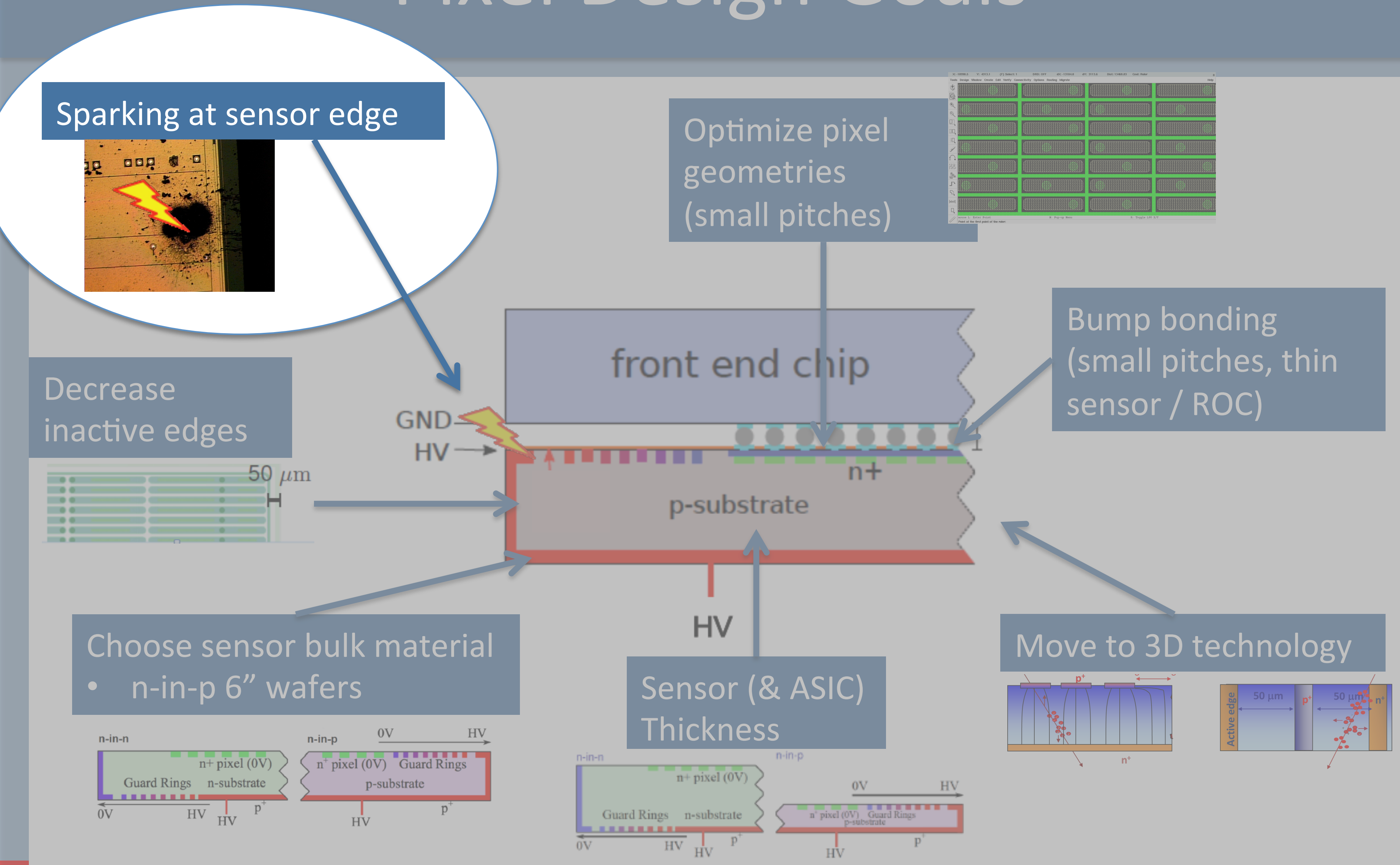




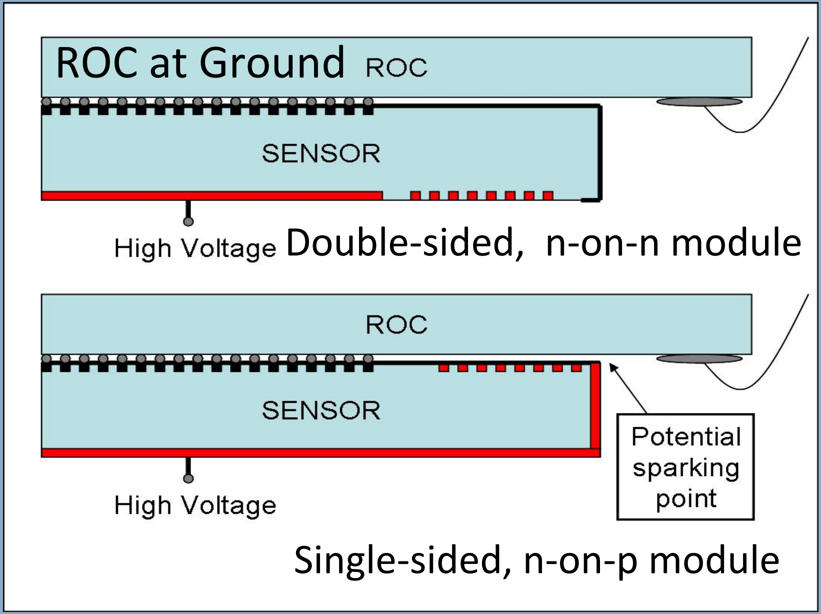
K. Motohashi et al. HSTD9 (DOI: 10.1016/j.nima.2014.05.092)

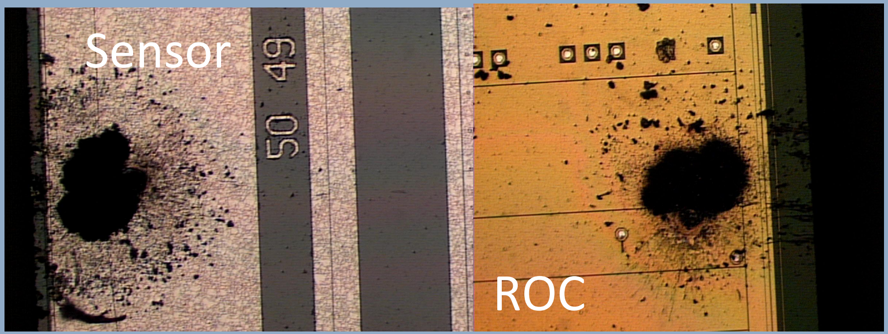
- Severe efficiency loss at the boundary of pixels, under bias rail
- Sight efficiency loss due to the routing of bias resistor

Pixel Design Goals



Spark protection

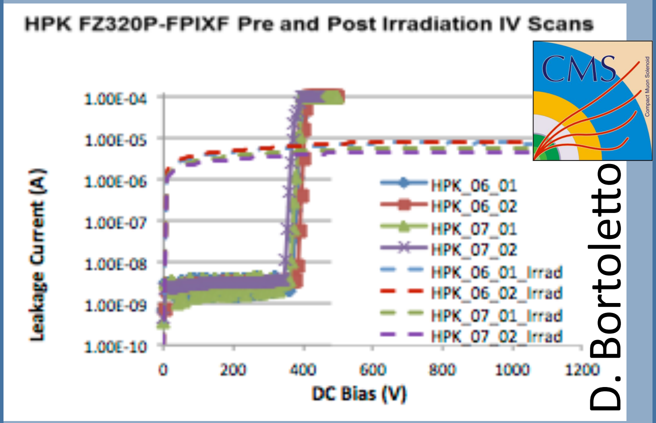




- Consequence of p-type choice: HV is close to ASIC and sparking can occur
- As voltages up to 1000 V may be required, protection is necessary

Post process solutions

- Encapsulation - becomes brittle after irradiation
- Paralyne-N coating (ATLAS & CMS) -Tests show very good radiation hardness



In process solutions

- BCB coating (ATLAS) with lithography on sensor surface
- N+ implantation + passivation barrier (under test)

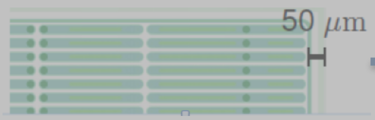
Pixel Design Goals

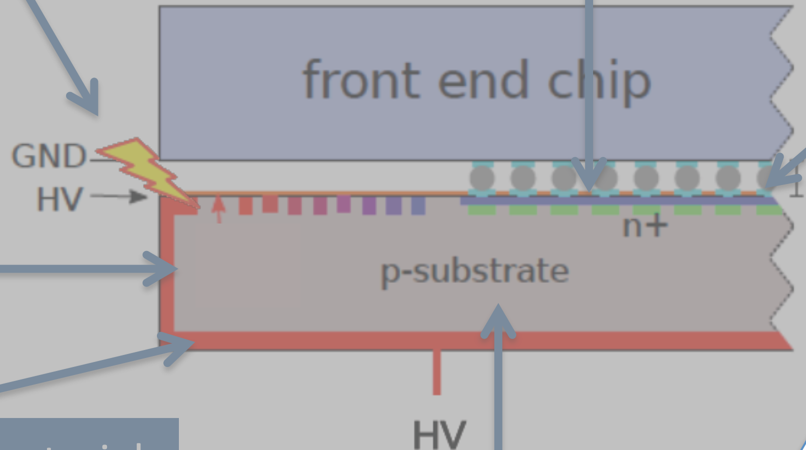
Sparking at sensor edge

Optimize pixel geometries (small pitches)

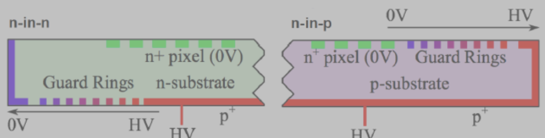
Bump bonding (small pitches, thin sensor / ROC)

Decrease inactive edges





Choose sensor bulk material
- n-in-p 6” wafers



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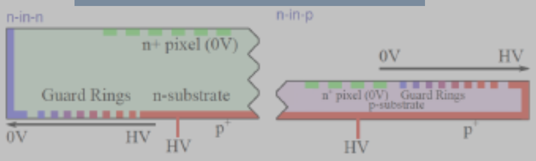
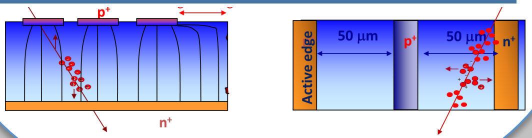
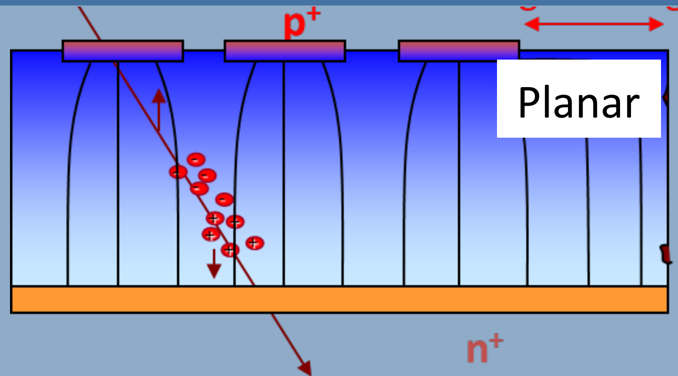


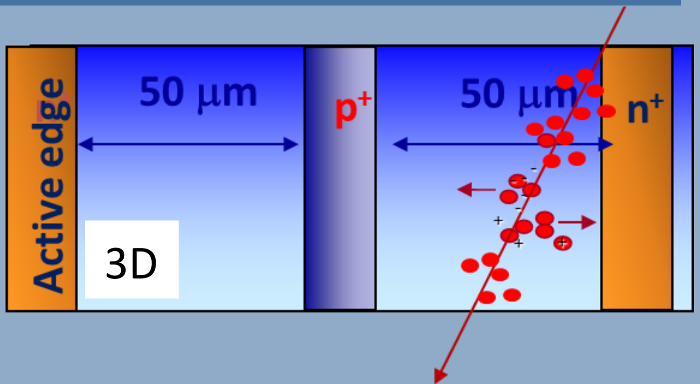
Move to 3D technology



Thin Planar Sensors and 3D

The most promising technologies that are options for the phase II pixel upgrade: 3D and planar pixel sensors





Common advantages:
Short drift path
Higher fields at same V_{bias}
Common problems:
ROC availability
Bump bonding

Thin planar sensors:
- Low total leakage after irradiation

Drawback:
- Smaller initial signal ($76e^-/\mu m$)
- Design limits for small pixels
- Thinning of handling wafer

3D sensors:
- Thick sensor possible

Drawback:
- Higher Capacity
- Low yield
- Are very small pitches possible?

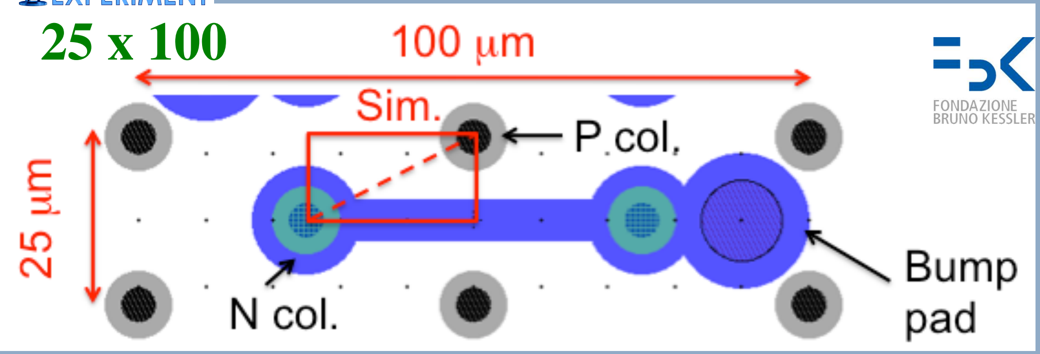
ATLAS and CMS are jointly submitting 2 new productions!

3D Sensors with Small Pitch

- Smaller pitches require very narrow columns
- And smaller inter-electrode spacing required for high Φ
- Defined aspect ratio between hole heights and width
- To keep aspect ratio, sensors need to be thinner

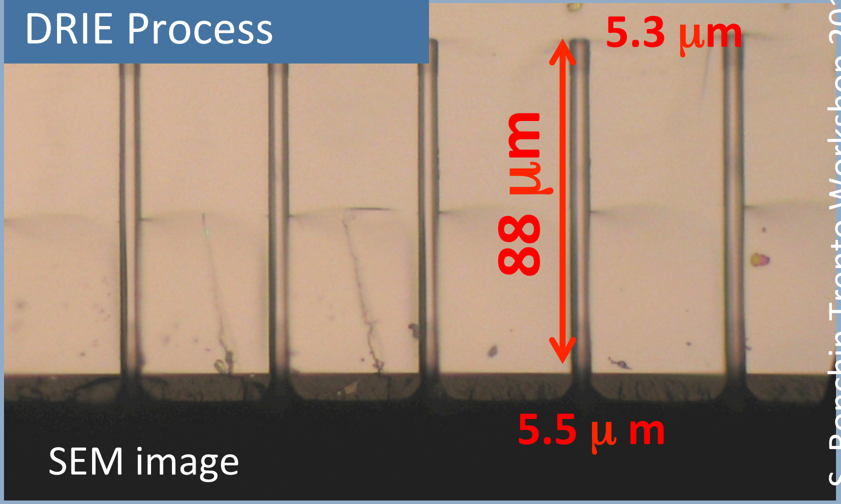
→ Use handling wafer, requires thinning

Issue could arise from placing bump pads over columns



R. Mendicino Trento Workshop 2015

DRIE Process



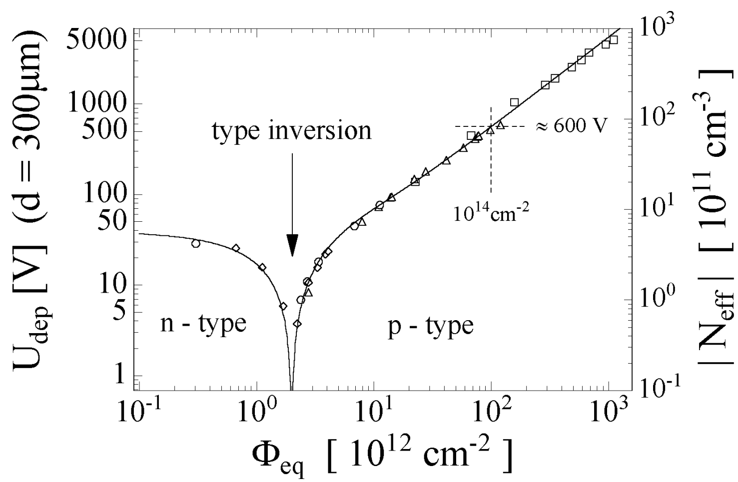
S. Ronchin Trento Workshop 2015

Summary

- The vast majority of the pixels is defined to be n-in-p
- Technical challenges are now to fine tune solutions
  - Technology choice for innermost layers
  - Choice of optimal thickness and material
  - Handling and processing of thinned sensors and ASICs
  - Industrial solution to prevent sparking
  - Layout and design of small pitch pixels
  - Cost effective large area production
- Sensor performance requirements at the HL-LHC result in huge synergies between the experiments
- No show stoppers!

Depletion voltage

With particle fluence:



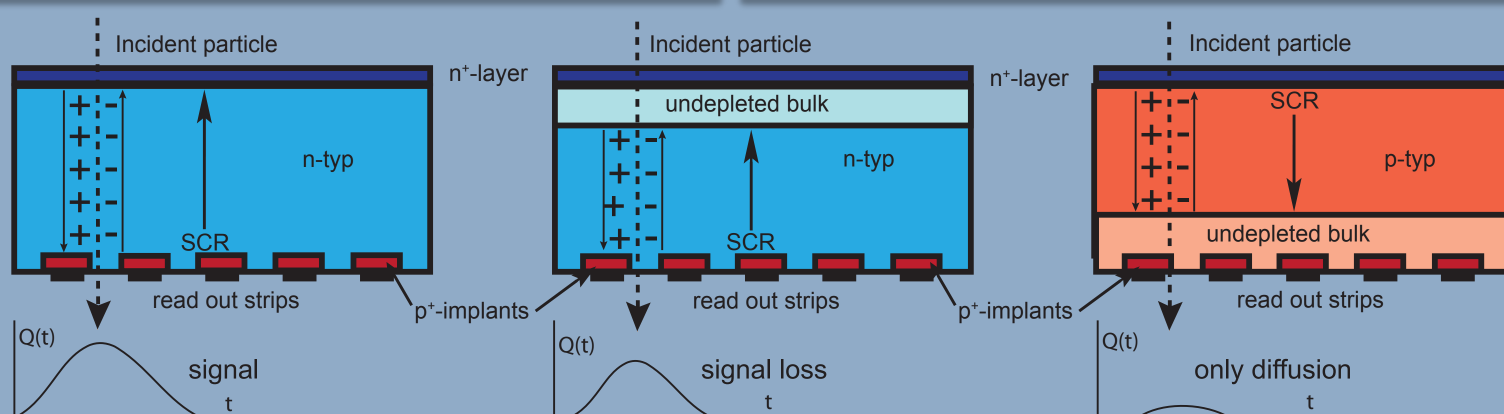
R. Wunsdorf, PhD thesis 1992, Uni Hamburg

$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$

- Acceptors compensate original doping
- Type inversion from n- to p-type
- Increase of depletion voltage after SCSI

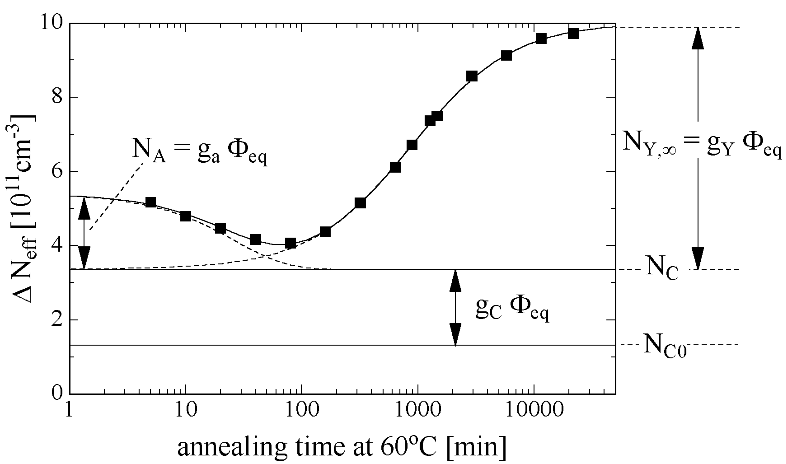
➔ Signal loss

- Annealing studies show impact of high T maintenance times



Depletion voltage

With annealing:



M. Moll, PhD thesis 1999, Uni Hamburg

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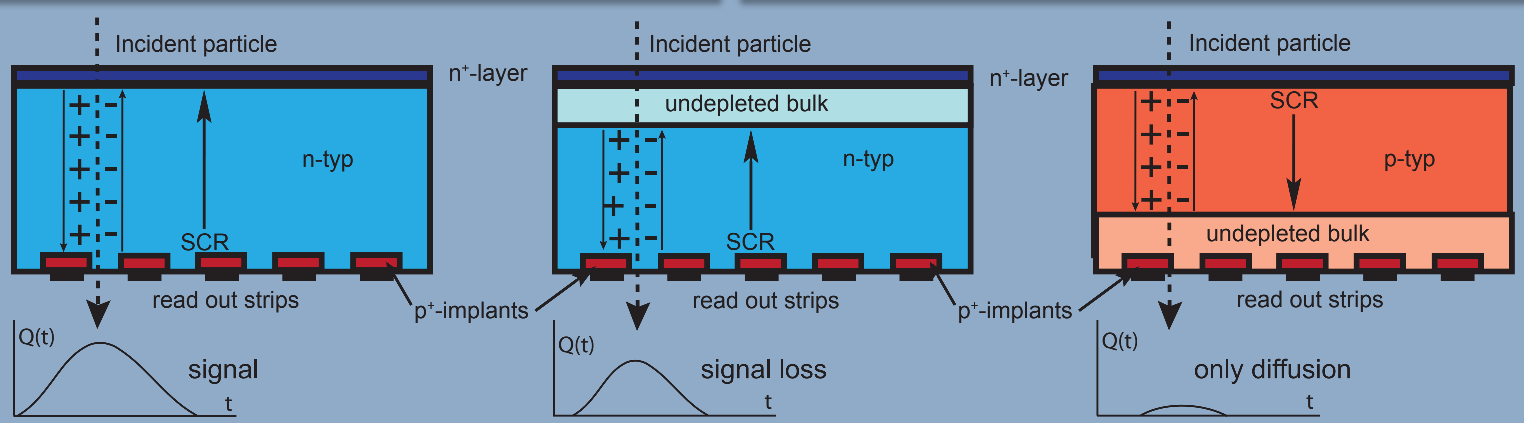
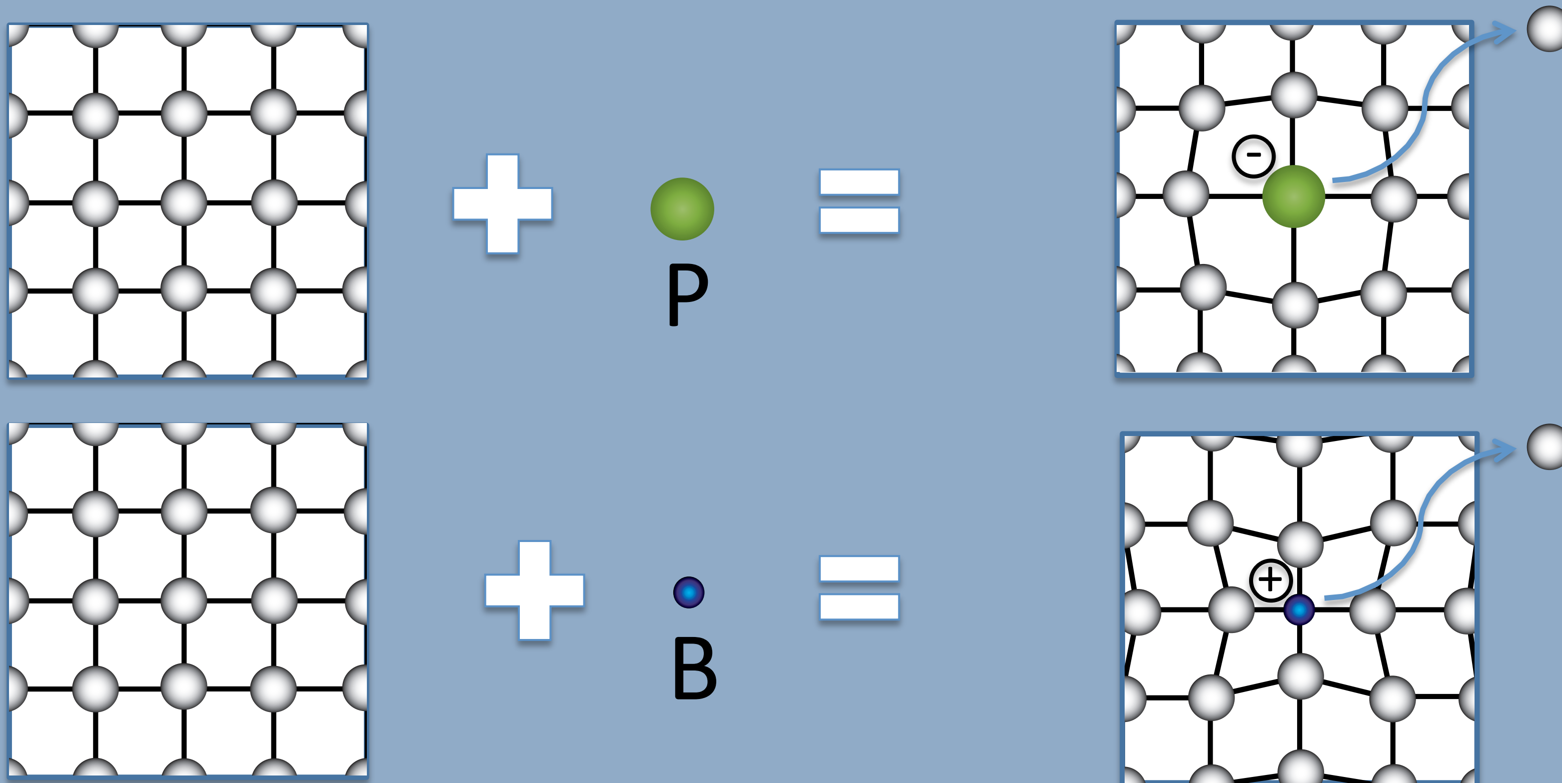


Doping atoms are "defects"…



…with desired impact on the detector properties.

Surface and Bulk damage

Today's knowledge:

Surface defects in p-on-n sensors:

- Oxide-charges build-up from photons
- Some understanding of the generation of interface-states

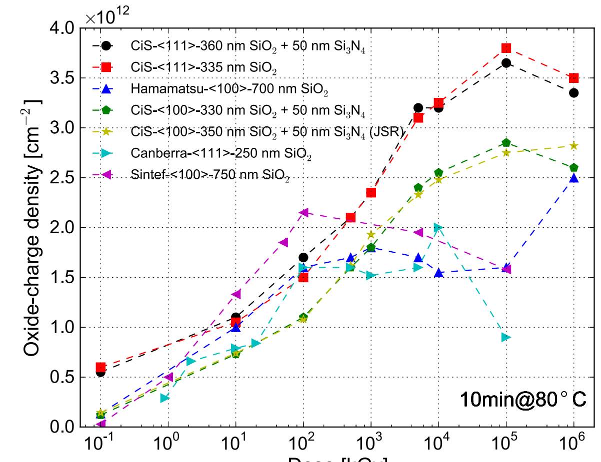
→ Effective model for simulations

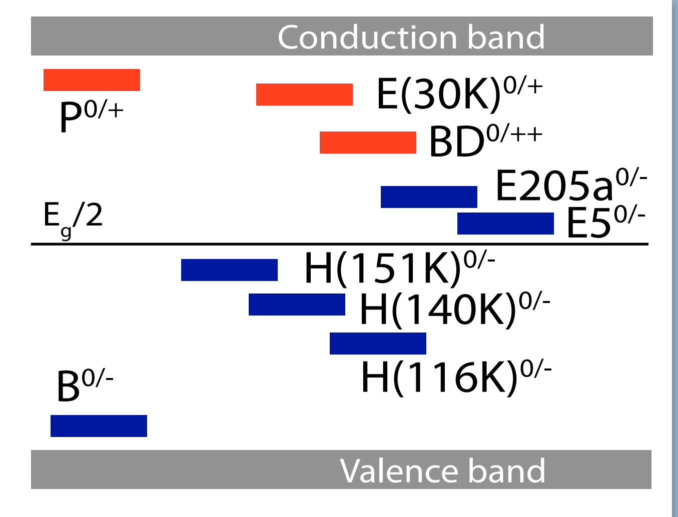
Bulk defects meanwhile also in n-on-p sensors:

- Leakage current scales with fluence, originates from cluster defects, mechanism not fully understood
- Several bulk defects with impact on depletion voltage found, impact on space charge not fully understood
- Some defects suspected to do trapping

→ Several models with 2-, 3-, 5- levels ("free parameters") available for up to $\Phi=10^{15}$ cm^{-2}

Dose dependence of oxide-charge density





Impact of Radiation damage

Surface damage (Ionising Energy Loss):

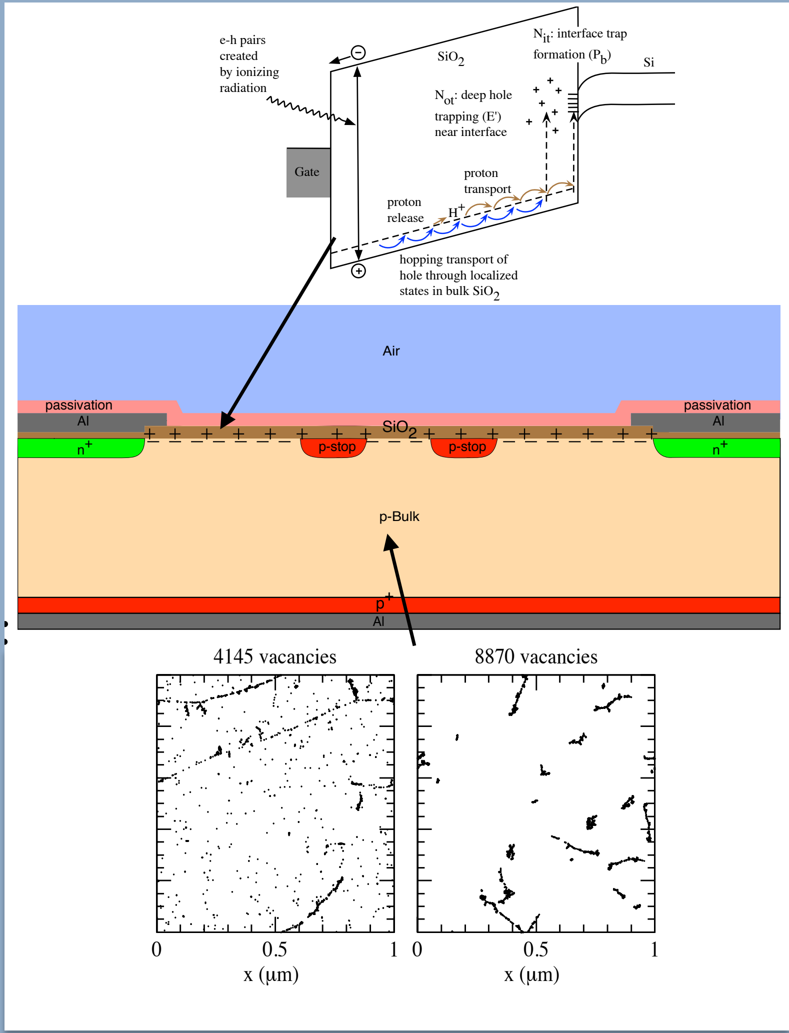
- Increase of oxide charge
- Increase of interface traps

➔ Increase of leakage current
➔ Change of break-down voltage
➔ Change of charge collection

Bulk damage (Non-Ionising Energy Loss):

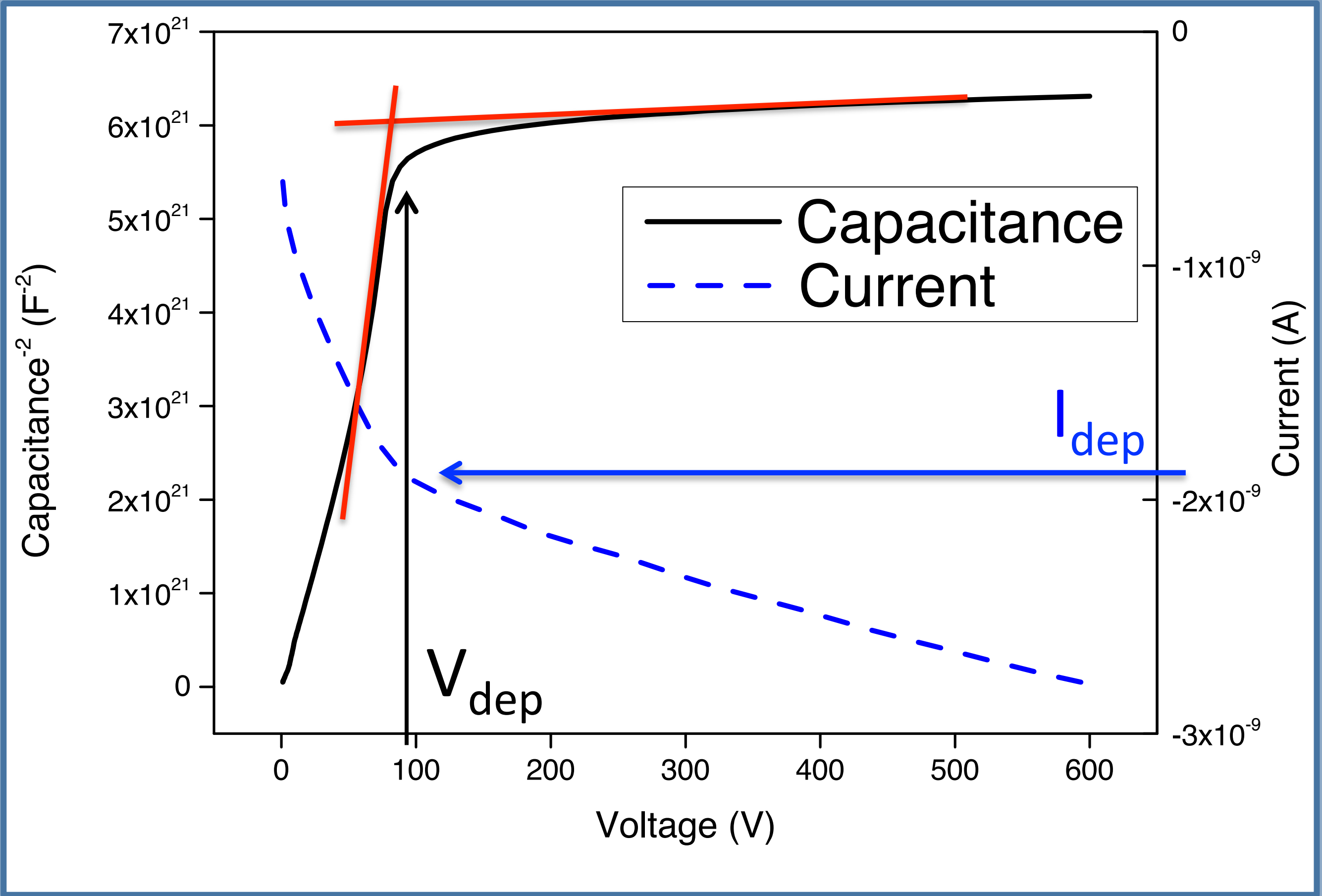
- Cluster and point defects

➔ Change of the space charge
➔ Change of depletion voltage
➔ Change of trapping



Extraction of sensor parameters

Capacitance-Voltage and Current-Voltage measurement



Capacitance measurement:
- 20 °C (10 kHz)
- 0 °C (at 1 kHz)
- -20 °C

(at 1 kHZ & 455 Hz)

➔ Extract depletion voltage V_{dep}

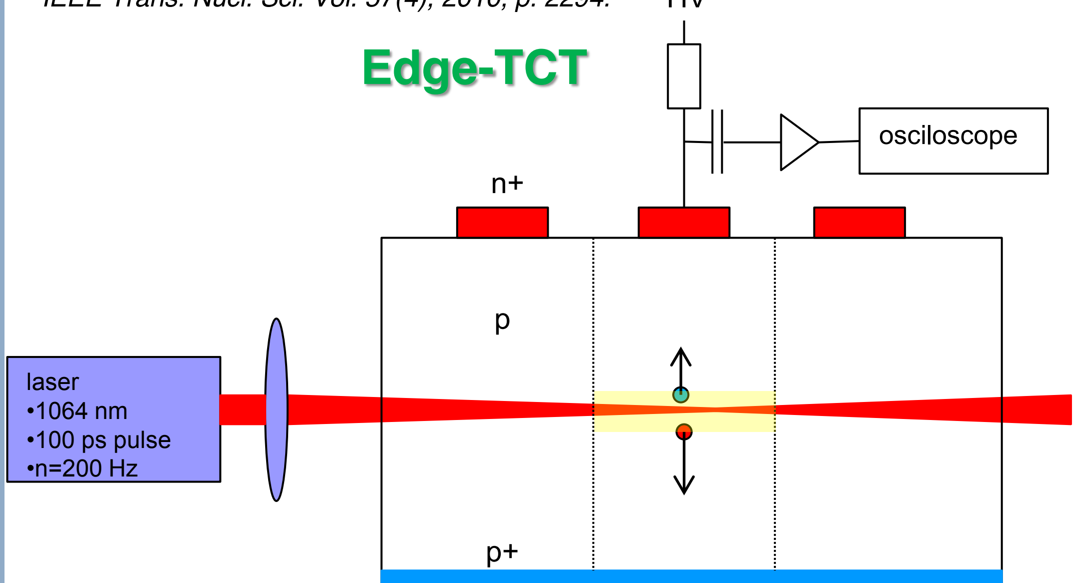
➔ Calculate:

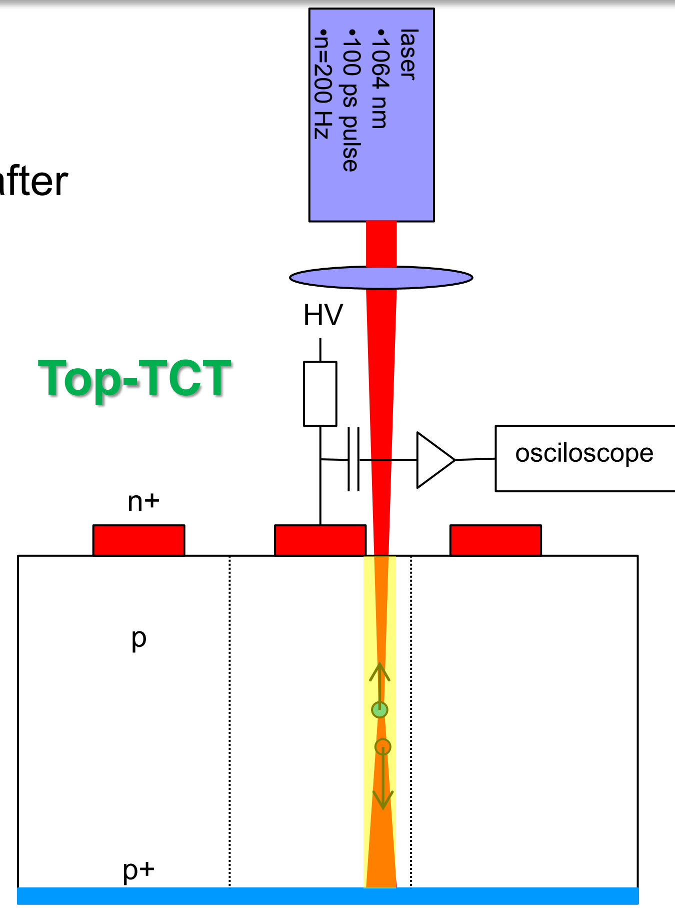
$N_{eff} = 2\varepsilon\varepsilon_0 V_{dep}/q_0\, d^2$

TCT techniques

Measuring induced currents with fast current amplifiers after e-h generation with the laser pulse!

IEEE Trans. Nucl. Sci. Vol. 57(4), 2010, p. 2294.





- Probing the field in depth (average)
  - Charge collection profile: $Q(y) = \int_0^{20ns} I(y,t)dt$
  - Velocity profile : $I(y, t{\sim}0) \propto (v_e + v_h)(y)$
- Probing the lateral field (average)
  - Properties of the mid-strip region
  - Multiplication profiles
  - Trapping induced charge sharing

G. Kramberger, Vertex 2012