Pixel Sensor Development Part I

Material, Small Pitch, 3D Technologies

A. Junkes

March 6th 2015
Alliance Detector Workshop
Berlin

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Universität Hamburg
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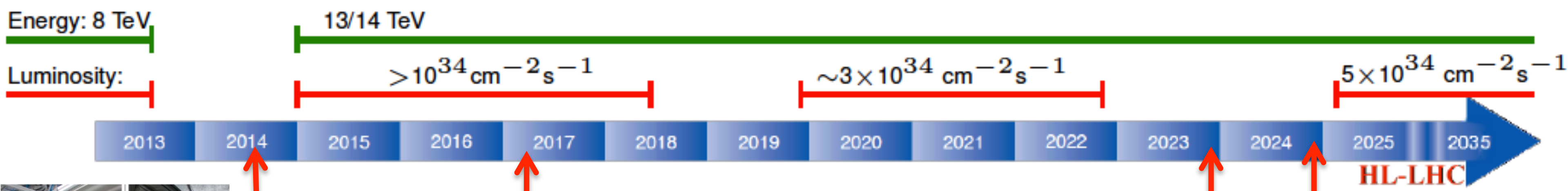
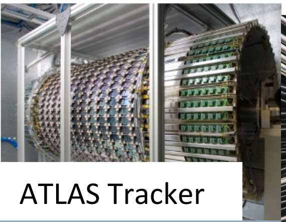
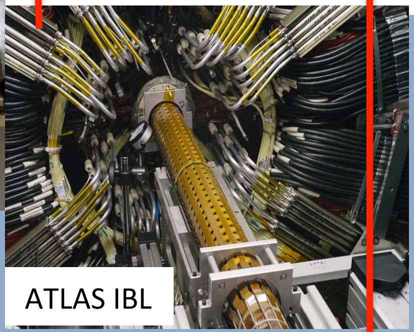
ATLAS EXPERIMENT

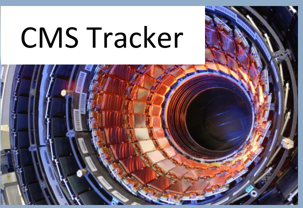
CMS
Compact Muon Solenoid

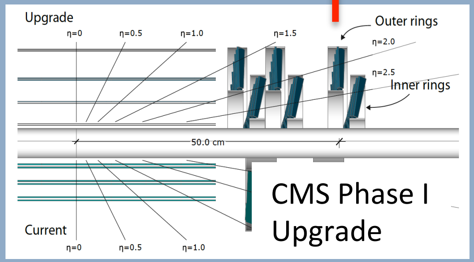
Pixel Detectors for HL-LHC

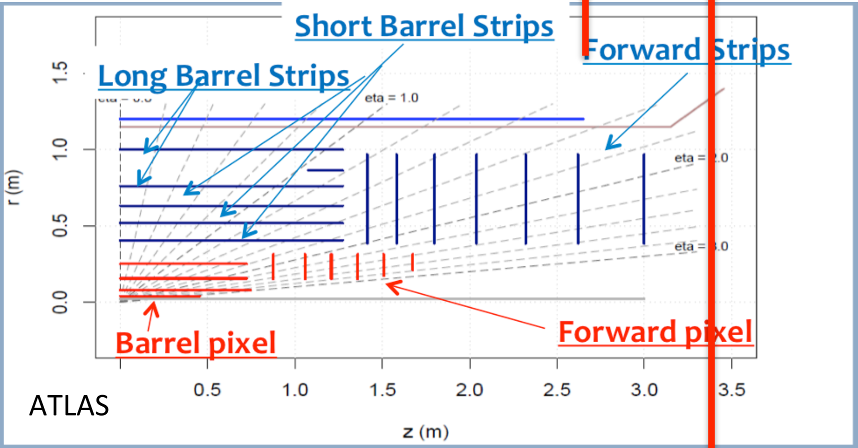


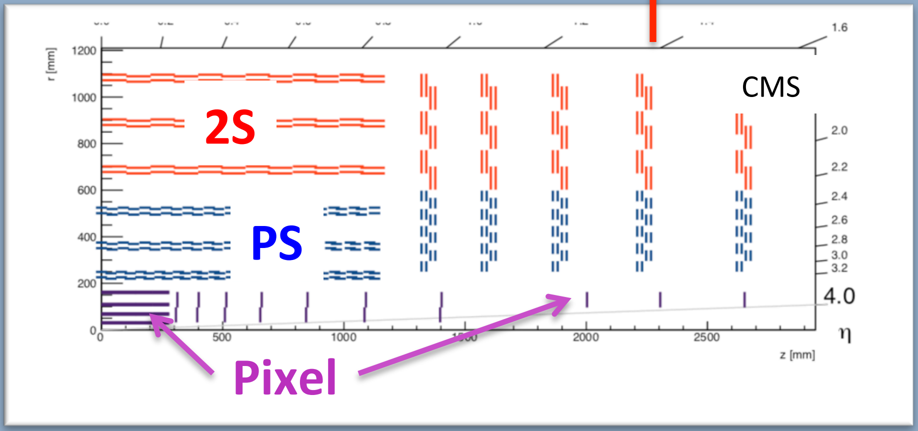




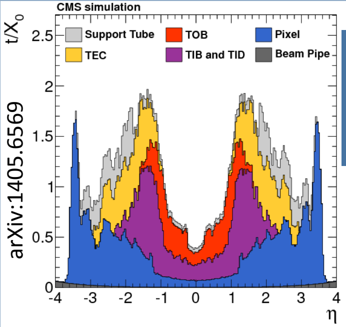






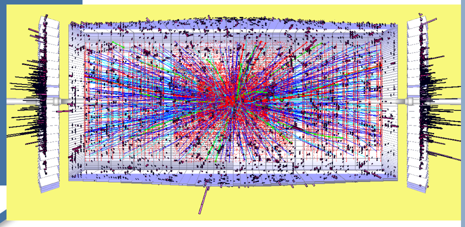


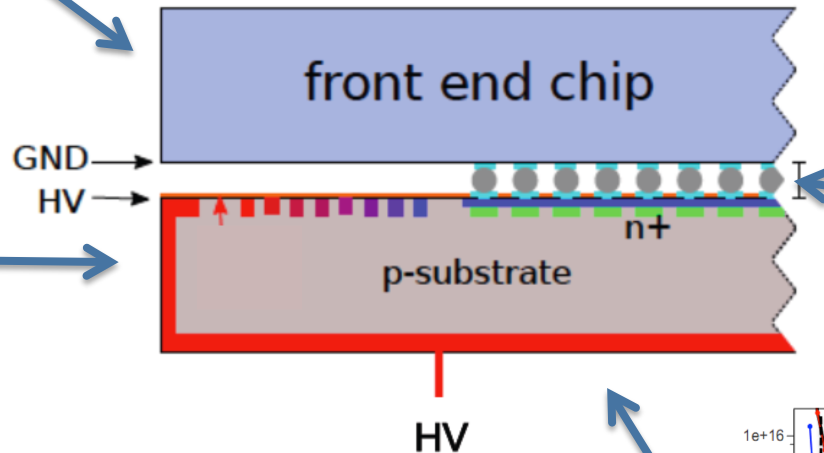
Pixel Design Challenges



Reduce material budget

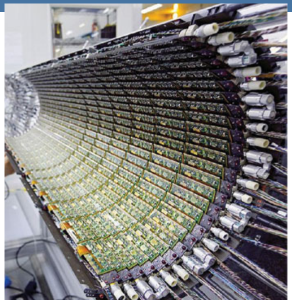
Luminosity: $5x10^{34}$ cm^{-2} s^{-1}
→ Improve spatial resolution and maintain occupancy at ≈ % level



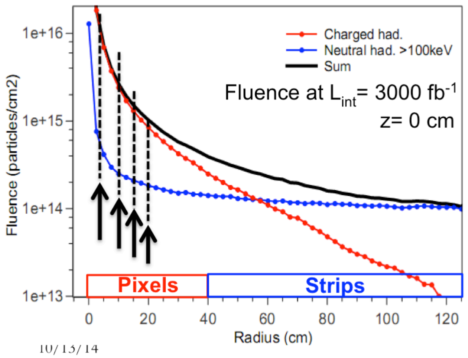


Each experiment has to cover 8 + ? m^2 with silicon
→ Be cheap and reliable

New inter-connection techniques

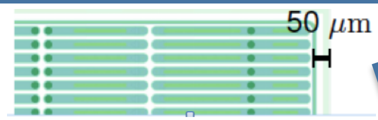


Improve radiation tolerance
→ Maximize efficiency and minimize noise hits

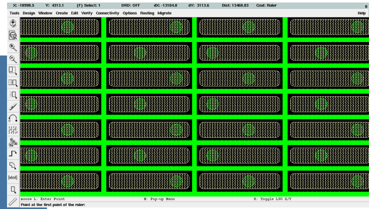


Pixel Design Goals

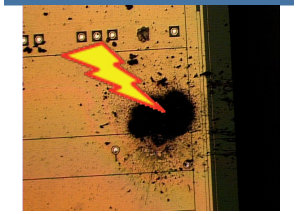
Decrease inactive edges

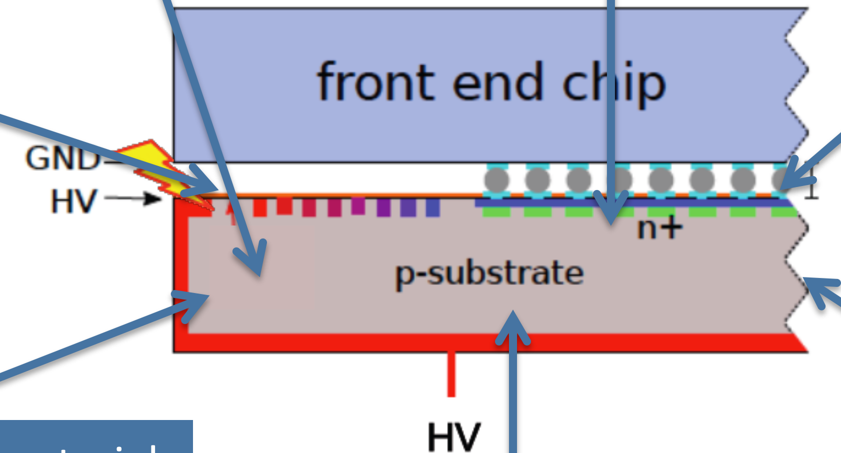


Optimize pixel geometries (small pitches)



Sparking at sensor edge

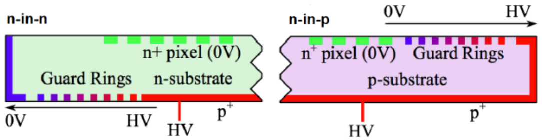




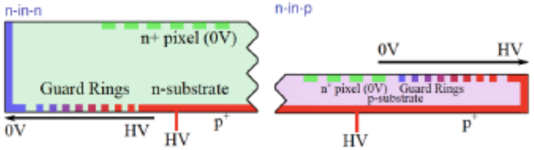
Bump bonding (small pitches, thin sensor / ROC)

Choose sensor bulk material

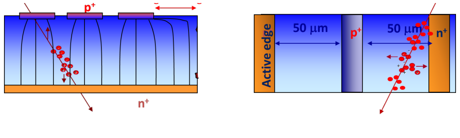
- n-in-p 6” wafers



Sensor (& ASIC) Thickness



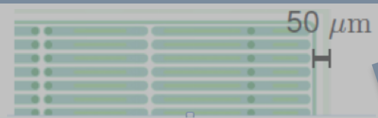
Move to 3D technology



Pixel Design Goals

This presentation

Decrease inactive edges



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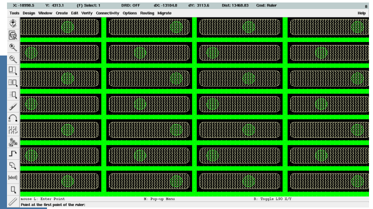
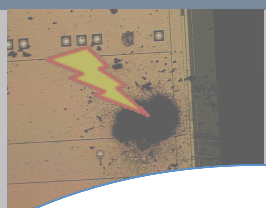
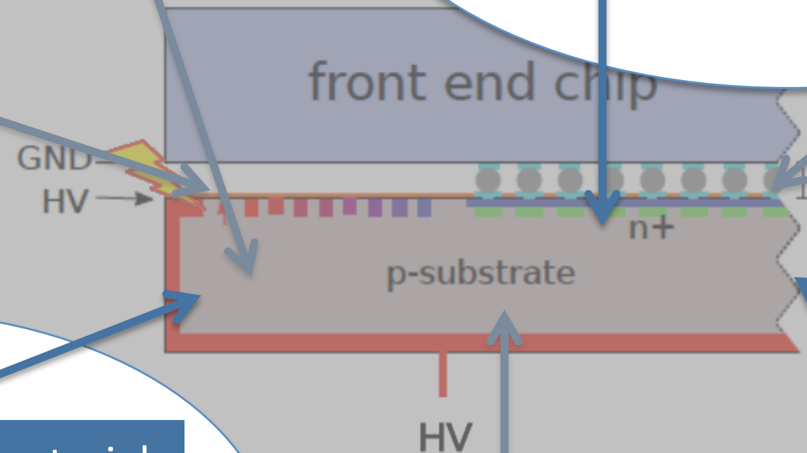


Sparking at Sensor edge





...onding (small pitches, thin sensor / ROC)

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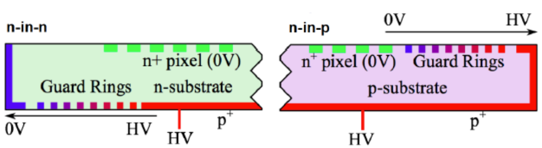

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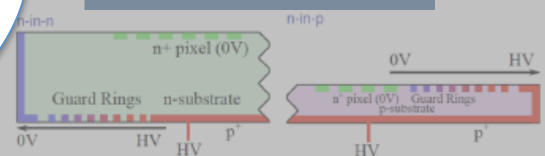
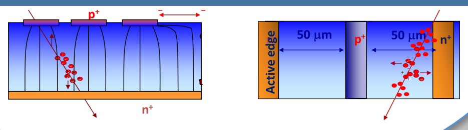
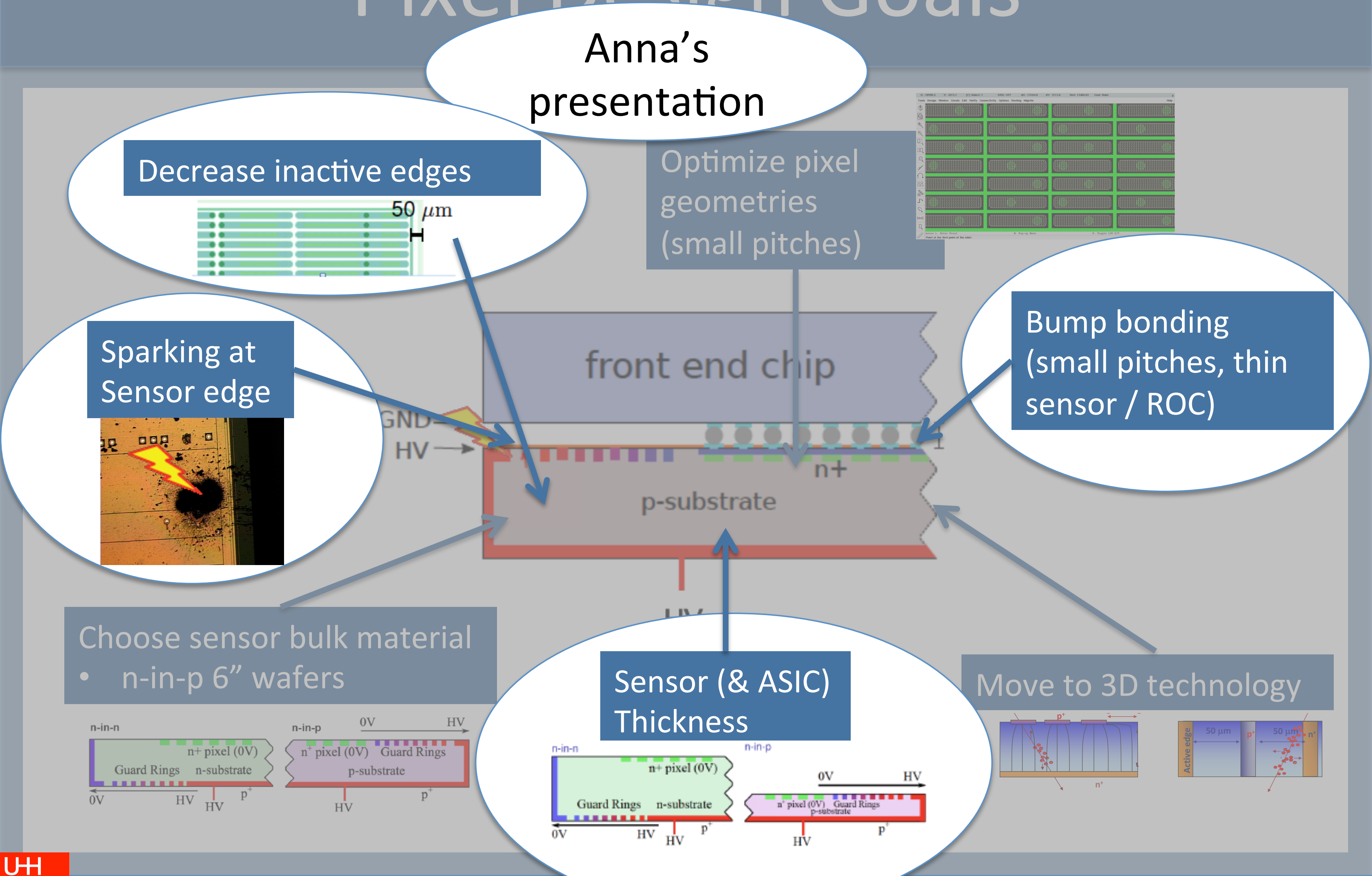


Move to 3D technology



Pixel Design Goals



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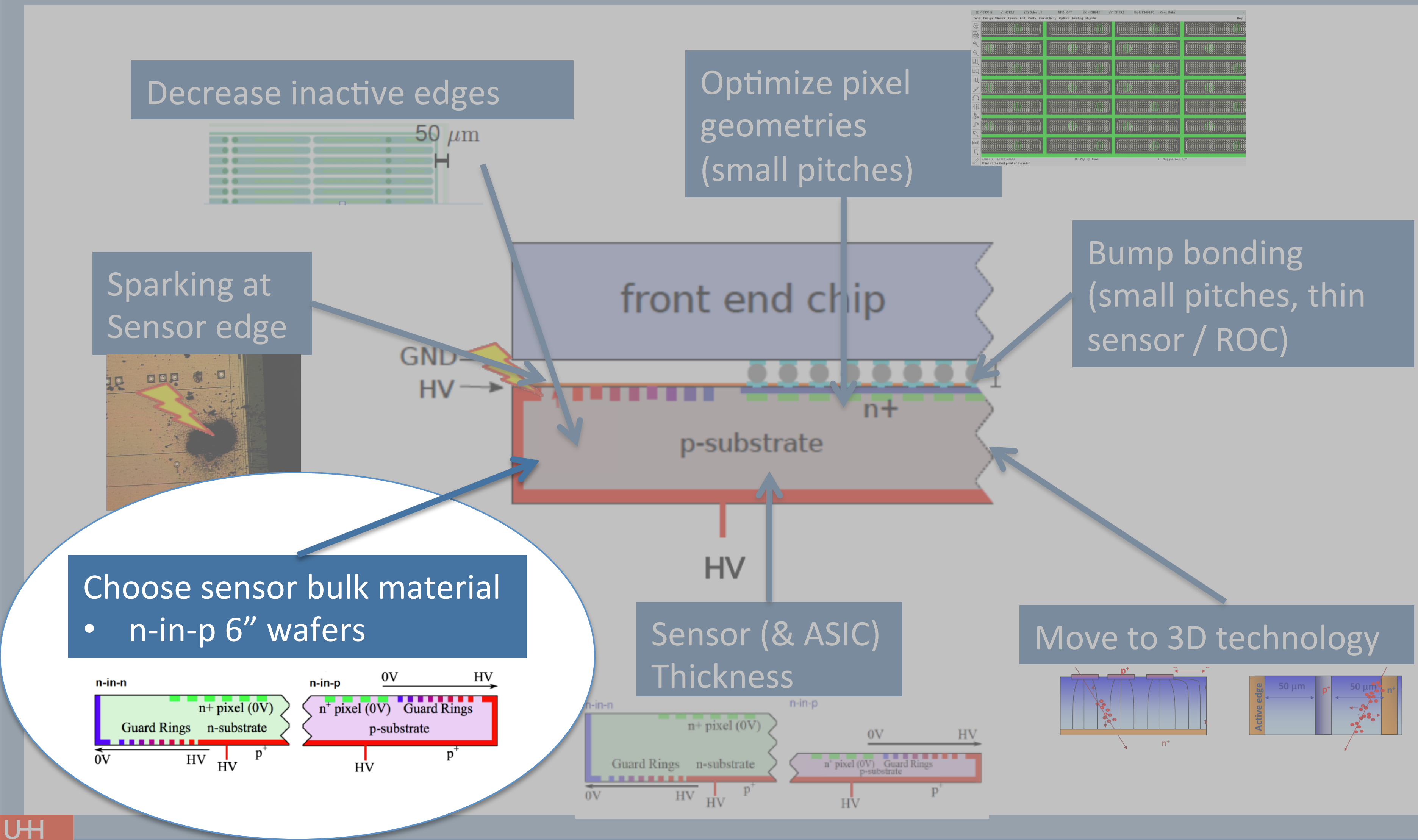
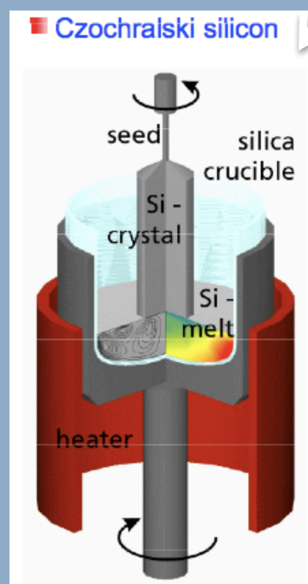


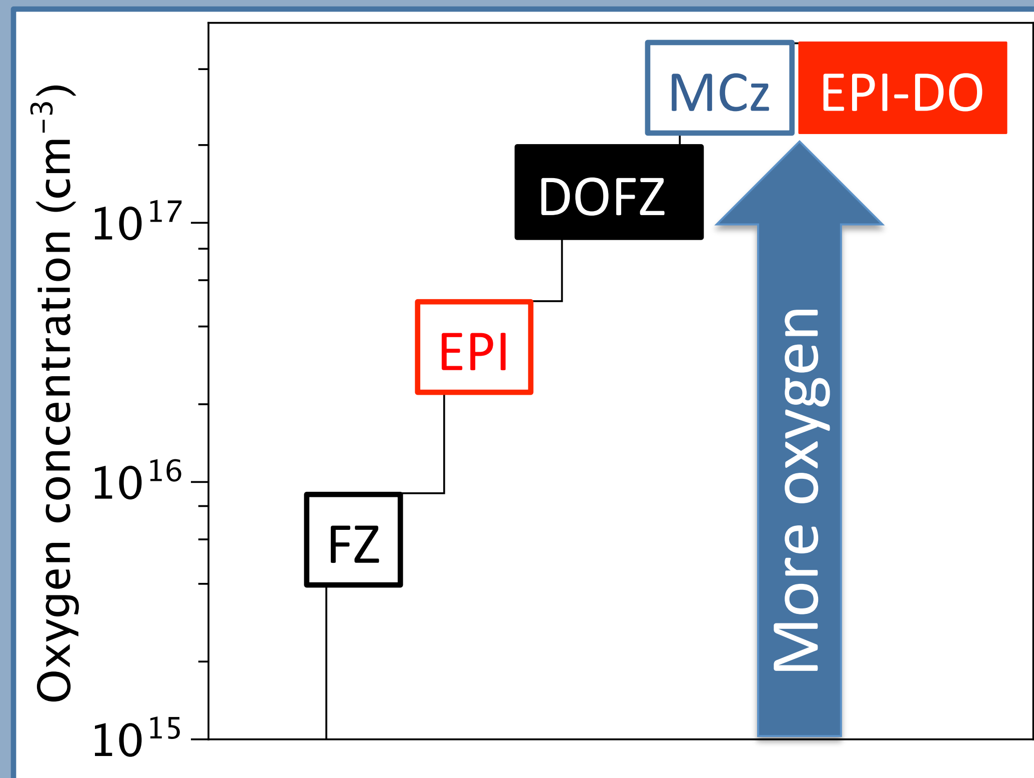
Silicon "Materials"

- 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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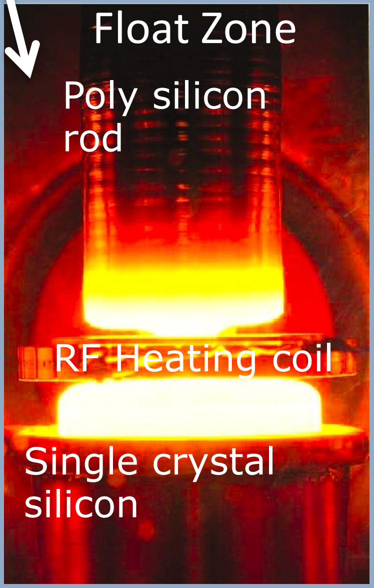

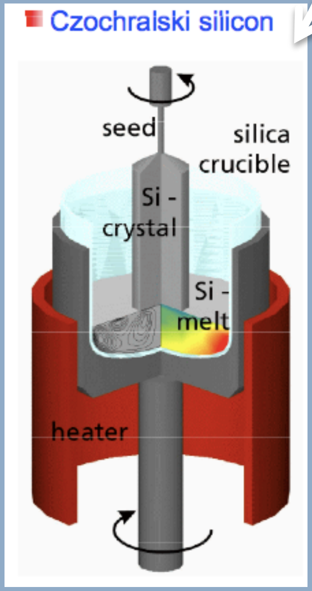

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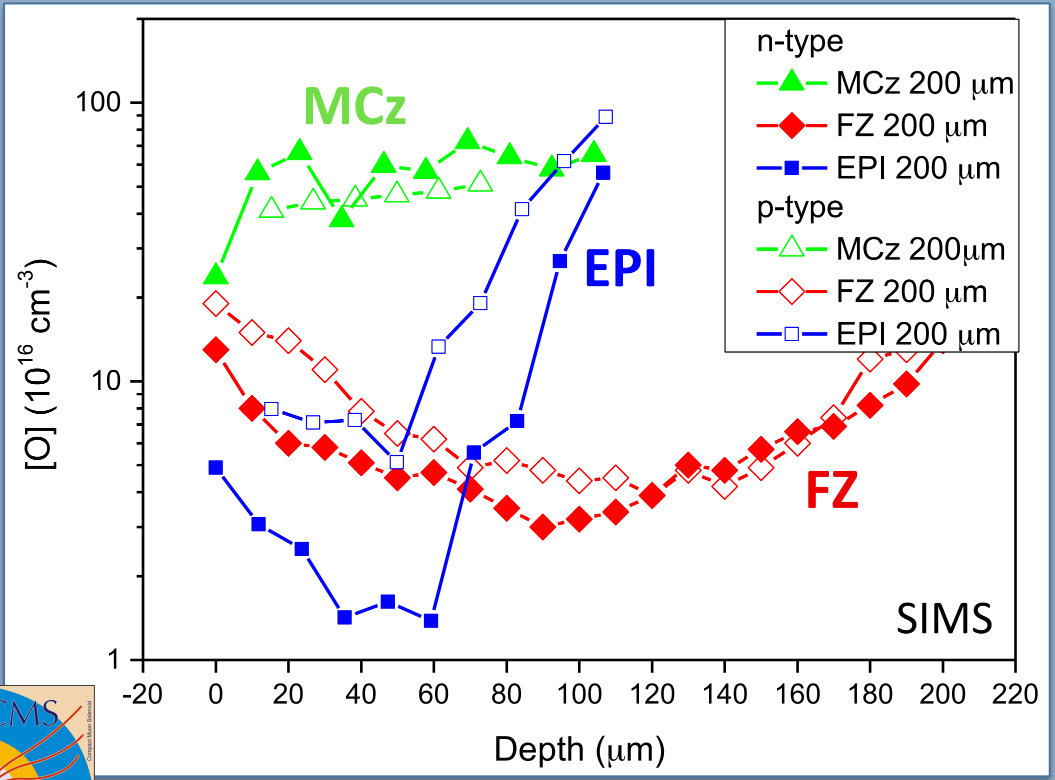
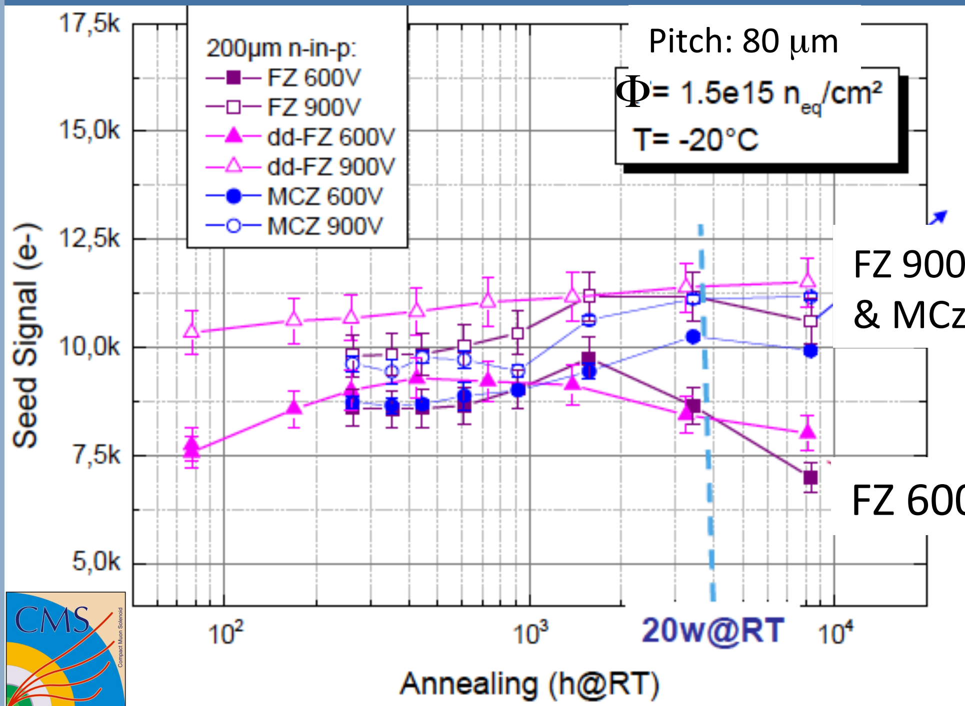
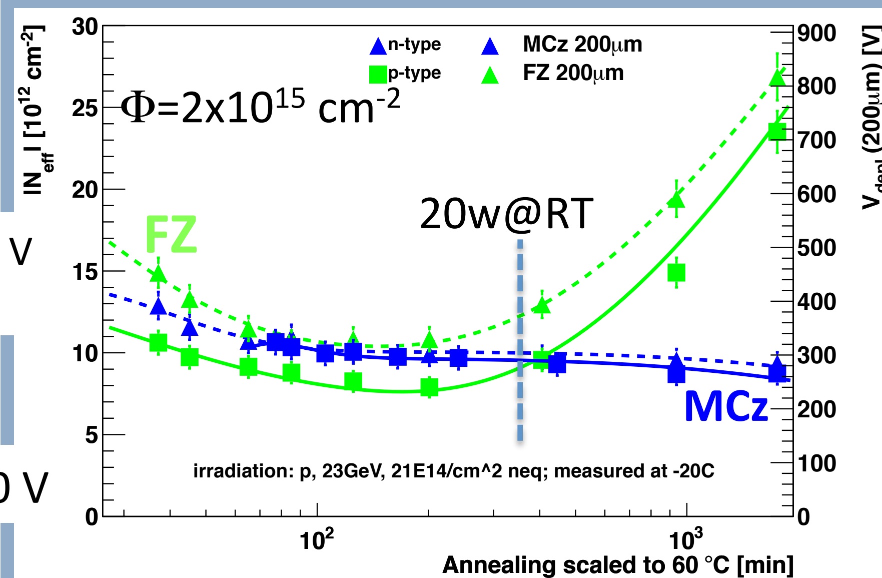


Advantageous Annealing Behavior of p-MCz

Proton & neutron irradiated strip sensors



Proton & neutron irradiated pad diodes



J. Erfle, PhD thesis, Hamburg University 2014

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

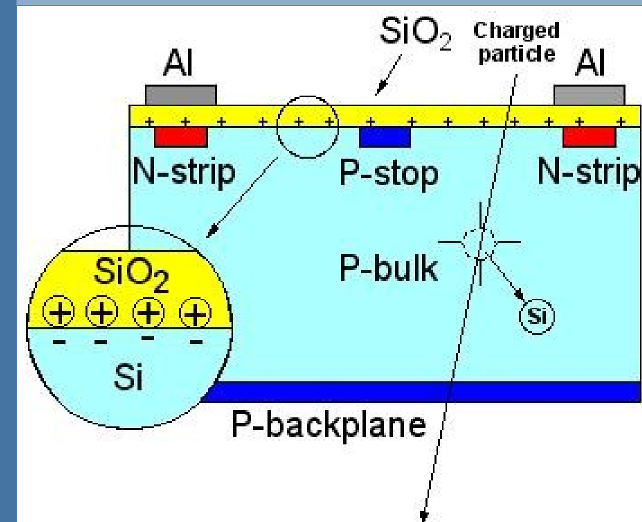
→ Longer warm up or controlled annealing periods possible

→ Potentially good for power dissipation

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

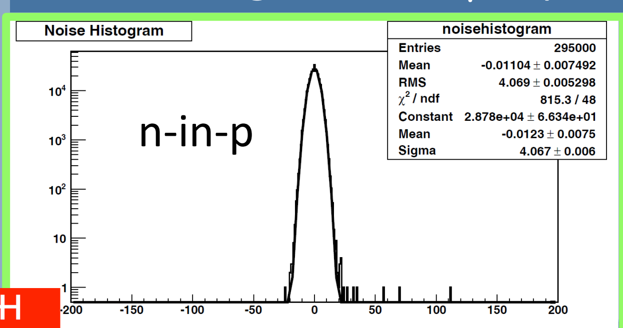
N-side read out is the preferred read out scheme

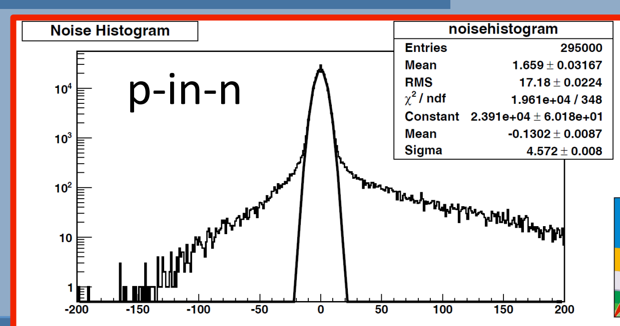
- Favourable combination of weighting and electric field in heavily irradiated detector
- CMS results show potential noise effects at doses > $1x10^{15}\ n_{eq}/cm^2$
- T-CAD simulations **confirm** the tendency of p-in-n strip sensors to exhibit higher electric fields at the strips for increasing oxide
- N-in-p is a single sided process → cost effective
- Thin silicon with a double-sided process unlikely because of much lower yield (handling)



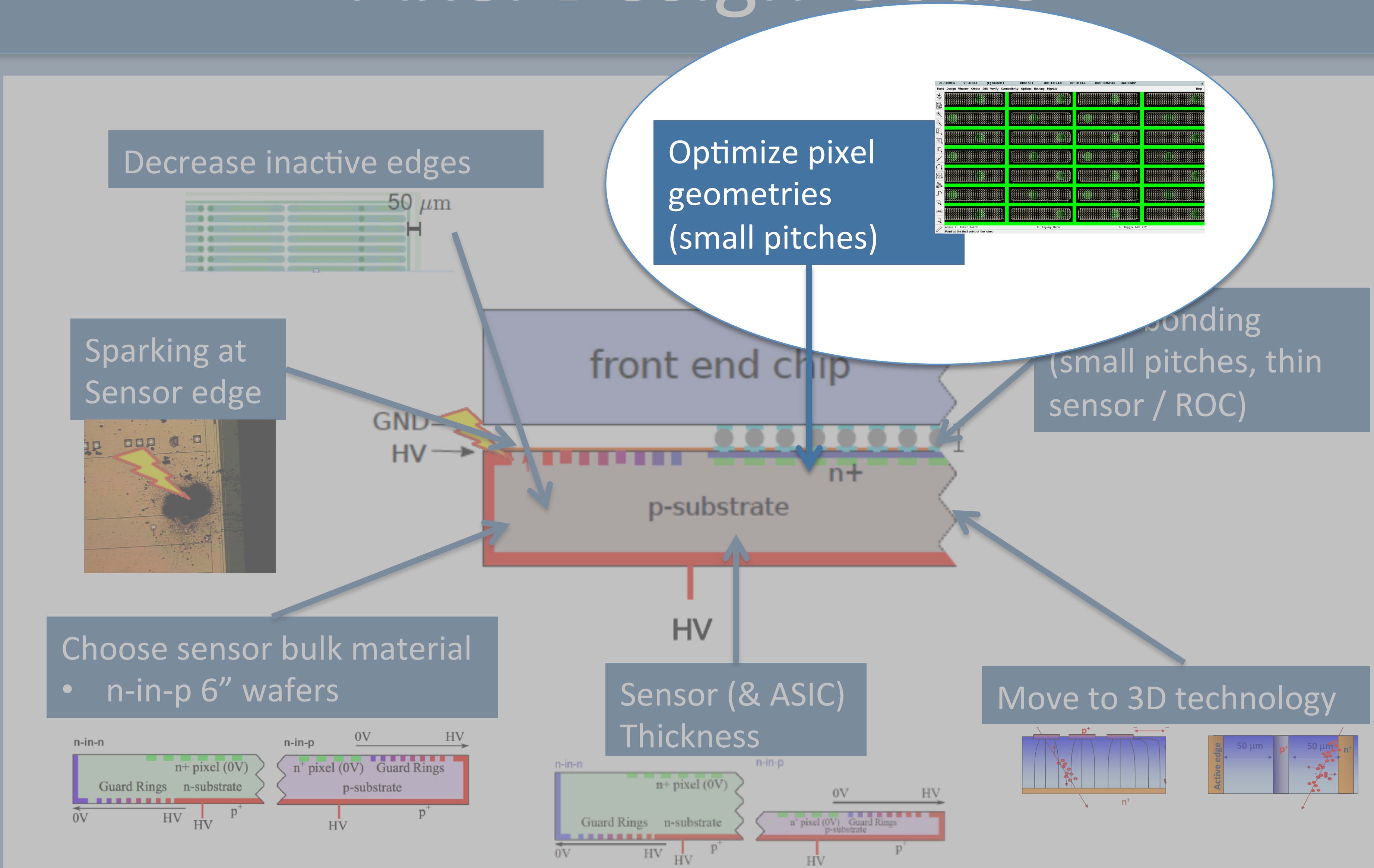
Pixel/Strip isolation required for n-in-p sensors

Noise histogram in 80 μm pitch strip sensor





Pixel Design Goals



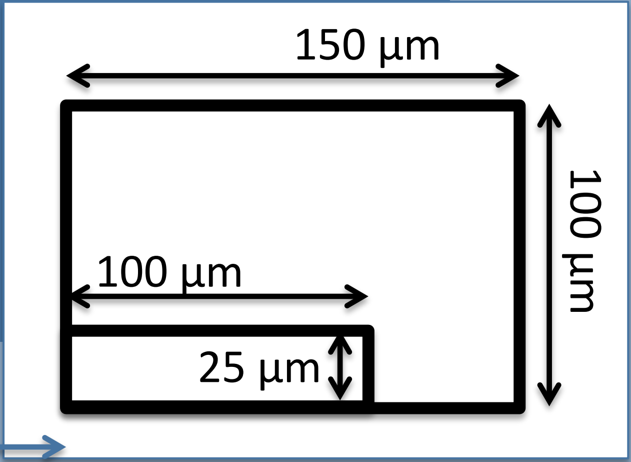
Investigate Fine-Pitch Pixel Sensors

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

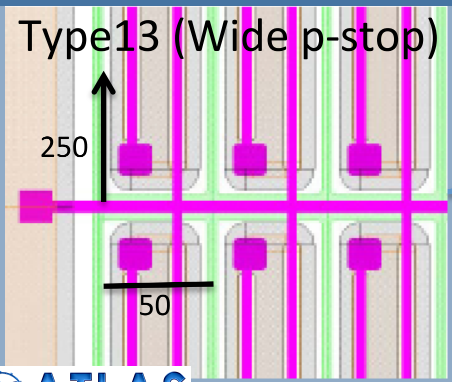
→ Investigate alternatives
  - Common p-stop
  - Common punch through
  - Poly-Si resistors
  - No biasing scheme



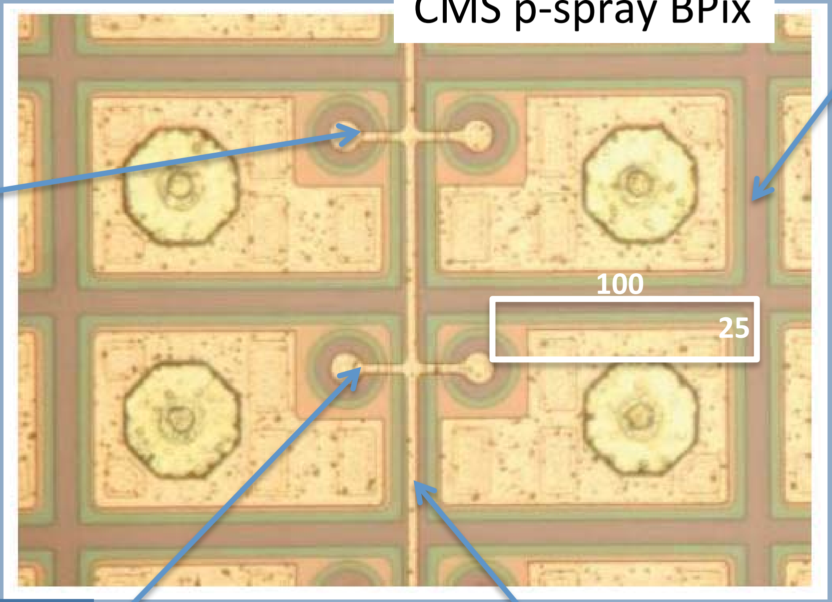
Comparison of current CMS pixel cell size to foreseen size

Investigate Alternatives

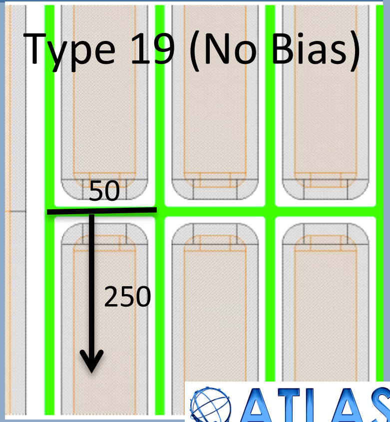
Poly-Si resistor



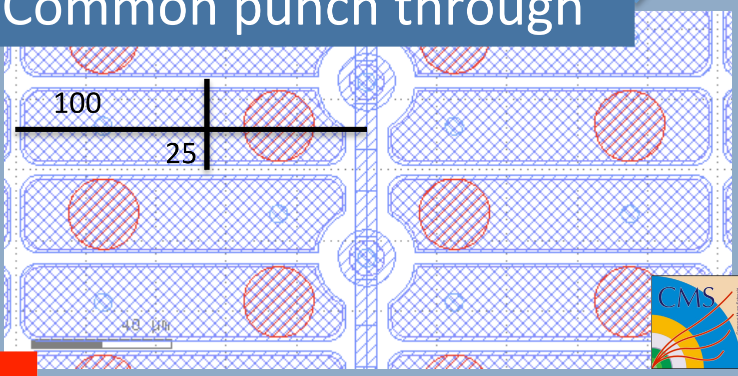
CMS p-spray BPix



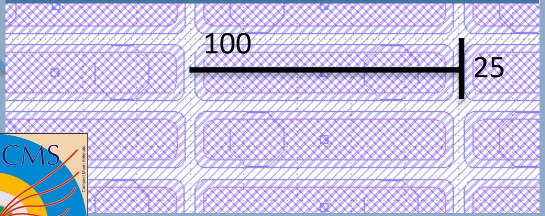
Common p-stop



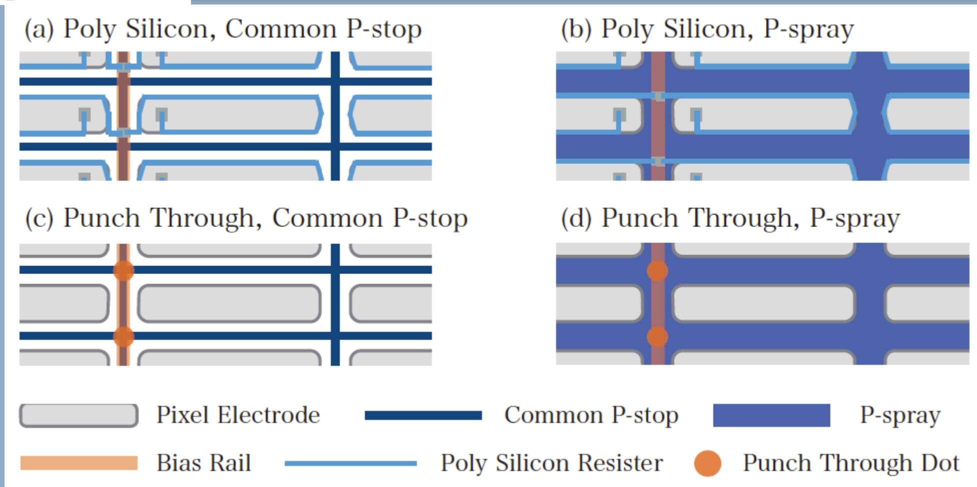
Common punch through

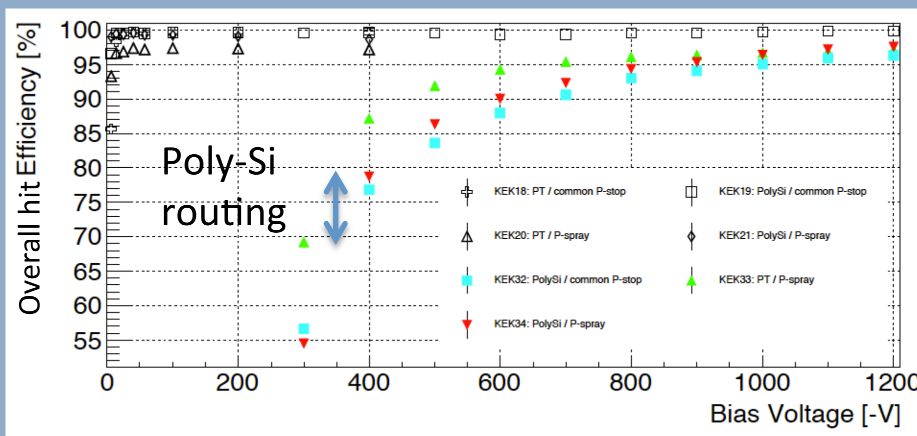


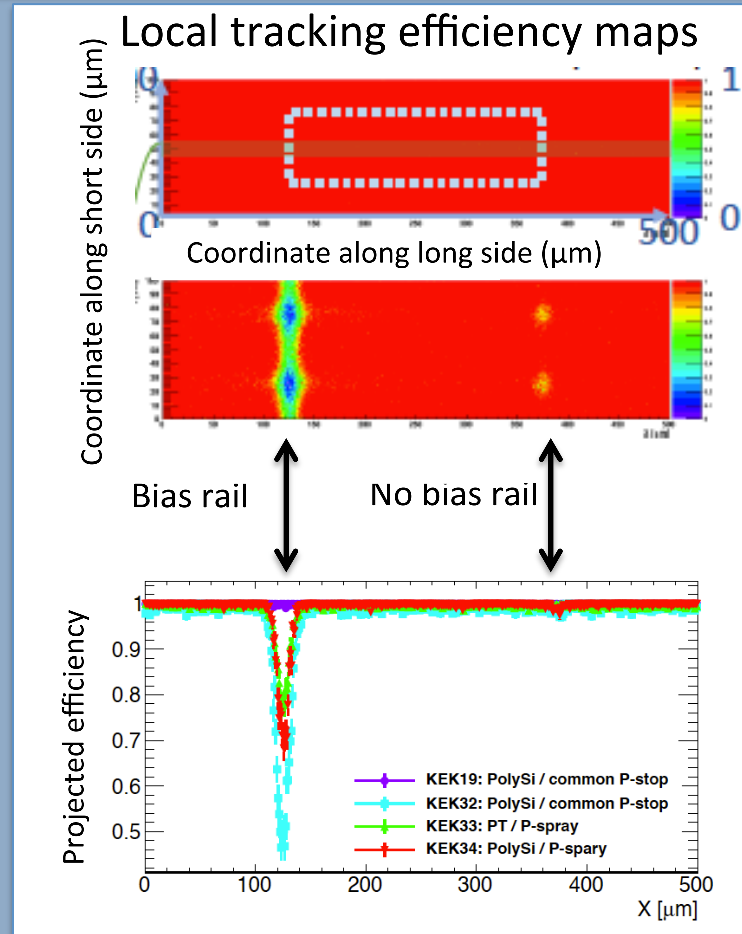
No biasing scheme P-spray



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





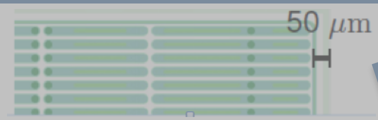


K. Motohashi et al. HSTD9 (DOI: 10.1016/j.nima.2014.05.092)

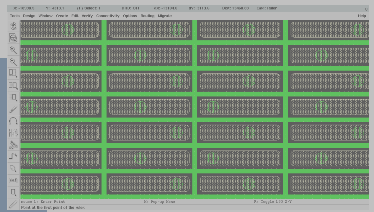
- Severe efficiency loss at the boundary of pixels, under bias rail
- Sight efficiency loss due to the routing of bias resistor

Pixel Design Goals

Decrease inactive edges

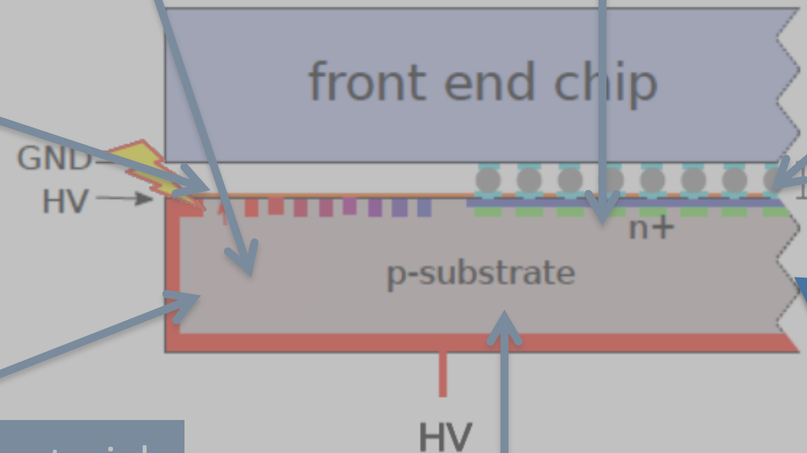


Optimize pixel geometries (small pitches)

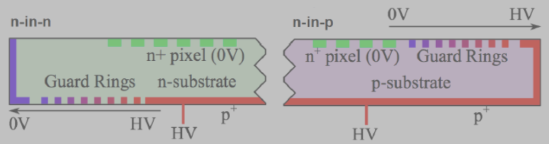


Sparking at Sensor edge

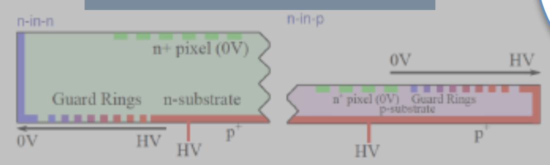
Bump bonding (small pitches, thin sensor / ROC)



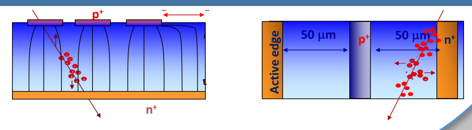
Choose sensor bulk material
- n-in-p 6” wafers



Sensor (& ASIC) Thickness

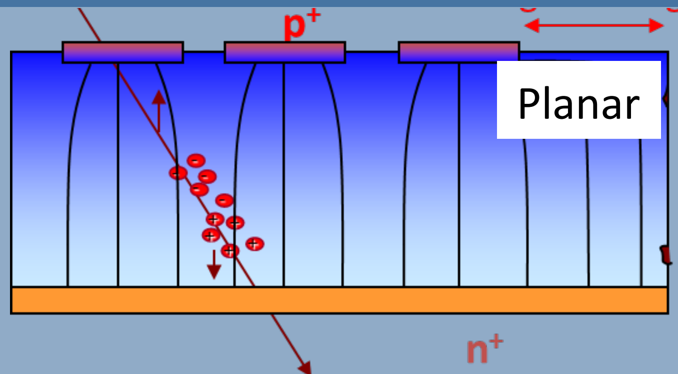


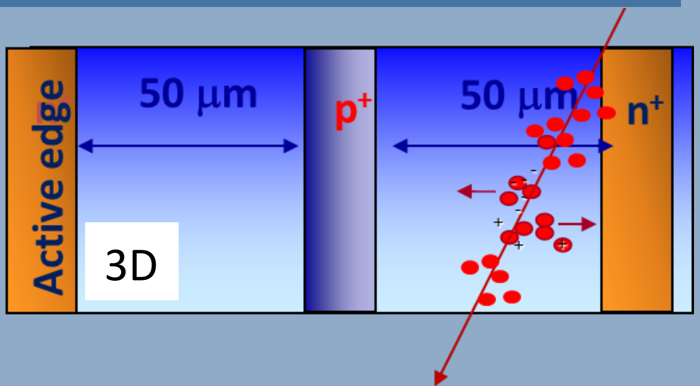
Move to 3D technology



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^-/µm)
- Design limits for small pixels
- Thinning of handling wafer

3D sensors:
- Thick sensor possible

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

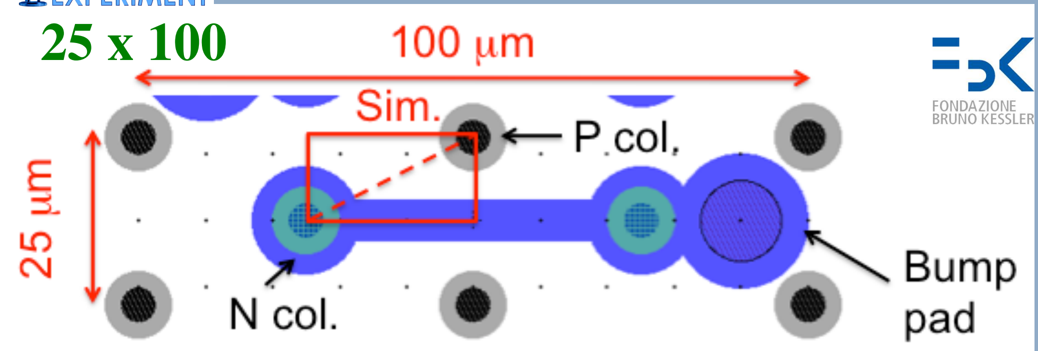
ATLAS and CMS are jointly submitting 2 new productions!

3D Sensors with Small Pitch

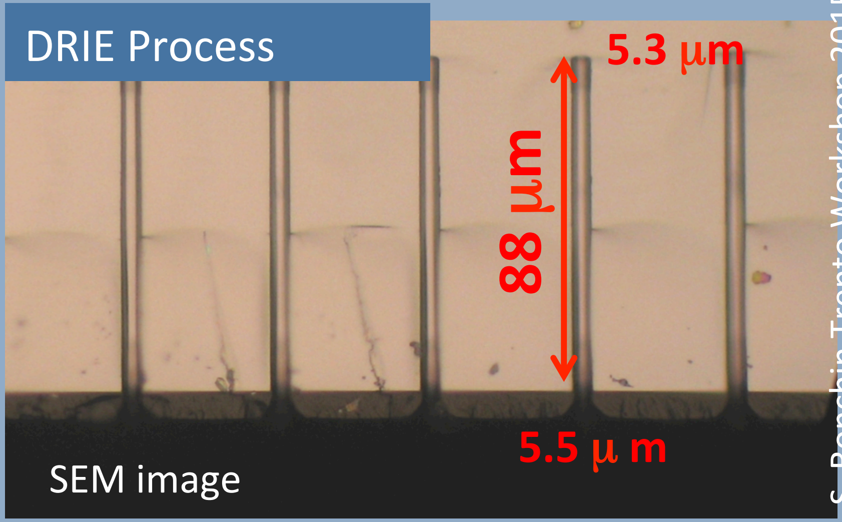
- Smaller pitches require very narrow columns
- And smaller inter-electrode spacing required for high Φ
- Defined aspect ratio between hole heights and width
- To keep aspect ratio, sensors need to be thinner

→ Use handling wafer, requires thinning

Issue could arise from placing bump pads over columns



R. Mendicino Trento Workshop 2015



S. Ronchin Trento Workshop 2015

Summary

TDR for pixel detector planned for 2016 -2017

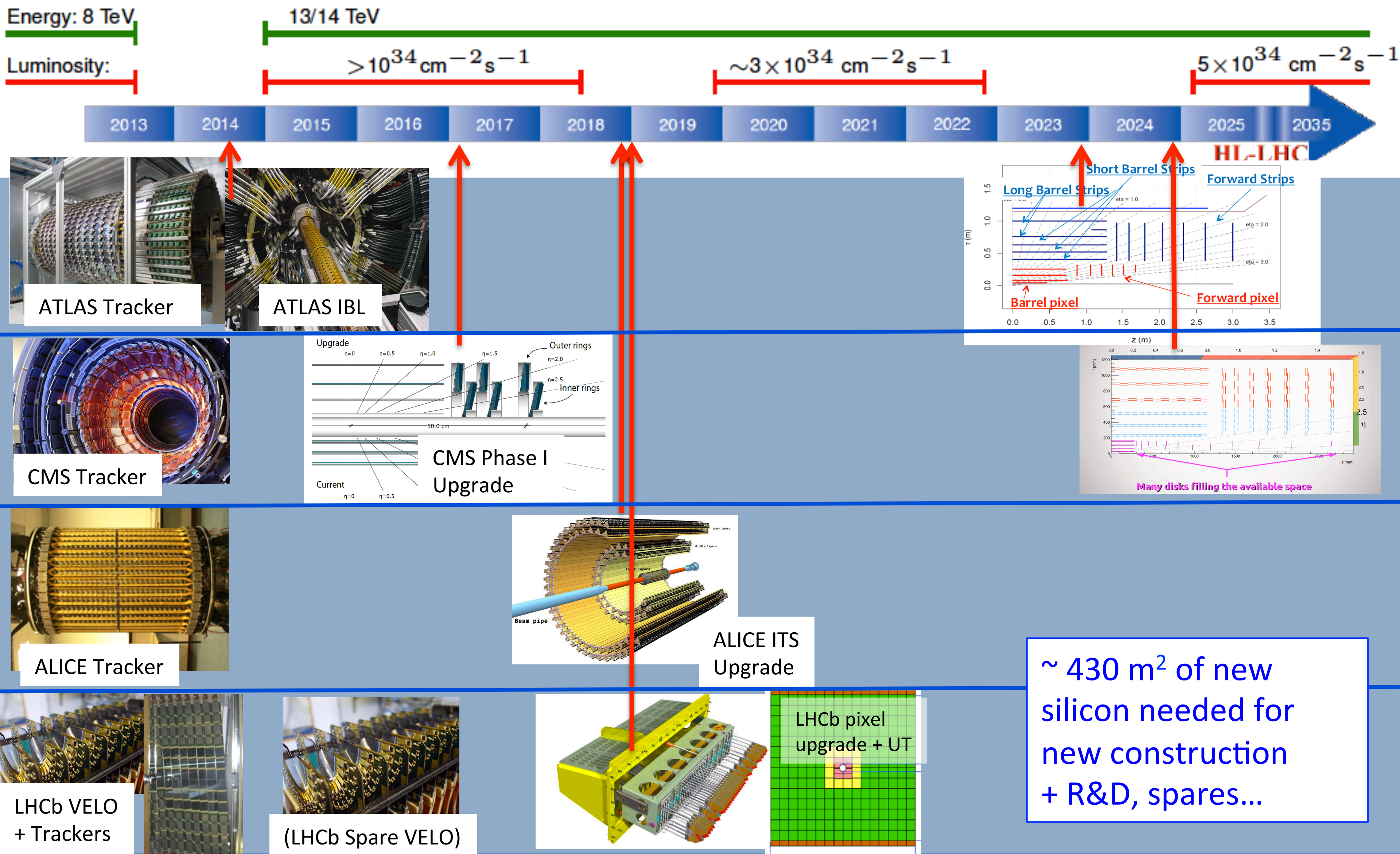
Material
- n-in-p technology cheaper and preferable
- Possible advantage of MCz due to annealing behavior

Small pitch
- Exploit planar and 3D technologies
- Exploit alternative/no biasing schemes

3D Sensor open questions
- Exploit benefit to radiation tolerance
- Exploit small pitch design

Back Up

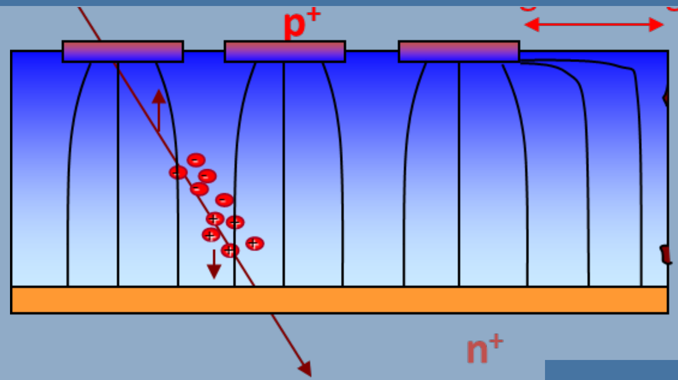
Silicon Detectors Present and Future



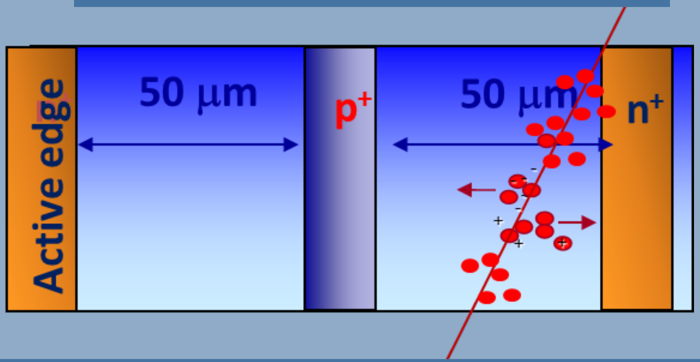
~ 430 m² of new silicon needed for new construction + R&D, spares...

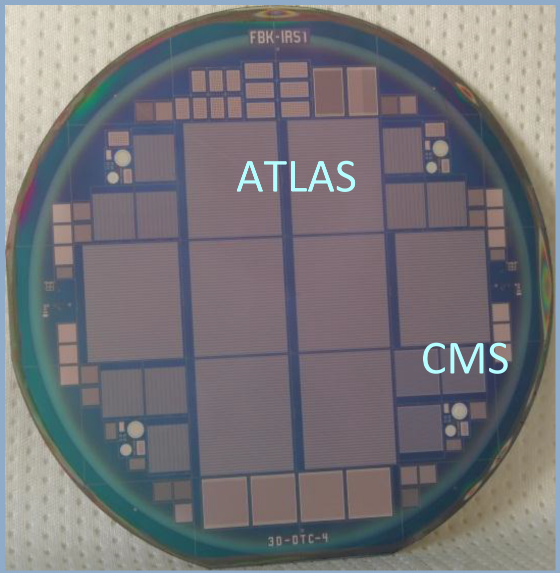
Move to 3D Technology

Planar - Candidate main part of detector



3D - Candidate for first layer





Depletion perpendicular to the sensor surface

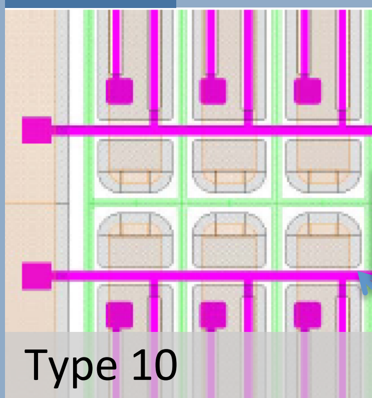
- Minimize signal drift distance and time
- Less trapping of signal
- Leads to improved radiation tolerance over planar design
- Lower bias voltages = lower power = less cooling load
- 1/4th of the ATLAS IBL layer made of 3D sensors, designed for Φ_{eq}=5x10^{15} cm^{2}

But:

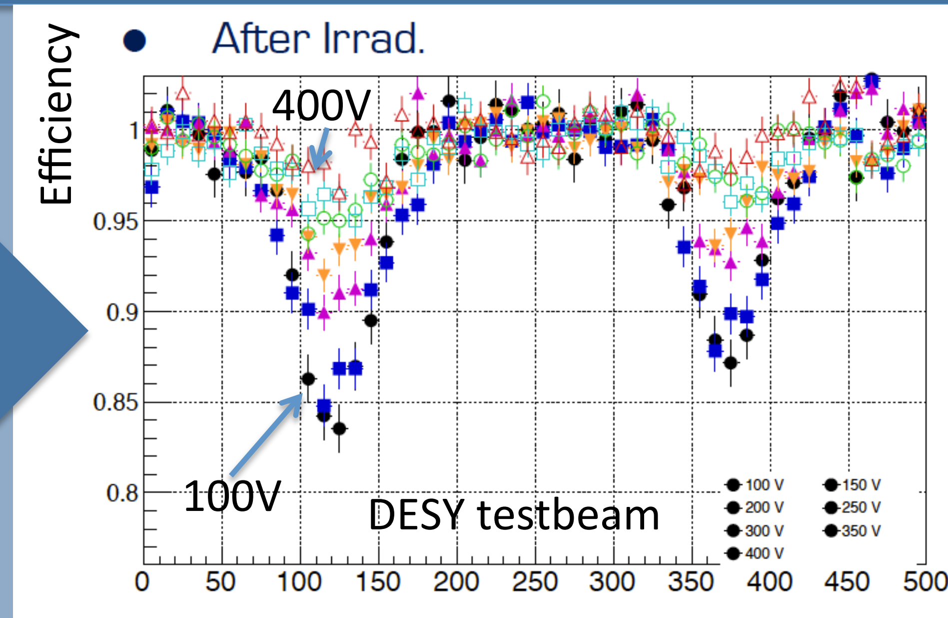
- Expensive & time-consuming production
- Small pitches require thin devices (one of the advantages)

Bias Rail and Poly-Si Routing

Poly-Si

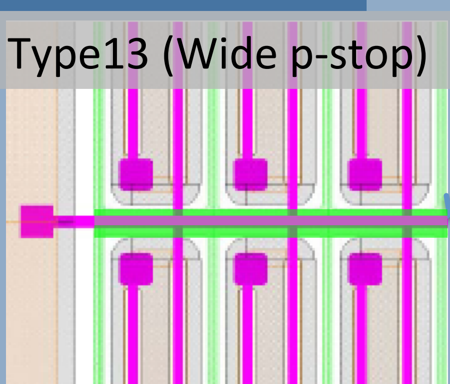


Bias rail effect is nearly eliminated

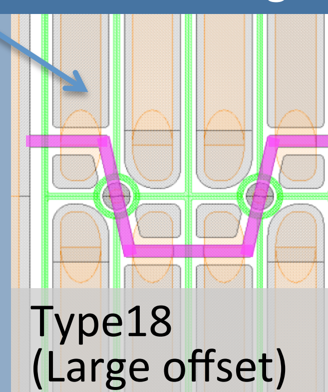


Bias rail

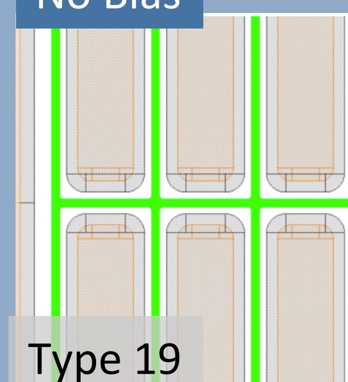
Poly-Si + bias rail



Punch Through



No Bias



Studies done with FE-I4,
Will change with new ROC

Poly-Si resistor with 1 MΩ difficult in

Detection of bulk defects

Technique	Based on/ measures	Results	Limits/ drawback
Deep Level Transient Spectroscopy (DLTS)	Charge capture-emission/ capacitance transients	Defects properties and concentration	- Low density of defects - Chemical nature (indirect)
Thermally Stimulated Current (TSC)	Charge capture-emission/ current	Defects properties and concentration	- Medium density of defects - Chemical nature (indirect)
Photoluminescence (PL)	Photon absorption-emission / luminescence	PL bands, defects ionisation energy	- Only for photo-active centers - Chemical nature (only indirect)
Infrared Absorption (IR)	Excitation of vibrational modes of molecules by IR absorption / Absorption of IR energy	Defects chemical structure and concentration	- Large density of defects - Electrical properties

No experimental technique provides all defects characteristics

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Electrical methods

No information about electrical properties

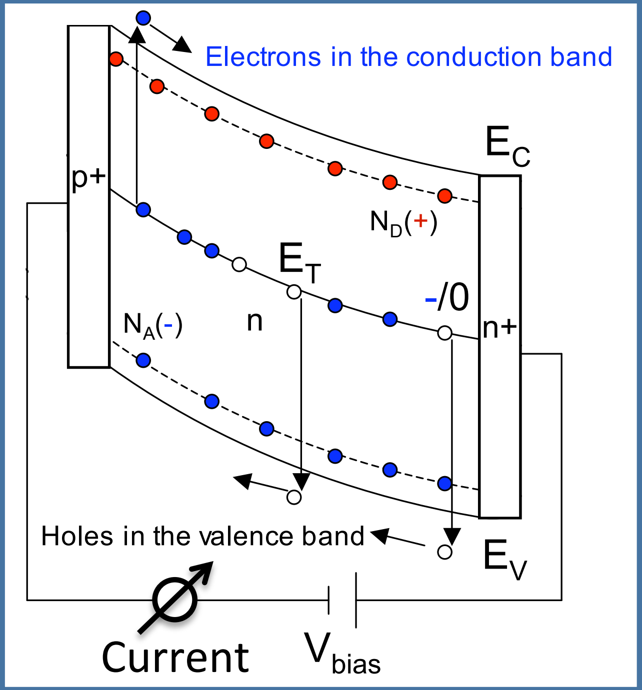
Not tried yet

No experimental technique provides all defects characteristics

UH

Thermally Stimulated Current technique

TSC principle

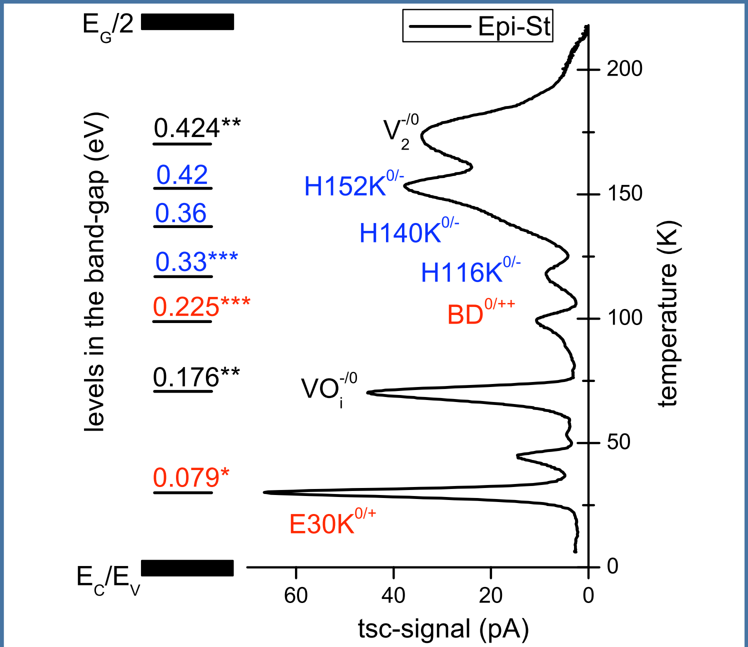


Single shot technique:

1. Filling of traps with charge carriers at low T (<30 K)

→Filling (majority carriers with zero bias, majority and minority carriers by forward bias, light)

- Signal as function of temperature

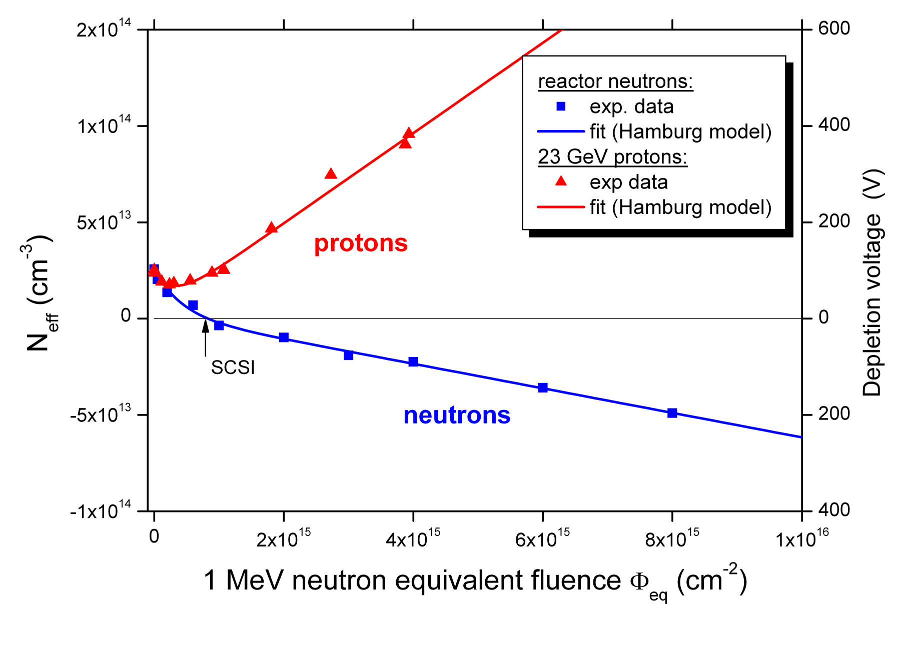


2. Recording of charge emission ($e_{n,p}$) from filled traps during constant heating
3. N_t from integral of TSC-current

Outline

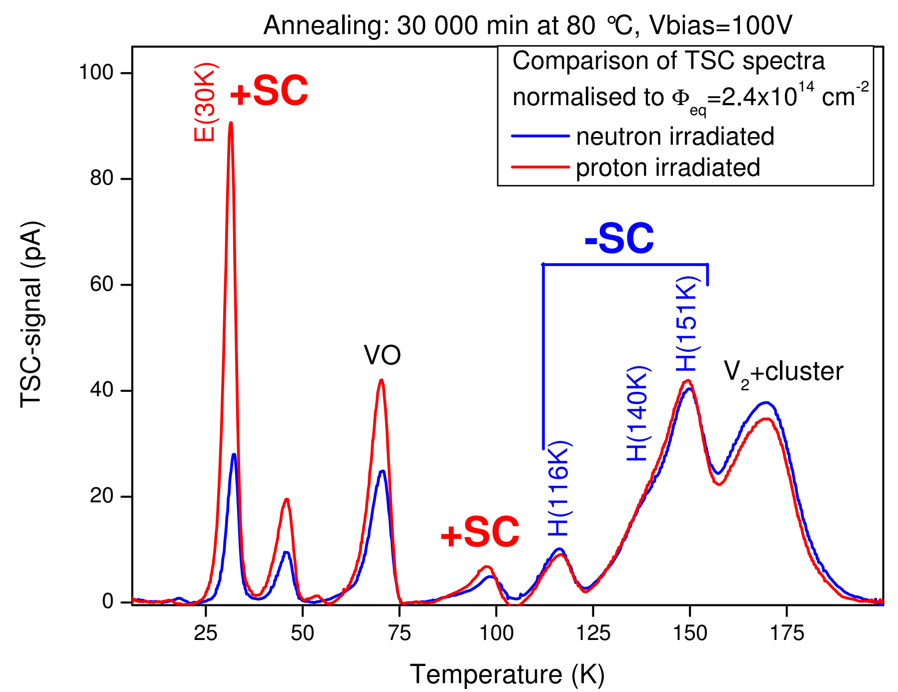
Defects with impact on N_{eff}

N_{eff} for n and p irradiation (CV) for Epi-Do



I. Pintilie et al. NIM A 611 (2009) 52

Corresponding defects (TSC)



- Cluster defect E(30K) enhanced after protons
- Shallow donor E(30K) overcompensates deep acceptors

Title

Silicon "Materials"

Si-growth process determines

Impurity concentration, mainly oxygen

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