Development of thin n-in-p pixel sensors with active edges and recent results of the ATLAS Planar Pixel R&D project

A. Macchiolo

on behalf of the ATLAS Planar Pixel R&D Project

L. Andricek, H.G. Moser, R. Nisius, R. Richter, S. Terzo, P. Weigell

MPP and MPI-HLL, Munich

A. Bagolini, M. Boscardin, G. Giacomini, N. Zorzi

Fondazione Bruno Kessler, CMM MTLab, Trento

M. Bomben, G. Calderini, J. Chaveau, G. Marchiori

LPNHE, Paris, France
L. Bosisio

University and INFN Trieste, Italy

A. La Rosa

DPNC, University of Geneva, Switzerland

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CONFERENCE ON
INSTRUMENTATION

Vienna Conference on Instrumentation, 12 February 2013

The ATLAS Planar Pixel Sensor R&D project

Goals:

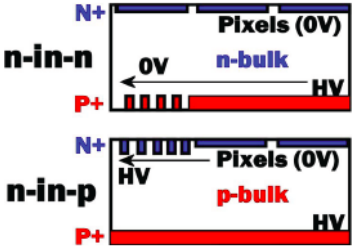
☐ Evaluate and improve the performance of PPS up to a fluence of 2x10^{16} n_{eq} cm^{-2}, to be accumulated in the inner layer of the new pixel system at Phase II

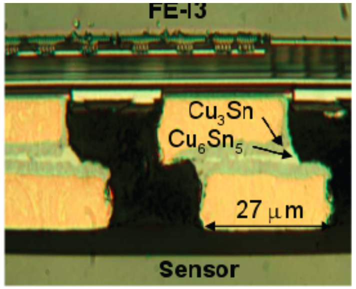
☐ Geometry optimization:

- Slim/ Active edges
- Pixel size and implant
- Bias grid

☐ Cost reduction:

- Bulk material: n-in-p vs n-in-n
- Interconnection technique
- Pixel production on 6“ wafers instead of 4“

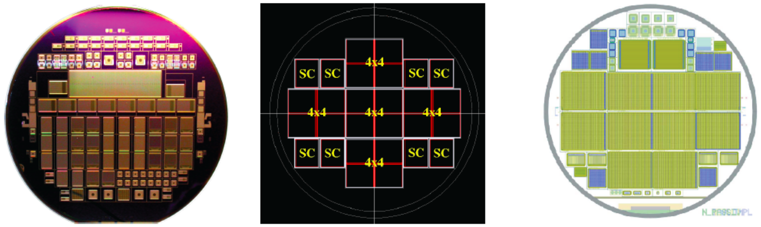




Tools:

☐ Productions:

CIS, MPP HLL, MICRON, HPK, VTT, FBK



☐ Irradiations:

- Reactor neutrons (Ljubljana)
- 26 MeV protons (Karlsruhe)
- 800 MeV protons (Los Alamos)
- 24 GeV protons (CERN)

☐ Lab …

- Radioactive sources

☐ ... and beam test measurements

- Eudet telescope
- 120 GeV pions (CERN)
- 4-6 GeV e (Desy)

☐ TCAD Simulation

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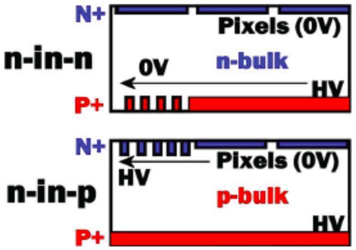

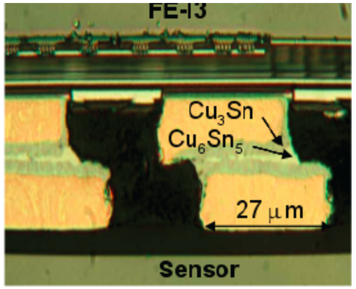

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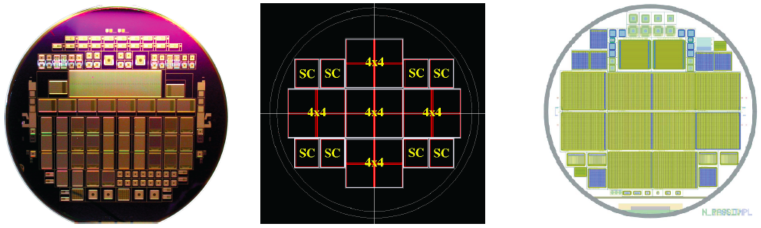

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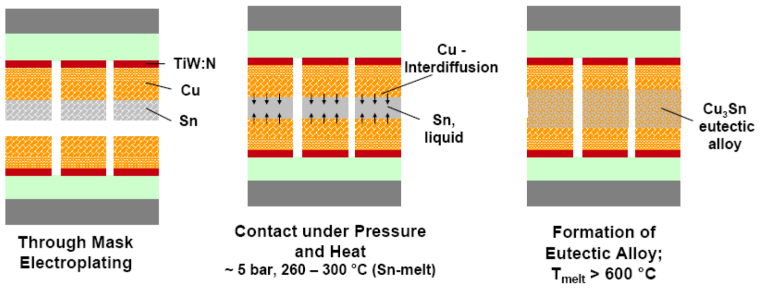
- TCAD Simulation

Phase II requirements for the inner pixel layers

Complete replacement of the ATLAS inner tracker during the shutdown ~ 2021-2022:

For the inner pixel layers the requirements are:

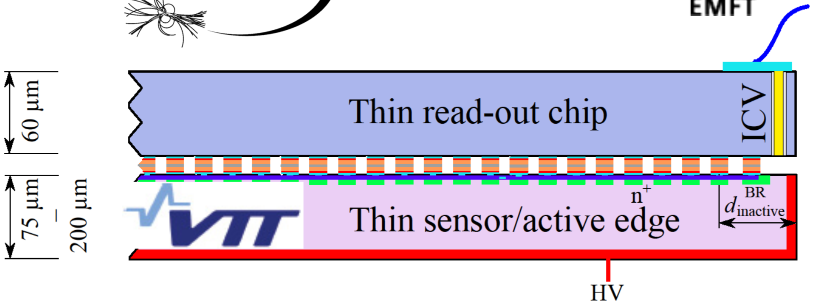
- ❑ Radiation hardness up to a fluence of $2 \cdot 10^{16}$ n_{eq} cm^{-2} in the inner pixel layer
- ❑ Best achievable resolution: reduce Rϕ pitch to 25 µm, for sensor and chip
  - Improved existing interconnection methods, or implement new ones, as for example SLID
- ❑ Smallest achievable radius → no z-overlap → minimize inactive edge
- ❑ Thin sensors and chips to reduce multiple scattering, PPS uses (75 − 200) µ m



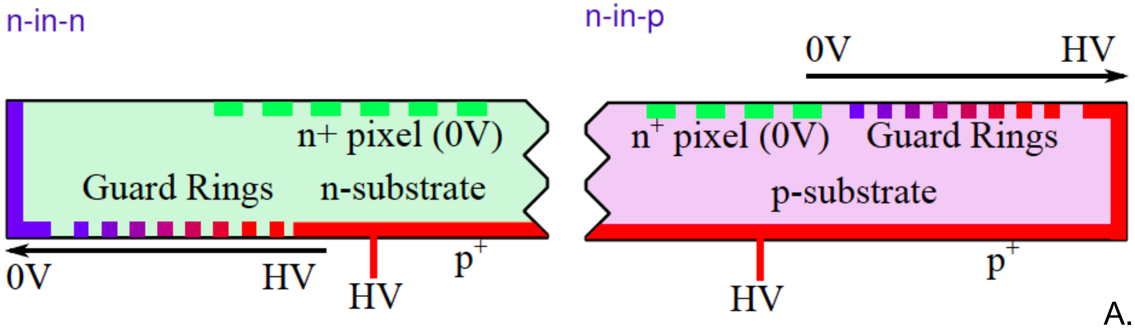
mpi halbleiterlabor

Fraunhofer EMFT

MPP 3D integrated demonstrator module to achieve a fully four-side buttable module, in collaboration with EMFT and VTT
Active edge pixels + SLID interconnection + ICV



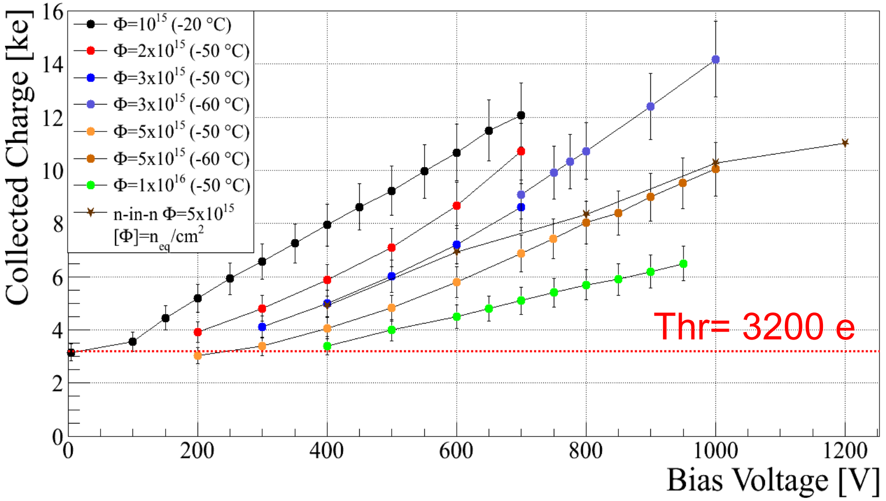
n-in-p planar pixel technology



N-in-p pixel technology allows for a single sided processing

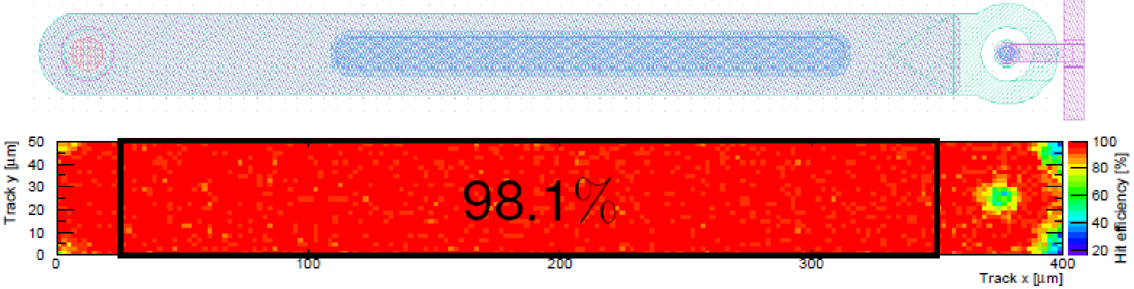
A. La Rosa et al., arXiv:1205.5305

- ☐ CIS n-in-p pixel production
  - FE-I3 compatible sensors
  - 285 μm thickness
  - Charge collection studies with a ^{90}Sr source
  - FE-I3 threshold = 3200 e



P. Weigell arXiv:1210.7661

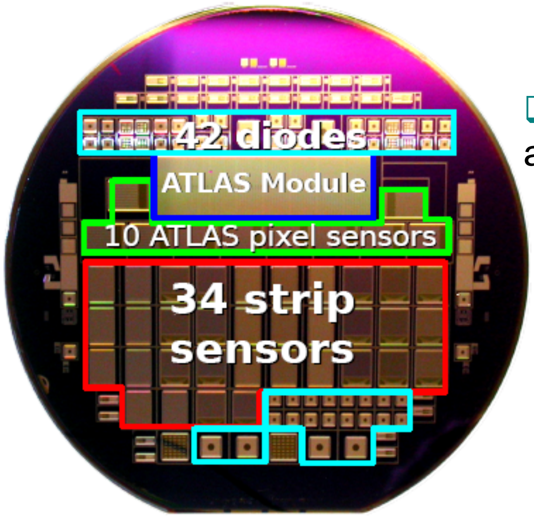
CERN-SPS 120 GeV pions, $\Phi=10^{16}\ n_{eq}\ cm^{-2}$



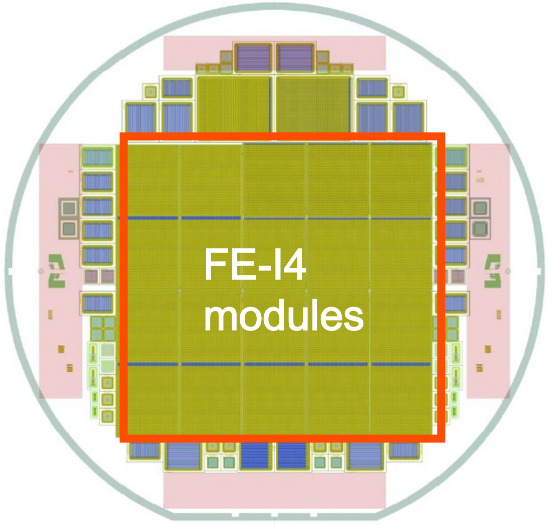
- ☐ Vbias =600V, perpendicular beams
- ☐ Threshold =2000, MPV charge ~ 6ke
- ☐ 97.2% hit efficiency at $10^{16}\ n_{eq}/cm^2$ (98.1% in the inner region)
- ☐ 99.2% hit efficiency at $10^{16}\ n_{eq}/cm^2$ with track angle = 45° (η=0.88)

Thin pixel technology at MPP HLL

1. implant backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. process on top side
5. structure resist, etch backside up to oxide/implant



☐75µm and 150µm active thickness



☐150µm active thickness

☐n-in-p 6“ wafers with FE-I3 compatible sensors

☐ 75 µm thick sensors interconnected with SLID to FE-I3 chips, thinned down to 200 µm, at EMFT

☐ n-in-p 6“ wafers with 150 µm thick FE-I4 sensors (pitch 50 µm x250 µm)

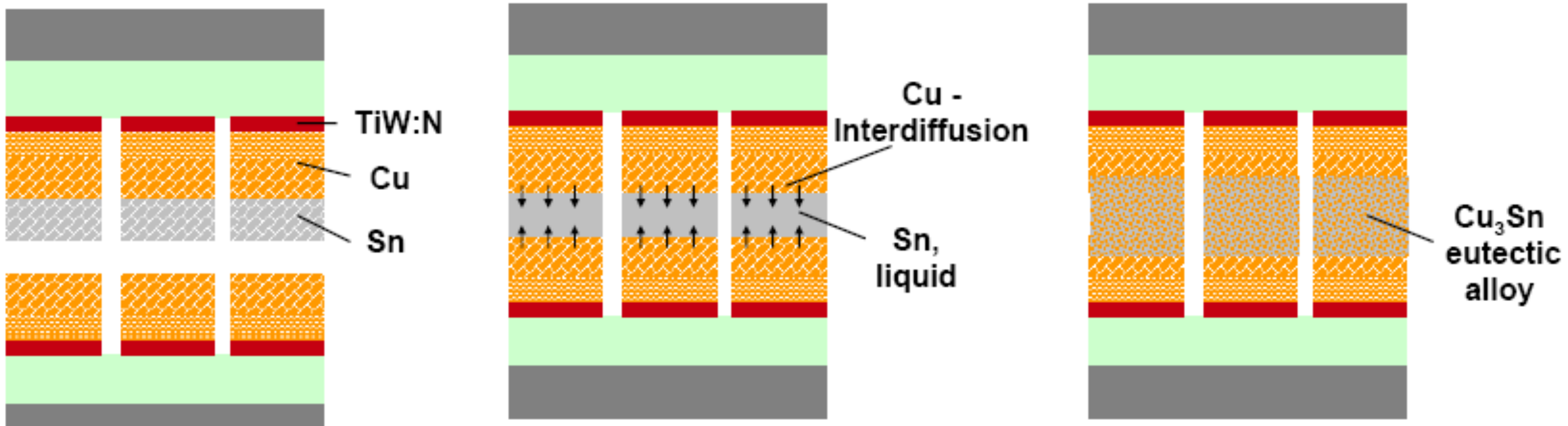
☐ IBL compatible GR → 450 µm dead edge

☐ Interconnected to FE-I4 chips with bump-bonding at IZM

EMFT SLID Process

Metallization SLID (Solid Liquid Interdiffusion)

Fraunhofer
EMFT



Through Mask Electroplating

Contact under Pressure and Heat
~ 5 bar, 260 – 300 °C (Sn-melt)

Formation of Eutectic Alloy;
$T_{melt} > 600$ °C

- ❑ Alternative to bump bonding (less process steps “lower cost” (EMFT)).
- ❑ Small pitch possible (~ 20 μm, depending on pick & place precision).
- ❑ Stacking possible (next interconnection process does not affect previous one).
- ❑ Wafer to wafer and chip to wafer approaches possible.
- ❑ For the analysis of the interconnection efficiency: arXiv:1202.6497

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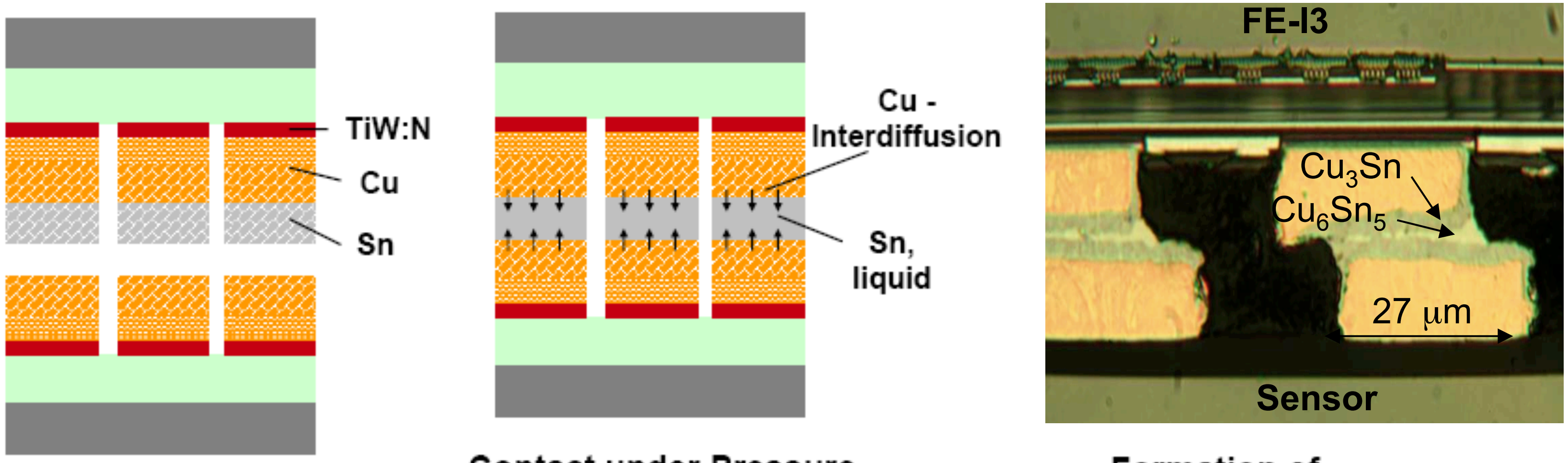
Fraunhofer
EMFT



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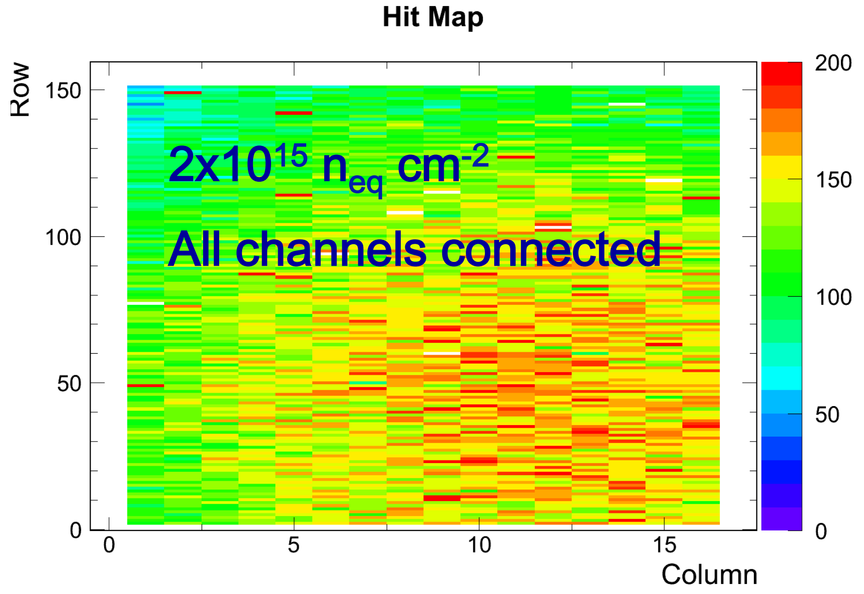
Characterization of SLID modules – 75 μm thick

Good Charge Collection efficiency after irradiation up to 10^{16} n_{eq} cm^{-2}

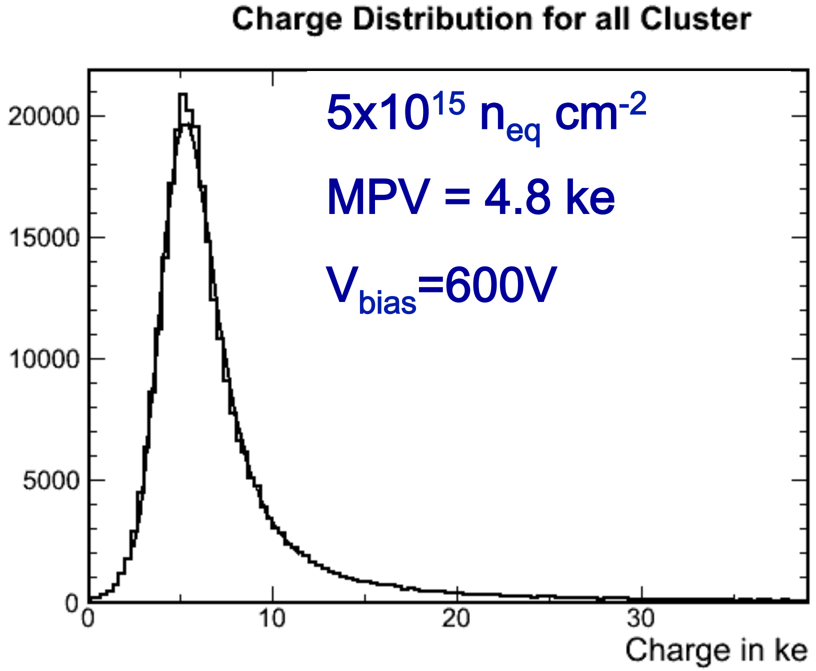
☐ Number of unconnected channels stable after irradiation and multiple thermal cycles (+20°C → -50°C)

SLID interconnection is radiation hard and withstands thermal cycling



$2x10^{15}$ n_{eq} cm^{-2}

All channels connected

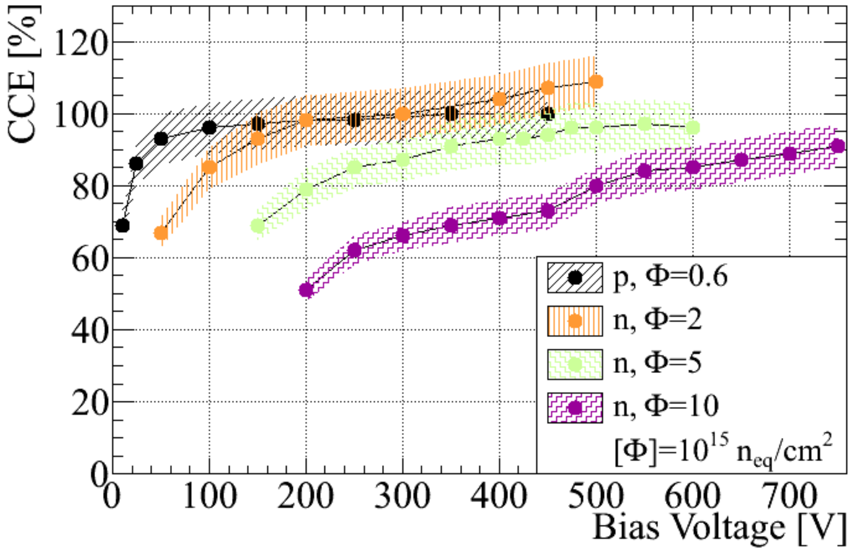


$5x10^{15}$ n_{eq} cm^{-2}

MPV = 4.8 ke

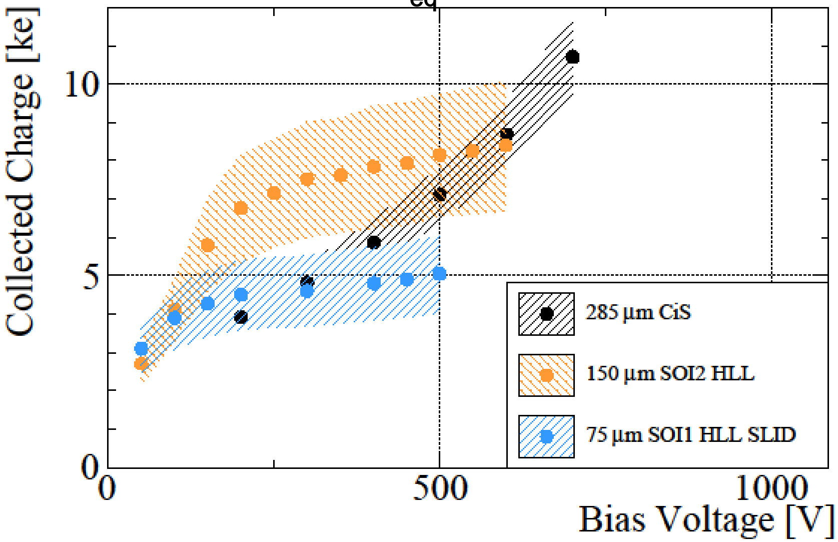
V_{bias}=600V

A. Macchiolo et al., arXiv:1210.7933

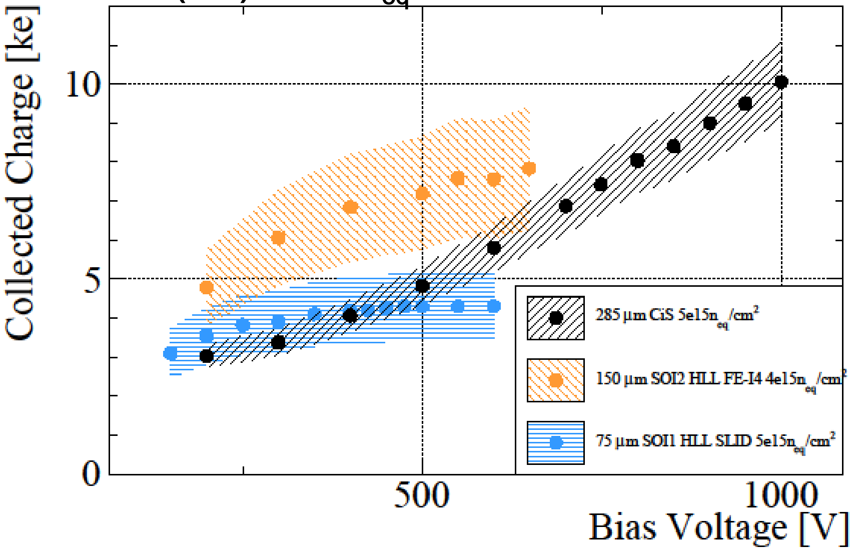


Comparison of CC for n-in-p pixels of different thickness

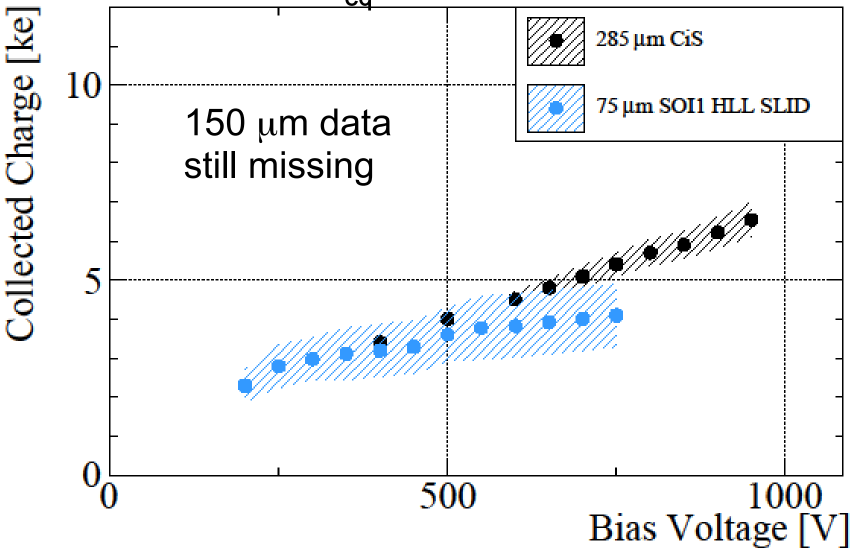
Φ= 2 x10^{15} n_{eq} cm^{-2}



Φ=(4-5) x10^{15} n_{eq} cm^{-2}



Φ= 10^{16} n_{eq} cm^{-2}



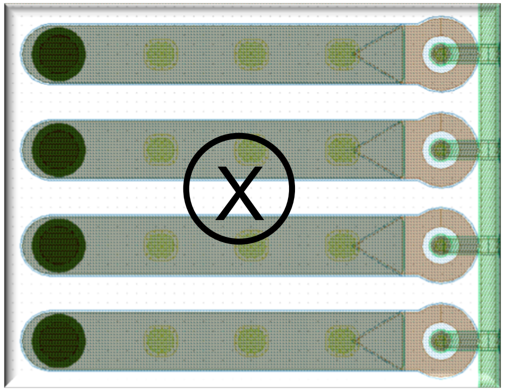
150 µm data
still missing

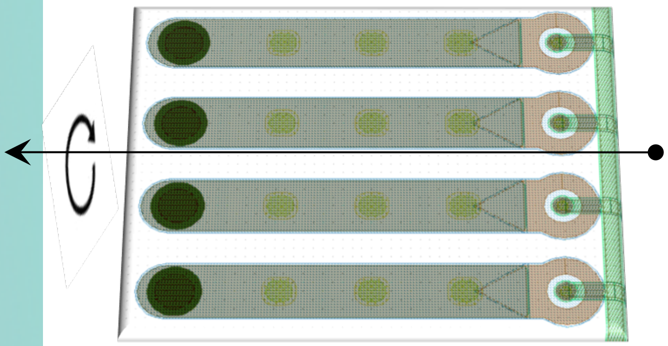
Higher charge with 150 µm thick sensors up to a fluence of Φ=(4-5)x10^{15} n_{eq} cm^{-2}

At higher fluences the charge of thin and thicker sensors tends to equalize

Hit efficiency with FE-I4 n-in-p pixel modules

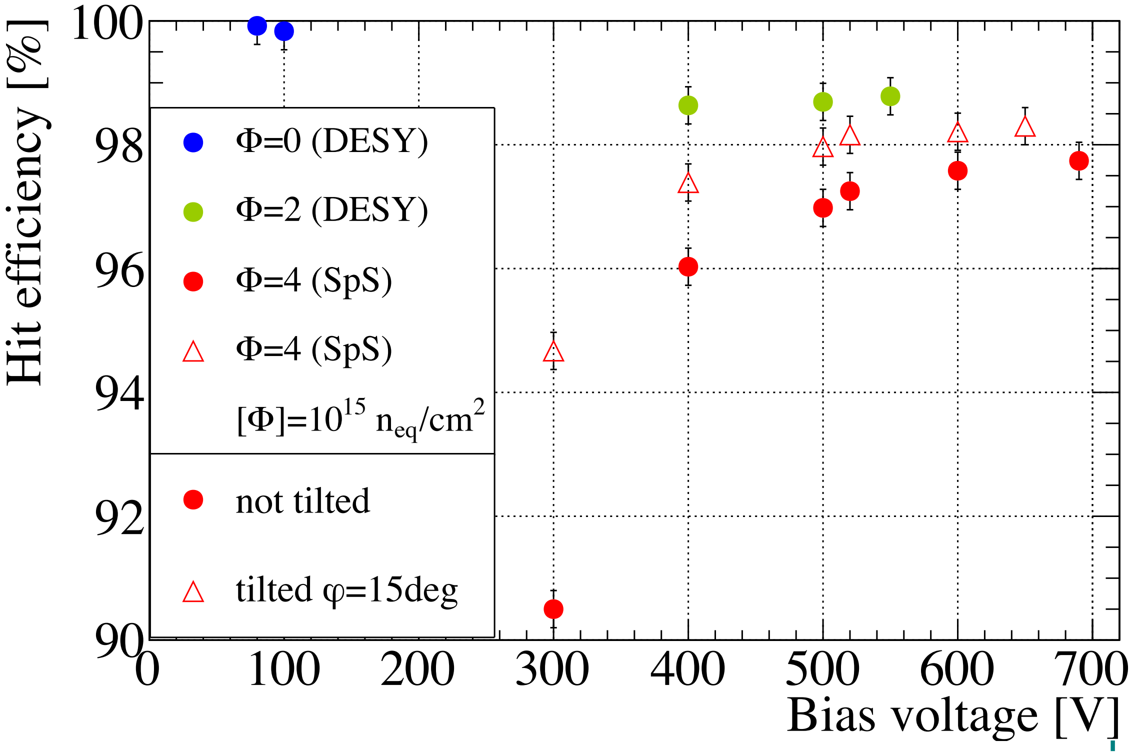
φ =0°





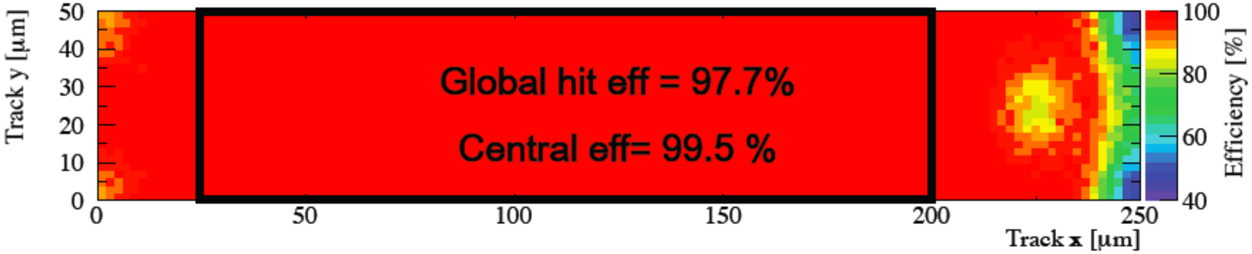
φ=15° (IBL case)

- FE-I4 n-in-p pixel sensors, 150 μm thick, produced at the MPP HLL
- Test-beams with EUDET telescope
- 120 GeV pions at CERN-SPS (●), 4-6 GeV electrons at DESY (●)



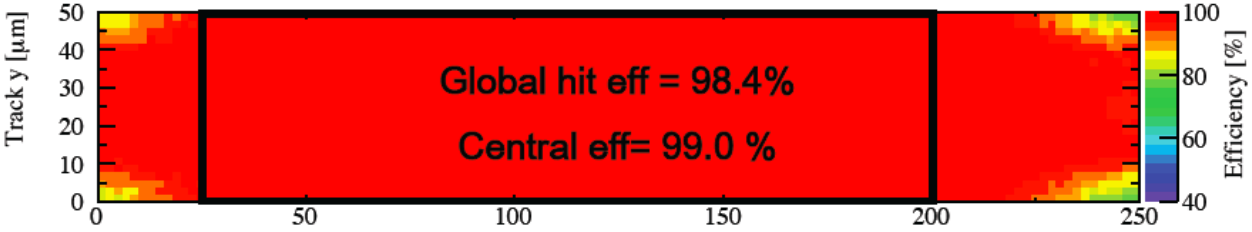
η-dependence of FE-I4 modules hit efficiency

Hit efficiency of the module projected in one single pixel cell,
Eudet telescope, 120 GeV pions at CERN-SPS Φ=4x10^{15} n$_{eq}$ cm^{-2}



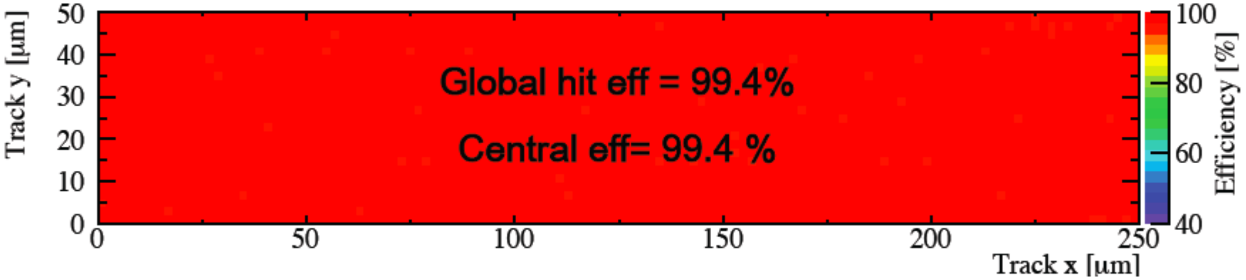
Vbias= 690 V, η= 0

Normal incidence



Vbias= 500 V, η= 0.55

Track angle with respect normal incidence = 30°

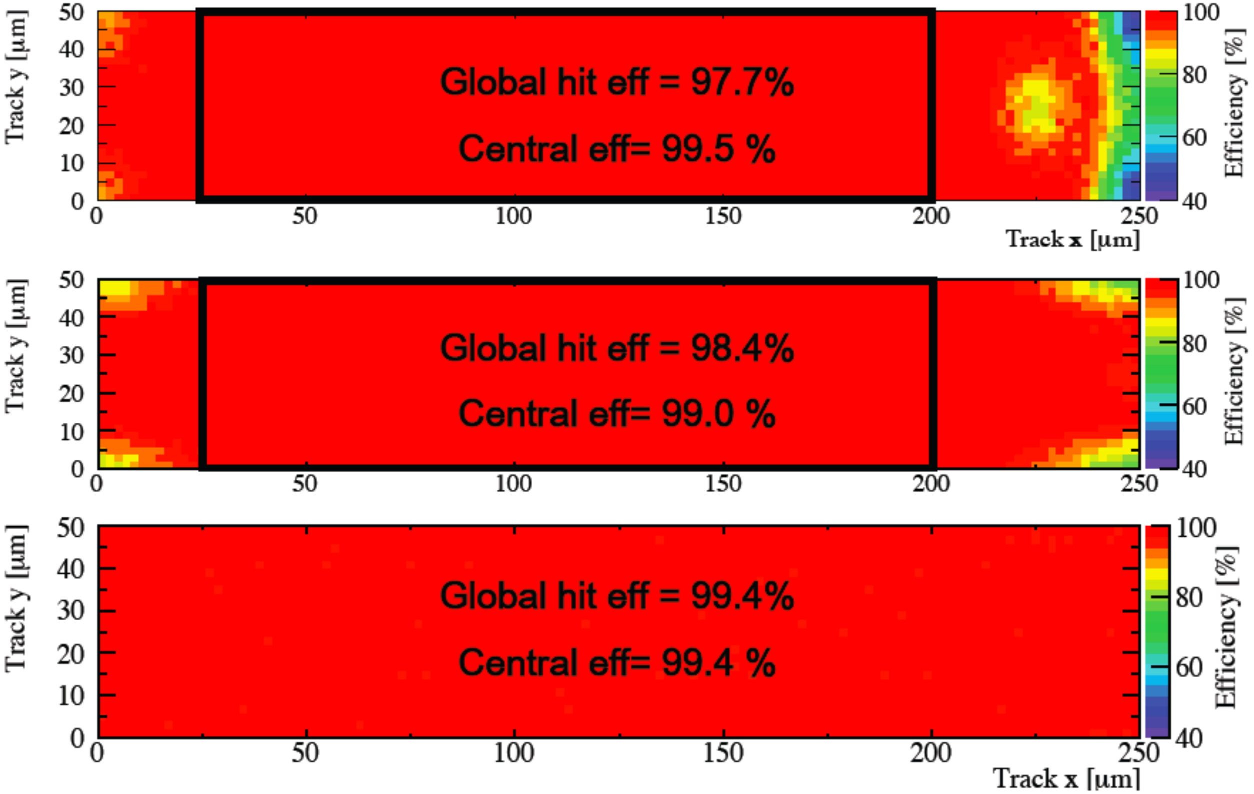


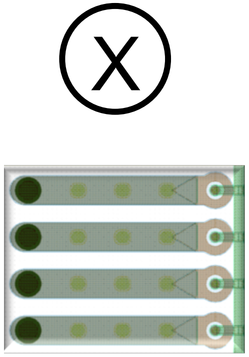
Vbias= 500 V, η= 0.88

Track angle with respect normal incidence = 45°

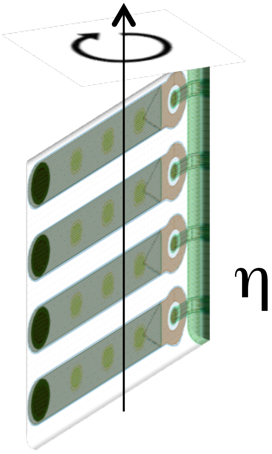
η-dependence of FE-I4 modules hit efficiency

Hit efficiency of the module projected in one single pixel cell,
Eudet telescope, 120 GeV pions at CERN-SPS $\Phi=4\text{x}10^{15}\ n_{eq}\ cm^{-2}$





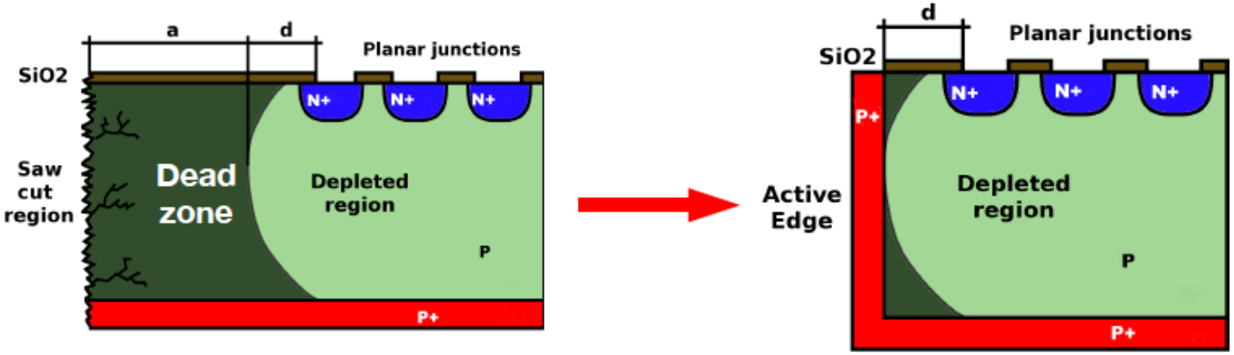
η= 0



η= 0.88

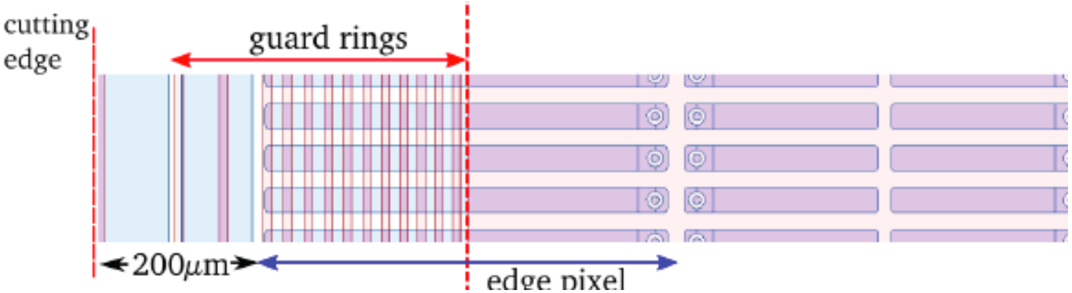
Planar slim edges pixel sensors

- Active edges: Deep Reactive Ion Etching + Side implantation



- Design optimization of the n-in-n sensors: GR on backside opposite to pixels on the front

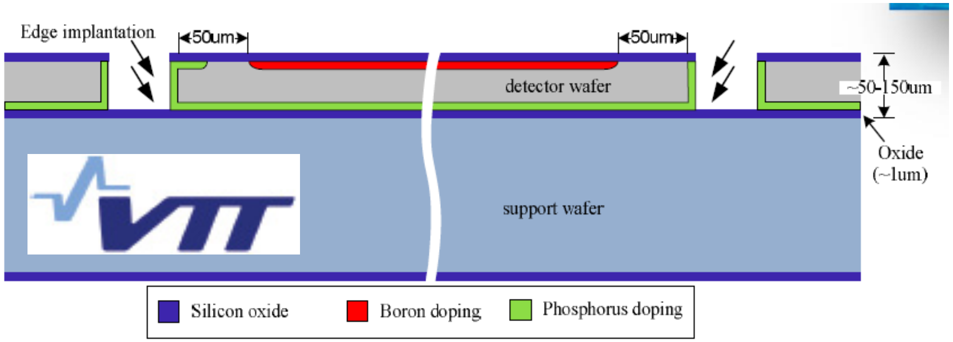
IBL design



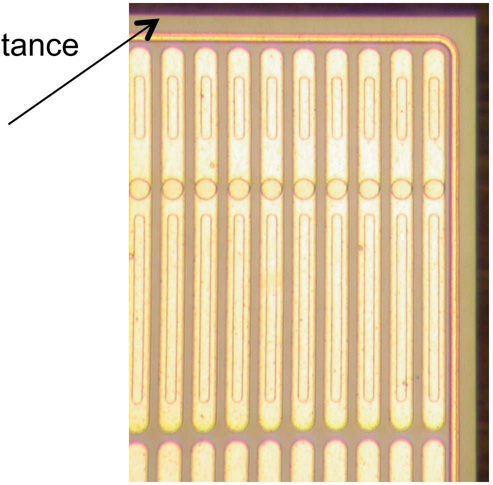
- Scribe Cleave Passivate (SCP) approach as post-processing step

Active edges planar pixel sensors: FE-I3 and FE-I4

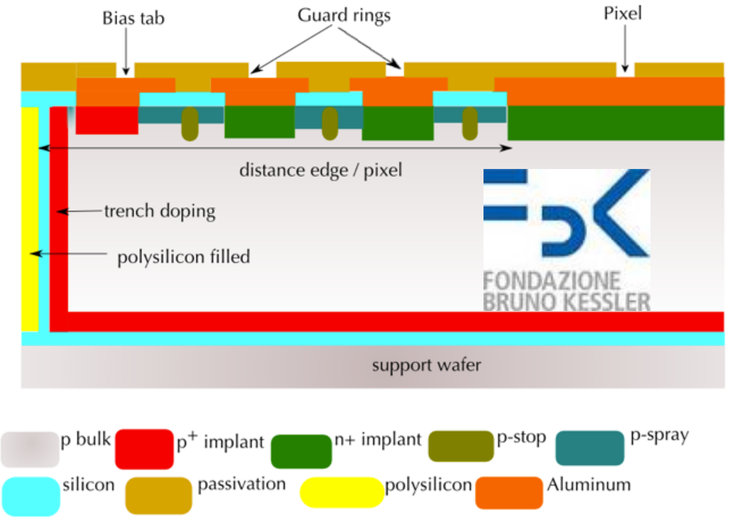
- Trench doped by four-quadrant implantation
- Sensor thickness 100-200 μm



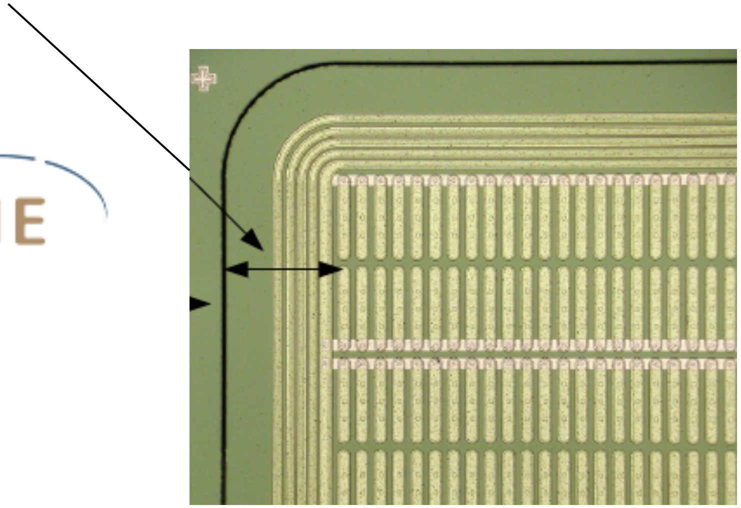
- Pixel-to-trench distance as low as 50 μm



- Trench doped by diffusion
- Sensor thickness 200 μm

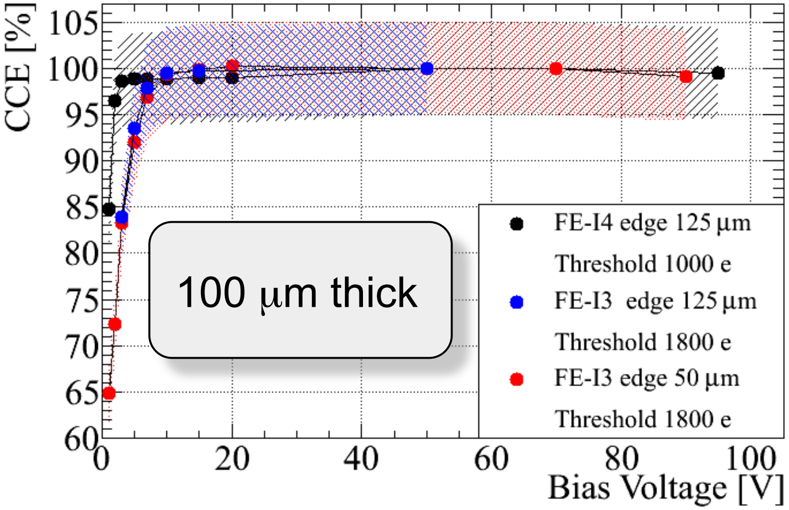


- Pixel-to-trench distance as low as 100 μm



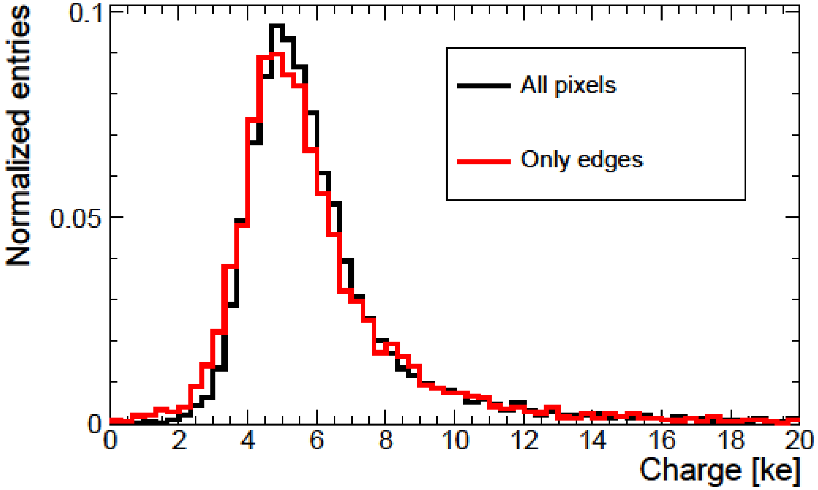
Characterization of MPP active edge n-in-p sensors

- ❑ CCE with ^{90}Sr scans before irradiation

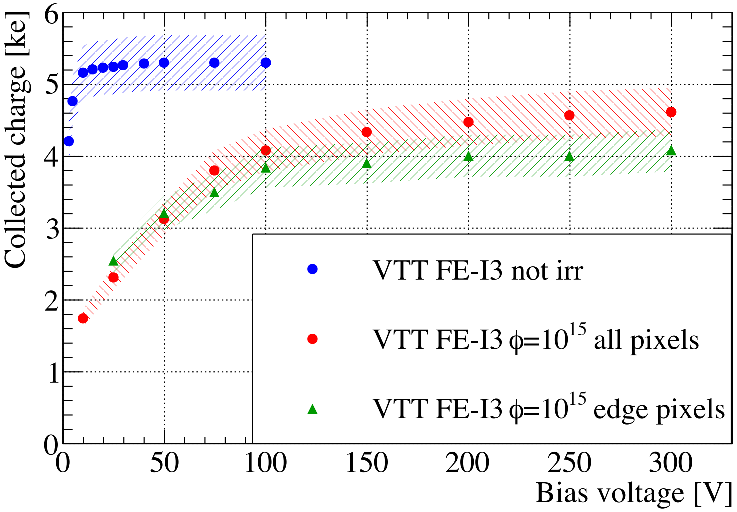


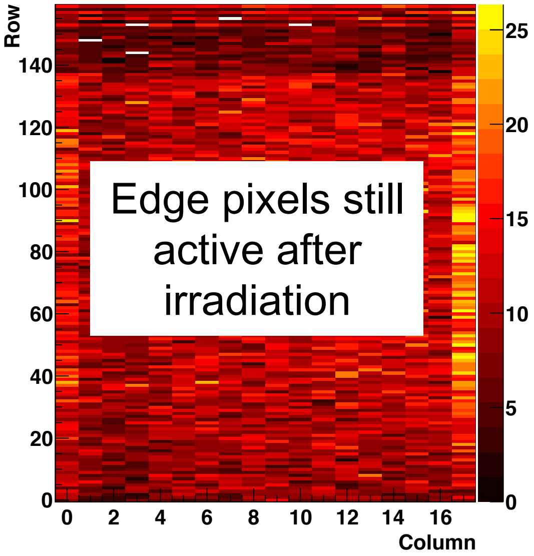
100 µm thick

- ❑ Edge pixels show the same charge collection properties as the central ones



After irradiation: $\Phi=10^{15}$ n_{eq} cm^{-2}

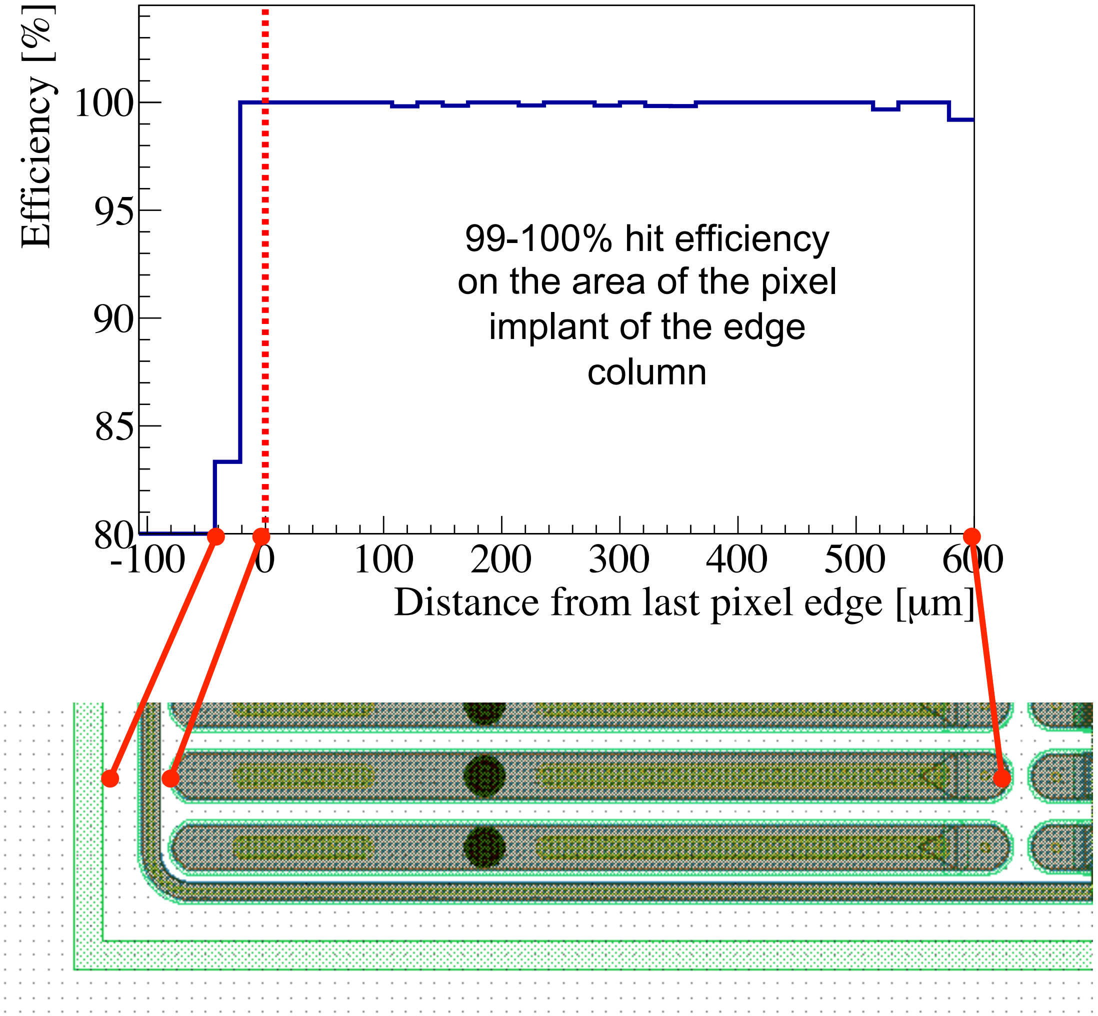




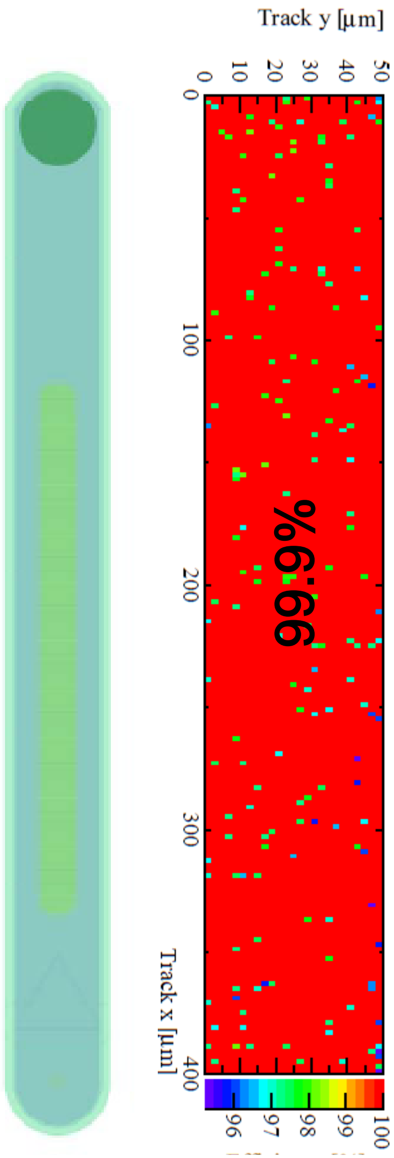
Edge pixels still active after irradiation

Hit efficiency for edge pixels – FE-I3 with 50 μm edge

Study of edge efficiency at CERN SPS beam test

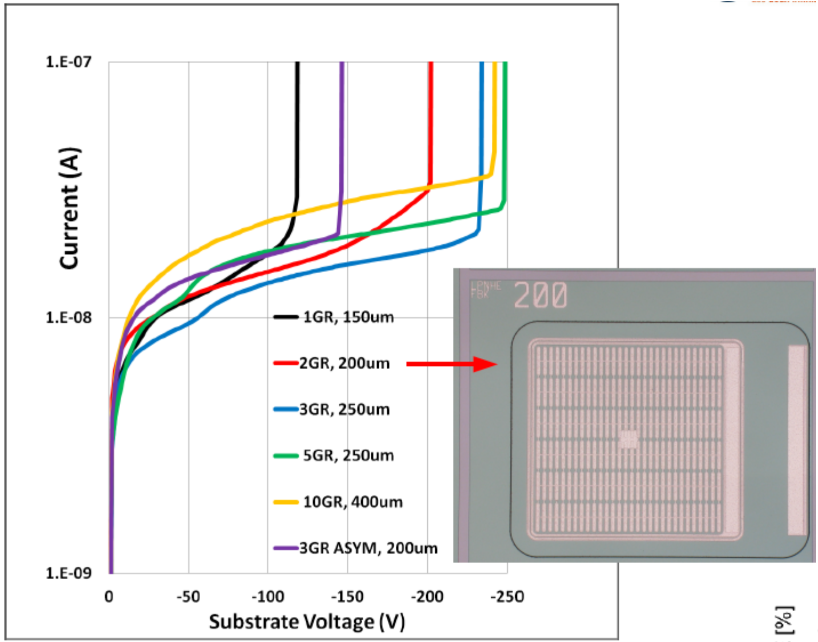


99-100% hit efficiency on the area of the pixel implant of the edge column



FE-I3, 50 μm edge, Vbias=20V

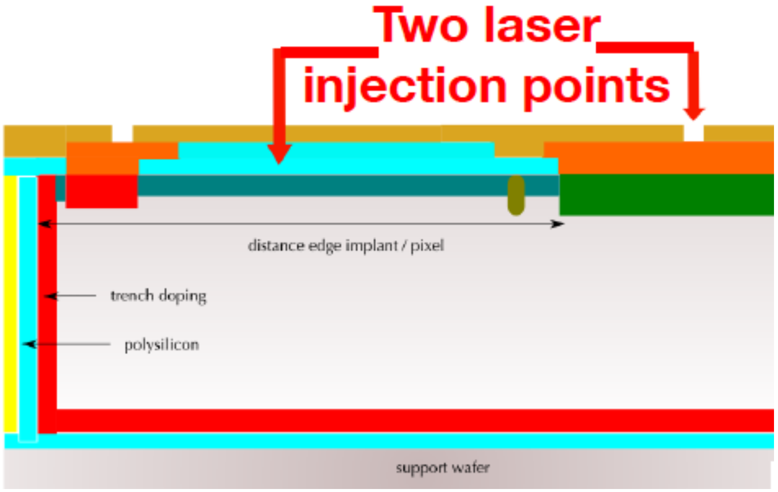
Active edge pixels – FBK LPNHE

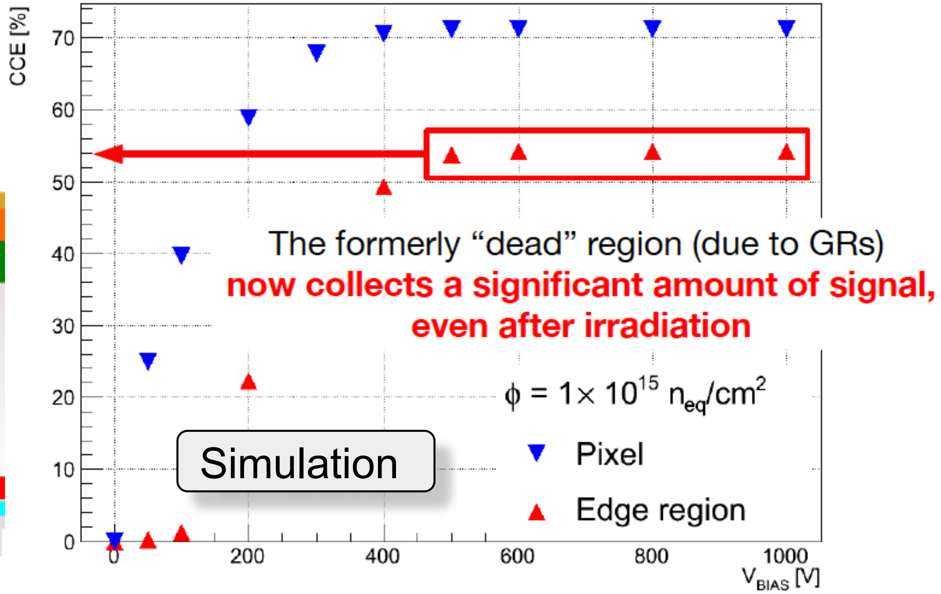


- ☐ First IV measurement on test pixels with FE-I4 geometry: all sensor type can be operated in over depletion.

Simulation

- ☐ CCE studied with SILVACO 2D TCAD simulation as a function of fluence and bias voltage.
- ☐ 1060 nm laser simulated pulse for charge collection
- ☐ CCE defined with respect to the charge collected before irradiation in the "pixel" region





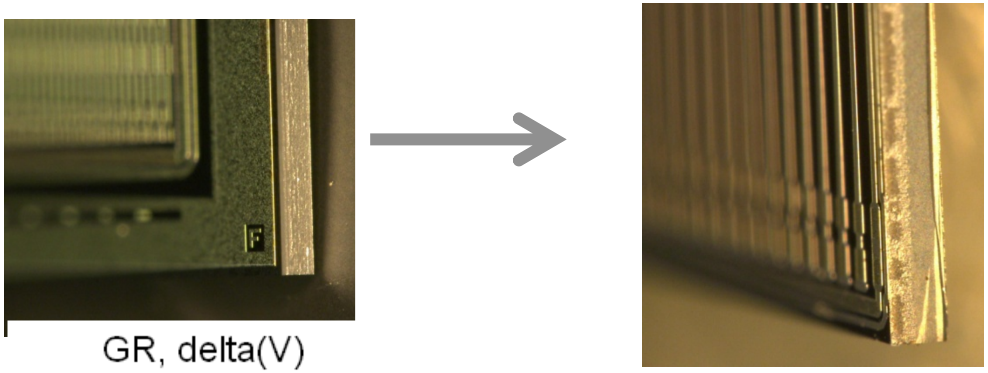
The formerly "dead" region (due to GRs) **now collects a significant amount of signal, even after irradiation**

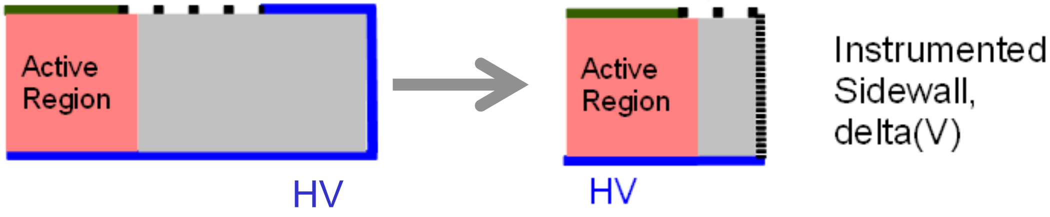
M. Bomben et al., arxive1212.3580

SCP: Projects and Technology Development

Basic Method:

- Instrument the sidewall in a close proximity to active area, such that it’s <u>resistive</u>.
- SCP – Scribe, Cleave, Passivate. The method is based on making low-defect surface on sensor sidewall edge, then passivating it in a similar way as top-level device surface. In development at SCIPP in collaboration with colleagues at NRL.





RD50 project since June 2011

Institute	Contact Person	Sensors	Status
CNM Barcelona	G. Pellegrini	3D diodes, strips, pixels	2nd round of tests (FE-I3 and FE-I4 pixels)
FBK Trento and INFN Trento	G.-F. Dalla Betta	3D diodes, strips	2 rounds of tests done
MPI Muenchen	A. Macchiolo	P-type planar pixels	In progress, sent strip devices
UNFN Bari	D. Creanza	N-type “SMART” detectors	First processed devices sent for evaluation
JSI Ljubljana	G. Kramberger	P- and N- type strip devices	Sent processed devices for laser TCT studies
Glasgow U.	R. Bates	P- and N- type strip devices	Devices sent, used in precision X-ray scan
TU Dortmund	T. Wittig	IBL-style n-on-n sensors	Initial tests done, iterations with IBL sensors

SCP: Physics Performance

- ☐ Two aspects of physics performance are under investigation:
- Charge collection near the edge. We do not see any problem:

Sensor Type	**Origin**	**Edge-Active area Distance [um]**	**Signal Read out**	**Beam**	**Ref**
P-type strips	PPS (CIS)	~200	Binary (PTSM)	^{90}Sr	V. Fadeyev *et al* Pixel 2012, submitted to NIM A
N-type strips	GLAST (HPK	~200	Analog (ALiBaVa)	^{90}Sr	R. Mori *et al*. 2012 JINST 7 P05002
P-type strips	PPS (CIS)	150	Analog (ALiBaVa)	Focused X-ray	R. Bates *et al*., 2013 *JINST* **8** P01018
P-type 3D pixels	IBL (CNM)	50	FE-I3 & FE-I4	CERN Test Beam	S. Grinstein *et al*., RESMDD12

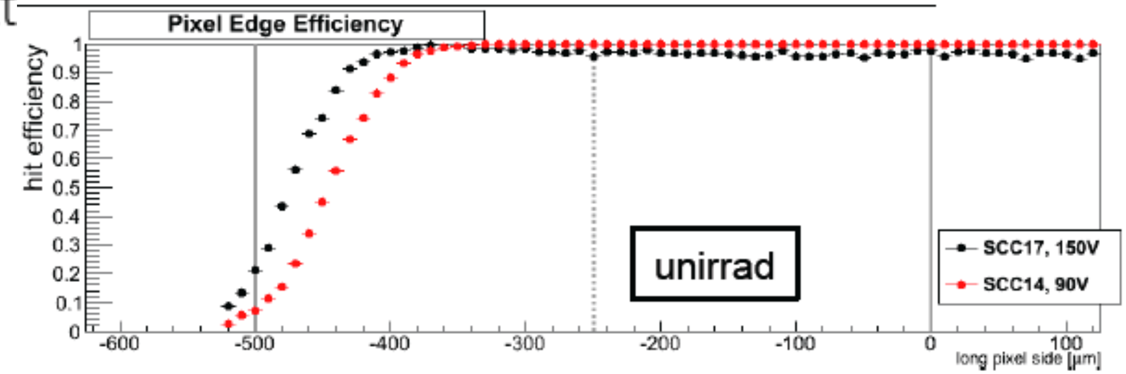
- Irradiation hardness:
  - Results with p-type sensors irradiated at Los Alamos were promising at ≥ 10^{15} n_{eq} cm^{-2}. They were ambiguous at ≤ 10^{14} n_{eq} cm^{-2}

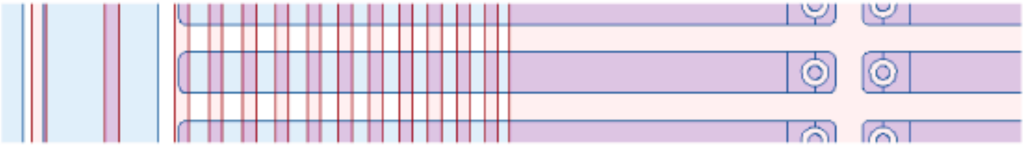
V. Fadeyev,
PIXEL2012 contribution

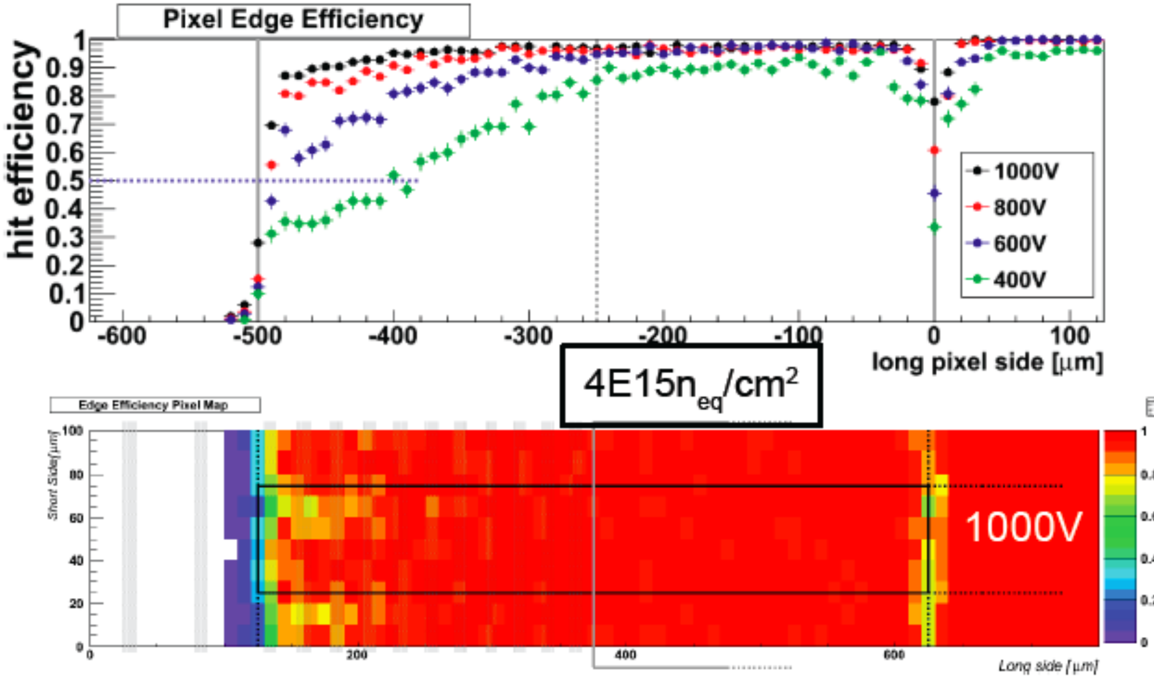
N-in-n pixels – Slim edge

technische universität
dortmund

CIS production of IBL sensors, 200 μm thickness



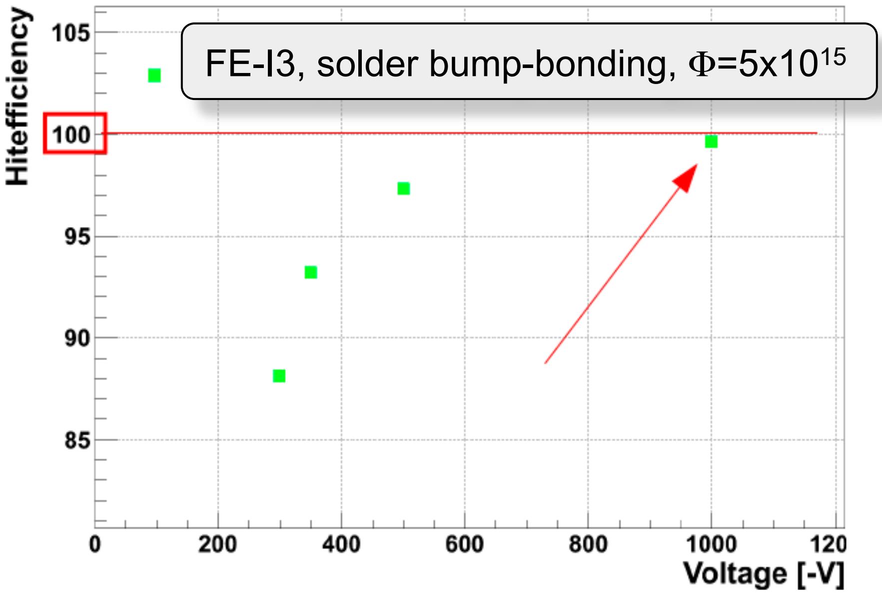




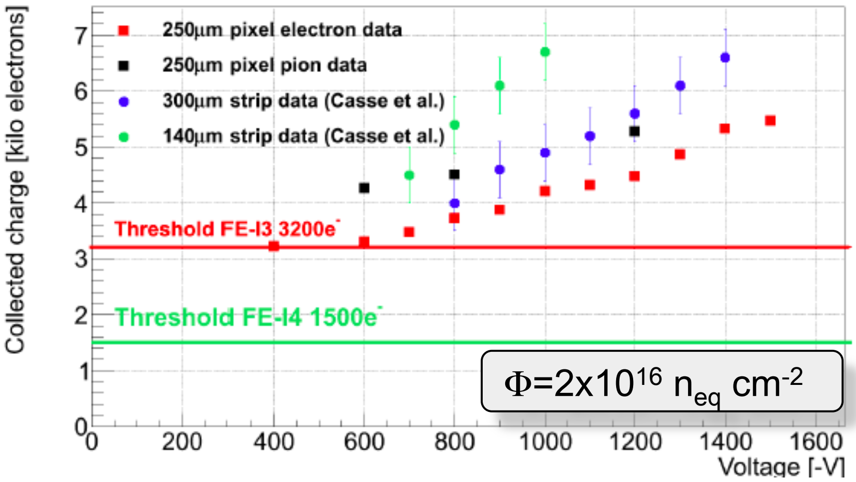
- Study of edge efficiency in beam tests for for FE-I4 n-in-n modules (IBL type)
- Before and after irradiation a clear dependence on the bias voltage is visible
- reduction of the inactive edge to ~200 μm demonstrated

N-in-n pixels – Radiation hardness

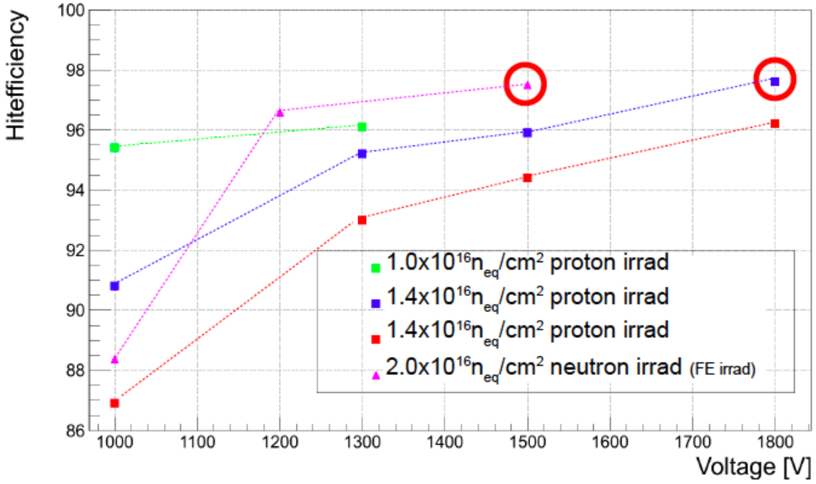
- required collected charges & hit efficiencies can be obtained by increasing the sensor bias voltage
- IBL fluence ($5x10^{15}$ n_{eq} cm^{-2})
  - hit efficiency of 99.6% was measured
  - more than 10ke at 1kV are collected
- Phase II fluence ($2x10^{16}$ n_{eq} cm^{-2})
  - hit efficiency >97%
  - collected charge well above threshold


FE-I3, solder bump-bonding, $\Phi=5x10^{15}$

T. Wittig,
[contribution to PIXEL2012 Conference](#)


$\Phi=2x10^{16}$ n_{eq} cm^{-2}

FE-I3 Indium bump bonded samples



Conclusions and Outlook

The High-Luminosity phase of LHC requires a new ATLAS pixel detector

- ☐ New pixel sensors for the inner layers must be radiation hard and with as high as possible geometrical efficiency
- ☐ The ATLAS PPS R&D Collaboration is investigating different solutions of n-in-p and n-in-n pixel sensors:

Slim edges:

- First measurements on different active edges n-in-p pixel productions show encouraging results before and after irradiations
- Slim edges reached by design optimization with n-in-n pixels
- SCP method represent a cost-effective option to deliver slim edges as a post-processing steps on sensors of any vendor.

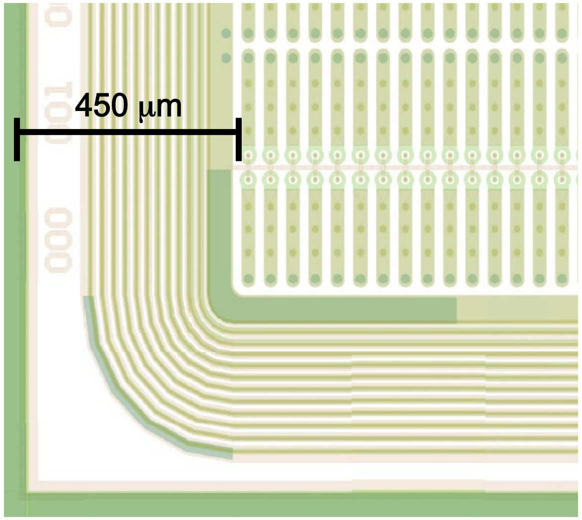
Radiation hardness:

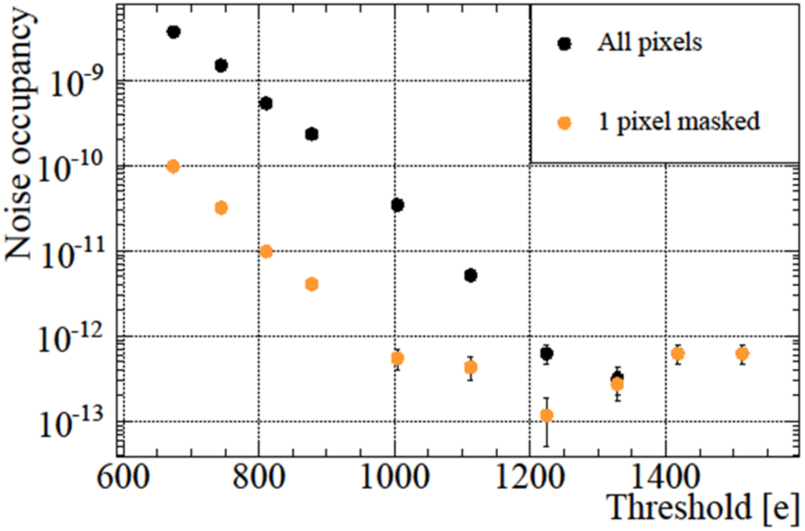
- Demonstrated for n-in-p pixels up to 10^{16} n_{eq} cm^{-2} and for n-in-n pixels up to $2x10^{16}$ n_{eq} cm^{-2}

Planar pixel sensors are promising candidates for use at HL-LHC !

Back-up slides

MPP-HLL SOI2 production: FE-I4 sensors, 150 µm thick

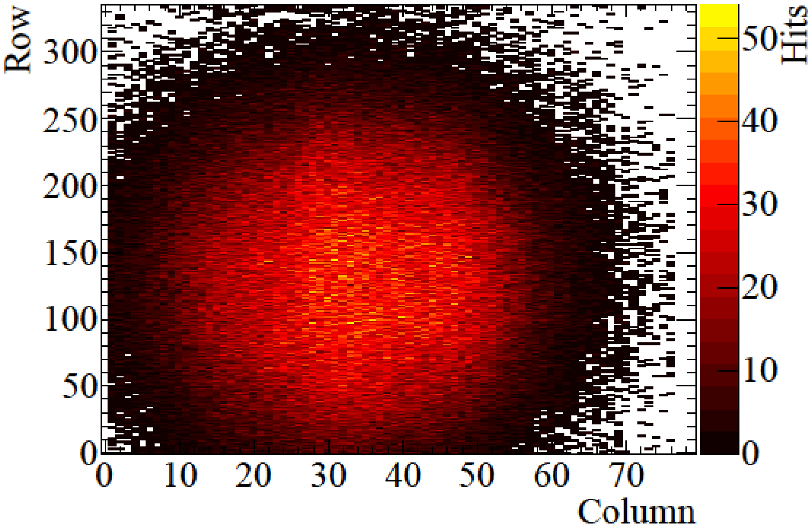




FE-I4 modules, 150 µm thick n-in-p sensors

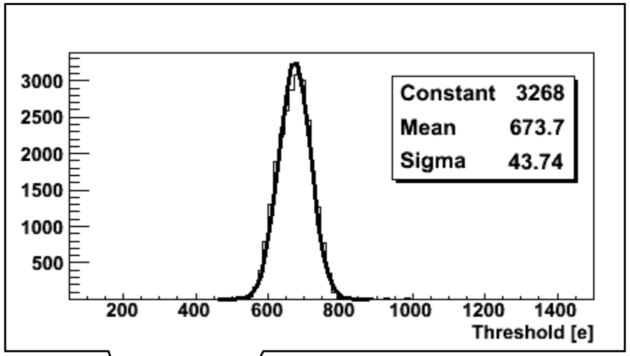
- Interconnection by bump-bonding at IZM
- 450 µm inactive width, compliant with the IBL specifications
- FE-I4 chip: very low noise and occupancy also at reduced threshold values
- 1 module irradiated at 2x10^{15} $n_{eq/}$ cm^2 at KIT with 25 MeV protons
- 3 modules irradiated at 4x10^{15} $n_{eq/}$ cm^2 in Los Alamos with 800 MeV protons

^{90}Sr source image

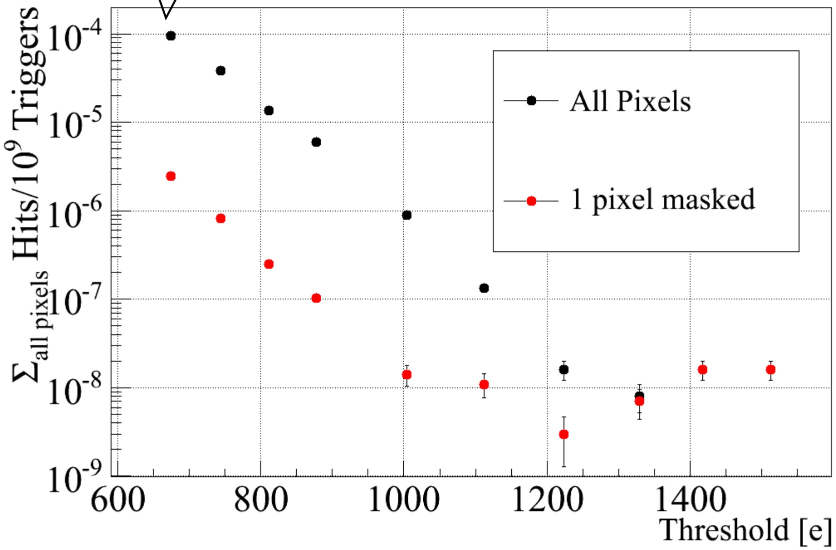


FE-I4 n-in-p modules: noise occupancy at low thresholds

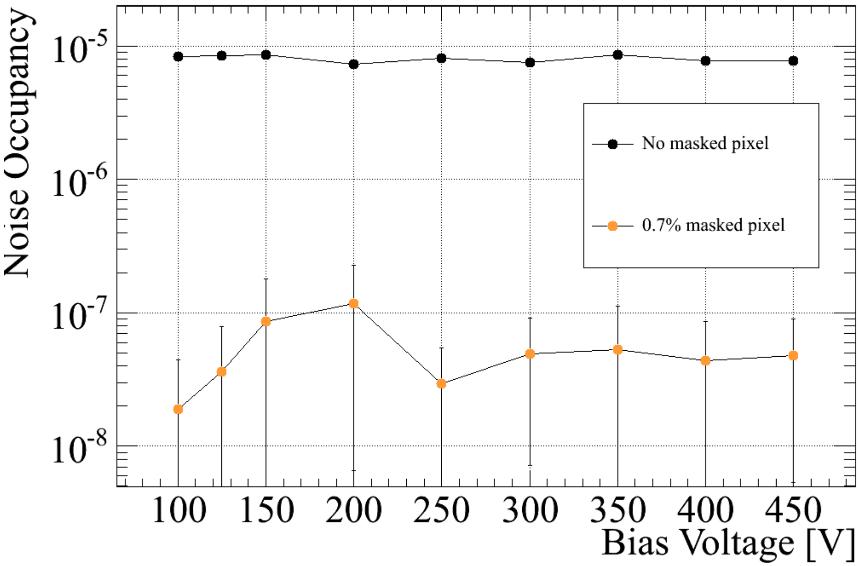
- FE-I4 chip: very low noise and occupancy also at reduced threshold values
- Low thresholds achievable with the FE-I4 chip help to deal with small charges after irradiation



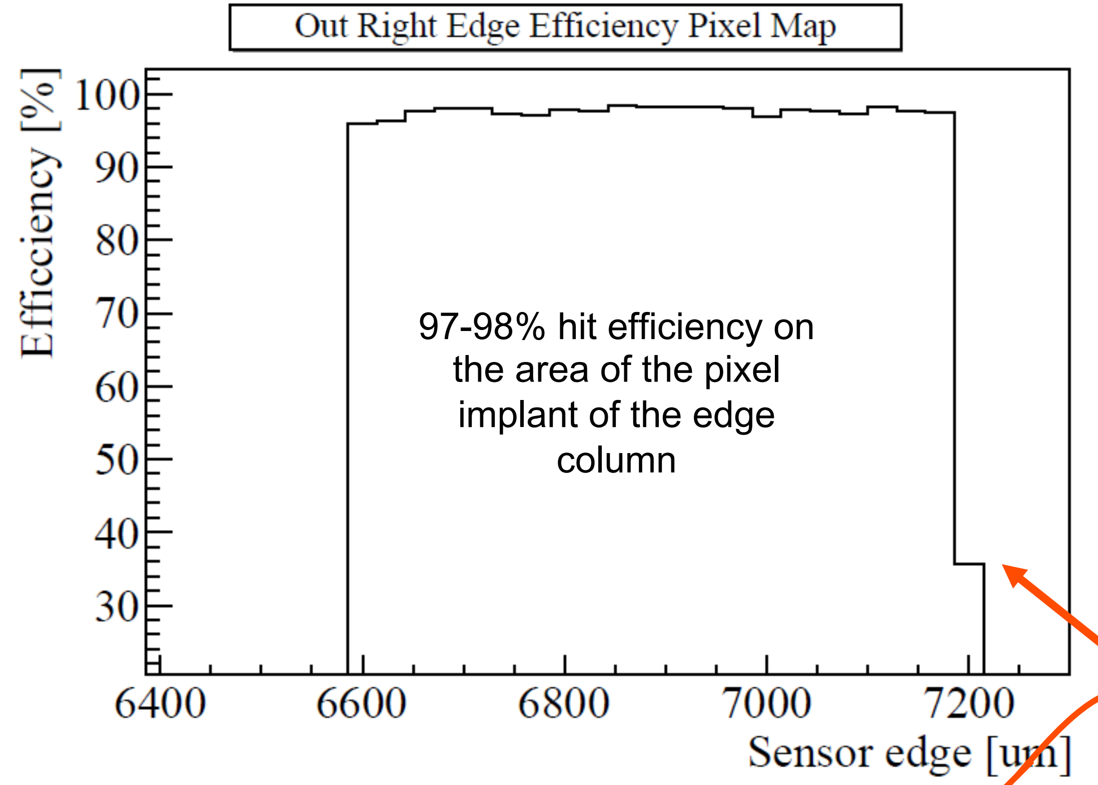
Before irradiation



Φ=4x10^{15} n_{eq} cm^{-2} , Threshold = 1500 e



Hit efficiency for edge pixels - FE-I3 with 125 μm edge

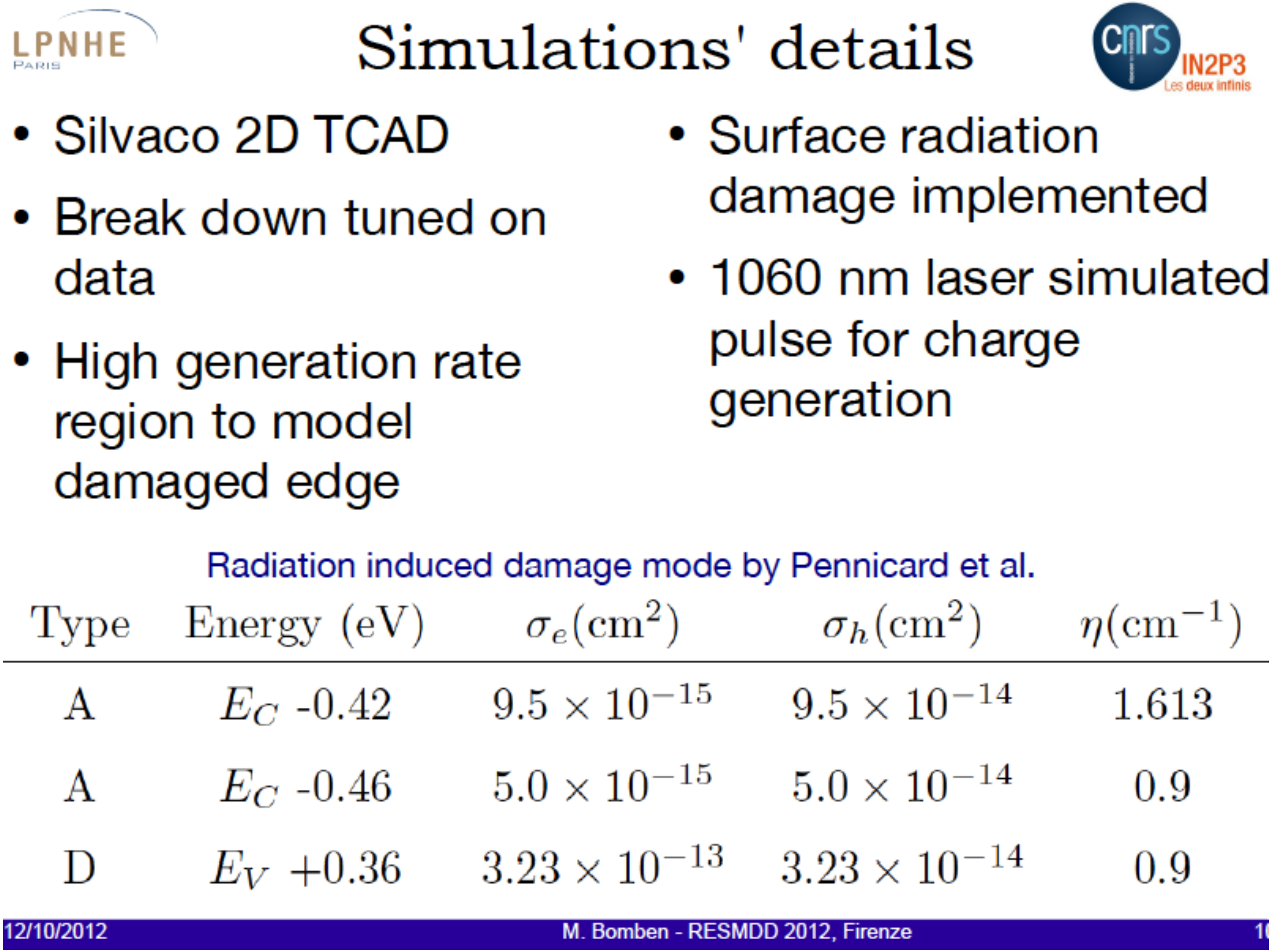


97-98% hit efficiency on the area of the pixel implant of the edge column

Grounded bias ring

35% hit efficiency in the area between last pixel implant and the bias ring

Active edge pixels simulation



LPNHE PARIS

Simulations' details

CNRS IN2P3 Les deux infinis

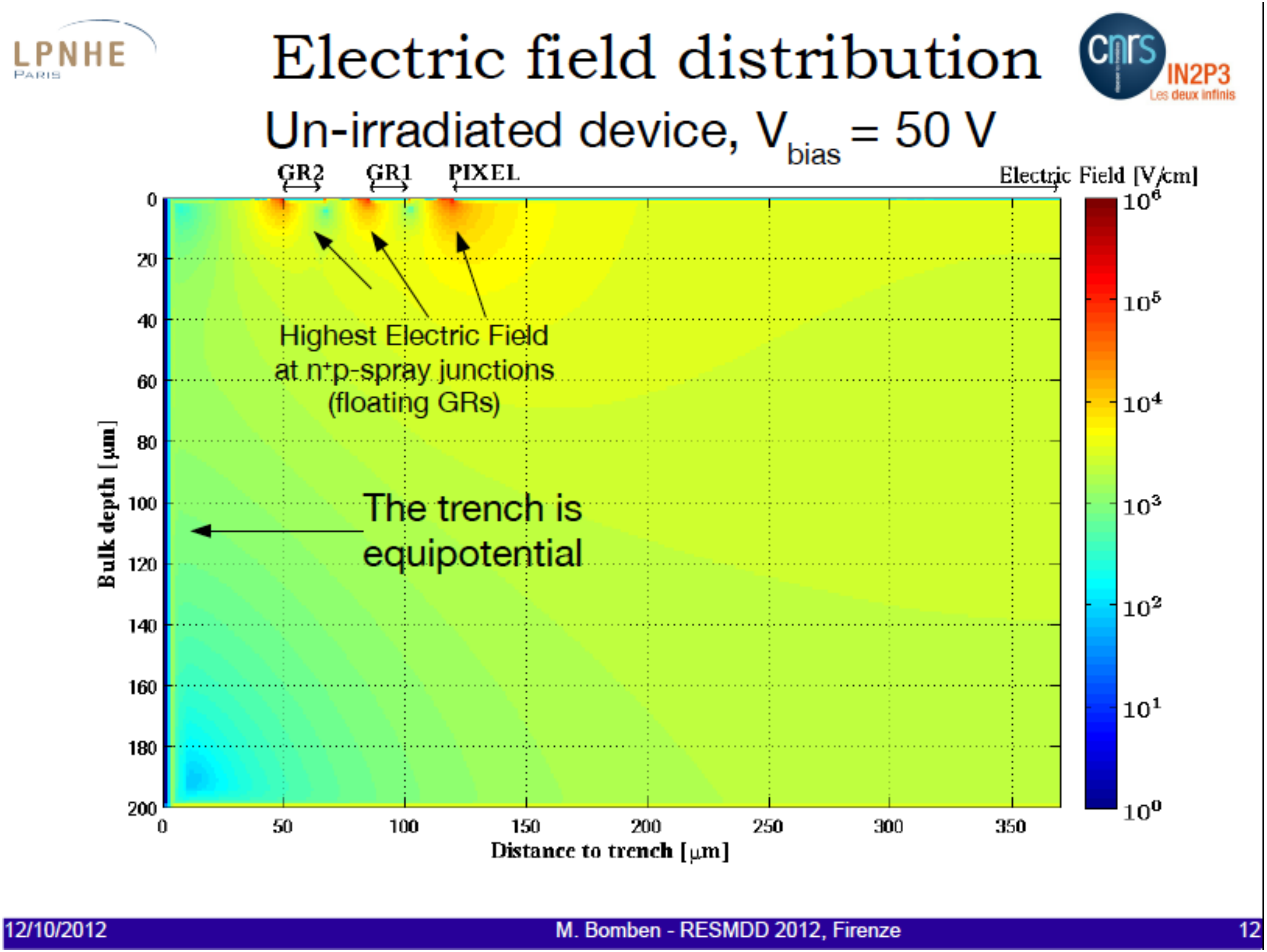
- Silvaco 2D TCAD
- Break down tuned on data
- High generation rate region to model damaged edge
- Surface radiation damage implemented
- 1060 nm laser simulated pulse for charge generation

Radiation induced damage mode by Pennicard et al.

Type	Energy (eV)	$\sigma_e(\mathrm{cm}^2)$	$\sigma_h(\mathrm{cm}^2)$	$\eta(\mathrm{cm}^{-1})$
A	E_C -0.42	9.5×10^{-15}	9.5×10^{-14}	1.613
A	E_C -0.46	5.0×10^{-15}	5.0×10^{-14}	0.9
D	E_V +0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

12/10/2012 M. Bomben - RESMDD 2012, Firenze 1

Active edge pixels simulation



Electric field distribution

Un-irradiated device, V_{bias} = 50 V

Highest Electric Field at n⁺p-spray junctions (floating GRs)

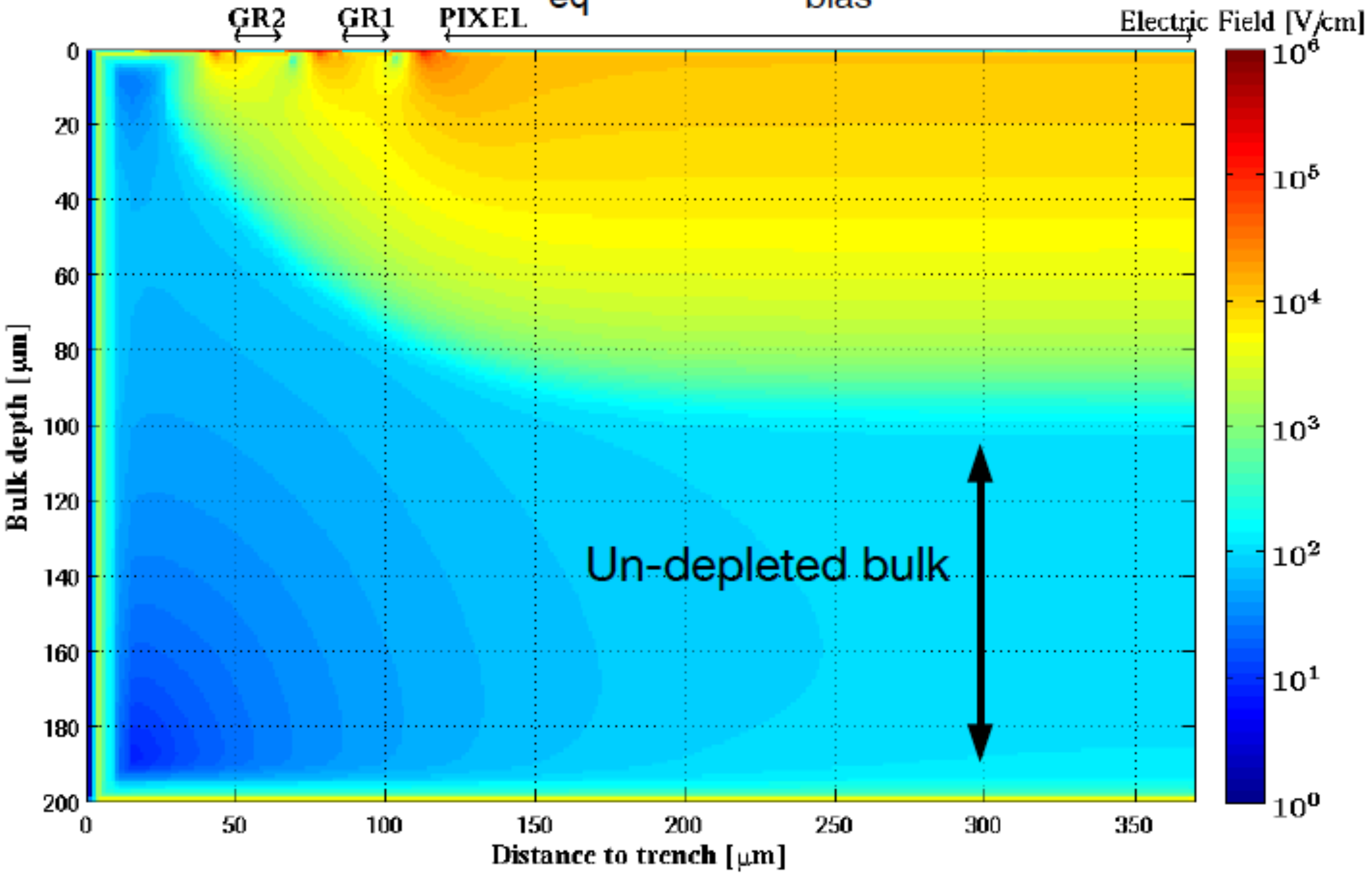
The trench is equipotential

12/10/2012 M. Bomben - RESMDD 2012, Firenze 12

Active edge pixels simulation

Electric field distribution

$\Phi = 10^{15}\ n_{eq}/cm^2$, $V_{bias} = 50$ V



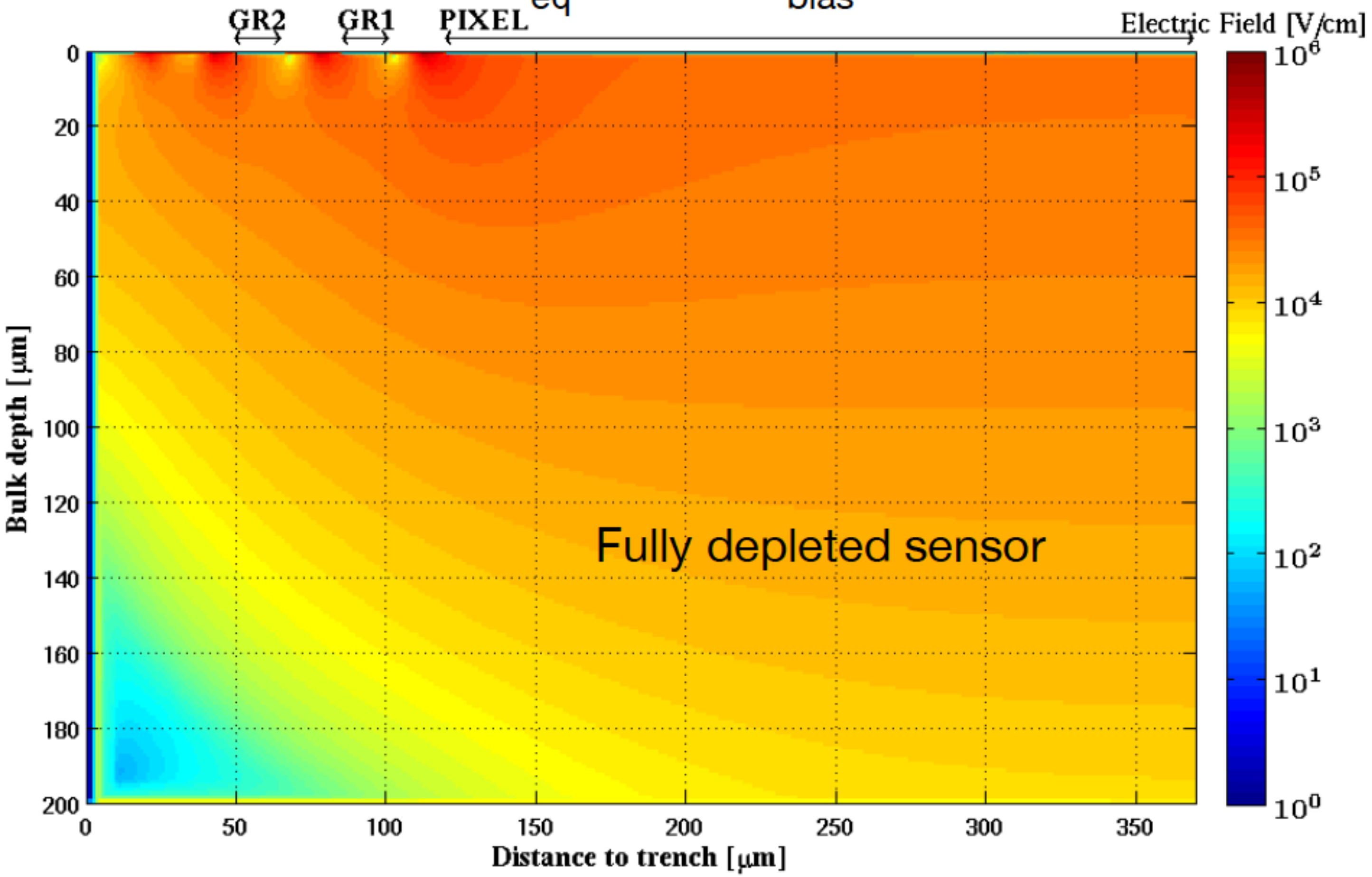
Active edge pixels simulation

LPNHE PARIS

Electric field distribution

cnrs IN2P3 Les deux infinis

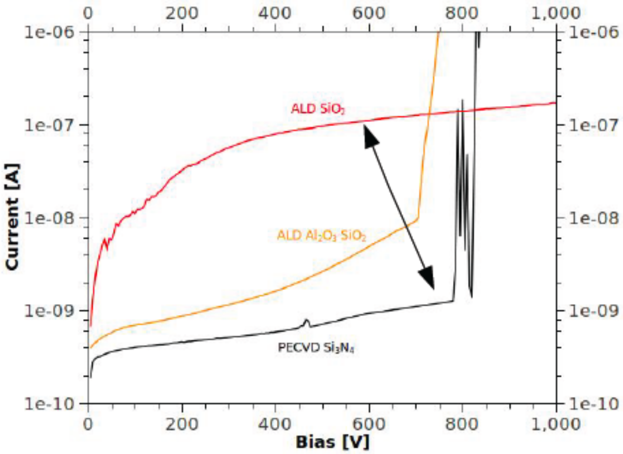
$\Phi = 10^{15}\ n_{eq}/cm^2$, $V_{bias} = 400$ V



Fully depleted sensor

SCP Method: Method

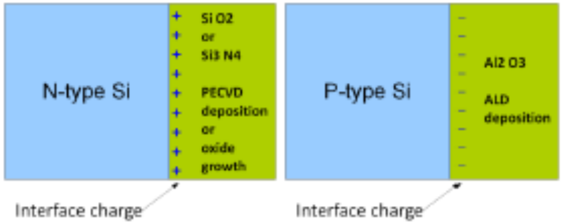
V. Fadeyev,
PIXEL2012 contribution



N-type

Key Steps

- Scribing along the lattice orientation of the Si wafer
  - Diamond
  - Laser
  - Etch-scribing with XeF2
  - DRIE scribing
- Cleaving
  - Manually with tweezers
  - With Industrial cleaving machines, e.g. by Dynatex or Loomis
- (optional) sidewall etch
- Passivation
  - N-type bulk requires positive interface charge with Si:
    - Native oxide formation with thermocycling, UV light
    - PECVD deposition of SiO2
    - PECVD deposition of Si3N4
    - ALD deposition of "nanostack" of SiO2 and Al2O3
  - P-type bulk requires negative interface charge with Si:
    - ALD deposition of Al2O3



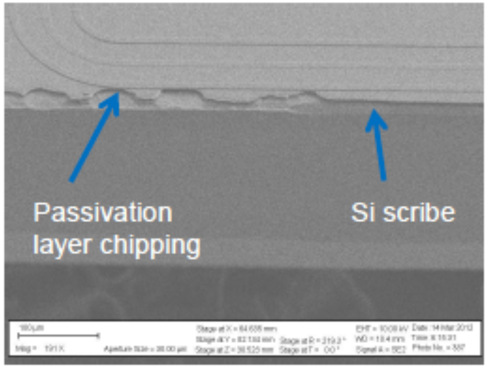
SCP Method: Scribing Methods

V. Fadeyev,
PIXEL2012 contribution

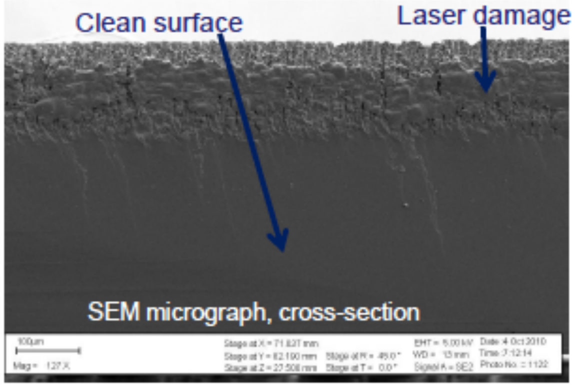
Scribing

There are many scribing options, with varying performance and reliability.

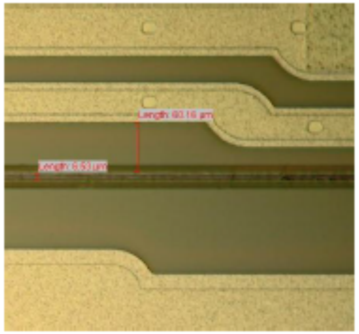
Diamond scribing



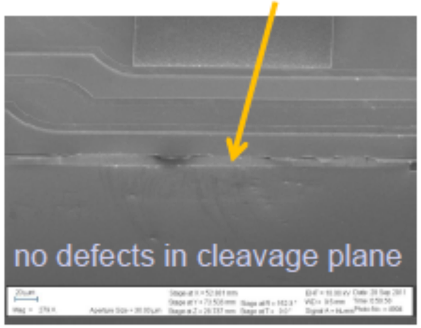
Laser scribing

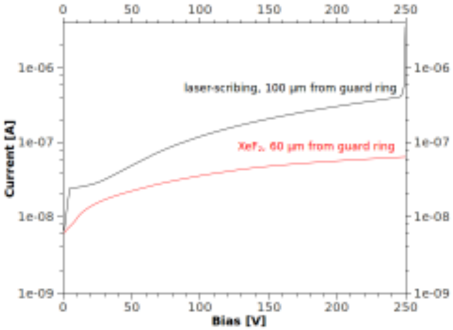


XeF2-based etch scribing



XeF$_2$ "scribe" with depth ~ 5 μm

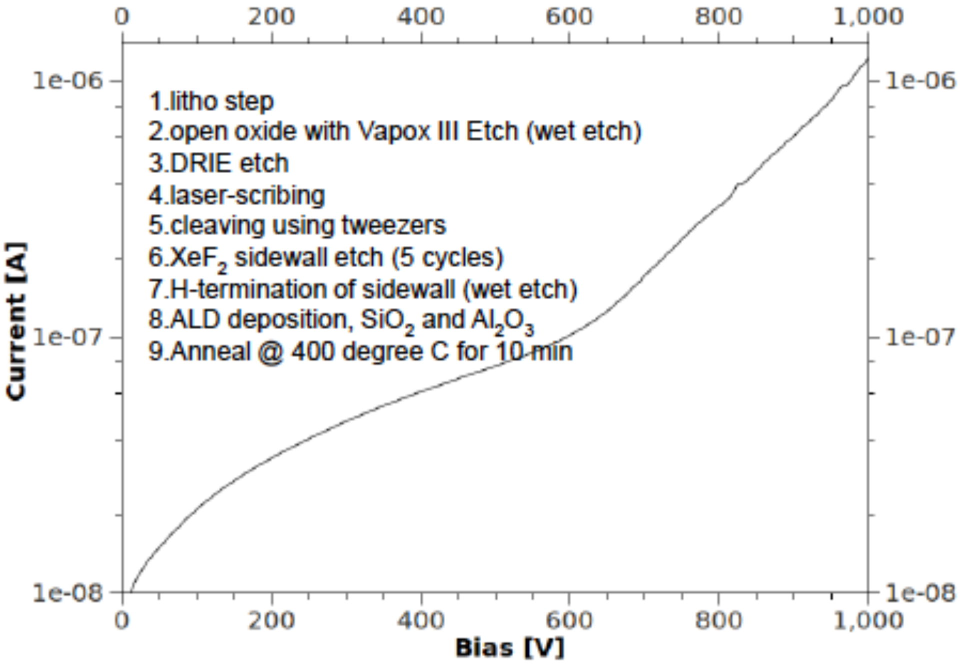


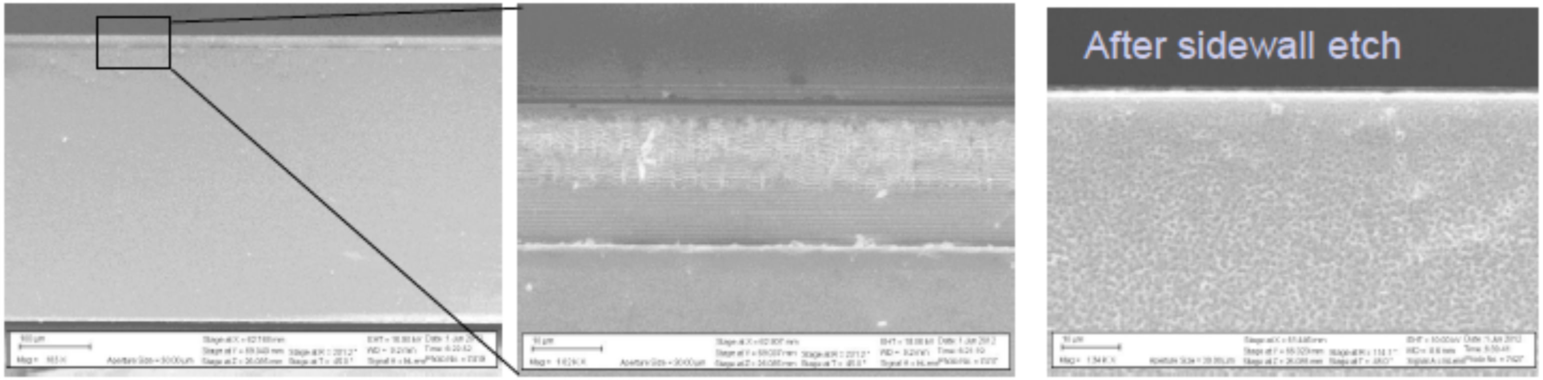


SCP Method: Scribing Methods

V. Fadeyev,
PIXEL2012 contribution

DRIE based etch scribing


1.litho step
2.open oxide with Vapox III Etch (wet etch)
3.DRIE etch
4.laser-scribing
5.cleaving using tweezers
6.XeF_2 sidewall etch (5 cycles)
7.H-termination of sidewall (wet etch)
8.ALD deposition, SiO_2 and Al_2O_3
9.Anneal @ 400 degree C for 10 min



SEM micrographs, cross-sections