Radiation Hardness Study on Double Sided 3D Sensors after Proton and Neutron Irradiation up to HL-LHC Fluencies

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RADFAC Thematic Day '15

INFN Laboratori Nazionali di Legnaro (Padova)

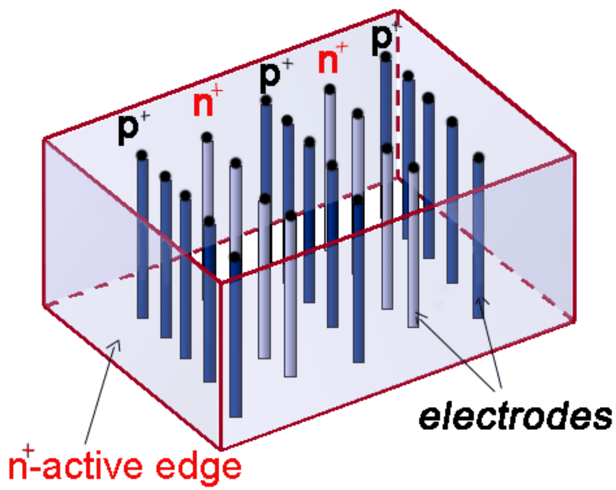
OUTLINE

- Introduction & Motivation
- Results from the electrical characterizations:
  - Passing-Through Columns (IBL technology)
  - Modified Non-Passing-Through Columns
- Comparative Investigations
- Conclusion

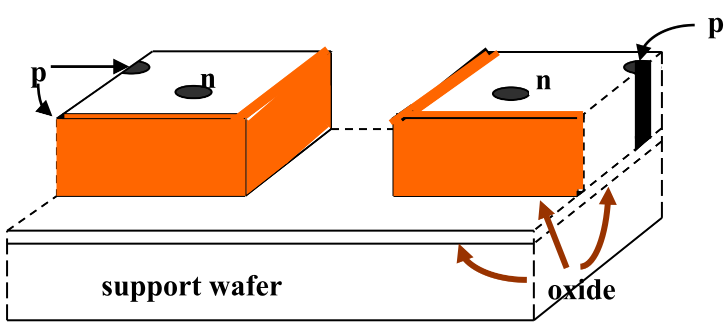
Introduction

3D Radiation Sensors

S. Parker et. al.
NIMA 395 (1997) 328



C. Kenney et. al.
IEEE TNS 48(6) (2001) 2405



ADVANTAGES:

- Electrode distance and active substrate thickness decoupled:
  - Low depletion voltage (~10 V, before irradiation)
  - Fast response times
  - smaller trapping probability after irradiation

  → **High radiation hardness**
- Cell Shielding Effect
- Active Edge and Slim-Edge Technology

  → **Sensitivity up to few µm from the edge**

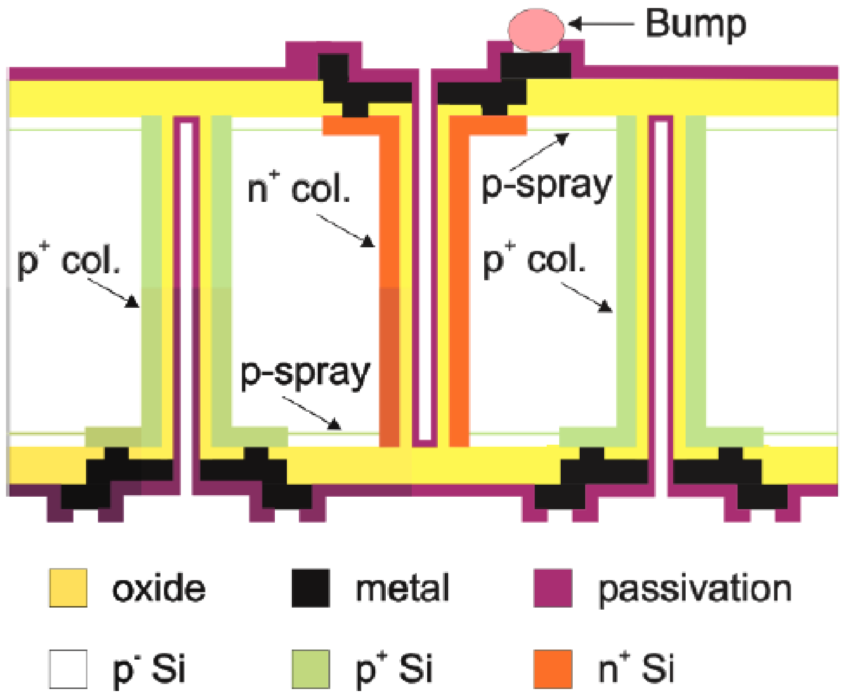
DISADVANTAGES:

- Non uniform spatial response
- Higher capacitance with respect to planar
- Complicated technology (wafer bonding, DRIE, etc.)

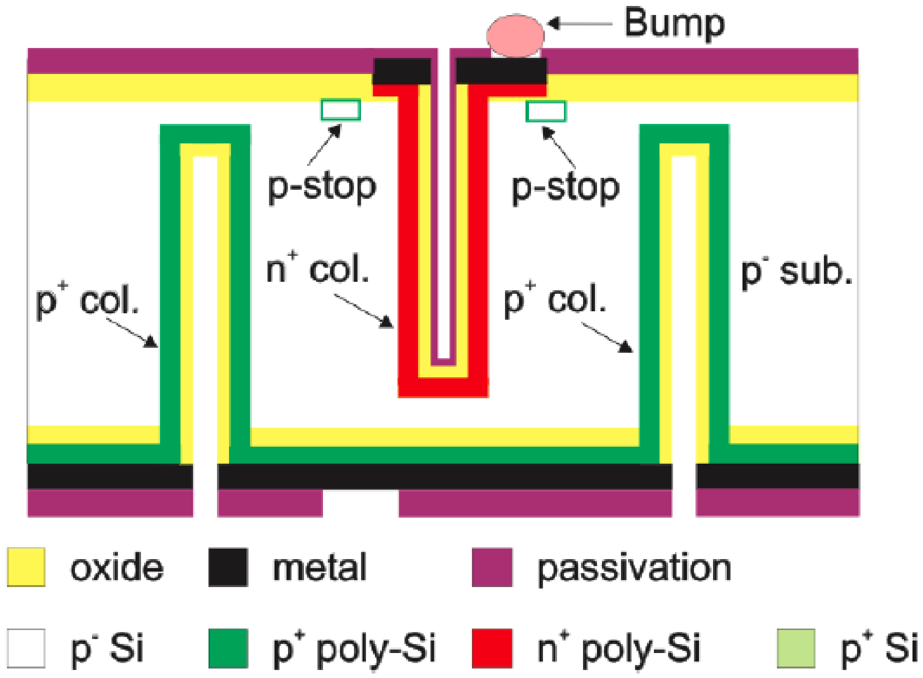
C. Kenney et. al.
IEEE TNS 46(4) (1999) 1224

Double-sided 3D sensors

FBK (Trento, Italy)



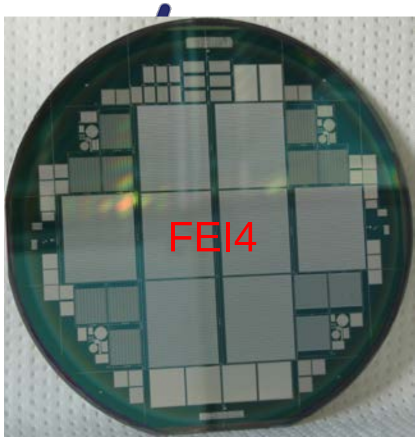
CNM (Barcelona, Spain)



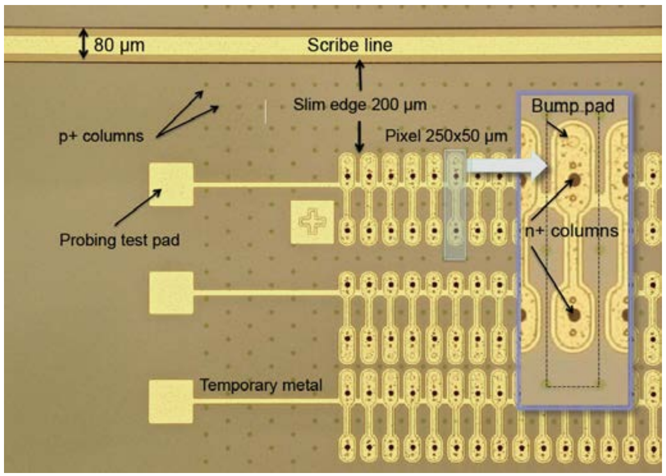
A. Zoboli et. al., IEEE TNS 55(5) (2008), 2775 G. Pellegrini et. Al. NIMA 592(2008), 38

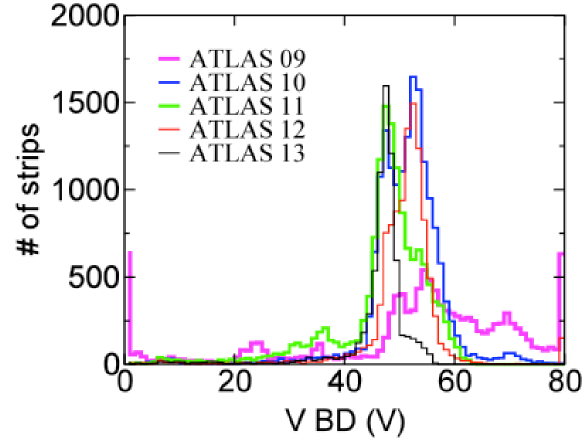
- Support wafer is not used → reduced process complexity
- First Joint Production of 3D pixels accomplished for ATLAS IBL (FBK & CNM)
- Back-side accessible → Easier assembly within a detector system
- Active edge not feasible → Slim edge

FBK 3D Pixels for ATLAS IBL

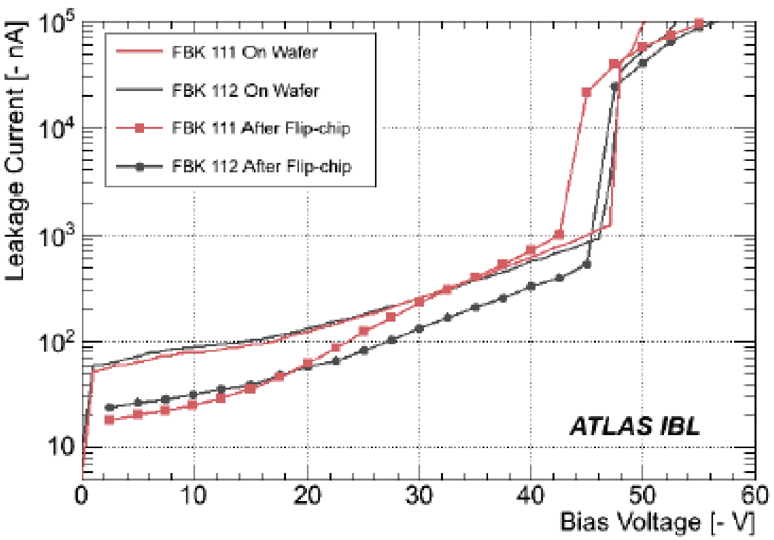


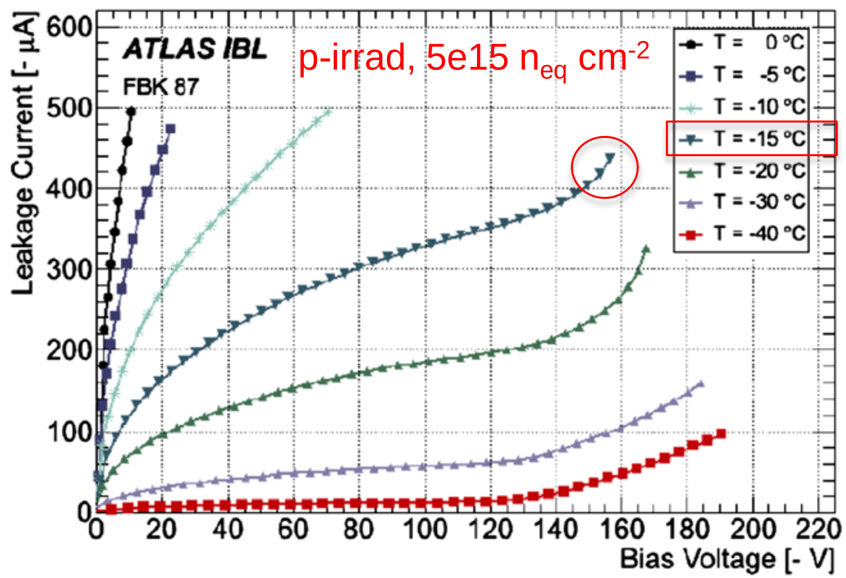
Electrical tests





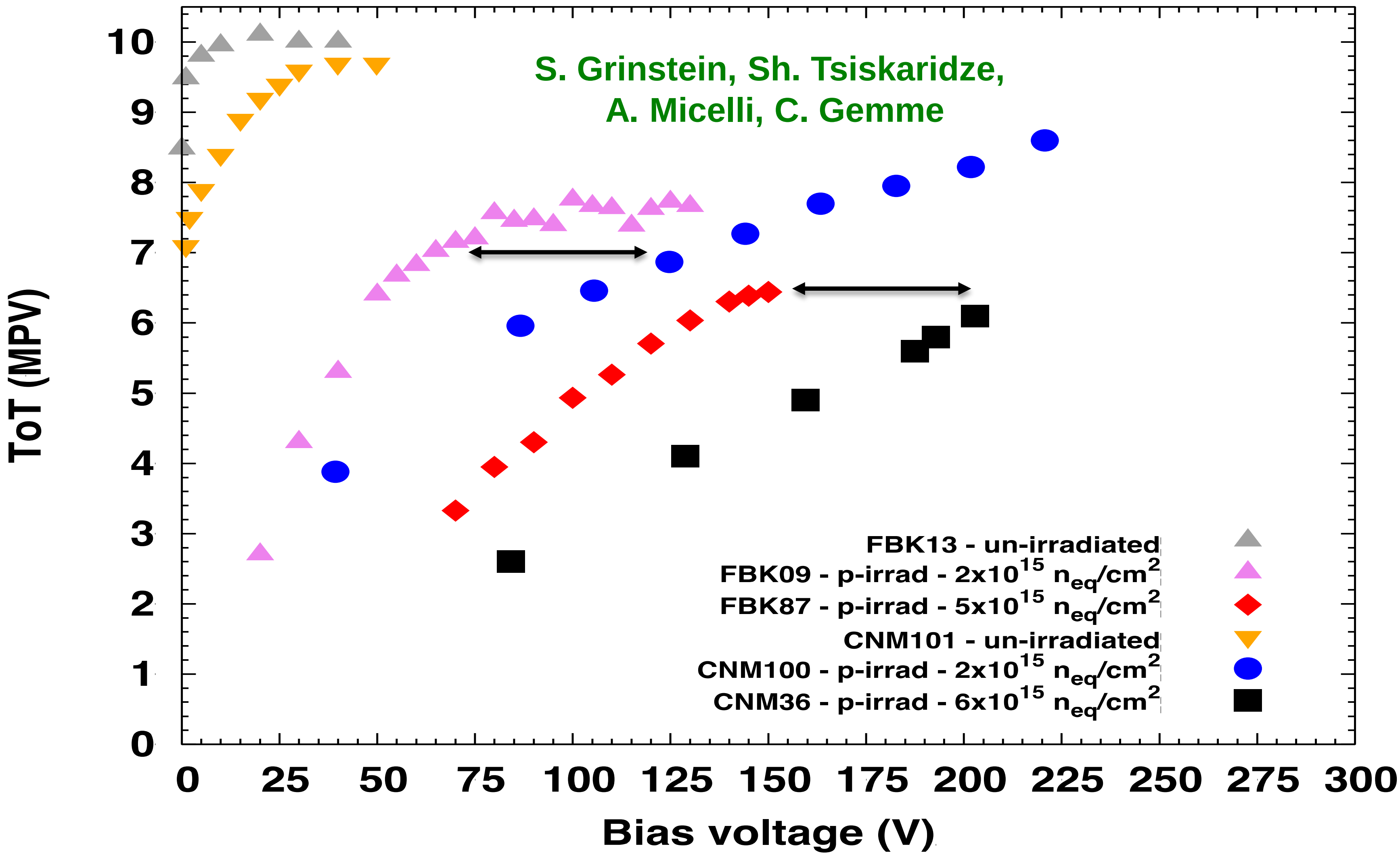
G. Giacomini, et al.,
IEEE TNS 60(3) (2013) 2357





The ATLAS IBL Collaboration, JINST 7 (2012) P11010

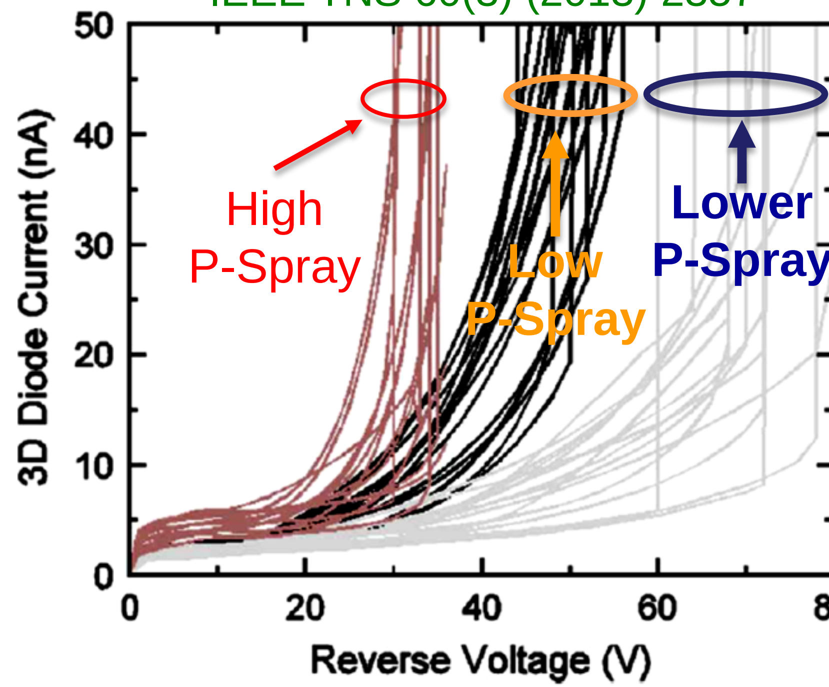
Charge collection in FE-I4 pixels with ^{90}Sr beta source

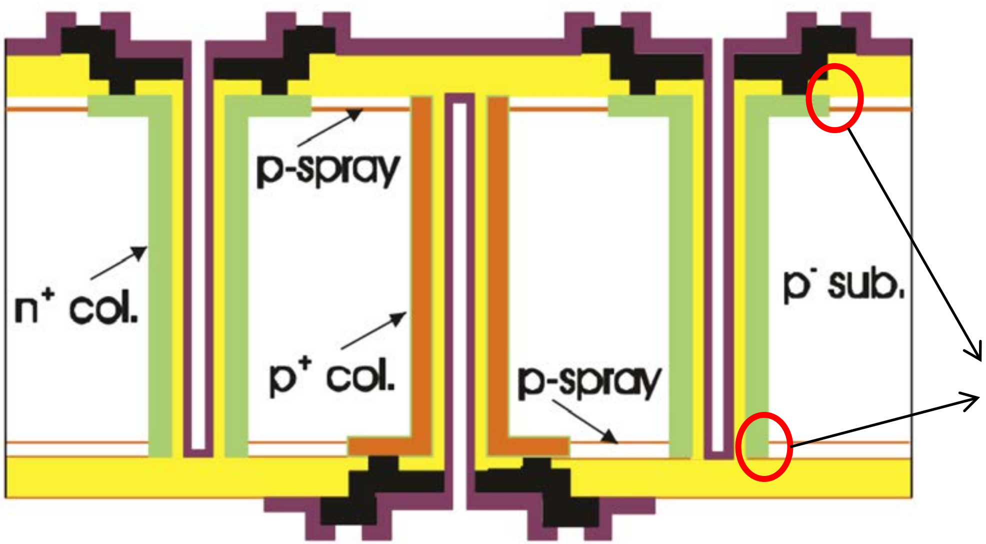


Breakdown voltage in FBK sensors

- In FBK 3D sensors the intrinsic breakdown occurs at the n^{+}/p-spray junctions
- P-spray doping reduction improved V_{bd} from ~20 V (ATLAS08) to >60 V (IBL production, A09-II)
- For further improvements, it is important to learn more about breakdown behavior

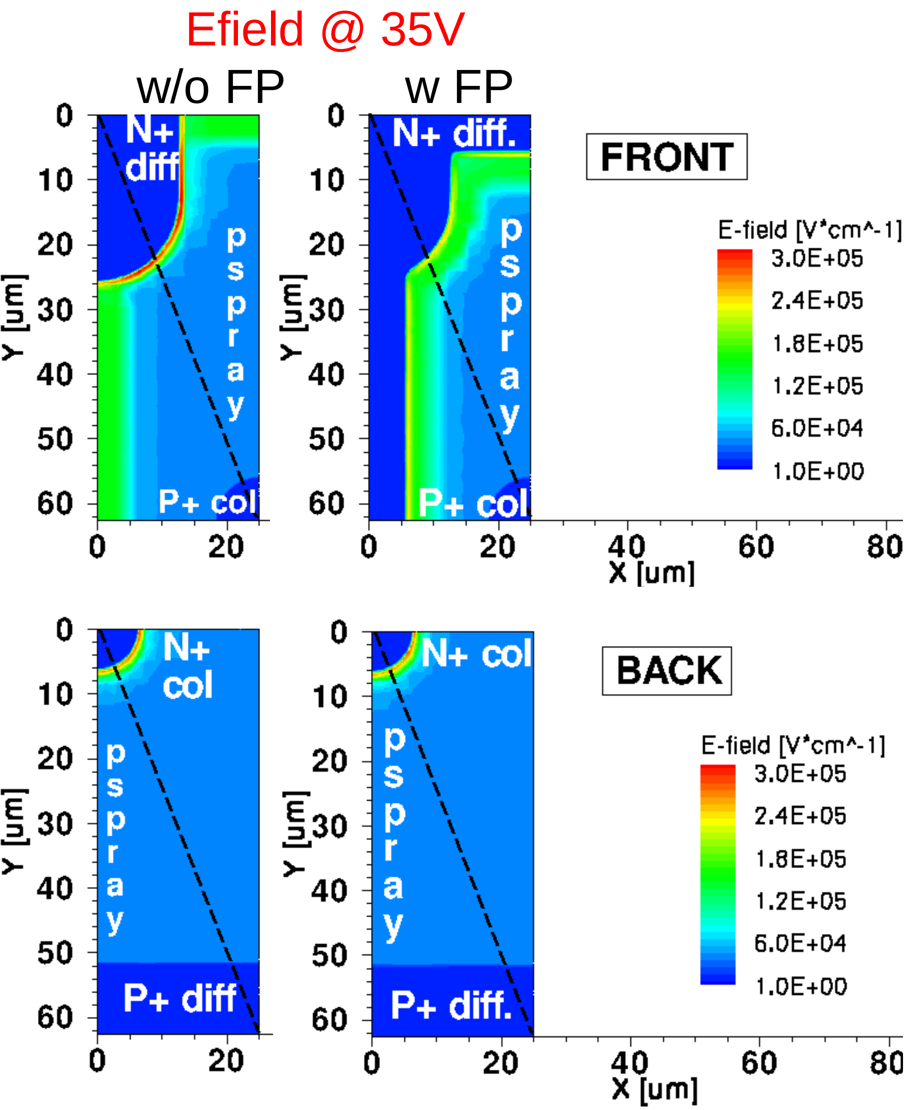
G. Giacomini et. al., IEEE TNS 60(3) (2013) 2357





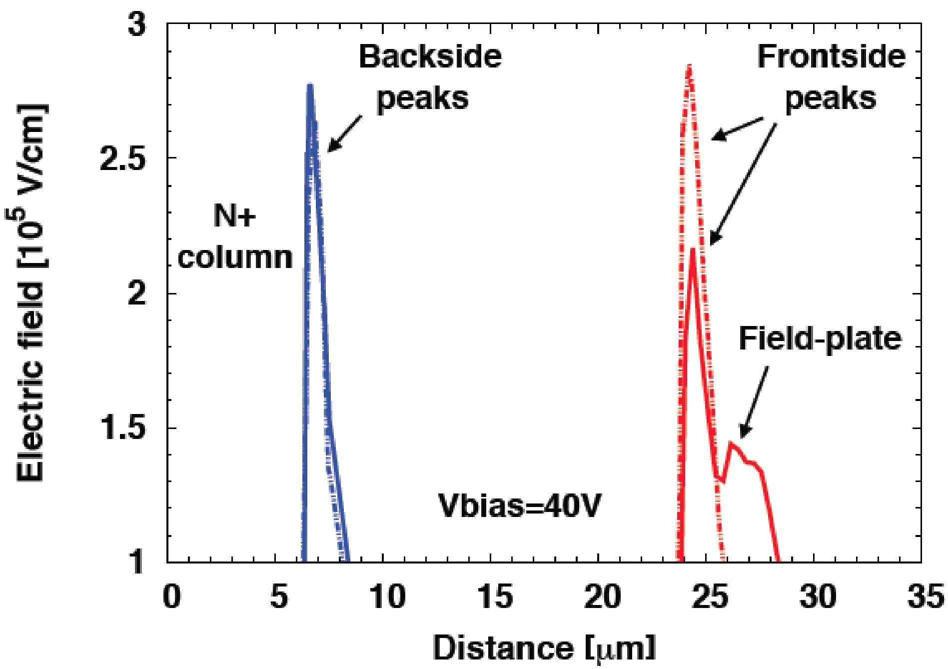
Most critical regions for breakdown

Field-Plate Effect on Electric field

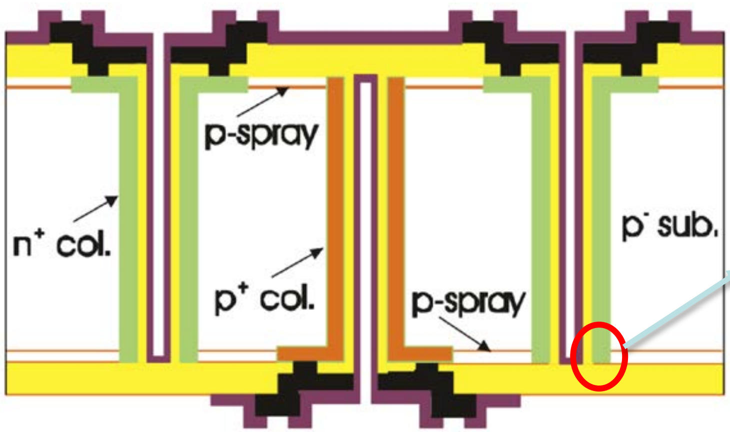


M. Povoli et al, NIMA 699 (2013) 22–26

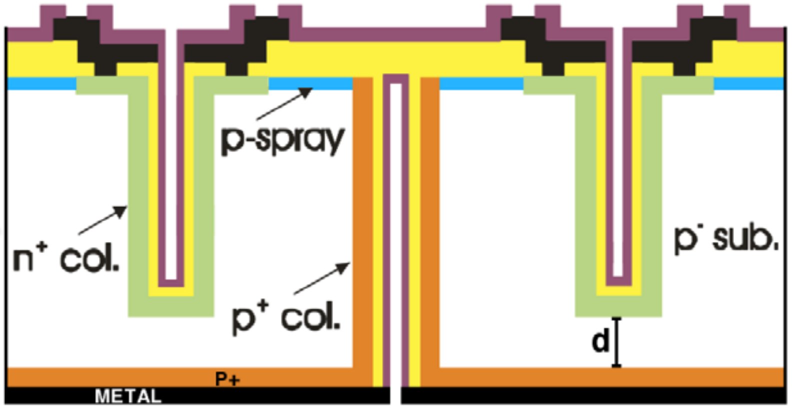
- Comparable electric field peaks on front side and back side for std. structures
- The field-plate helps in redistributing and lowering the E-field on the front side (breakdown on the back side …)

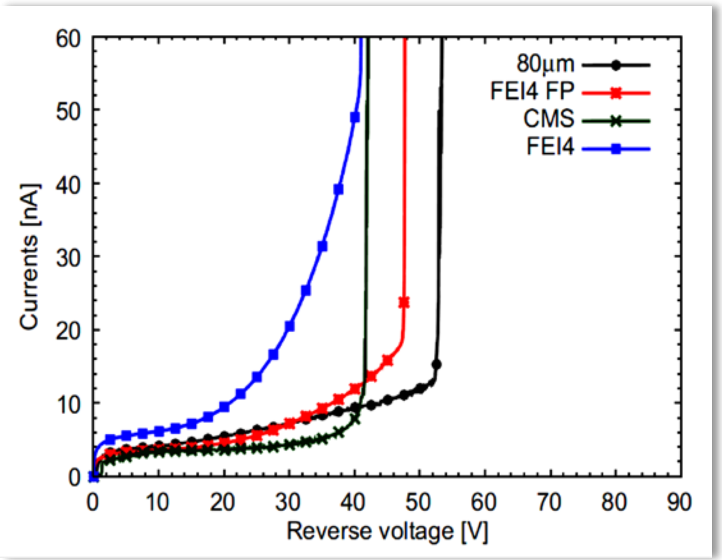


Improved design



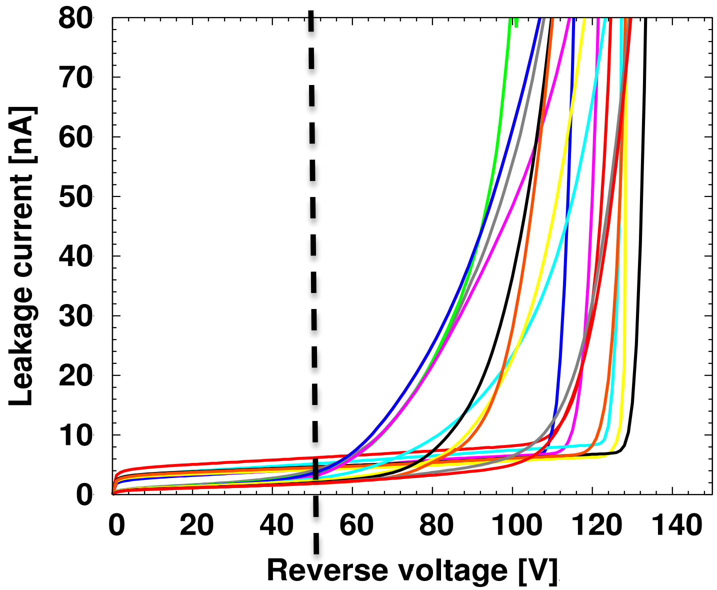
Most critical zone for V_{bd} removed





M. Povoli et al, NIMA 699 (2013) 22–26

Intrinsic Breakdown Increases up to 70 V - 130 V

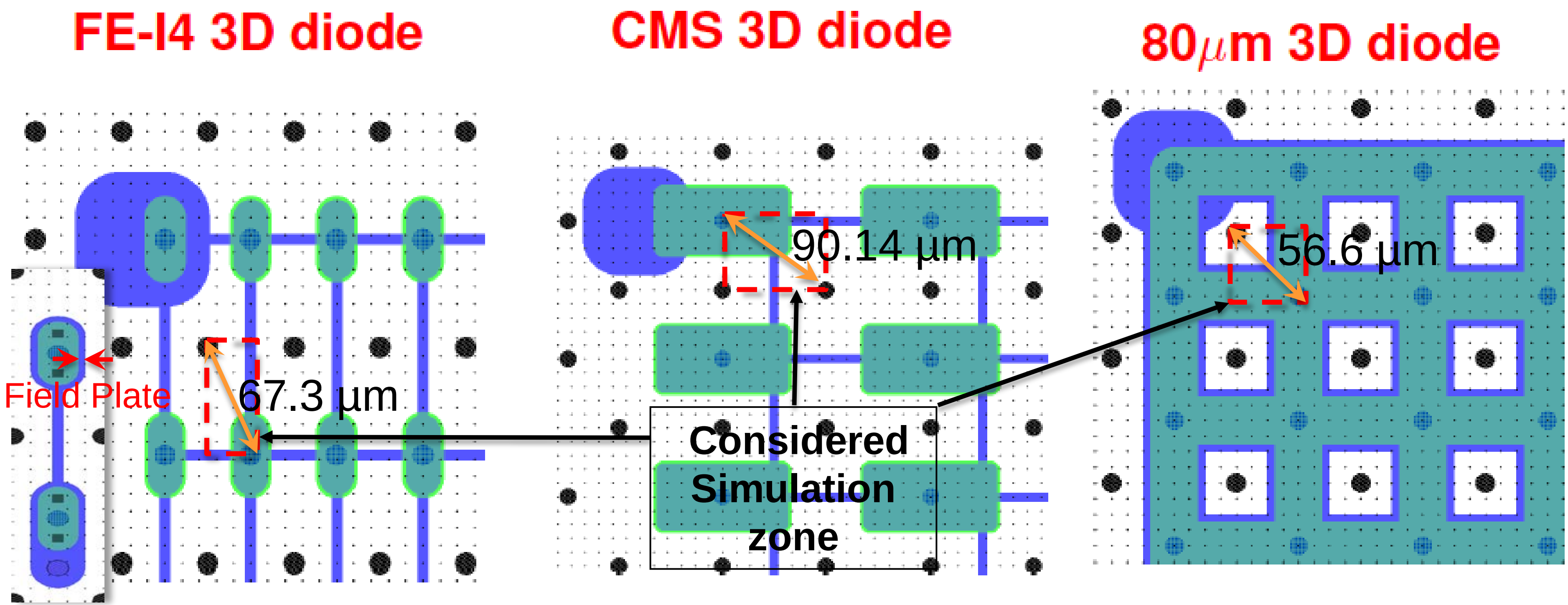


Dalla Betta et al, (NSS/MIC), 2013 IEEE

Is it also better after irradiation ?

- Since breakdown voltage improves with ionizing dose (higher oxide charge), the same improvement should be observed after irradiation
- Dedicated irradiation tests were performed to check this point
  - a) 800 MeV protons at LANSCE facility
    - Thanks to Martin Hoeferkamp and Sally Seidel
  - b) TRIGA reactor neutrons at JSI Ljubljana, Slovenia
    - Thanks to Vladimir Cindro

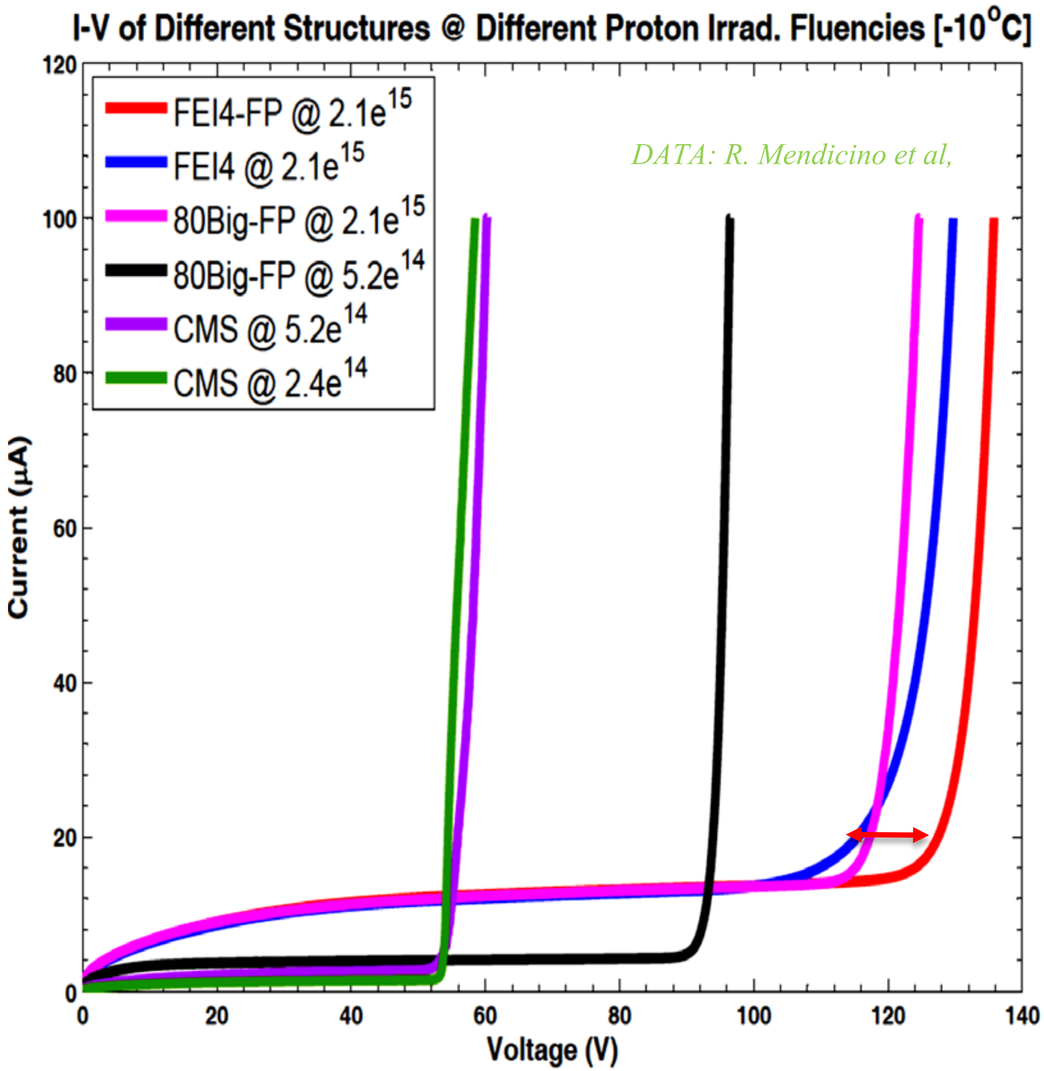
Layout Diversity



- Different shapes, sizes and column configurations
- Different distances between n+ and p+ regions
- With and without field-plate (Passing Through Col. 3D Si Sensors)

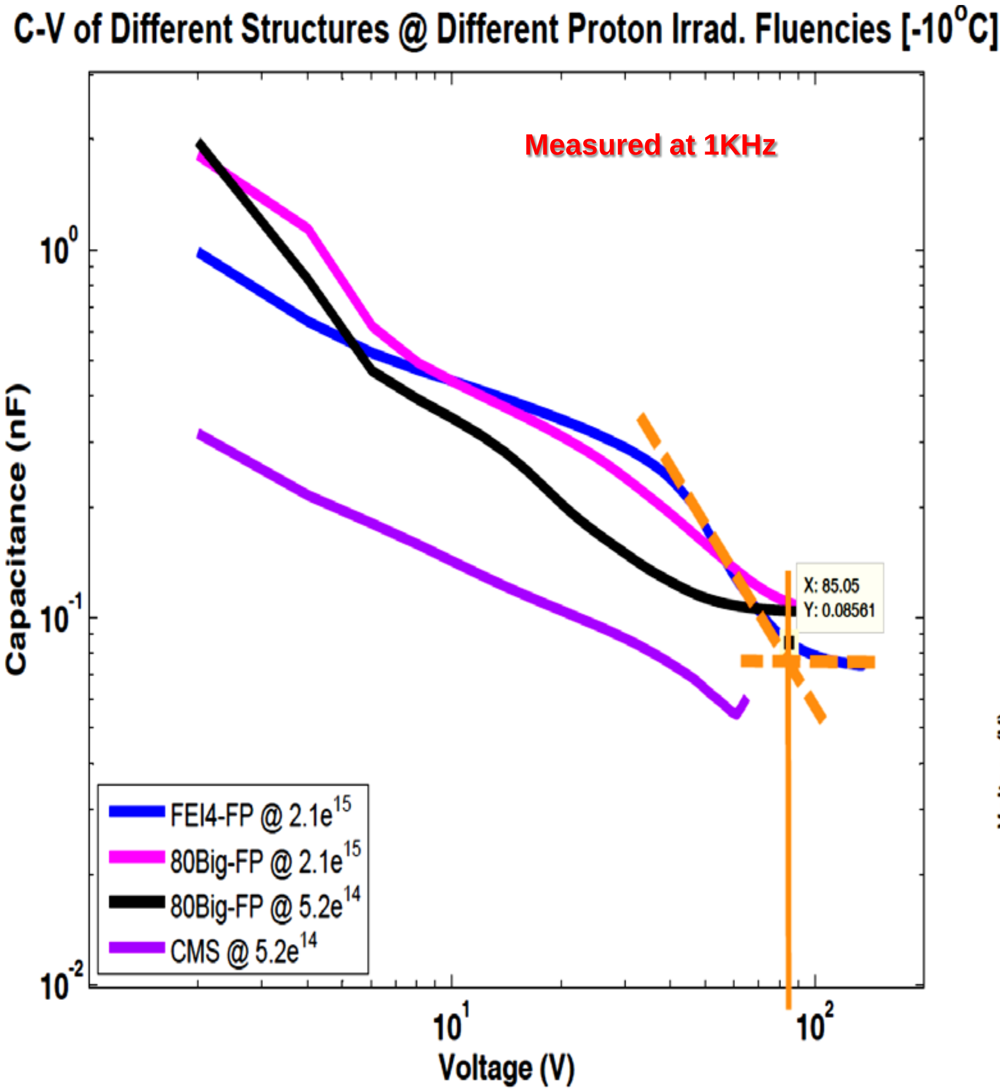
& Only with field plate (Non Passing Through Col. 3D Si Sensors)

IBL 3D Passing-Through Sensor with Proton Irrad.

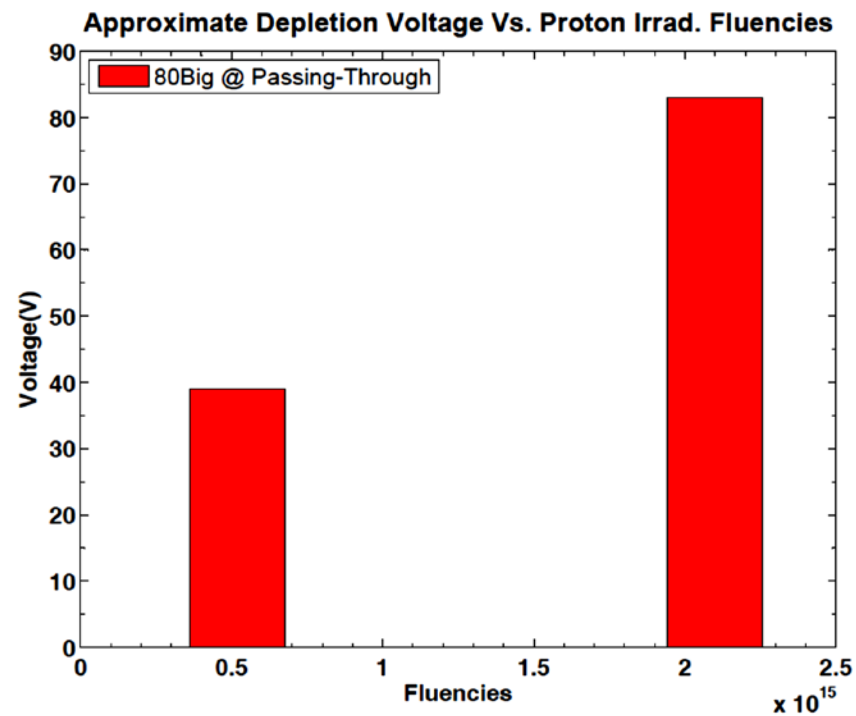


- V_{bd} has shown to be dependent of Layout Diversity, Field-plate inclusion and Irrad. fluencies.
- Field-plate improves to have Greater Breakdown Voltage.
- High fluencies evidently improves the breakdown voltage
- Field-plate has maintained on all Modified IBL process and next generation

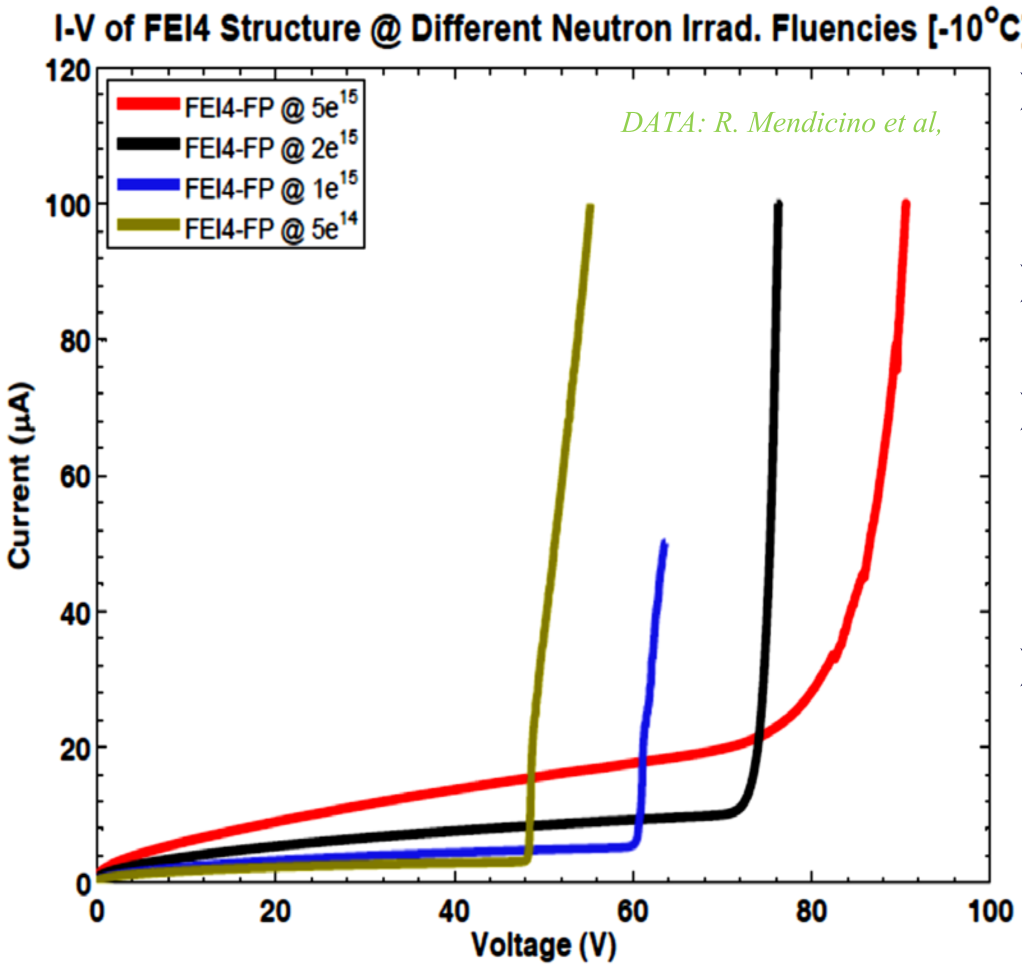
IBL 3D Passing-Through Sensor with Proton Irrad.



Depletion Voltage increases around 100 V for proton irradiation fluencies up to $2x10^{15} n_{eq}/cm^2$

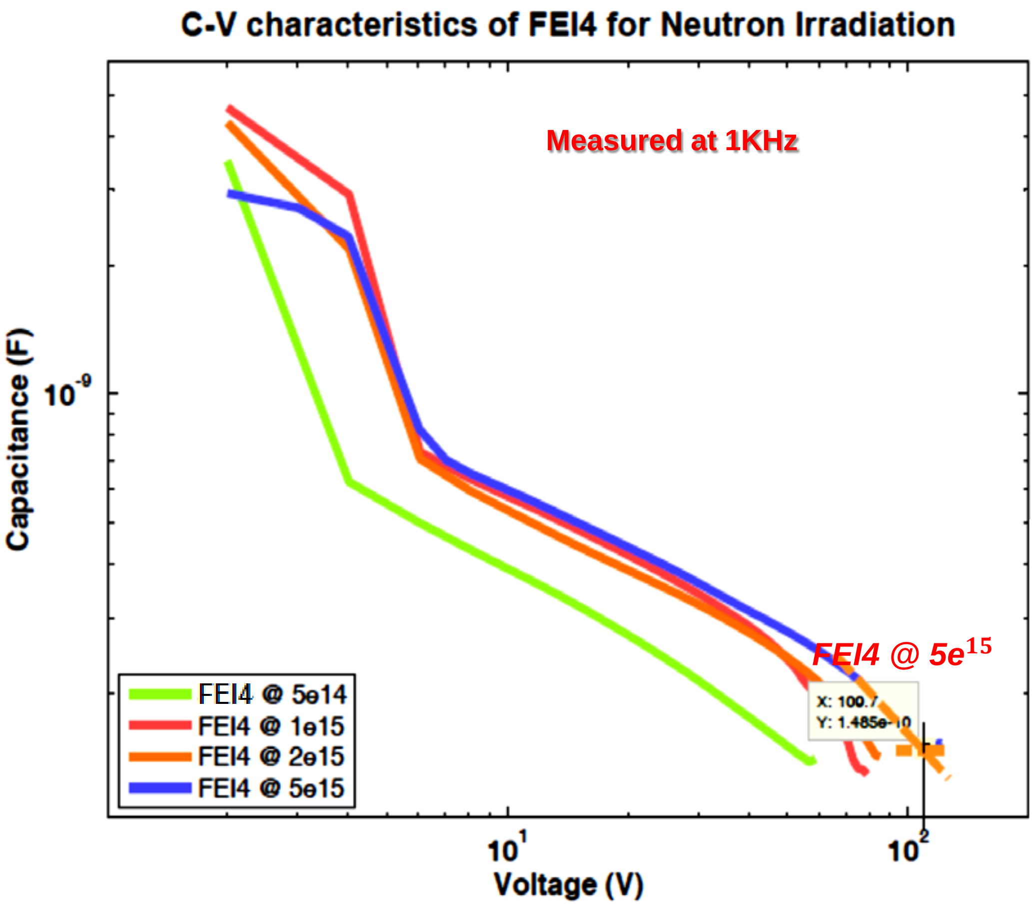


IBL 3D Passing-Through Sensor with Neutron Irrad.



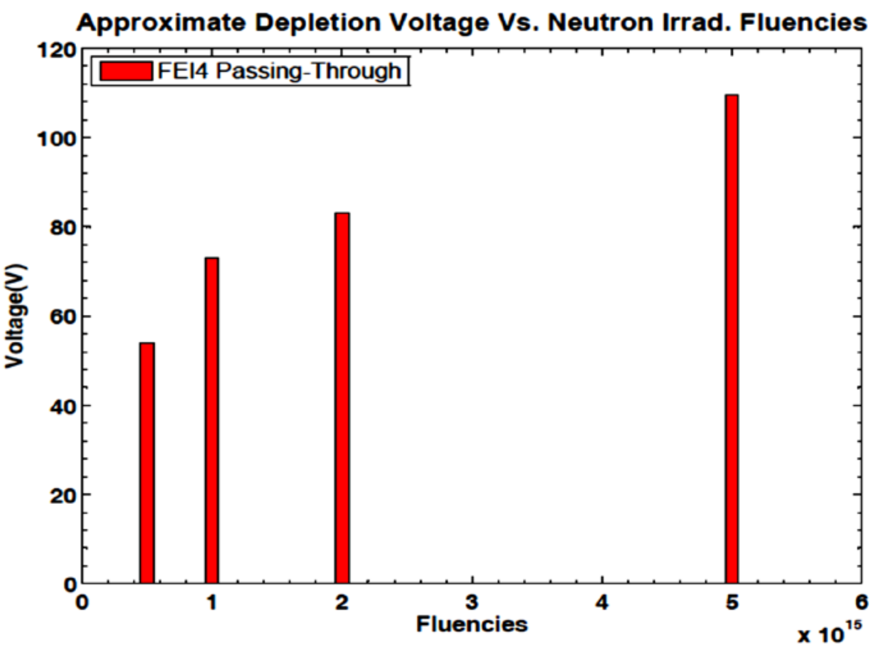
- Breakdown voltage dependance upon different neutron irrad. fluencies has addressed
- Leakage current increases with higher fluencies
- Smooth increase of breakdown voltage shows quite good agreement with expectation
  (low gamma ray background
  → **Lower Surface Damage**)
- Lower breakdown achieved here in comparison to the effect from Proton irrad. anticipates the contribution from bulk damage mostly!

IBL 3D Passing-Through Sensor with Neutron Irrad.



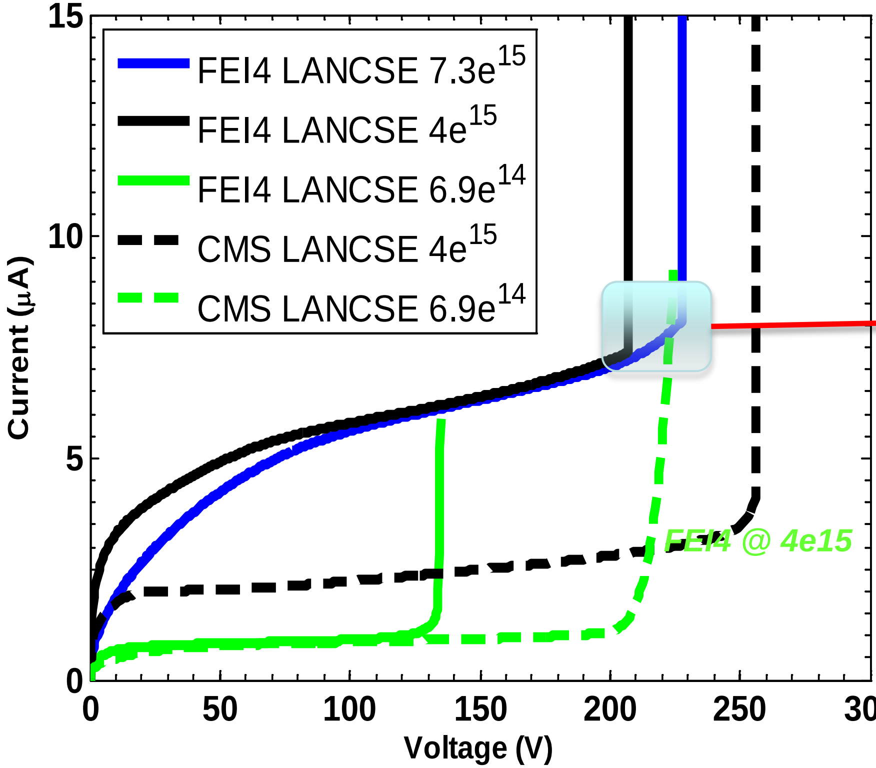
Good agreement with expectation!!

- Depletion voltage increases with higher irradiation fluences
- At high fluencies, full depletion voltage can not be achieved due to breakdown



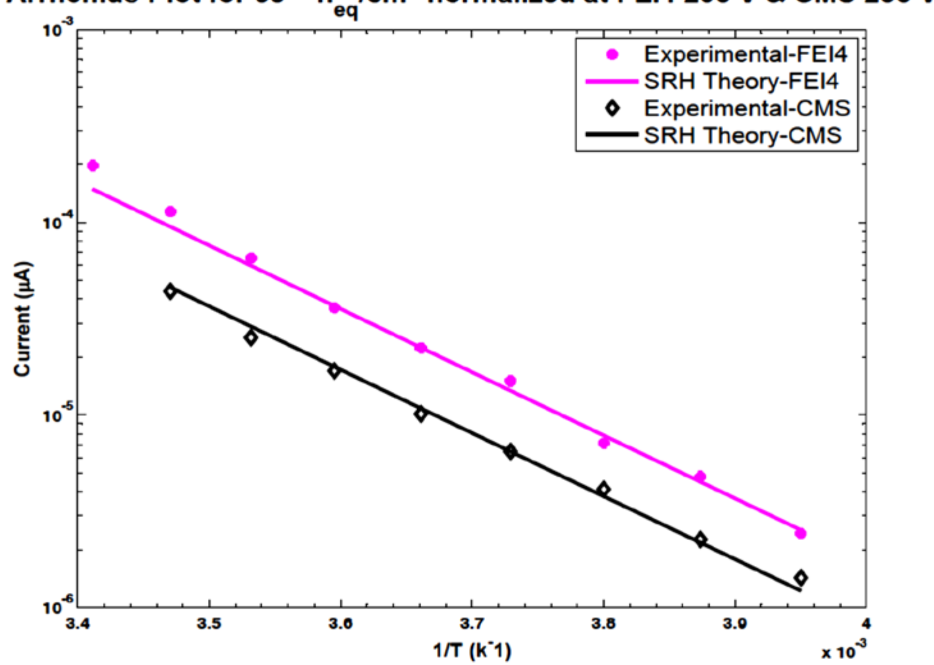
3D Non Passing-Through Sensor with Proton

I-V of FEI4 @ Different Proton Irrad. Fluencies [-10°C]



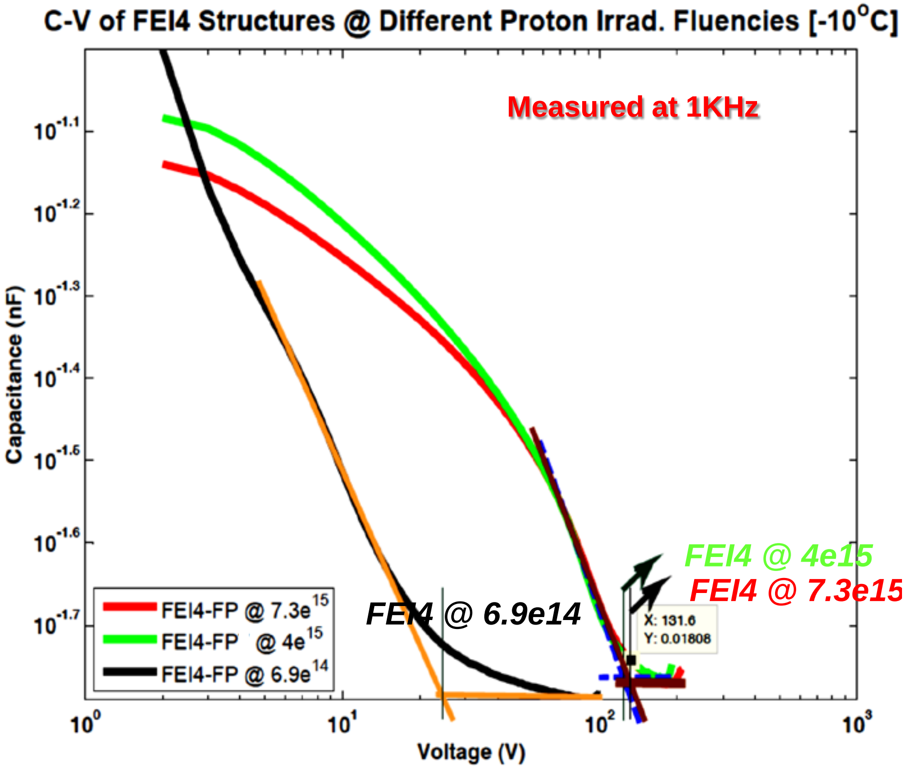
- Breakdown Voltage, V_{bd}, increased upto 260V for FEI4 & 290V for CMS at higher irrad. Dose
- For CMS, V_{bd} has seen ~290 V just for nominal $4e^{15}\ n_{eq}/cm^2$
- At V_{bd},sharp increase in the current points to probable n-col. tip-effect

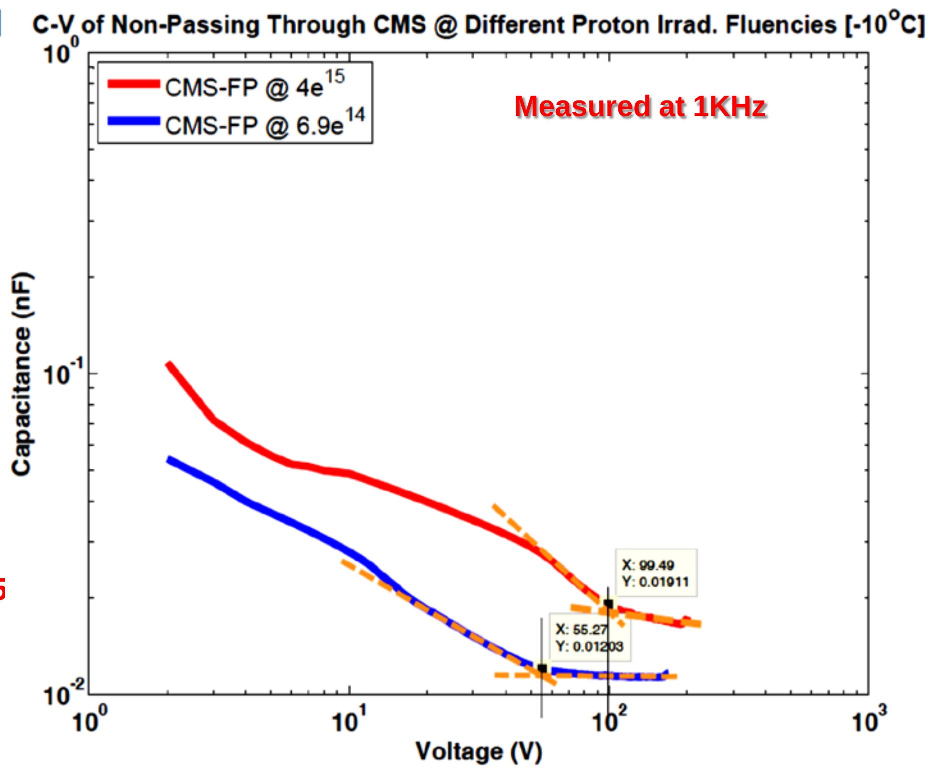
Arrhenius Plot for $5e^{15}\ n_{eq}/cm^2$ normalized at FEI4 205 V & CMS 256 V



- SHR Agrreement up to large voltages near to V_{bd} both CMS & FEI4
- Activation Energy has considered 1.21 eV.

3D Non Passing-Through Sensor with Proton

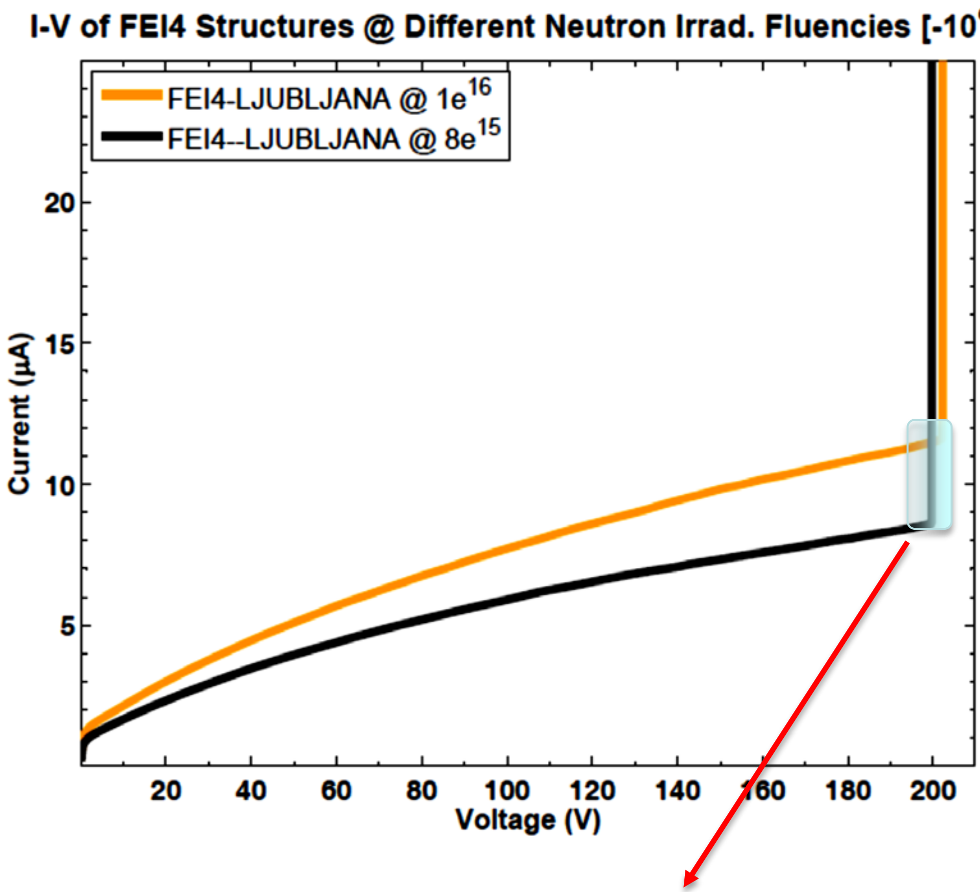




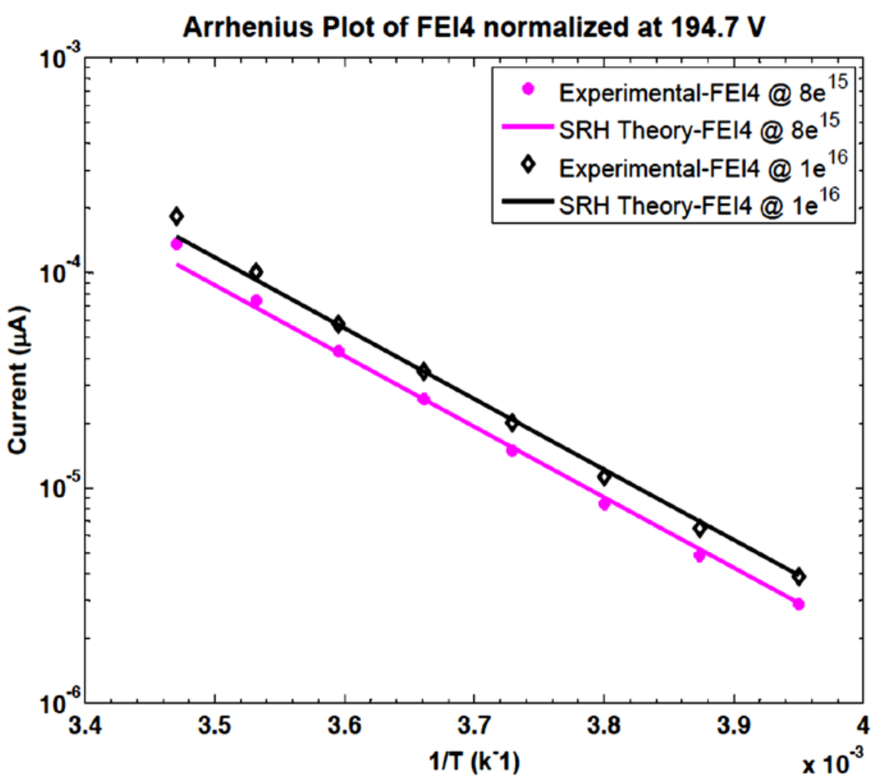
- Full depletion voltage shifts at higher voltage with the appliance of higher irrad. Dose.
- For the fluence, $5e^{15}\ n_{eq}/cm^2$, it is evedent that Full depletion voltage shifts to >~100V

  → **Bias Operation range becomes limited at higher fluencies**
- At more LH-HLC fluence, this effect would appear more adversely.

3D Non Passing-Through Sensor with Neutron Irrad.

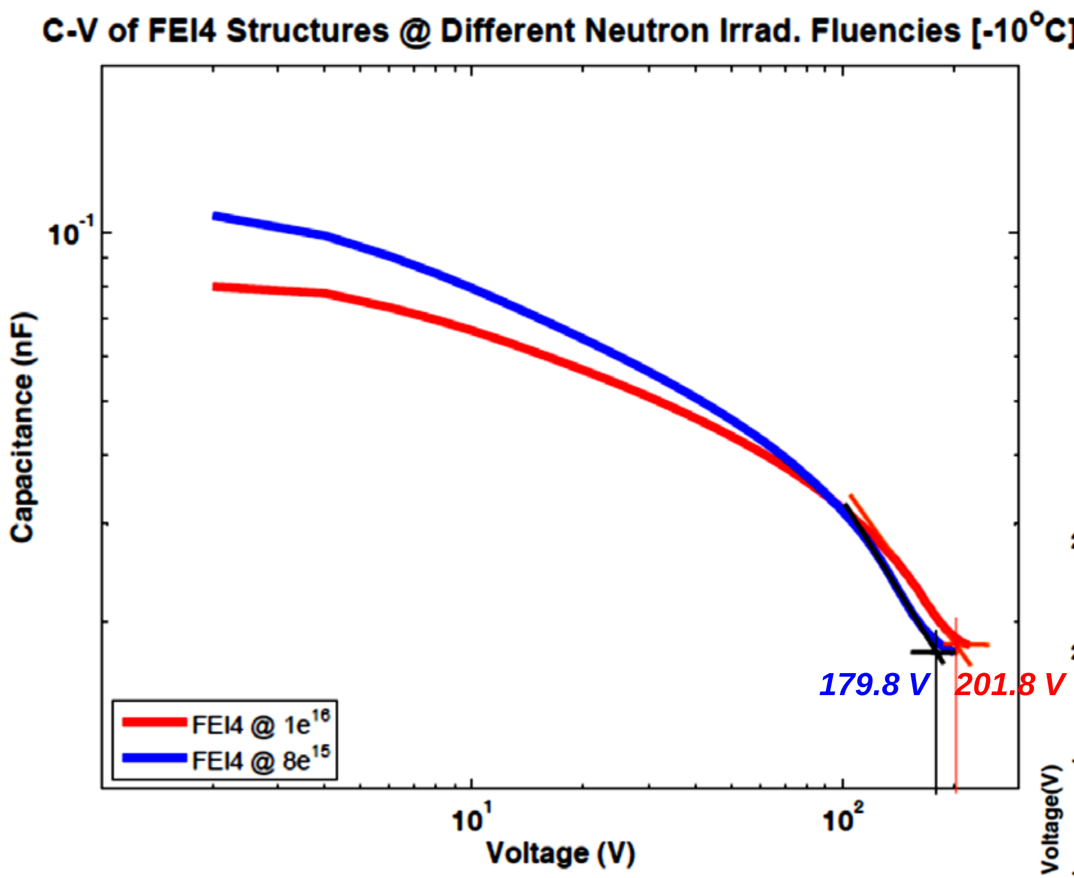


- Breakdown Voltage, V_{bd}, reaches up to 200 V at higher neutron Irradiation fluencies @ $10^{16}\ n_{eq}/cm^2$
- Neutron irrad. V_{bd} is lower than Proton irrad.



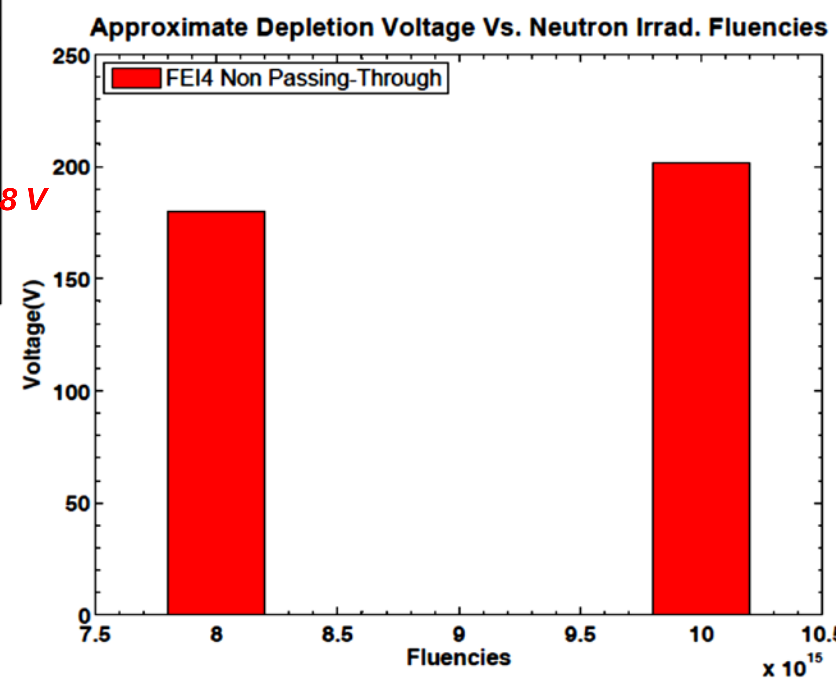
- Still the sharp breakdown appeared.
- Arrhenius plot has shown quite good agreement with SRH theory up to large voltage

3D Non Passing-Through Sensor with Neutron



As expected, full depletion voltage appears at very near to Breakdown Voltage, V_{bd}.

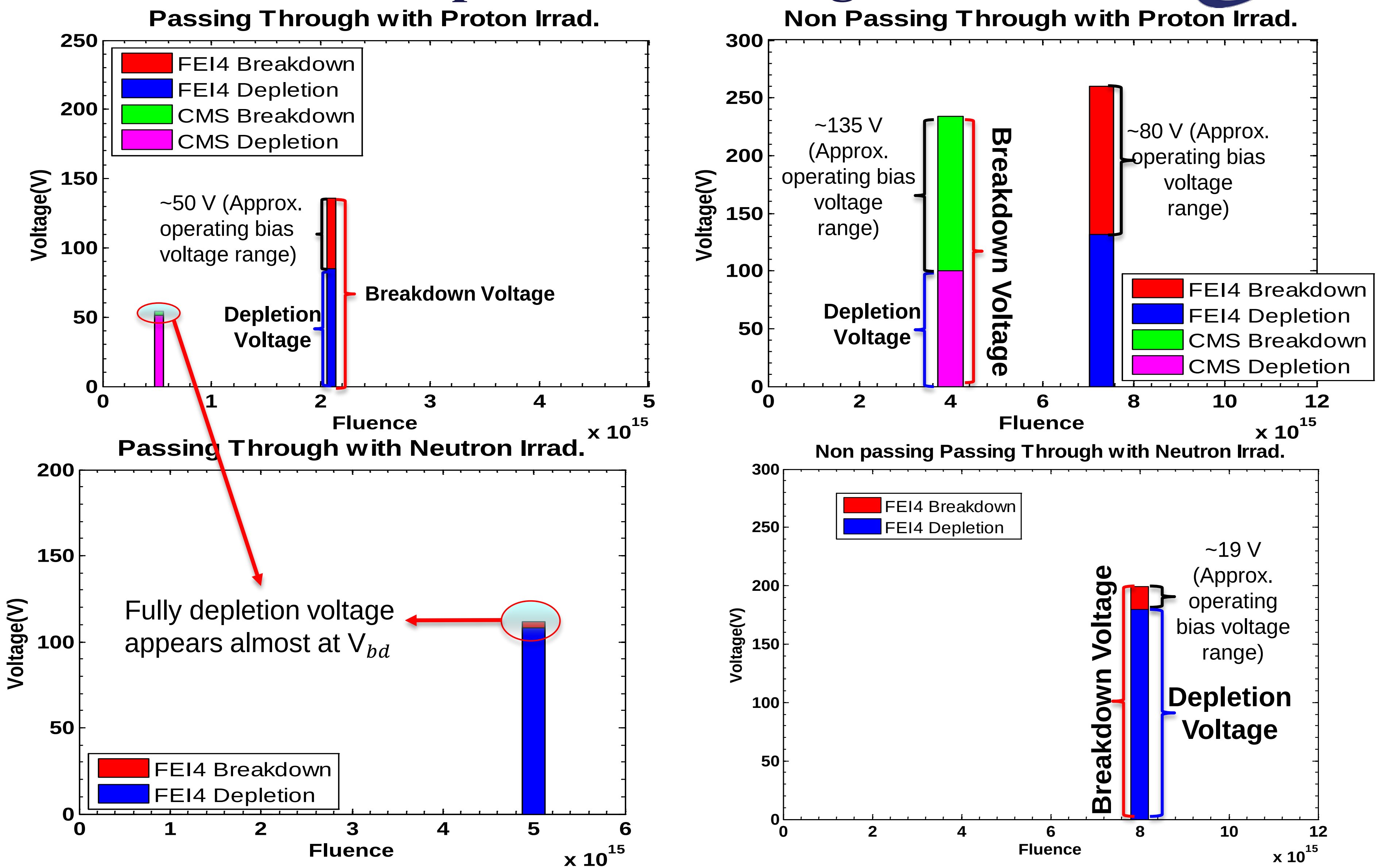
→ **Surface damage is comparatively Smaller in Neutron Irrad. than Proton Irrad.**



Increment of irrad. dose increases the full depletion voltage

→ **Significantly, limiting bias operating range!**

Comparative Investigations



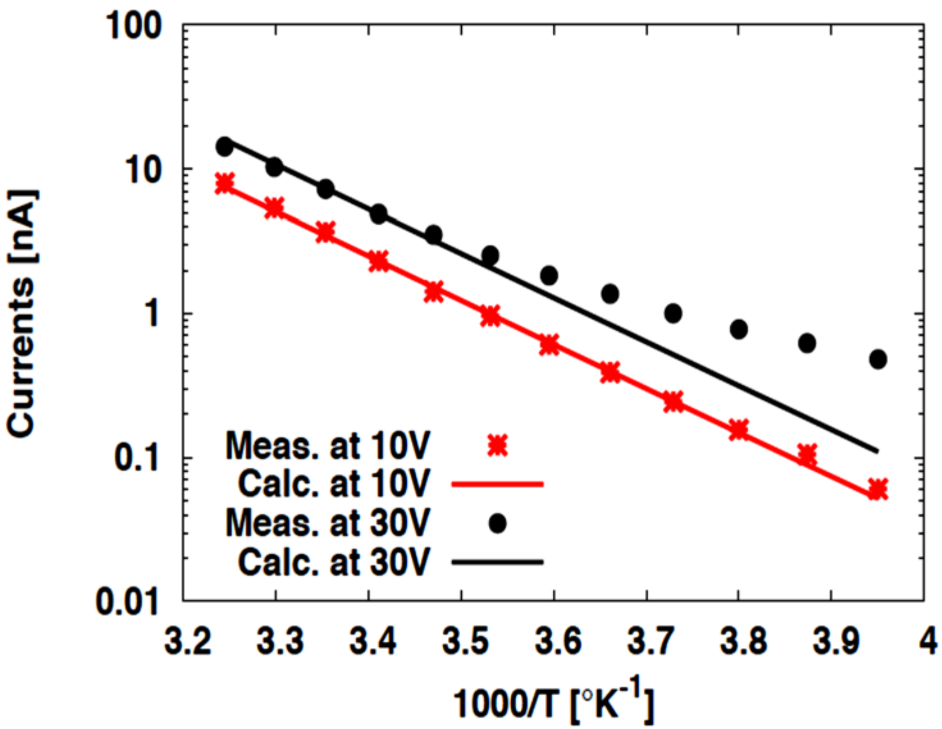
Conclusion

- The extended electrical characterization of IBL and modified 3D-DDTC sensors of FBK 4-inch tech. has been shown up to large fluencies
- The critical analysis of IBL 3D batches limitation regarding V_{bd} has been addressed
- Ongoing limitation of Modified IBL 3D batches has pointed to n-column tip effect
- Modified technology showed promising candidate for complying the radiation hardness of foreseen HL-LHC
- Charge collection efficiency within new non-passing through technology yet to be investigated.

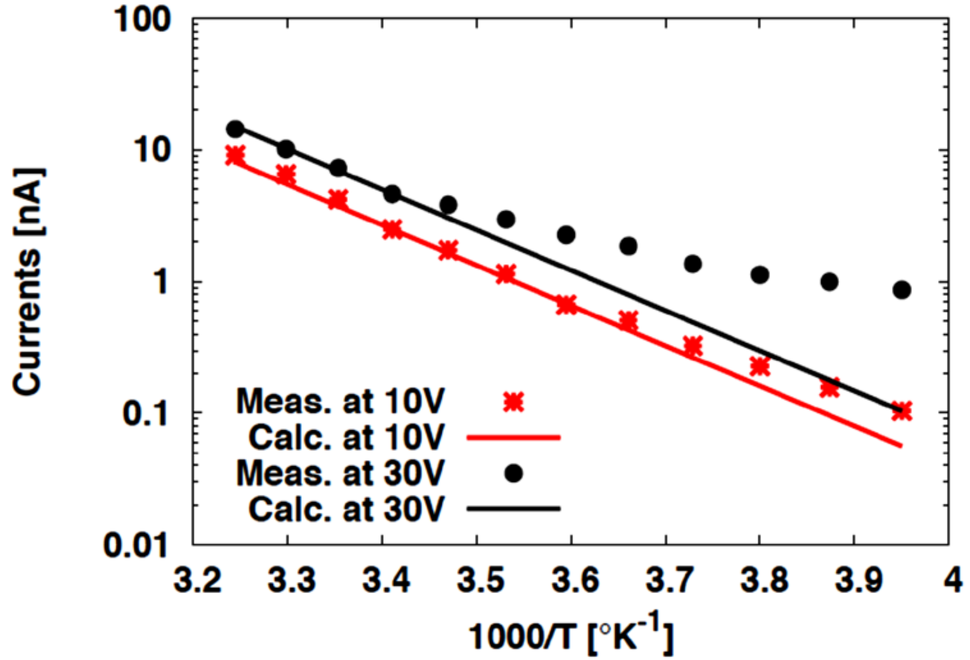
Thank You for Paying Your Attention!

Backup Slides

Marco Povoli et al,

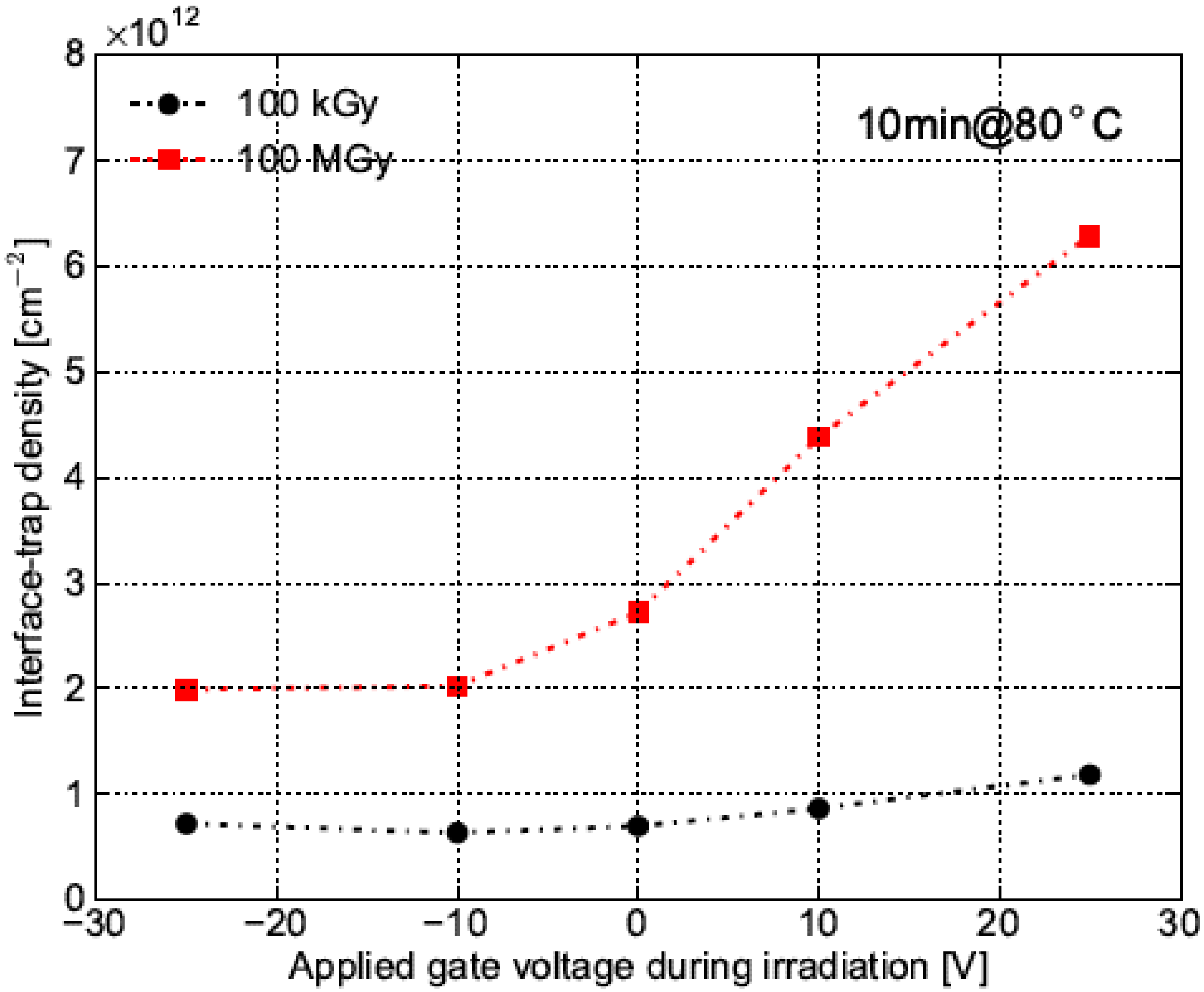


(a) FE-I4 FP



(c) 80 μm pitch

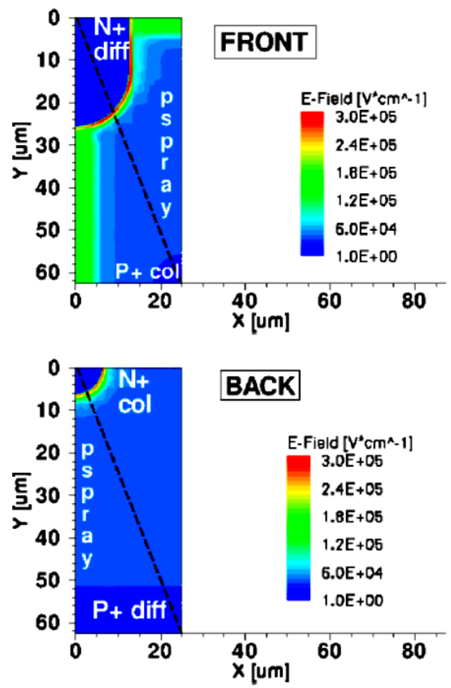
Impact Ionization effect (@ Pre-Irrad. Condition) on leakage current was widely seen on Passing Through Col. 3D Sensors at lower temperature



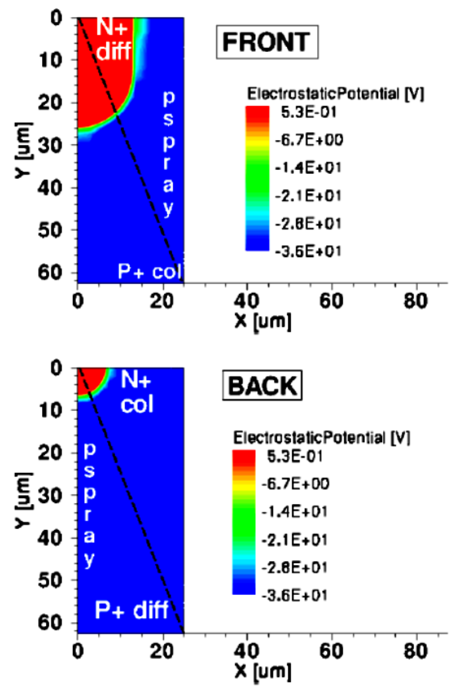
Jiaguo Zhang, PhD Thesis, University of Hamburg, 2013

Selected simulation results - FE-4 diode ($V_B = -35V$)

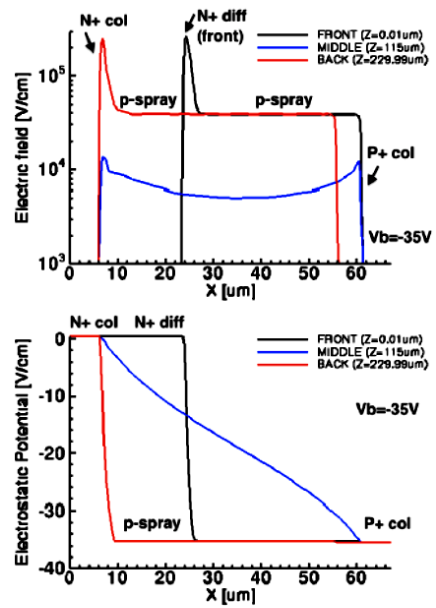
E-field



Elec. Potential



1D slices



Electric Field distribution

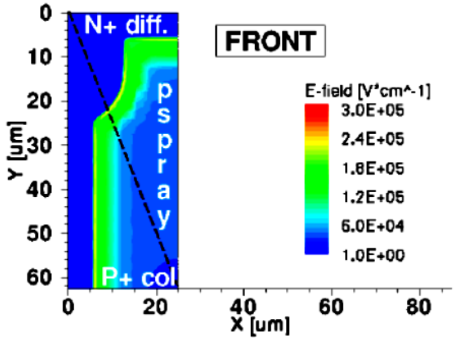
- High field at the N^+/p-spray junction on the front side (**2.65e5 V/cm**)
- High field at the N^+ column/p-spray junction on the back side (**2.48e5 V/cm**)
- E-field also increases under the front side metal (vertical and horizontal metal connections)

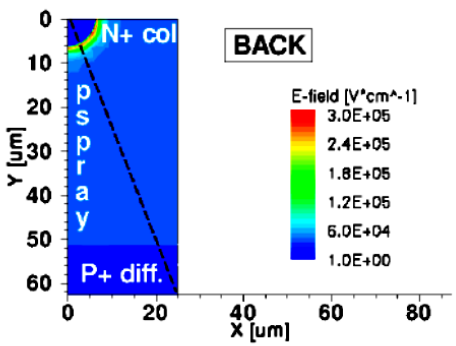
Electrostatic potential

- P^+ column brings the bias voltage directly on the front side p-spray
- Back side p-spray is also biased at high voltage

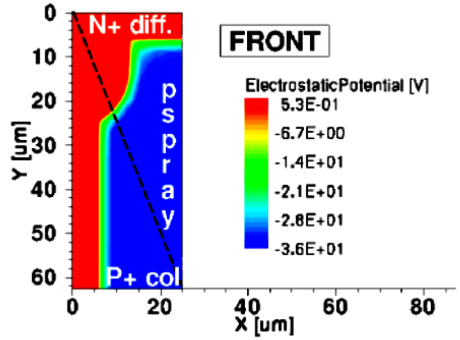
Selected simulation results - FE-4 FP diode ($V_B = -35V$)

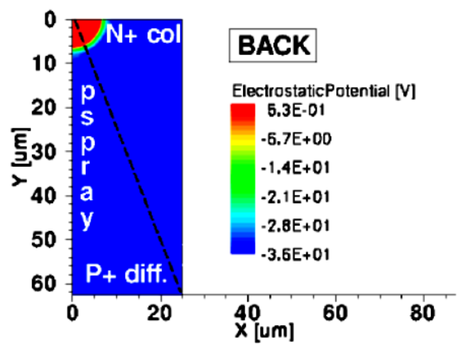
E-field



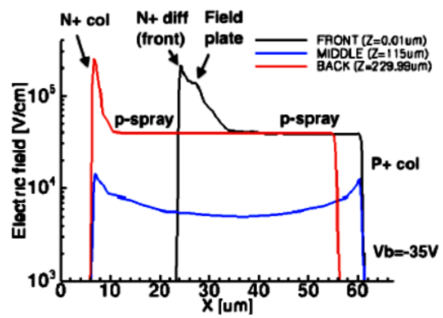


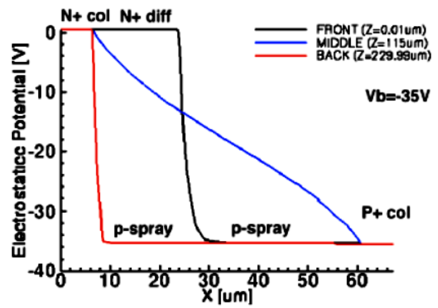
Elec. Potential





1D slices



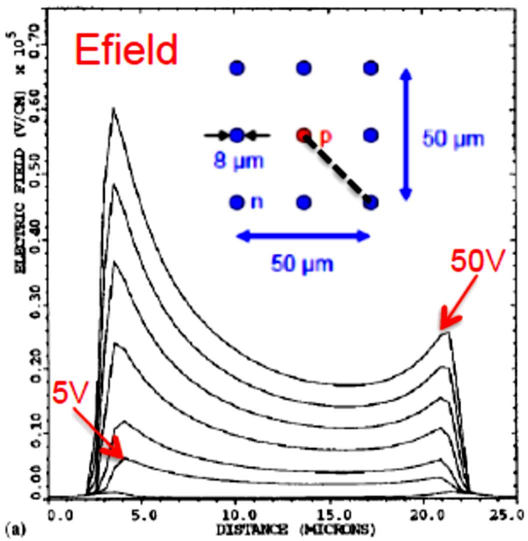


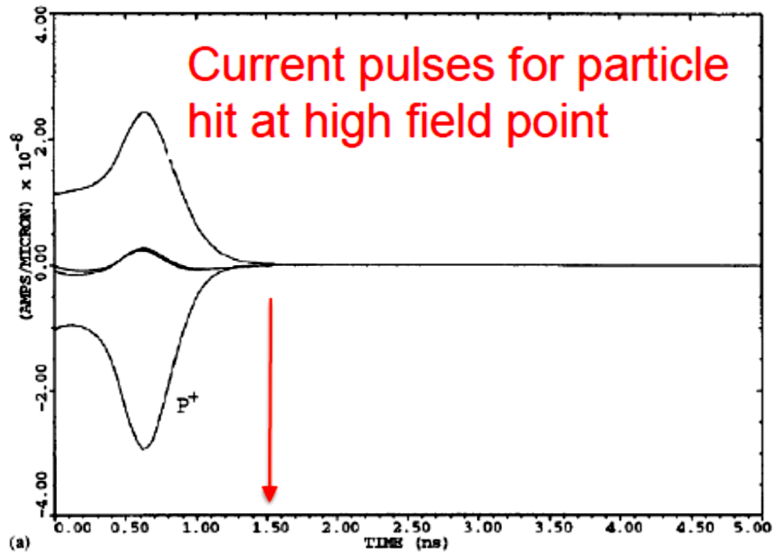
Electric Field distribution

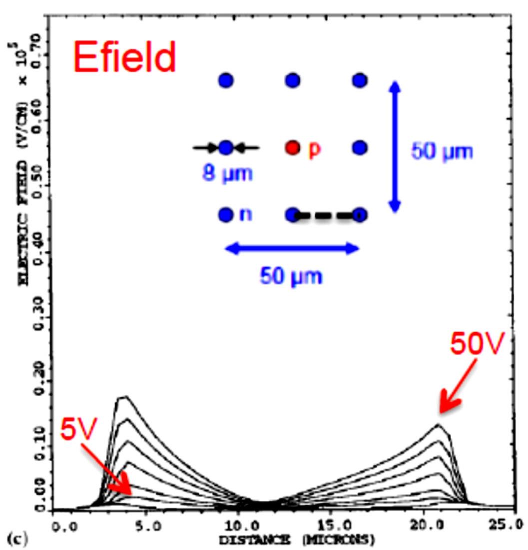
- High field at the N^+/p-spray junction on the front side (**2.11e5 V/cm**)
- High field at the N^+ column/p-spray junction on the back side (**2.53e5 V/cm**)
- The field-plate helps in redistributing and lowering the E-field on the front side

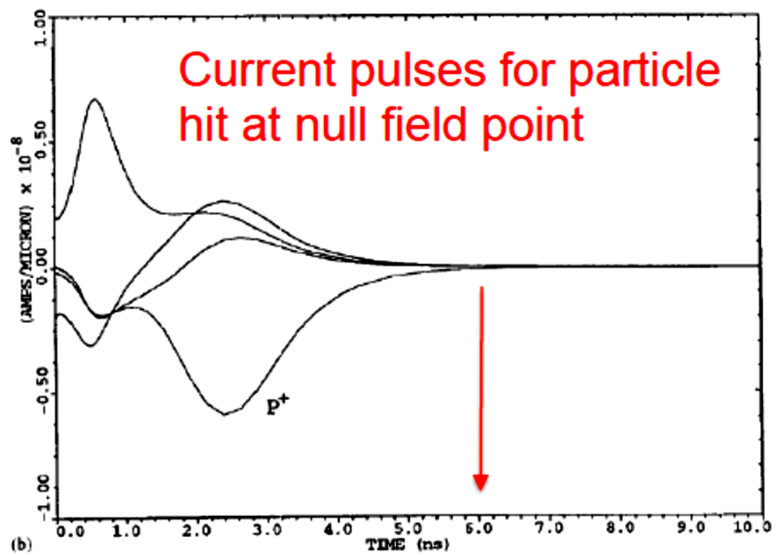
Electrostatic potential

- The field-plate helps depleting part of the p-spray close to the N^+ diffusion
- The potential of the p-spray now drops on a wider region
- Higher breakdown voltage (breakdown probably occurs on the back side)









S. Parker et al.
NIMA395 (1997) 328

3D structure implies null field points in between columnar electrodes of the same doping type

Carriers generated at null field points first have to diffuse before drifting, thus delaying signals

This can be improved with trenched electrodes, but at the expense of higher capacitance and reduced geometrical efficiency