Optimization of Charge Collection and Radiation Hardness of Edgeless Silicon Pixel Sensors for Photon Science and HEP Applications

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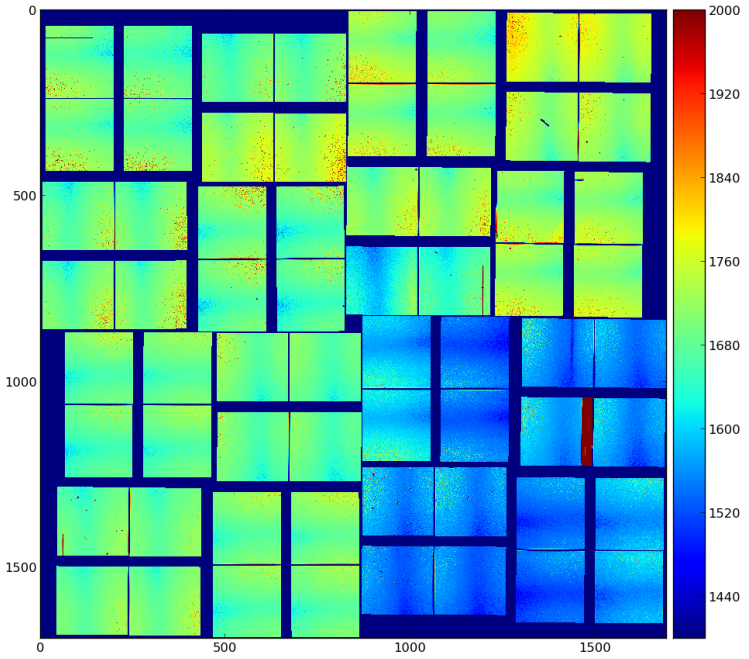
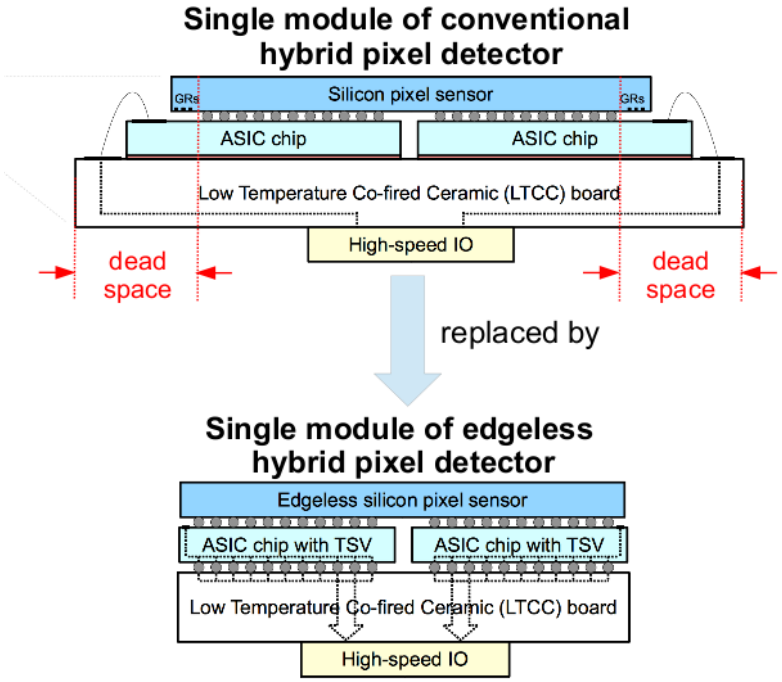
Outline

- Motivation
- Requirements and challenges of edgeless sensors
- Simulation of active volume and breakdown
- Modeling of charge-collection behavior
- Summary

Motivation of edgeless detectors in photon science

- Drawback of conventional large-area tiled hybrid pixel detectors
  - information missing within dead space → problems in image reconstruction





- Goal: Development of edgeless hybrid silicon pixel detectors using
  - edgeless sensor + ASIC chips with TSV + chip-to-board integration through BGA

Requirements and challenges of edgeless sensors

- Requirements of edgeless sensor for photon science application:
  - Good quantum efficiency
  - Full active sensor volume (no dead region)
  - Small last pixel-to-edge distance (edge space)
  - Low leakage current
  - High breakdown voltage
  - Radiation tolerant to ionizing radiation (surface damage)
  - Consistent response to photons with different energies

  → Main challenges

- Procedures to optimize an edgeless sensor:
  - TCAD simulations for edgeless sensors from available commercial designs

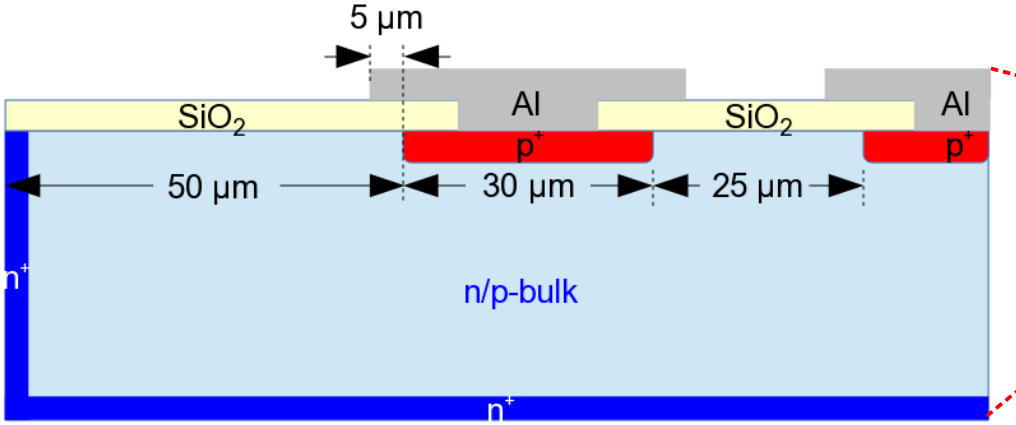
    → guideline for the sensor optimization with respect to technology choice
  - Modeling charge-collection behavior of edgeless sensors

    → guideline for the choice of sensor thickness and last pixel-to-edge distance

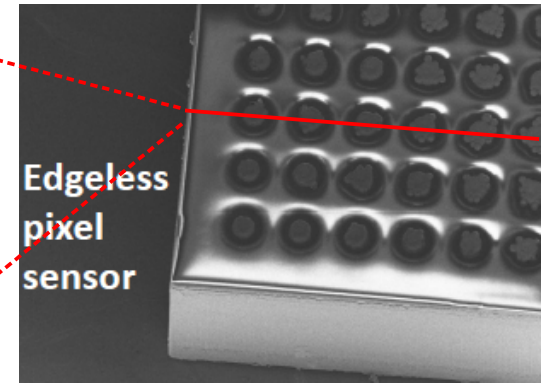
Simulation of commercial edgeless sensors

- Layouts and cross sections of commercial edgeless sensors
  - 6 different layouts: p^+n, p^+p, n^+p and n^+n with p-spray, n^+p and n^+n with p-stop
  - Si-thickness: 150 µm, 300 µm & 500 µm (only results for 300 µm to be shown)
  - Last pixel-to-edge distance: 50 µm
  - Junction depth of 1.2 µm and oxide thickness of 700 nm

Cross section of p^+n/p^+p sensors along cut line



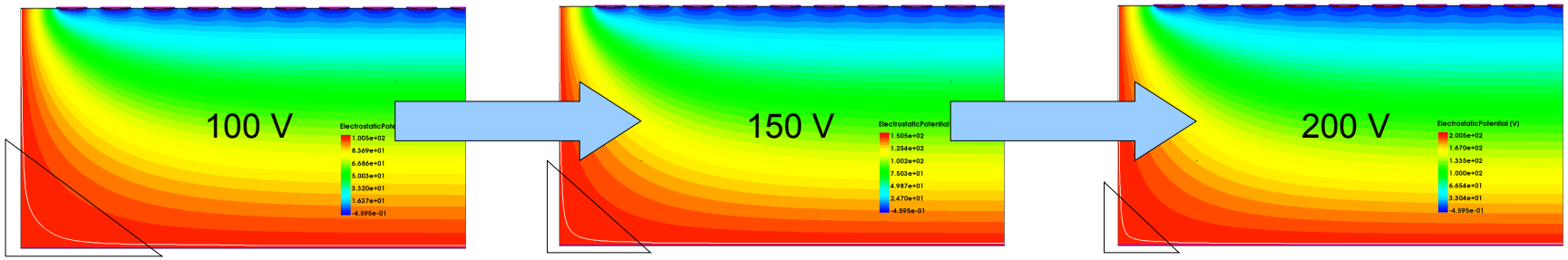
Top view of a commercial product



- Radiation-damage parameters (N_{ox} & S_0) from measurements input

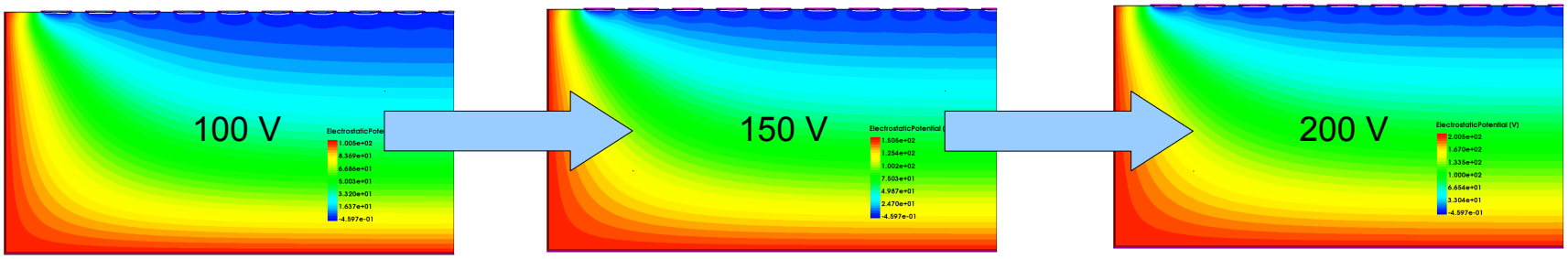
Simulation of sensor active/depletion volume

- Active volume of p^+n and n^+p (p-stop/p-spray) sensors



  - Inactive volume shrinks with voltage (at least 100 V above V_{dep} needed?)
  - Higher doping, thicker Si → larger additional voltage needed

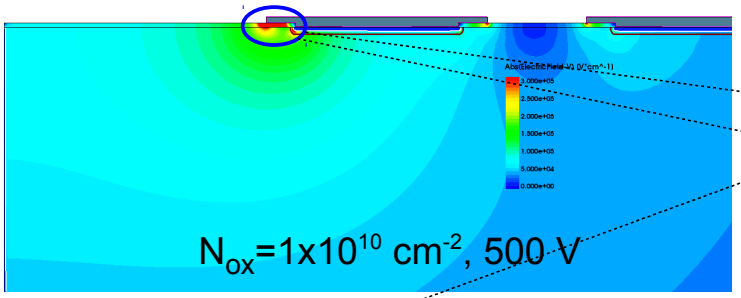
- Active volume of n^+n (p-stop/p-spray) and p^+p sensors

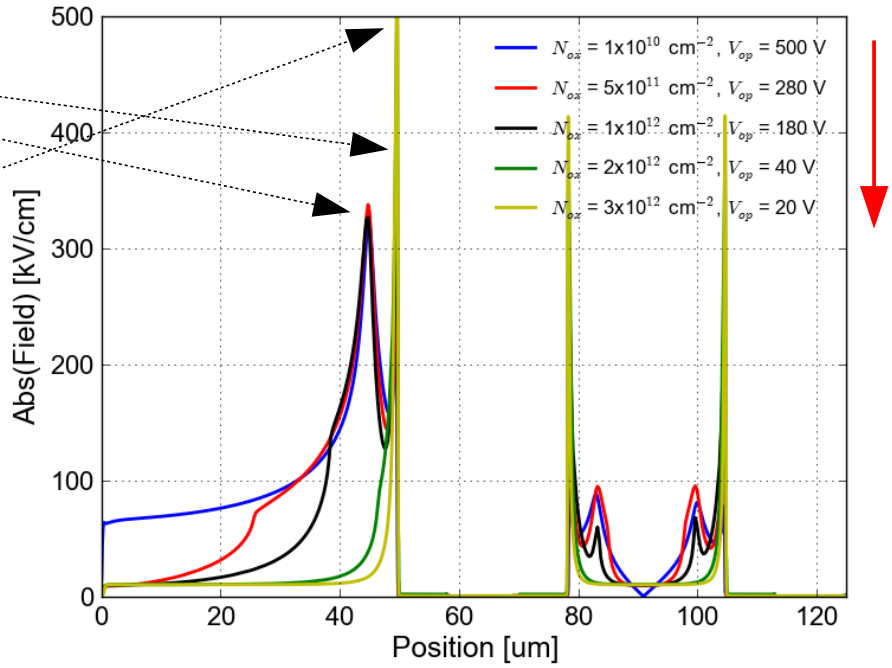


  - Sensor depletion starting from edge and backside → no inactive region
  - No/Small additional voltage above V_{dep} needed (typically 10-15 V)

Breakdown simulation of p^+n (p^+p) sensor

- High field region:
  - $N_{ox} \leq 1x10^{12}$ cm^{-2}, high field below metal overhang and at junction of 1st pixel
  - $N_{ox} > 1x10^{12}$ cm^{-2}, high field at implant junction of 1st pixel





- 1st pixel behaves like CCR of a conventional sensor → breakdown first
- Breakdown voltage drops gradually with increasing oxide charges

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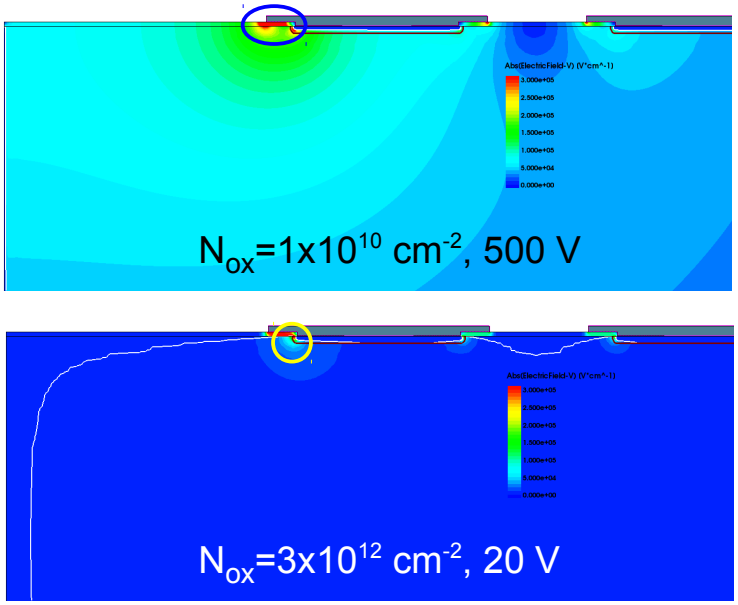
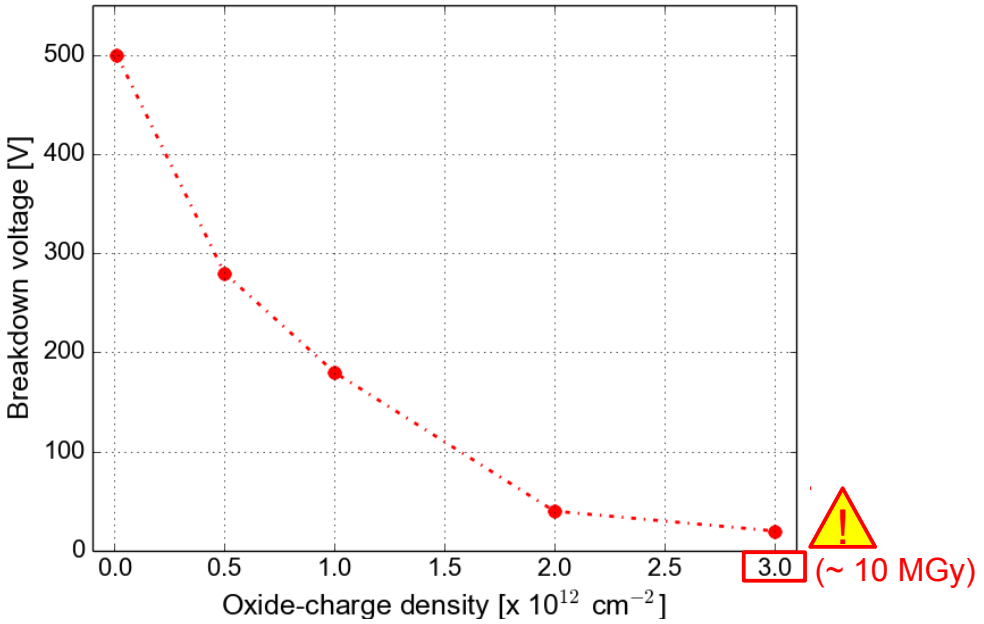
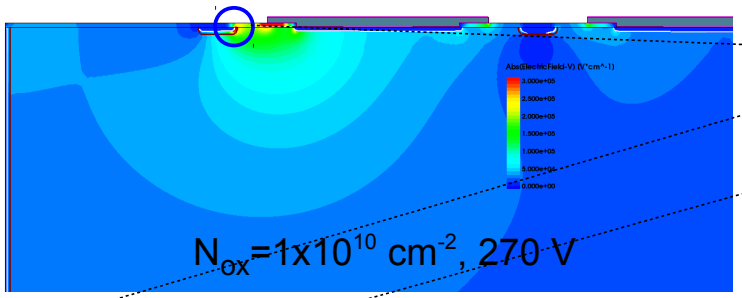


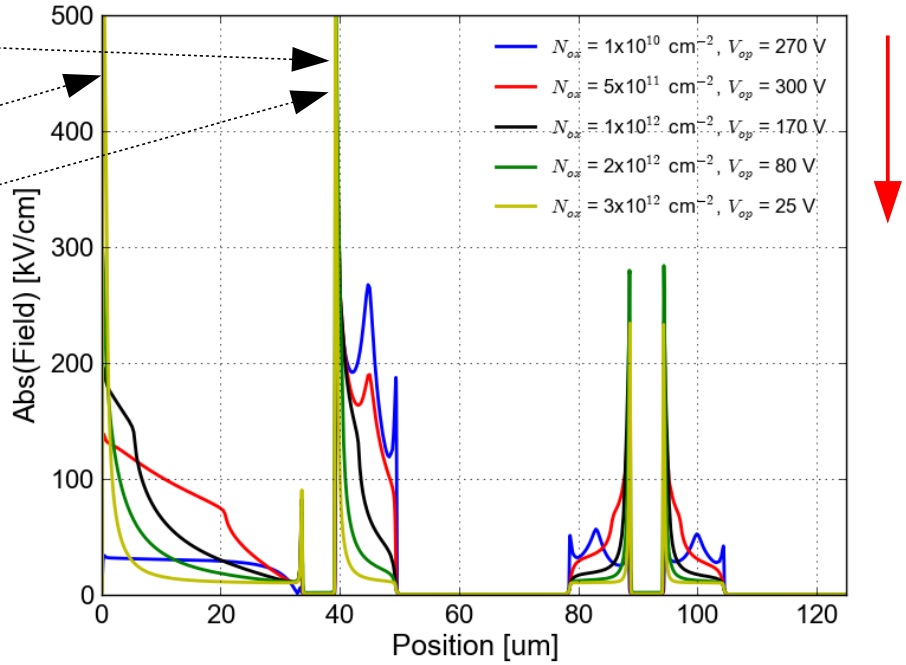


- 1st pixel behaves like CCR of a conventional sensor → breakdown first
- Breakdown voltage drops gradually with increasing oxide charges

Breakdown simulation of n^+n (n^+p) sensors with p-stop

- High field region:
  - $N_{ox} \leq 1x10^{12}$ cm^{-2}, high field at implant junction of p-stop
  - $N_{ox} > 1x10^{12}$ cm^{-2}, high field at implant junctions of p-stop and sensor edge





- High field at sensor edge ← direct exposure to oxide charges
- Breakdown voltage drops to 25 V at high oxide charges!

Breakdown simulation of n^+n (n^+p) sensors with p-stop

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  - $N_{ox} \leq 1x10^{12}$ cm^{-2}, high field at implant junction of p-stop
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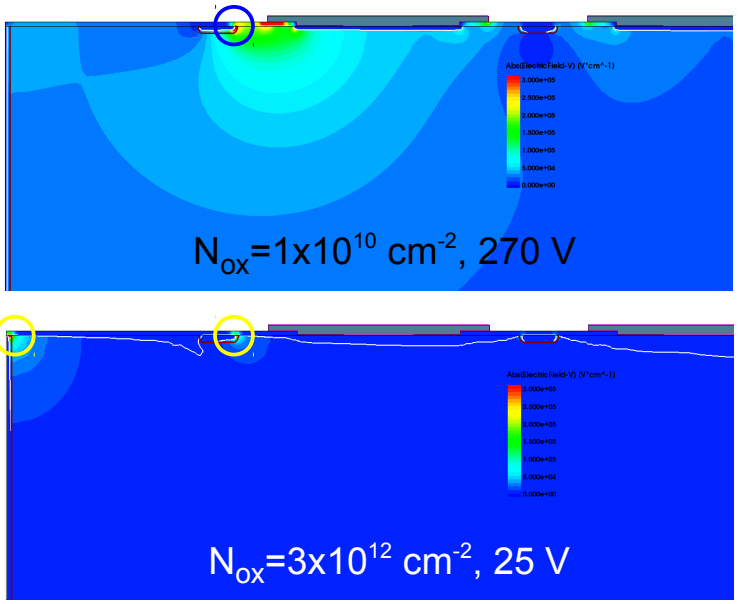
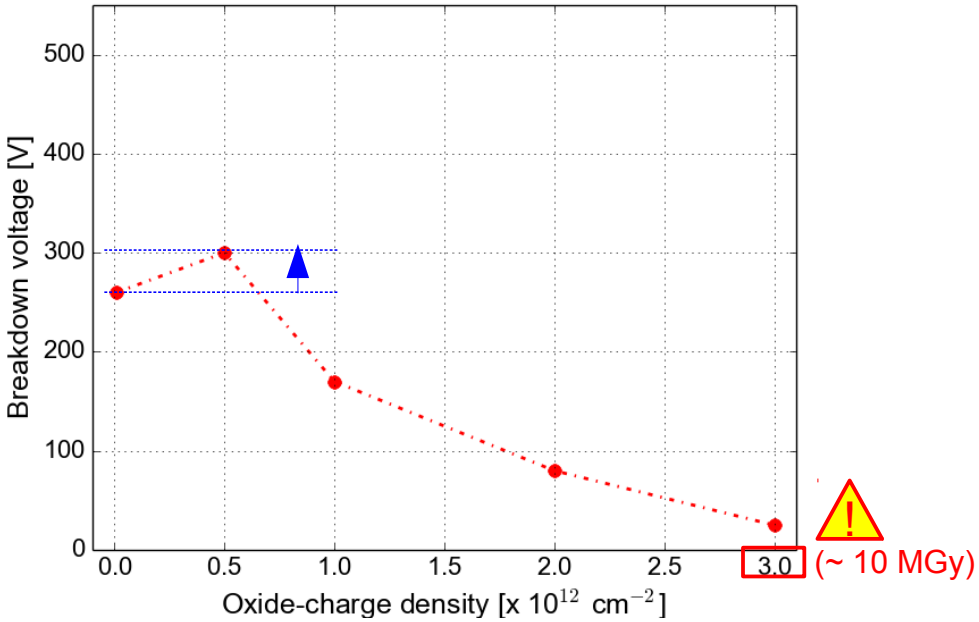
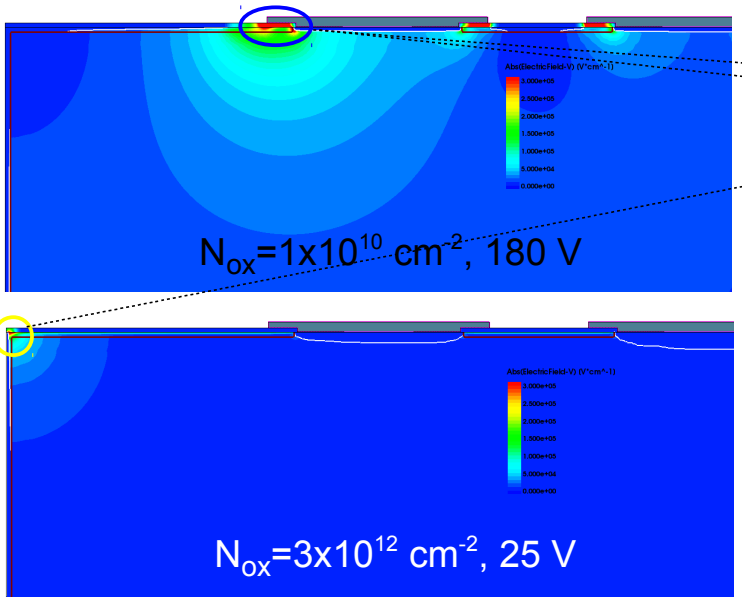


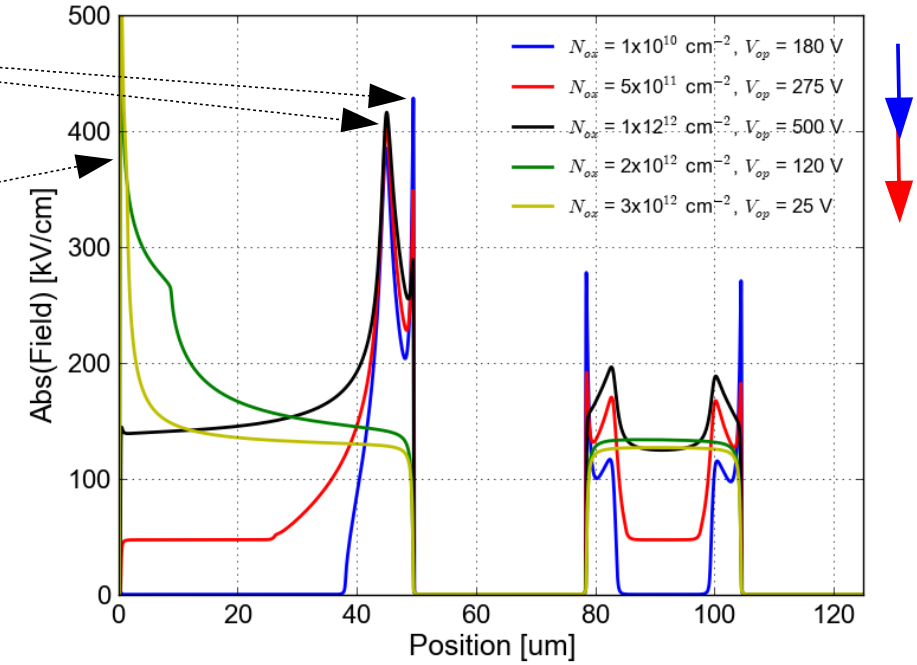


- High field at sensor edge ← direct exposure to oxide charges
- Breakdown voltage drops to 25 V at high oxide charges!

Breakdown simulation of n^+n (n^+p) sensors with p-spray

- High field region:
  - $N_{ox} \leq 1x10^{12}$ cm^{-2}, high field at pixel-implant/p-spray interface and below metal
  - $N_{ox} > 1x10^{12}$ cm^{-2}, high field at sensor edge





- High field at sensor edge → improved by increasing p-spray dose
- Breakdown improves with N_{ox}, but decreases when $N_{ox} > N_{p\text{-}spray}$

Breakdown simulation of n^+n (n^+p) sensors with p-spray

- High field region:
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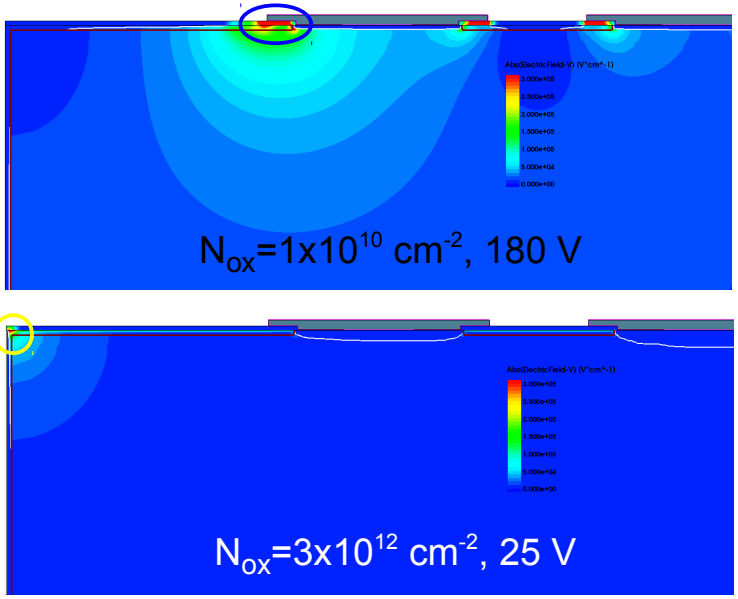
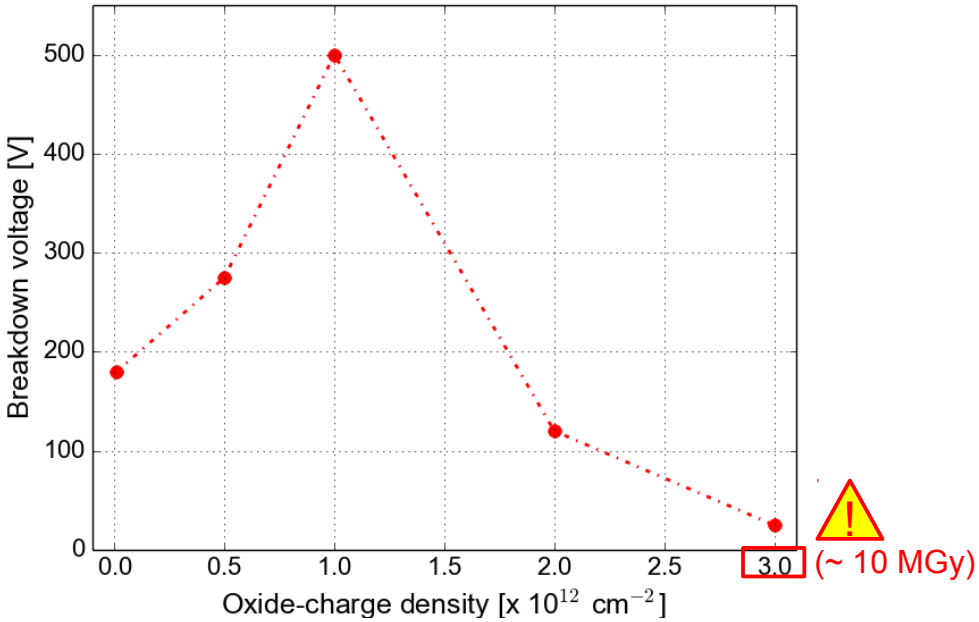
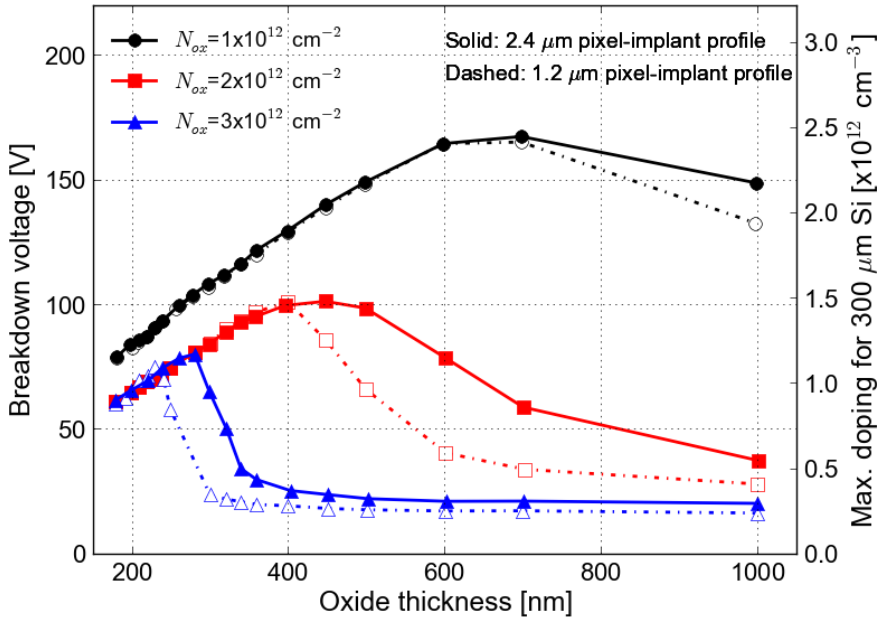




- High field at sensor edge → improved by increasing p-spray dose
- Breakdown improves with N_{ox}, but decreases when $N_{ox} > N_{p\text{-}spray}$

How to improve the radiation hardness of edgeless sensors

- Lessons learnt from AGIPD p^+n sensors:
  - Improved breakdown voltage with optimized technological parameters
  - 75 V per guard ring → guard ring needed for high operation voltage



Min. requirement for sensor operation:

$$V_{dep} = \frac{q_0 T_{si}^2 N_d}{2\varepsilon_0 \varepsilon_{si}} - V_{bi} < V_{bd}$$

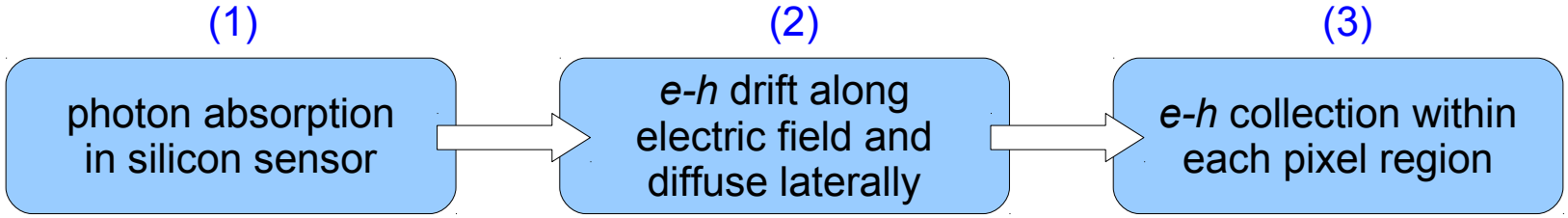
→ max. doping N_d

e.g. for 700 nm SiO_2, N_d < 3x10^{11} cm^{-3} is required for full depletion of a 300 µm thick Si.

- Indication for edgeless sensors: careful selection of tech. parameters
  - Junction depth + oxide thickness + doping concentration in Si
- Similar optimization procedures for other polarities

Charge-collection behavior: Model development

- Motivation of modeling charge collection of edgeless sensors:
  - Understand measurement results with developed model
  - Predict charge-collection behavior for sensors with different thicknesses
  - Optimize sensor layout with best charge-collection behavior
- The physics model for $E_{x\text{-}ray}$ < 20 keV (can/to be extended):



- Photoelectric effect
- Probably calculated with attenuation length λ(E):

$$\frac{dI}{dy} \propto \frac{I_0}{\lambda(E)} \cdot exp(-\frac{y}{\lambda(E)})$$

- Initial charge cloud neglected
- *e-h* drift along field lines (TCAD field simulation result as input):

$$t = \int_{y_0}^{y_{pix}} \frac{dy}{\mu \cdot E(y)}$$

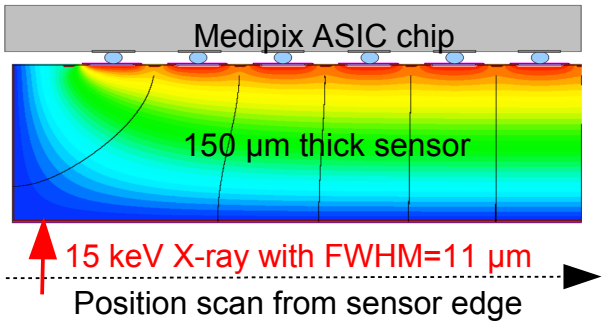
- Carrier lateral diffusion:

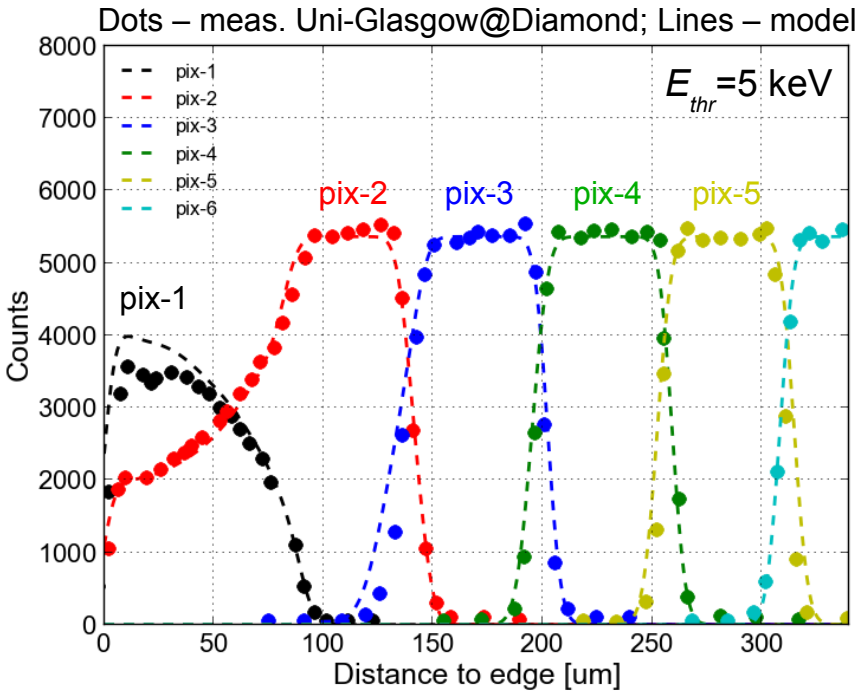
$$\sigma = \sqrt{2D \cdot t}$$

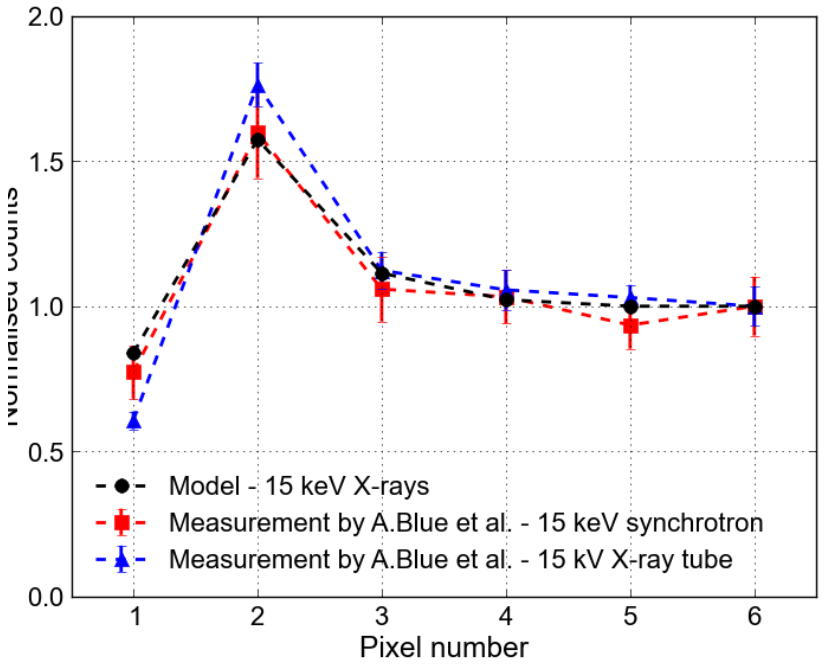
- Carriers collected by each pixel
- Counting/Integrating mode
- Electronic threshold E_{thr}
- Spectrum deconvolution with the size of beam spot

Charge-collection behavior: Comparison to measurements

- From model calculation to measurement result:
  - 15 keV X-rays with FWHM = 11 µm
  - 150 µm thick sensor
  - X-ray backside scan from sensor edge



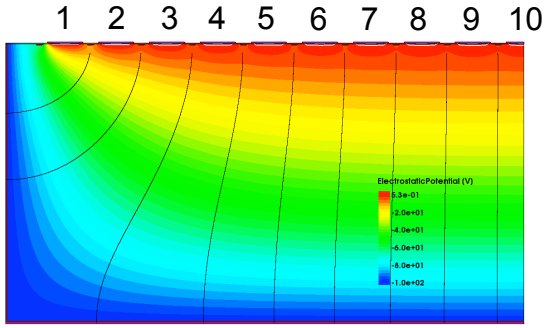




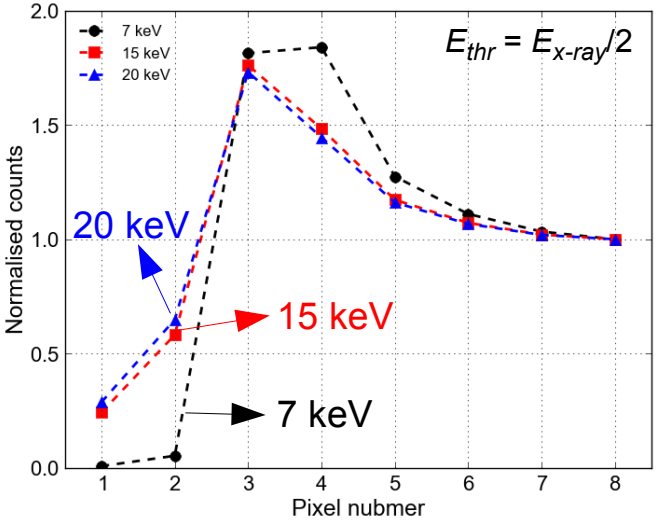
- Measurement results explained by developed model!

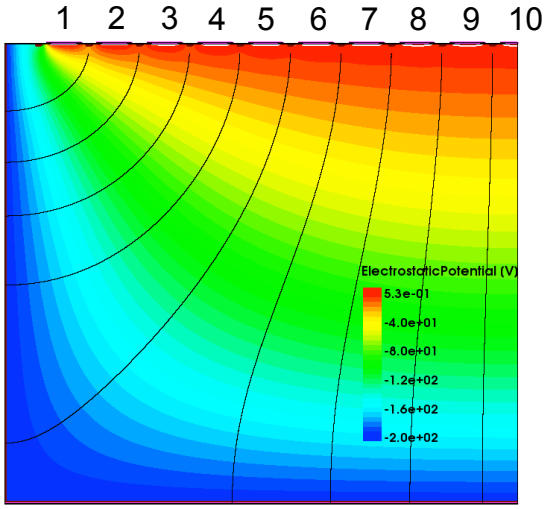
Charge-collection behavior: Prediction

- Charge-collection behavior of edge pixels for thick Si sensors:

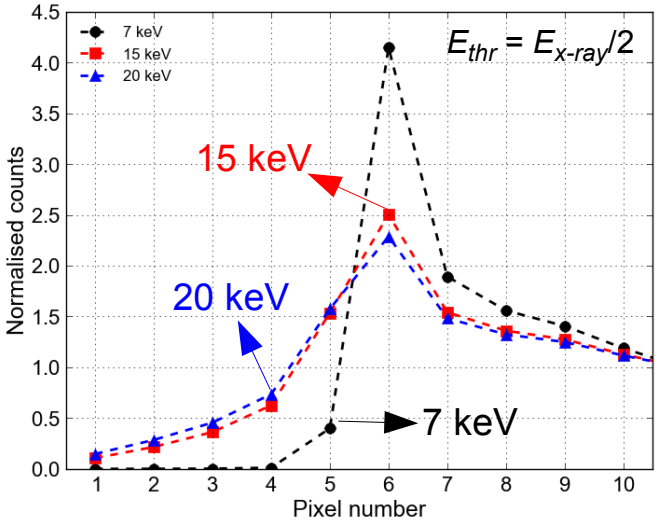


300 µm thick sensor
(volume full depleted)





500 µm thick sensor
(volume full depleted)



Charge-collection behavior: Prediction

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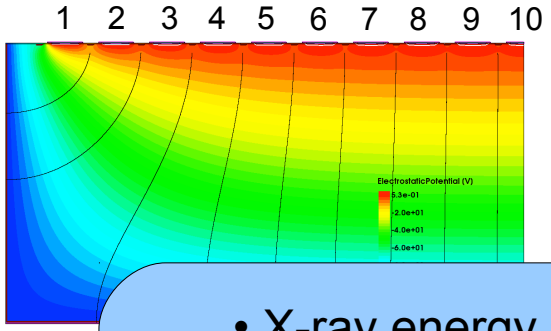
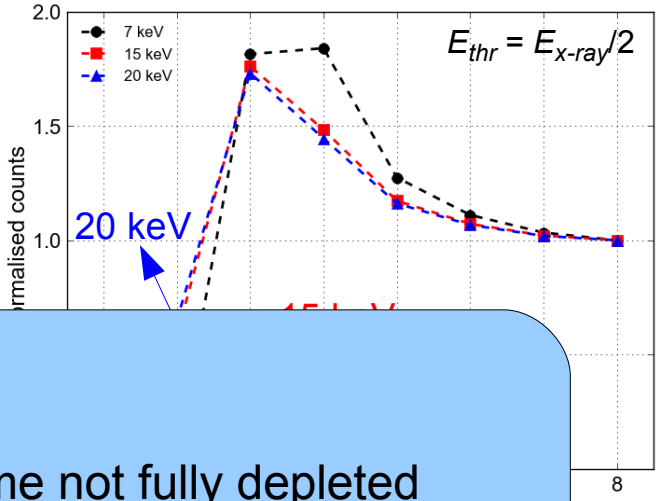
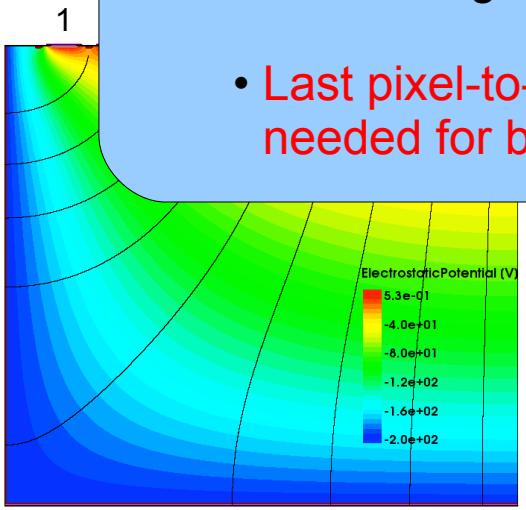




- X-ray energy dependent
- Sensor thickness dependent
- Bias voltage dependent if volume not fully depleted

- Last pixel-to-edge distance larger than 50% Si thickness needed for better sensitivity to low-energy photons



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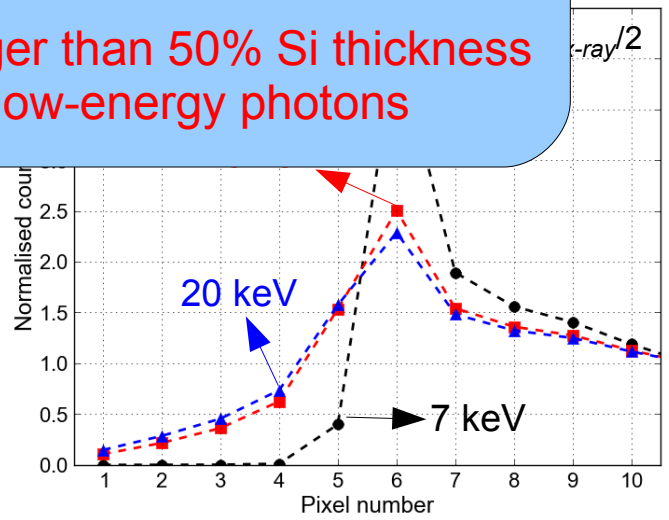

Summary and conclusion

- Current understanding on edgeless sensors based on TCAD simulation and model calculation
- TCAD simulations with measurement parameters implemented used for the understanding of
  - Sensor active volume
  - Breakdown
  - Radiation tolerance
- To improve radiation hardness, careful selection of technological parameters and doping concentration
- Model developed for the understanding of charge-collection behavior of edgeless sensors:
  - Measurement results explained by developed model
  - Charge-collection behaviors predicted for thicker Si
- To ensure sensitivity of edge pixels to low energy photons, last pixel-to-edge distance should be > 50% Si-thickness

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LAMBDA

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PERCIVAL

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- Elettra

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- RAL / STFC

There are open positions for PostDocs and Master/PhD students!

http://photon-science.desy.de/research/technical_groups/detectors/index_eng.html

Thanks go to...

- Thanks for your attention!
- Thank Juha Kalliopuska of Advacam co. for providing technological parameters for simulation, and Dima Maneuski of Uni-Glasgow sharing the measurement data at Diamond beamline for comparison of results.

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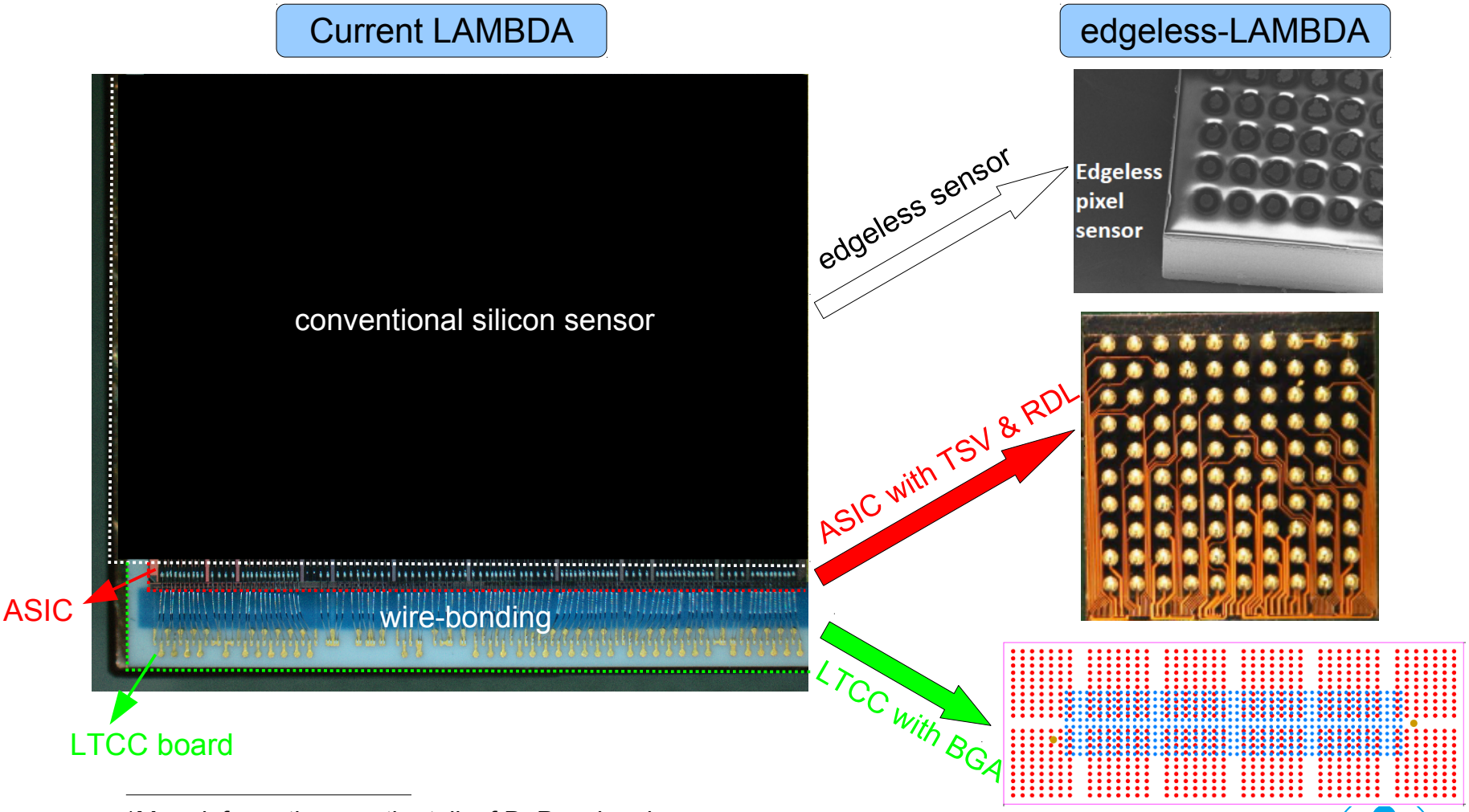
Backup slides

Development of edgeless detector @ DESY

- LAMBDA*-based edgeless detector as an example



*More information see the talk of D. Pennicard

Requirements and challenges of edgeless sensors

- Requirements of edgeless sensor for photon science application:
  - Good quantum efficiency
  - Full active sensor volume (no dead region)
  - Small last pixel-to-edge distance (edge space)
  - Low leakage current
  - High breakdown voltage
  - Radiation tolerant to ionizing radiation (surface damage)
  - Consistent response to photons with different energies

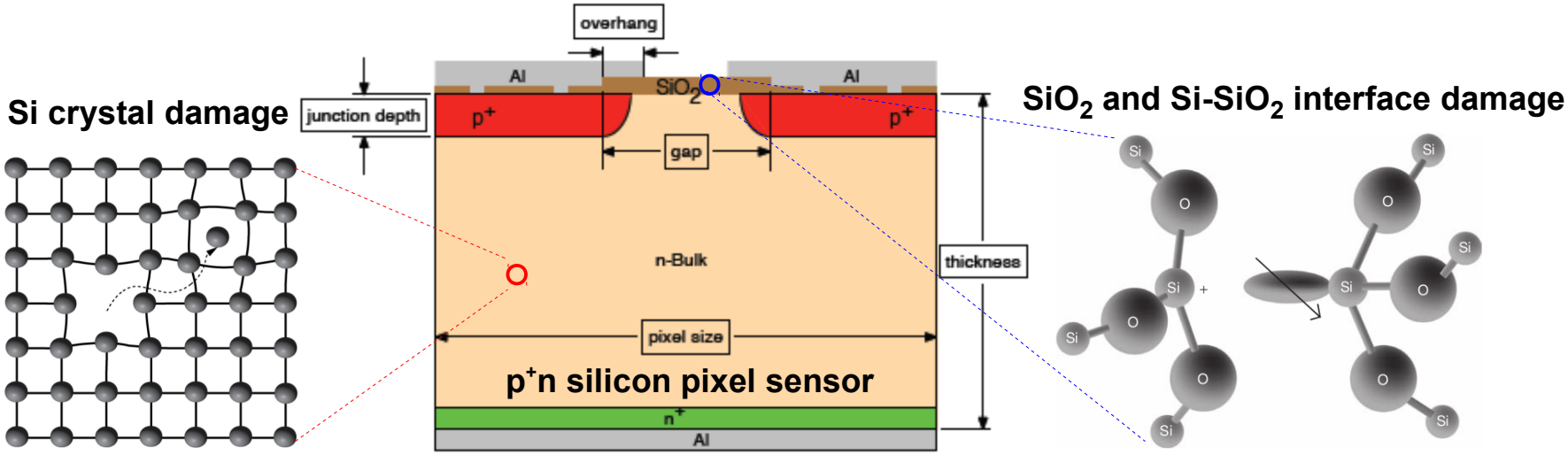
  → Main challenges

- Procedures to optimize an edgeless sensor:
  - Understand electrical properties and radiation hardness of edgeless sensors from available commercial designs according to TCAD simulations

    → guideline for the sensor optimization with respect to technology choice
  - Understand charge-collection behavior of edgeless sensors with different Si thicknesses by measurements and model calculation

    → guideline for the choice of sensor thickness and last pixel-to-edge distance

Introduction to radiation damage



- Bulk damage (Si crystal damage):
  - Non Ionizing Energy Loss of incident particles (gamma-rays, electrons and hadrons) in silicon
  - Clusters of defects/or and point defects (Vacancy + Interstitial)
- Surface damage (SiO_2 and Si-SiO_2 interface damage):
  - Ionizing Energy Loss of "charged" particles and X-rays in SiO_2
  - Types of defects: Oxide charges, interface traps and etc.

Main concern in photon science & increased interest from HL-LHC

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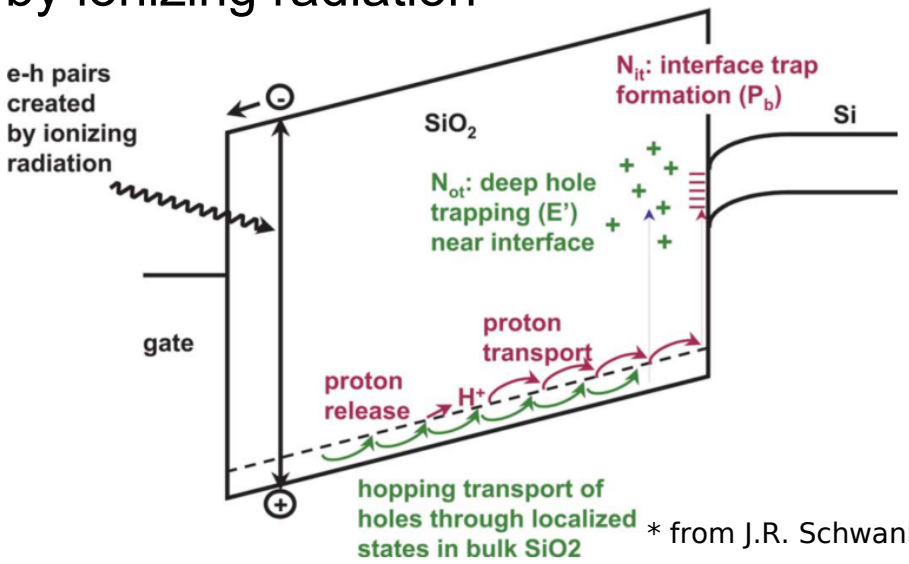
Mechanism of radiation-induced surface damage

- Formation of defects induced by ionizing radiation

Generation of e-h pairs in SiO_2 (18 eV/pair)

Prompt recombination of e-h pairs (E-field dependence)

Transport of free carriers
e: $\mu_e \sim 20\ cm^2/(V \cdot s)$, escape
h: $\mu_h < 10^{-5}\ cm^2/(V \cdot s)$, hopping



* from J.R. Schwank, 2008

$$e.g., V_{ox}H_2 + h^+ \rightarrow V_{ox}H + H^+$$

Release and transport of protons

$$e.g., V_{ox} + h^+ \rightarrow V_{ox}^+$$

$$e.g., H^+ + SiH_{int} \rightarrow Si\bullet + H_2$$

Trapped in SiO_2 by oxygen vacancies V_{ox}
→ oxide charges (N_{ox})

Impact on sensor performance

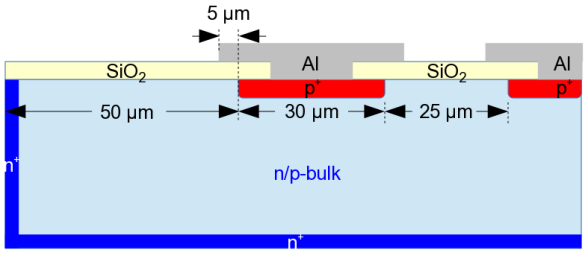
Depassivate compensated Si bonds at Si-SiO_2 interface
→ interface traps (N_{it})

DESY

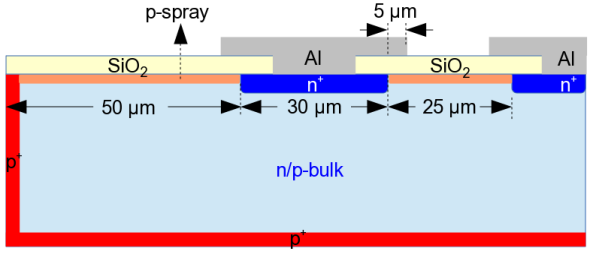
Simulation of edgeless sensors: Layouts

- Layouts and cross sections of edgeless sensors with active edges used in simulation
  - 6 different ones: p^+n, p^+p, n^+p and n^+n with p-spray, n^+p and n^+n with p-stop
  - Pixel pitch: 55 µm (Medipix compatible)
  - Width of pixel implant: 30 µm; gap between pixel implants: 25 µm
  - Metal overhang: 5 µm
  - Last pixel-to-edge distance: 50 µm
  - Width of p-stop: 5 µm

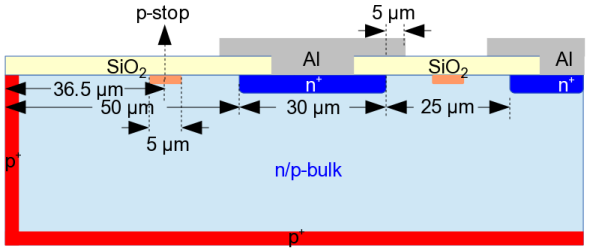
p^+n/p^+p sensors



n^+n/n^+p sensors with p-spray

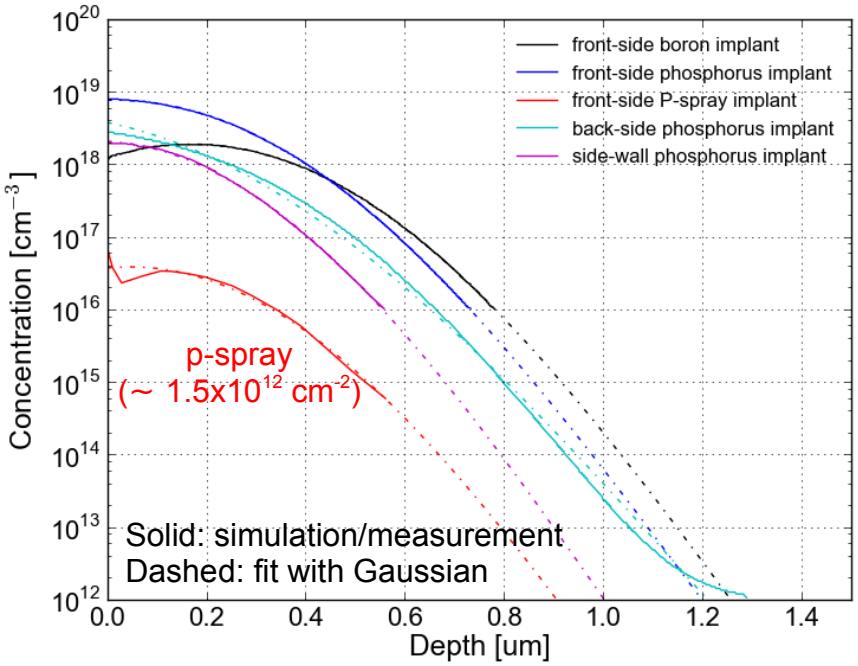


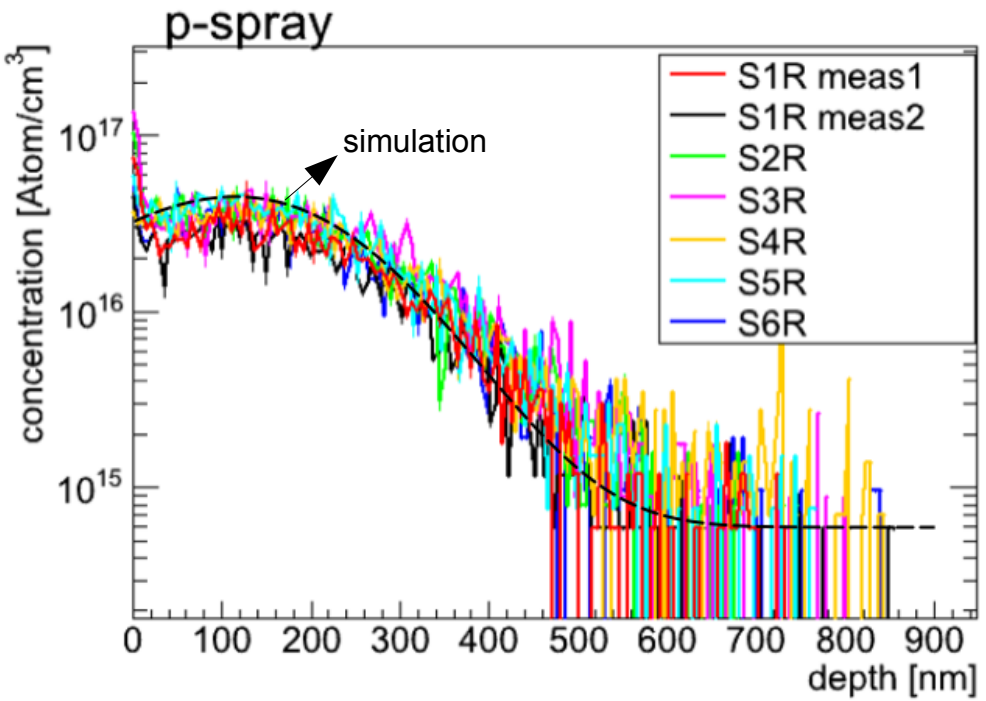
n^+n/n^+p sensors with p-stop



Simulation of edgeless sensors: Input parameters

- Implant profiles (critical for breakdown simulation)
  - All profiles obtained from the output of process simulation
  - p-spray profile simulation result checked with SR measurement





- All profiles fit with Gaussian functions → fit parameters used as inputs in simulation

Simulation of edgeless sensors: Input parameters

- Parameters/physics models implemented in TCAD simulation
  - Parameters extracted from measurements: MOS, diode, and GCD
  - Radiation damage parameters used for breakdown simulation

Parameters:

	n-type silicon			p-type silicon	
Polarity	p^+n	n^+n (p-spray)	n^+n (p-stop)	n^+p (p-spray)	n^+p (p-stop)
Doping	7×10^{11} cm^{-3}			1.1×10^{12} cm^{-3}	
T_{ox}	700 nm			680 nm	
e/h lifetime	equiv. 1.35 ms				
N_{ox}	1.0×10^{10} cm^{-2} (non-irra.) 3.0×10^{12} cm^{-2} (irra.)			3.0×10^{10} cm^{-2} (non-irra.) 3.0×10^{12} cm^{-2} (irra.)	
S_0	1.35 cm/s (non-irra.) 12,000 cm/s (irra.)			3.54 cm/s (non-irra.) 12,000 cm/s (irra.)	
T_{si}	150 µm 300 µm 500 µm	150 µm 200 µm 300 µm 500 µm		150 µm 300 µm 500 µm	

Physics models:

- Drift diffusion
- Statistics: Fermi
- T = 293 K
- Band gap: band-gap narrowing
- Mobility: doping dependence, high-field saturation, carrier-carrier scattering and degradation at the interface
- Recombination: doping, temperature dependence and electric field enhancement
- Auger recombination
- Band-to-band tunneling with Hurkx model
- Avalanche: vanOverstraetenMan model with the gradient of quasi-Fermi potential as driving force
- Si-SiO_2 interface: surface recombination, fixed charge
- Boundary condition: Neumann

- Simulation done with fixed layout but different silicon thicknesses
- Only results on sensor active volume and breakdown for 300 µm thick sensor will be shown

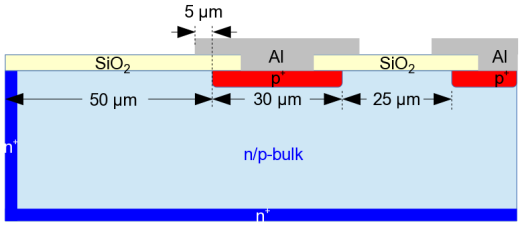
Summary on sensor simulation

- Active volume/X-ray sensitive volume:
  - Full active volume for n^+n and p^+p sensors
  - Inactive volume at sensor corner of n^+p and p^+n sensors: sensor thickness, bias voltage, doping (and last pixel-to-edge distance) dependence
- Breakdown and radiation hardness:
  - High current due to breakdown flows into 1st pixel
  - All sensor layouts/polarities stand for >180 V without irradiation
  - Breakdown voltage gradually decreases with X-ray irradiation for p^+n, p^+p, and n^+n/n^+p sensors with p-stop
  - n^+n/n^+p sensors with p-spray withstand certain irradiation with $N_{ox} \approx N_{p\text{-}spray}$
  - Edge breakdown for n^+n/n^+p sensors with p-stop and with p-spray dose at high irradiation doses

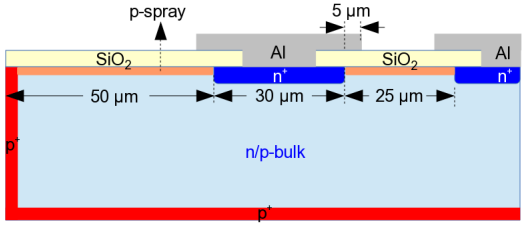
Simulation of commercial edgeless sensors

- Layouts and cross sections of commercial edgeless sensors
  - 6 different ones: p^+n, p^+p, n^+p and n^+n with p-spray, n^+p and n^+n with p-stop
  - Junction depth of 1.2 µm and oxide thickness of 700 nm

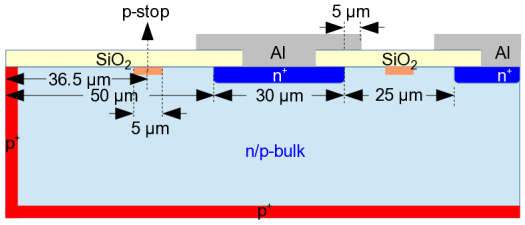
p^+n/p^+p sensors



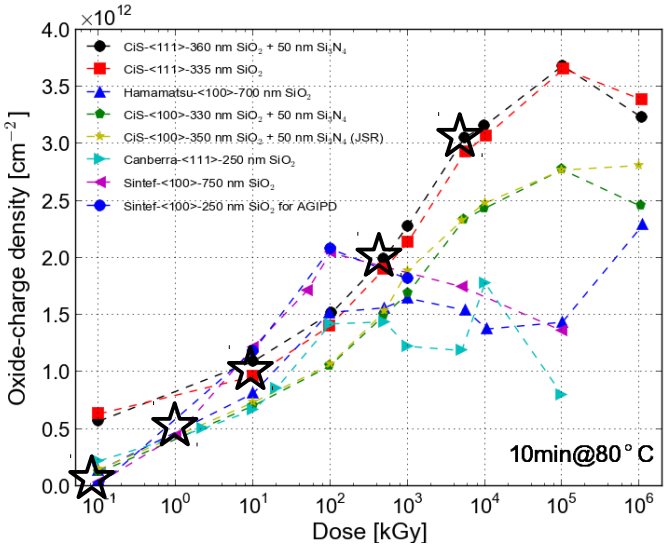
n^+n/n^+p sensors with p-spray

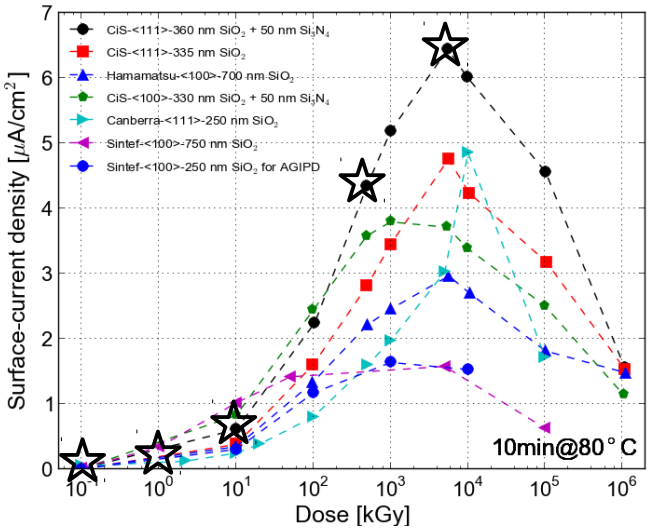


n^+n/n^+p sensors with p-stop



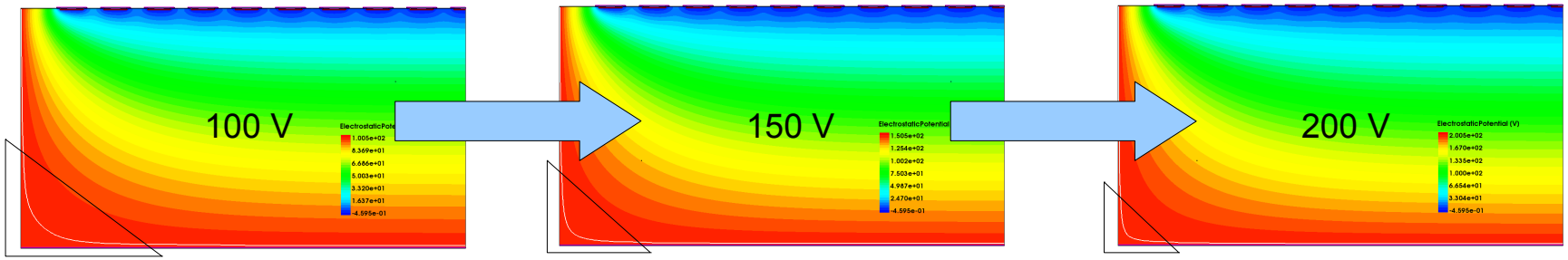
- Radiation-damage parameters (☆) from measurements implemented



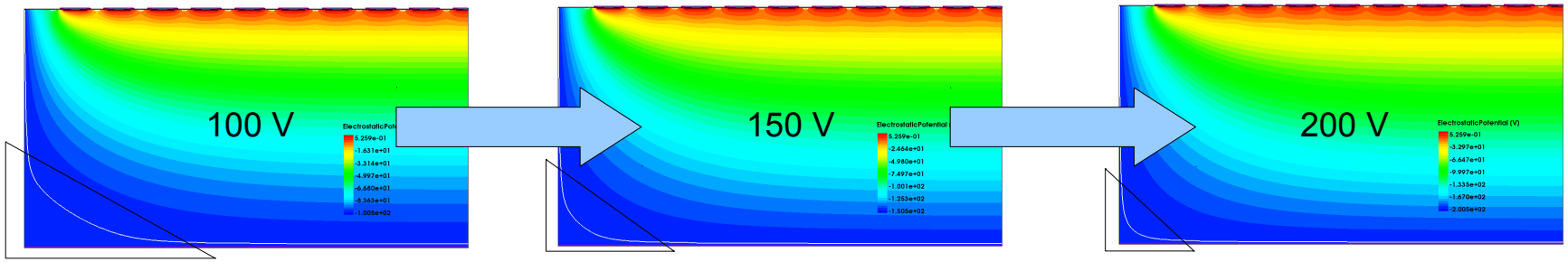


Simulation of sensor active/depletion volume

- Active (depletion) volume of p^+n sensor



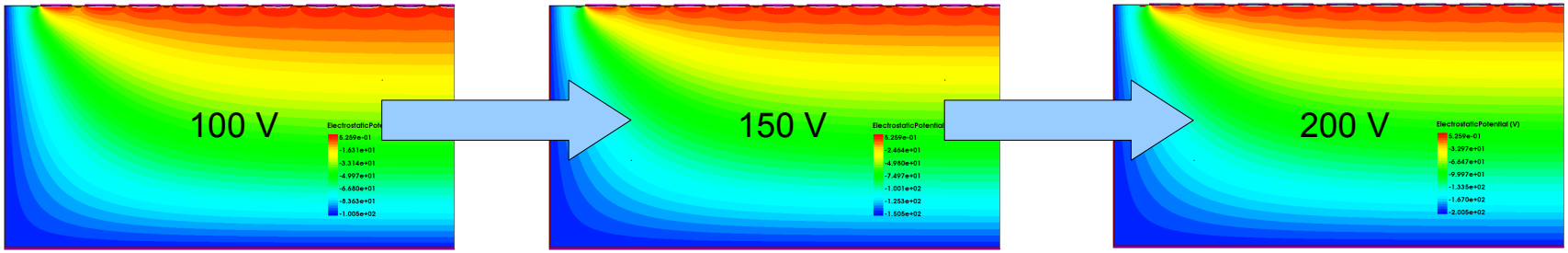
- Active volume of n^+p sensor (with p-spray or p-stop)



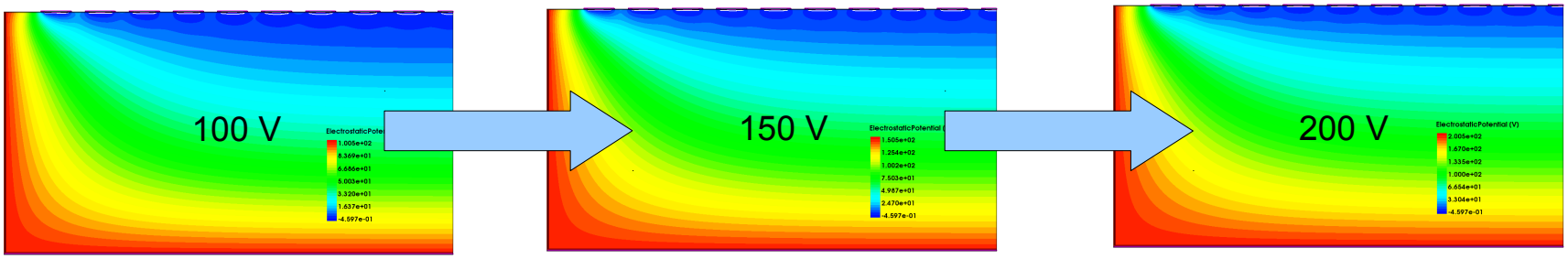
- Conclusion for p^+n and n^+p sensors:
  - Sensor depletion starting from pixels → inactive region at sensor corner
  - Inactive volume shrinks with voltage (at least 100 V above V_{dep} needed?)
  - Higher doping, thicker Si → larger additional voltage needed

Simulation of sensor active/depletion volume

- Active volume of n^+n sensor (with p-spray or p-stop)



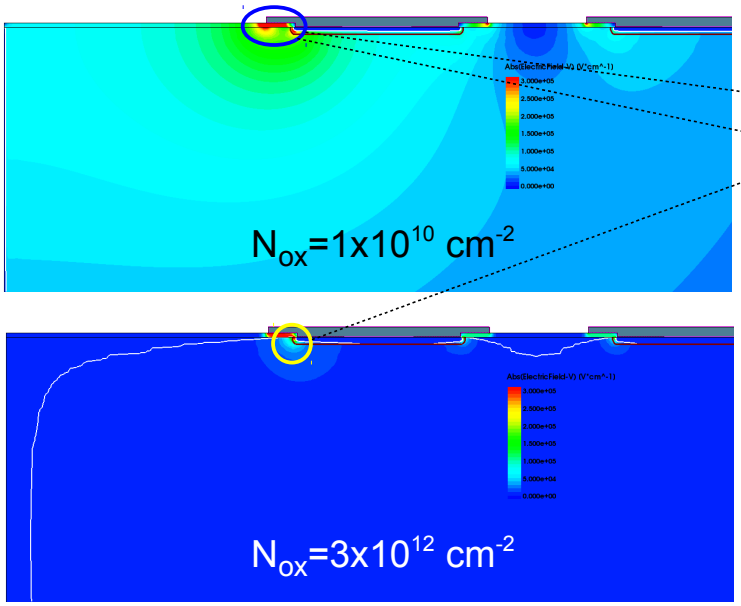
- Active volume of p^+p sensor

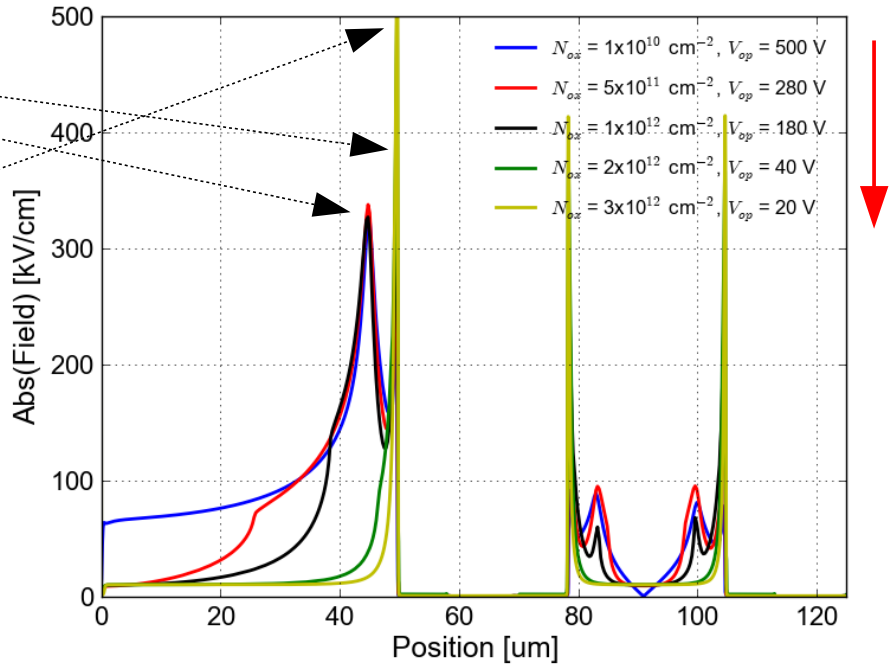


- Conclusion for n^+n and p^+p sensors:
  - Sensor depletion starting from edge and backside → no inactive region
  - No/Small additional voltage above V_{dep} needed (typically 10-15 V)

Breakdown simulation of p^+n sensor

- High field region:
  - $N_{ox} \leq 1x10^{12}$ cm^{-2}, high field below metal overhang and at junction of 1st pixel
  - $N_{ox} > 1x10^{12}$ cm^{-2}, high field at implant junction of 1st pixel

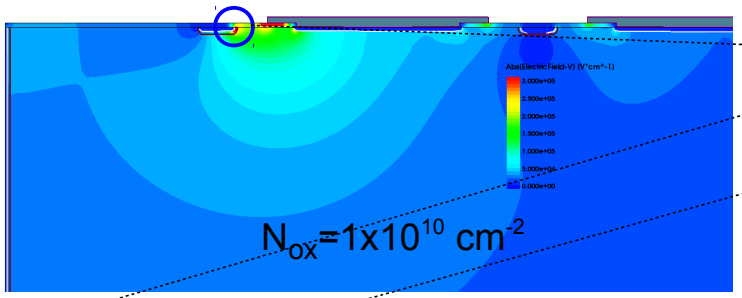


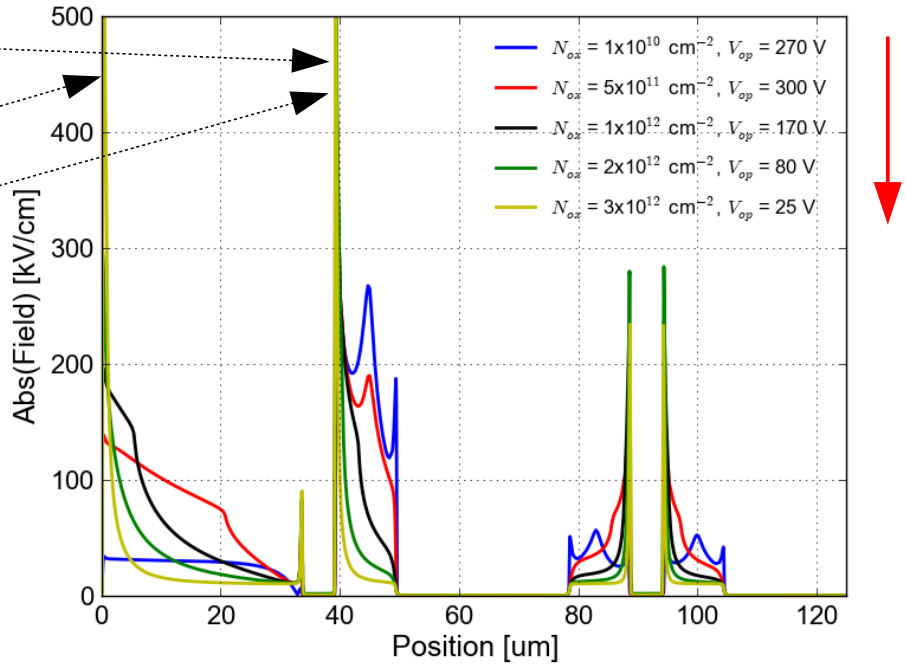


- 1st pixel behaves like CCR of a conventional sensor → breakdown first
- Breakdown voltage drops gradually with increasing oxide charges

Breakdown simulation of n^+n/n^+p sensors with p-stop

- High field region:
  - $N_{ox} \leq 1x10^{12}$ cm^{-2}, high field at implant junction of p-stop
  - $N_{ox} > 1x10^{12}$ cm^{-2}, high field at implant junctions of p-stop and sensor edge

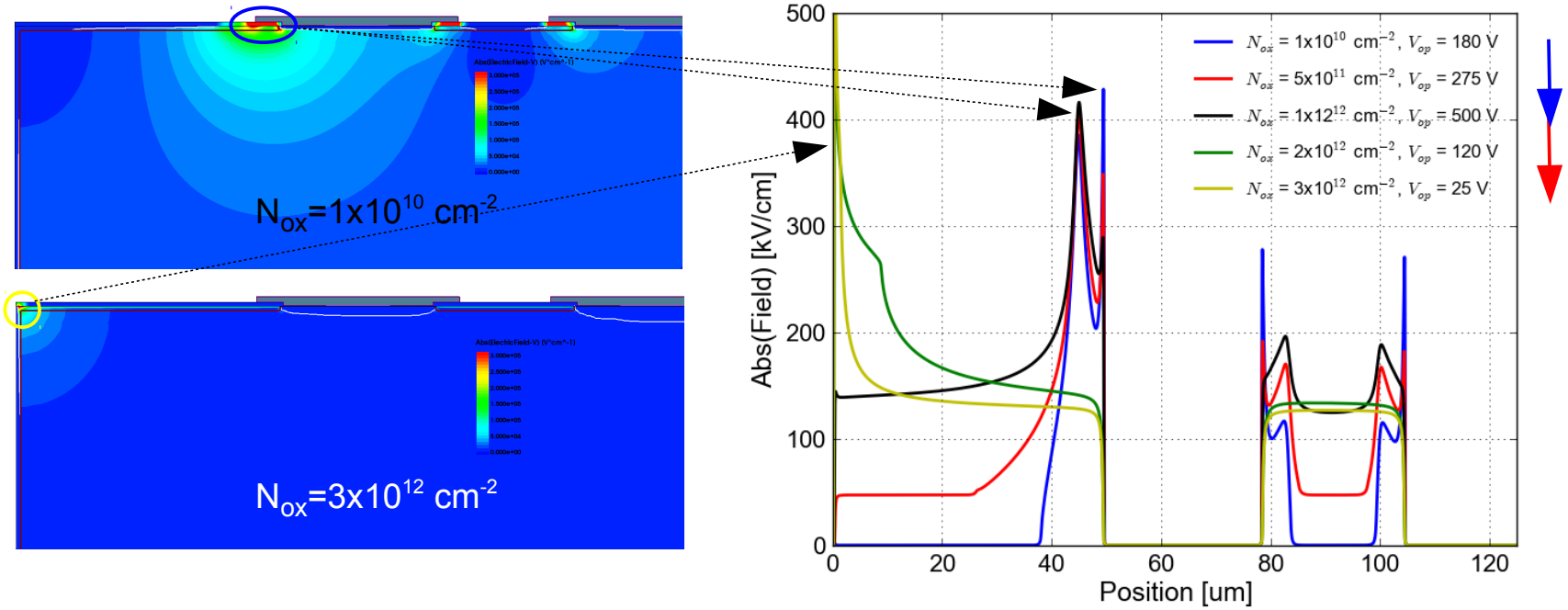




- High field at sensor edge ← direct exposure to oxide charges
- Breakdown voltage drops gradually with increasing oxide charges

Breakdown simulation of n^+n/n^+p sensors with p-spray

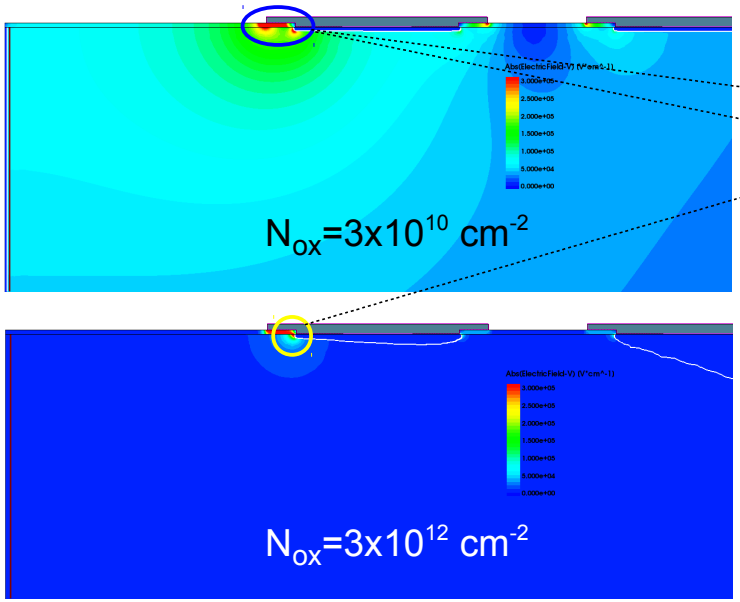
- High field region:
  - $N_{ox} \leq 1x10^{12}$ cm^{-2}, high field at pixel-implant/p-spray interface and below metal
  - $N_{ox} > 1x10^{12}$ cm^{-2}, high field at sensor edge

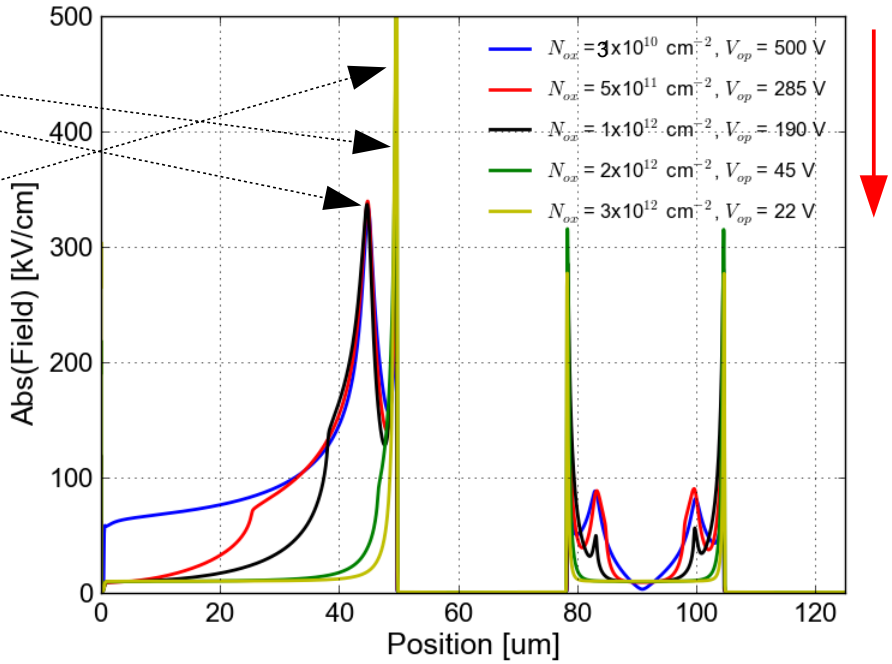


- High field at sensor edge → improved by increasing p-spray dose
- Breakdown improves with N_{ox} , but decreases when $N_{ox} > N_{p\text{-}spray}$

Breakdown simulation of p^+p sensor

- High field region:
  - $N_{ox} \leq 1x10^{12}$ cm^{-2}, high field below metal overhang of 1st pixel
  - $N_{ox} > 1x10^{12}$ cm^{-2}, high field at implant junction of 1st pixel

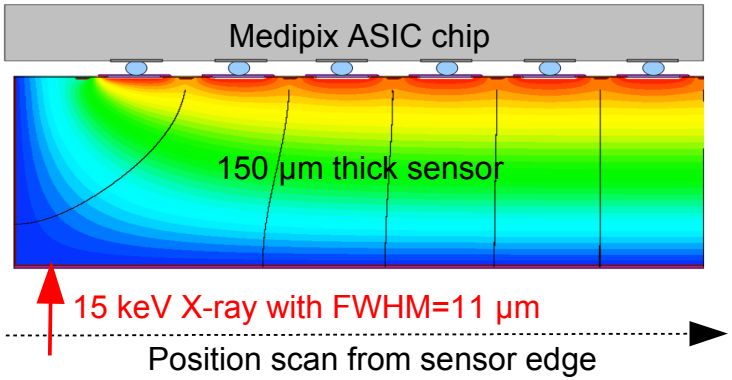




- Results (V_{bd} and high field region) similar to p^+n sensor
- Breakdown voltage drops gradually with increasing oxide charges

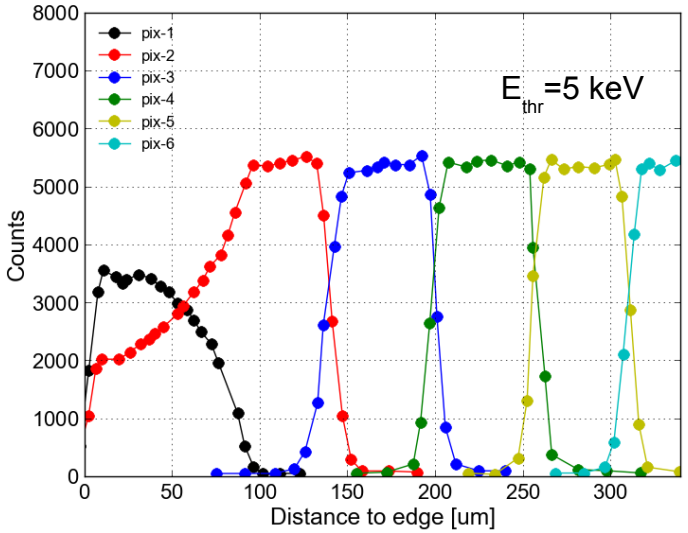
Charge-collection behavior: Measurement results on thin-Si

- X-ray scan on sensor backside (Uni-Glasgow@Diamond Light Source)

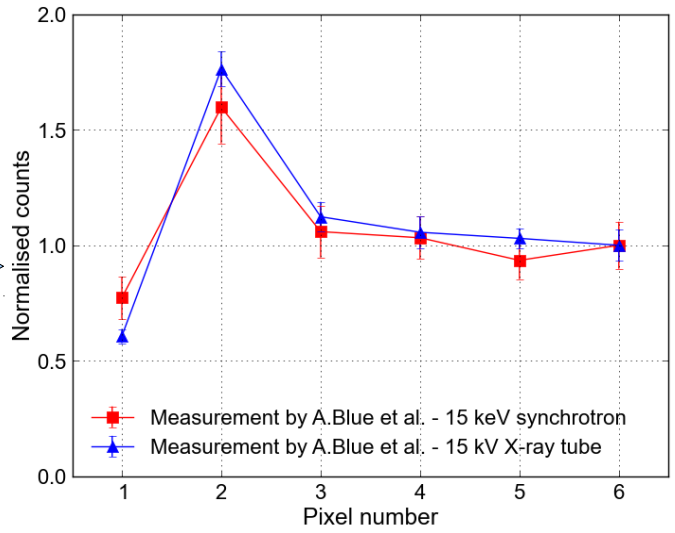


- Non-uniform charge collection
- Different counting behaviors in flat field image

Reason: bending electric field



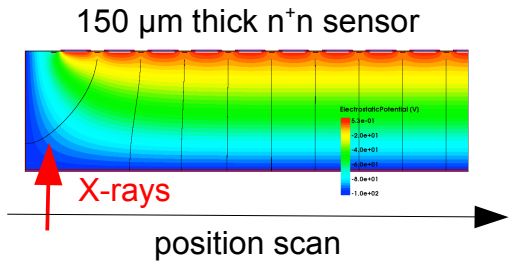
integration

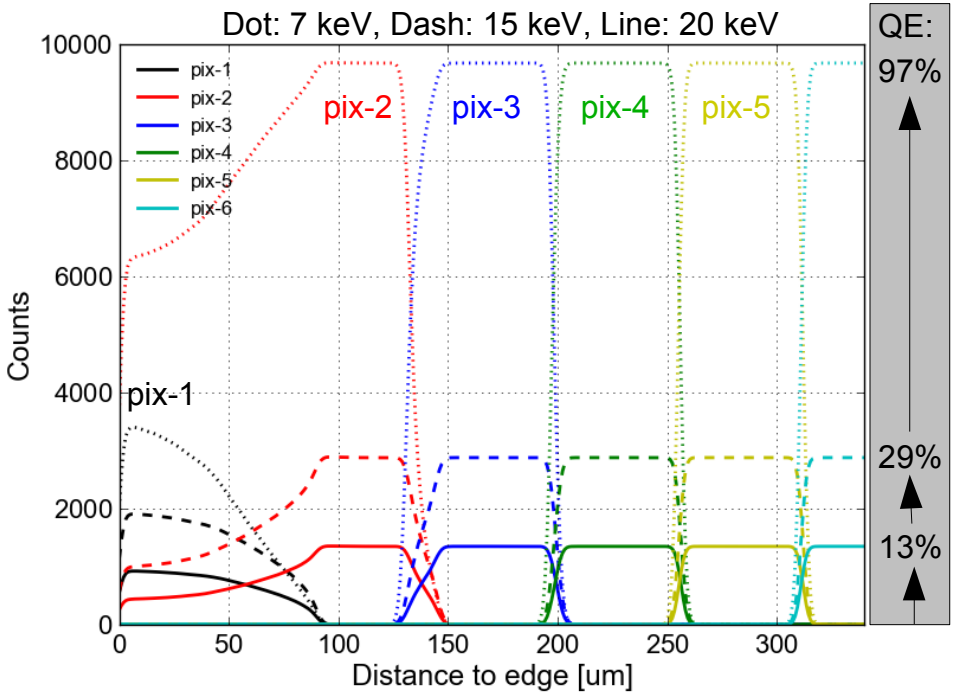


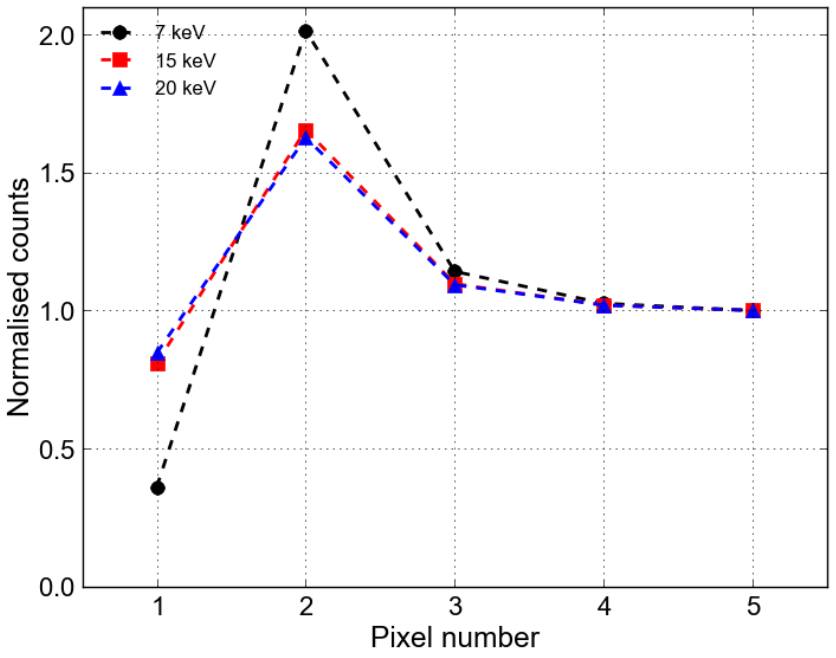
- Similar observation from mesh scan

Charge-collection behavior: Model calculation for 150 µm Si

- X-ray scan on sensor backside (10^4 entries):
  - 7 keV, 15 keV and 20 keV X-rays (5 µm beam)
  - 150 µm thick Si with 50 µm edge space
  - Edge pixel counts vs. distance ($E_{thr} = E_{x\text{-}ray}/2$)



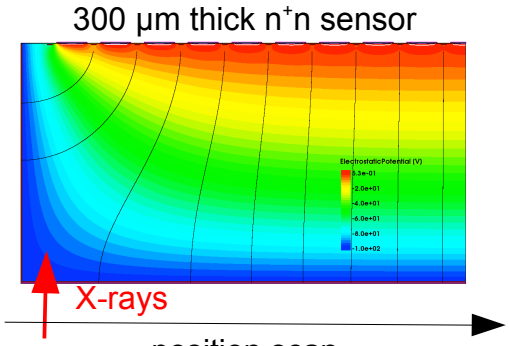


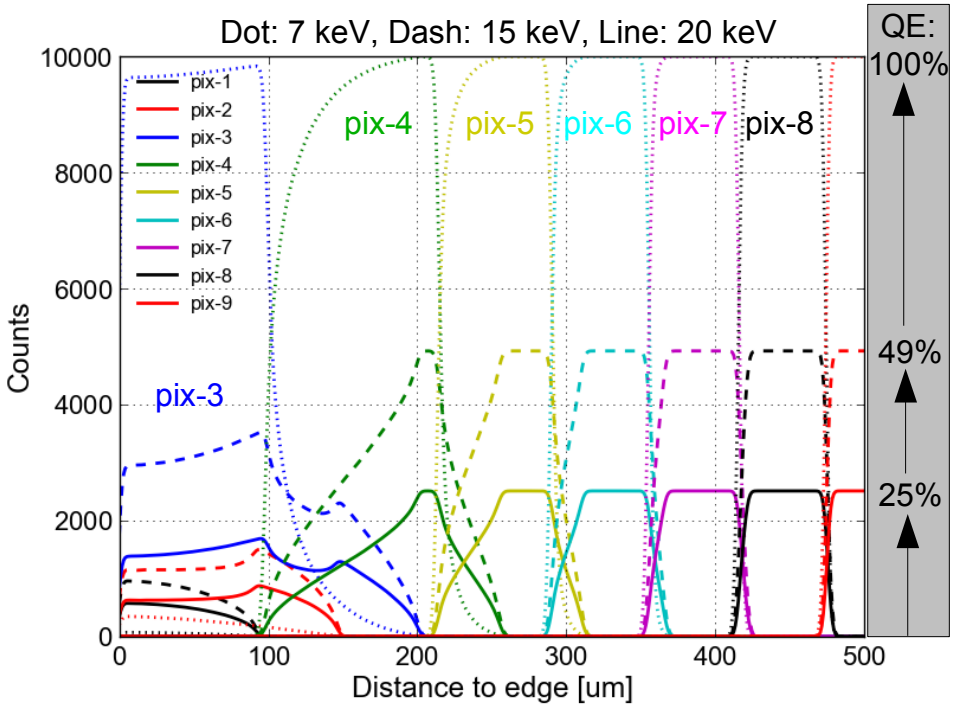


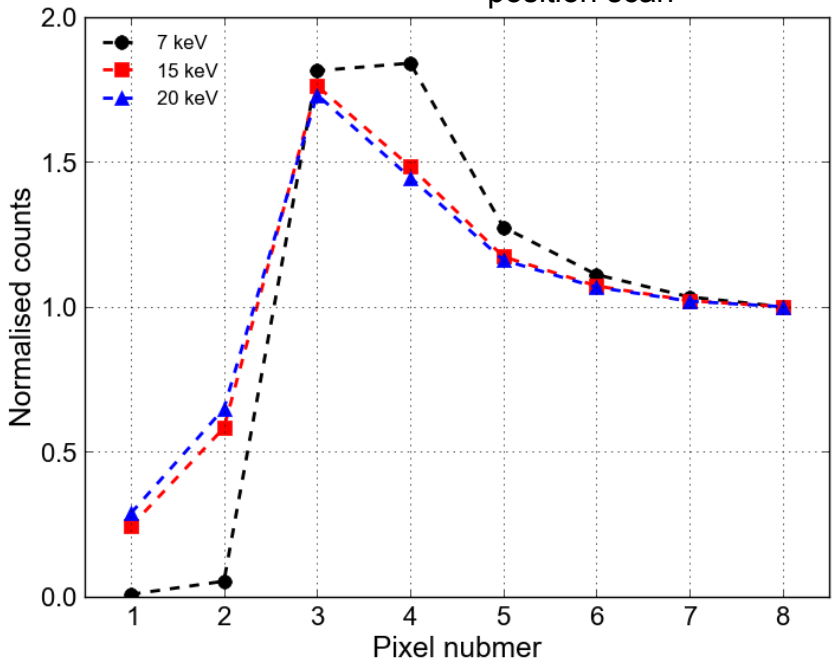
- Count of last edge pixel decreases with photon energy

Charge-collection behavior: Model calculation for 300 µm Si

- X-ray scan on sensor backside (10^4 entries):
  - 7 keV, 15 keV and 20 keV X-rays (5 µm beam)
  - 300 µm thick Si with 50 µm edge space
  - Edge pixel counts vs. distance ($E_{thr} = E_{x\text{-}ray}/2$)



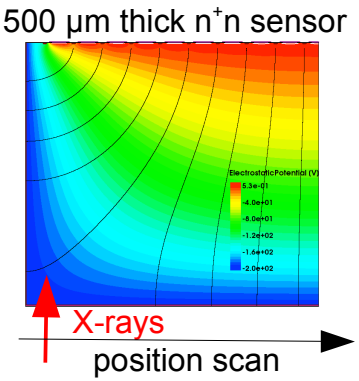


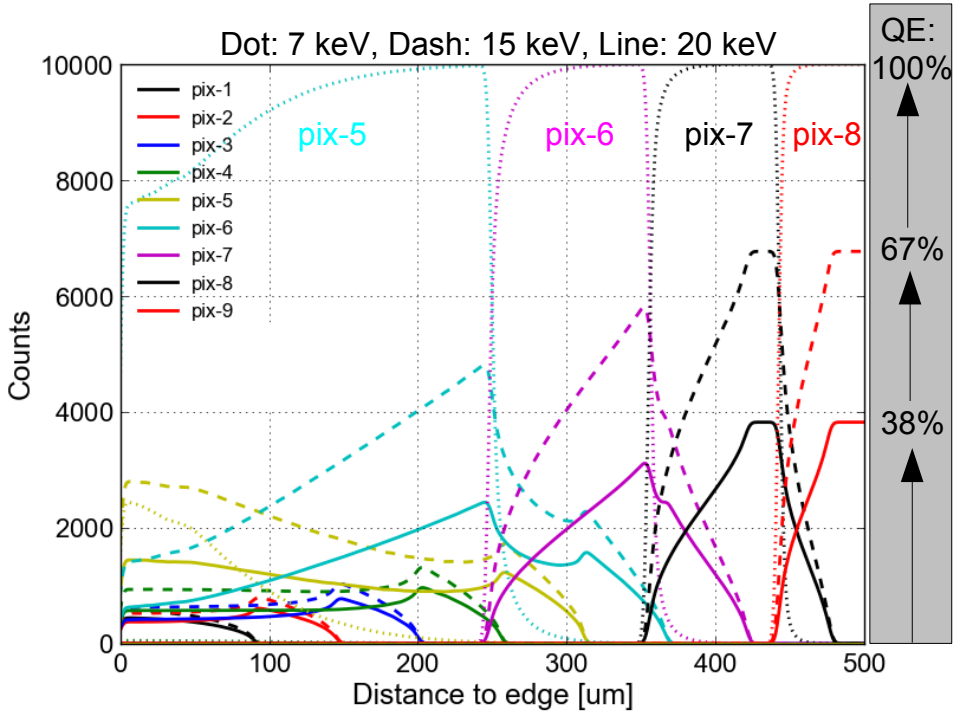


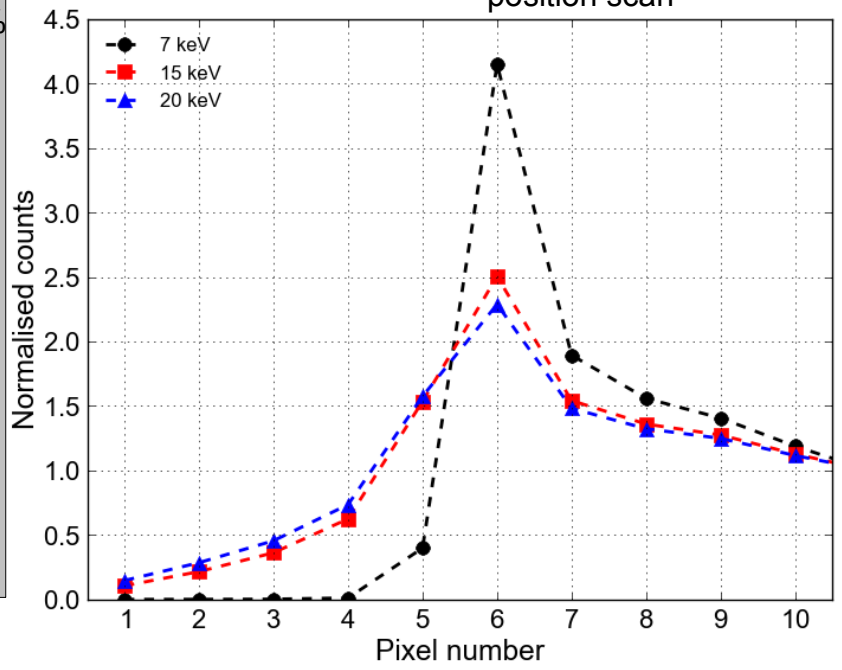
- Last <u>two edge pixels</u> respond to <u><10%</u> 7 keV photons

Charge-collection behavior: Model calculation for 500 µm Si

- X-ray scan on sensor backside (10^4 entries):
  - 7 keV, 15 keV and 20 keV X-rays (5 µm beam)
  - 500 µm thick Si with 50 µm edge space
  - Edge pixel counts vs. distance ($E_{thr} = E_{x\text{-}ray}/2$)



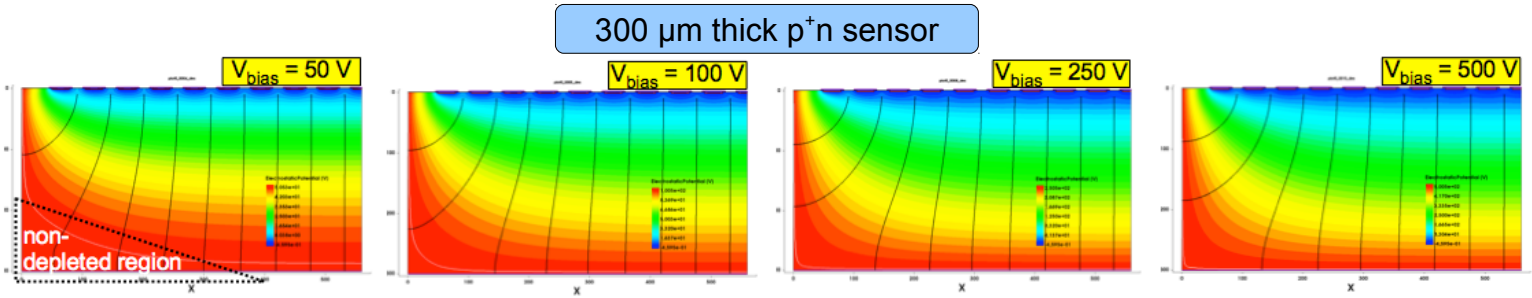




- Last four edge pixels respond to <10% 7 keV photons

Charge-collection behavior: Summary

- Non-uniform charge collection for edge pixels: X-ray energy, sensor thickness, last pixel-to-edge distance, and sensor polarity dependence
  - Low X-ray energy → good QE for central pixels but poor charge collection for edge pixels
  - Thin silicon and large last-to-edge distance → good charge collection for edge pixels but poor QE for high energy X-rays
  - Charge collection of p^+p sensor similar to n^+n sensor, p^+n similar to n^+p
  - Bending of electric field for p^+n and n^+p sensors are bias voltage dependent → voltage dependence of charge collection



- Conclusion: To obtain the optimized charge collection for edge pixels and guarantee the low energy photon sensitivity, last pixel-to-edge distance should be kept > 50% of the sensor thickness