TCAD for Atlas Planar Pixel Sensors

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ATLAS

outlook

- *TCAD Activities for planar pixel sensor design Improvements for IBL & SLHC*

- Contents
  - The TCAD tool
    - Optimization of GR number in PPS
    - Edge reduction and GR strutures & wafer Thinning
    - Charge amplification for heavily irradiated sensors

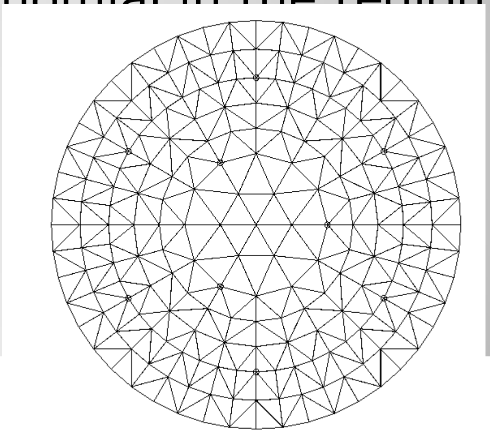
Conclusions and prospects

TCAD principles

- TCAD uses partial, differential equations describing charge carrier’s motion and interactions with the cristal lattice in semiconductor coupled to finite element method to simulate electrical parameters of the device.

- Finite element method use a linearized version of the transport equation to describe the problem in terms of linear system of equations that can be solved by linear algebra methods.

- Meshing : to obtain a solution of transport equation in an arbitrary geometry, we must subdivide the surface or volume in rectangular, triangular, pyramidal… sub-elements with small enough sizes that the solution is locally polynomial in the region.



General framework of the device simulation

ψ is the electrostatic potential
E is the electric field
n, p are electron and hole concentration
J are electron and hole current densities
G are generation rates for electron and holes
R are combination rates for electrons and holes
μ are mobilities
D Einstein relation
q is the electron charge

Continuity equations

$$\vec{E} = -\nabla \Psi$$

$$\frac{\delta n}{\delta t} = \frac{1}{q} div \vec{J}_n + G_n - R_n$$

$$\frac{\delta p}{\delta t} = \frac{1}{q} div \vec{J}_p + G_p - R_p$$

Drift diffusion model:

$$J_{n,p} = qn \mu_{n,p} . \vec{E}_{n,p} + qD_{n,p} \nabla n(p)$$

Poisson's equation

$$div(\varepsilon \nabla \Psi) = -\rho$$

It Relates variation in electrostatic potential to local charge densities

Continuity equation

Constitutive equations

Describe the way electron and hole densities evolve as a result of transport, generation and recombinaison process

Basic equations

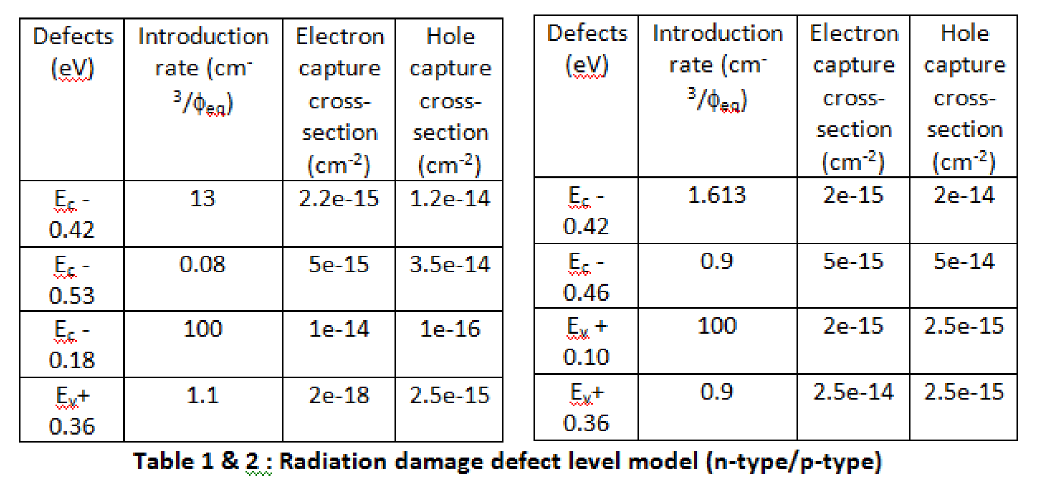
Physics

Irradiation conditions

Physics	Models
Mobility	Concentration-dependent mobility (fit to experimental data), Parallel field dependent mobility (fit to experimental saturation velocities)
Generation recombination and trapping	Modified concentration dependent Shockley-Read-Hall Generation/recombination (for treatment of defects)
Impact ionization	Selberherr's Impact ionization model
Tunnelling	Band-to-band tunnelling, Trap-Assisted tunnelling
Oxide physics	Fowler-Nordheim tunnelling, interface charge accumulation

Irradiation simulations

Non-ionizing Energy loss

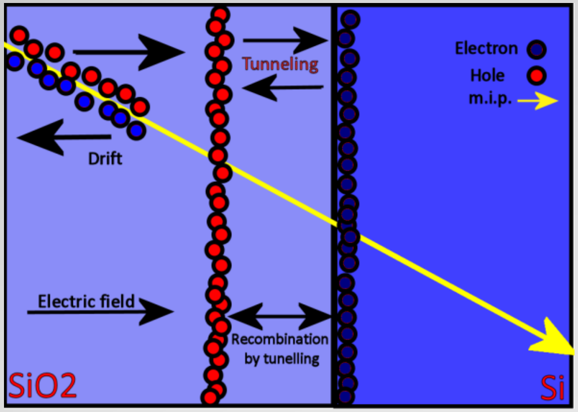


Defects (eV)	Introduction rate (cm^{-3}/ϕ_{eq})	Electron capture cross-section (cm^{-2})	Hole capture cross-section (cm^{-2})
E_c - 0.42	13	2.2e-15	1.2e-14
E_c - 0.53	0.08	5e-15	3.5e-14
E_c - 0.18	100	1e-14	1e-16
E_v+ 0.36	1.1	2e-18	2.5e-15

Defects (eV)	Introduction rate (cm^{-3}/ϕ_{eq})	Electron capture cross-section (cm^{-2})	Hole capture cross-section (cm^{-2})
E_c - 0.42	1.613	2e-15	2e-14
E_c - 0.46	0.9	5e-15	5e-14
E_v + 0.10	100	2e-15	2.5e-15
E_v+ 0.36	0.9	2.5e-14	2.5e-15

Table 1 & 2 : Radiation damage defect level model (n-type/p-type)

Ionizing Energy loss

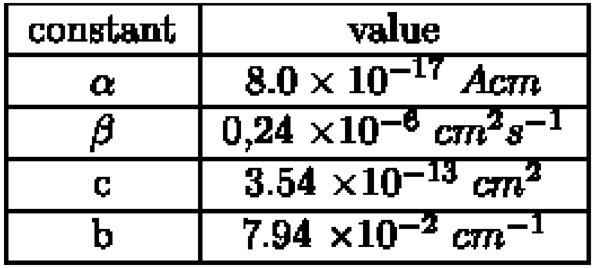


Hamburg Parametrisation

$$\frac{\Delta I_{vol}}{V} = \alpha\Phi$$

$$\frac{1}{\tau_t(\Phi)} = \frac{1}{\tau_{t0}} + \beta\Phi$$

$$N(\Phi) = N_{D0}e^{-c\Phi} - N_{A0} - b\Phi$$



constant	value
α	$8.0 \times 10^{-17}\ Acm$
β	$0{,}24 \times 10^{-6}\ cm^2 s^{-1}$
c	$3.54 \times 10^{-13}\ cm^2$
b	$7.94 \times 10^{-2}\ cm^{-1}$

D. Menichelli, M. Bruzzi, Z. Li, and V. Eremin, **"Modelling of observed double-junction effect,"** *Nucl. Instrum. Meth. A, vol. 426, pp.* 135–139, Apr. 1999.

F. Moscatelli *et al.*, ***"An enhanced approach to numerical modeling of*** **heavily irradiated silicon devices,"** *Nucl. Instrum. Meth. B, vol. 186,* no. 1-4, pp. 171–175, Jan. 2002.

F. Moscatelli *et al.*, ***"Comprehensive device simulation modeling of*** **heavily irradiated silicon detectors at cryogenic temperatures,"** *IEEE Trans. Nucl. Sci., vol. 51, no. 4, pp. 1759–1765, Aug. 2004.*

M. Petasecca, F. Moscatelli, D. Passeri, G. Pignatel, and C. Scarpello, **"Numerical simulation of radiation damage effects in p-type silicon detectors,"** *Nucl. Instrum. Meth. A, vol. 563, no. 1, pp. 192–195, 2006.*

- Impact ionization
  - An impact ionization model "selberherr Model " has been implemented in the generation rate of the drift diffusion equation:
  - Local generation rate of electrons/holes: G

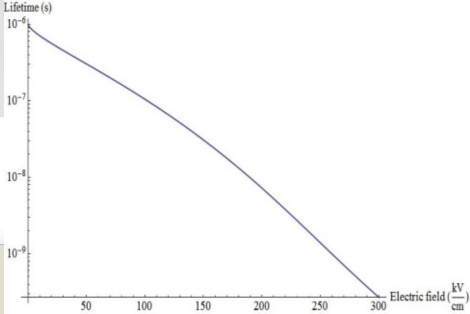
$$G_{impact} = \alpha_n(\vec{E})\left|\vec{J}_n\right| + \alpha_p(\vec{E}).\left|\vec{J}_p\right|$$

$$\alpha_{n,p}(\vec{E}) = A_{n,p}.e^{\frac{-B_{n,p}}{\vec{E}}}$$

– α is the number of electrons holes generated per carrier per unit distance travelled and is dependant of electric Fied
- $A_{n,p}$ and $B_{n,p}$ are determined experimentaly are function of the material

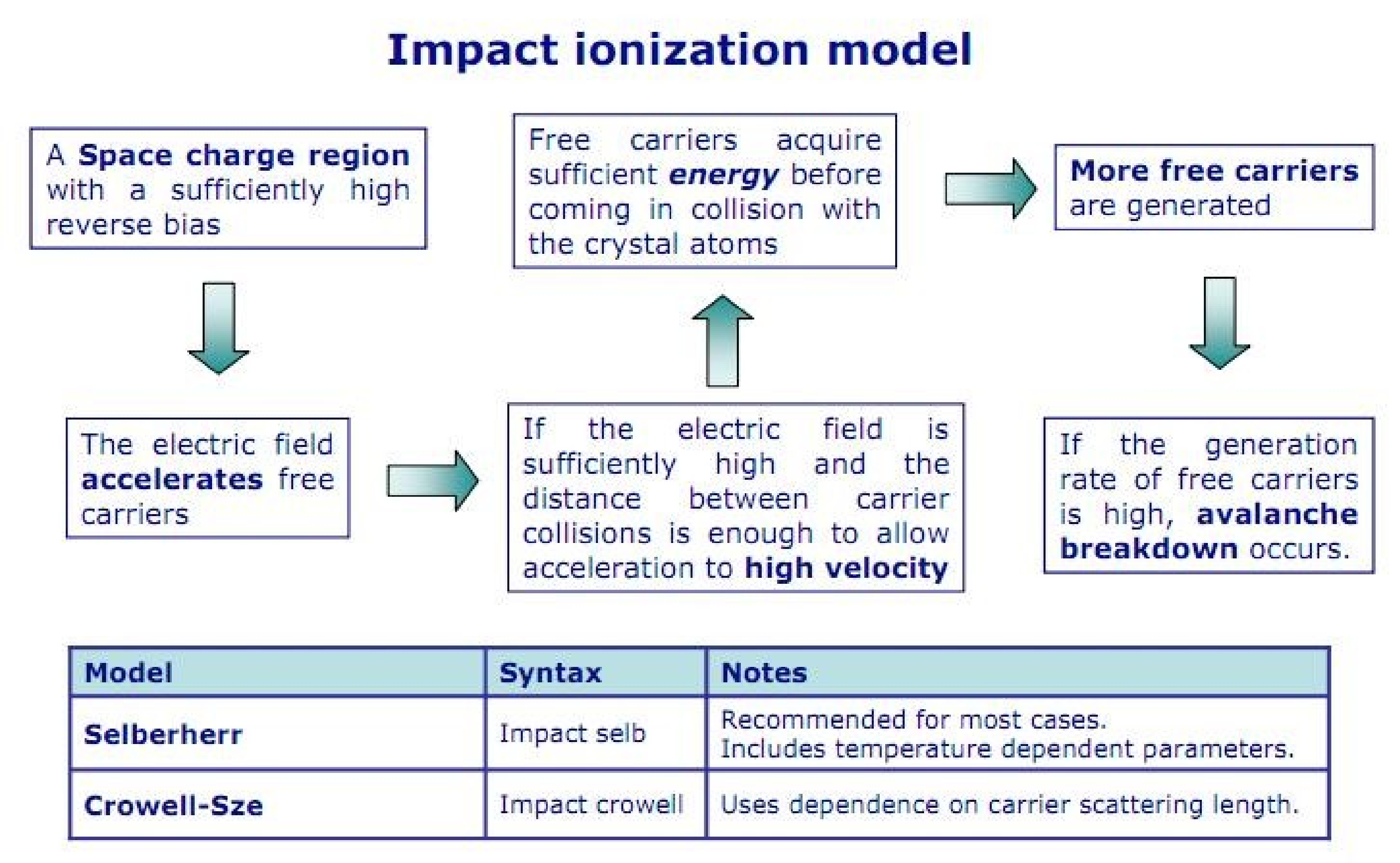
If E inside the irradiated sensor is >100 KV/cm, some multiplication effects leading to increased Charge Collection is expected

- Trap to band tunneling
  - This affect the lifetime of electrons and holes trapped in the defects in the bandgap of silicon;
  - An increased field E in the bulk will bend the band gap of silicon modifying the energy levels of the **C** conduction and **V** valence band;
  - If the bending is sufficient, tunneling of the carriers trapped in the **V** or **C** band can occur, reducing the effective lifetime of the trapped carriers and thus contribute **to the leakage current and to the generation rate term of the drift diffusion equation**



Physics mechanisms

TCAD Tool description



Impact ionization model

A **Space charge region** with a sufficiently high reverse bias

The electric field **accelerates** free carriers

If the electric field is sufficiently high and the distance between carrier collisions is enough to allow acceleration to **high velocity**

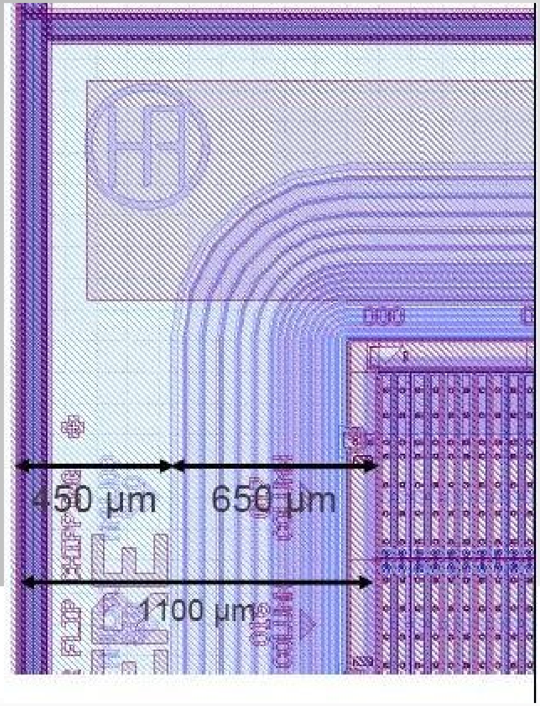
Free carriers acquire sufficient ***energy*** before coming in collision with the crystal atoms

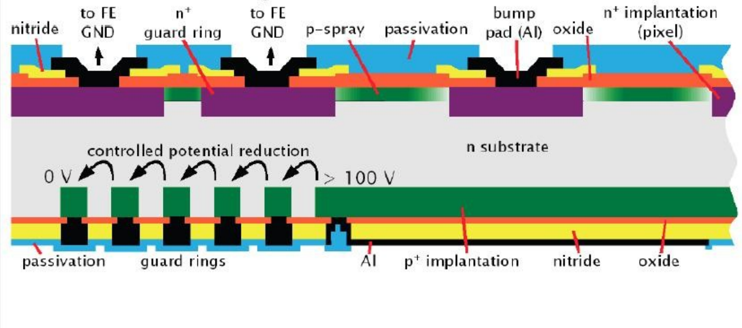
More free carriers are generated

If the generation rate of free carriers is high, **avalanche breakdown** occurs.

Model	Syntax	Notes
Selberherr	Impact selb	Recommended for most cases. Includes temperature dependent parameters.
Crowell-Sze	Impact crowell	Uses dependence on carrier scattering length.

- Starting point : Atlas present geometry
  - Planar n^+ in n design produced by CiS
  - 16 Guard rings with overhanging metal
  - 250 um thick DOFZ bulk
  - 400 um x 500 um pixel cells
  - Current pixel has been shown to work up 1.1 E15 n_{eq}/cm^2



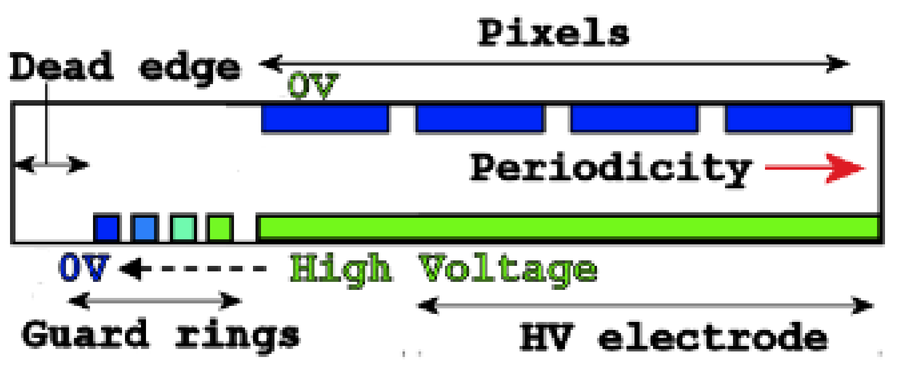

Schematic Layout of the ATLAS Pixel Sensor

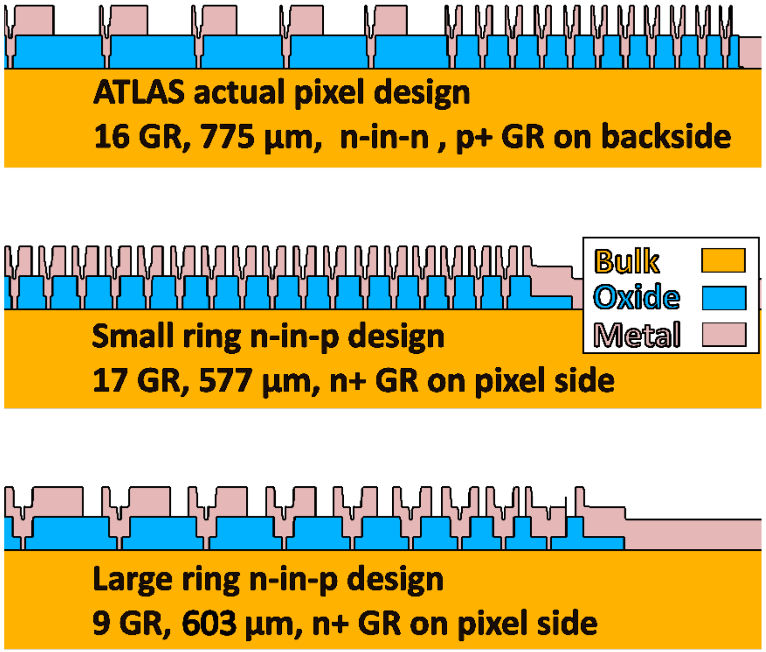
Atlas configuration

Work on main sensor candidates : n-in-n and n-in-p

- The first approach that was studied to reduce edge was to miminize the span of the GR structure and reduce the dead edge width
  - Reducing number of GR
    100 micron edges
    What happens after irradiation

- We also performed simulation on n-in-p structure
  - Two type of structure , large and small GR

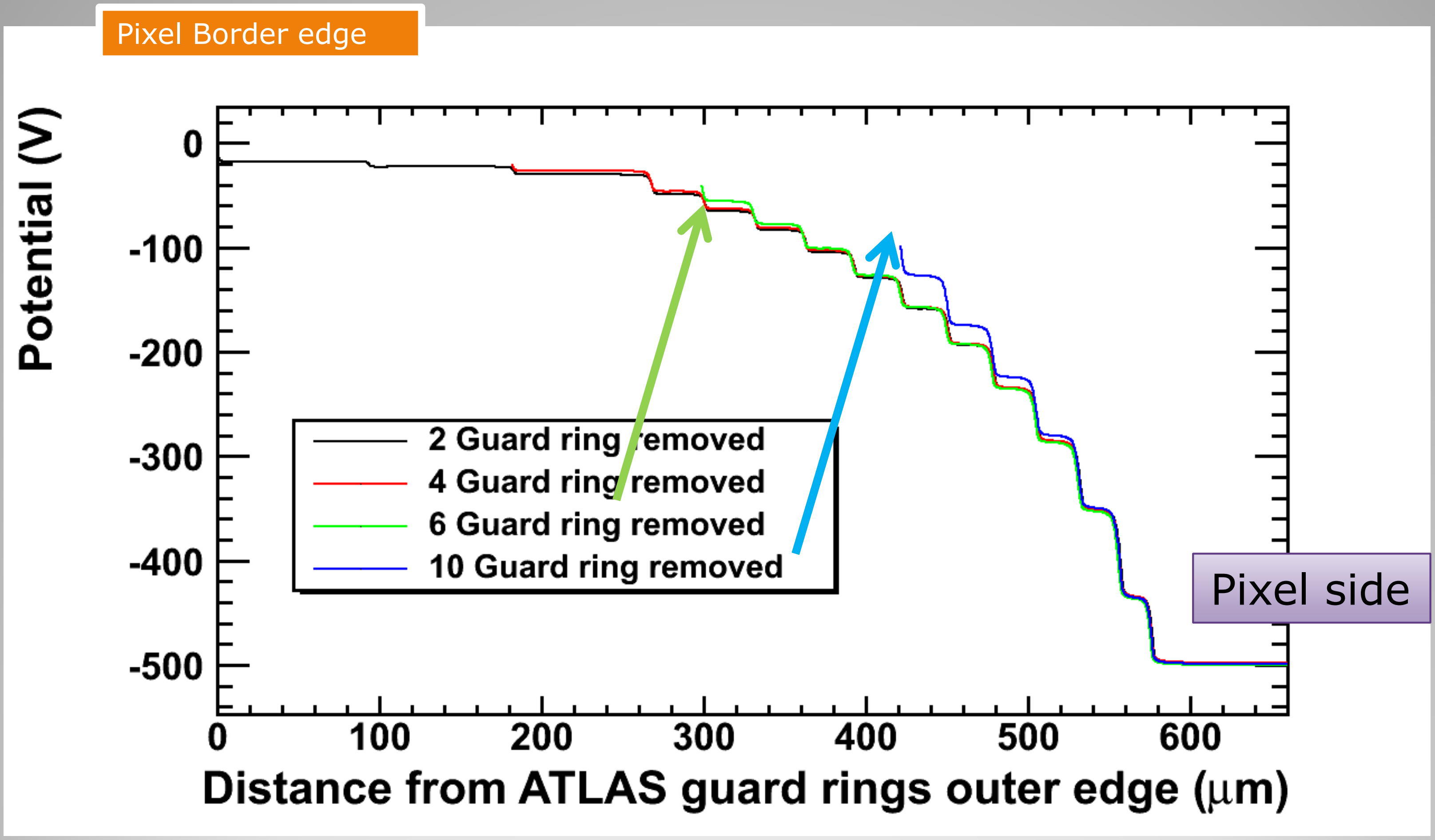




ATLAS actual pixel design
16 GR, 775 µm, n-in-n , p+ GR on backside

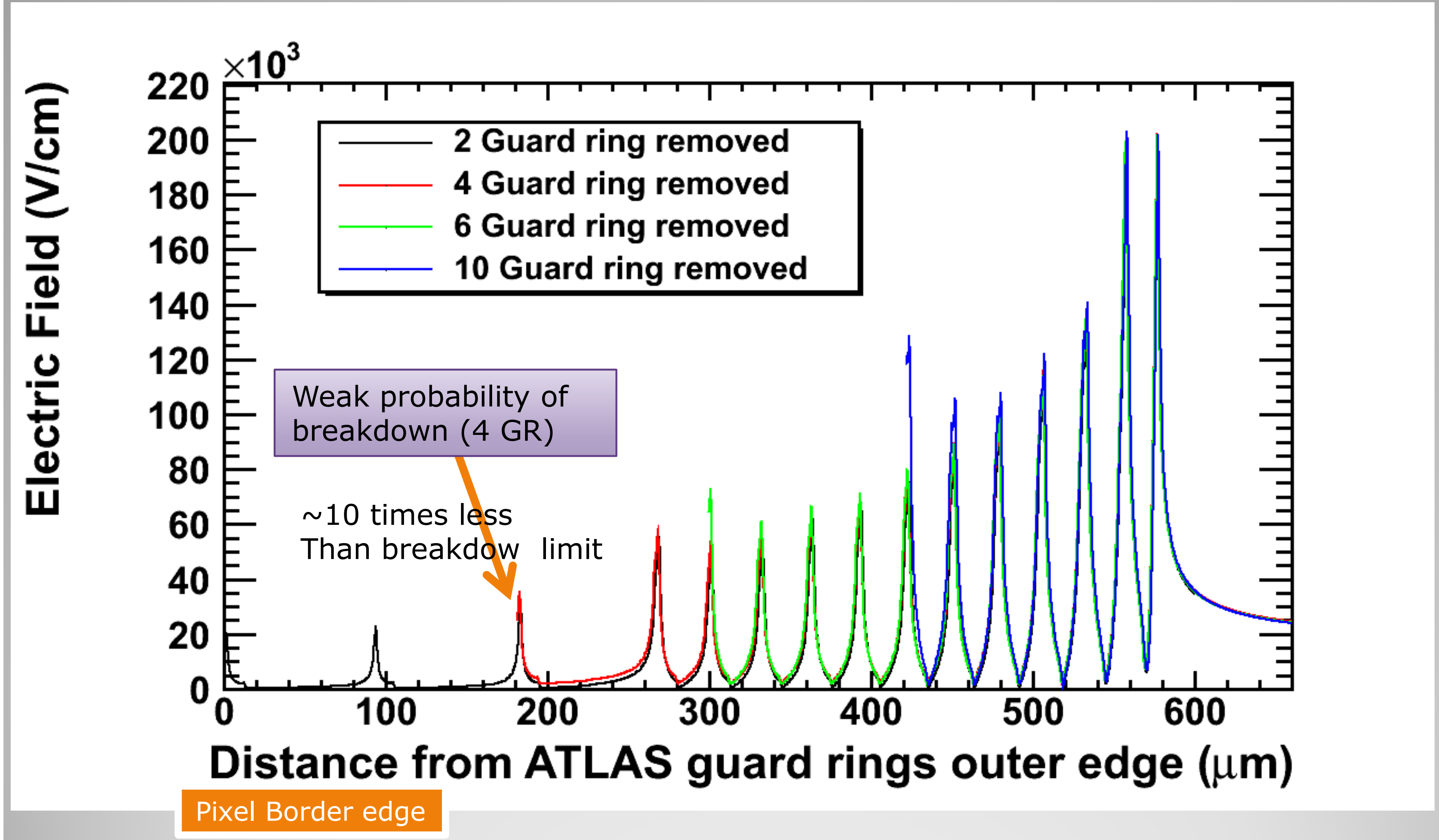
Small ring n-in-p design
17 GR, 577 µm, n+ GR on pixel side

Large ring n-in-p design
9 GR, 603 µm, n+ GR on pixel side



Reduction of the number of guard rings (ATLAS n-in-n)

Reduction of the number of guard rings (ATLAS n-in-n)

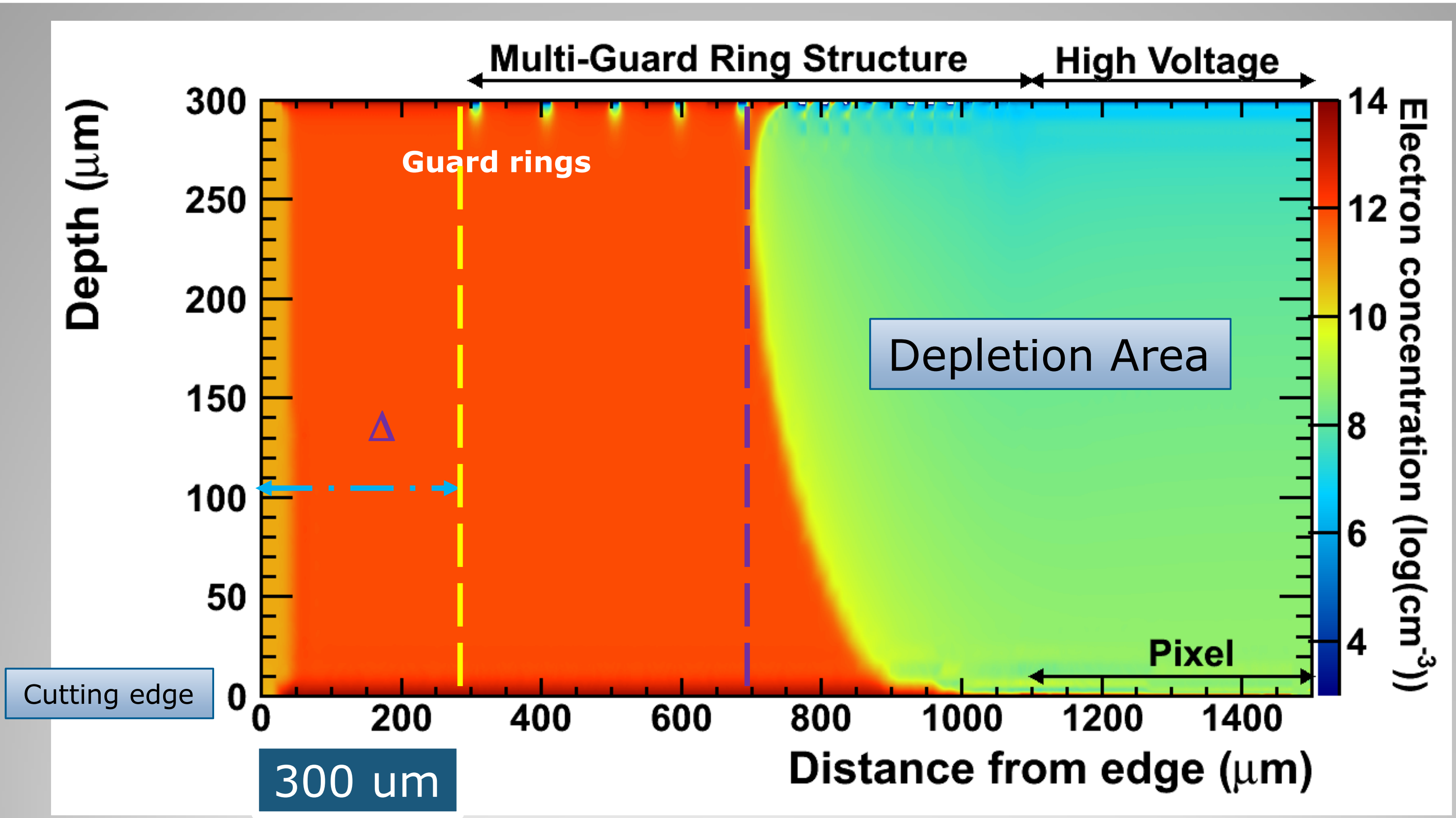


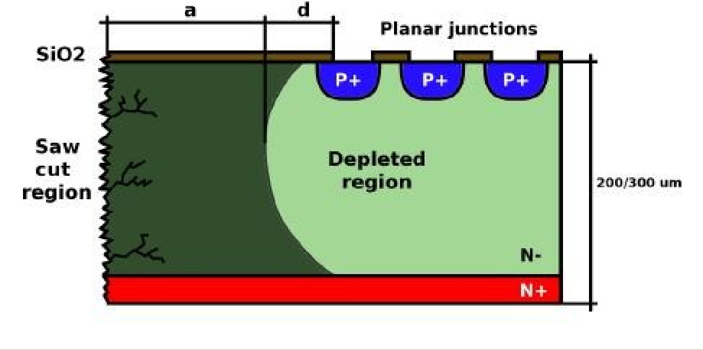
Weak probability of breakdown (4 GR)

~10 times less
Than breakdow limit

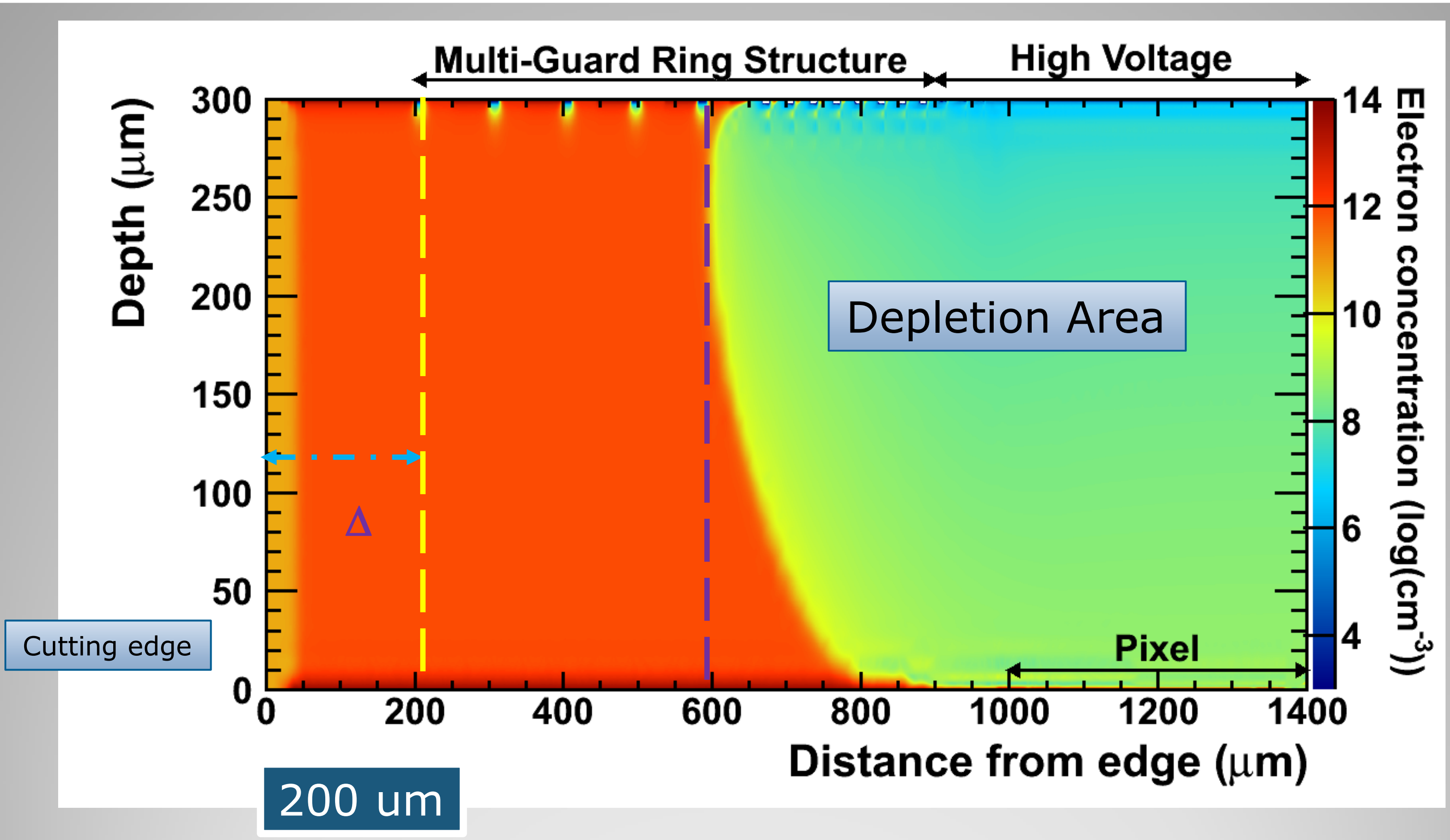
Pixel Border edge

Electric field at 0,1 um under the GR, Vbias=500 V

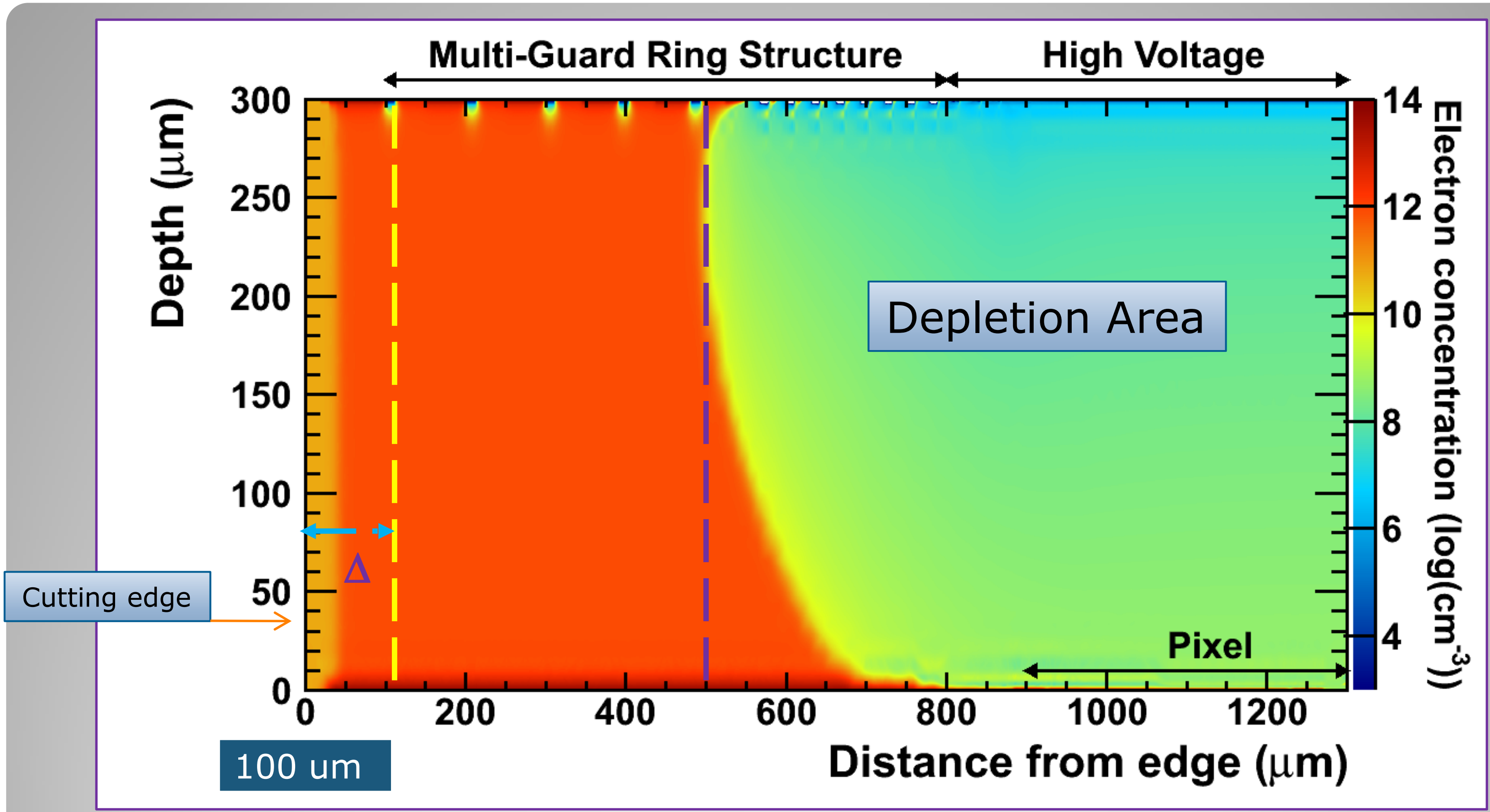




Edge width 300 um



Edge width (200 um)



Edge width (100 um)

Conclusion : Δ region could be safely reduced to 100 um

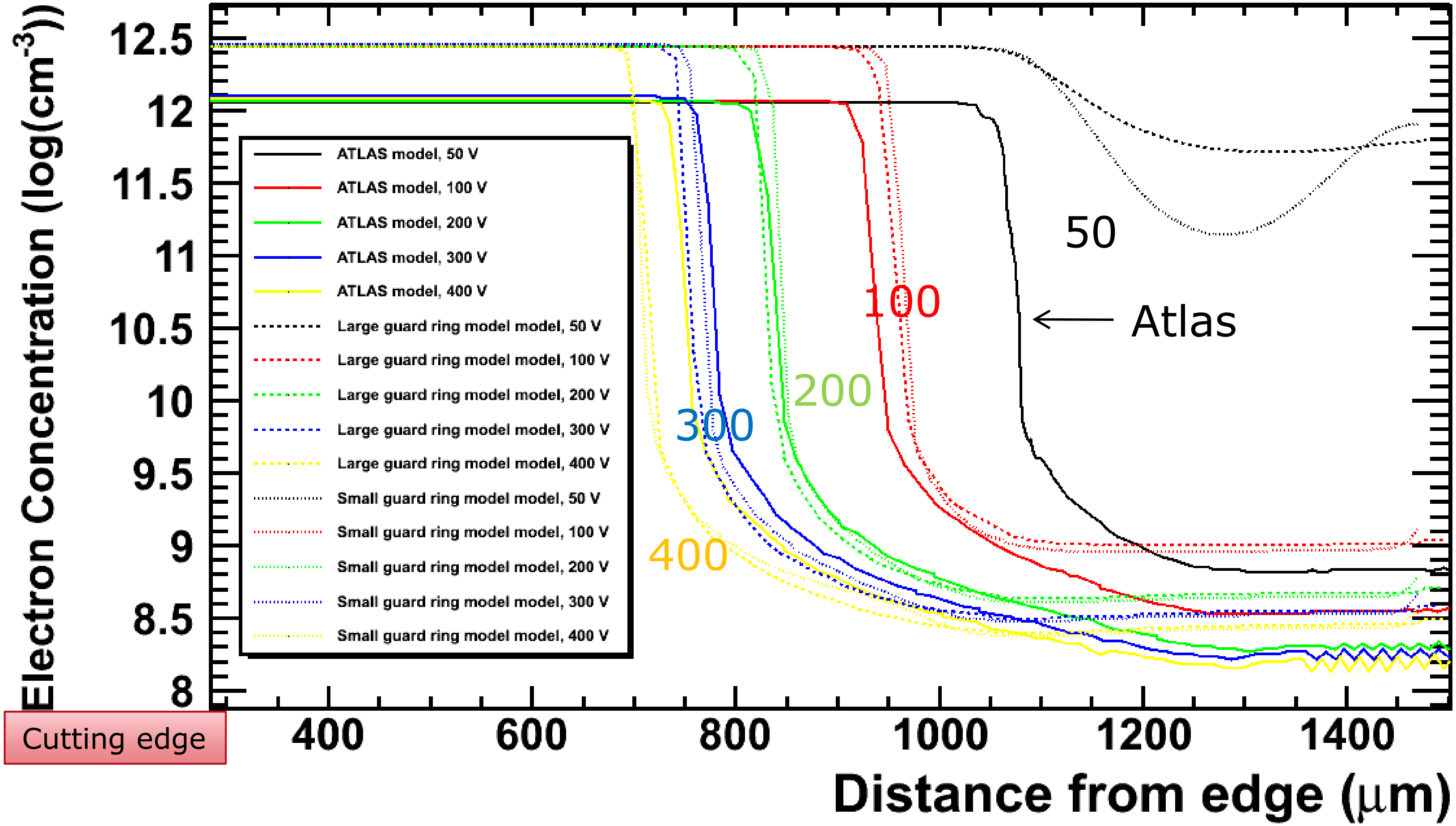
Electron concentration at half depth

(VBIAS = 50,100,200,300,400 V)

——— ATLAS LHC design, n+ on n

– – – – – – – – ATLAS Large guard Ring model, 9 GR,603 um, n+ GR on pixel side

------------- ATLAS small guard Ring model, 17 GR, 577 um, n+ GR on pixel side



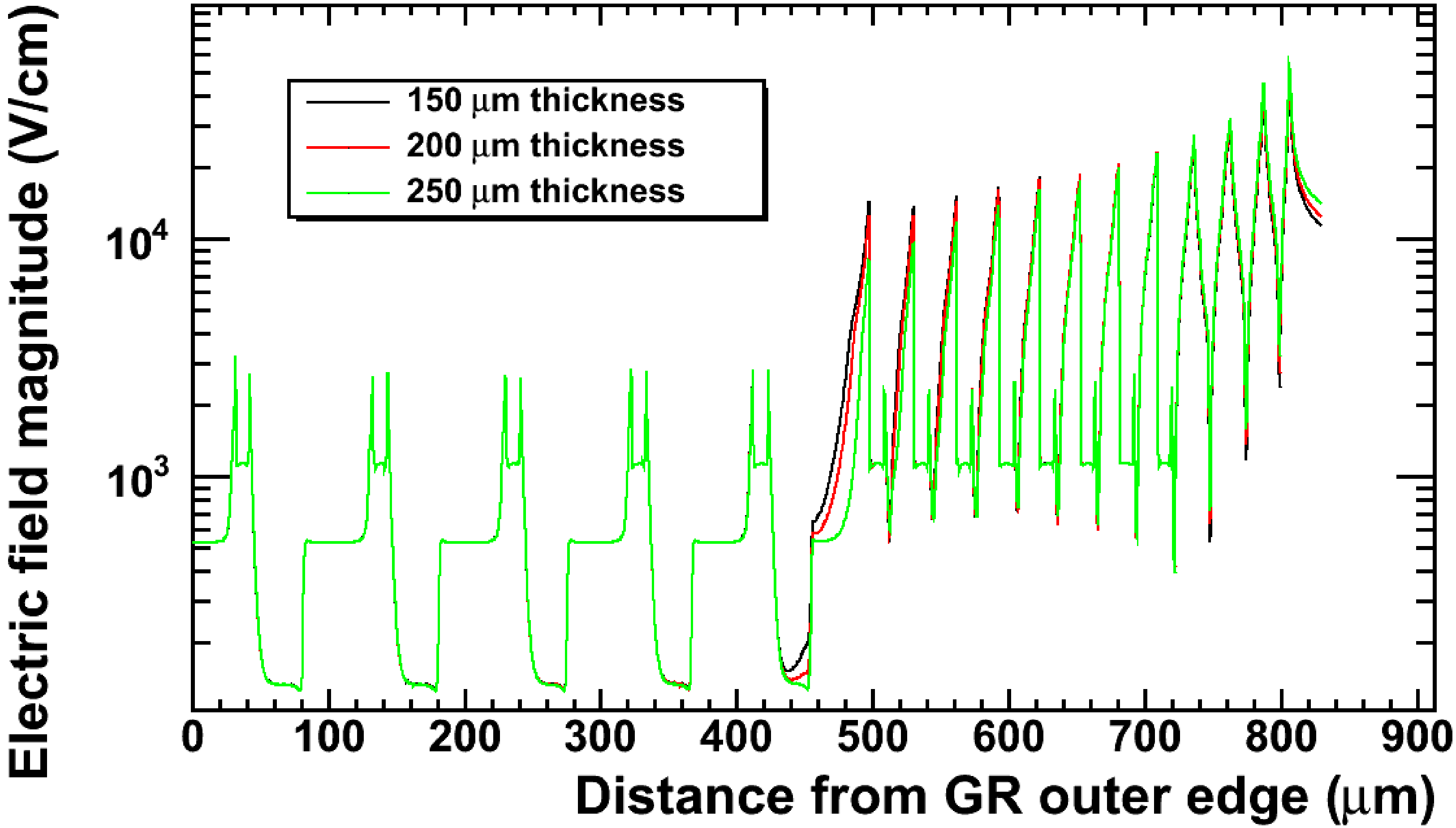
Cutting edge

Conclusion : Minor influence of GR type on lateral depletion

Sensor thinning issue

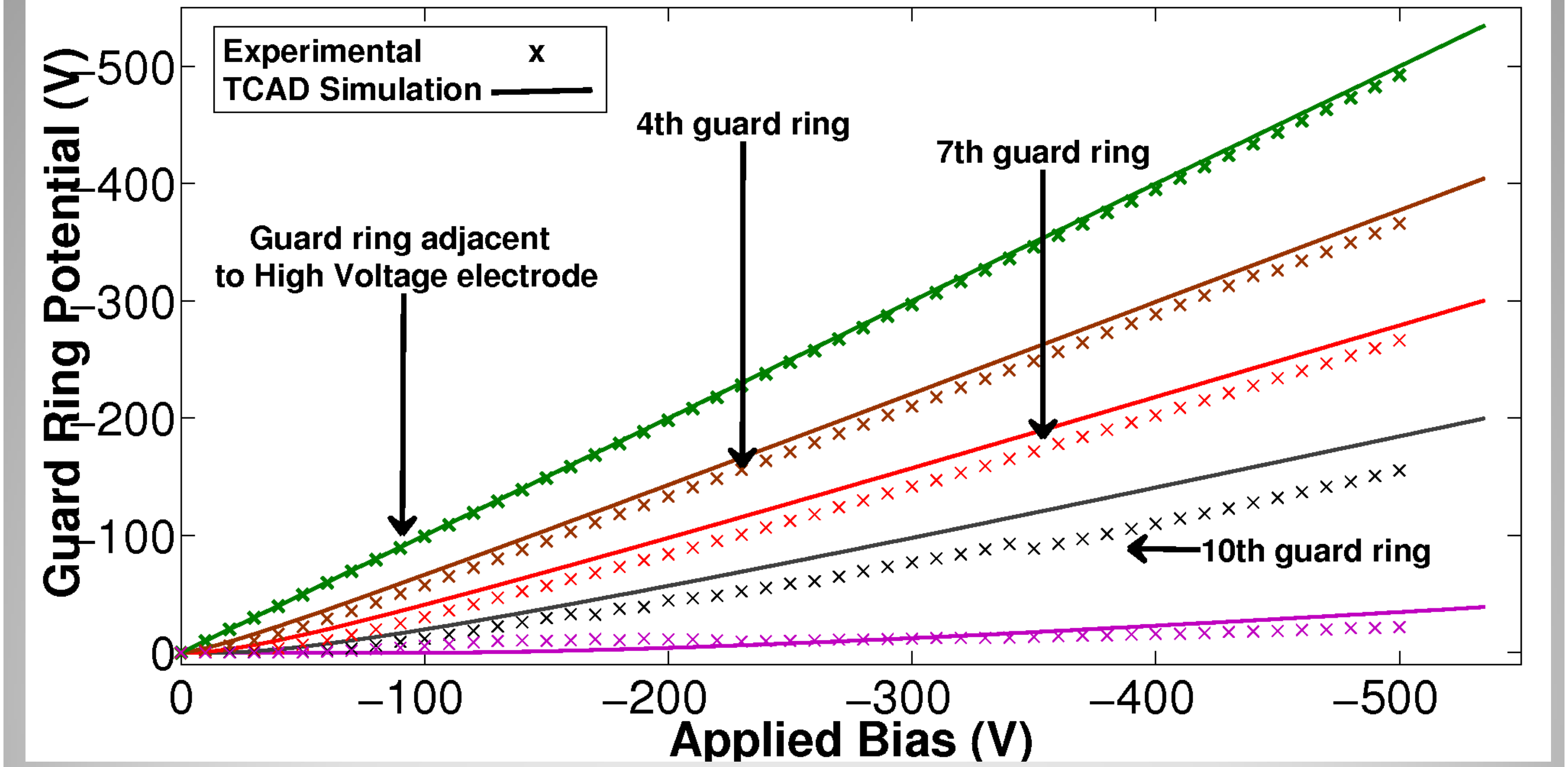
Vbias = 150 V

Electric field at 1um under the pixel



Conclusion : almost no influence on the GR electric field as function of sensor thickness “ field distribution is related to lateral depletion

GR Potential versus measurements

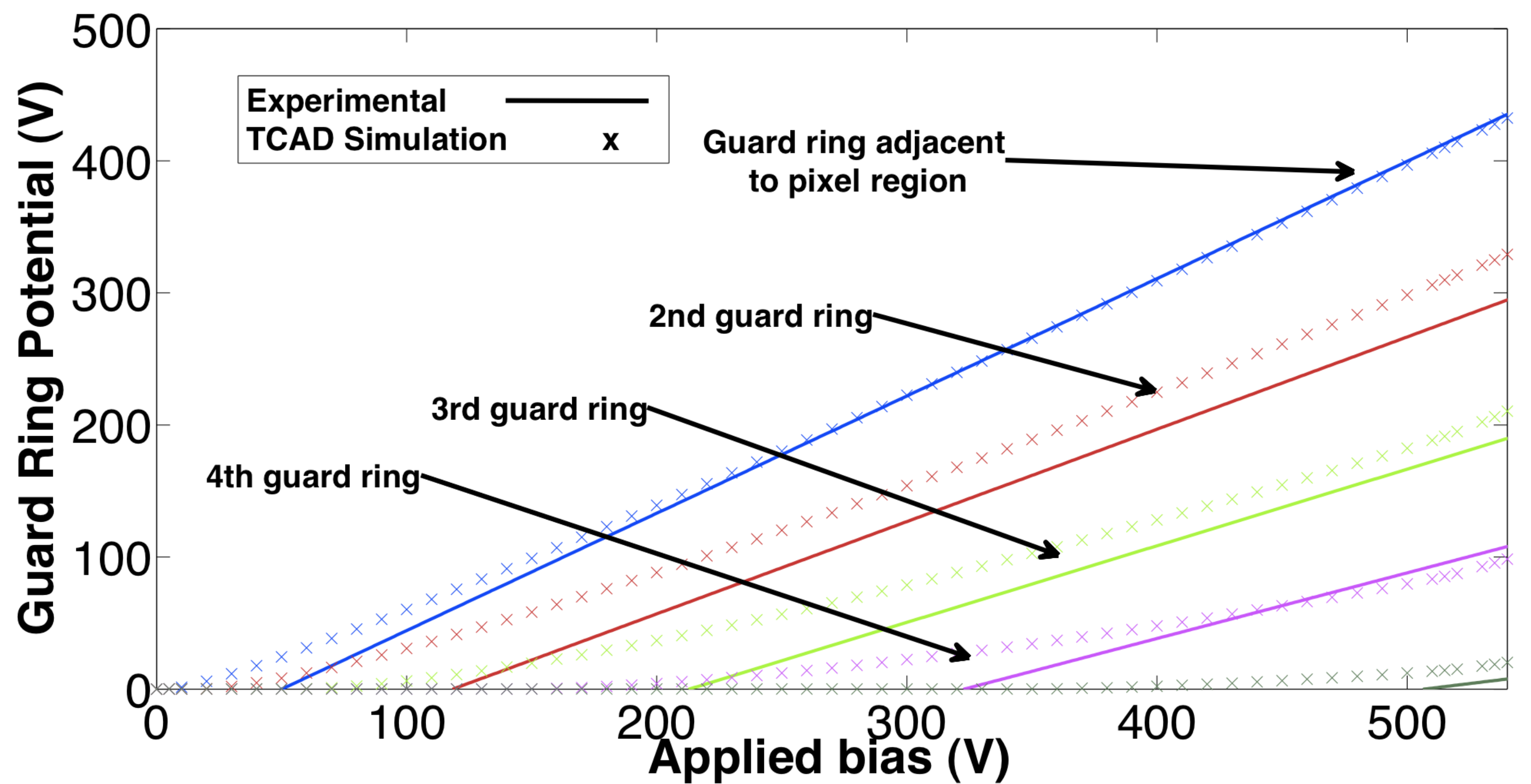


ATLAS standard structure

Measurements performed by ATLAS PPS group (U. Dortmund)

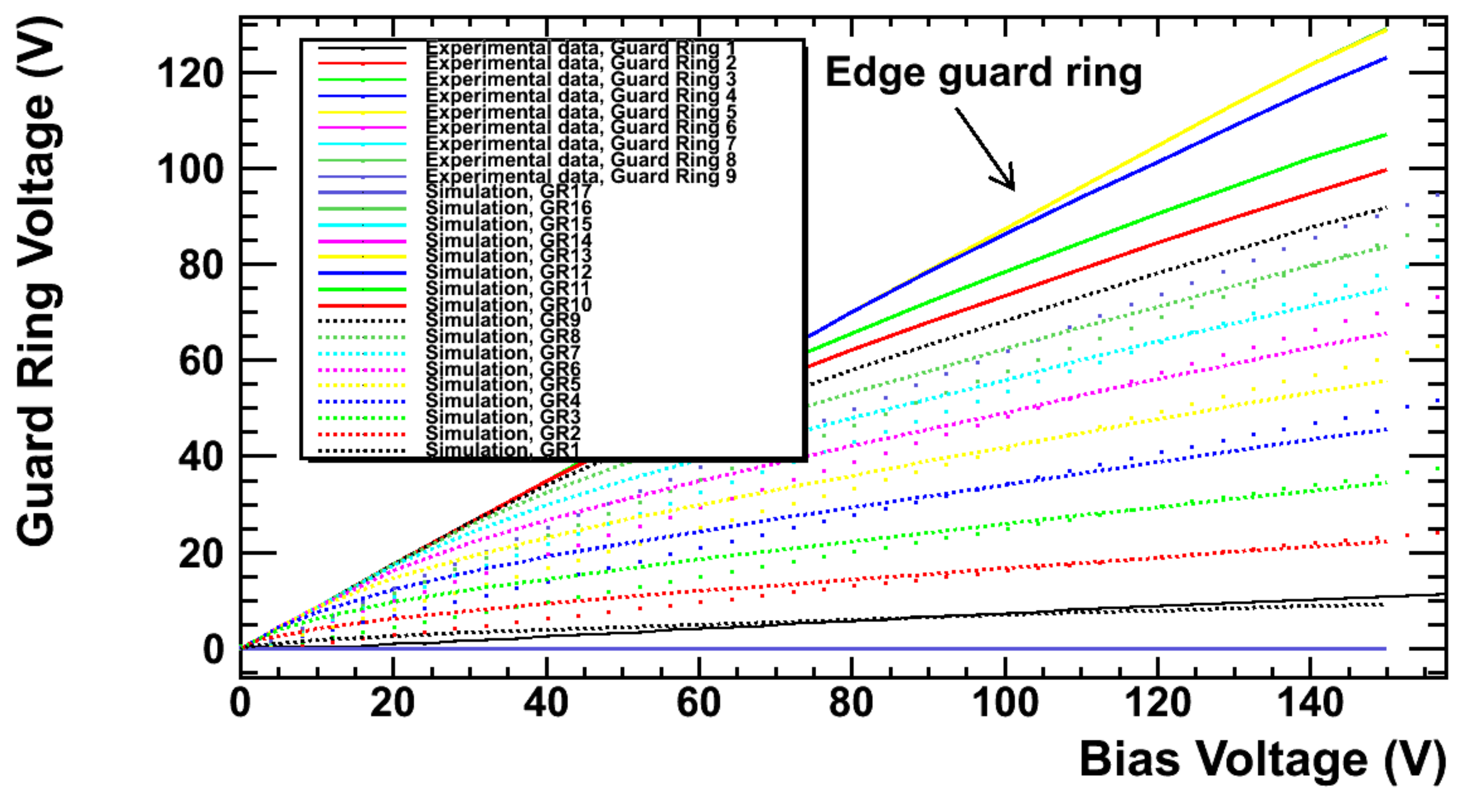
ATLAS PPS09 production

Good agreement between Experimental and TCAD



Large GR structure

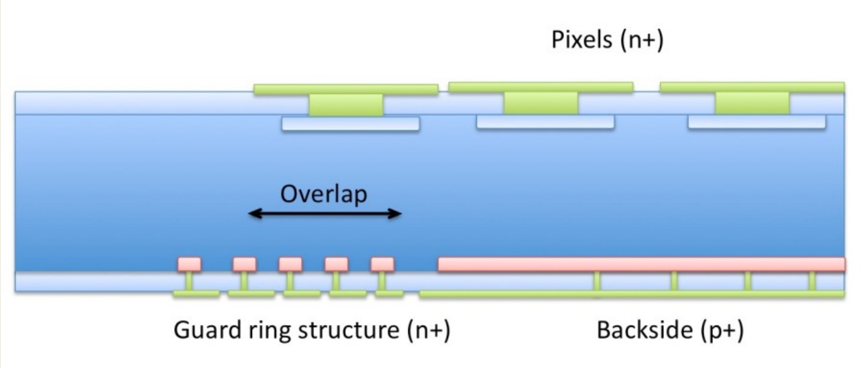
Experimental data (ATLAS PPS group)
ATLAS PPSU09 production

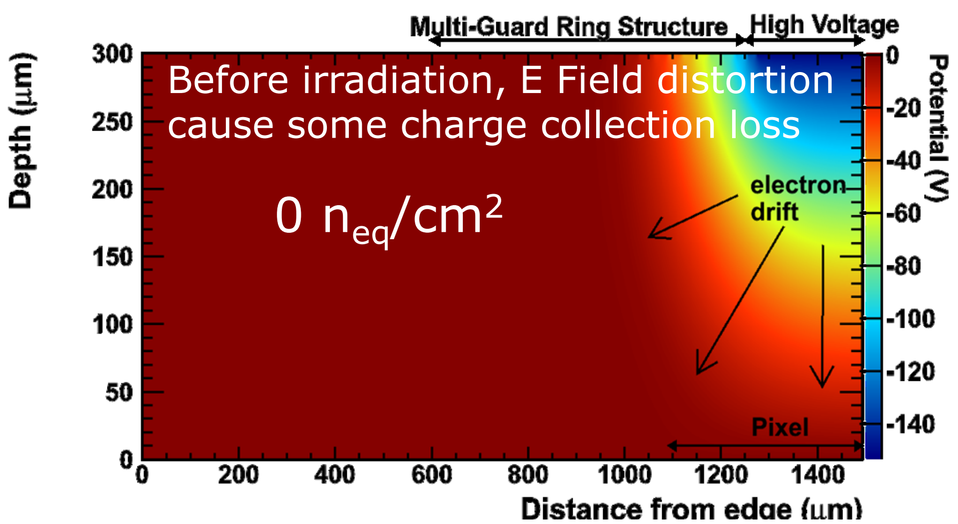


Small GR structure

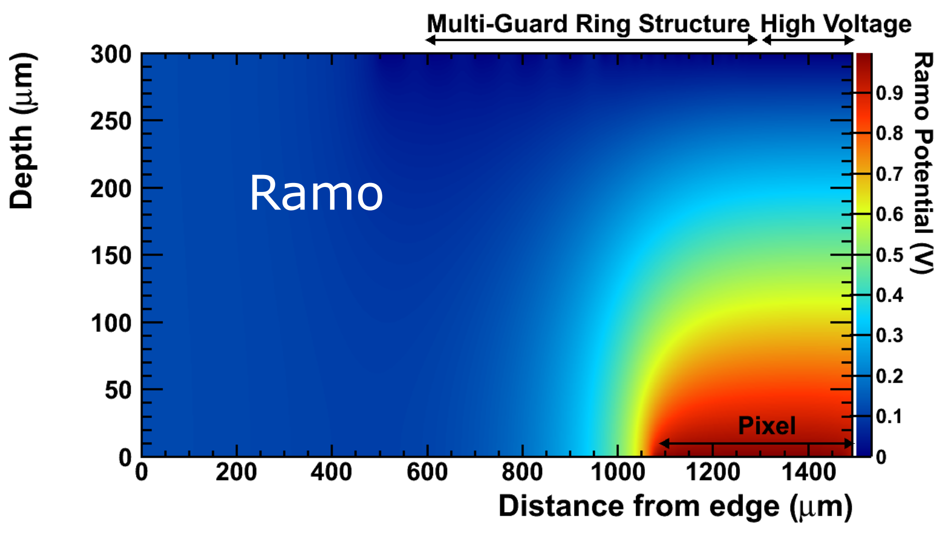
ATLAS PPSU09 production

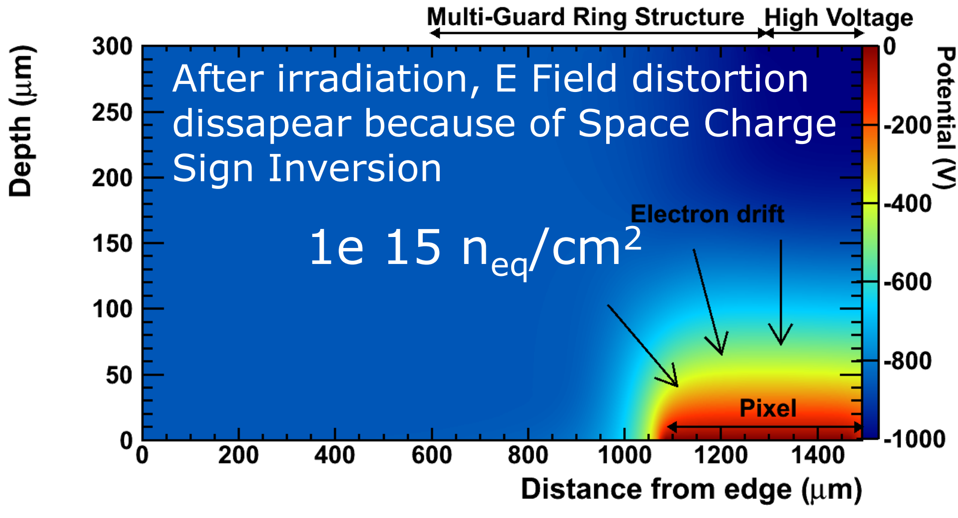
Slim edge structure



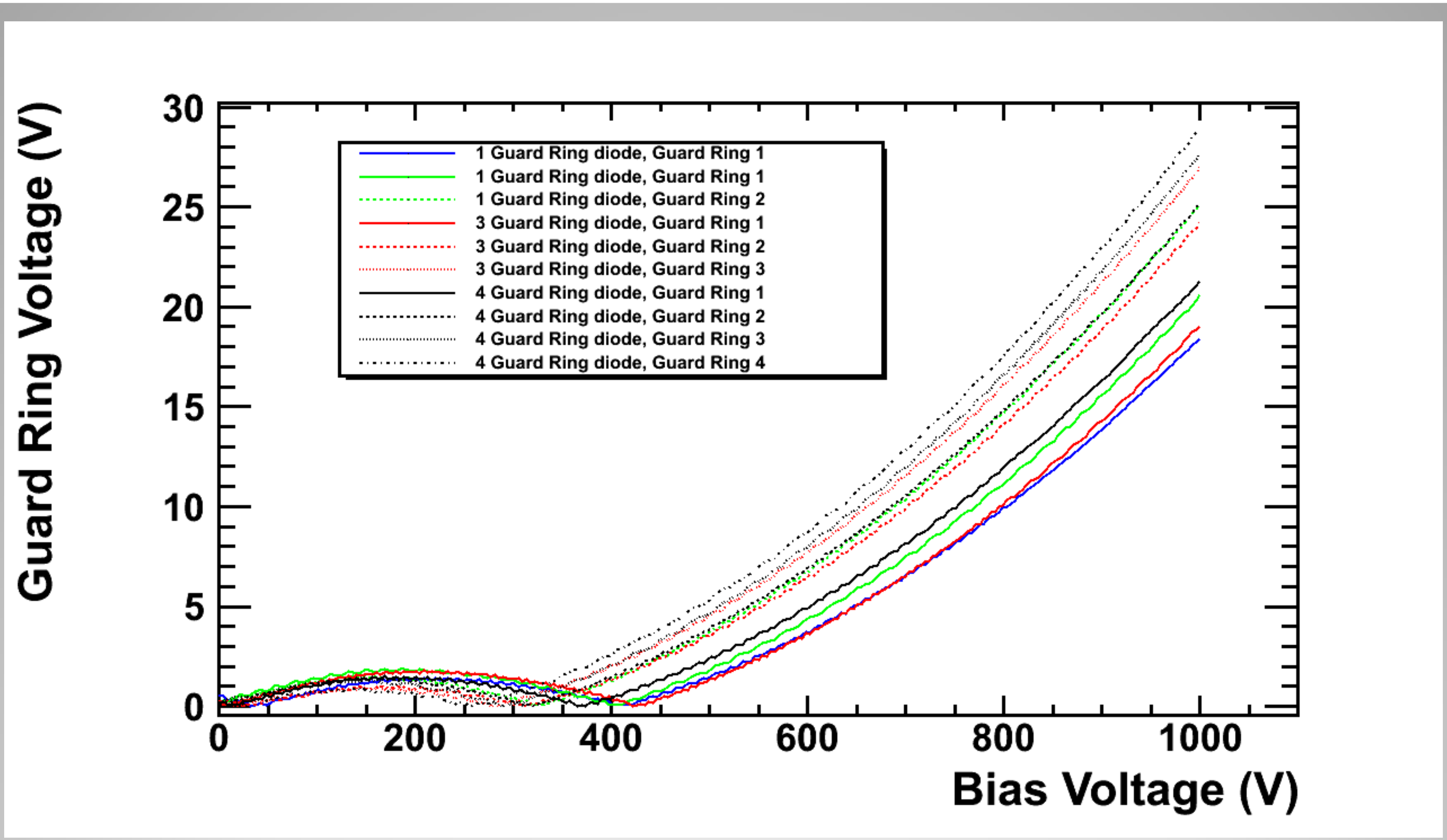

Before irradiation, E Field distortion cause some charge collection loss

$0\ n_{eq}/cm^2$




After irradiation, E Field distortion dissapear because of Space Charge Sign Inversion

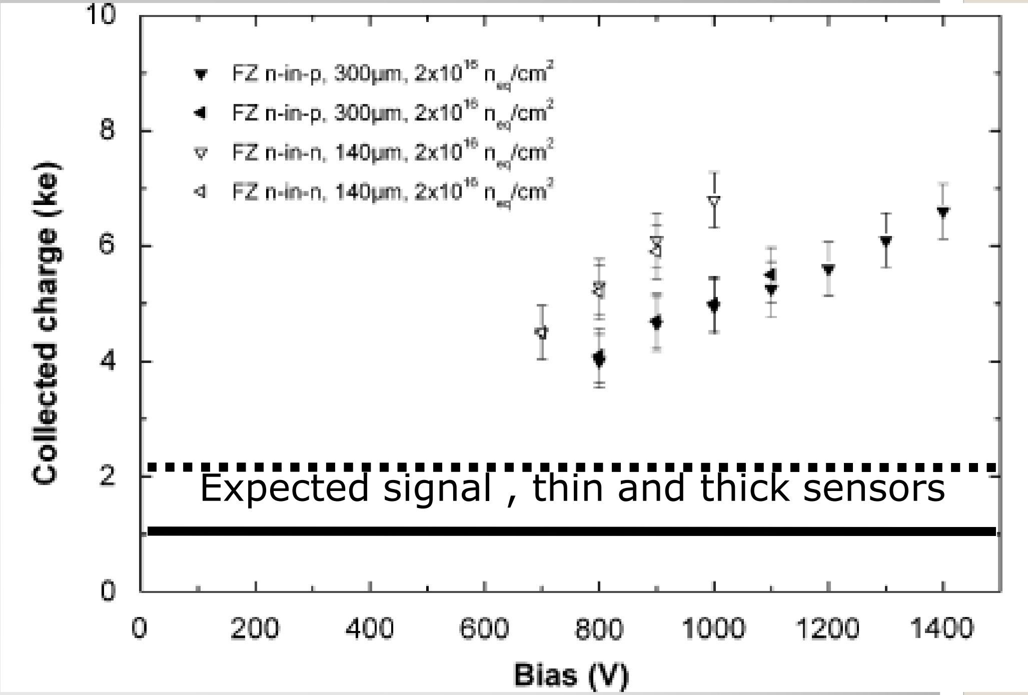
$1e\ 15\ n_{eq}/cm^2$



n-in-n irradiated 2.5e15 neq

Charge multiplication in silicon planar sensors

- Recent measurements performed on diode irradiated to sLHC fluence show anomalous charge collection that cannot be explained in terms of our present knowledge of irradiated sensors
- Use the radiation damage model in TCAD and include the impact ionization and trap-to-band tunnelling into the simulation to see if these physical effects can reproduce the observed behavior

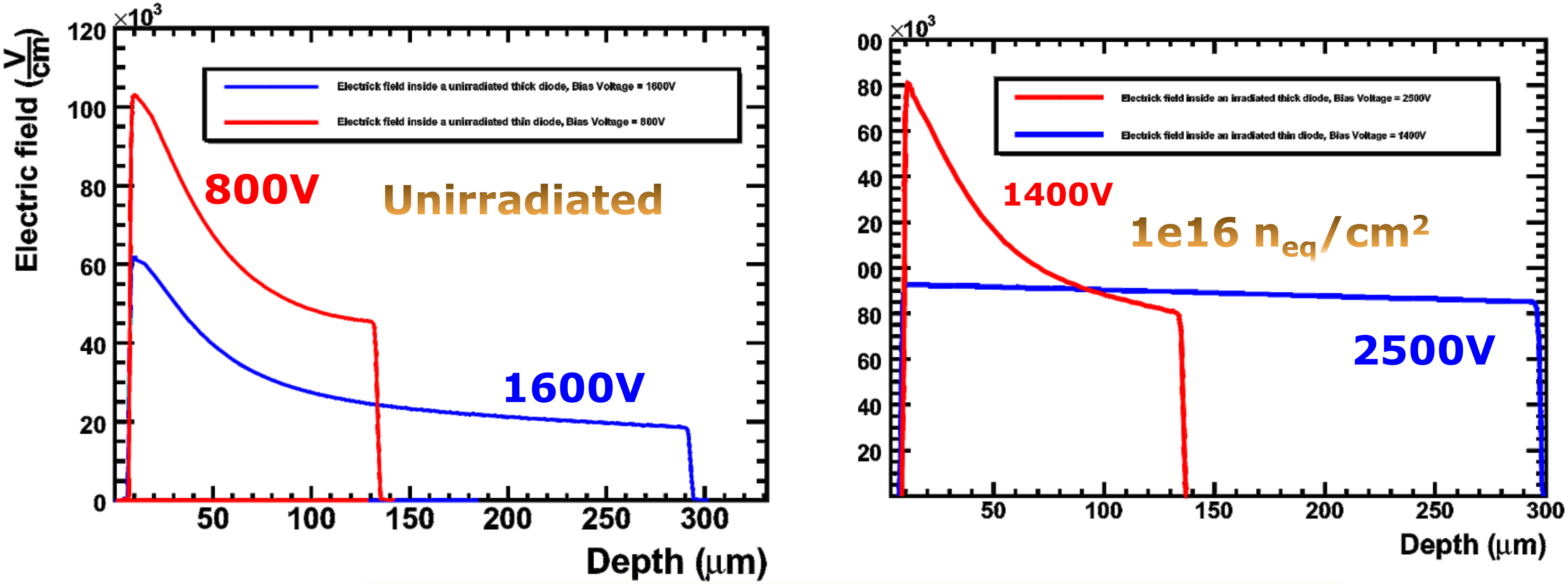


G. Casse and al., “Evidence of enhanced signal response at high bias voltages in pla- nar silicon detectors irradiated up to 2.2x10e16 neq cm-2,” Nucl. Instrum. Meth. A , j.nima.2010.04.085,, vol. In Press, Corrected Proof, pp. –, 2010.

M. Mikuz, V. Cindro, G. Kramberger, I. Mandic, and M. Zavrtanik, “Study of anoma- lous charge collection efficiency in heavily irradiated silicon strip detectors,–,j.nima, 2010.

Electric field profiles

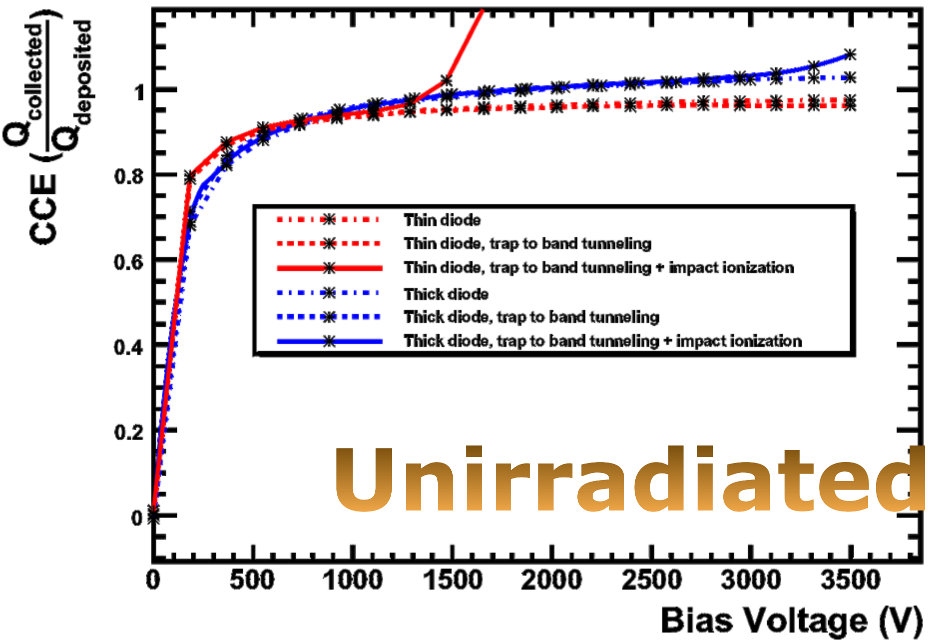
Sensor can be biased to HV after irradiation without reaching hard breakdown allowing multiplication in the high electric field produced by this bias

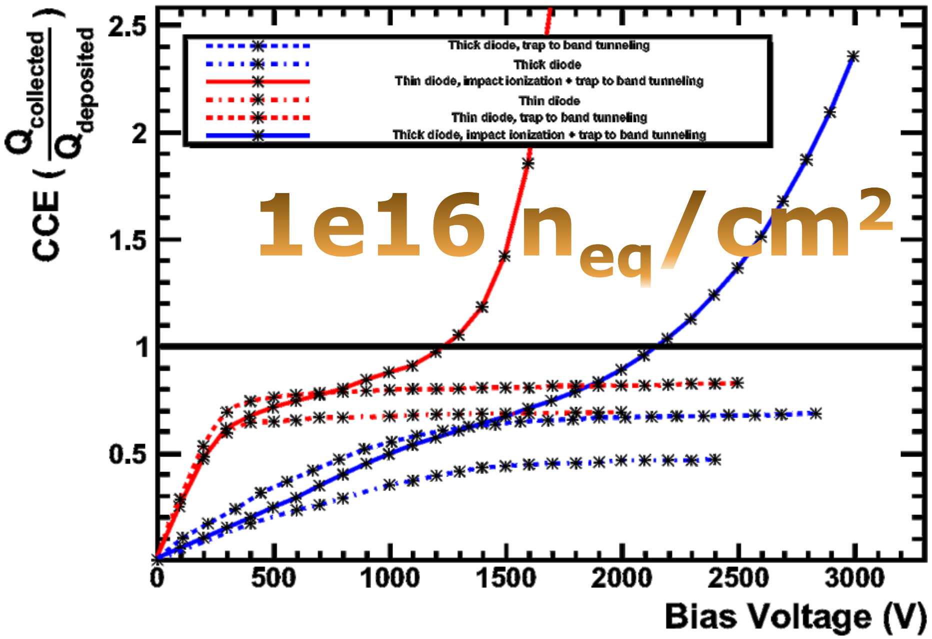


Electric field before hard junction breakdown.

Charge collection efficiency

Unirradiated diode see not much difference if TTBT and II are off. However, they both contribute to CCE after irradiation because of the presence of the > 200kV/cm field





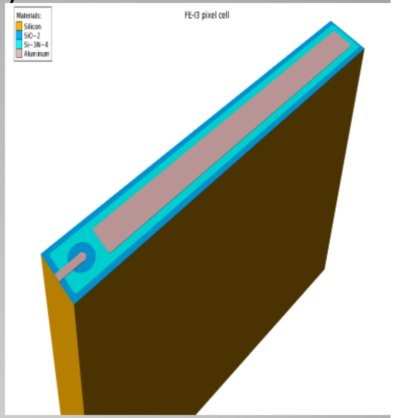
Summary

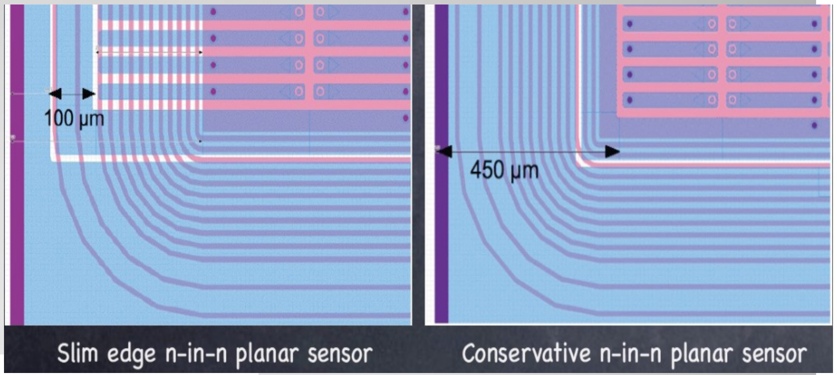
- TCAD offers a good tool to optimize geometrical parameters of the sensors (GR reduction, minimize dead region)
- It offers the opportunity to find a physical explanation or interpretation of charge collection amplification of heavily irradiated sensors
- Could have a transcient simulation of the device (luminous) and calculate charge deposition by ionization
- Give a mean to exploit new ideas (edgless)
- Knowing the process is the ultimate goal to make good quantitative simulation

  - SIMS , AFM methods,
- More could be done! :
  - 3D simulator
  - (under evaluation)
  - Complex structures
  - interpixel zones

  punchtrough, etc..

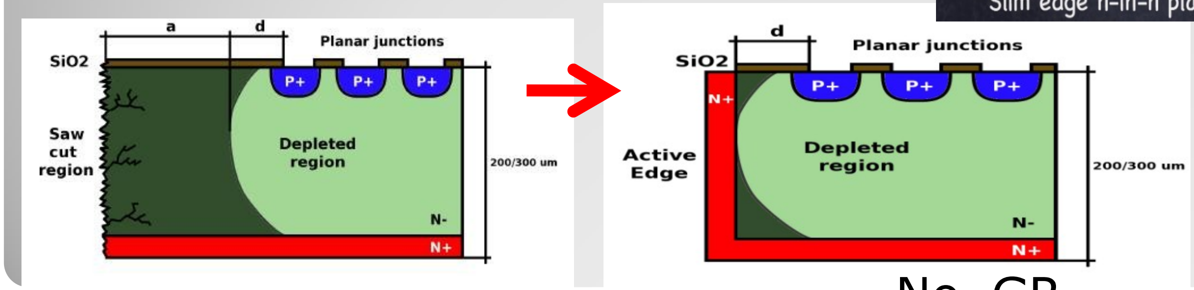
  Innovate !!



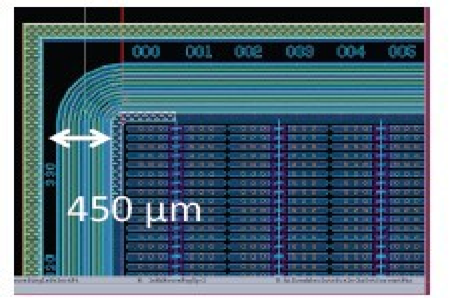


Slim edge n-in-n planar sensor

Conservative n-in-n planar sensor

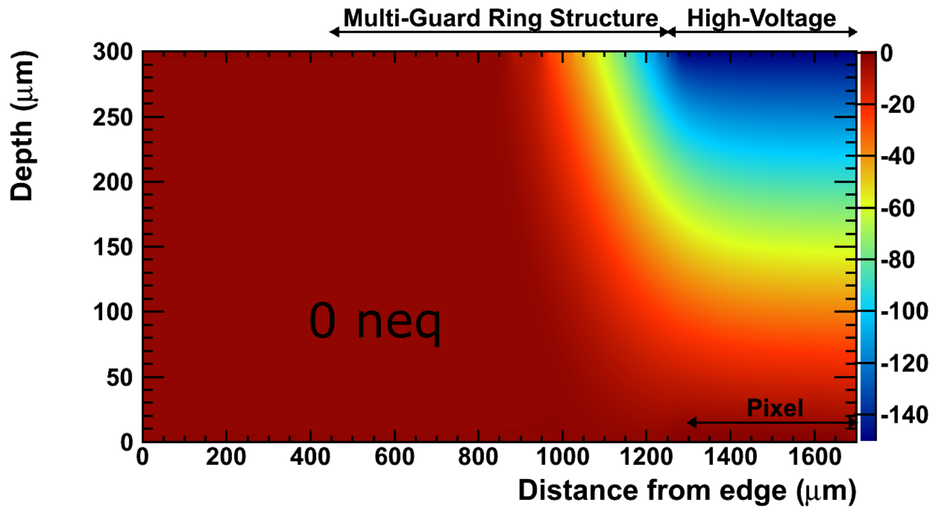


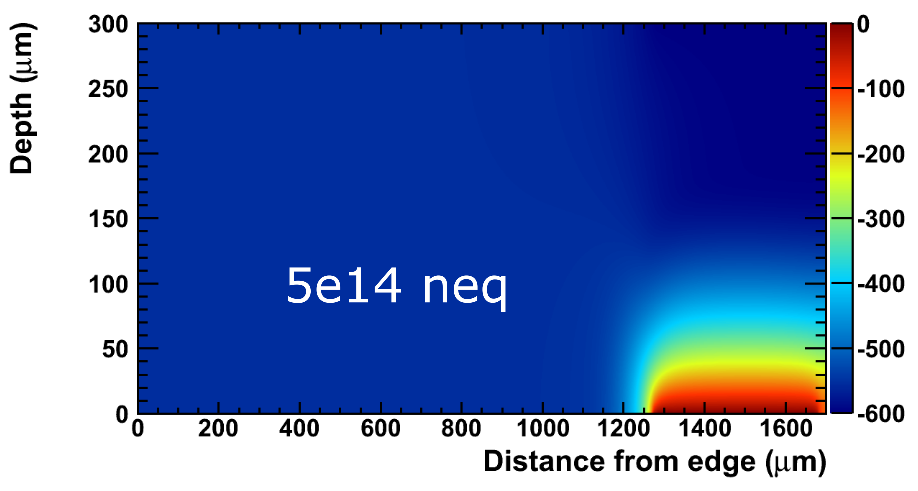
No GR

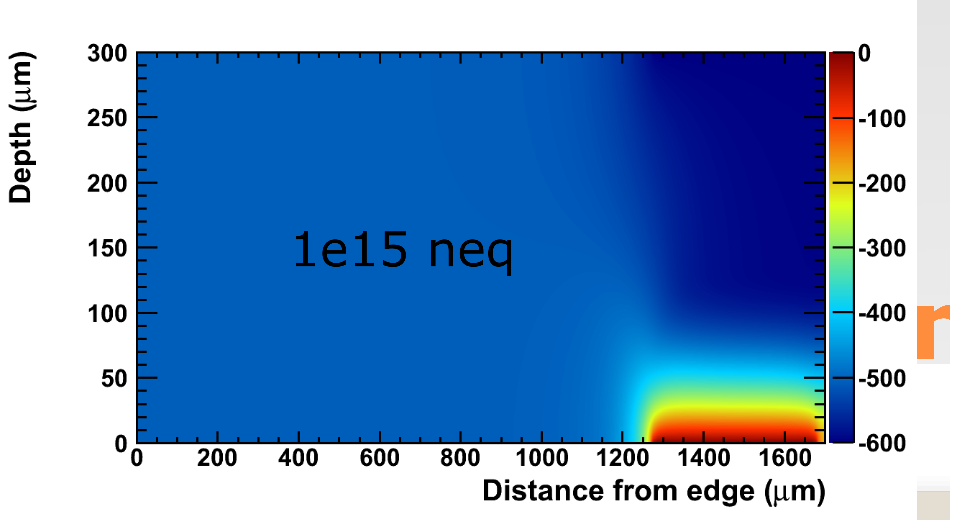


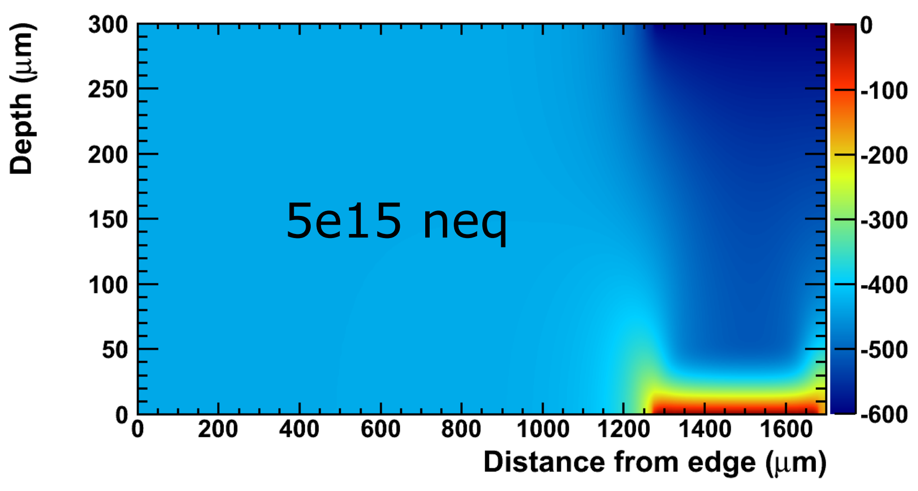
n-in-p

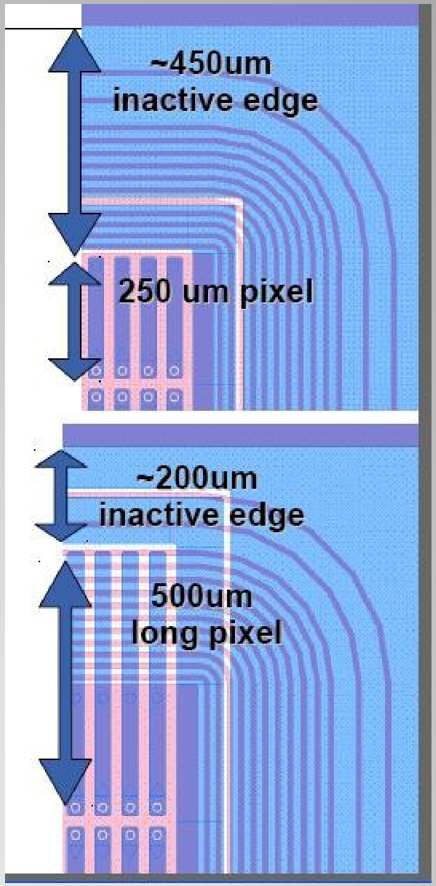
Thank you

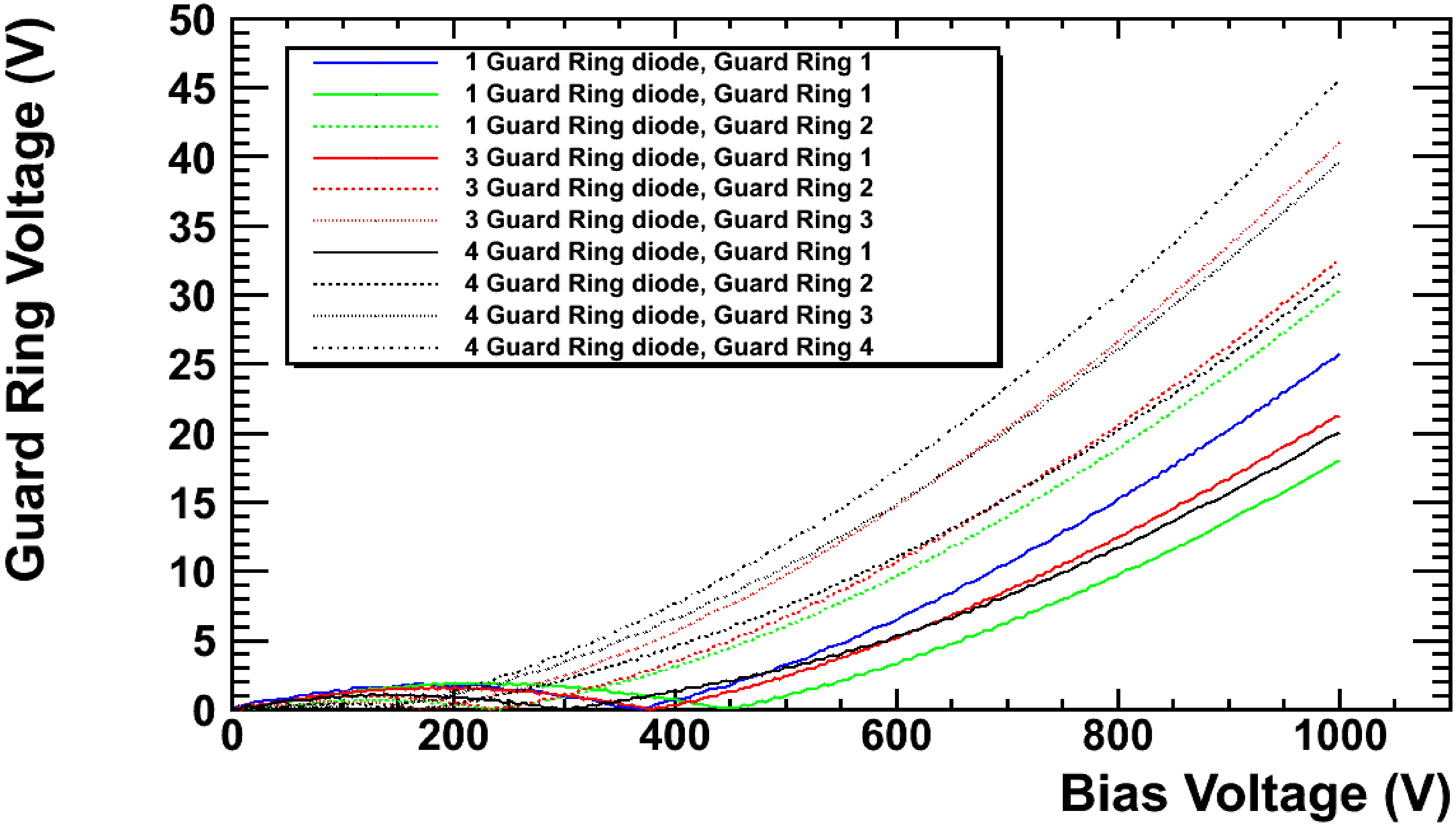

Multi-Guard Ring Structure
High-Voltage
Depth (μm)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Distance from edge (μm)
0 neq
Pixel
0
-20
-40
-60
-80
-100
-120
-140

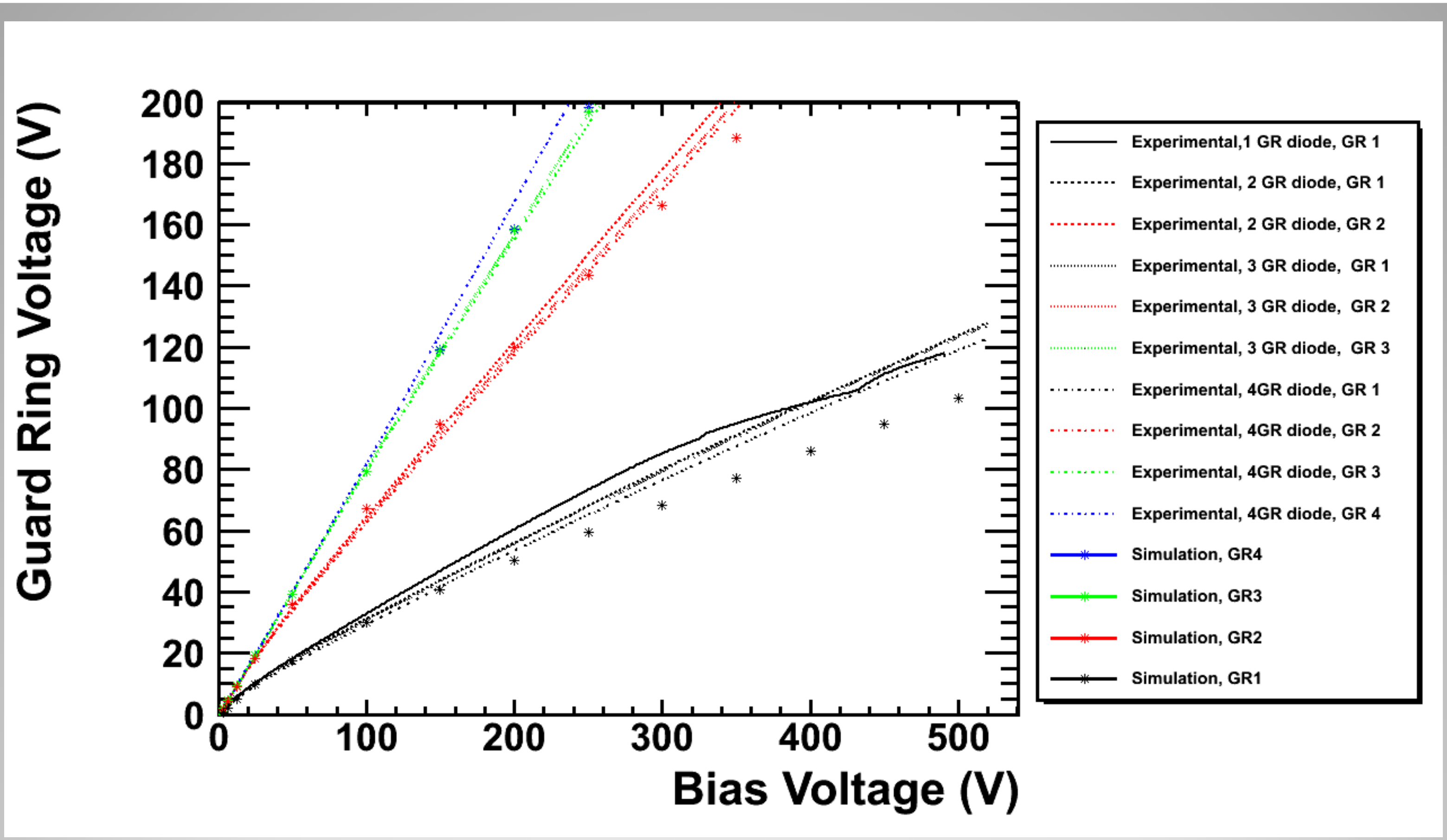

Depth (μm)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Distance from edge (μm)
5e14 neq
0
-100
-200
-300
-400
-500
-600


Depth (μm)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Distance from edge (μm)
1e15 neq
0
-100
-200
-300
-400
-500
-600


Depth (μm)
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
Distance from edge (μm)
5e15 neq
0
-100
-200
-300
-400
-500
-600


~450um
inactive edge
250 um pixel
~200um
inactive edge
500um
long pixel


Guard Ring Voltage (V)
50
45
40
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
Bias Voltage (V)
1 Guard Ring diode, Guard Ring 1
1 Guard Ring diode, Guard Ring 1
1 Guard Ring diode, Guard Ring 2
3 Guard Ring diode, Guard Ring 1
3 Guard Ring diode, Guard Ring 2
3 Guard Ring diode, Guard Ring 3
4 Guard Ring diode, Guard Ring 1
4 Guard Ring diode, Guard Ring 2
4 Guard Ring diode, Guard Ring 3
4 Guard Ring diode, Guard Ring 4



LAL Diodes before and After Irradiation (n-in-p here)

- Transient behaviour of traps

Generation/Recombination

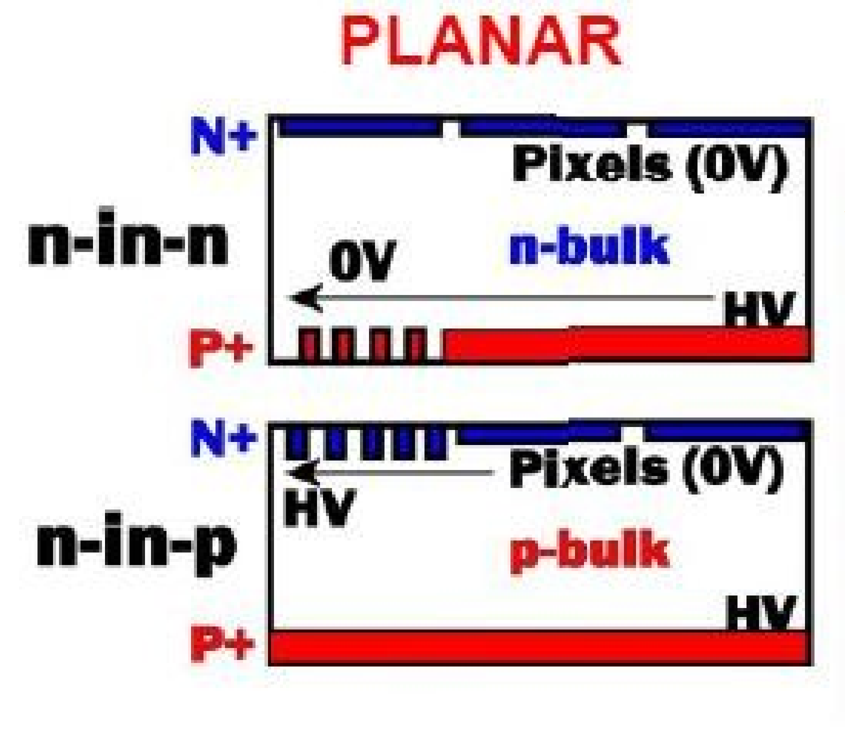
$$\frac{dN_{tD}^{+}}{dt}=\rho_t\left\{\overbrace{v_p\sigma_p(p(1-F_{tD})}^{\text{hole capture}}-\overbrace{F_{tD}n_i\Gamma e^{E_i-E_t/kT})}^{\text{hole emmission}}-v_n\sigma_n(\overbrace{nF_{tD}}^{\text{electron capture}}-\overbrace{\frac{(1-F_{tD})n_i}{\Gamma}e^{E_t-E_i/kT})}^{\text{electron emmission}}\right\}$$

$$\frac{dN_{tA}^{-}}{dt}=\rho_t\left\{\underbrace{v_n\sigma_n(n(1-F_{tA})}_{\text{Electron capture}}-\underbrace{F_{tA}n_i\Gamma e^{E_t-E_i/kT})}_{\text{Electron emmission}}-v_p\sigma_p(\underbrace{pF_{tA}}_{\text{Hole capture}}-\underbrace{\frac{(1-F_{tA})n_i}{\Gamma}e^{E_i-E_t/kT})}_{\text{Hole emmission}}\right\}$$

$$\sigma_{n,p}=\frac{1}{\rho_{trap}\tau_{n,p}v_{n,p}}$$

$\sigma_{n,p}$	is trap capture cross-section
$\nu_{n,p}$	is thermal velocity
n_i	is intrinsic concentration
$F_{tA,TD}$	the probability of ionization
$N_{tA,TD}$	space charge density

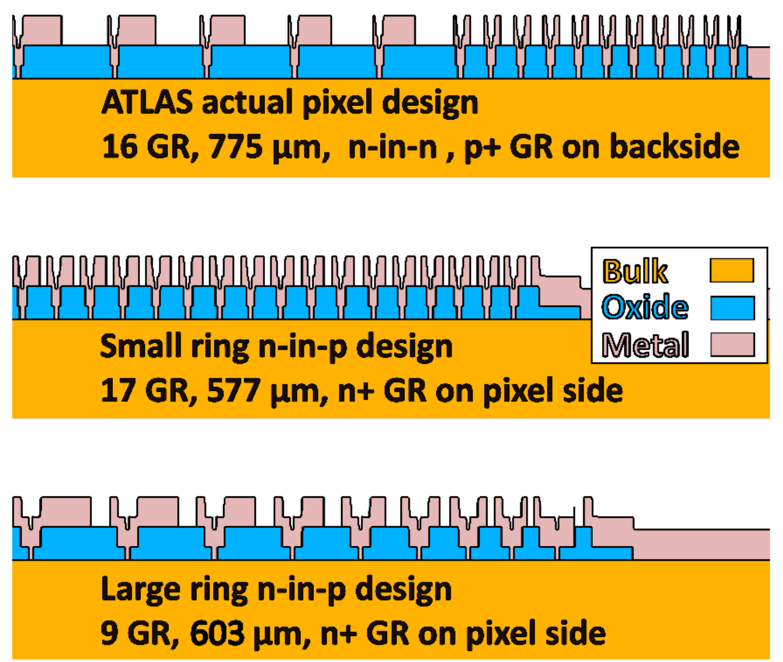
- Planar pixel sensors:



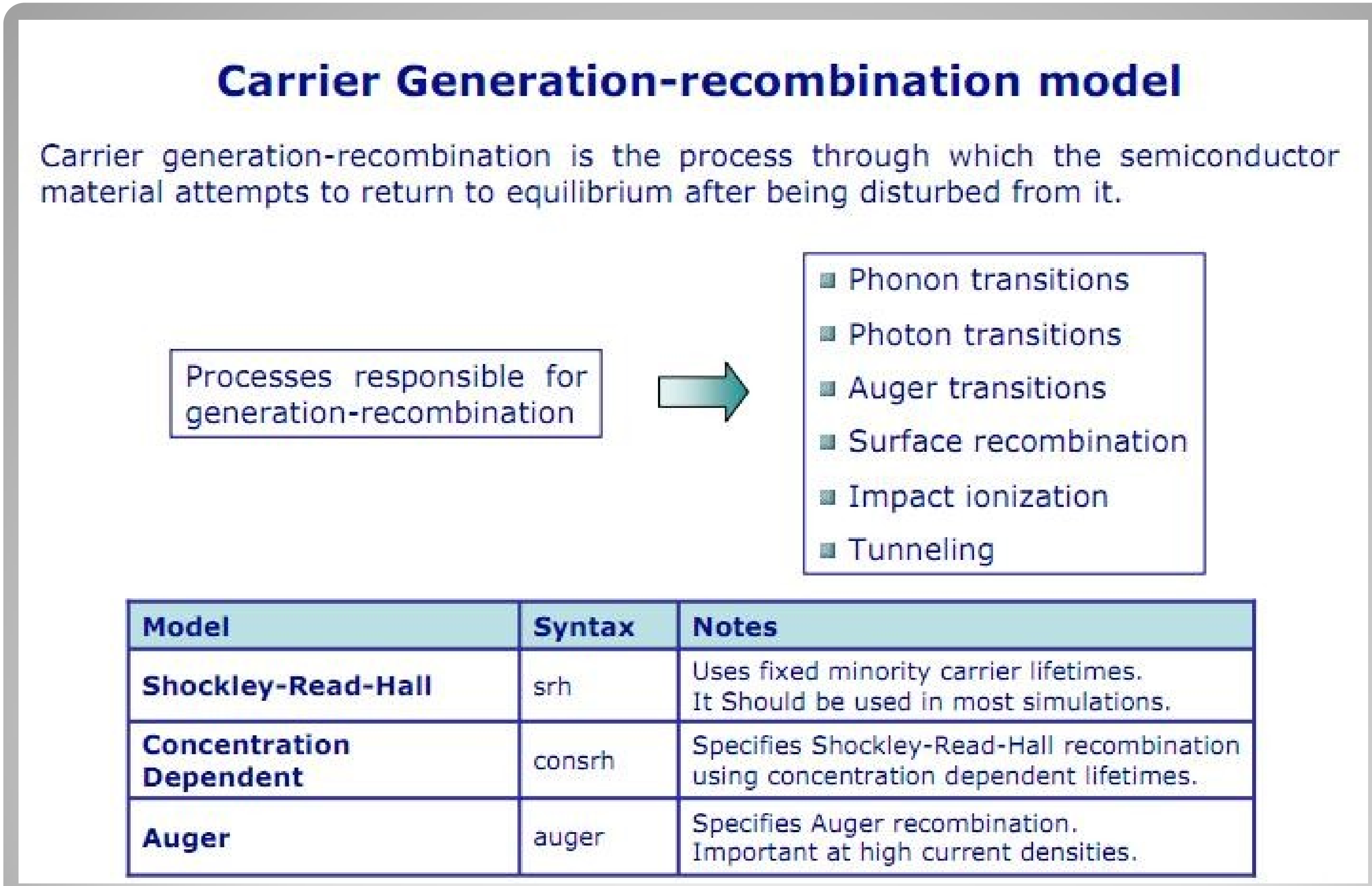
N-in-N pixel structure

n-in-n Pixel : GR on Backside

N-in-P pixel: GR on pixel side



Guard ring structure



Carrier Generation-recombination model

Carrier generation-recombination is the process through which the semiconductor material attempts to return to equilibrium after being disturbed from it.

Processes responsible for generation-recombination

- Phonon transitions
- Photon transitions
- Auger transitions
- Surface recombination
- Impact ionization
- Tunneling

Model	**Syntax**	**Notes**
Shockley-Read-Hall	srh	Uses fixed minority carrier lifetimes. It Should be used in most simulations.
Concentration Dependent	consrh	Specifies Shockley-Read-Hall recombination using concentration dependent lifetimes.
Auger	auger	Specifies Auger recombination. Important at high current densities.

TCAD using Silvaco^{TM} tools