Optimization of Silicon Pixel Sensors for the high X-ray Doses of the European XFEL

Jörn Schwandt*

Institute for Experimental Physics
University of Hamburg

Outline:
- Introduction
- Radiation damage measurements and results
- TCAD simulations for the AGIPD sensor
- Summary

* work of the Detector Lab.

Introduction

European XFEL Requirements (for imaging Si-pixel detectors):

1. Integrated 12 keV photon flux up to 10^{16} cm^{-2} (1 GGy SiO_2) for 3 years of operation

→ No bulk damage is expected (threshold 300 keV), but

- Surface damages (buildup of oxide-trapped charges and Si-SiO_2 interface traps)

  → change of electric field distribution (device stability), charge collection
  → increase of dark current → noise + impact on read-out electronics

2. Instantaneous (less than 100 fs) 12 keV photon flux up to 10^5/pixel

→ plasma effects → high operational voltage needed → high breakdown voltage

Aims:

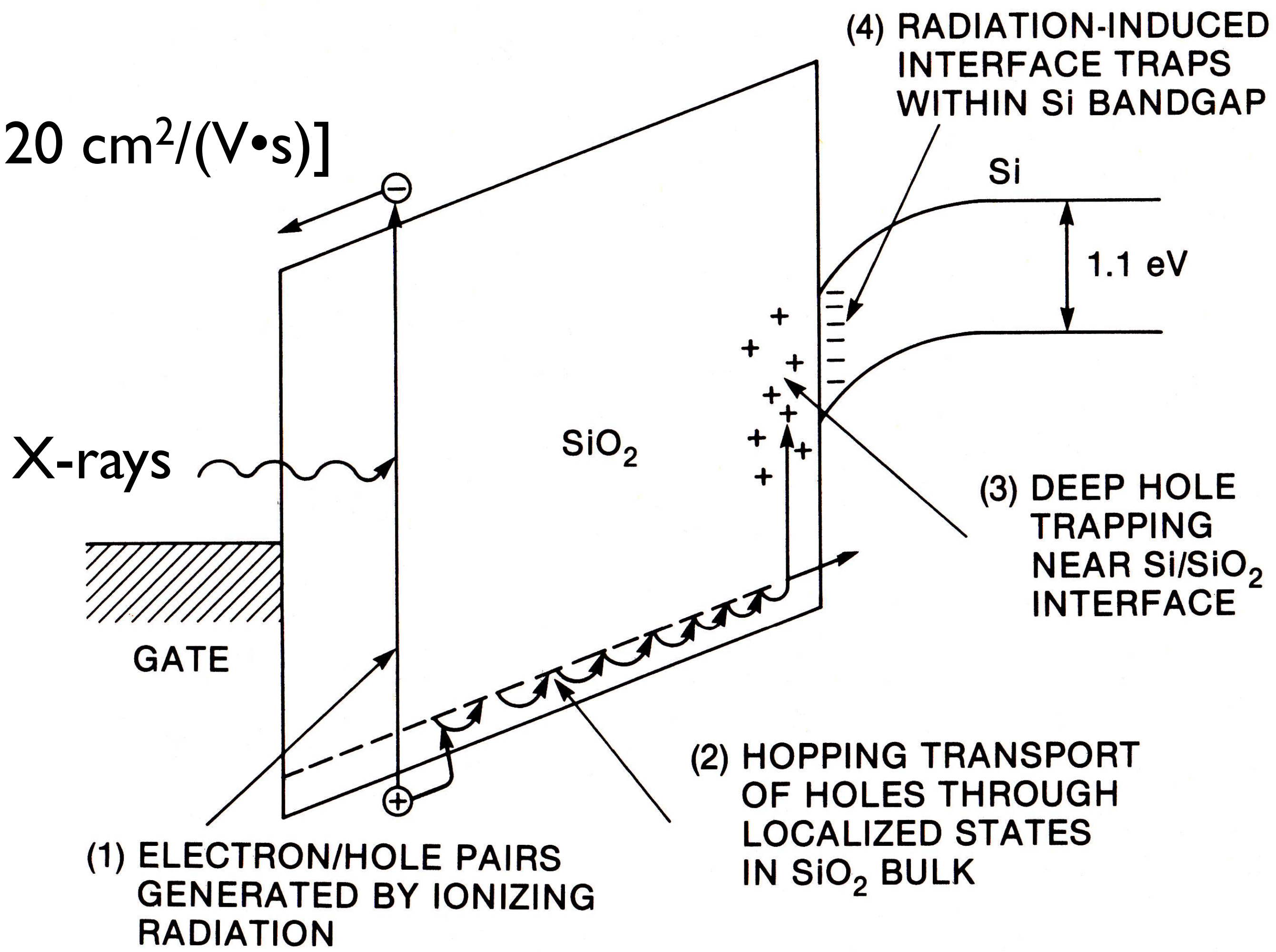
- Determine relevant parameter for device simulations
- Predict sensor performance vs. dose for optimization of the sensor design

Check:

- Test structures ↔ strip sensors

Formation of defects induced by X-rays

- X-rays produce electron-hole pairs in SiO_2
- Fraction of electron-hole pairs recombine
- Remaining electrons escape from SiO_2 [$\mu_e \sim 20\ cm^2/(V\cdot s)$]
- Remaining holes will move toward the Si-SiO_2 interface [$\mu_h \sim 5\times10^{-5}\ cm^2/(V\cdot s)$]



→ 1. Fixed oxide charges: N_{ox}
2. Interface traps: N_{it}

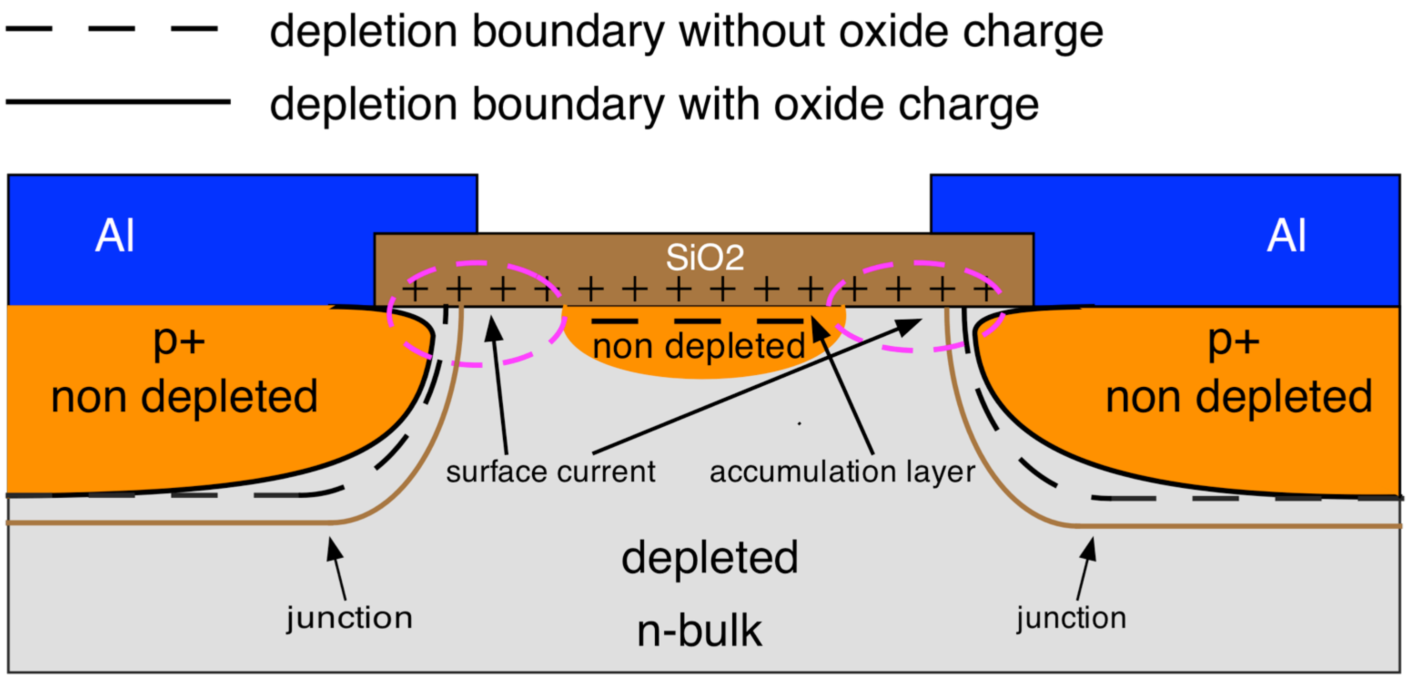
Details depend on:

- Oxide thickness
- Electrical field
- Dose, dose rate
- Temperature
- Crystal orientation
- Technology

from T.P. Ma and Paul V. Dressendorfer, „Ionizing Radiation Effects in MOS Devices and Circuits“, Wiley 1989

Impact of surface damage on p^+-n sensors

- Positive oxide charge:
  - Strong curvature of the depletion boundary near the interface
    - → high electric field
    - → low breakdown voltage
  - Negatively charged accumulation layer
    - → not fully depleted surface
    - → charge losses

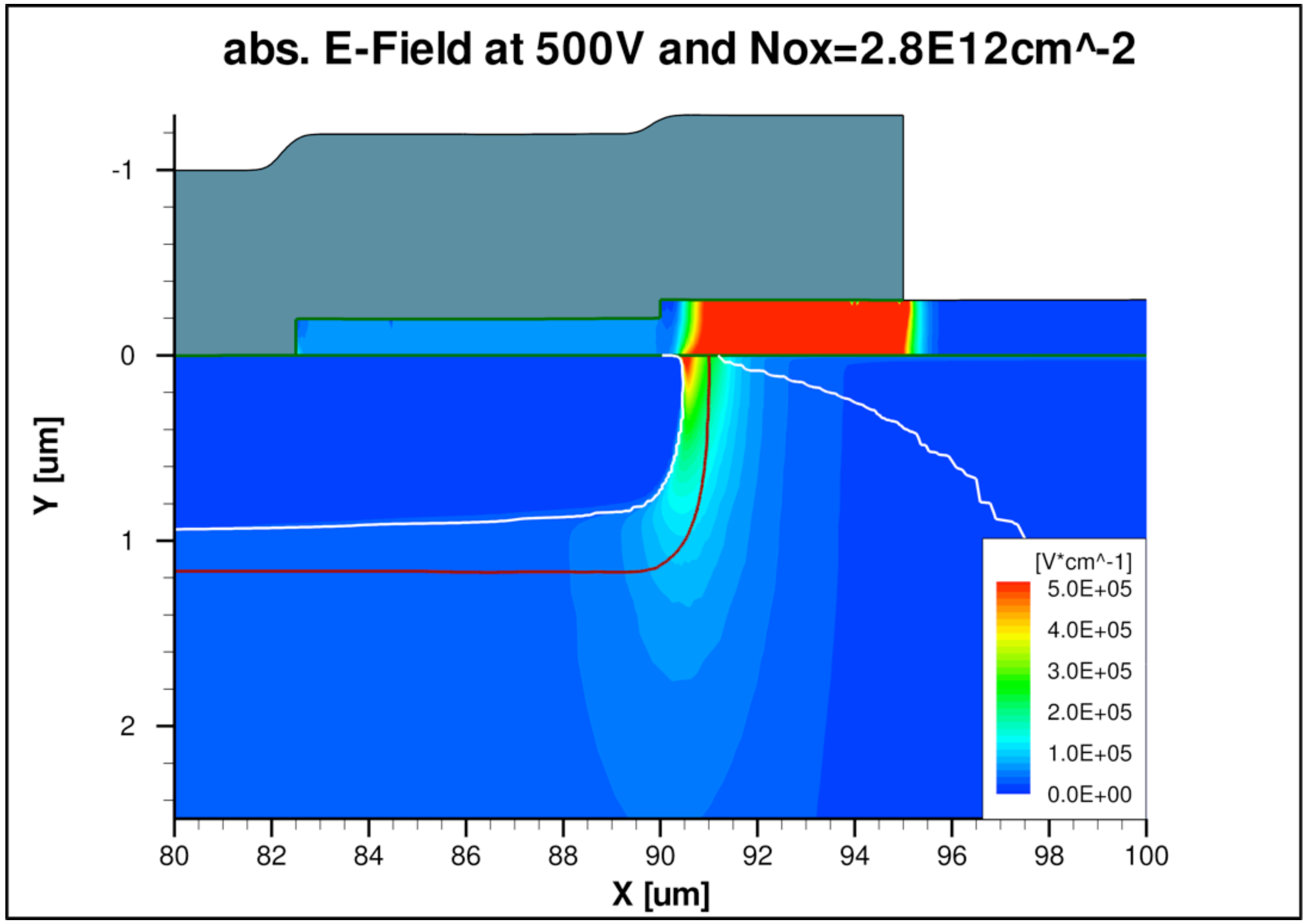


- Interface traps:
  - Distributed within the Si bandgap
  - Charge state depends on type, energy and Fermi level
  - Surface current: $I_s \cong \frac{q s_0 n_i A_s}{2}$

    n_i intrinsic carrier concentration

    A_s depleted surface:

    $s_0 = \sigma v_{th} N_{it}$ surf. recombination velocity:


abs. E-Field at 500V and Nox=2.8E12cm^-2

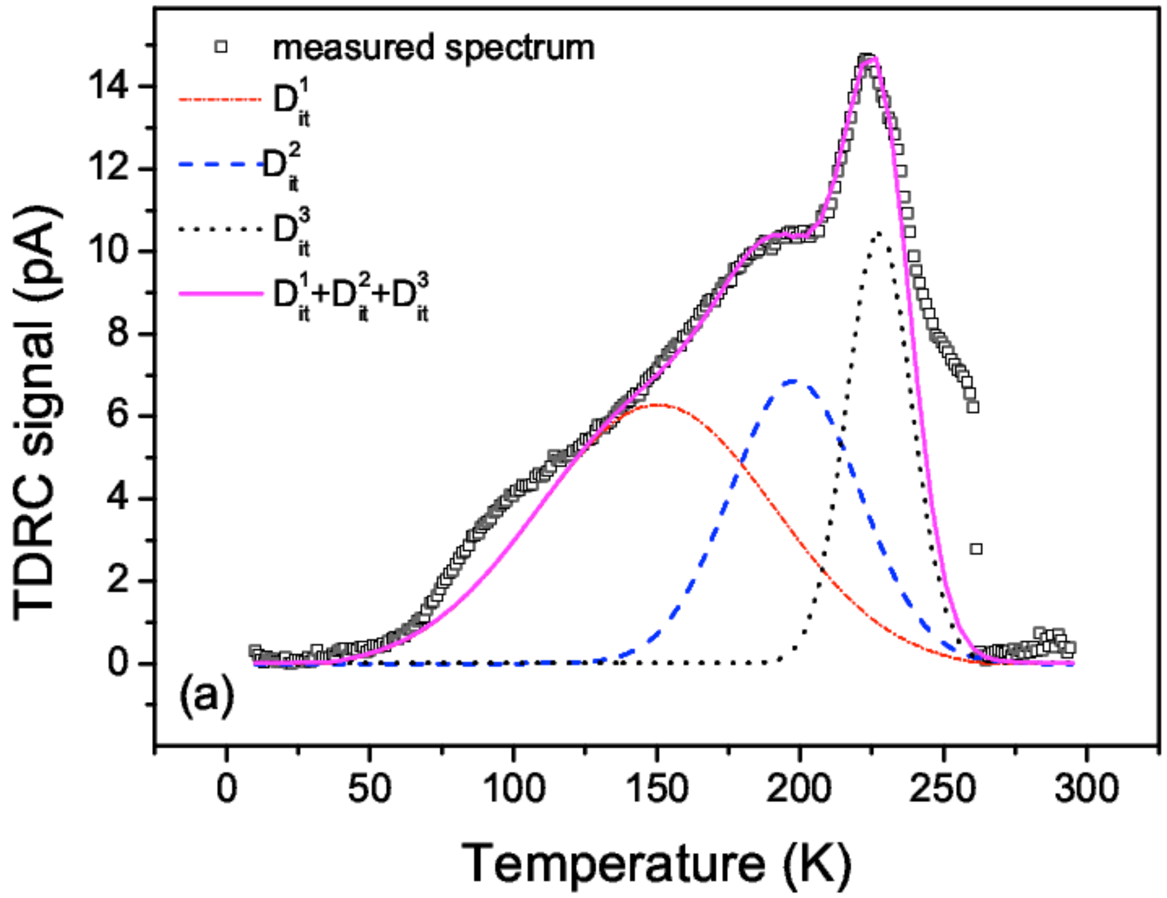
Radiation damage measurements

- Test structures: MOS capacitors, gate controlled diodes
- Irradiations: X-rays at DORIS (DESY) up to 1GGy
  - „White“ photon beam
  - Maximum flux at 12 keV
  - FWHM 10 keV
  - Dose rate 18 kGy/s (except for highest and lowest dose)

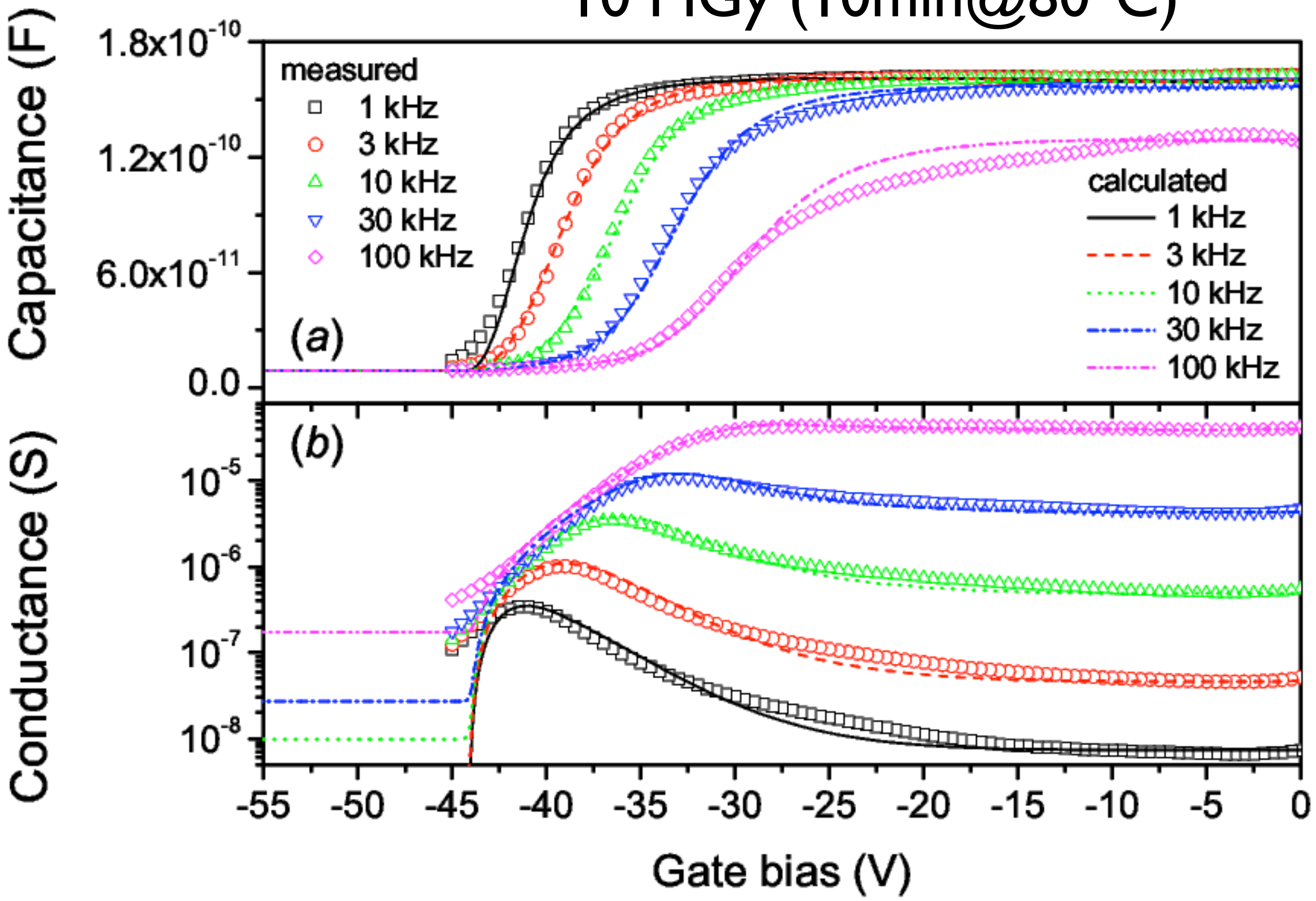
Vendor	CiS
Doping	n-type (P)
Orientation	<100> & <111>
Resistivity	~5kΩcm
Thickness	285±10 µm
Insulator	350nm SiO_2 + 50nm Si_3N_4

- Measurements: Thermally Dielectric Relaxation Current (TDRC), C/V , G/V and I/V
- Analysis: Based on TDRC, C/V, G/V measurements and model calculation (details arXiv:1107.5949)

10 MGy (10min@80°C)



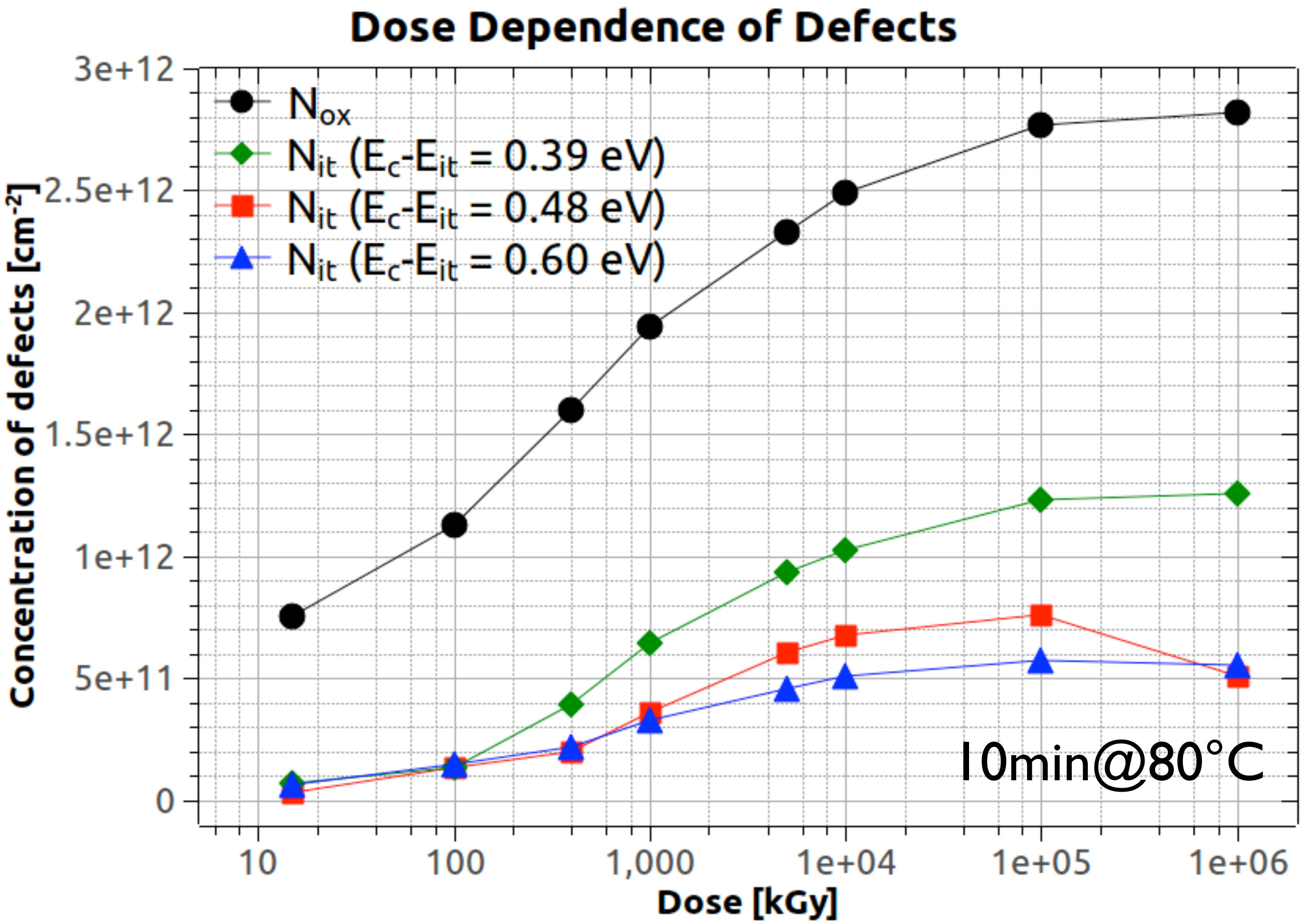
10 MGy (10min@80°C)



Measurement results for <100>

- TDRC spectrum can be described by 3 dominant acceptor like interface traps

	D^1_{it}	D^2_{it}	D^3_{it}
E_c - E_t [eV]	0.39	0.48	0.6
FWHM [eV]	0.26	0.13	0.071
σ [cm^2]	1.2x10^{-15}	5x10^{-17}	1x10^{-15}



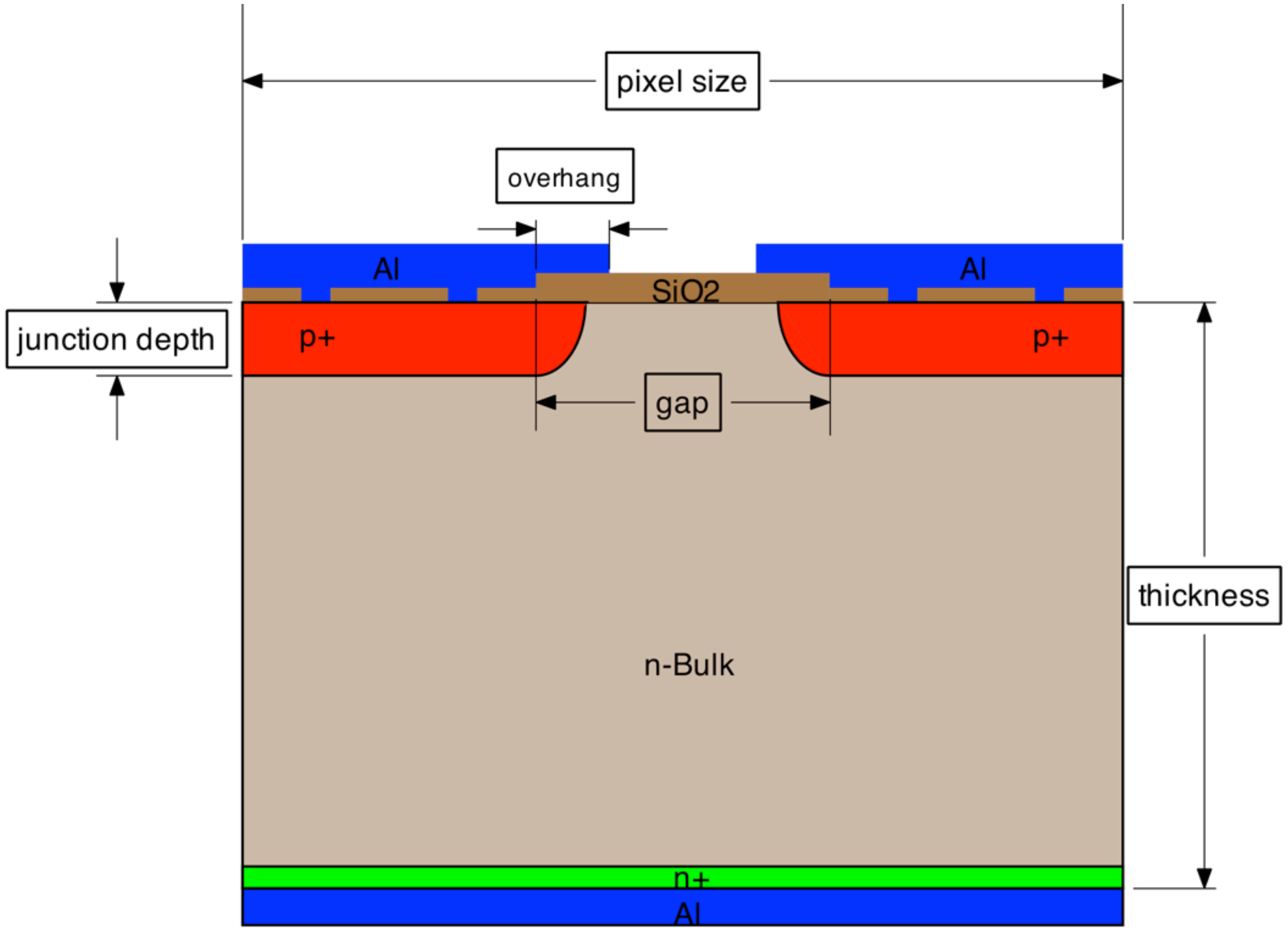
- N_{ox} and N_{it} saturate at dose value between 10 MGy and 100 MGy
- Saturation value of N_{ox} is 2.8x10^{12} cm^{-2}
- Similar results obtained for orientation <111>

AGIPD sensor specifications

- Adaptive Gain Integrating Pixel Detector (see talk from M. Kuster and J. Becker)
- Specified sensor parameters: for dose 0 - 1GGy

Parameter	Specification
thickness	500 µm
pixel size	200 µm x 200 µm
type	p+ n
resistivity	~5 kΩ·cm
V_{fd}	< 200 V
V_{op}	500 V
C_{int}	< 0.5 pF
I_{leak}	< 1 nA/pixel

plasma effects!



- Left to define:
  - Gap
  - Metal overhang
  - Curvatures of implant edges
  - Guard ring structure

- Determine optimum values using TCAD

TCAD

TCAD (**T**echnology **C**omputer **A**ided **D**esign)

- Process simulation (oxidation, ion implantation, annealing etc.) → doping profile
- Device simulation → electrical behavior
  - Takes mesh, applies semiconductor equations and boundary conditions (in discrete form) and solves
  - **Physics models:** Works by modeling electrostatic potential (Poisson's equation) and carrier continuity equations

Poisson $$\nabla \cdot \epsilon \nabla V = -(p - n + N_D - N_A) - \rho_{trap}$$

Electron continuity $$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_n + R_{net}$$ where $$J_n = q n \mu_n E + q D_n \frac{dn}{dx}$$

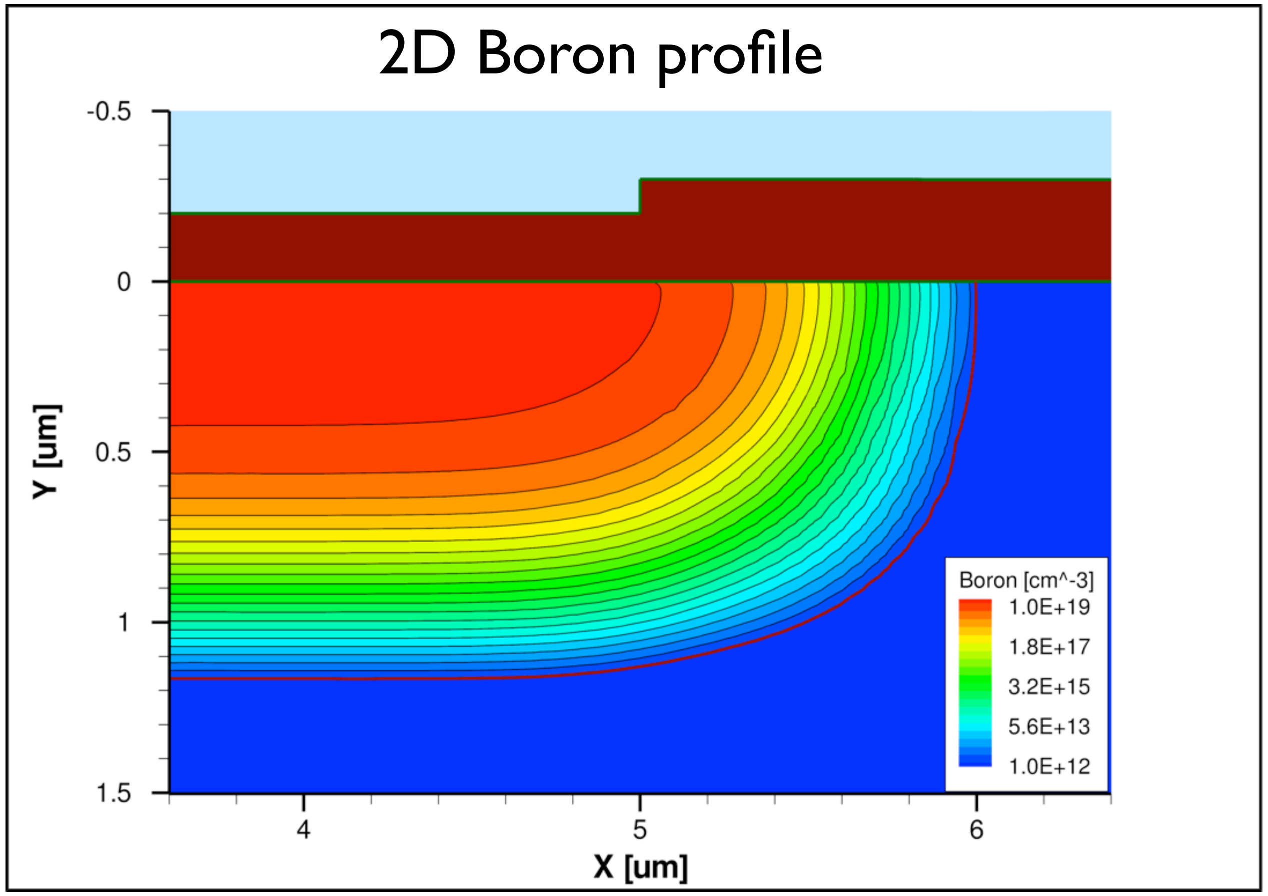
Hole continuity $$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot J_p + R_{net}$$ where $$J_p = q p \mu_p E - q D_p \frac{dp}{dx}$$

  - Different versions of physics models available
    - Different models of mobility, bandgap...
    - Generation-recombination models (SRH, Auger, impact ionization, traps...)
  - Caveat
    - Choosing the right models and calibrations can be difficult
    - „You get out what you put in“

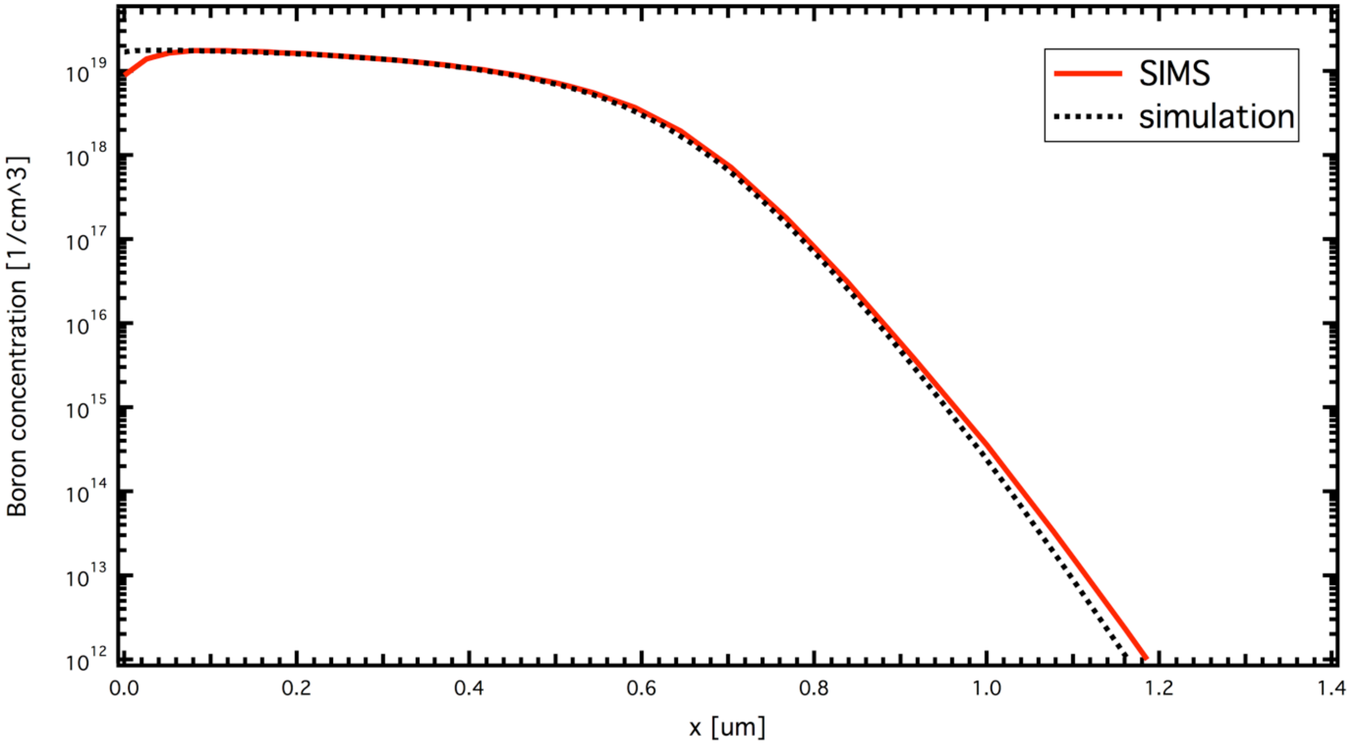
Process simulation

- Why process simulation? Doping profile is critical for breakdown
- Simulation of ion implantation and drive in:

Doping	10^{12} [cm^{-3}] (P)
Orientation	<111>
Tilt angle	0°
Implant	Boron
Doses	1×10^{15}, 5×10^{15}, 1×10^{16} [cm^{-2}]
Energy	70, 150, 200 keV


2D Boron profile

1D Boron profile



- Simulation is calibrated with a SIMS measurement for the same process.
- „Standard“ process:
  - Junction depth: 1.2 µm
  - Lateral extension: 1 µm
- In the following for comparison:
  - Junction depth: 2.4 µm
  - Lateral extension: 1.95 µm

2D Device simulation (strips)

- Why 2D?
  - Faster then 3D
  - But values have to be scaled from 2D → 3D

- Geometries:
- Oxide thickness: 300 nm

gap [µm]	20	30	40
overhang [µm]	0, 2.5, 5	5, 10	0, 2.5, 5, 10

- Models to account for surface effects:
  - Neumann boundary conditions
  - Mobility: Degradation at interfaces
  - Avalanche Generation: van Overstraeten - de Man
  - Fixed charges: homogenous distribution at interface
  - Surface SRH Recombination

- At gated diodes measured values for <111>

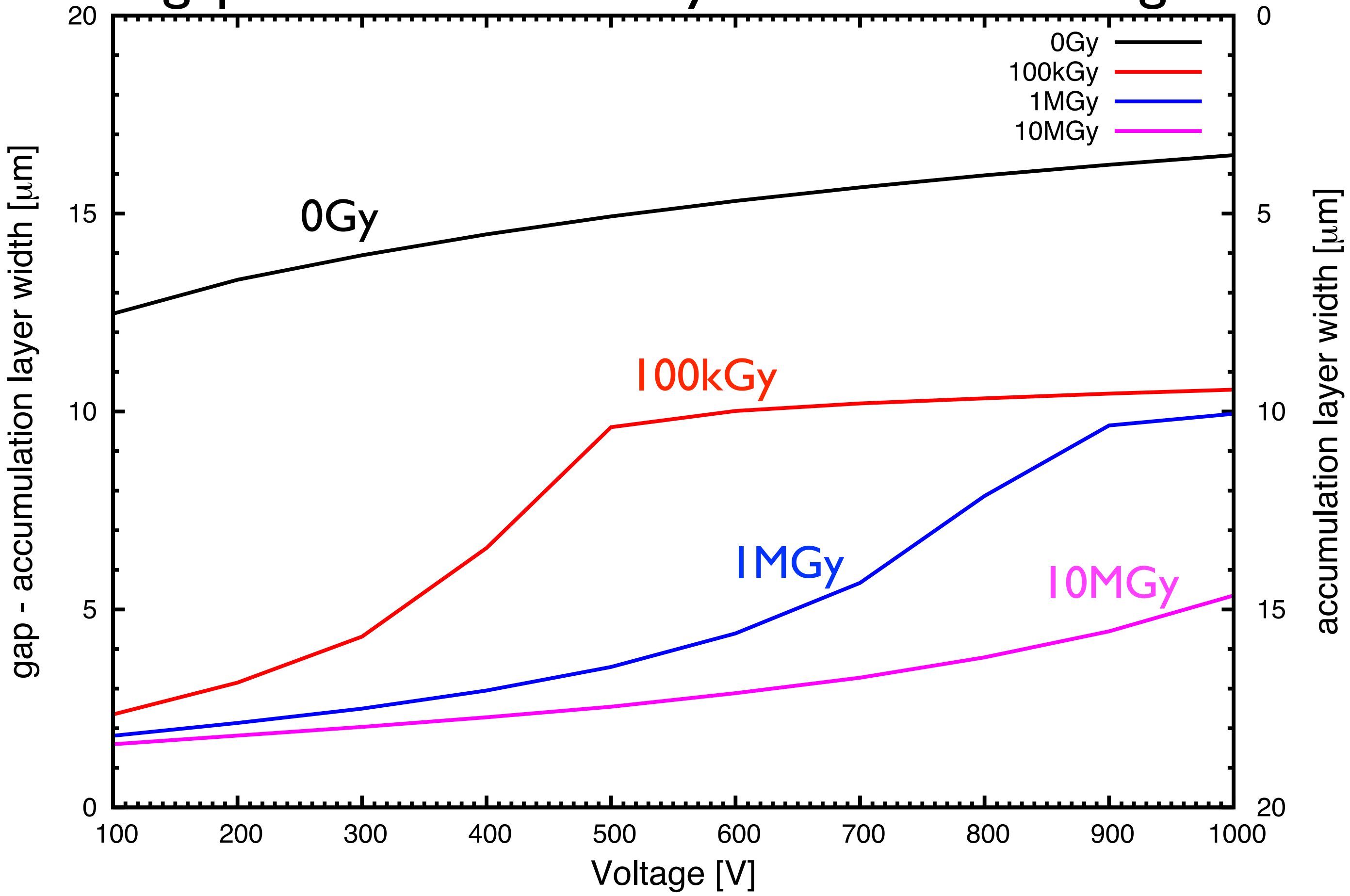
Dose [MGy]	N_{ox}[cm^-2]	S_0[cm/s]
0	$1\text{x}10^{11}$	8
0.1	$1.33\text{x}10^{12}$	$3.5\text{x}10^{3}$
1	$2.07\text{x}10^{12}$	$7.5\text{x}10^{3}$
10	$2.78\text{x}10^{12}$	$1.2\text{x}10^{4}$
100	$2.87\text{x}10^{12}$	$1.05\text{x}10^{4}$

- Breakdown criteria: Ionization integral for electron or holes = 1

Accumulation layer

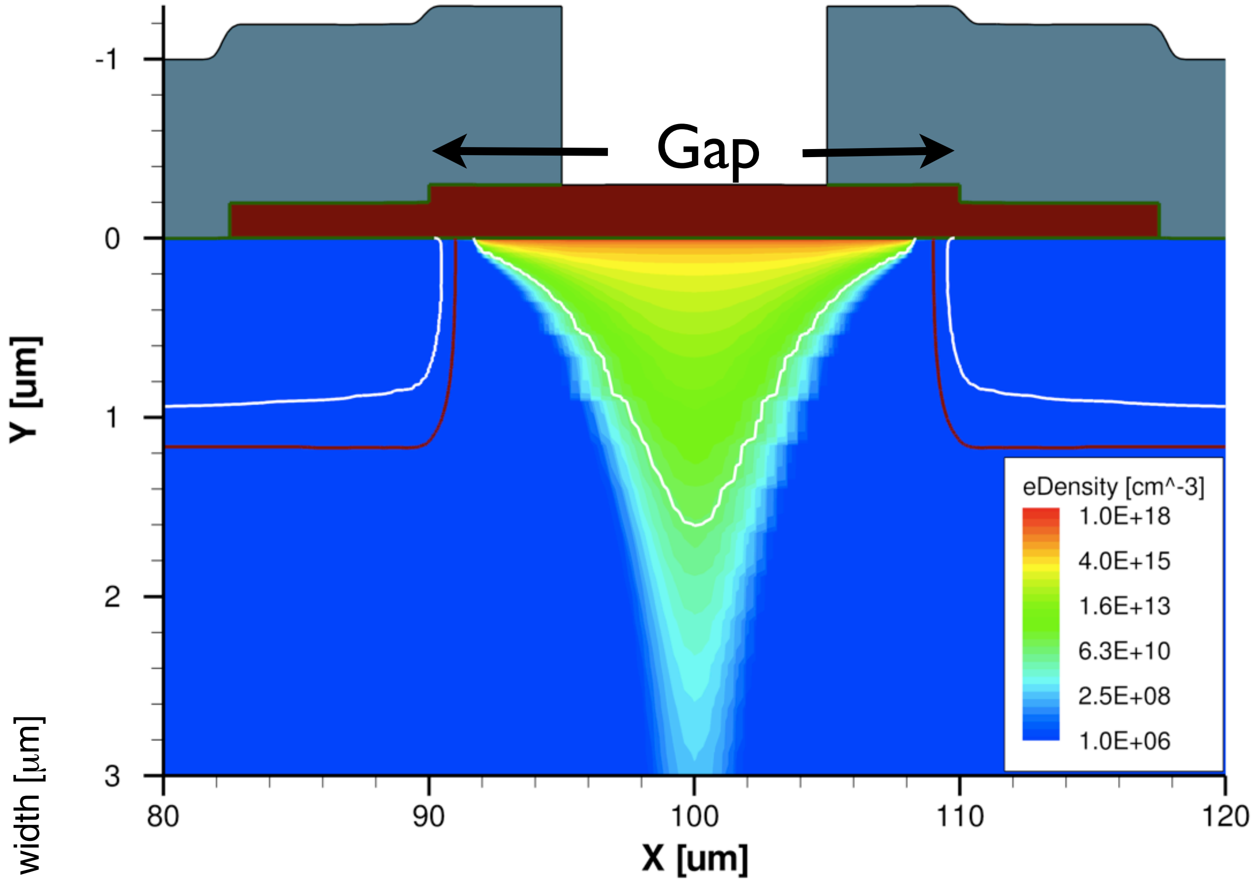
- Smaller accumulation layer
  ➡ larger dark current
  ➡ lower breakdown voltage
- Simulations:
  - Gap: 20 µm
  - Overhang: 5 µm
  - Junction depth: 1.2 µm

gap - accumulation layer width vs. voltage



Accumulation layer width 0.01 µm below SiO_2-Si interface
Condition: electron density = bulk doping

Electron density at 500V and 1MGy



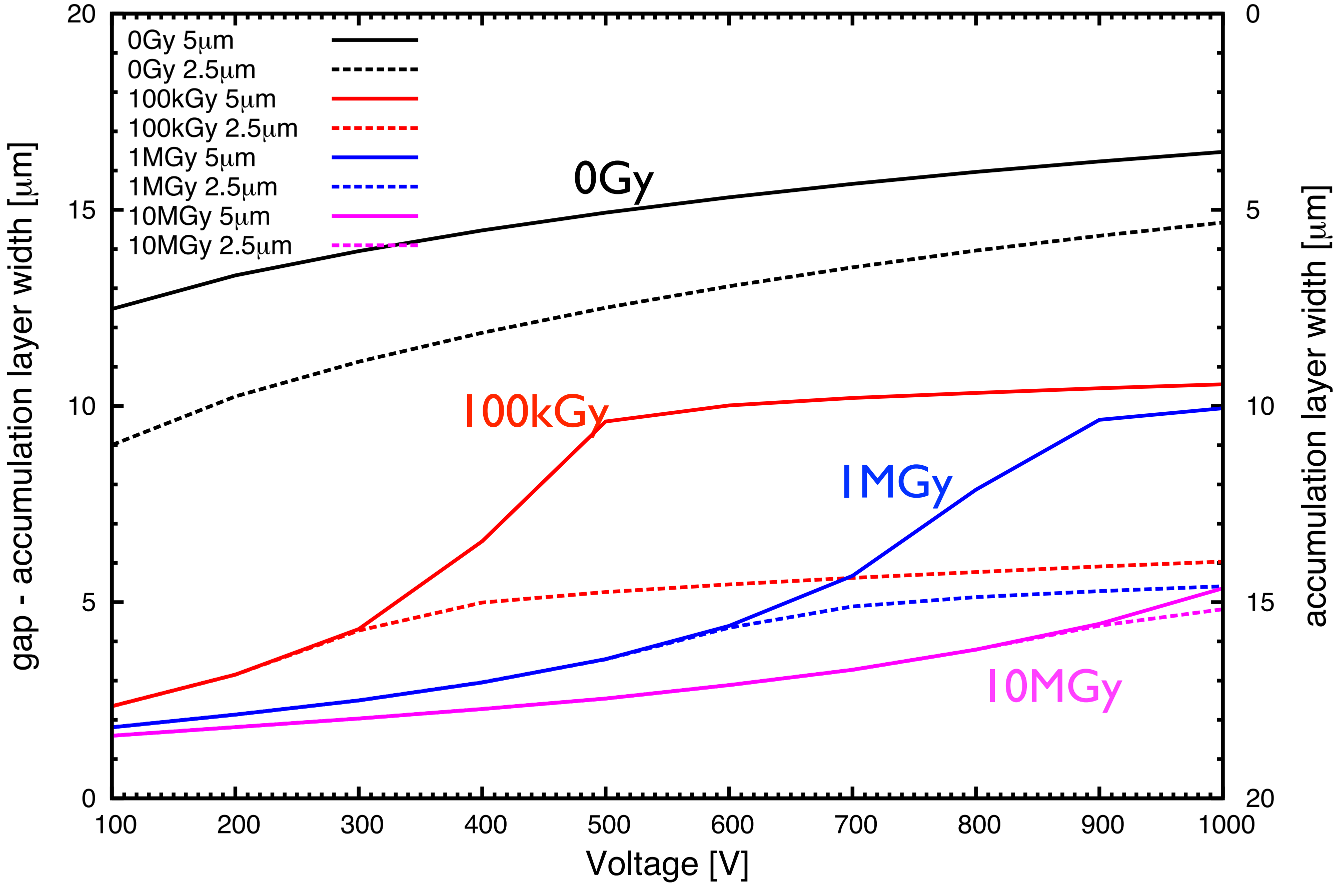
- Width of accumulation layer:
  - Non-irradiated:
    Small, only weakly V-dependent
  - 0.1, 1MGy:
    Low voltage - practically entire region between junctions
    High voltage - region under Al depletes
  - 10MGy:
    Breakdown before region under Al depletes

Overhang values

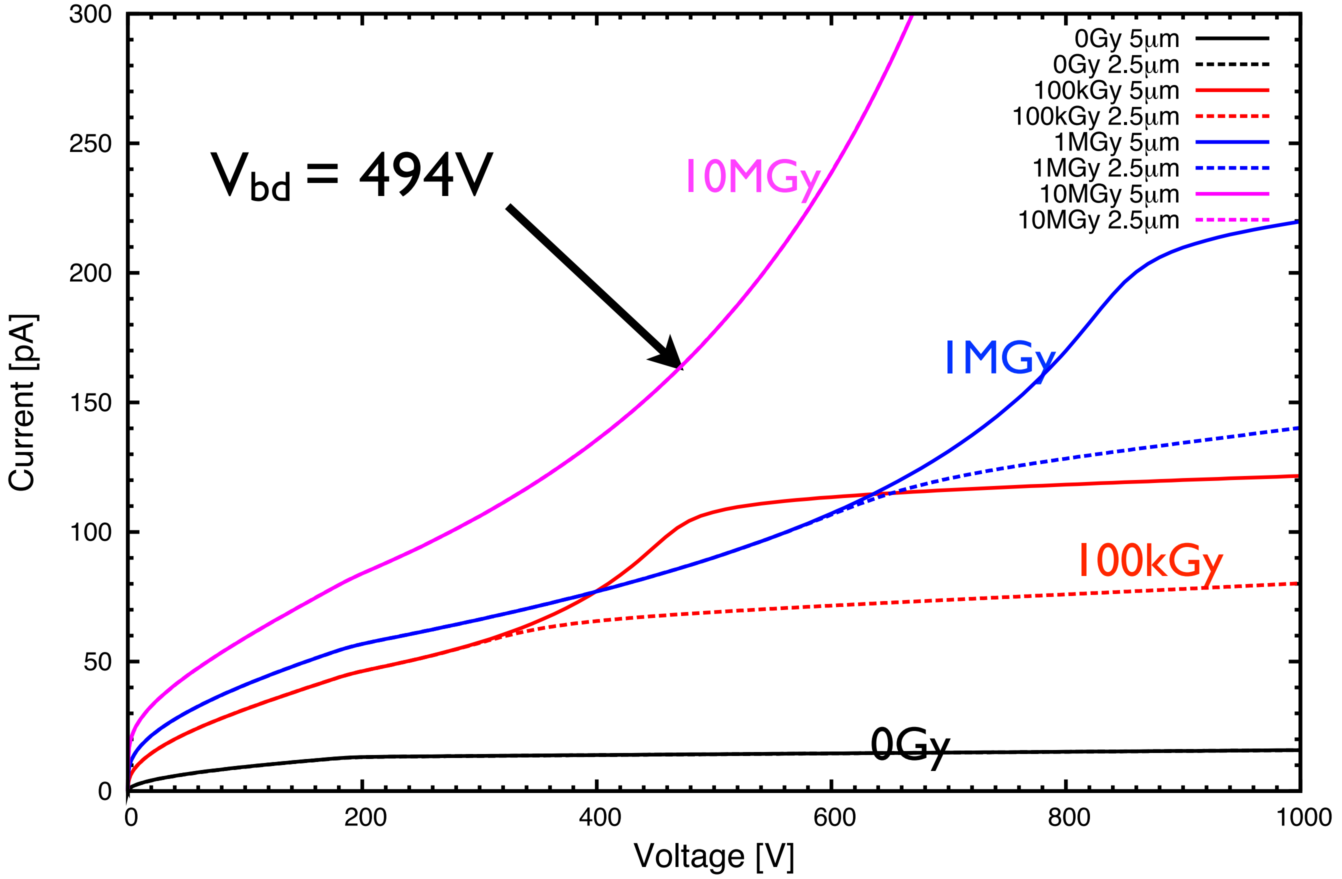
—— Overhang 5 µm

- - - - Overhang 2.5 µm

gap - accumulation layer width vs. voltage



current vs. voltage

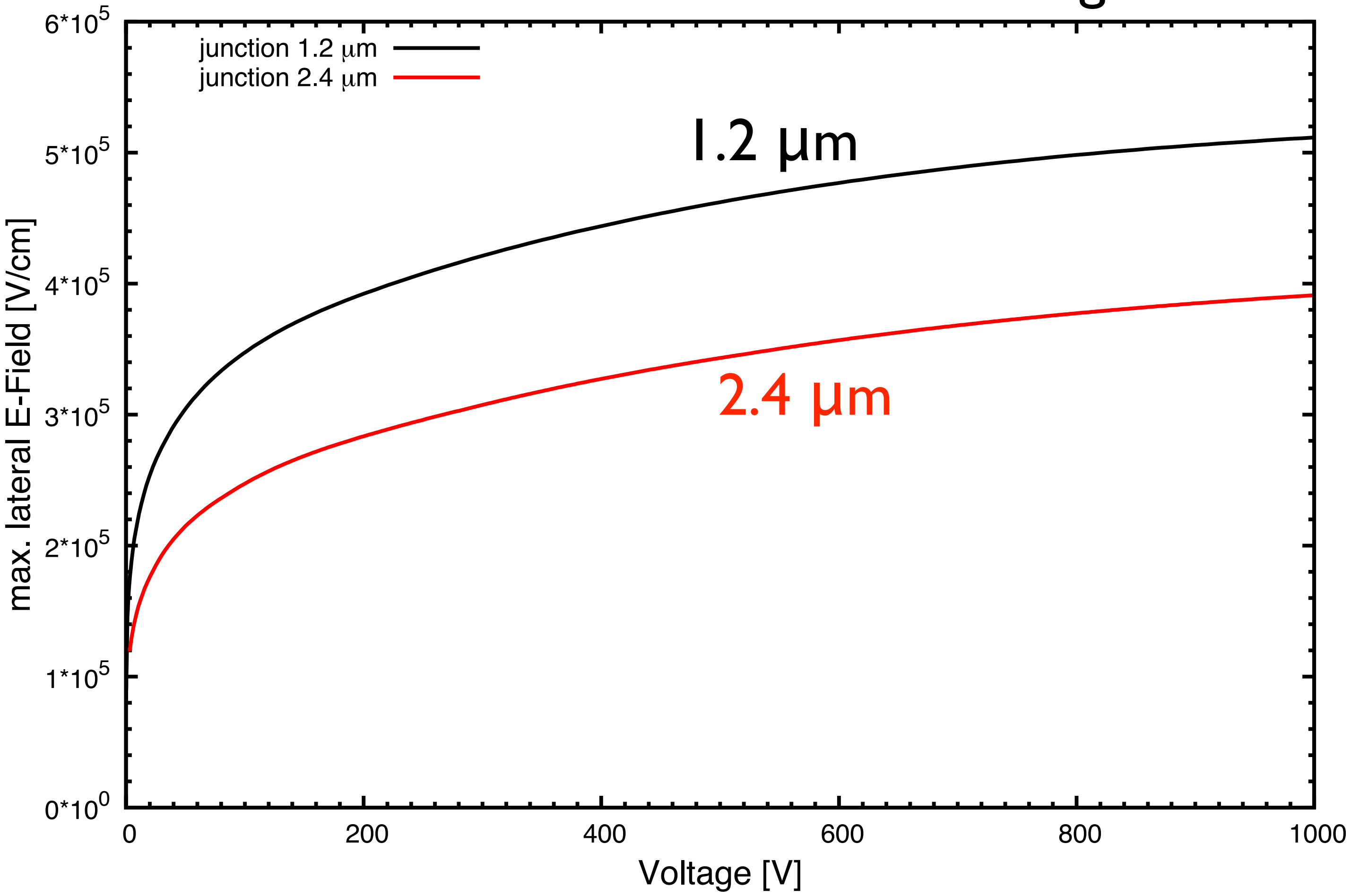


- Confirms above findings
- For irradiated sensors: accumulation layer for 5 µm overhang < then for 2.5 µm
- Current ∝ depleted width ≈ (gap - accumulation layer width)
- For 10 MGy the breakdown voltage is 494V (overhang 2.5 µm and 5 µm)

Junction depth

- Maximum lateral E-Field
  - Gap 20 µm
  - Overhang 5 µm
  - Junction depth 1.2 µm and 2.4 µm
  - 10 MGy
- Junction 1.2 µm: 4.6x10^5 V/cm at 500 V
- Junction 2.4 µm: 3.4x10^5 V/cm at 500 V
- No breakdown up to1000 V for 2.4 µm junction depth

max. lateral E-Field in Si vs. voltage



- Gap: 30 µm and 40 µm
- Overhang: 5 µm and 10 µm
- Junction depth: 2.4 µm
- 10 MGy
- Breakdown voltage:
  - gap 40 µm with 5 µm overhang: 722V
  - other cases: >1000V
- Current < 1nA/pixel

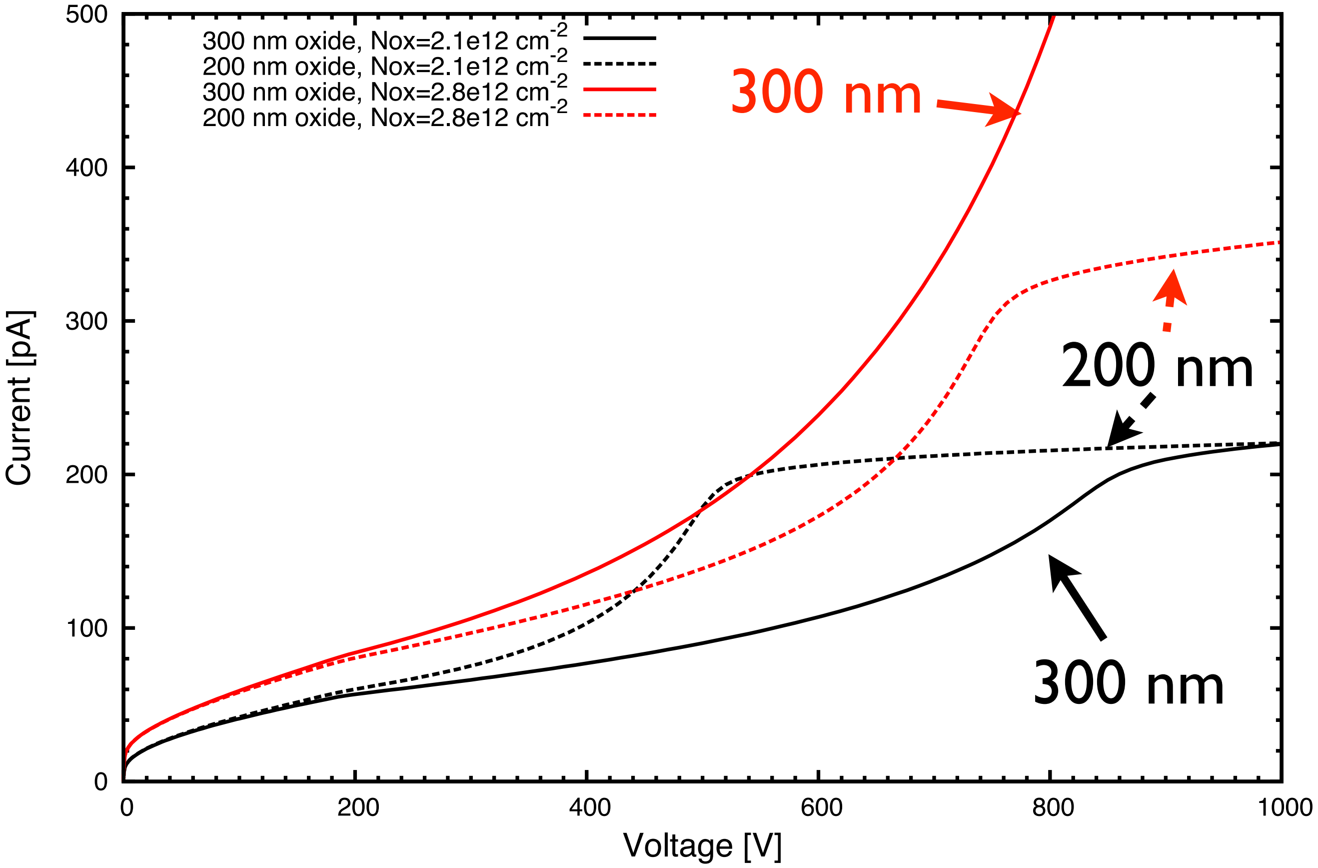
→ deeper implant
→ higher breakdown voltage

Oxide thickness

- Oxide thickness: 200 nm and 300 nm
- Assumption: same value of fixed charge and surface recombination
  - $N_{ox} = 2.1*10^{12}$ cm^{-2} (1 MGy for 300 nm oxide)
  - $N_{ox} = 2.8*10^{12}$ cm^{-2} (10 MGy for 300 nm oxide)

- Geometry:
  - Gap: 20 µm
  - Overhang: 5 µm
  - Junction depth: 1.2 µm

current vs. voltage

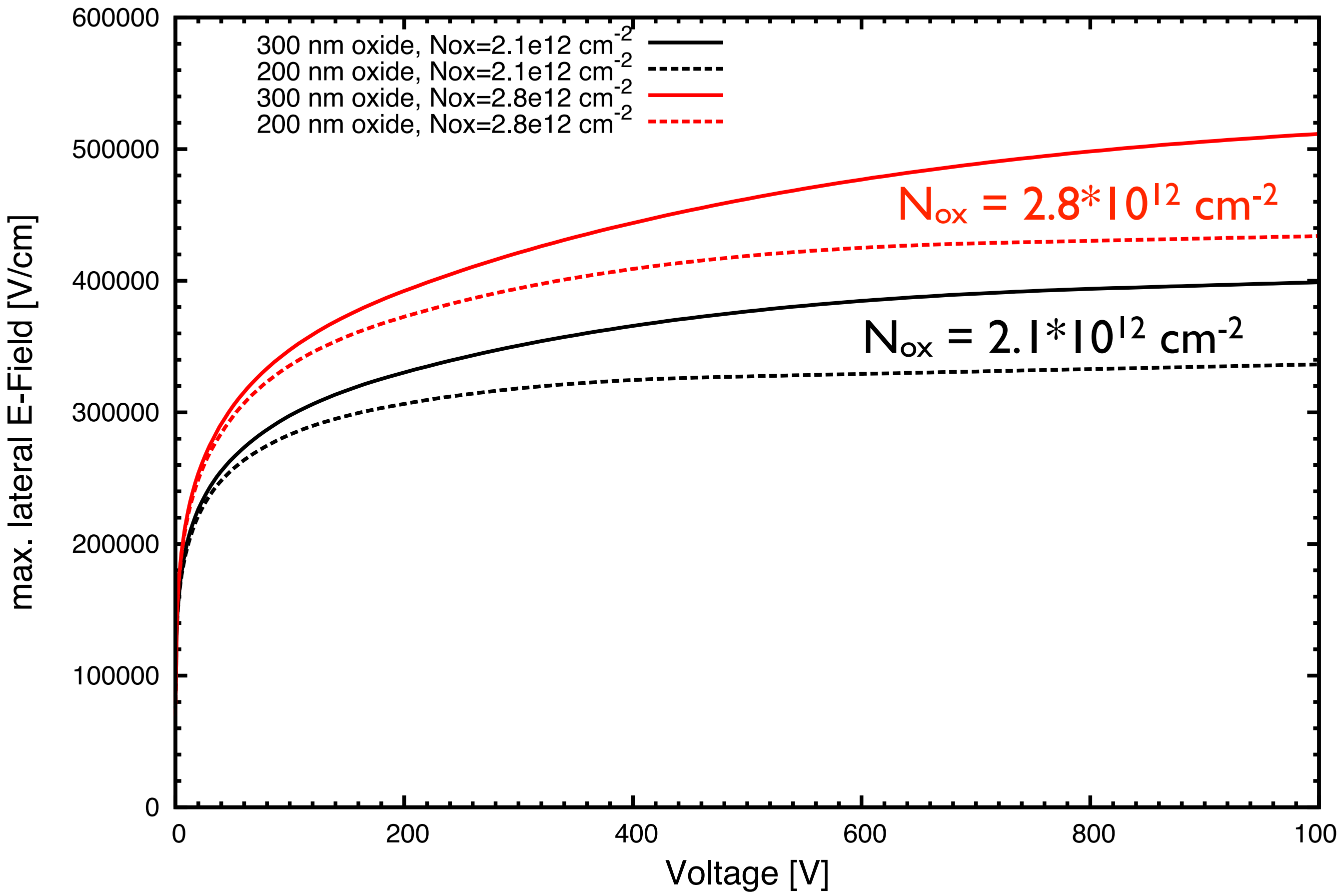


300 nm

200 nm

300 nm

max. lateral E-Field in Si vs. voltage



$N_{ox} = 2.8*10^{12}$ cm^{-2}

$N_{ox} = 2.1*10^{12}$ cm^{-2}

- For thinner oxide the region under the metal depletes at lower voltage
- Thinner oxide: lower max. lateral field strength in Si and breakdown voltage > 1000V

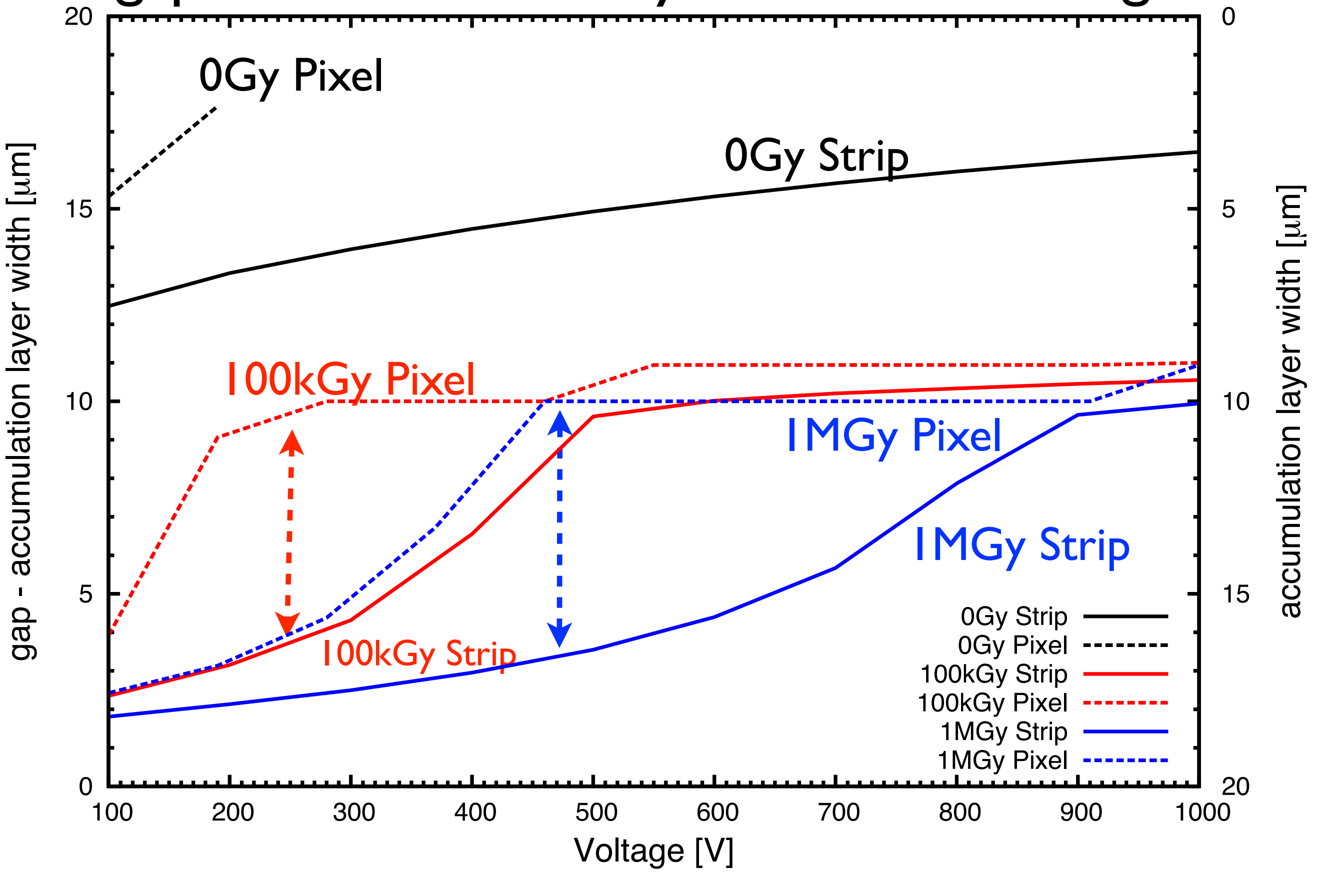
→ From breakdown point of view: thinner oxide preferred

2D vs. 3D

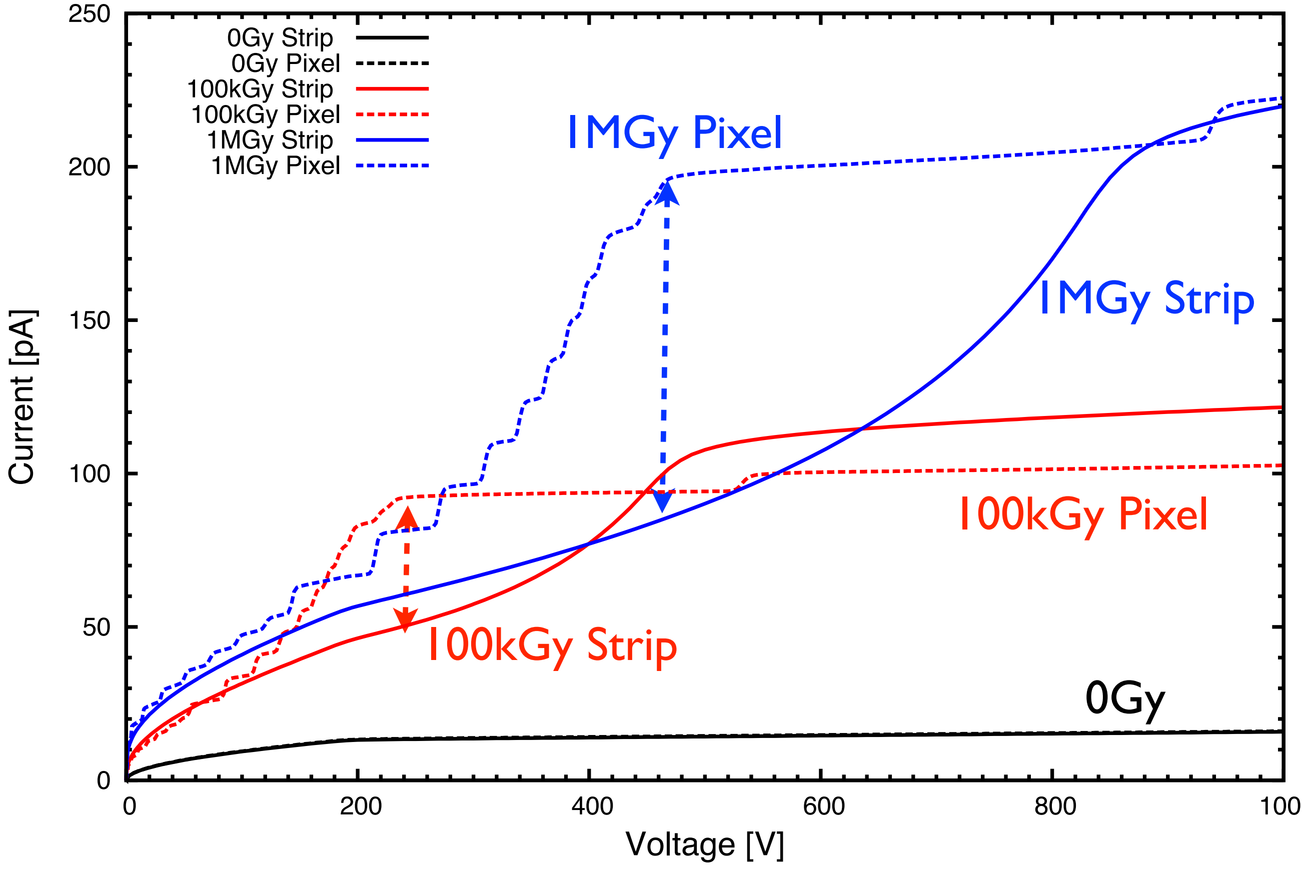
- 3D:
  - Quarter pixel with gap 20 µm, overhang 5 µm and edge radius 5 µm
  - Gaussian doping profile with junction depth 1.5 µm
  - Very time and memory consuming

For pixel the accumulation layer width measured to the direct neighbor

gap - accumulation layer width vs. voltage



current vs. voltage



- Qualitatively same results of optimization
- Similar values for currents at low and high voltages (simple geom. scaling)
- Differences in voltage dependence
- For 3D depletion under metal appears at lower voltage

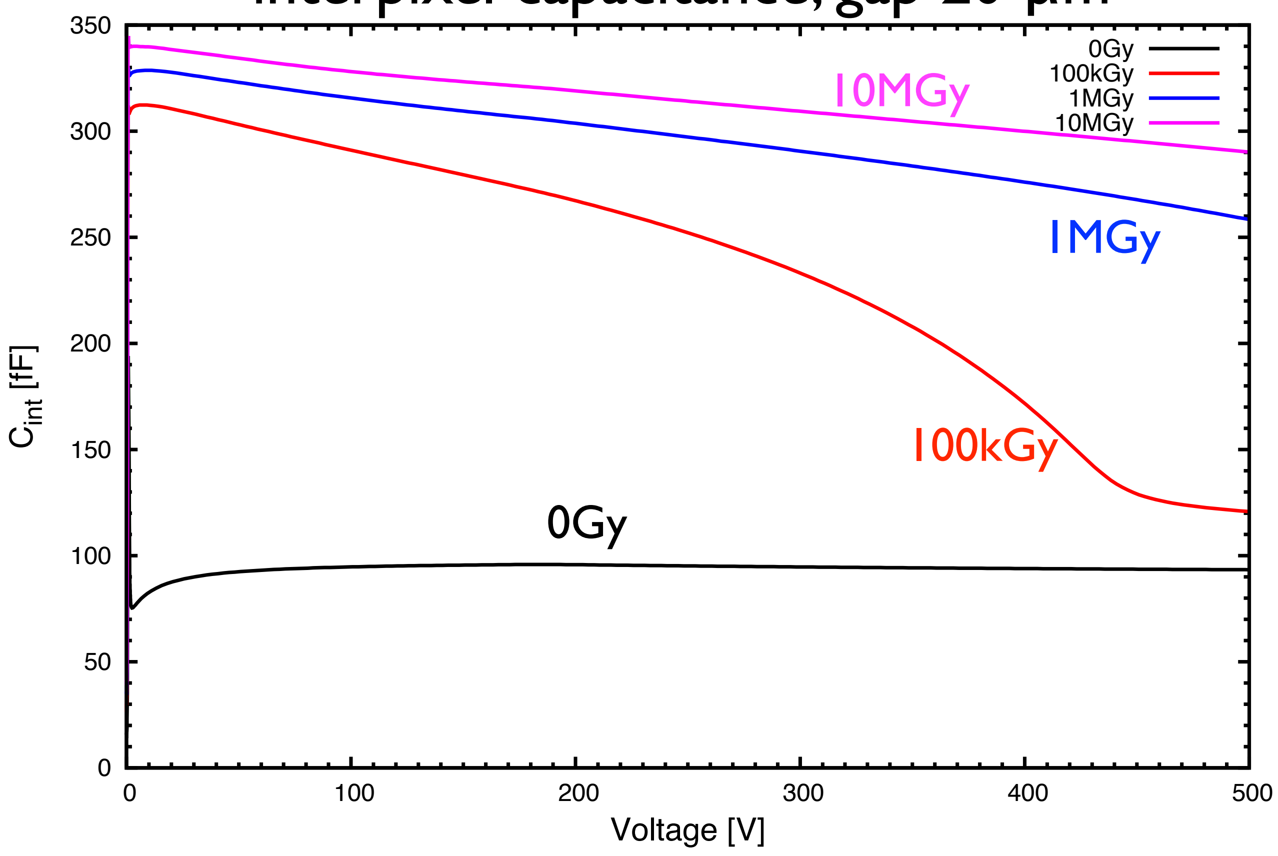
Capacitance simulations

- Junction depth: 1.2 µm
- V_{fd} = 188 - 194 V compared to 193 V for pad sensor and doping 1×10^{12} cm^{-3}
- C_b = 8.5 - 8.56 fF compared to 8.43 fF for pad sensor

- Interpixel capacitance for 5 µm overhang:

Gap	Doses	C_{int}[fF] at V_{fd}	C_{int}[fF] at 500V
20 µm	0Gy 1MGy	96 305	93 259
30 µm	0Gy 1MGy	73 117	71 92
40 µm	0Gy 1MGy	59 163	56 82

interpixel capacitance, gap 20 µm



- Decrease of interpixel capacitance with voltage due to accumulation layer
- Interpixel capacitances are within specifications (< 0.5 pF)

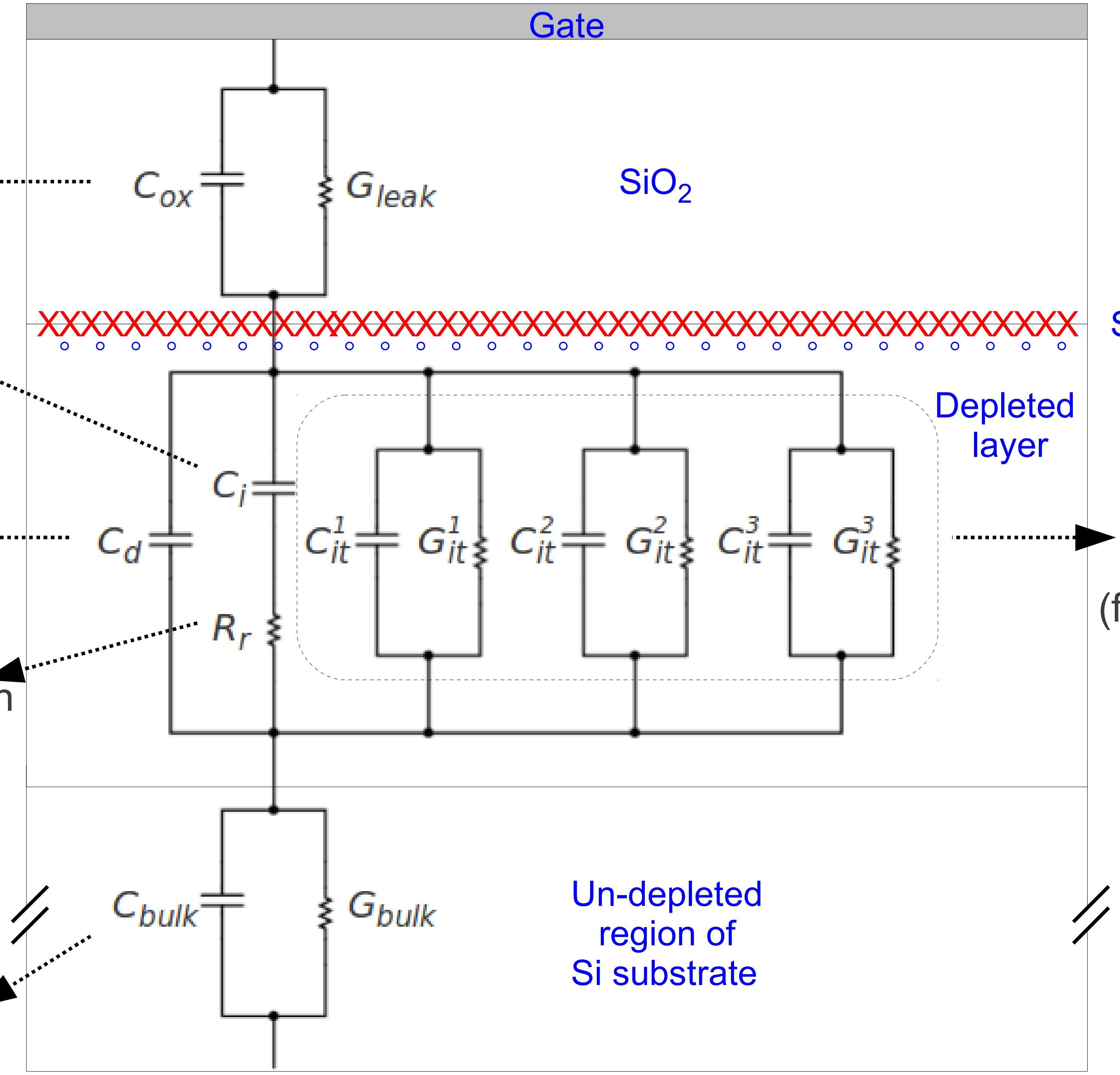
Summary

- Measurements on irradiated test structures:
    - 3 dominant interface D_{it} traps
    - C/G-V measurements can be described by D_{it} and N_{ox}
    - N_{it} and N_{ox} saturate with dose
    - similar dose dependence of <100> and <111>

- Sensor optimization
    - AGIPD specifications can be met
    - small gap
    - metal overhang > 2.5 µm
    - deep implant
    - from breakdown point of view, thinner oxide preferred

Backups

Model of MOS with interface traps



Capacitance and conductance of isolation layer

Inversion capacitance

Depletion capacitance depends on thickness of depletion layer

Recombination/generation resistance

Capacitance and conductance of un-depleted region

Capacitance and conductance due to interface traps (frequency dependent)

Detail list of TCAD models

- Used models:
  - Drift-Diffusion
  - Newton boundary conditions
  - Temperature: T = 293K
  - Statistics: Fermi
  - Bandgap: Bandgap narrowing model
  - Mobility: Doping dependent , High-field saturation, Carrier-Carrier Scattering, Degradation at interfaces
  - SRH Recombination: Doping dependent (lifetime 1ms), Temperature dependent, Field enhancement
  - Auger Recombination
  - Hurkx Band-to-Band Tunneling
  - Avalanche Generation: van Overstraeten - de Man Model , Driving force: Gradient of the quasi-Fermi level
  - Physics at the Si/SiO2 interface:
    1. Fixed charge (measured values, homogenous distribution at interface)
    2. Surface SRH Recombination (measured values)

- Breakdown criteria: Ionization integral for electron or holes = 1

$$I_p := \int_0^{W_d} \alpha_p \exp\left[-\int_0^x (\alpha_p - \alpha_n) dx' \right] dx$$

α_p, α_n ionization coefficients for hole and electron

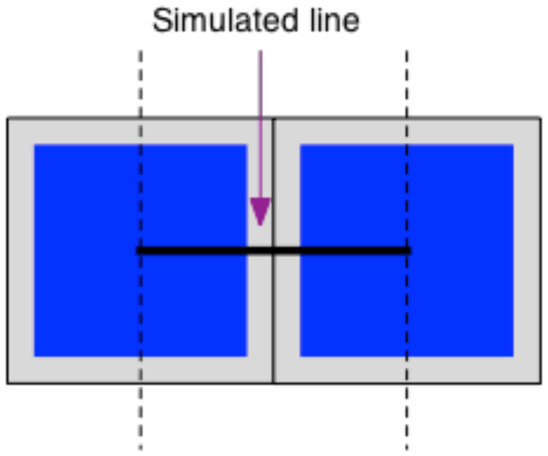
W_d width depleted region

Because the multiplication factor M_p satisfies $1 - \frac{1}{M_p} = I_p$

we have $M_p \to \infty$ for $I_p \to 1$

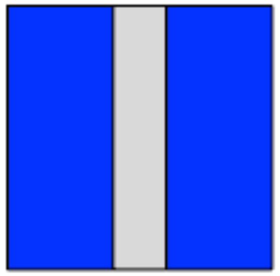
Scaling from 2D to 3D

- Current:



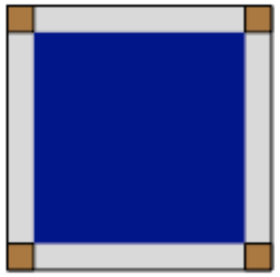
1um in 3rd direction

Area factor 200



if surface current is negligible

Area factor 2*200



if surface current is dominant (brown areas are counted twice)

20 um	5 %
30 um	8 %
40 um	11 %

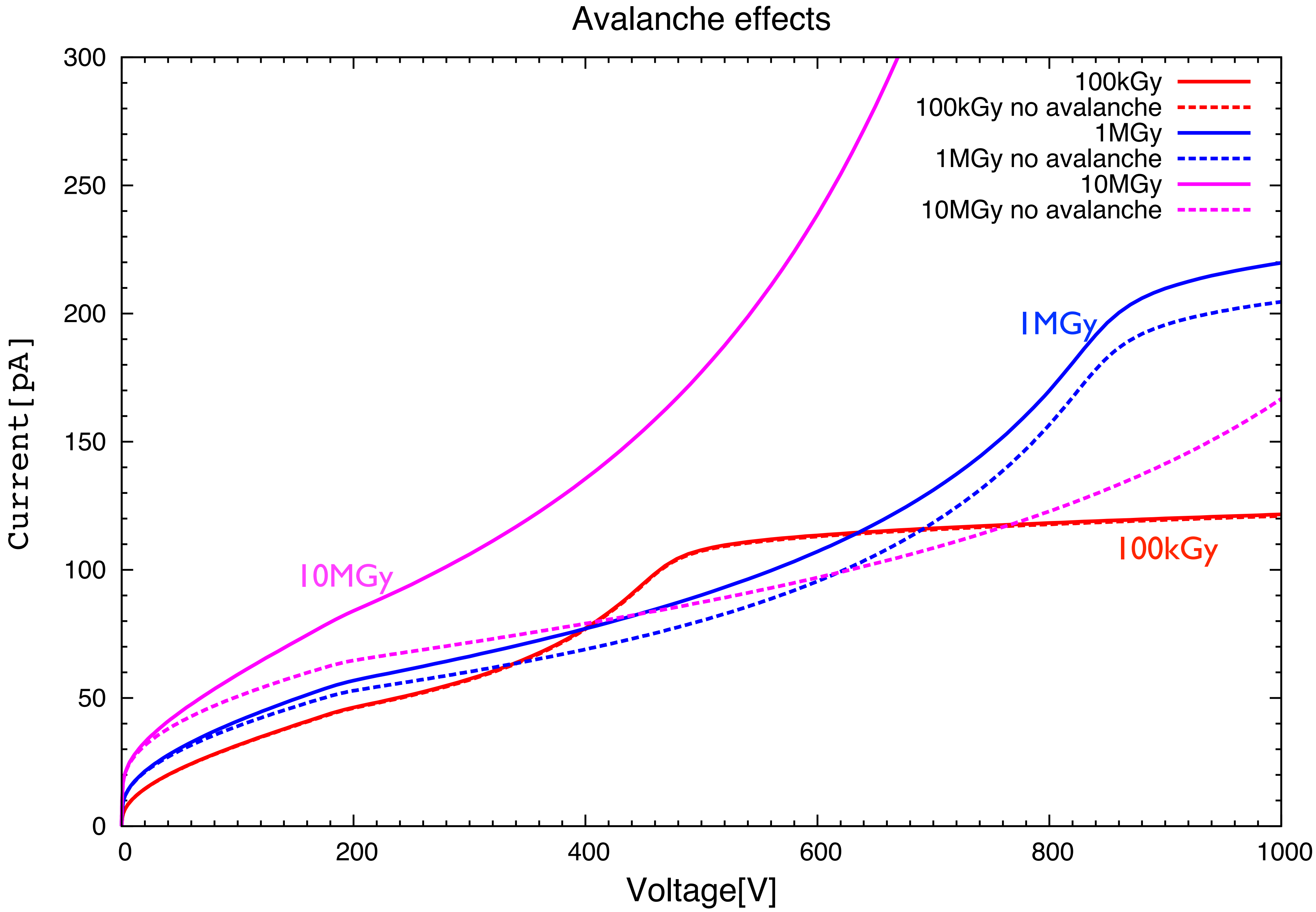
- Interpixel capacitance:

1. Analytical expression for pixel (Cerdeira et.al IEEE T Nucl Sci Vol. 44 No1 pp.63)
2. Analytical expression for strip (Cattaneo Solid State Elec. Vol 54(3) pp. 252)
3. Assumption:

$$\frac{C^{Pix}_{int,Sim}}{C^{Pix}_{int,theo}} = \frac{C^{Str}_{int,Sim}}{C^{Str}_{int,theo}}$$

Avalanche effects

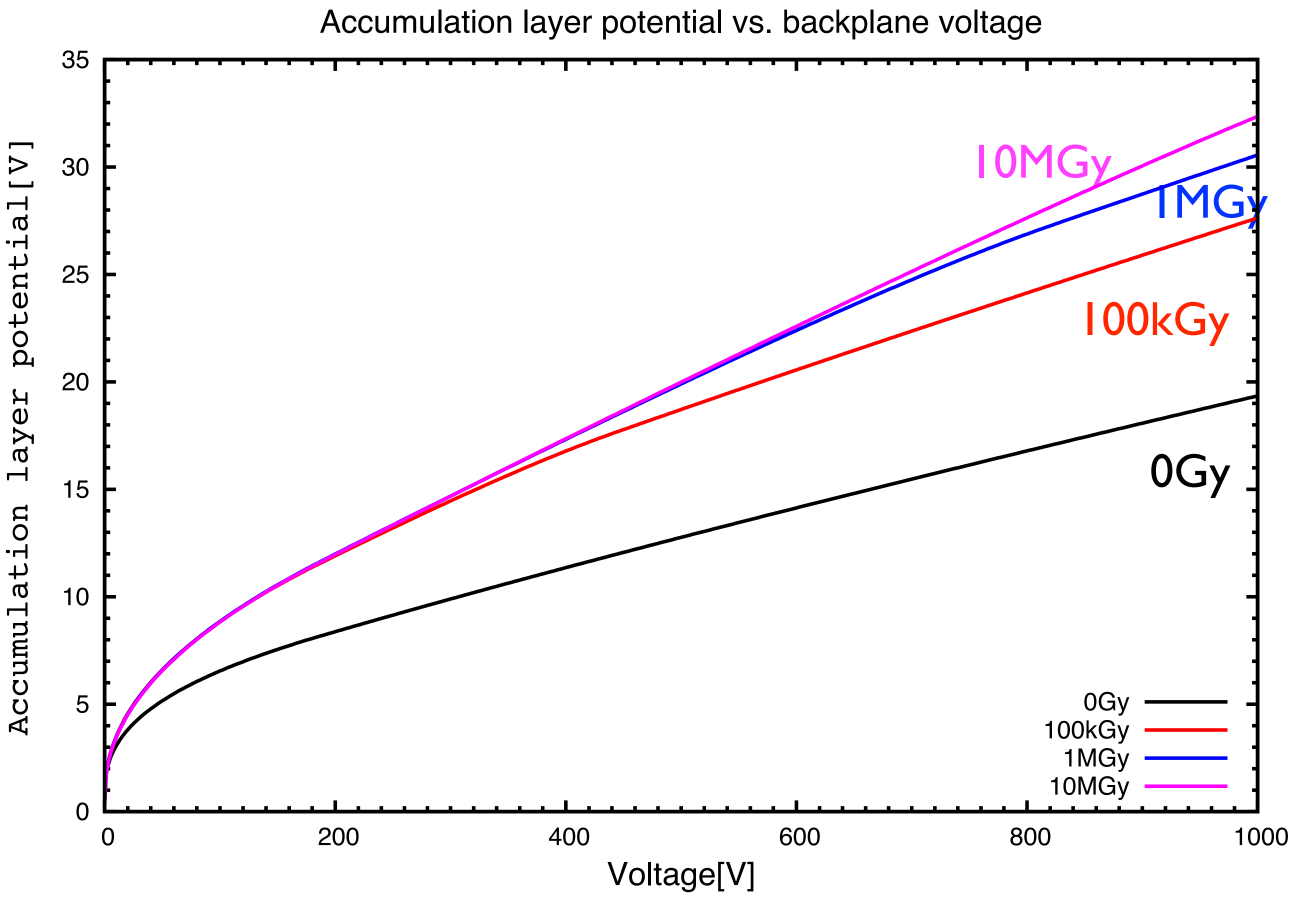
- Gap 20um, overhang 5um, junction depth 1.2um
- Simulation with and without avalanche

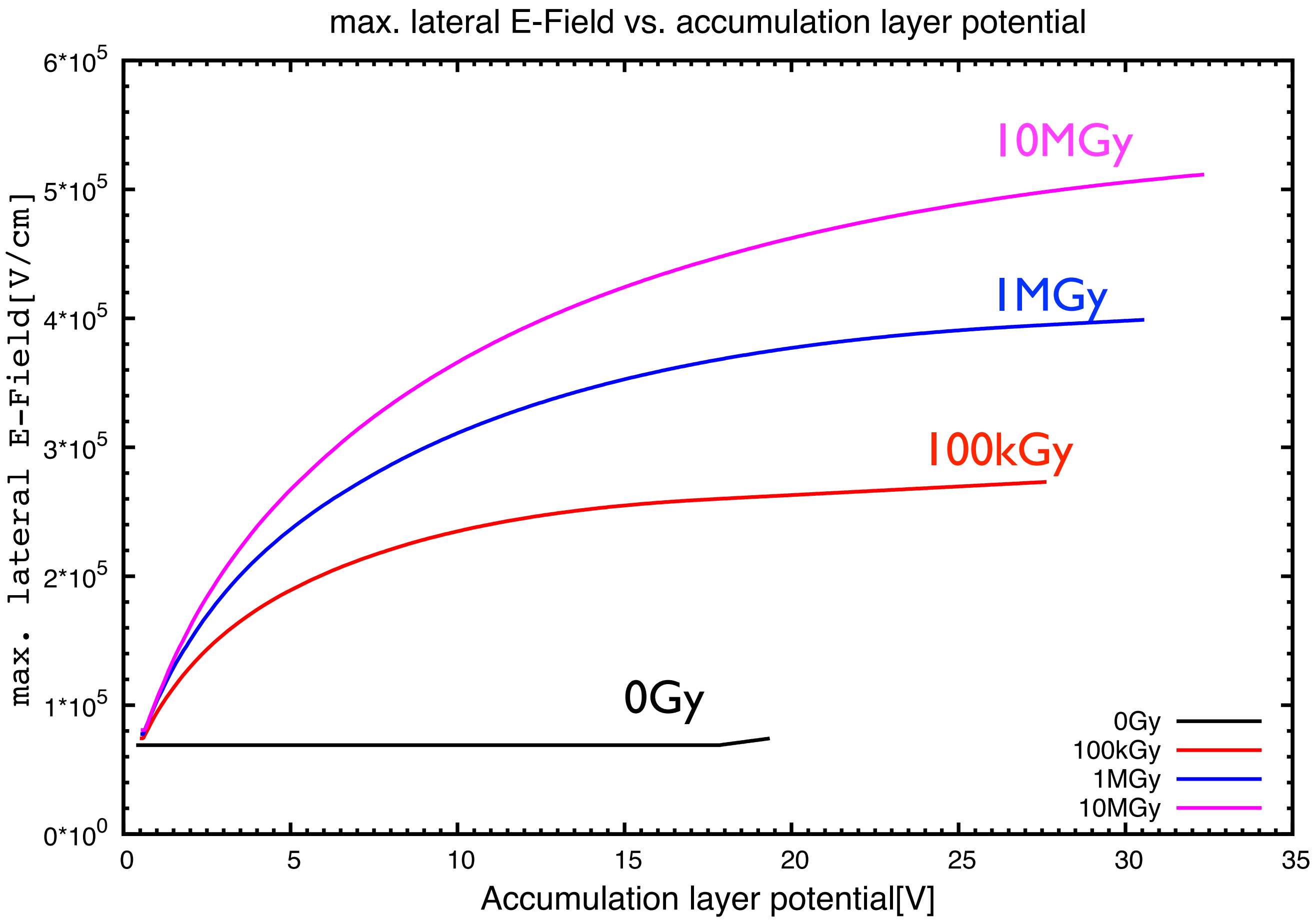


- 100kGy no contribution of impact ionization

Accumulation layer potential

- Gap 20um, overhang 5um, junction depth 1.2um





- Up to 300V the accumulation layer potential is the same for 1kGy, 1MGy and 10MGy

Max. lateral E-Field

- Gap 20um, overhang 2.5 vs. 5um, junction depth 1.2um