Sensor optimisation

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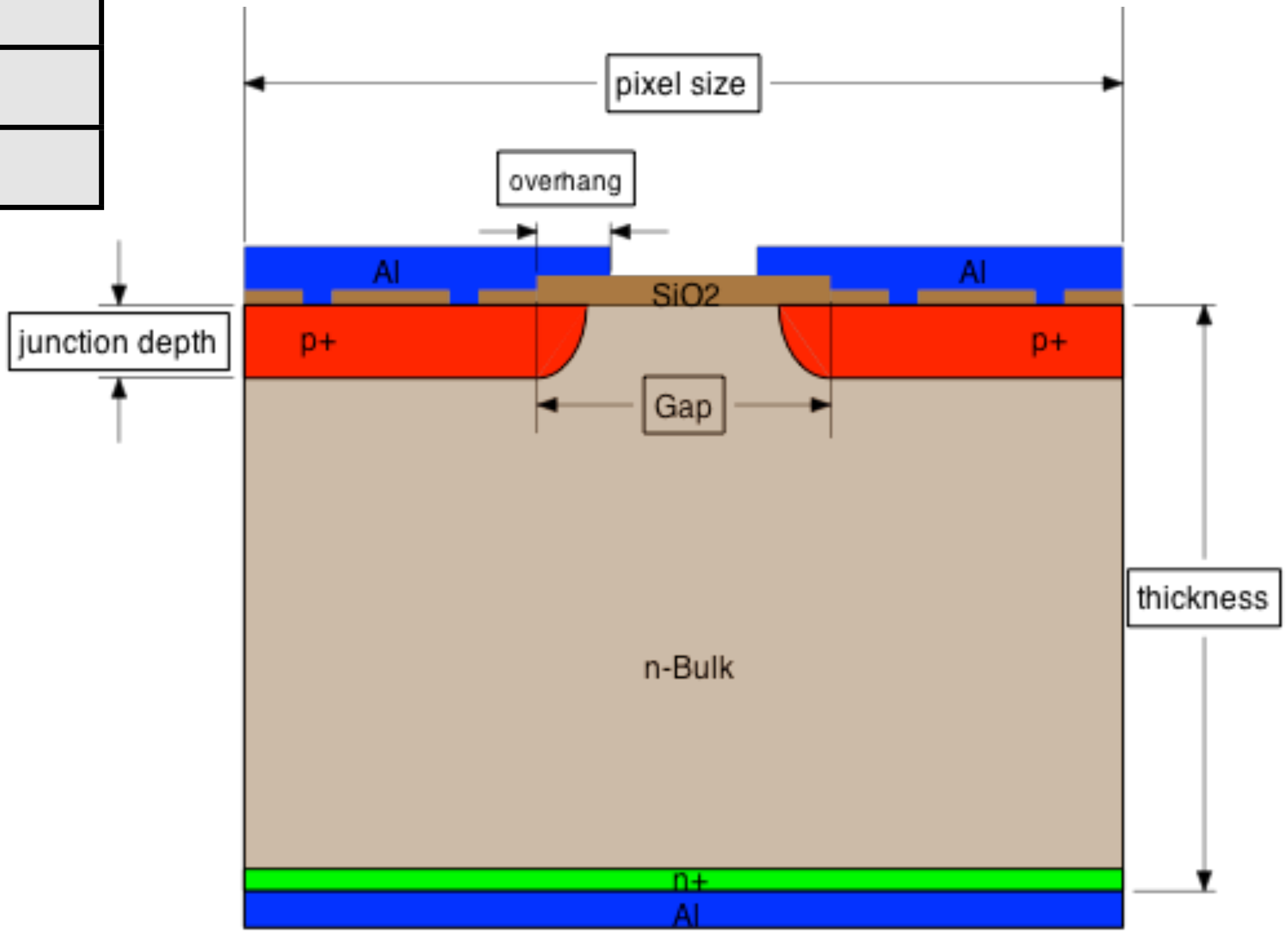
AGIPD Consortium Meeting
PSI 8.3.2010

Introduction

- Some of the so far specified sensor parameters:

Parameter	Specification
thickness	500µm
pixel size	200µm x 200µm
type	p+ n
resistivity	~5kΩ·cm
V_fd	< 200V
V_op	500V
C_int	< 0.5pF
I_leak	< 10 nA/pixel

- Left to define:
  - gap
  - metal overhang
  - curvatures at edges
  - guard ring structure



Introduction

- The problem: Surface damages → 1. higher oxide charge 2. higher surface recombination velocity

- At gated diodes measured values:

Dosis [MGy]	Nox [cm^-2]	S_0[cm/s]
0	1.00E+11	8
0.1	1.33E+12	3.50E+03
1	2.07E+12	7.50E+03
10	2.78E+12	1.20E+04
100	2.87E+12	1.05E+04

- Question:

  What is the fill state of the traps?

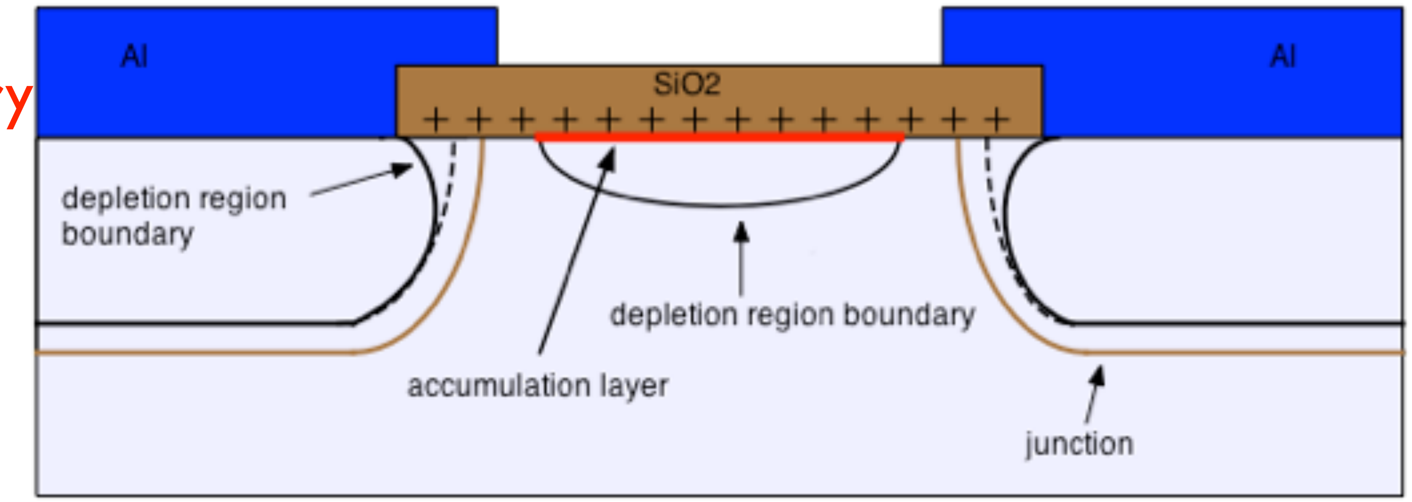
  We assume acceptor like, but have not taken this into account in the simulations.

- The effects will be:

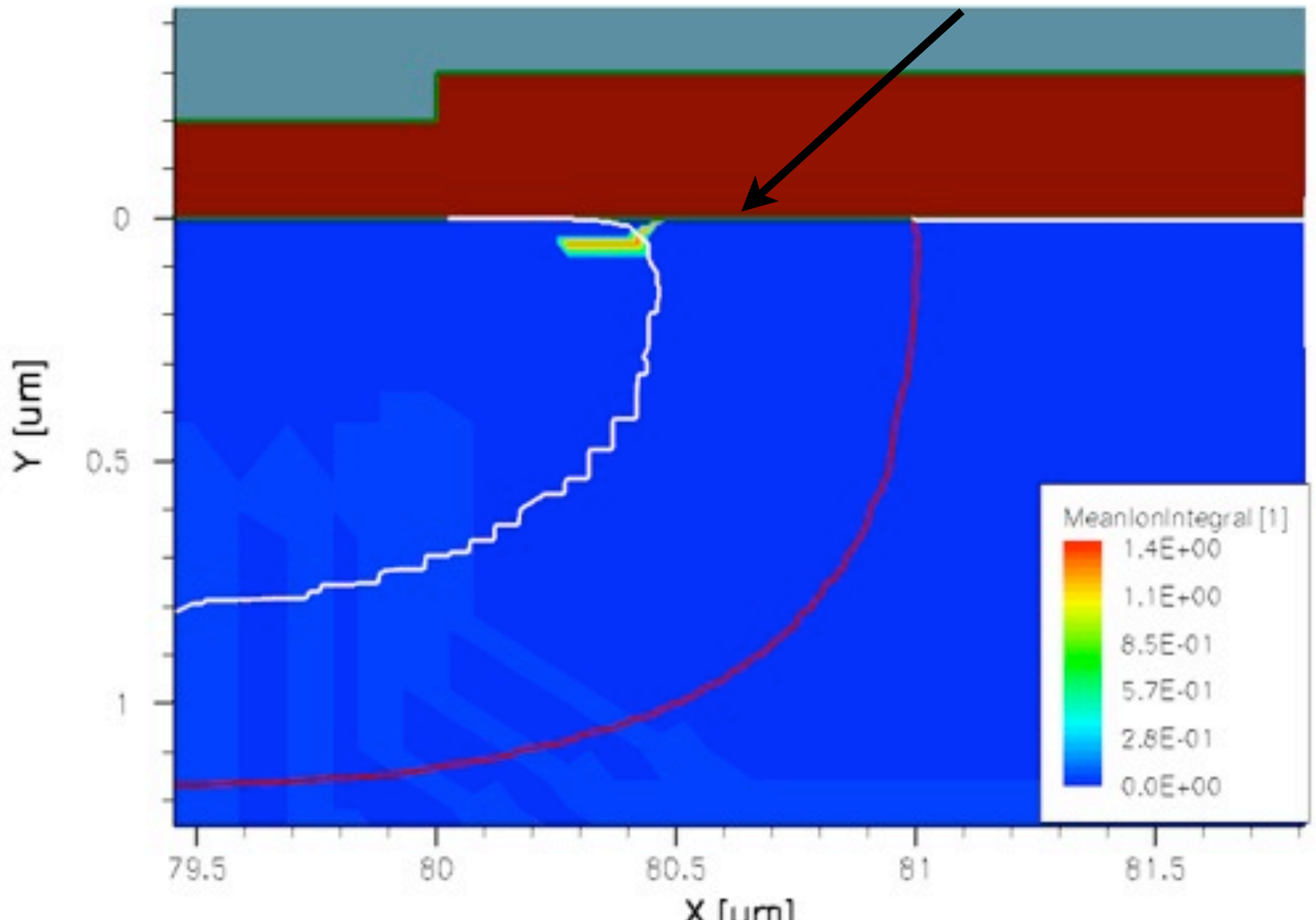
  1. Increased leakage current
  2. Increased inter-pixel capacitance
  3. Lower breakdown voltage

Introduction

- Oxide charge effects in p-n Sensor:
- Strong curved depletion region boundary
  → high electric field
- Negatively charged accumulation layer
  → not fully depleted surface
  → high electric field (over short path)
  → charge losses
- Surface current ∝ not depleted surface



Breakdown path



- For a correct simulation we need:
  1. Oxide charge density distribution
  2. Surface recombination velocity
  3. Oxide thickness
  4. Realistic implant profile
- How to get implant profiles?

  Process simulation ↔ SIMS

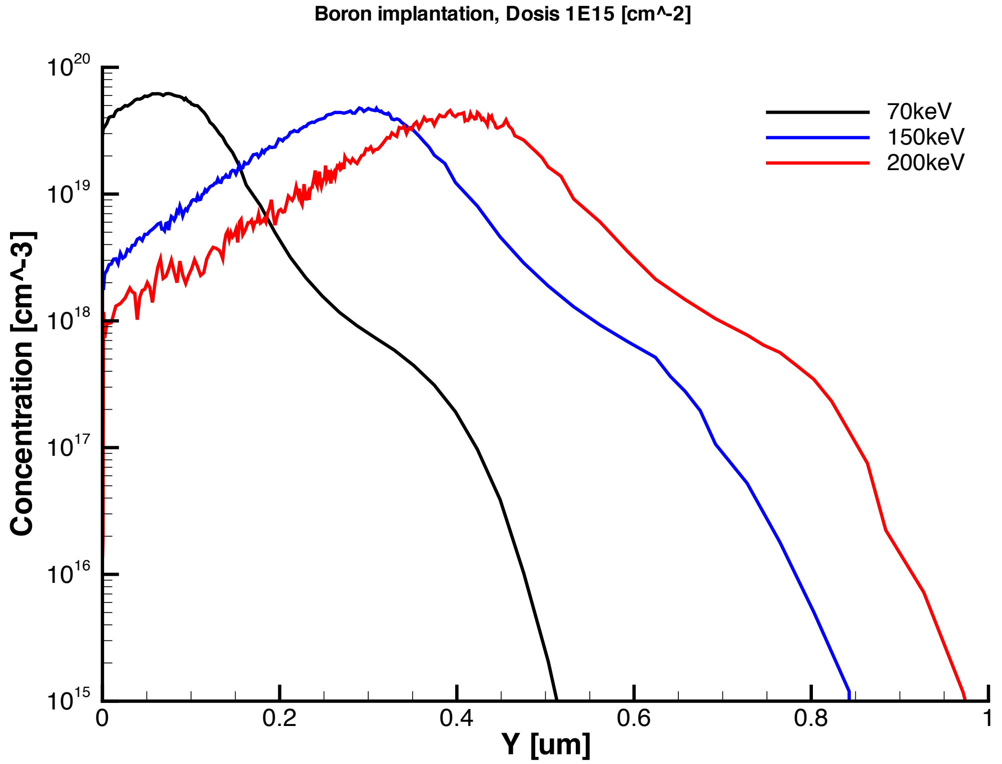
Process simulation I

- Commonly used technique for p+ junction formation: Ion Implantation
- Steps:

1. Implantation:

Simulations:

Wafer dop	P 1E12[cm^-3]
Orientation	(1 1 1)
Tilt angle	0°
Species	Boron
Dosis	1E15,5E15,1E16[cm^-2]
Energy	70,150,200keV

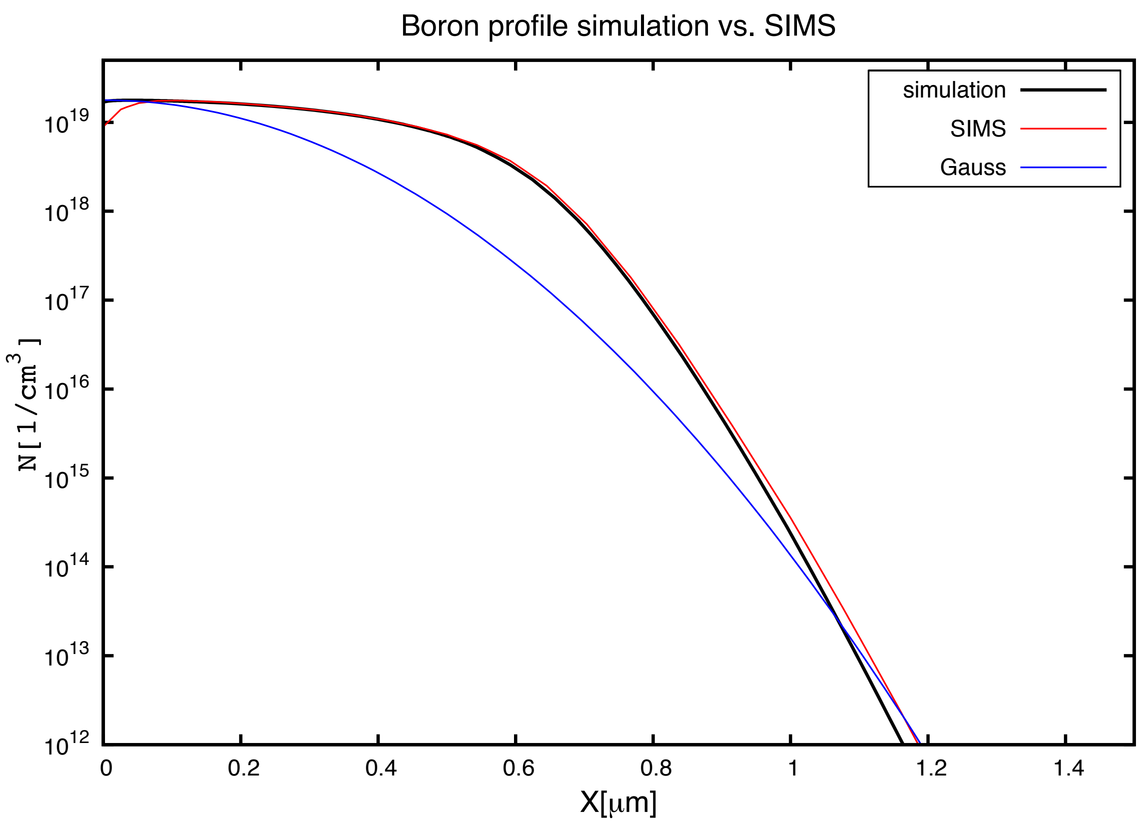


2. Drive in:

Simulations:

Temp.	975, 1025 °C
Time	same for both

- The simulation is calibrated with a SIMS measurement for the same process.



Process simulation 2

- Results: Standard process →

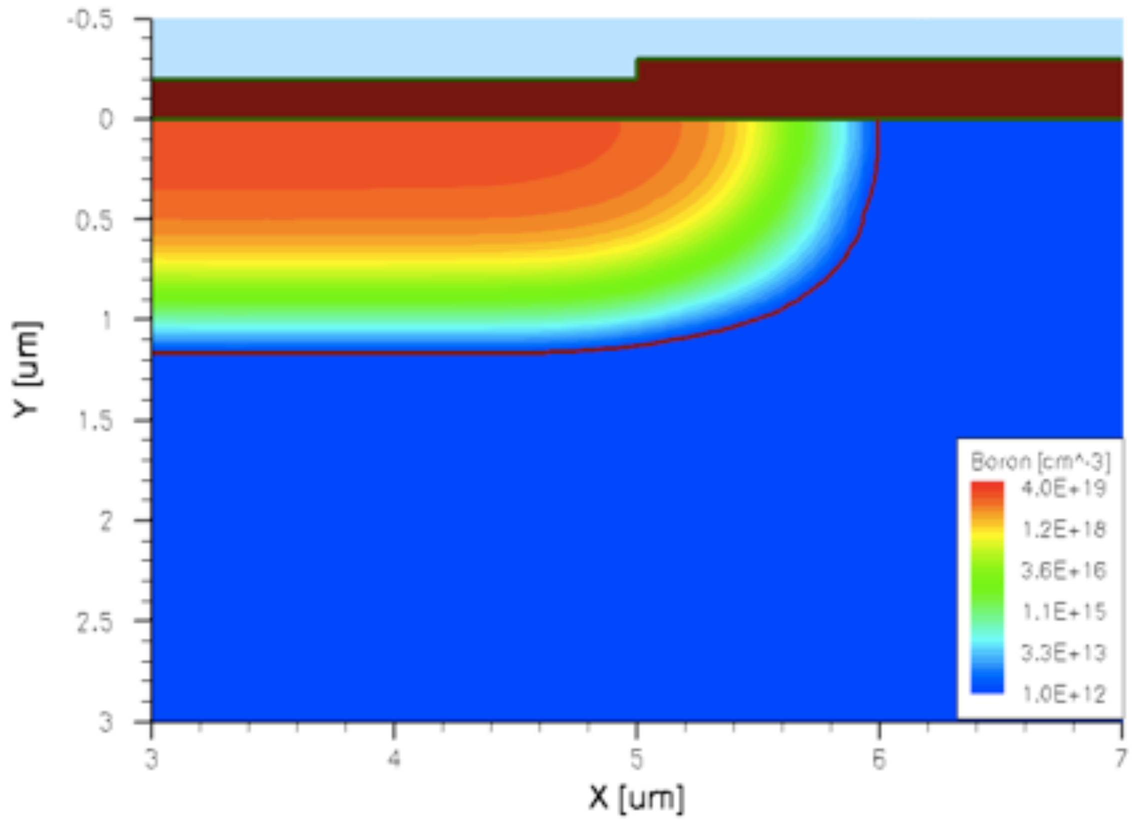
Dosis [cm^-2]	Energy [keV]	Temp. [C]	Junction depth [um]	lateral length [um]	Peak con[cm^-3]
1.00E+15	70	975	1.16	0.99	1.77E+19
5.00E+15	70	975	1.48	1.29	5.30E+19
1.00E+16	70	975	1.76	1.43	8.50E+19
1.00E+15	150	975	1.46	1.07	1.65E+19
5.00E+15	150	975	1.72	1.22	5.80E+19
1.00E+16	150	975	1.98	1.61	9.50E+19
1.00E+15	200	975	1.61	1.12	1.32E+19
5.00E+15	200	975	1.82	1.32	5.40E+19
1.00E+16	200	975	2.06	1.54	9.75E+19
1.00E+15	70	1025	1.92	1.71	1.27E+19
5.00E+15	70	1025	2.4	1.95	3.89E+19
1.00E+16	70	1025	2.75	2.35	6.12E+19
1.00E+15	150	1025	2.16	1.7	1.33E+19
5.00E+15	150	1025	2.57	2.16	4.30E+19
1.00E+16	150	1025	2.91	2.4	6.87E+19
1.00E+15	200	1025	2.28	1.75	1.18E+19
5.00E+15	200	1025	2.6	2.1	4.24E+19
1.00E+16	200	1025	2.97	2.35	6.81E+19

- Conclusion:

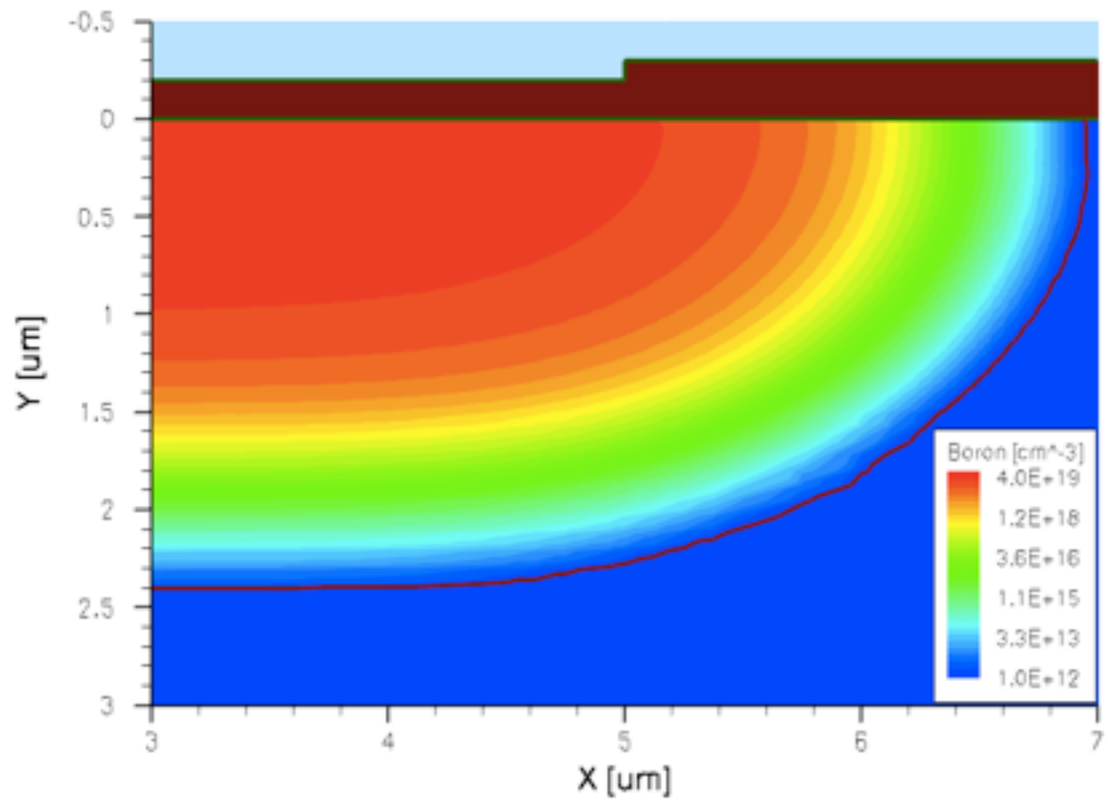
  Junction depth up to 3um are possible with slightly increases temperature.

- In the following used profiles:

depth 1.2



depth 2.4



Device simulation

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

- Geometries:
- Oxide thickness: 300 nm
- 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 Tunnelling
  - 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: Ionisation 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

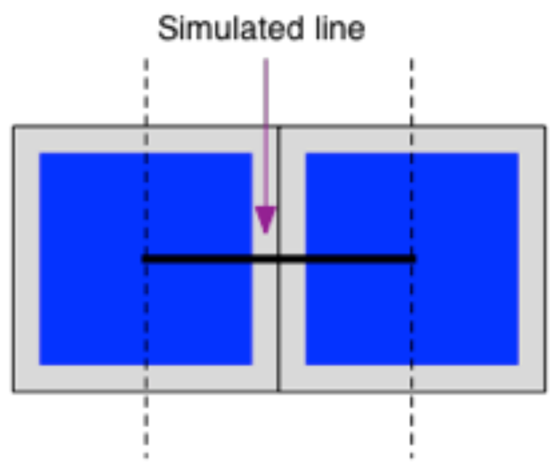
W_d width depleted region

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 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)

- Interpixel capacitance:

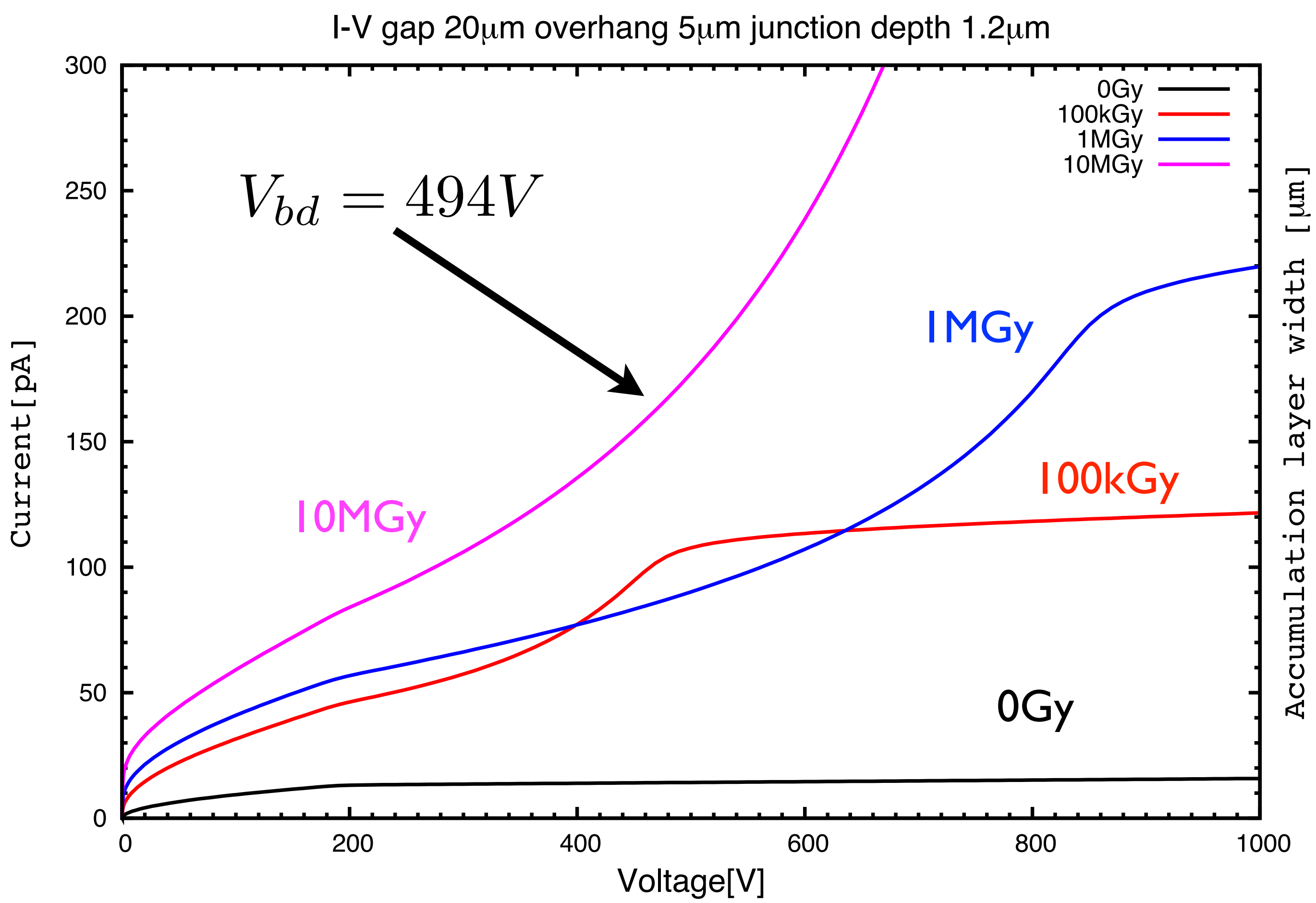
1. Analytical expression for pixel (Cerdeira et.al IEEE T Nucl Sci Vol. 44 No1 pp.63)
2. Analytical expression for strip (Cattaneo Solid State Elec. Vol 54(3) pp. 252)
3. Assumption:

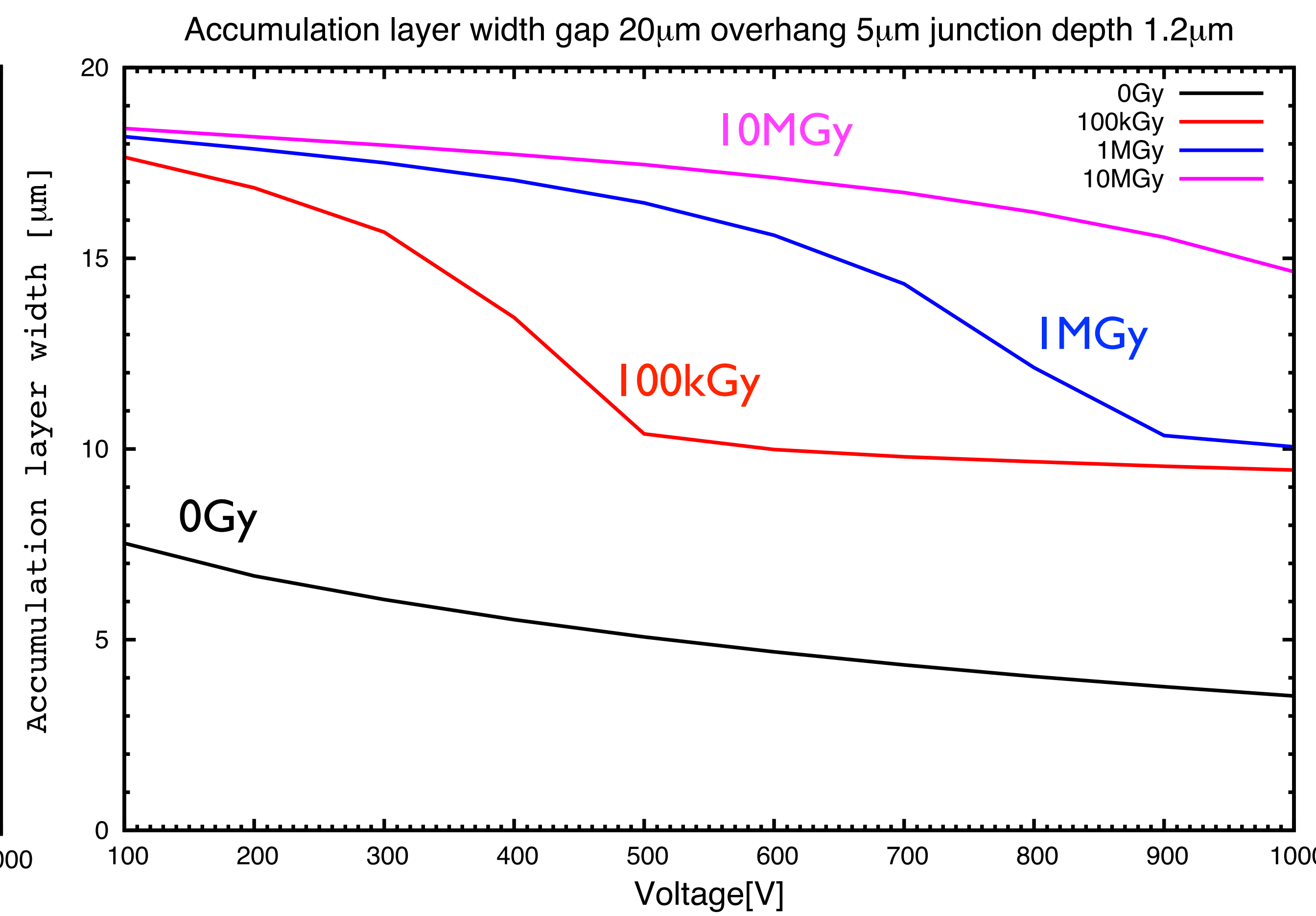
$$\frac{C^{Pix}_{int,Sim}}{C^{Pix}_{int,theo}} = \frac{C^{Str}_{int,Sim}}{C^{Str}_{int,theo}}$$

Results

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

Accumulation layer width was measured by cutting at 0.02um below SiO2/Si interface and measure the decrease of the electron density to 1e12[cm^-3].

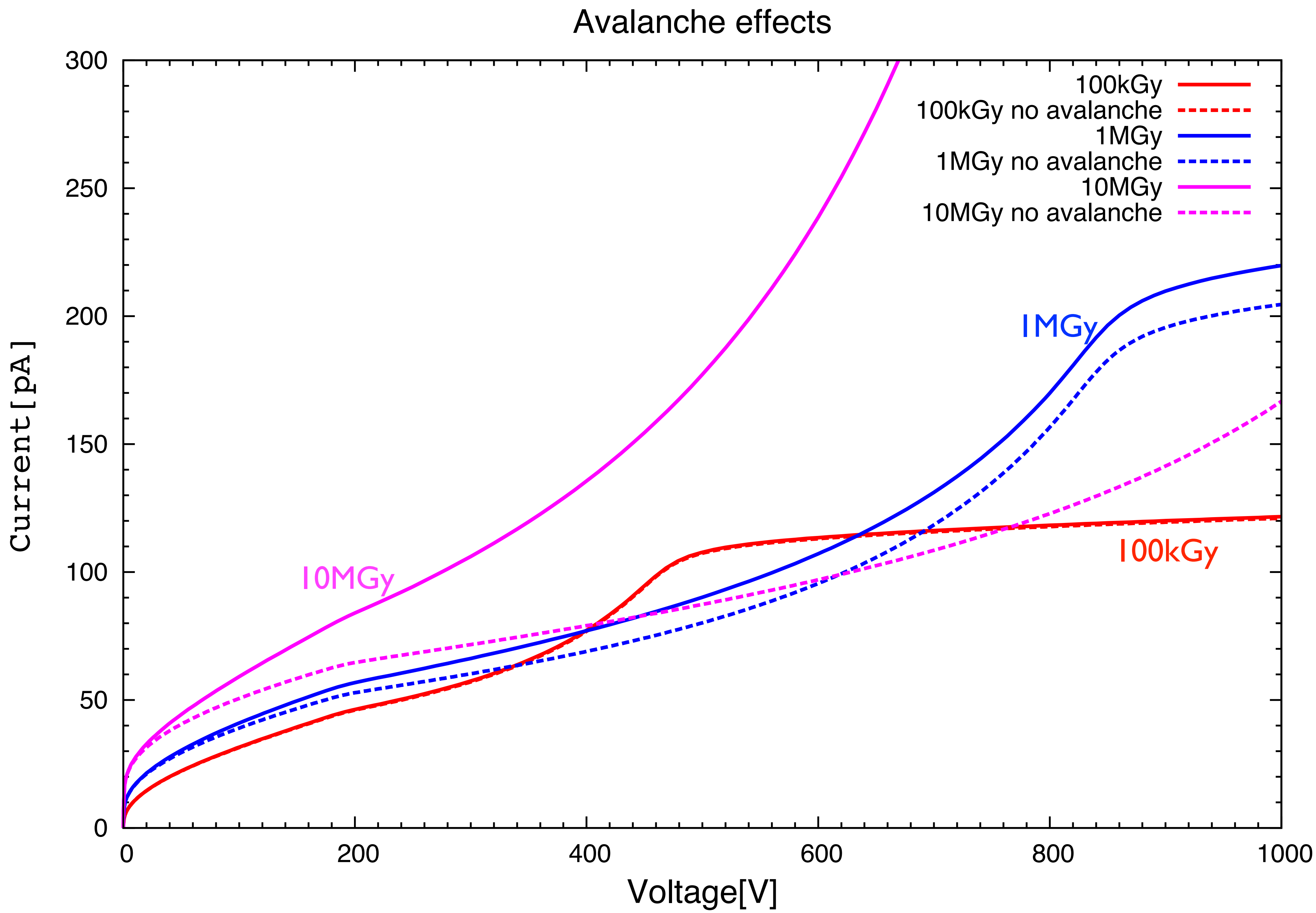




- Breakdown for 10MGy at 494V
- Accumulation layer does not vanish for non irradiated sensor at high voltage

Results

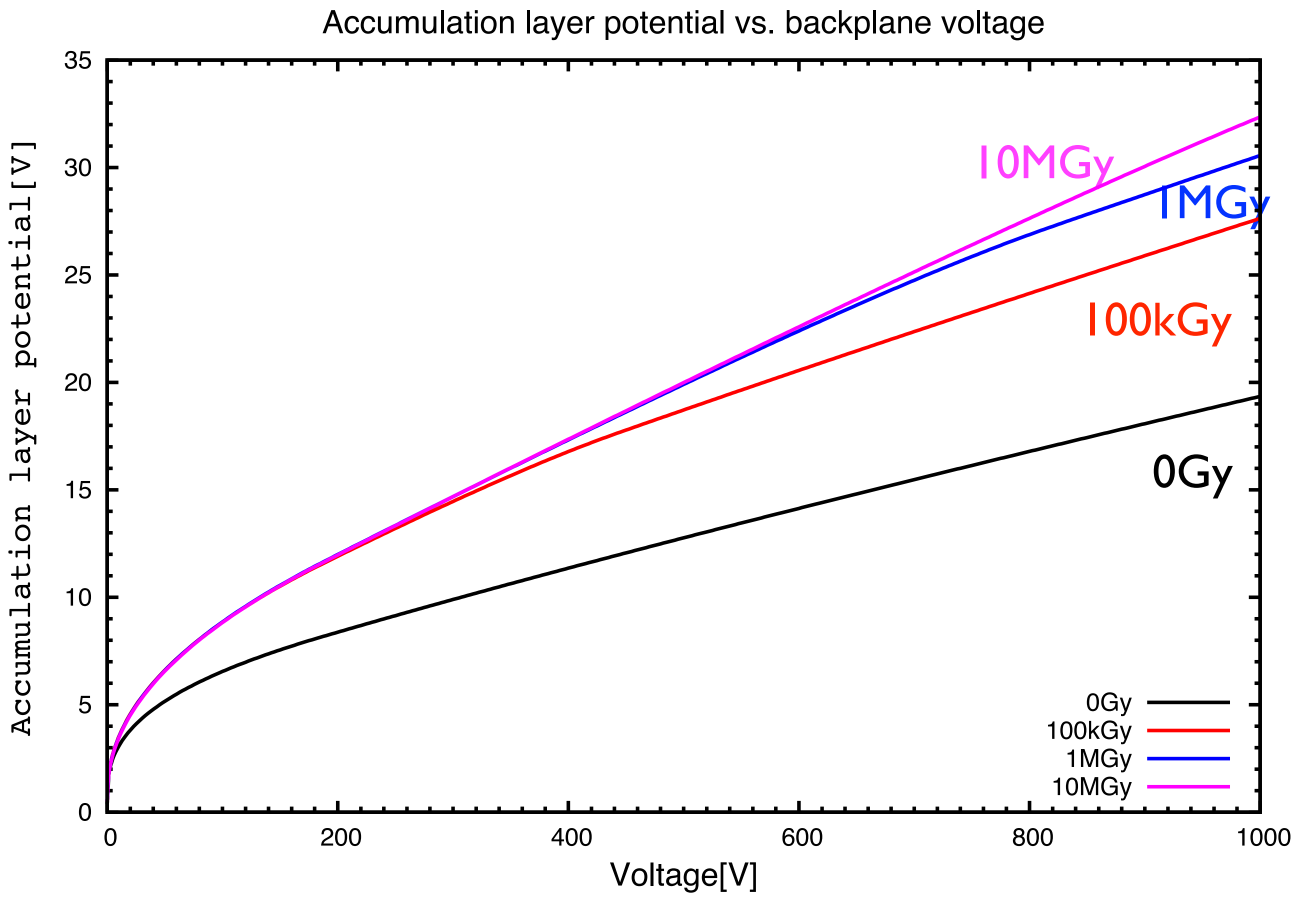
- Gap 20um, overhang 5um, junction depth 1.2um
- Simulation with and without avalanche

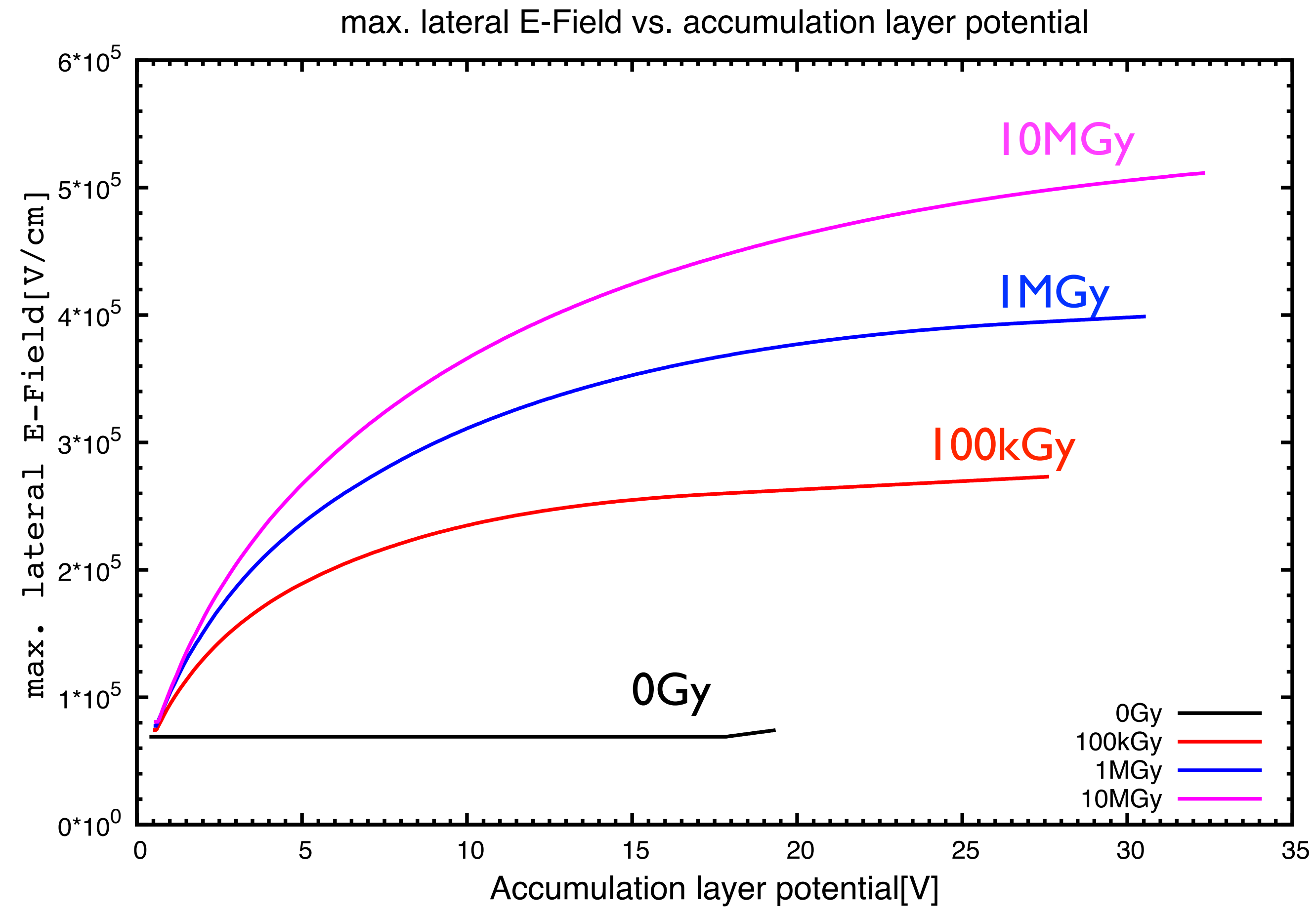


- 100kGy no contribution of impact ionisation

Results

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

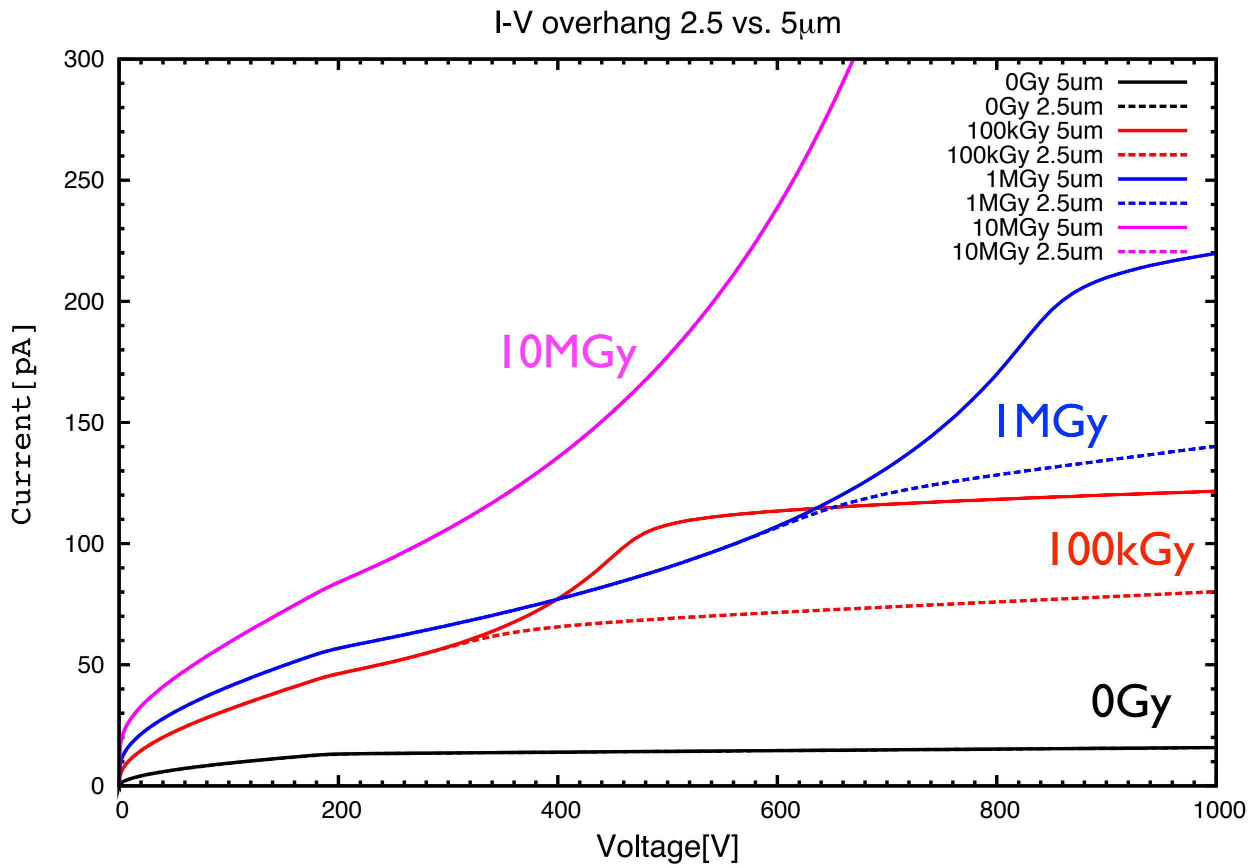


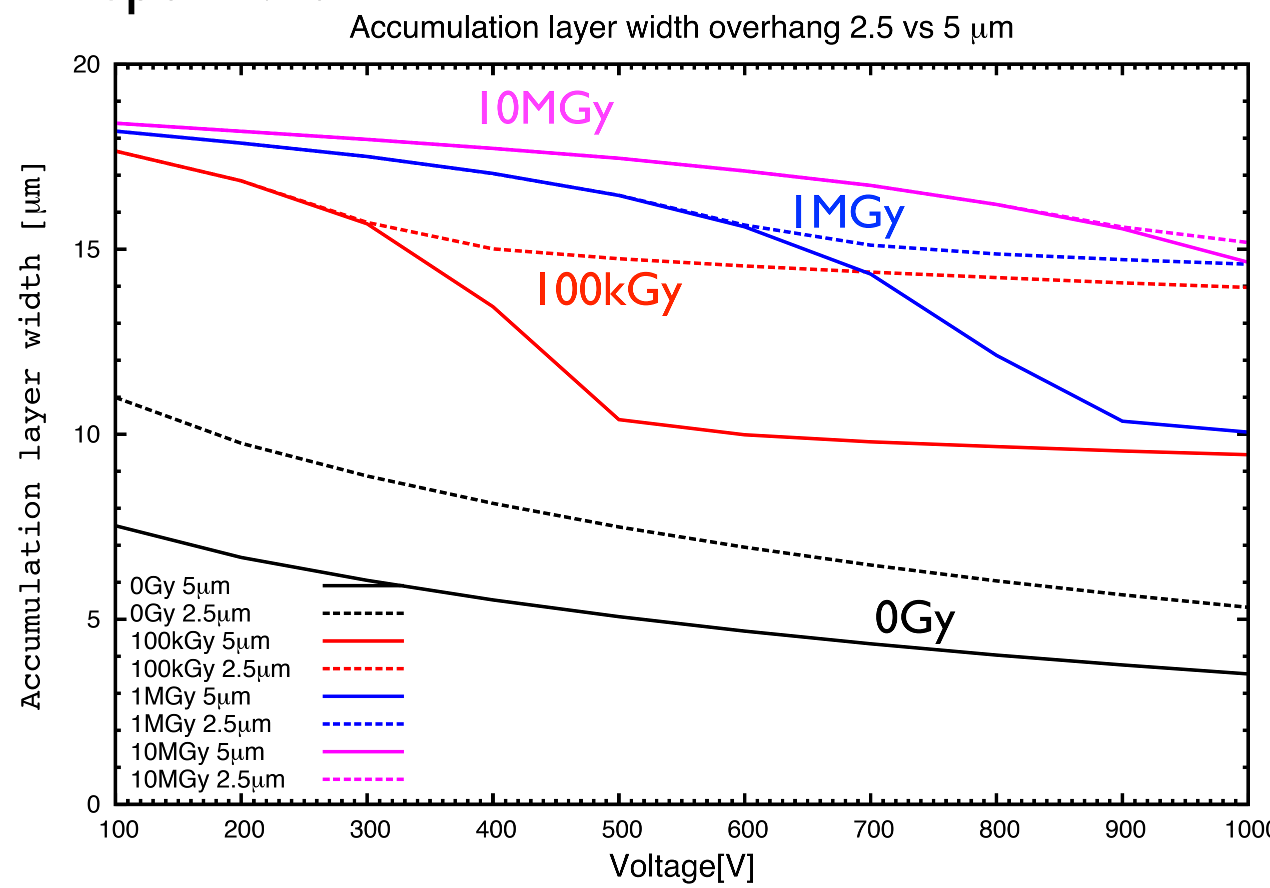


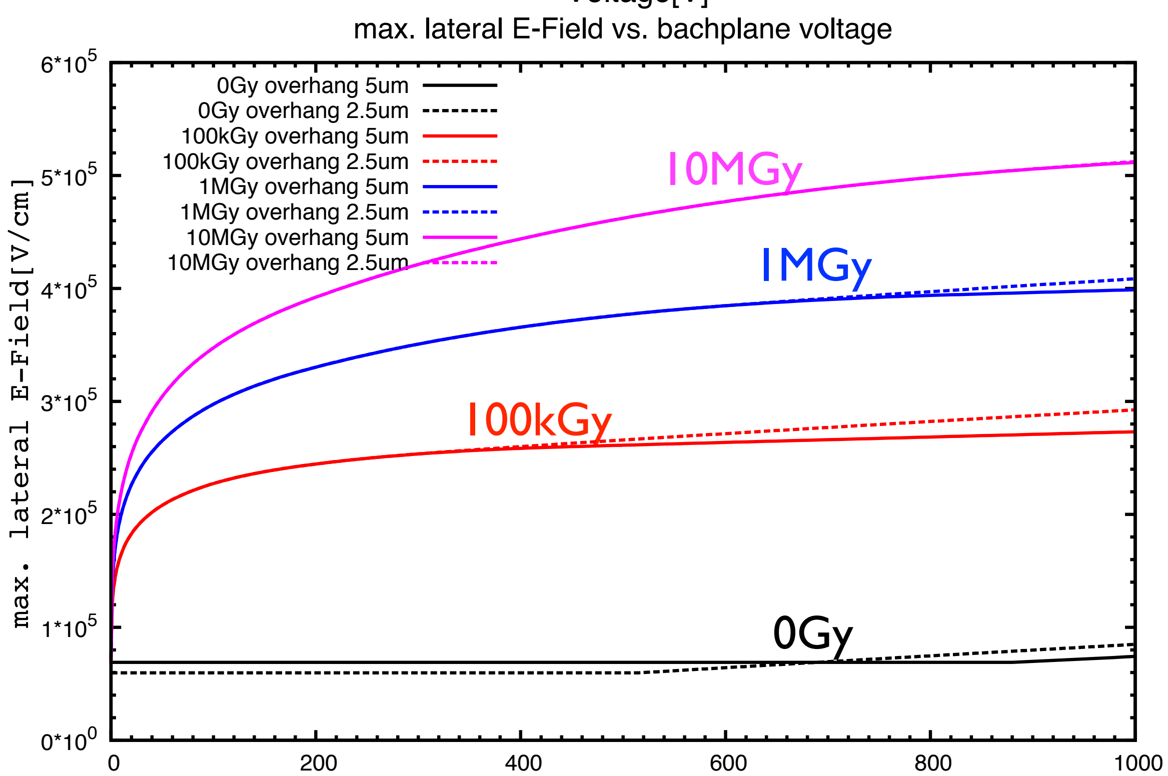
- Up to 300V the accumulation layer potential is the same for 1kGy, 1MGy and 10MGy

Results

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



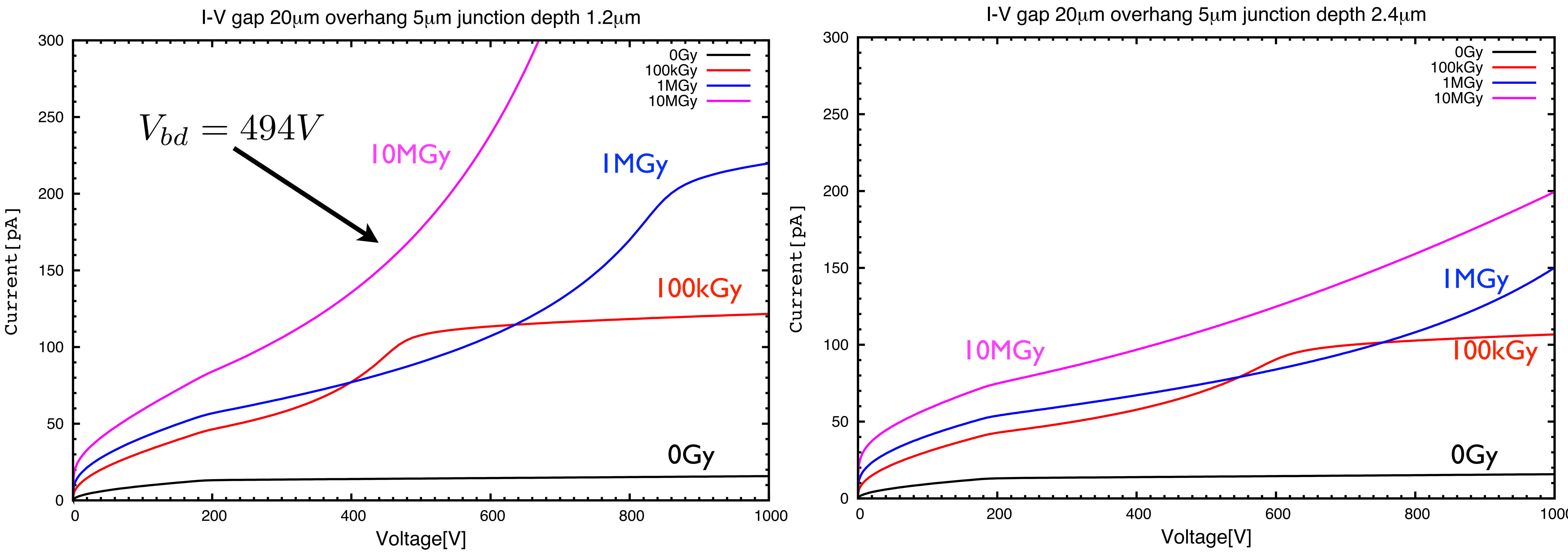




- For sufficient high voltage the smaller gap develops a smaller current.
- For 10MGy same breakdown voltage.
- Similar max. lat. E-Field.

Results

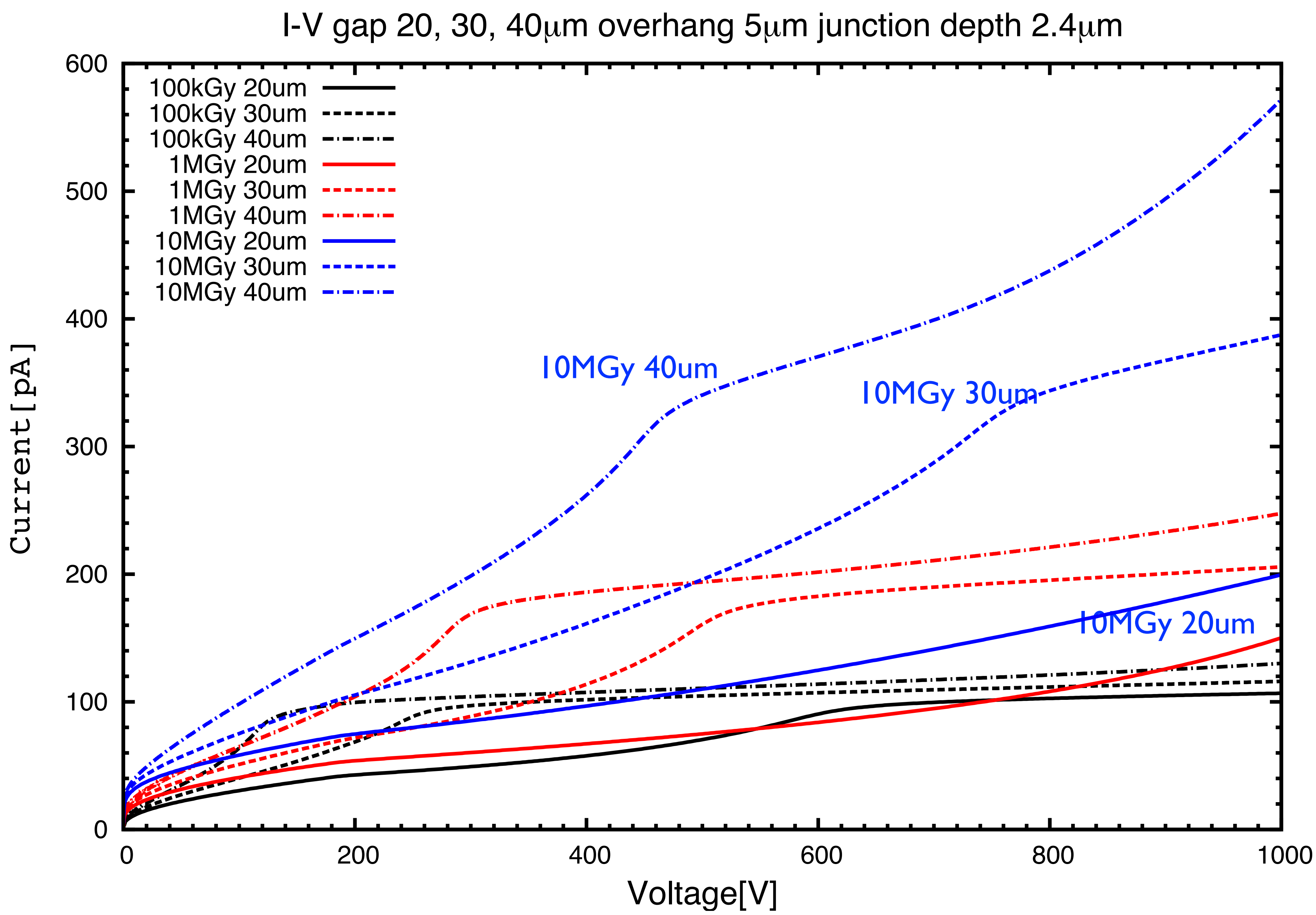
- Gap 20um, overhang 5um , junction depth 1.2um vs. 2.4um



- The deeper junction shows for the 10MGy case no breakdown up 1000V and for 1kGy and 1MGy a slightly smaller current.

Results

- Junction depth 2.4um



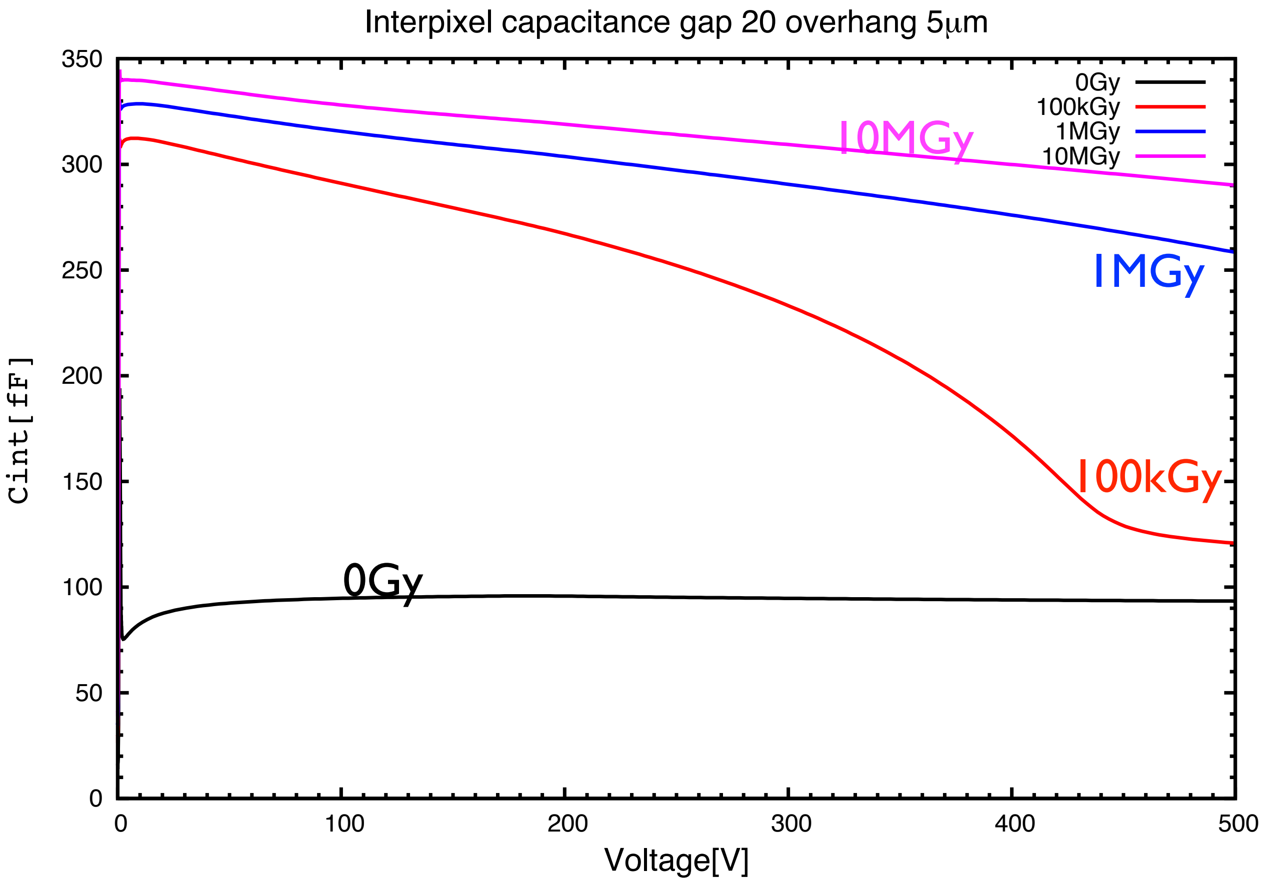
- No breakdown up to 1000V
- Keep in mind: diagonal of pixel is sqrt(2)*gap

Results

- Capacitance simulations: 100kHz, junction depth 1.2um
- V_fd = 188 - 194V compared to 193V for pad sensor and dop. 1E12
- C_b = 8.5 - 8.56fF compared to 8.43fF for pad sensor

- C_int for 5um overhang:

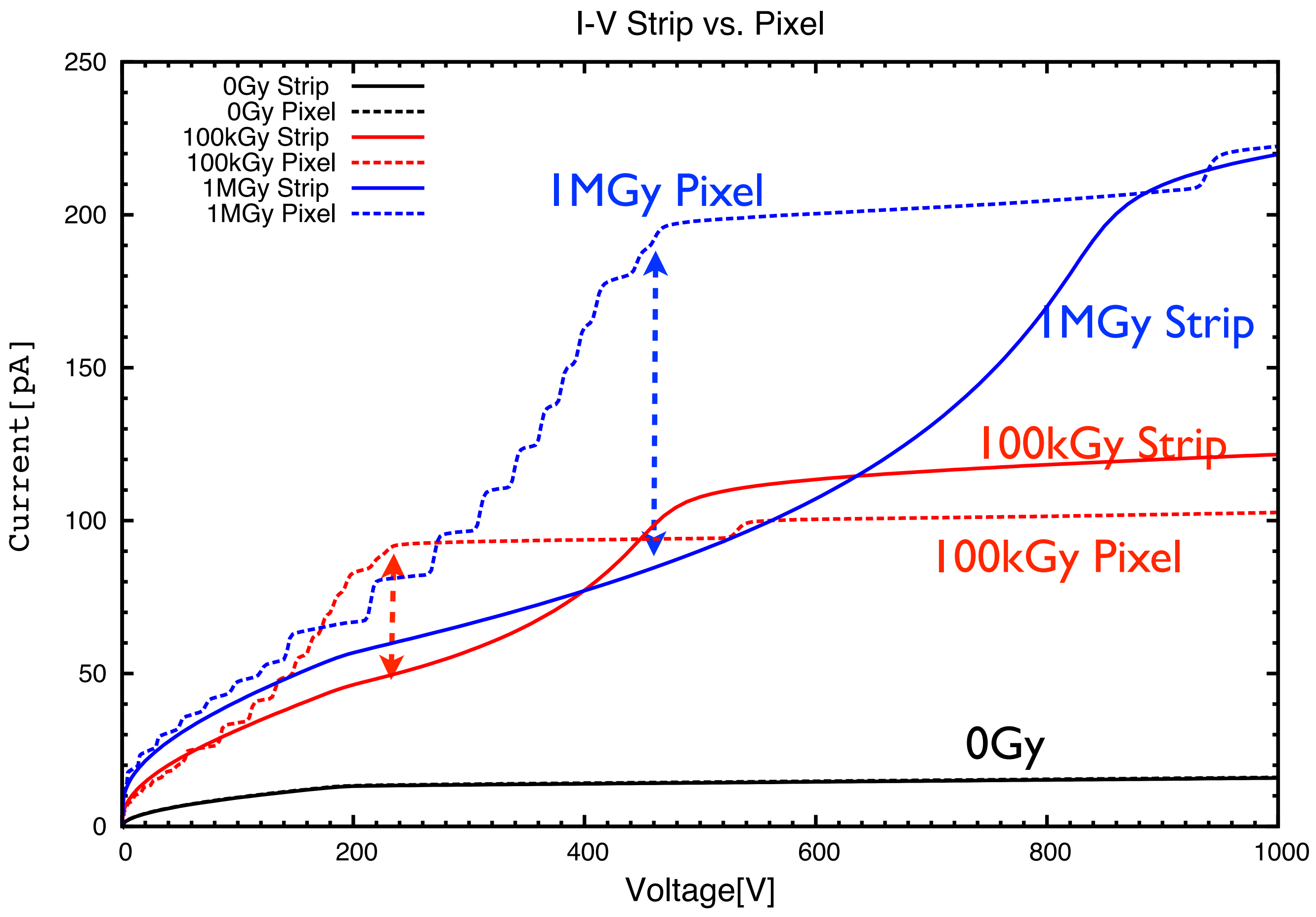
Gap	Dosis	C_int[fF] at V_fd	C_int[fF] at 500V
20um	0Gy 1MGy	96 305	93 259
30um	0Gy 1MGy	73 117	71 92
40um	0Gy 1MGy	59 163	56 82

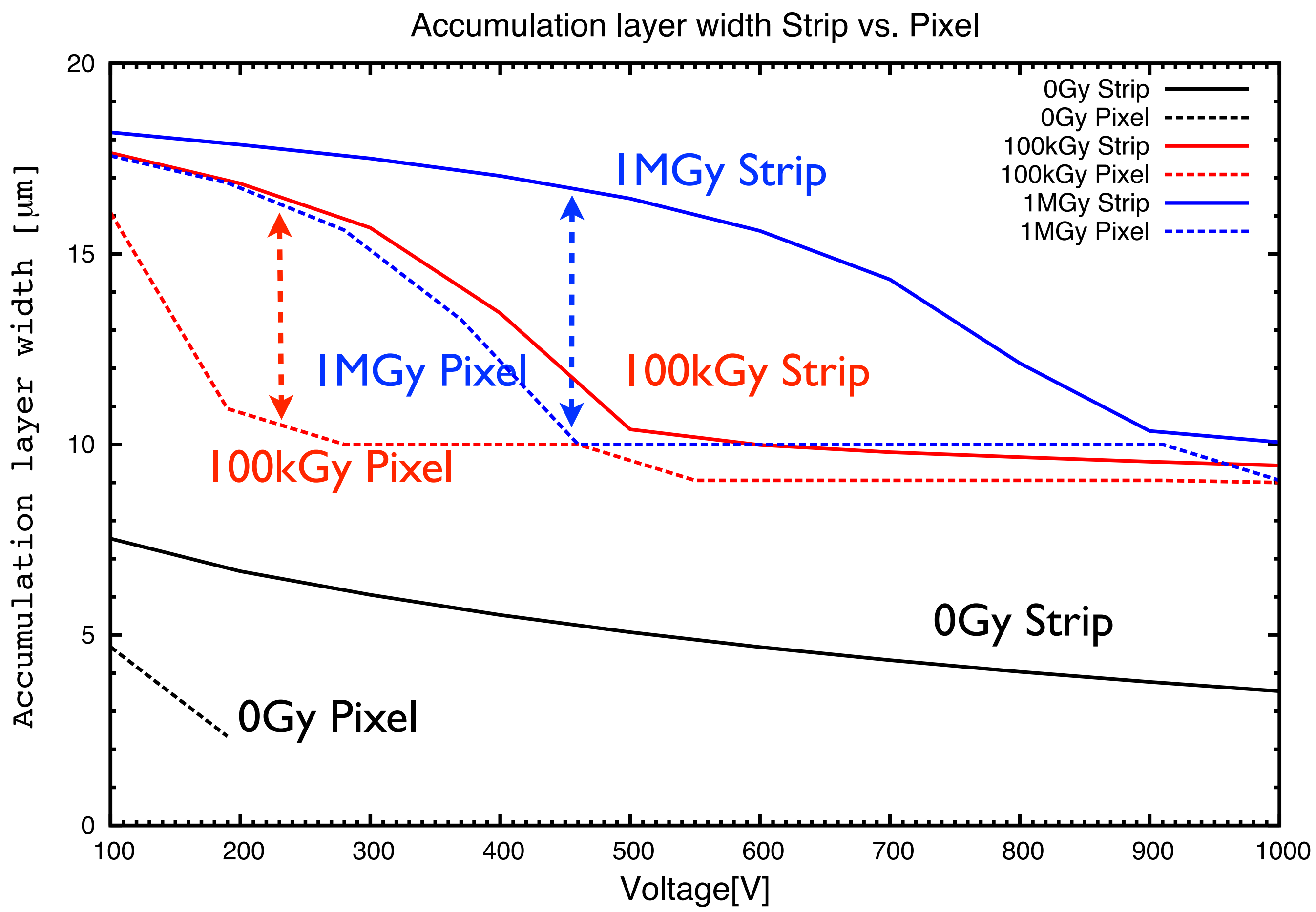


- Decrease of interpixel capacitance with voltage due to accumulation layer

Results

- First results of 3D Pixel simulation
- Quarter of full Pixel with gap 20um and overhang 5um simulated
- Gaussian doping profile with junction depth 1.5um





- 0Gy Pixel: Accumulation layer only around the diagonal for higher voltages
- Irradiated: Different behavior of surface depletion for pixel and strip

→ Scaling of current from strip to pixel difficult

Conclusions

1. Successful simulation of implantation profile
2. Simple recipe for scaling of 2D to 3D capacitance
3. Breakdown voltage for irradiated sensor:

   Design with 20um gap and 1.2um junction depth ~ 500V

   Design with 20um gap and 2.4 um junction depth > 1000V
4. current/pixel < 1nA seems to be no problem
5. accumulation layer decrease with voltage

⇒ first detailed results

Backups

TCAD Simulation flow

- Used software Synopsys TCAD
- ICWBEV: Editing GDS files, mark simulation region
- Sentaurus Process:
  1. 1-dim simulation for Phosphorus profile
  2. 2-dim simulation for Boron profile (10um around implant window)
  3. 2-dim simulation for geometry generation
- Structure Editor:
  1. Positioning of profiles
  2. Refinement windows for mesh
  3. Defining contacts
- Sentaurus Mesh: Generate mesh for device simulation
- Sentaurus Device:
  1. Simulation of I-V
  2. Small-signal analysis for C-V