Status Report:
Optimization and Layout Design of AGIPD Sensor

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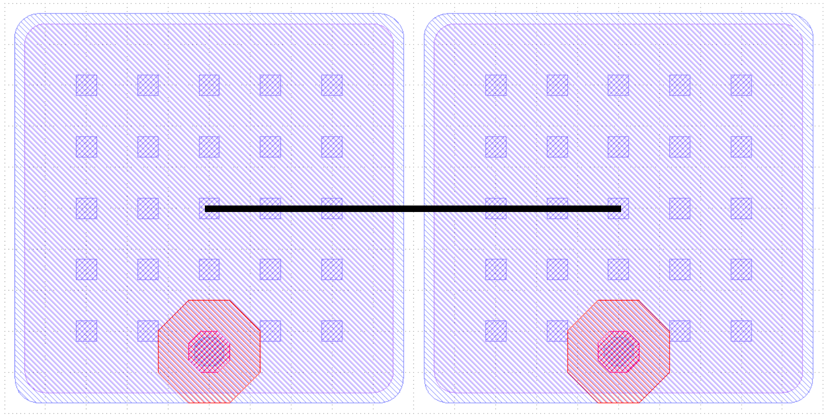
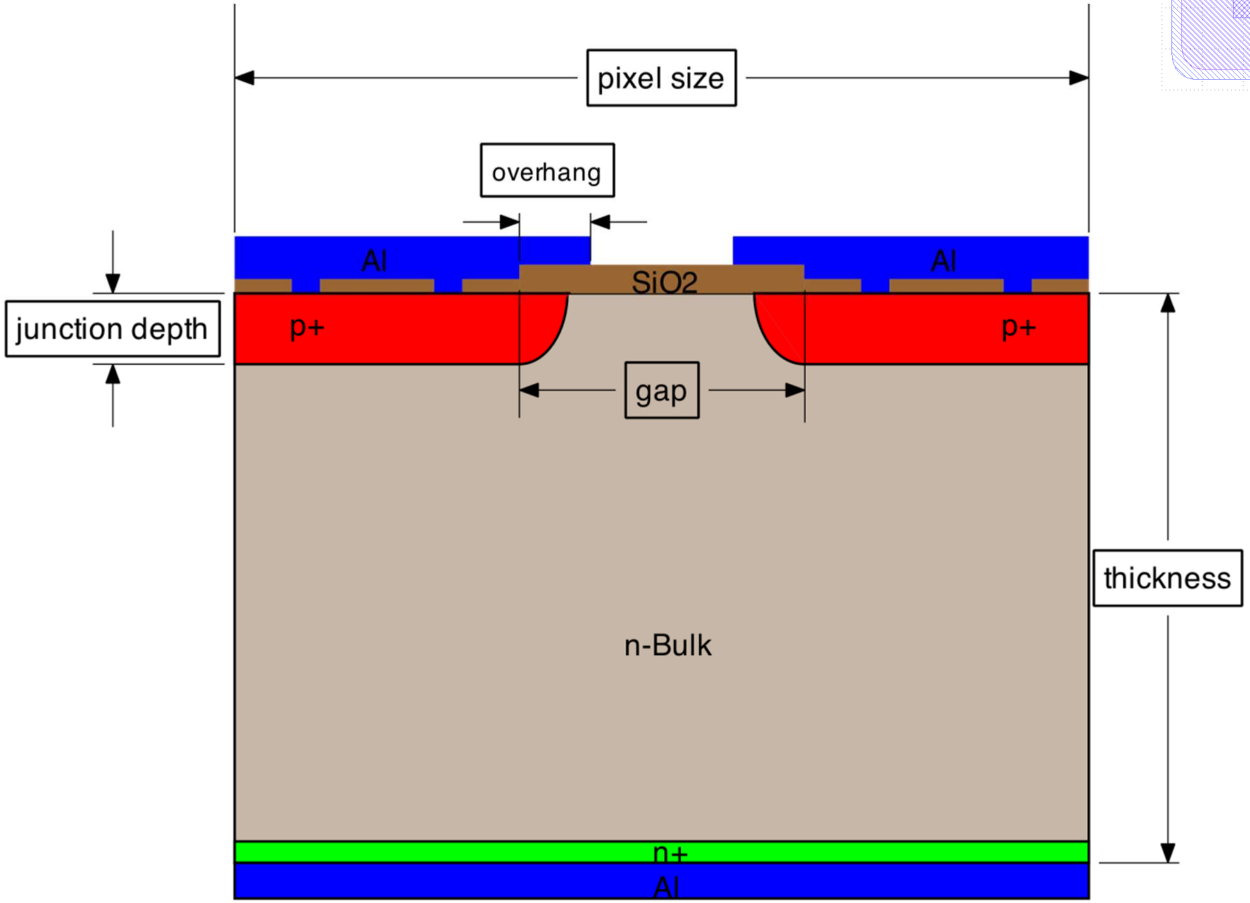
Outline

- Effects of X-ray radiation damage on silicon sensor
- Optimization of pixel layout
- Optimization of guard ring layout
- Open questions
- Conclusions

Effects of X-ray radiation damage on silicon sensors

Pixel layout:

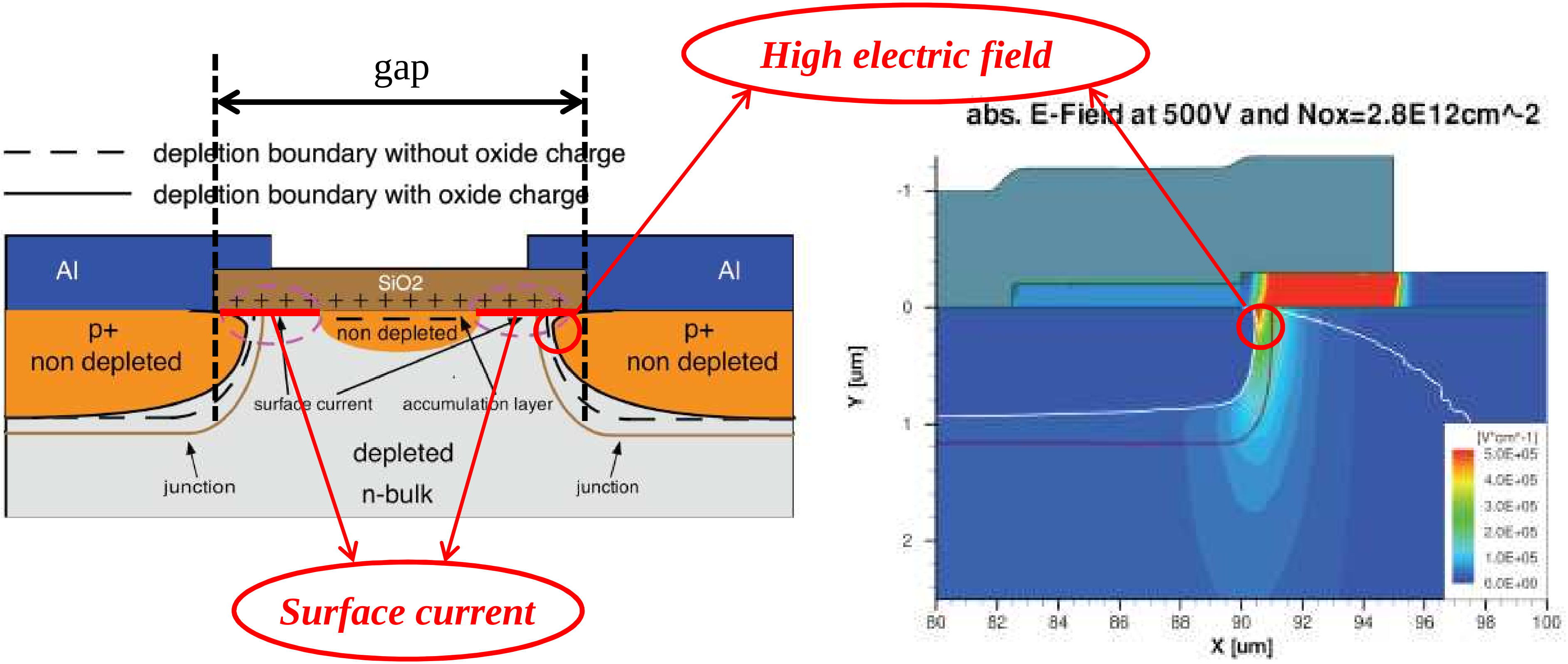




Effects of X-ray radiation damage on silicon sensors

What are the problems for X-ray radiation hard pixel sensors:

- Breakdown (high electric field) ← accumulation layer (oxide charges + interface traps)
- Inter-pixel capacitance ← accumulation layer
- Increase of depletion voltage ← accumulation layer
- Surface current ← traps at the depleted Si-SiO_2 interface

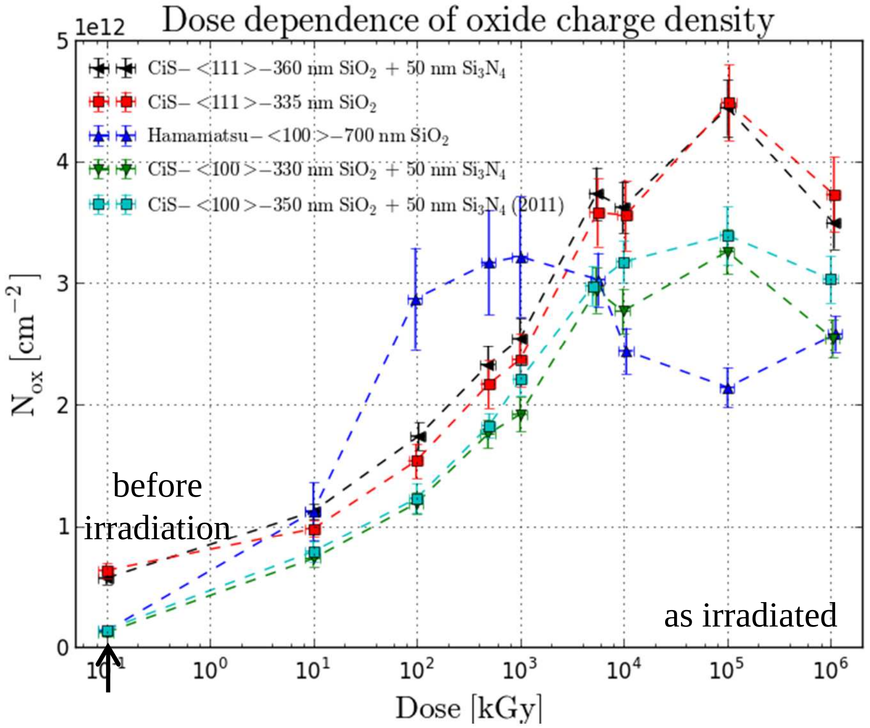


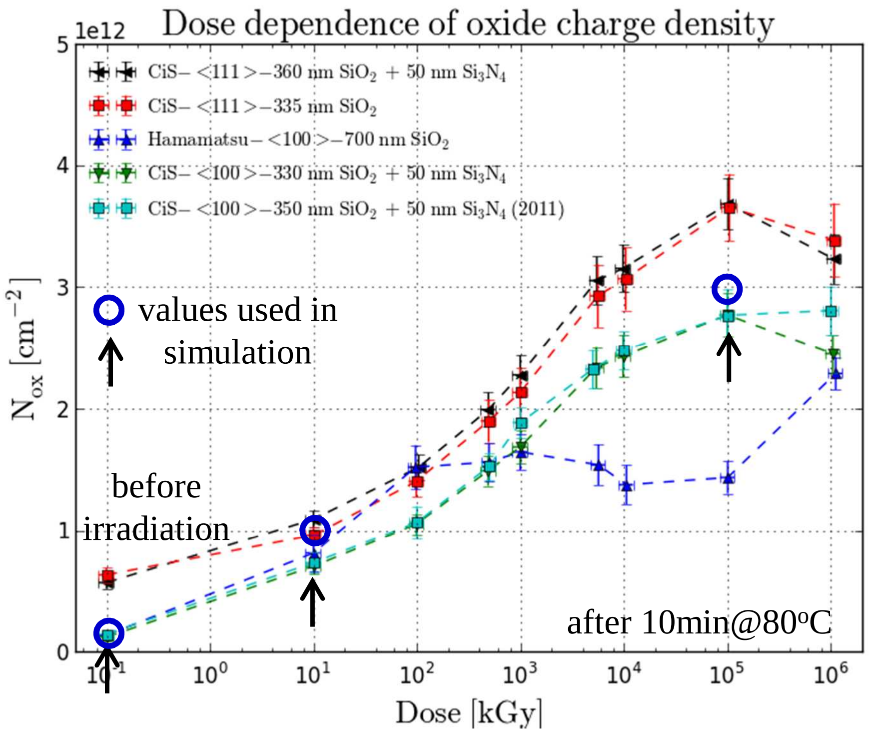
N_{ox} used in TCAD simulations

Parameters related to X-ray induced radiation damage (new measurements 2012):

→ **oxide charge density *N_{ox}*** → **~ compatible with previous measurements**

→ surface recombination velocity $S_0 = I_{surface}/(q_0 \cdot n_i \cdot A_{gate})$





- *N_{ox}* used in TCAD simulations:

  1×10^{11} cm^{-2} ← 0 kGy

  1×10^{12} cm^{-2} ← 10 kGy

  3×10^{12} cm^{-2} ← 100 MGy

Characterized test structures:

→ CiS, <100>, DOFZ, 330 nm SiO_2 + 50 nm Si_3N_4, doping: 7.6×10^{11} cm^{-3}

→ CiS, <111>, DOFZ, 360 nm SiO_2 + 50 nm Si_3N_4, doping: 1.1×10^{12} cm^{-3}

→ CiS, <111>, Epitaxial, 335 nm SiO_2, doping: 7.8×10^{13} cm^{-3}

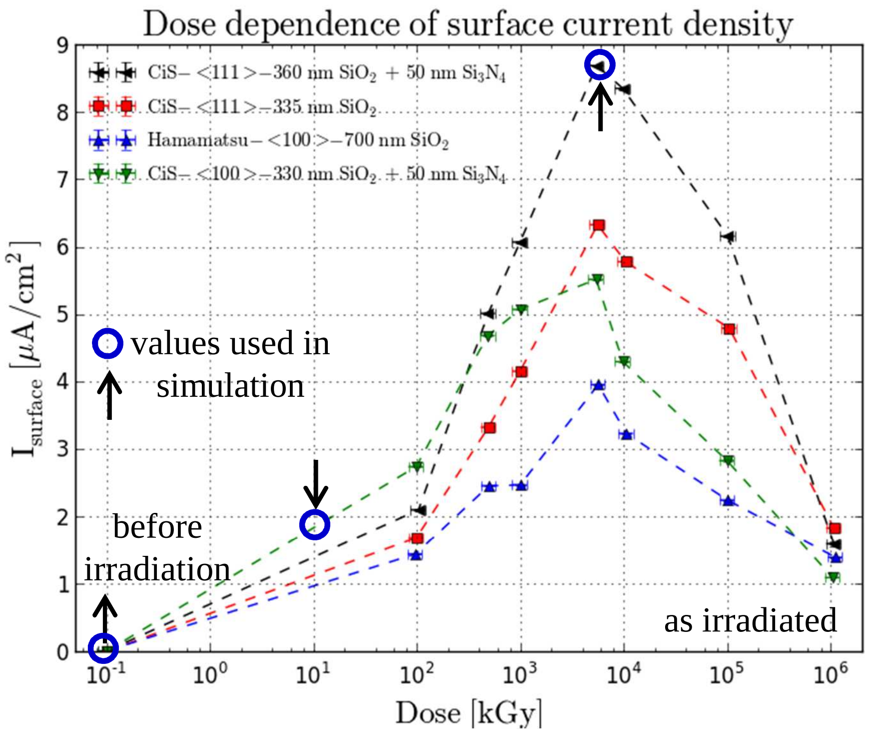
→ Hamamatsu, <100?>, 700 nm SiO_2, doping: 9.0×10^{11} cm^{-3}

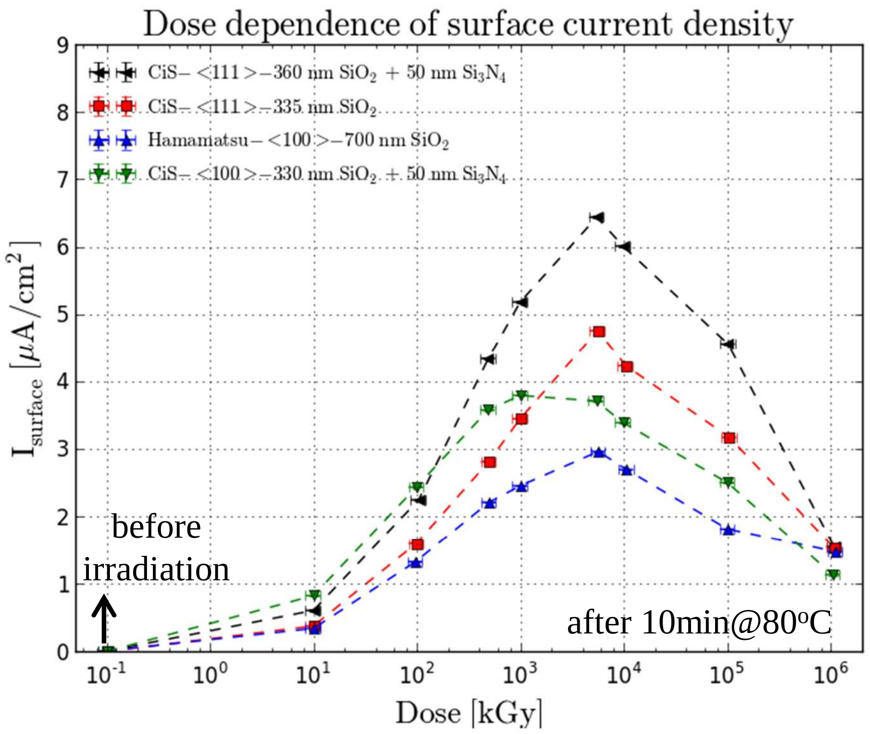
S_0 used in TCAD simulations

Parameters related to X-ray induced radiation damage:

→ oxide charge density N_{ox}

→ **surface recombination velocity $S_0 = I_{surface}/(q_0 \cdot n_i \cdot A_{gate})$** **(for T = 20 °C; $I \sim T^2 \cdot e^{-0.6eV/kT}$)**





- S_o used in TCAD simulations:

  8 cm/s ← 10 nA/cm^2 ← 0 kGy

  1400 cm/s ← 2.0 µA/cm^2 ← 10 kGy

  6020 cm/s ← 9.0 µA/cm^2 ← 5 MGy

Characterized test structures:
→ CiS, <100>, DOFZ, 330 nm SiO_2 + 50 nm Si_3N_4, doping: 7.6×10^{11} cm^{-3}
→ CiS, <111>, DOFZ, 360 nm SiO_2 + 50 nm Si_3N_4, doping: 1.1×10^{12} cm^{-3}
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Pixel optimization: strategy

Strategy of pixel optimization (2D “strip sensor” calculation used):

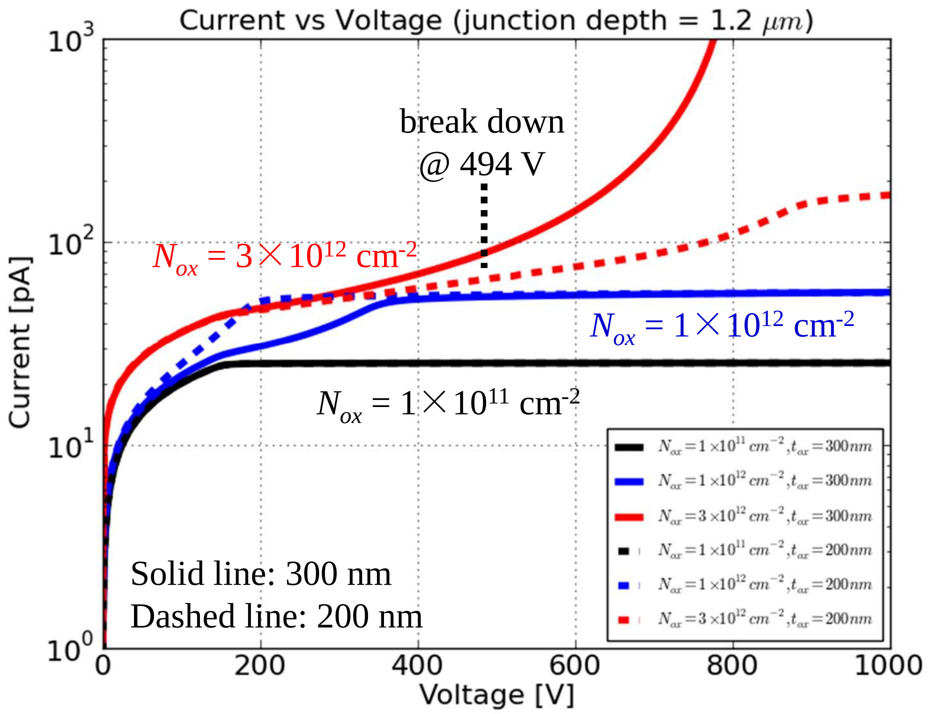
- Optimize oxide thickness, Al overhang, gap and implantation depth with respect to breakdown voltage, dark current and capacitance
- Simple extrapolation to “3D numbers”
- Check breakdown voltage + dark current with 3D simulation (only 1/4 pixel due to number of nodes)

Pixel optimization: oxide thickness + junction depth

Optimization of oxide thickness (200 nm vs. 300 nm):

All plots show current/pixel!

- Assumption: same value of N_{ox} and S_0 for 200 nm and 300 nm thick SiO_2
- Geometry: gap – 20 µm, overhang – 5 µm, junction depth – 1.2 and 2.4 µm, **oxide thickness – 200 and 300 nm**



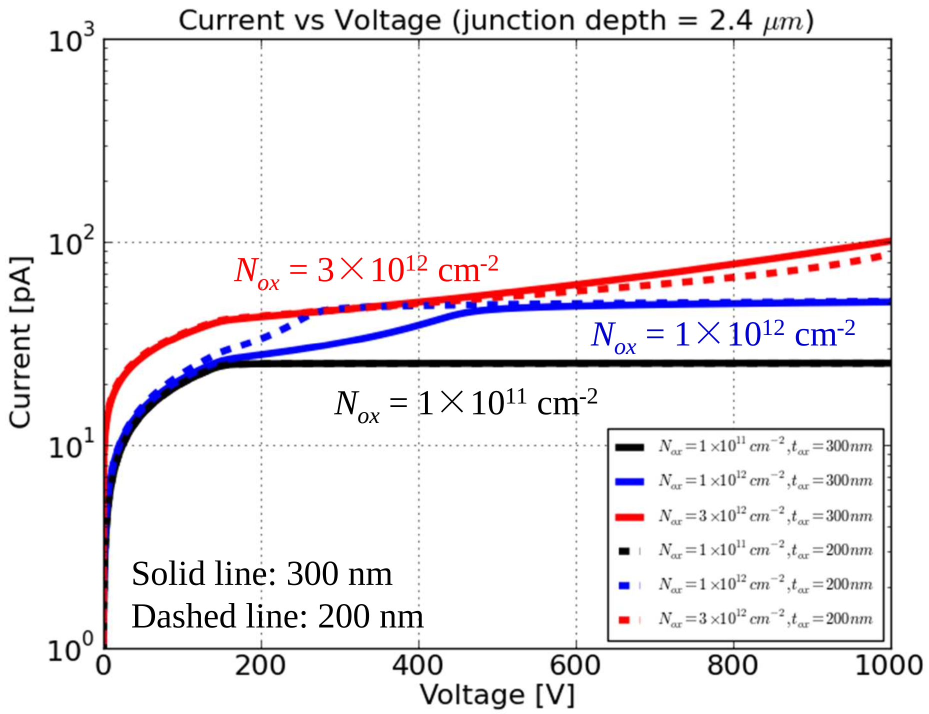
break down @ 494 V

$N_{ox} = 3 \times 10^{12}$ cm^{-2}

$N_{ox} = 1 \times 10^{12}$ cm^{-2}

$N_{ox} = 1 \times 10^{11}$ cm^{-2}

Solid line: 300 nm
Dashed line: 200 nm



$N_{ox} = 3 \times 10^{12}$ cm^{-2}

$N_{ox} = 1 \times 10^{12}$ cm^{-2}

$N_{ox} = 1 \times 10^{11}$ cm^{-2}

Solid line: 300 nm
Dashed line: 200 nm

- For thinner oxide, the region under the metal depletes at lower voltages
- Thinner oxide: lower max. lateral field strength in Si and $V_{bd} > 1000$ V

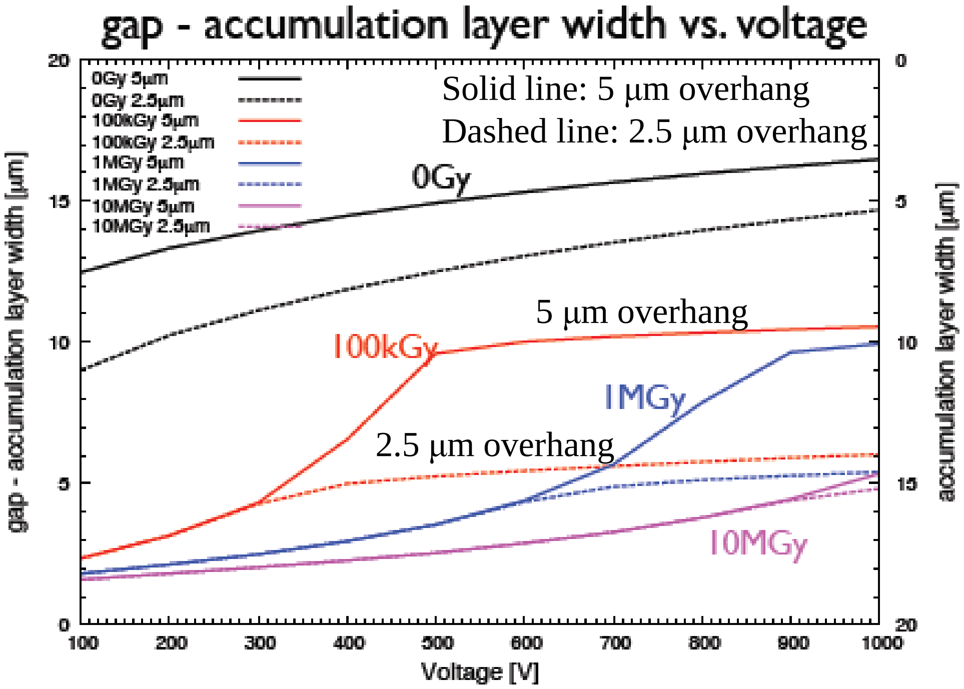
→ Maximum breakdown voltage: thinner oxide + deeper junction

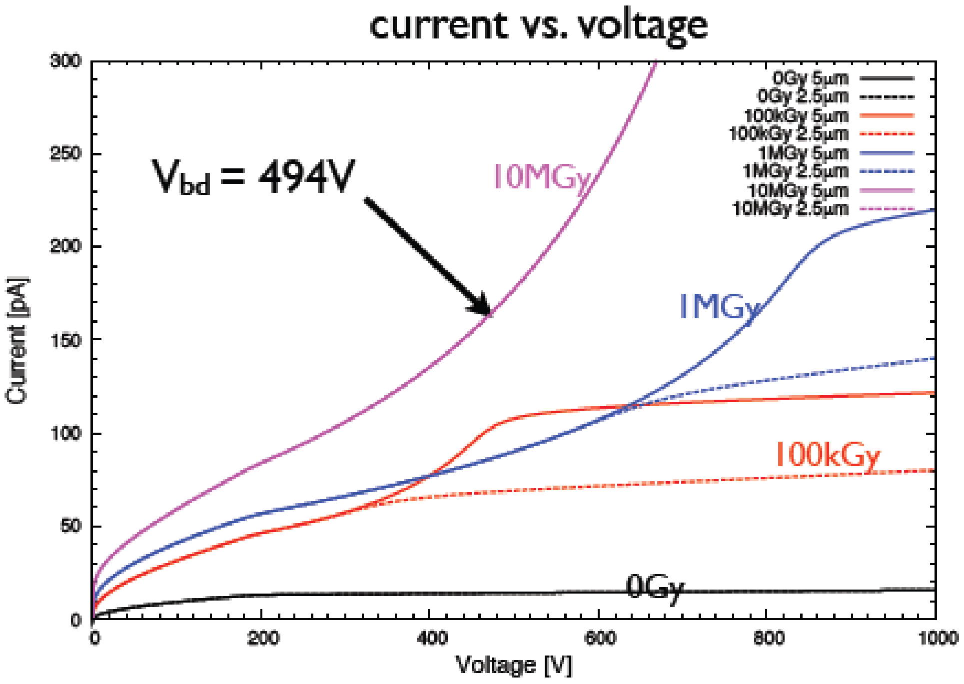
Pixel optimization: overhang

Optimization of Al metal overhang:

All plots show current/pixel!

- Geometry: gap – 20 µm, **overhang – 2.5 and 5 µm**, junction depth – 1.2 µm,
  oxide thickness – 300 nm





- For irradiated sensor: $I_{surface} \propto W_{dep}\ (= gap - W_{acc})$
- Larger overhang → larger current (depleted interface extended to the edge of overhang)
- For an oxide charge density $N_{ox} = 3 \times 10^{12}$ cm^{-2}, breakdown@494 V for both overhang values

  → Overhang > 2.5 µm, no differences in affecting breakdown behavior

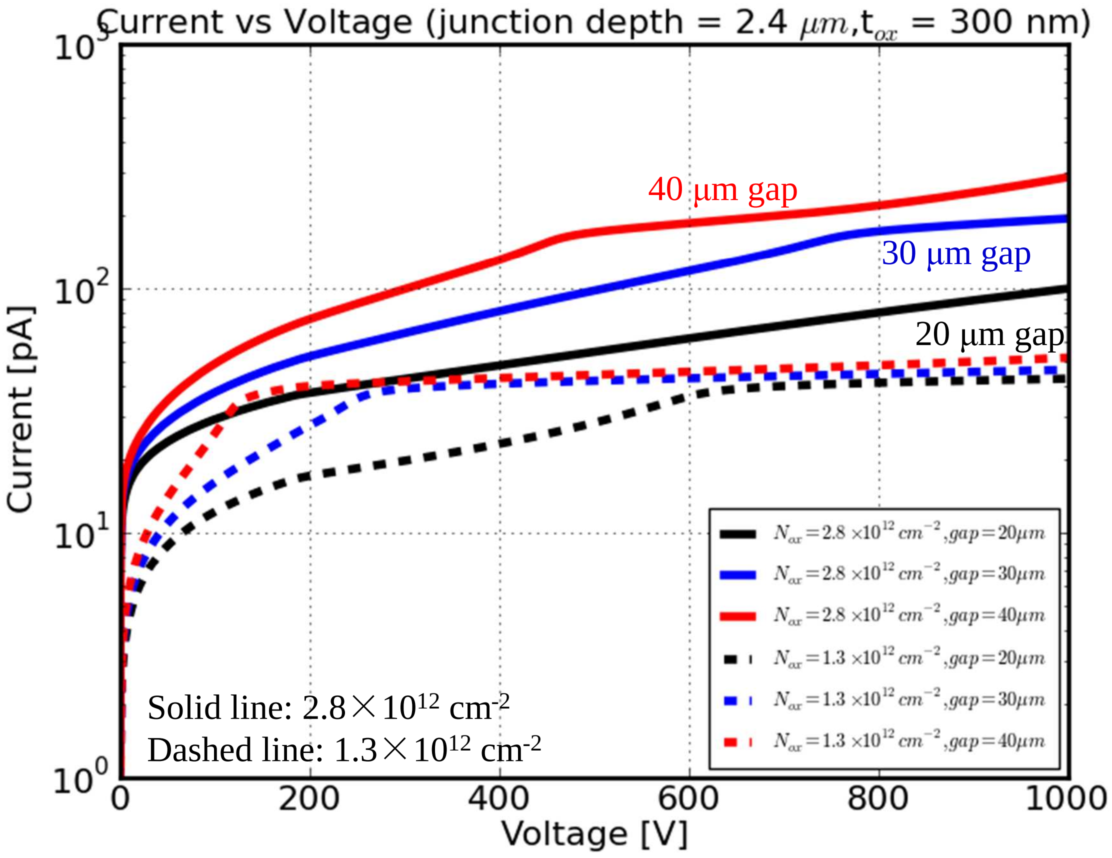
  (above 5 µm for tolerance)

Pixel optimization: gap (2D scaled to 3D)

Optimization of gap between p^+ implants of neighboring pixels:

- Geometry: **gap – 20, 30 and 40 µm**, overhang – 5 µm, junction depth – 2.4 µm,
  oxide thickness – 300 nm

Plot shows current/pixel!



Solid line: 2.8×10^{12} cm^{-2}
Dashed line: 1.3×10^{12} cm^{-2}

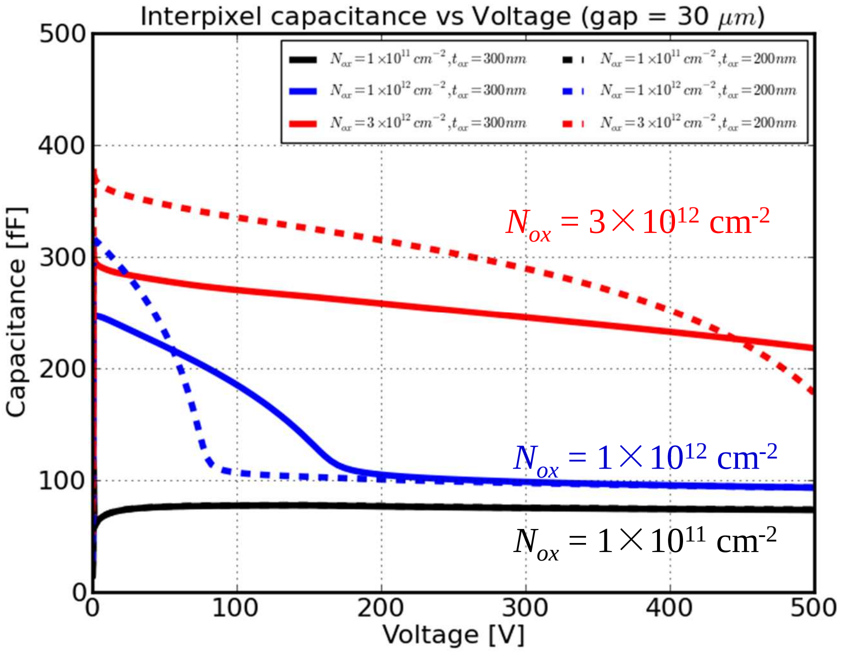
- **No breakdown up to 1000 V for 2.4 µm deep junction**

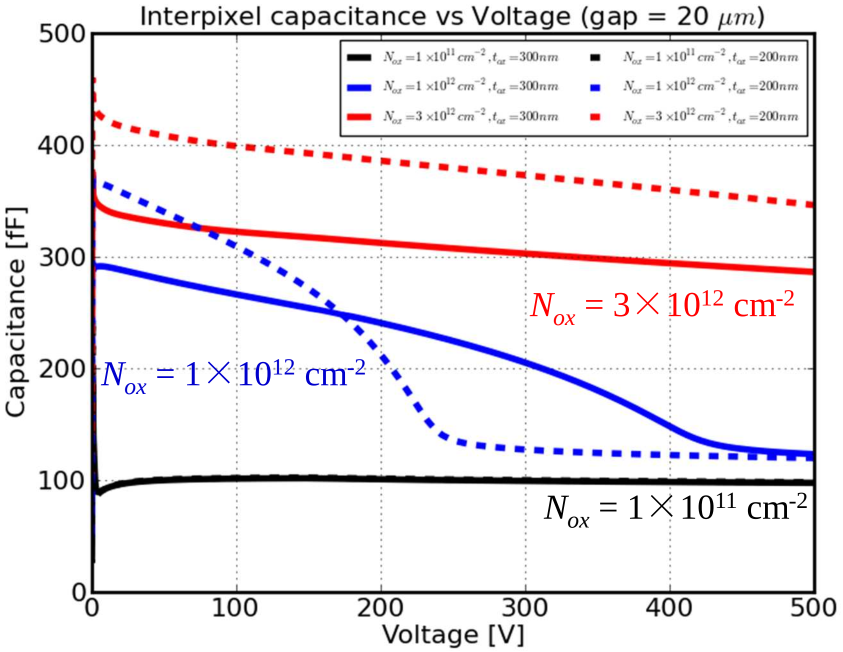
Pixel optimization: gap (2D scaled to 3D)

Inter-pixel capacitance C_{int}:

Plots show capacitance/pixel!

- Geometry: **gap – 20 and 30 μm**, overhang – 5 μm, junction depth – 2.4 μm, oxide thickness – 200 and 300 nm





- Voltage dependence of inter-pixel capacitance due to the change of width of accumulation layer

  → **specification < 0.5 pF/pixel**

gap	oxide thickness	C_{int} (N_{ox} = 1×10^{11} cm^{-2})	C_{int} (N_{ox} = 1×10^{12} cm^{-2})	C_{int} (N_{ox} = 3×10^{12} cm^{-2})
20 μm	200 nm 300 nm	98 fF 97 fF	120 fF 123 fF	346 fF 286 fF
30 μm	200 nm 300 nm	77 fF 73 fF	93 fF 93 fF	178 fF 218 fF

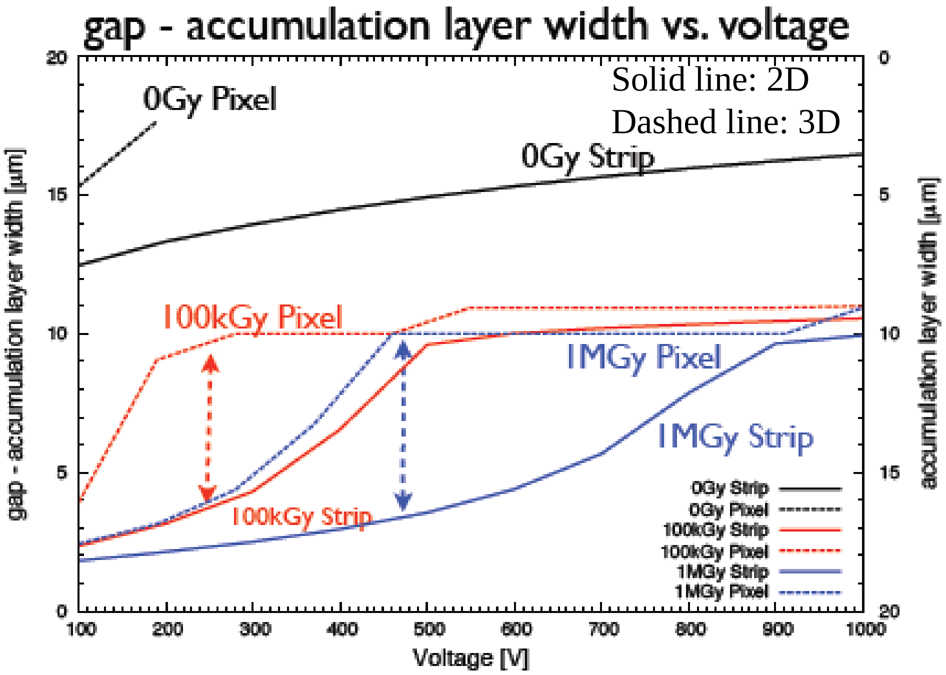
C_{int} @ 500 V

Pixel optimization: 2D vs. 3D

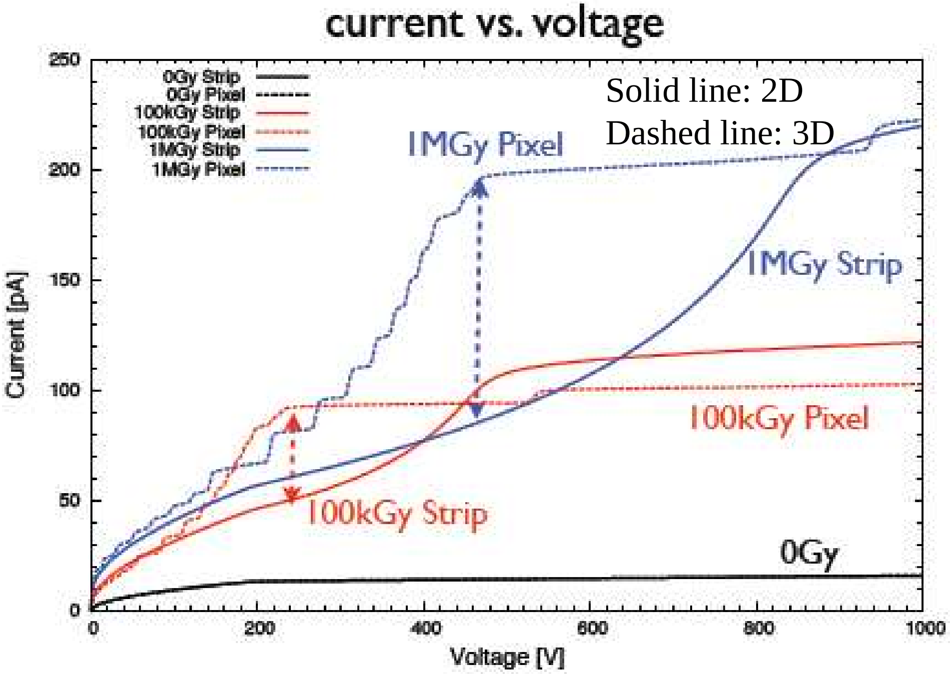
All plots show current/pixel!

From 2D to 3D simulation:

- 3D geometry: gap – 20 μm, overhang – 5 μm, junction depth – 1.5 μm, oxide thickness – 300 nm
  radius of pixel corner – 5 μm (for simulation – changed to 10 μm)



Solid line: 2D
Dashed line: 3D



Solid line: 2D
Dashed line: 3D

- Qualitatively similar results for 2D and 3D geometry
- Different voltage dependence for 3D: interface below Al depletes at lower voltages

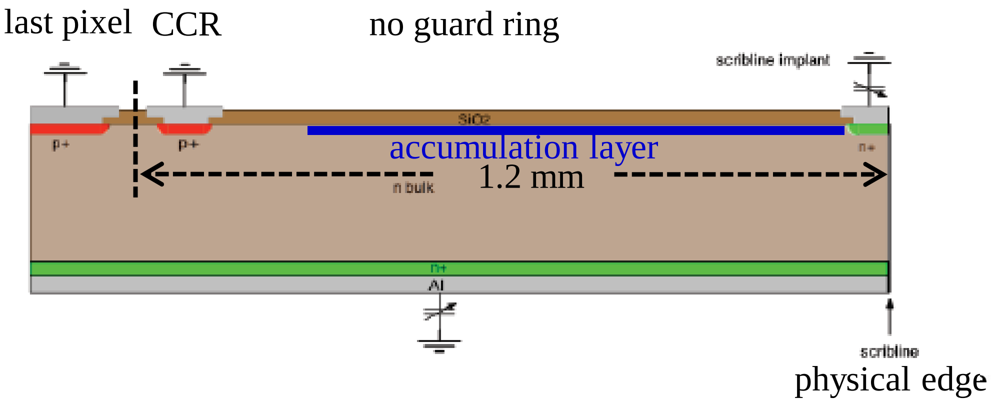
Guard ring optimization: strategy

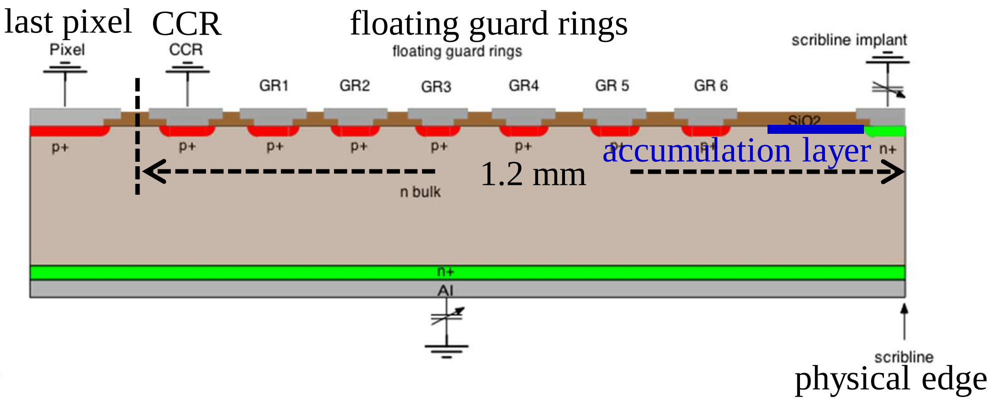
Problems:

- Same as for the pixels (i.e. high field, surface current…), plus
- 1000 V drop over 1.2 mm for doses between 0 and 1 GGy
- Zero electric field (not depleted bulk) at sensor edge

Strategy of optimization (GR = guard ring):

1. 0 GR: optimize breakdown voltage (V_{bd}) vs. junction depth, oxide thickness and metal overhang → V_{bd} ~ **70 V**
2. 1 GR: verify parameters and V_{bd} from 0 guard ring optimization; determine distance CCR to GR for 1000 V → **15 GRs**
3. Choose metal overhang and distance between GRs to achieve equal voltage drop between GRs
4. Check dependence of CCR current and breakdown voltage on design parameters



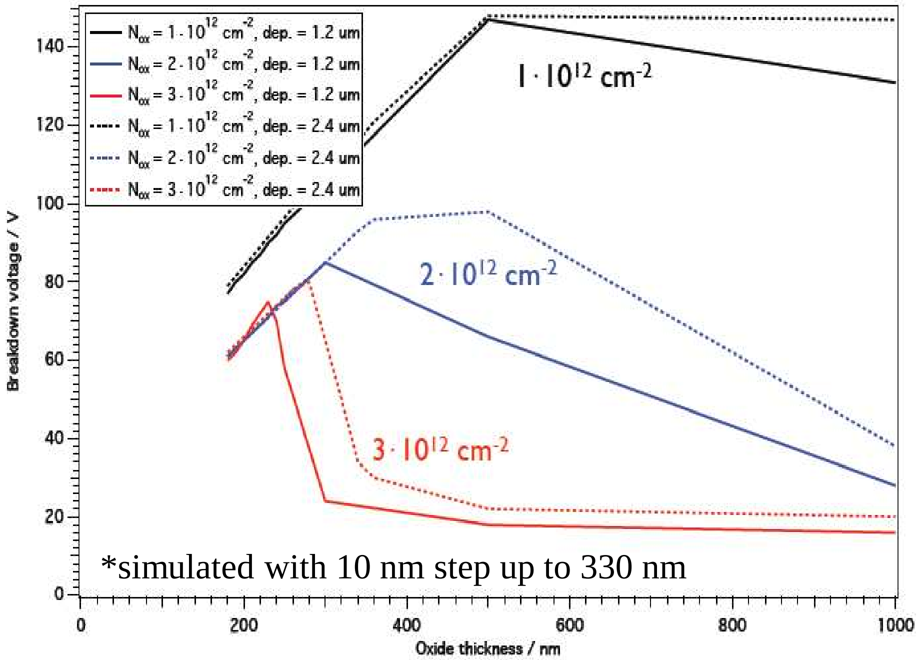


Guard ring optimization: 0 GR

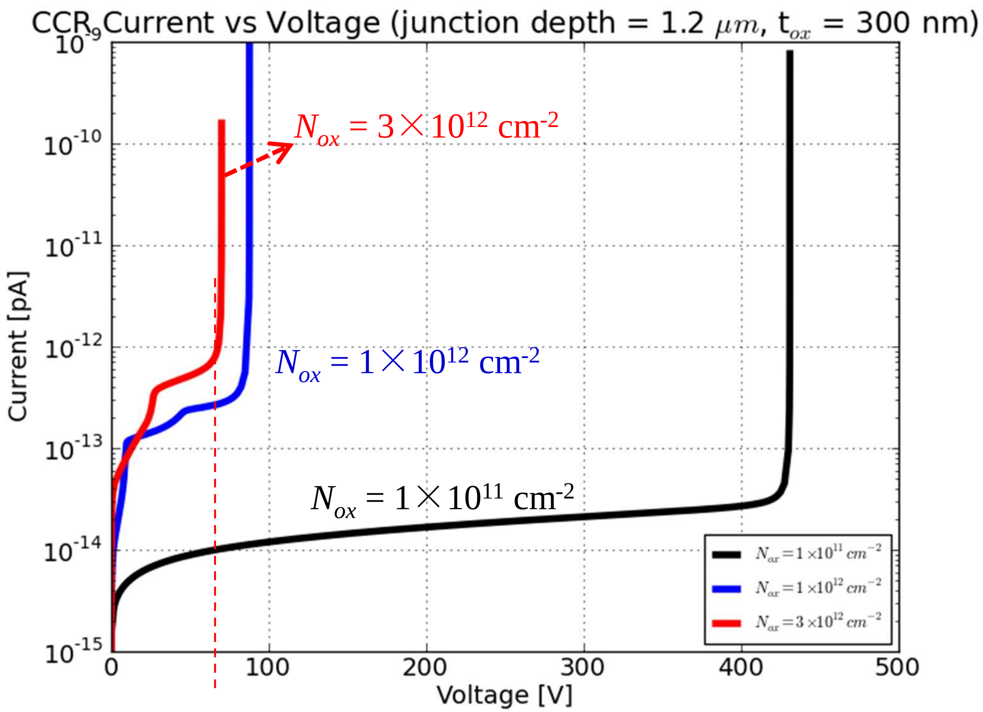
Optimization of SiO_2 thickness and junction depth for 0 GR:

- Geometry: Al overhang – 5 μm, CCR implant width – 20 μm (for simulation – changed to 90 μm)

CCR Current vs. Voltage



*simulated with 10 nm step up to 330 nm



V_{bd} = 70 V

- For $N_{ox} < 1\times10^{12}$ cm^{-2}, thicker oxide (i.e. 500 nm) better
- For $N_{ox} = 3\times10^{12}$ cm^{-2}, optimum value: 230 nm (1.2 μm junction), 270 nm (2.4 μm junction)

→ ~ 250 nm SiO_2 thickness and 2.4 μm junction depth optimized for high doses
→ Al overhang > ~ 3 μm → choose 5 μm for tolerances (optimization not shown here; Al overhang only towards sensor edge important)

Guard ring optimization: results

Optimized design (CCR with 15 floating GRs):

- Break down voltage for 1 ring with $N_{ox} = 3 \times 10^{12}$ cm^{-2}: ~ 70 V
- Ideally 16 rings (1 CCR + 15 g.r.) needed for 1000 V (16 × 70 V = 1120 V)
- Geometry of guard ring structure:

  - Gap pixel to CCR: 20 µm
  - Width implantation window CCR: 90 µm
  - Al overhang CCR: 5 µm
  - Gap CCR to 1st guard ring (GR): 12 µm
  - Width of implantation window GR 25 µm
  ● Al overhang left (towards pixel) of GR 1, 2, … 15: 2, 3, … 16 µm
  ● Al overhang right (away from pixel) of GR 1 – 15: 5 µm
  ● Gap between GR 1-2, 2-3, … 14-15: 12, 13.5, … 33 µm

- Bulk resistivity:

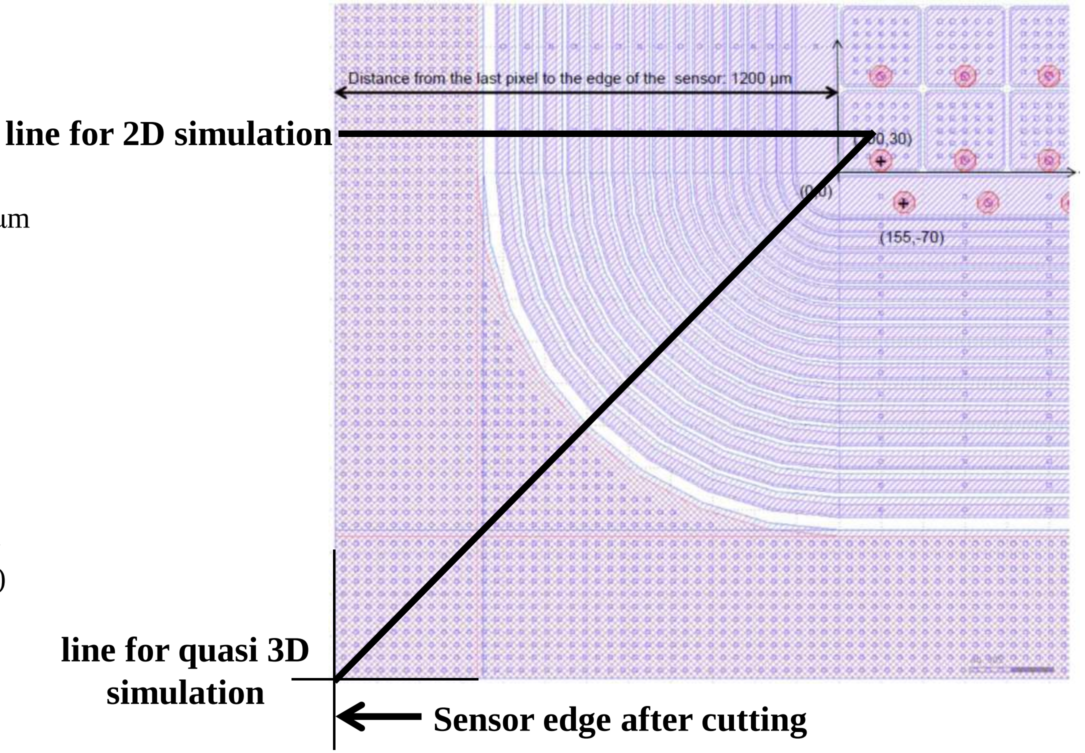
  - 5.1 kΩ·cm (and 3, 8 kΩ·cm to check effects of possible range)

- p^+ implantation:

  - 5×10^{15} cm^{-2} B, junction depth: 2.4 µm, lateral extension: 2 µm
  - (5×10^{15} cm^{-2} B@70 keV through 200 nm SiO2; 4h @ 1025°C)

- Oxide and passivation:

  - SiO2 field thickness: 250 nm
  - Oxide charge before irradiation: 5.0×10^{10} cm^{-2}
  - Oxide charge after irradiation: 3.0×10^{12} cm^{-2}
  - Surface current density before irradiation: 10 nA/cm^2
  - Si_3N_4: not simulated
  - Neumann boundary conditions on top of oxide
  - Surface current density after irradiation: 9 µA/cm^2
  - Passivation: not simulated



line for 2D simulation

line for quasi 3D simulation

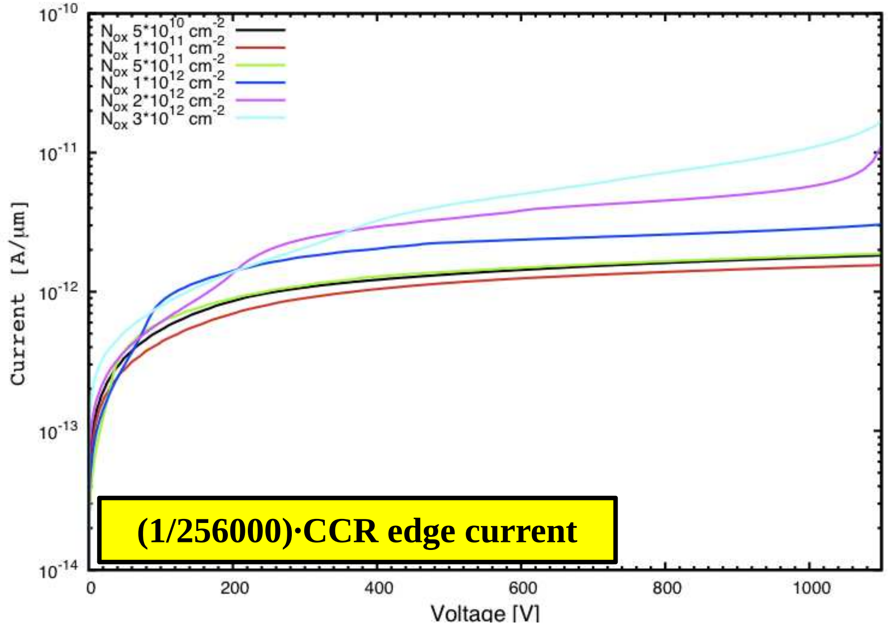
Sensor edge after cutting

Guard ring optimization: verification

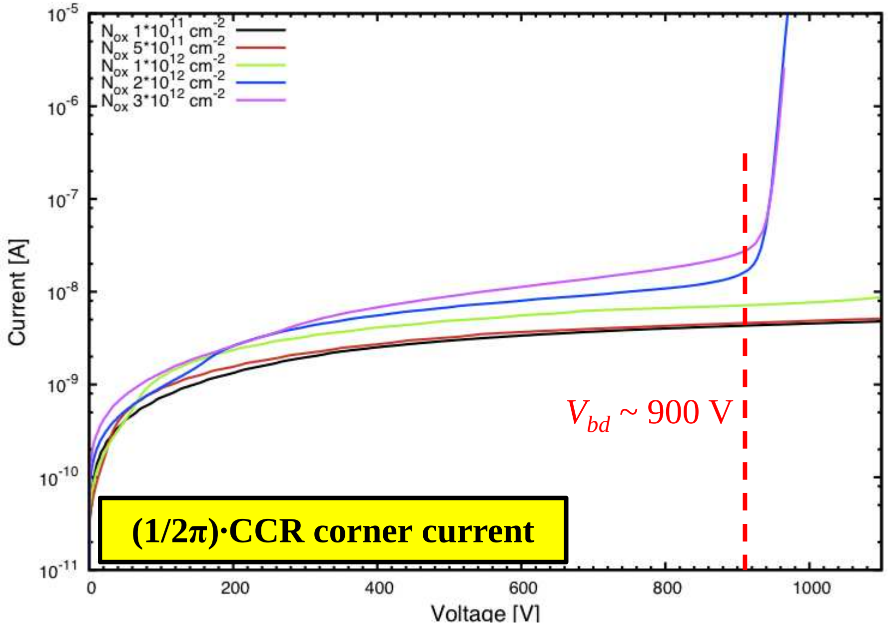
CCR current for optimized design:

- From 2D, no break down up to 1000 V for $N_{ox} = 3 \times 10^{12}$ cm^{-2}
- Quasi 3D (r, z) shows a breakdown voltage of about 900 V

CCR Current vs. Voltage (2.4 µm junction, 2D)



CCR Current vs. Voltage (2.4 µm junction, quasi 3D)



→ 2.4 µm (deeper) junction is possible to achieve high breakdown voltage!

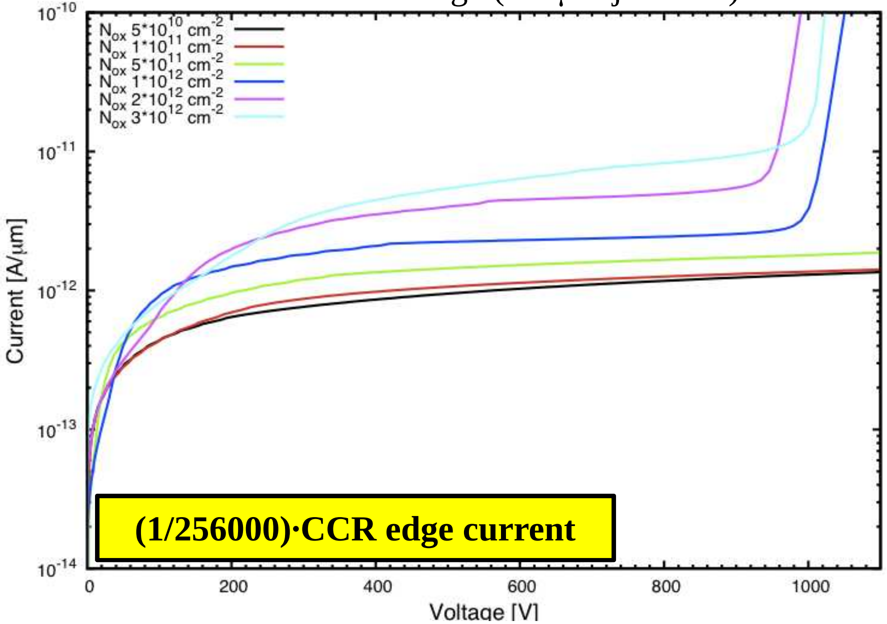
- breakdown voltage at corners ~ 900 V for $N_{ox} = 3 \times 10^{12}$ cm^{-2}

- total current ~ 10 µA = 3 µA (CCR) + 7 µA (pixels) at 900 V for $N_{ox} = 3 \times 10^{12}$ cm^{-2}

Guard ring optimization: verification

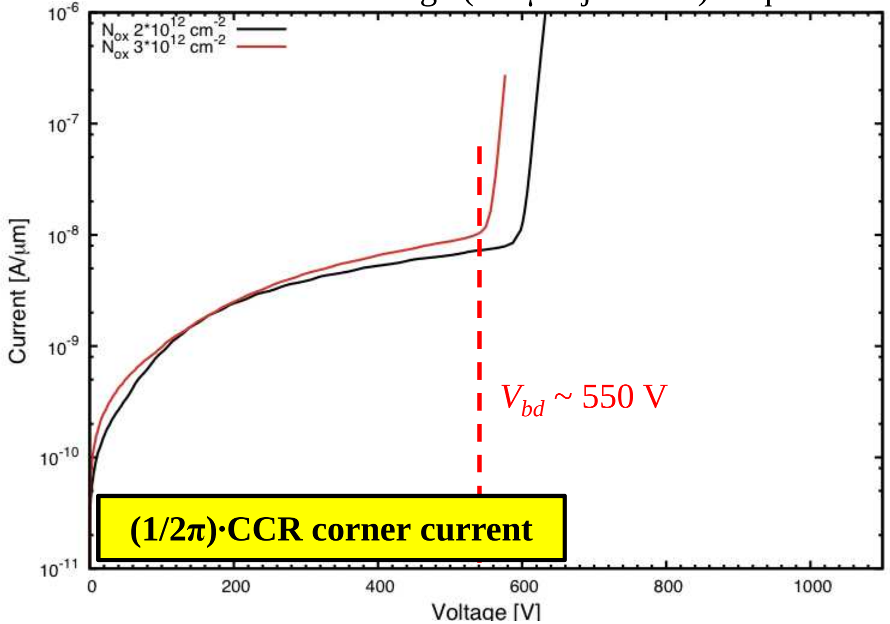
CCR current for 1.2 μm junction depth:

CCR Current vs. Voltage (1.2 μm junction) in 2D



(1/256000)·CCR edge current

CCR Current vs. Voltage (1.2 μm junction) in quasi 3D



V_{bd} ~ 550 V

(1/2π)·CCR corner current

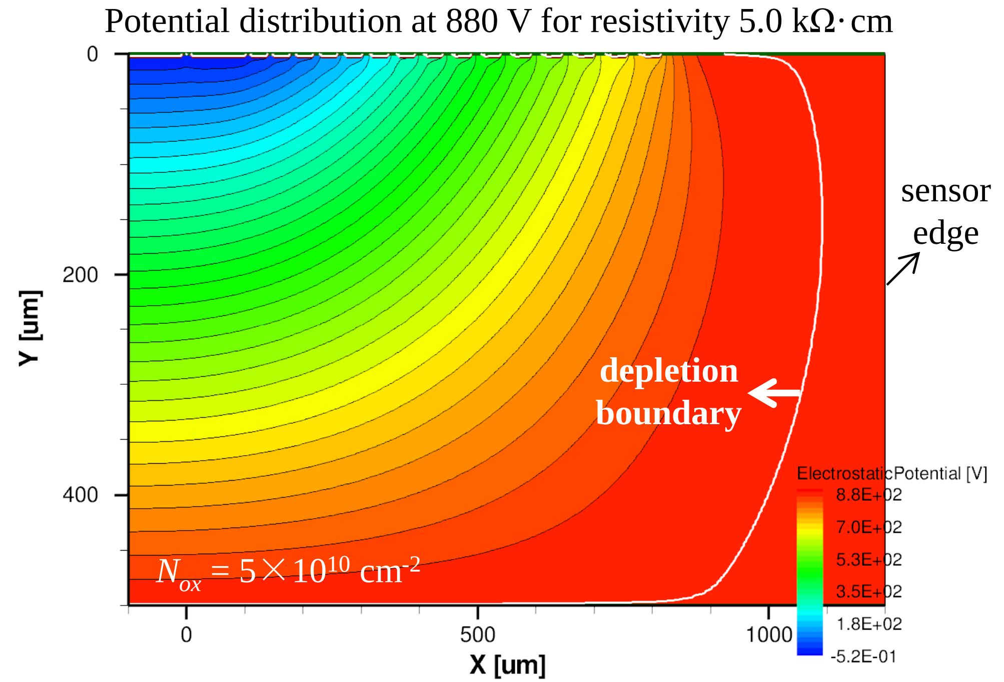
- 2D: breakdown voltage < 1000 V for $N_{ox} > 1 \times 10^{12}$ cm^{-2}
- 3D: breakdown voltage ~ 550 V for high dose
- Breakdown voltage for 1.2 μm junction:
  - → V_{bd} ~ 550 V for $N_{ox} = 2 \times 10^{12}$ cm^{-2}
  - → V_{bd} ~ 600 V for $N_{ox} = 3 \times 10^{12}$ cm^{-2}

→ 1.2 μm junction can not achieve 900 V! (may depend on technology)

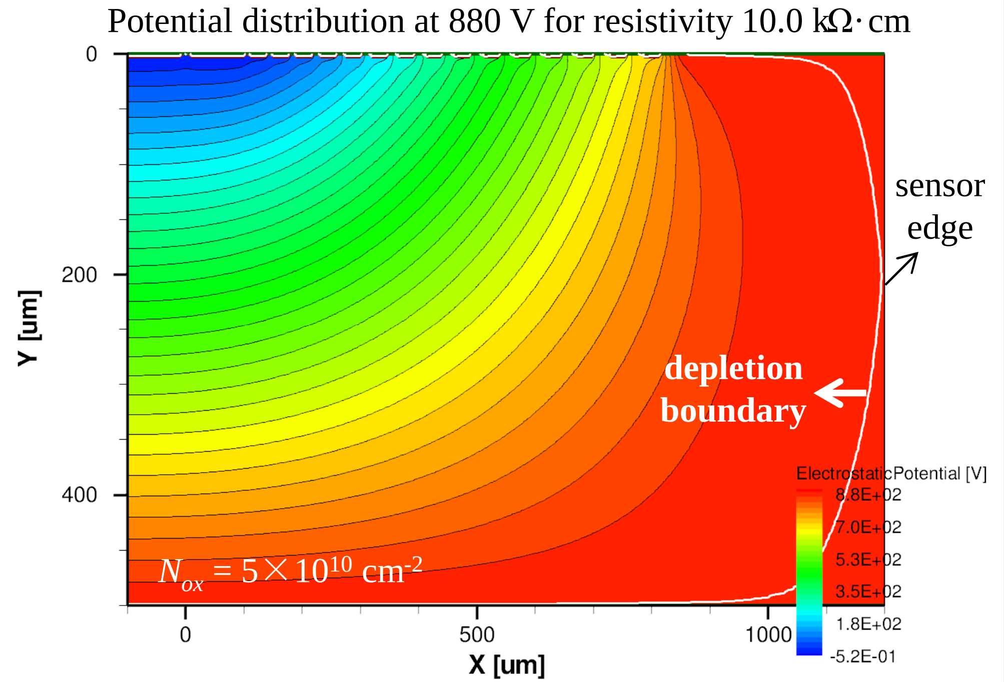
Guard ring optimization: verification

Effect of resistivity on depleted region close to the edge:

- High resistivity → risk of depletion region touching the edge at low oxide charges



Potential distribution at 880 V for resistivity 5.0 kΩ·cm



Potential distribution at 880 V for resistivity 10.0 kΩ·cm

- Effect pronounced for high resistivity (low doping concentration)

→ resistivity of 5.1 kΩ·cm is OK ← (3.0 - 8.0) kΩ·cm

Open questions

Factors, not considered, affecting the sensor performance:

- Are assumptions on technology correct?
- Si_3N_4 layer on top of SiO_2
- “Final” passivation
  - → boundary condition on sensor surface
  - → additional interface layer
  - → effect of operating environment of sensor

Summary

AGIPD sensor design based on:

- Radiation damage measurements
- Detailed TCAD simulations

Are we ready to order???

Thank you!