*WP 1.1 Radiation Damage*
*WP 2.1 Sensors*

# Sensor Development for AGIPD

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# Outline

- Optimization of sensor design for AGIPD
- Charge (holes) losses in accumulation layer
- Characterization of segmented $n^+n$ test sensors
- Irradiation of $p^+n$ microstrip sensors with bias
- Summary and next steps

# Optimization of sensor design for AGIPD

Specification of AGIPD sensor with an aim for 1 GGy radiation tolerance:

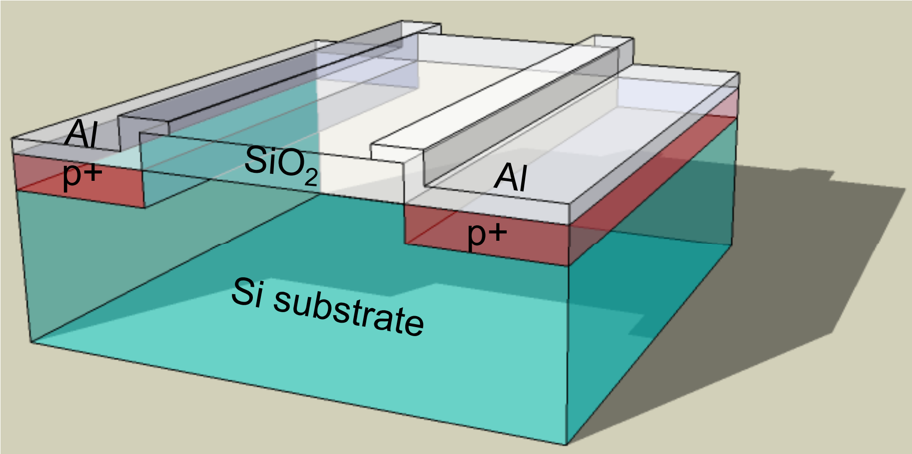
| Wafer | |
|---|---|
| Thickness | 500 µm |
| Flatness | < 25 µm |
| Material | FZ |
| Orientation | <111> or<br><100>(preferred) |
| Doping | p+ on n |
| Resistivity | ~ 5 kΩ·cm |
| Doping Con. | ~ $10^{12}$ $cm^{-3}$ |
| $V_{dep}$ | < 200 V |
| Passivation | tbd, $SiO_2+Si_3N_4$ |

| Pixel cell | |
|---|---|
| Pitch | 200 x 200 $\mu m^2$ |
| Coupling | DC |
| $C_{inter\text{-}pixel}$ | < 0.5 pF |
| $R_{inter\text{-}pixel}$ | > 100 MΩ |

| Module properties | |
|---|---|
| Insensitive edge | ≤ 0.5 mm |
| $I_{dark}$ | < 10 nA/pixel<br>< 3 mA (tot) |
| $V_{bd}$ | 1000 V |
| Stability-$I_{dark}$, $C_{int}$ | < 30% |

# Optimization of sensor design for AGIPD

## Pixel gaps optimization from TCAD simulation:



Synopsys TCAD model:

- Pixel size: 200 μm
- Thickness: 500 μm
- Doping: 1.0 x $10^{12}$ /$cm^3$ (~ 5 kΩ·cm)
- Orientation: <100>
- Isolation: $SiO_2$ (no $Si_3N_4$ – for simulation only)

| gap | dose | $C_{inter\text{-}pixel}$ | $I_{leakage}$ | $V_{dep}$ | $C_{dep}$ |
|---|---|---|---|---|---|
| 20 μm | 0 MGy | 140 fF | 2.6 pA | 189 V | 8.7 fF |
| | 5 MGy | 340 fF | 5.3 pA | 190 V | |
| 40 μm | 0 MGy | 90 fF | 2.6 pA | 187 V | |
| | 5 MGy | 230 fF | 36 pA | 190 V | |
| 80 μm | 0 MGy | 50 fF | 2.6 pA | 194 V | |
| | 5 MGy | 110 fF | 100 pA | 198 V | |

***First result from Simulations!***

# Optimization of sensor design for AGIPD

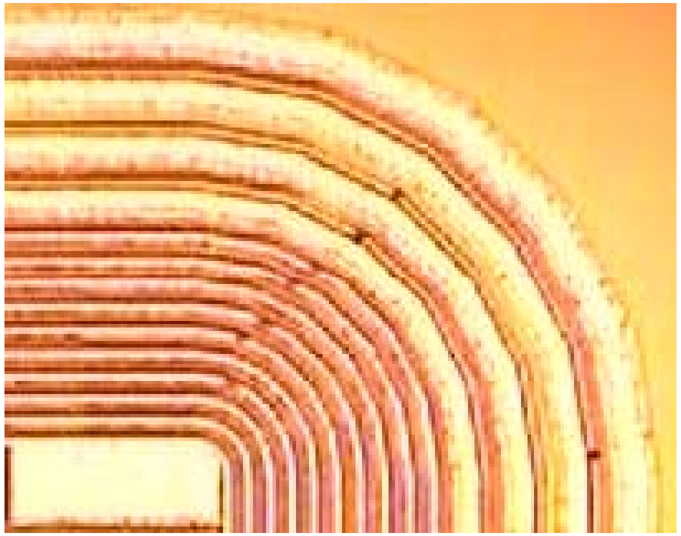
Guard ring design for $p^+n$ sensor:

- 2 options: **(1) multiple guard rings** ← CIS

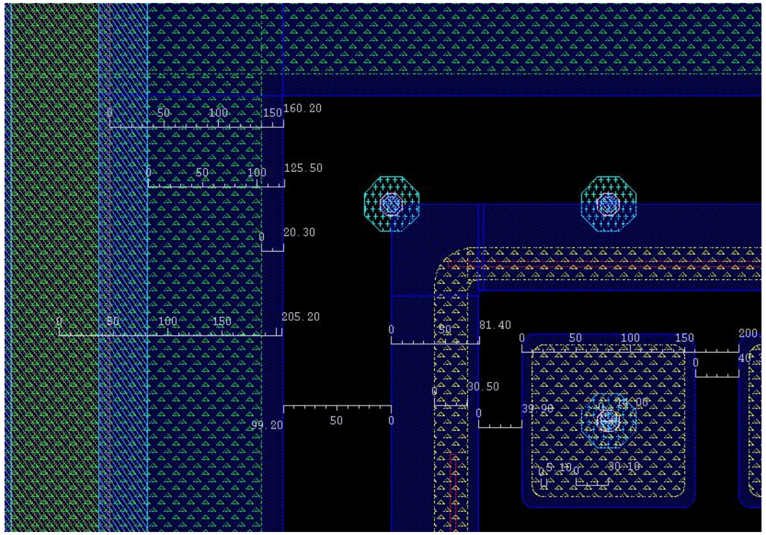
  **(2) single guard ring (for current collection)** ← Hamamatsu

Studies: (i) experimental study for CIS and Hamamatsu sensors

(ii) simulation as function of dose



Multiple guard rings design



Hamamatsu guard ring design

# Optimization of sensor design for AGIPD

Status of sensor design:

- Learn how to use cadence
- Geometry parameters still have to be decided:
    - **i. gap between implantations!**
    - **ii. overhang of metal!**
    - iii. size and arrangement of contact between metal and implant
    - of bump metal

  } not critical
- Detailed guard ring and cut edge design!

# Charge (holes) losses in accumulation layer

To understand pulse shape & signal losses → weighting field/potential:

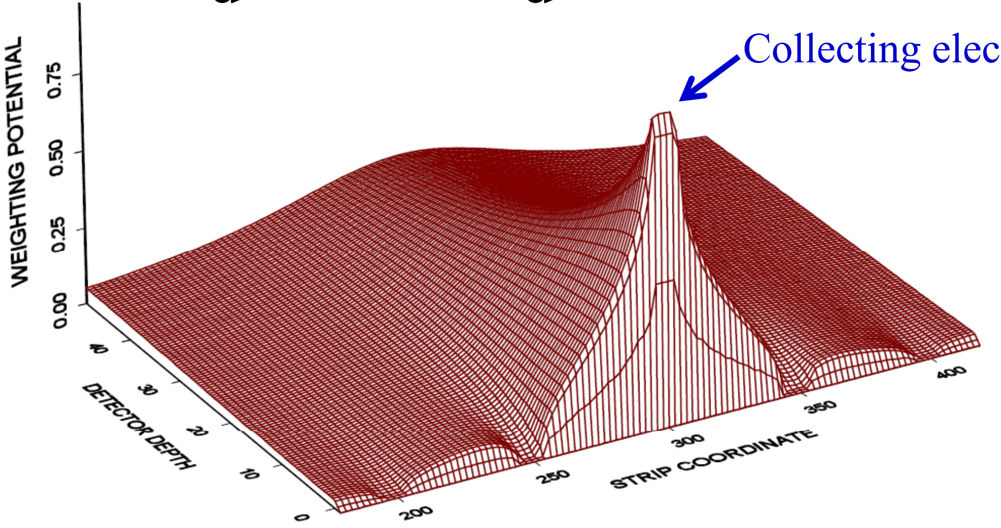
- **Intrinsic electric field:** $\vec{\upsilon}_D = \mu \cdot \vec{E}$
- **Weighting field/potential:**

$$I = -q \cdot \vec{\upsilon}_D \cdot \vec{E}_w = -q \cdot \vec{\upsilon}_D \cdot \nabla \Phi_w$$

$$\Longrightarrow \Delta Q(\vec{r}_1 - \vec{r}_2) = q \cdot \left[ \Phi_w(\vec{r}_2) - \Phi_w(\vec{r}_1) \right]$$

i. pad diode: $\vec{E}_w = \frac{\vec{e}_z}{d}$ $\Phi_w = \frac{z}{d}$ $\Delta Q(z = 0 \rightarrow a) = q$

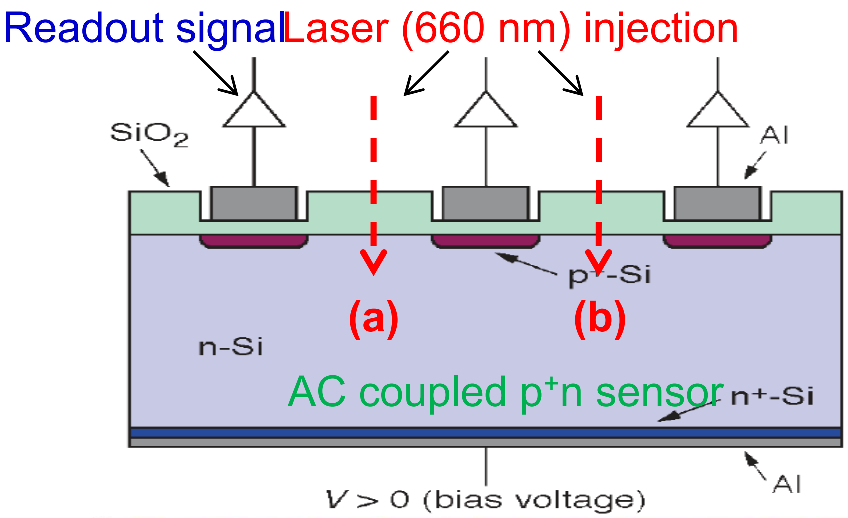
ii. strip sensor:

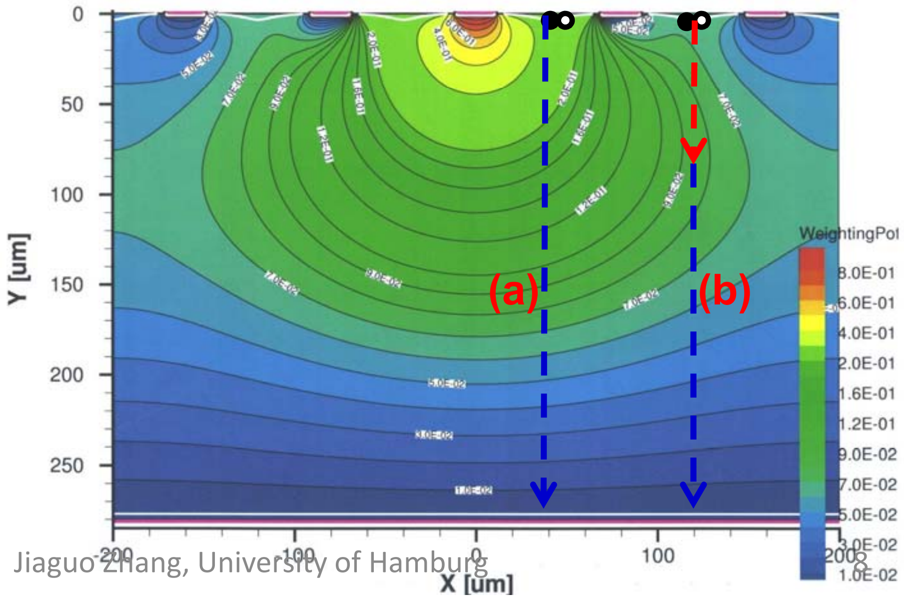


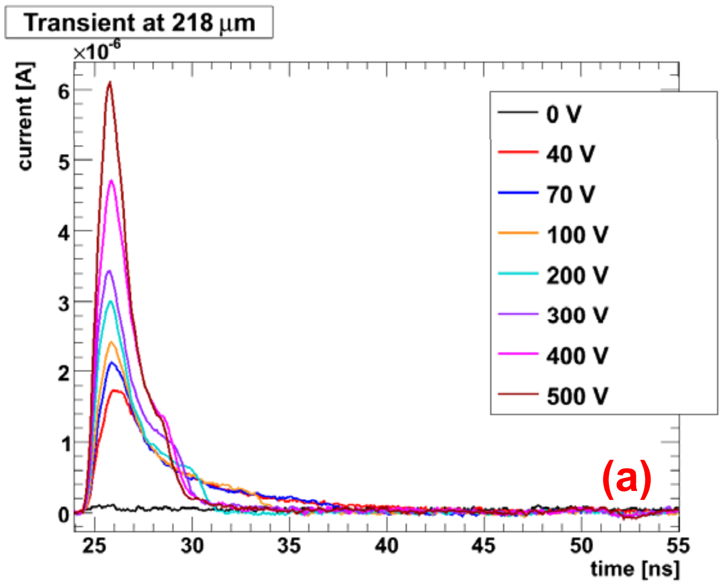
Collecting electrode

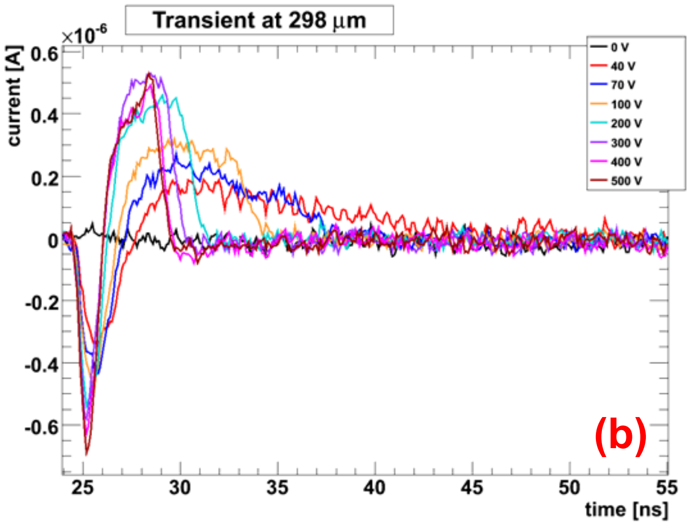
# Charge (holes) losses in accumulation layer

Electric signals (before irradiation):





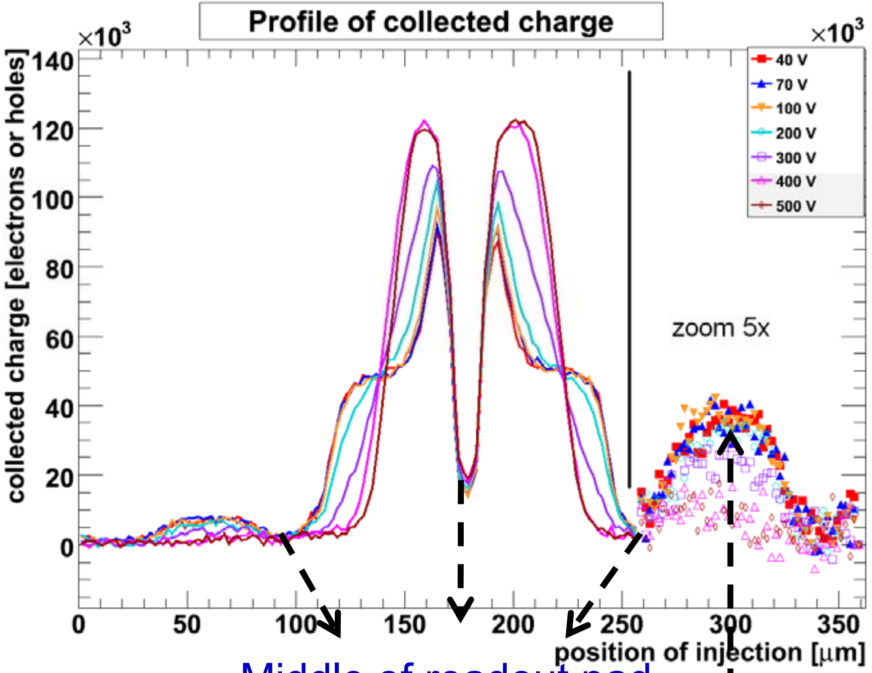




# Charge (holes) losses in accumulation layer

Charge collection in a p⁺n sensor with 80 μm pitch and 60 μm gap:

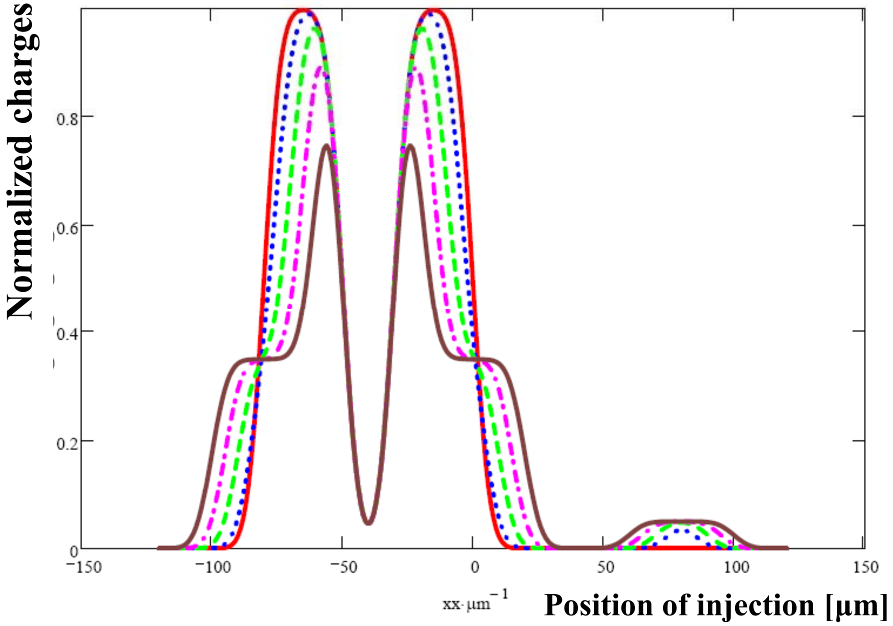
<Measurement>



Middle of readout pad

Partly due to stuck charges in accumulation layer

<Simulation>



Reconstruction of collected charges on one electrode based on weighting potential (Ramos theorem)

# Charge (holes) losses in accumulation layer

Conclusion on charge losses:

Laser light used → absorption length = 3 µm (XFEL 12 keV → 230 µm)

- **Holes lost in accumulation region:**
  - **→ signals on neighbor pixel reduced by ~ 25%**
  - **→ signals on next neighbor pixel ~ 5%**

  } for $\lambda_{abs}$ = 3 µm !
- Do we see a signal after 200 ns?
- Evidence that accumulation layer disappears at high voltage
- **Try to avoid accumulation layer**
  - **→ small gap between $p^+$ implantation**
  - **→ high operation voltage**

# Characterization of segmented $n^+n$ test sensors

CMS $n^+n$ test pixel sensor (PSI 8613-22):

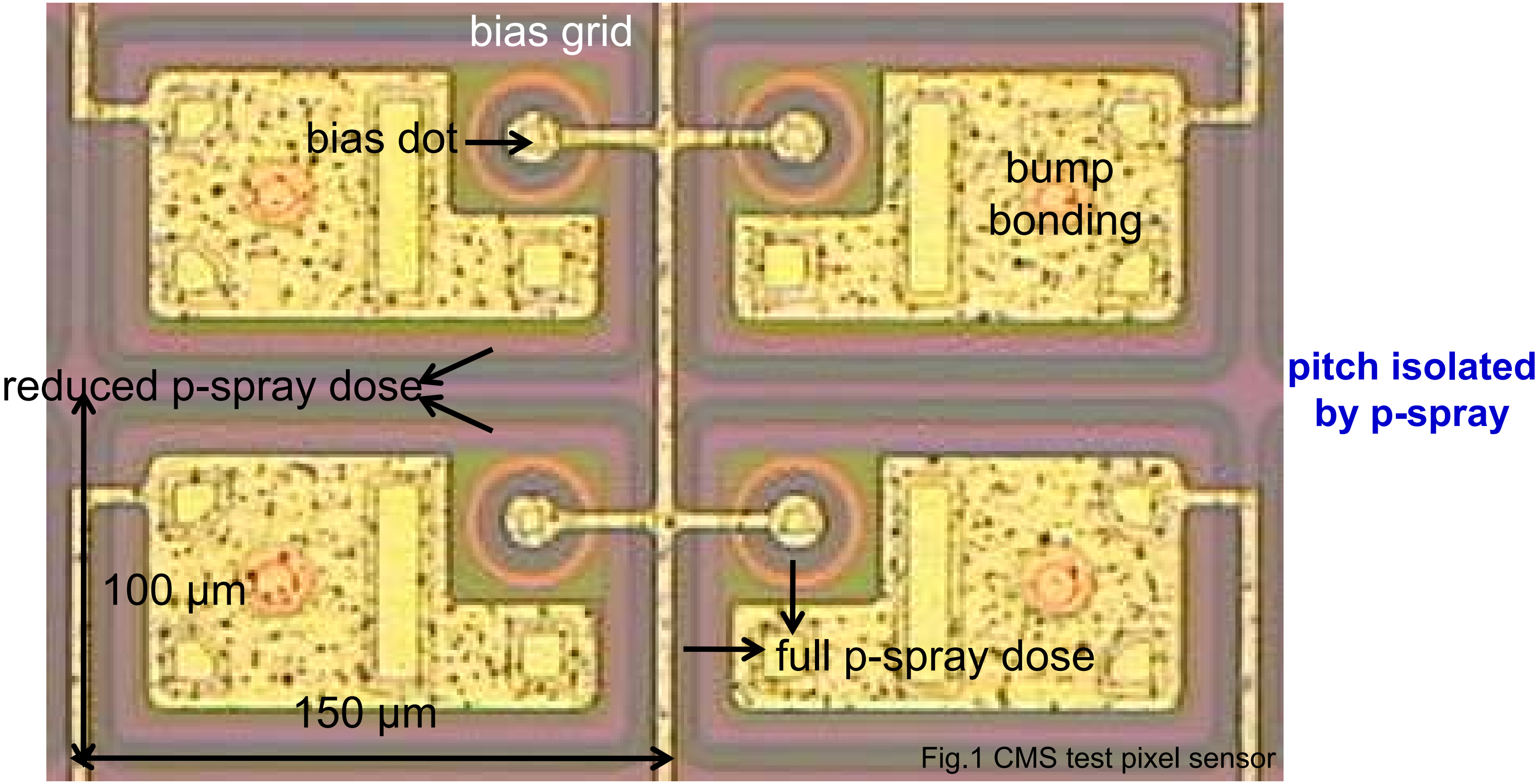


Fig.1 CMS test pixel sensor

- Pixel size: 150 µm x 100 µm
- Crystal orientation: <111>
- Substrate: n-doped silicon
- Sensor thickness: ~ 300 µm
- Resistivity: ~ 4 kΩ·cm
- Active area: 1.96 mm x 2.27 mm

# Characterization of segmented $n^+n$ test sensors

CMS $n^+n$ test pixel sensor's performance up to 1 MGy:

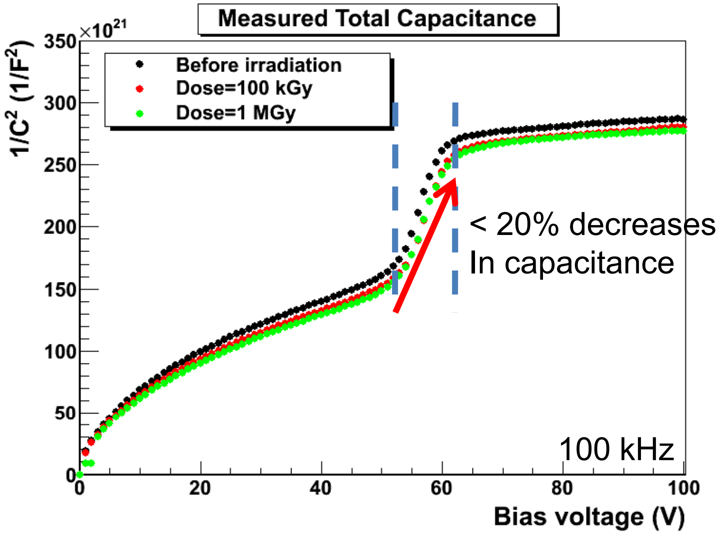


Fig.2 Total capacitance of pixel sensor

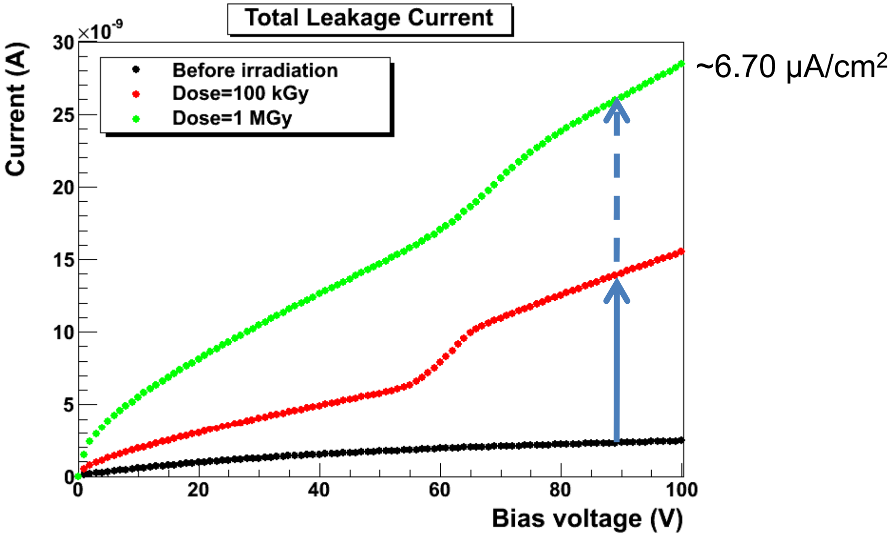


Fig.3 Total leakage current

- **No change of full depletion voltage due to irradiation (no accumulation layer)***
- Jump of capacitance around full depletion voltage

  → **merge of bulk depletion and p-spray depletion**
- Step of leakage current → depleted Si-$SiO_2$ interface (p-spray isolation)
- Increase of leakage current with bias voltage → **increase of depleted area $S_{dep}$**

**Decrease of inter-pixel capacitance*** ←

***) advantages compared to $p^+n$ sensors!**

# Characterization of segmented $n^+n$ test sensors

NMOS Field Effect Transistor:

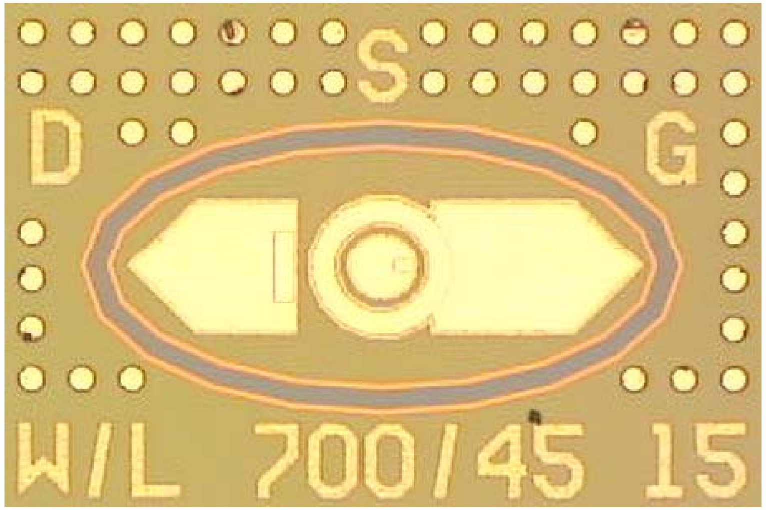


Fig.4 Image of NMOSFET

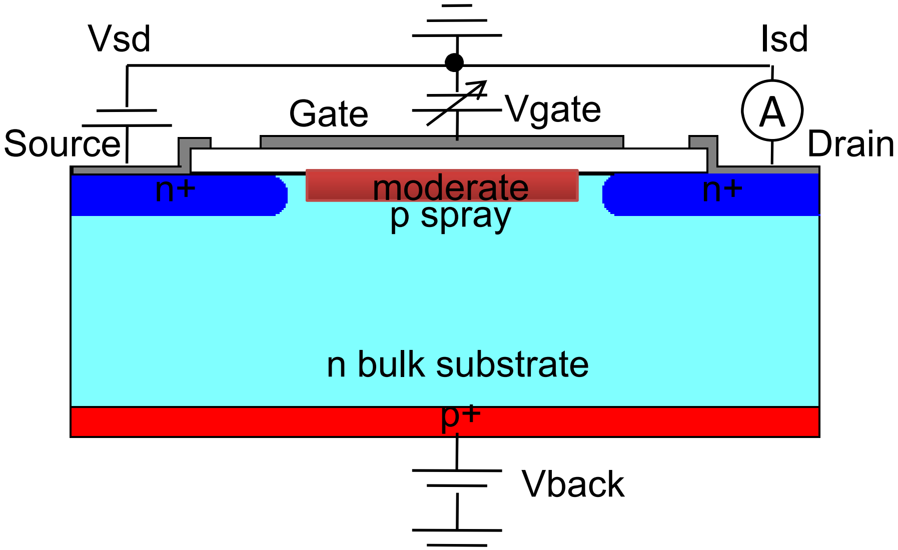


Fig.5 Sketch of threshold voltage measurement

- Gate doped with moderated p-spray (other specification refer to pixel sensor)
- Used to estimate:
  **1) Change of free holes density at Si-SiO$_2$ interface due to irradiation**
  **2) Surface mobility**

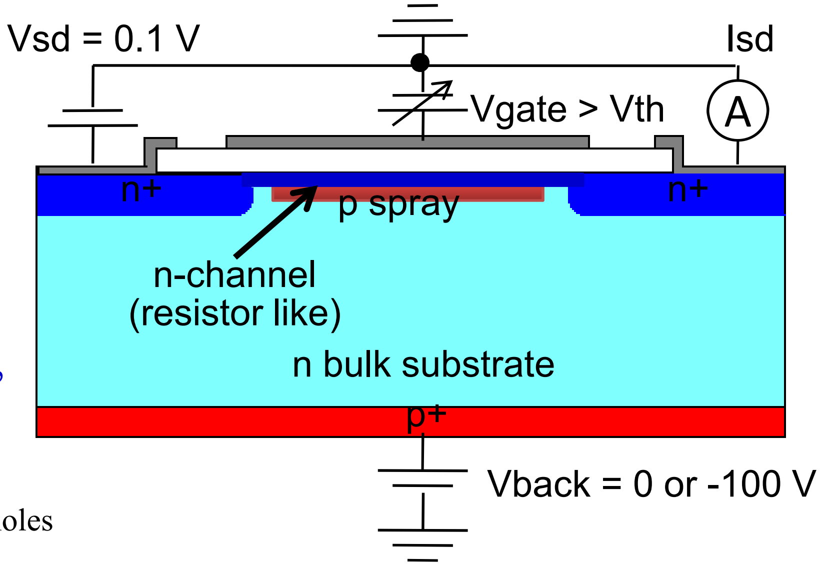
$$I_{sd} = \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot \left[ (V_{gate} - V_{th}) \cdot V_{sd} - \frac{1}{2} \cdot V_{sd}^2 \right]$$

# Characterization of segmented n$^+$n test sensors

<u>Determination of free holes density:</u>

- MOS dominated by p-spray
- Small $V_{sd}$: $I_{sd}$ proportional to $V_{sd}$ (linear region)
- Once n-channel formed ($V_{gate} > V_{th}$), $I_{sd}$ sharply increases with $V_{gate}$
- Change of free holes density $\Delta N_{\text{free-holes}}$ is due to oxide charges and interface traps due to irradiation

$$\Delta N_{\text{free-holes}} \approx \frac{C_{ox} \cdot \Delta V_{th}}{q_0}$$



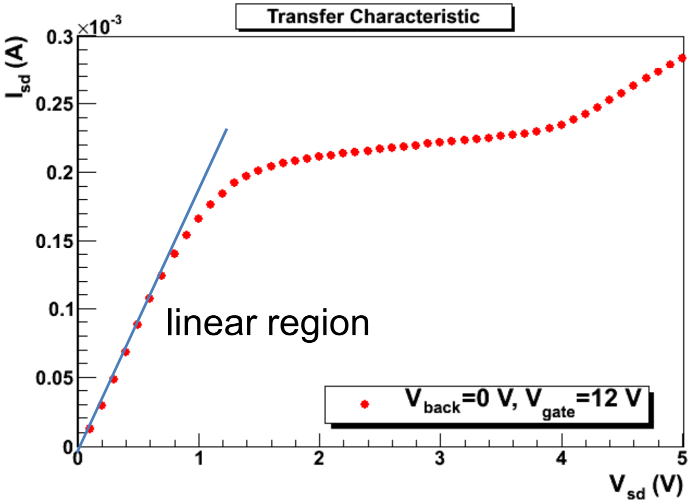
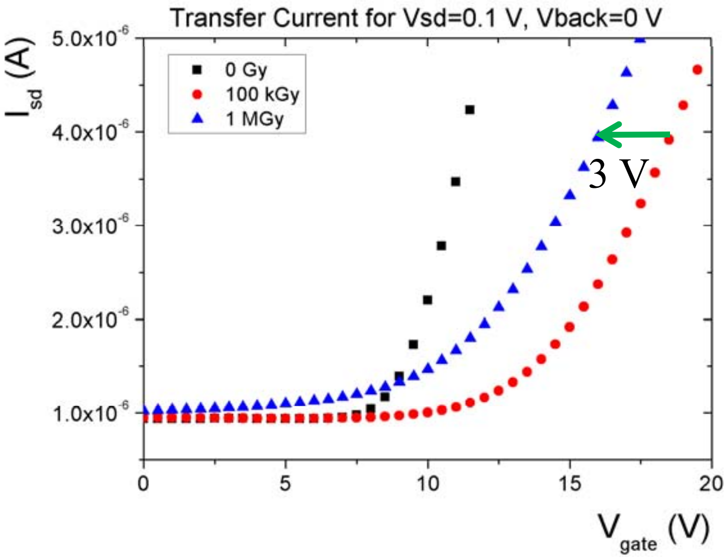
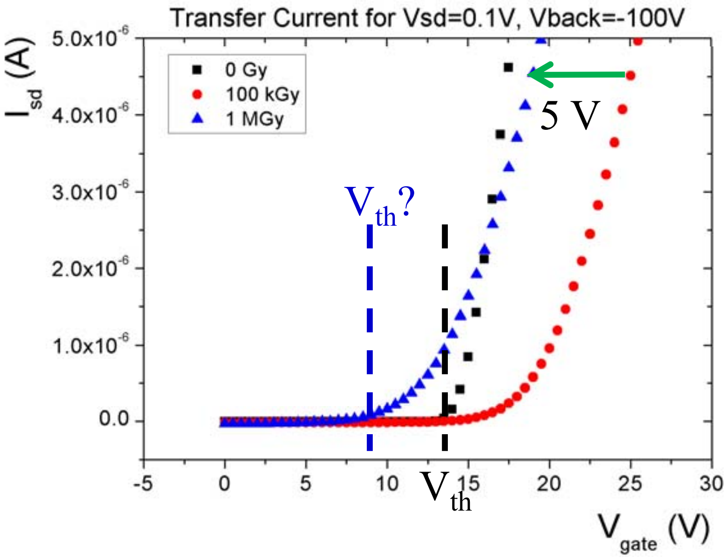


Fig.6 Linear response determination

# Characterization of segmented n$^+$n test sensors

Determination of free holes density changes due to X-ray irradiation:





Samples irradiated up to 1 MGy:

- Change of slope → decrease of surface mobility $\mu_n$ and
- Decrease of electron mobility $\mu_n$ saturates at dose < 100 kGy
- Isolation between pixels is still sufficient ($V_{th} > 0V$)
- The change of free holes density is of order ~ $10^{12}$ cm$^{-2}$ → ( $N_{ox} + N_{it}$ )

# Irradiation of $p^+n$ microstrip sensors with bias

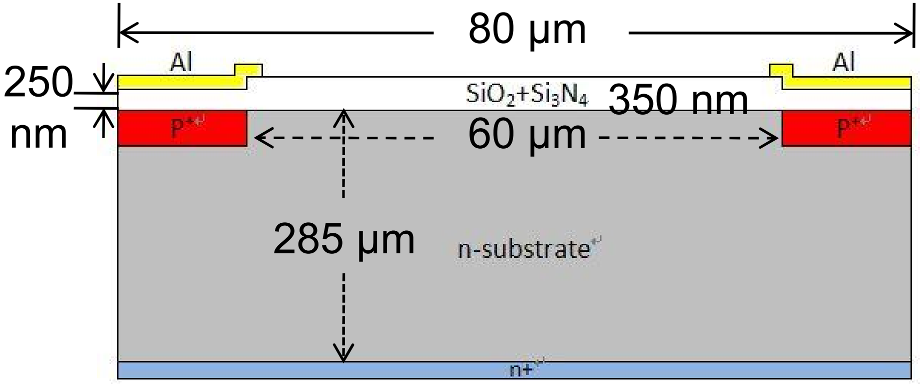


Fig 7. Cut view of the test sensor

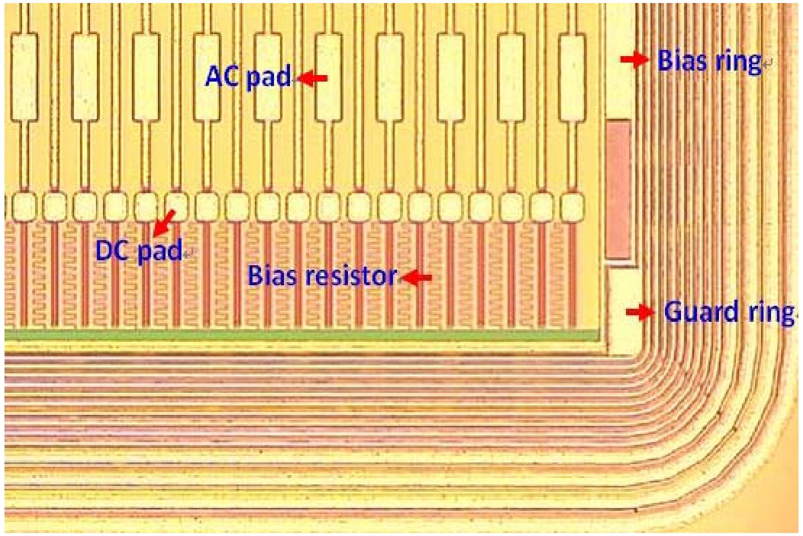


Fig 8. Top view of the test sensor

**$p^+$ on n Si strip sensor:**

- <100> n-substrate
- High resistivity: 2 - 5 kΩ·cm
- Thickness: 285 ± 10 µm
- Active area: 0.62 $cm^2$
- "Oxide": 300 nm $SiO_2$+50 nm $Si_3N_4$
- Strip length: 7.8 mm
- Strip pitch: 80 µm
- Strip number: 98

**X-ray irradiation environments:**

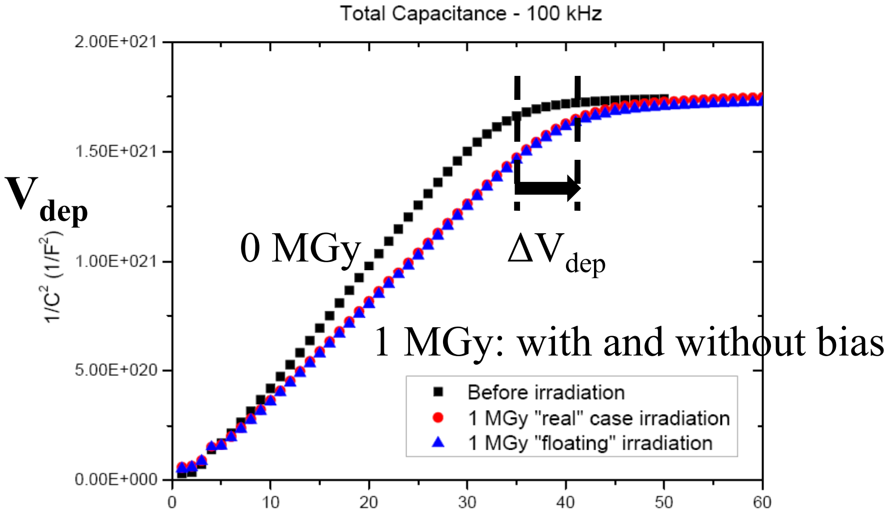
- @DESY DORIS III beamline F4
- Typical energy is 12 keV
- Dose rate in $SiO_2$: 200 kGy/s
- ***Doses: 1 MGy***
- ***Irradiated sensors:***
  - ***sensor 1: irradiated without bias***
  - ***sensor 2: irradiated with 35 V bias (enough to deplete surface)***

# Irradiation of p$^+$n microstrip sensors with bias

Results comparison for irradiations with and without bias:

- Total capacitance:

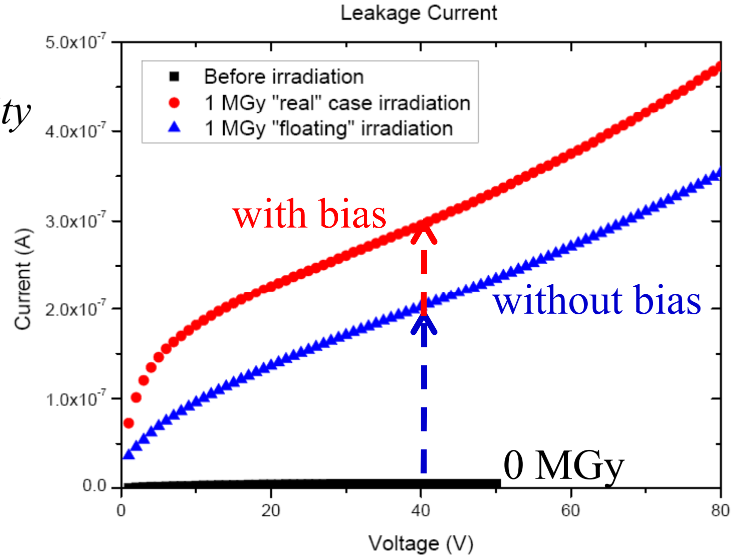
  1. **Change of full depletion voltage $V_{dep}$ (as expected)**
  2. **No difference of CV curves between with and without bias**



- Total leakage current:

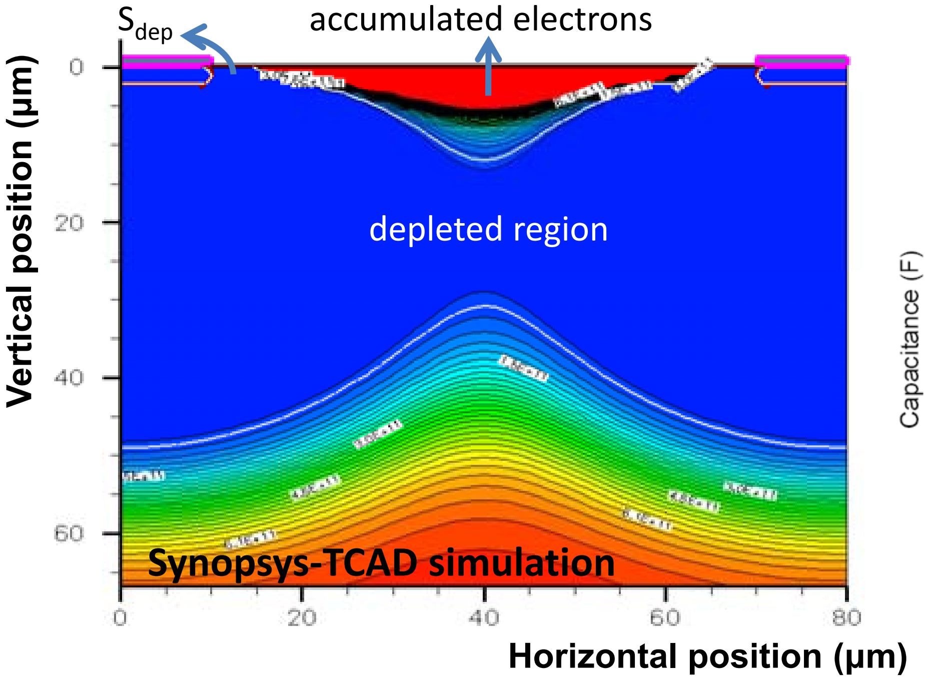
  $$I_{ox} \rightarrow \textit{depleted surface} \bullet \textit{interface trap density} \rightarrow S_{dep} \cdot N_{it}$$

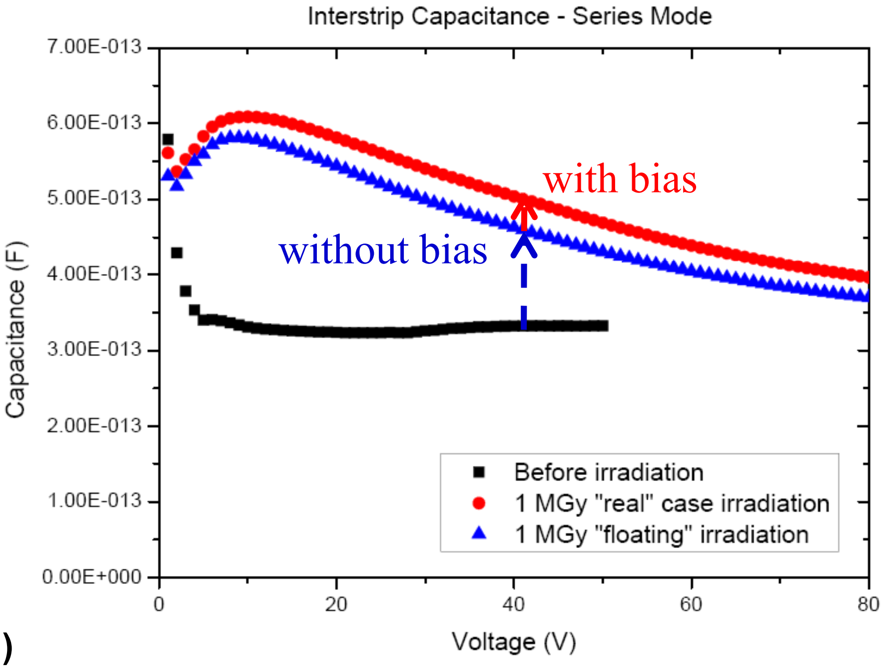
  1. **$S_{dep}$ increases with bias voltage**
  2. **$S_{dep}$ decreases with oxide charges and interface traps (donor)**
  3. **$I_{ox}/S_{dep}$ increases with $N_{it}$**



# Irradiation of $p^+n$ microstrip sensors with bias

Results comparison for irradiations with and without bias:





- Interstrip capacitance $C_{int}$

**$C_{int}$ decrease with surface depleted area $S_{dep}$**

- **Irradiation with bias → larger leakage current and inter-pixel capacitance!**
- Tentative conclusion: more interface traps in the mid-gap were generated!

(oxide charges and interface traps close to conductance band need to confirm)

**Surface charges depend on electric field during irradiation!**

# Summary and next steps

## Summary:

- Pixel gap investigation was done! (criteria needs to be confirmed?) Guard ring and cut edge design (based on Hamamatsu and CIS) is under way
- Study of charge collection in unirradiated $p^+n$ strip sensor was done; simulation shows good agreement with measurement
- Characterization of $n^+n$ pixel sensors and investigation of free holes density due to X-ray irradiation up to 1 MGy
- Irradiation for $p^+n$ sensor with bias was investigated! Surface charges and electric properties (leakage current and inter-strip capacitance) show strong dependent on irradiation environment

# Summary and next steps

## Next steps:

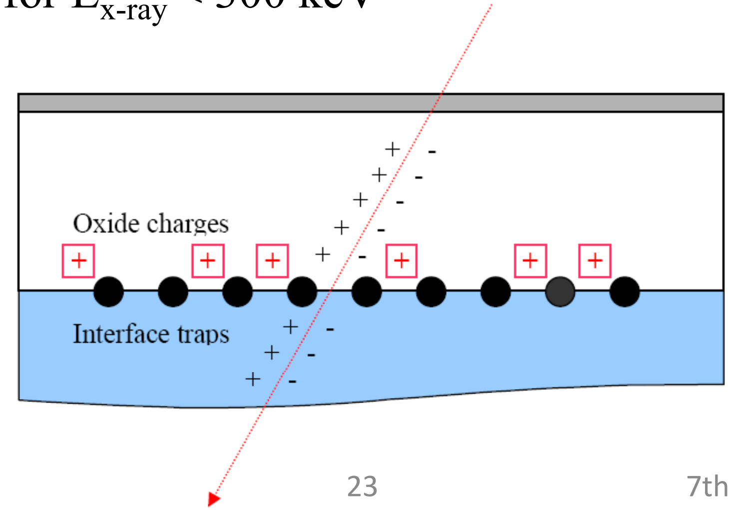
- Complete charge collection study for $p^+n$ sensors with/without irradiation
- Effects on sensor performance of irradiation with bias
- Publication: summary radiation damage studies
    1. Radiation damage on test structures
    2. Simulation of test structures and $p^+n$ sensors, and
    3. Comparison with measurement on test structures and segmented sensors
- Design of sensors & test structures:
    1. Decision on missing parameters
    2. Design sensors
    3. Discussion with Vendor
    4. Protocol for measurement of specification
- Fabrication of sensor and test for prototype

# Thanks for your patience!

# Achievements in the first year

Introduction to the physics in devices due to X-ray irradiation:

- Oxide charge: fast sweep out of electrons from oxide → positive charges left
  - ▸ with positive charges
  - ▸ in the oxide but quite close to the Si-$SiO_2$ interface
  - ▸ change the band bending
- Interface trap: new energy levels forms in the silicon band gap
  - ▸ at the Si-$SiO_2$ interface
  - ▸ can be charged and discharge (act as a capacitor)
  - ▸ change the band bending
- No bulk damage for $E_{x\text{-}ray} < 300$ keV



# Achievements in the first year

Understanding the beam of HASYLAB white light X-ray source:

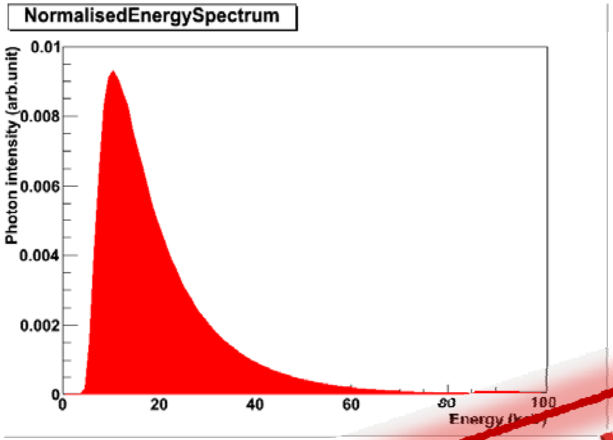


Fig.1 X-ray energy spectrum

**Energy spectrum of photons:**

- ***Typical energy: 12 keV***
- FWHM: 15 keV
- Average Energy: 20 keV
- ***Flux density: $1.08 \times 10^{14}$ [illegible] $\mathrm{mm}^2$)***

Basis to determine dose

**Beam profile:**

- ***Beam spot: 4 mm × 6 mm***
- Horizontal: rectangle distribution
- Vertical: gaussian distribution

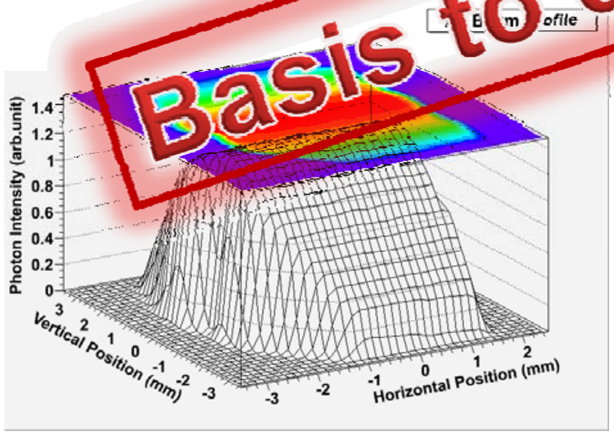


Fig.2 Beam profile at beamline F4

**Dose rate:**

- ***Beam centre: 200 kGy/s***
- 2D scan: 500 kGy/scan

# Achievements in the first year

Parameters ($N_{ox}$ and $N_{it}$) extraction from MOS capacitors and gated diodes:

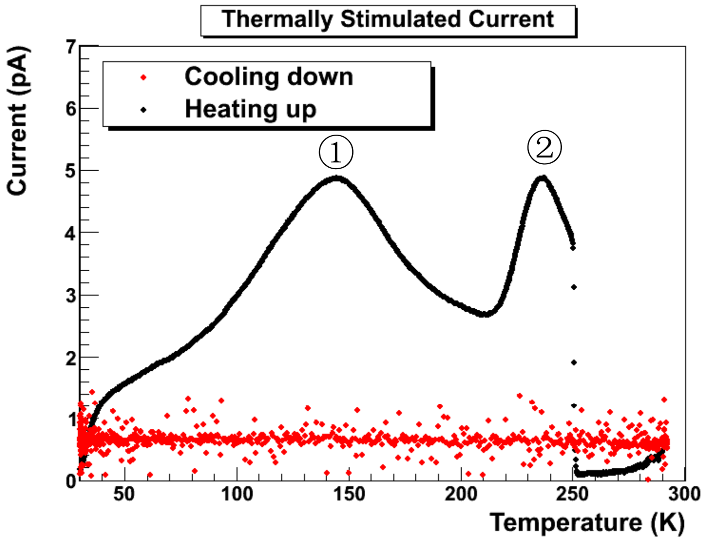


Fig.3 TSC spectrum

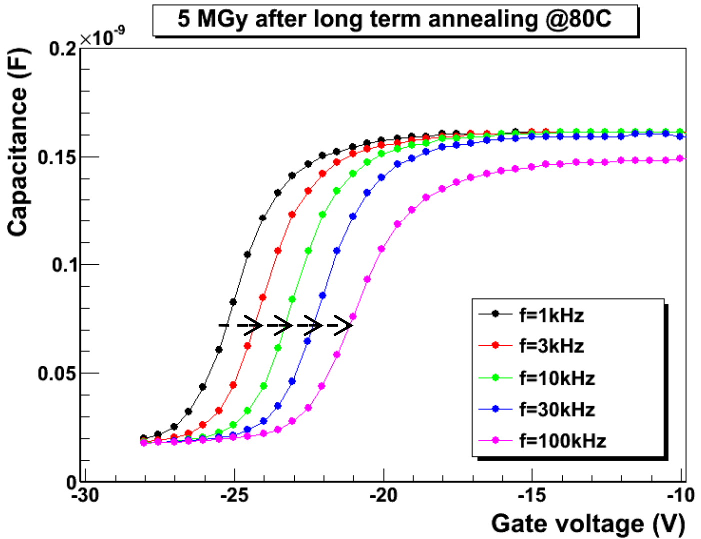


Fig.4 CV curves for different frequencies

From microscopic to macroscopic behavior:
① → frequency dependence of capacitance; ② → surface current

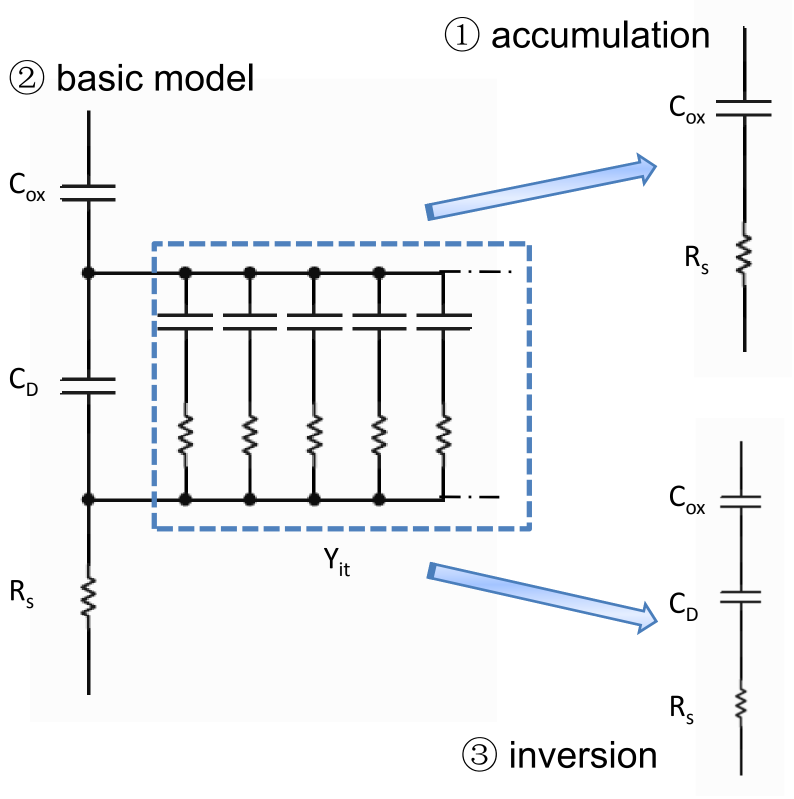
**$N_{it}$ – derived from TSC spectrum**

$$\left.\begin{array}{l} I_{Temp} \rightarrow D_{it}\ (\mathrm{cm^{-2}eV^{-1}}) \\ Temp \rightarrow E_c - E_{it}\ (\mathrm{eV}) \end{array}\right\} \xRightarrow{\text{integration of } D_{it} \text{ distribution}} \mathbf{N_{it}}$$

**$N_{ox}$ – by the change of $V_{FB}$,(once $N_{it}$ is determined)**

# Achievements in the first year

Model calculation for CMOS capacitors:



- $C_{ox}$ → geometry dependence (S, $t_{ox}$)
- **$C_D$ → Lindner approximation**
- $R_s$ → doping dependence
- **$Y_{it} = -jw(\delta Q_{it} / \delta\psi_s)$**
- **$I_{ox}$ → SRH model**

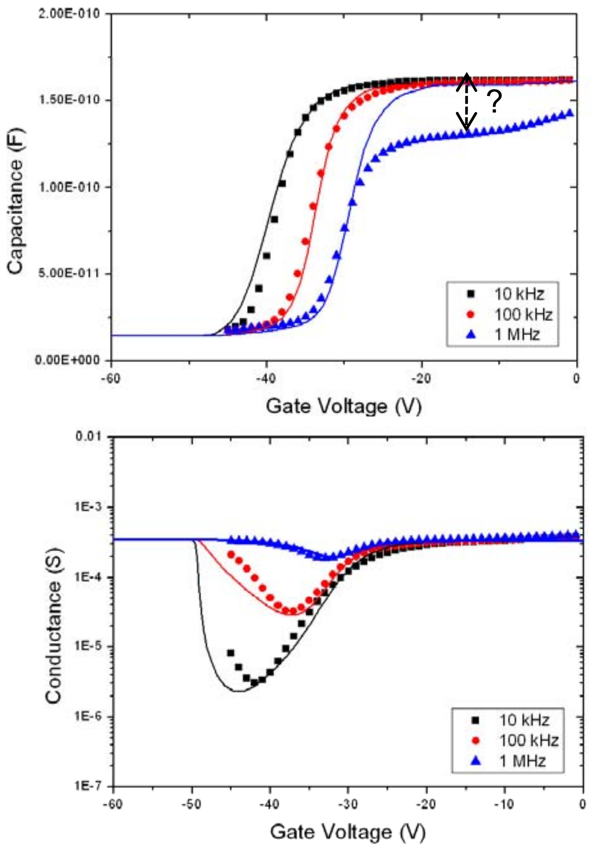


Fig.5 CV and GV reconstruction

(Modification of the model and full comparison with 1-D TCAD simulation are under way)

# Achievements in the first year

Characterization of p+ on n strip sensor for 0 MGy, 1 MGy and 10 MGy:

- No change of total capacitance due to irradiation → **fixed geometry**
- Frequency dependence of total capacitance

  → **interface traps close to the conductance band**

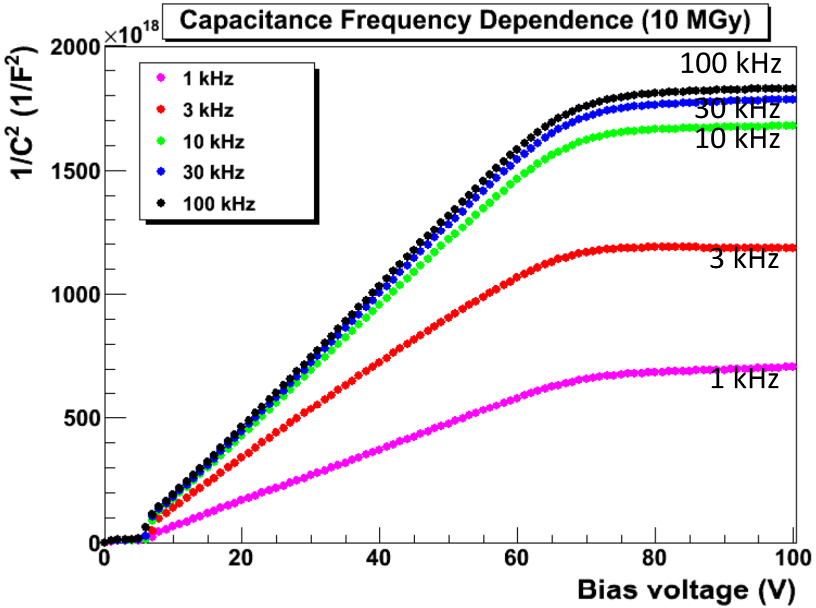


Fig.6 Frequency dependence of total capacitance

- Increase of leakage current → **interface traps near the mid gap**
- Increase of interstrip capacitance & decrease of interstrip resistance

  → **degradation of interface isolation**

# Achievements in the first year

Characterization of p+ on n strip sensor for 0 MGy, 1 MGy and 10 MGy:

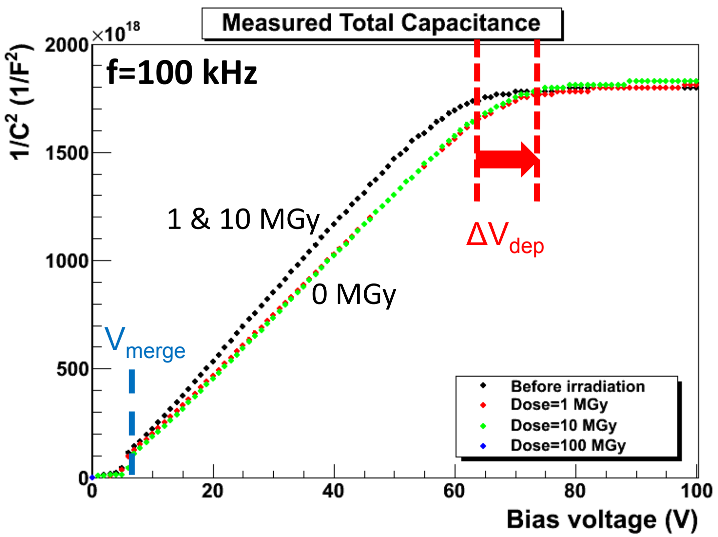


Fig.7 Total capacitance

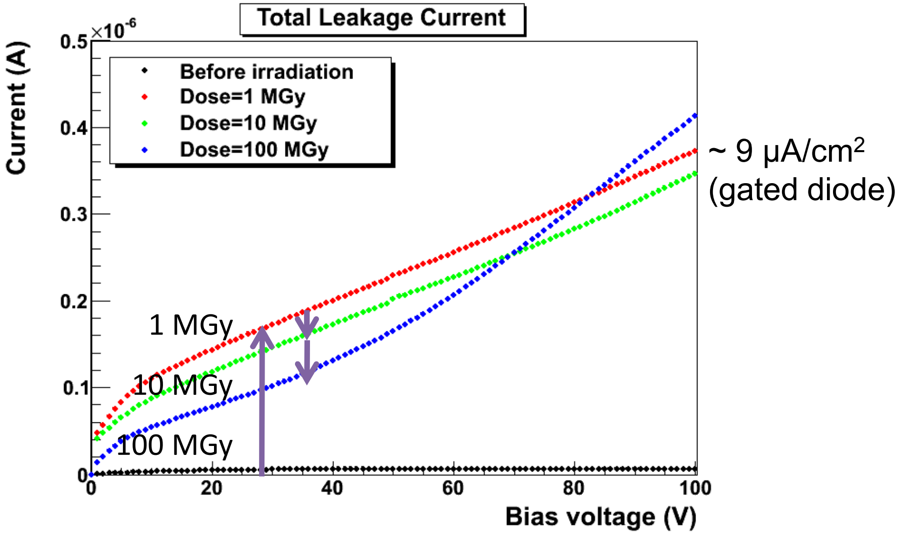


Fig.8 Total leakage current

- Change of full depletion voltage!

  → **accumulated electrons close to the Si-SiO$_2$ interface**
- Increase of leakage current with bias voltage

  → **change of surface depleted area S$_{dep}$**

# Achievements in the first year

## Spice simulation for unirradiated strip sensor:

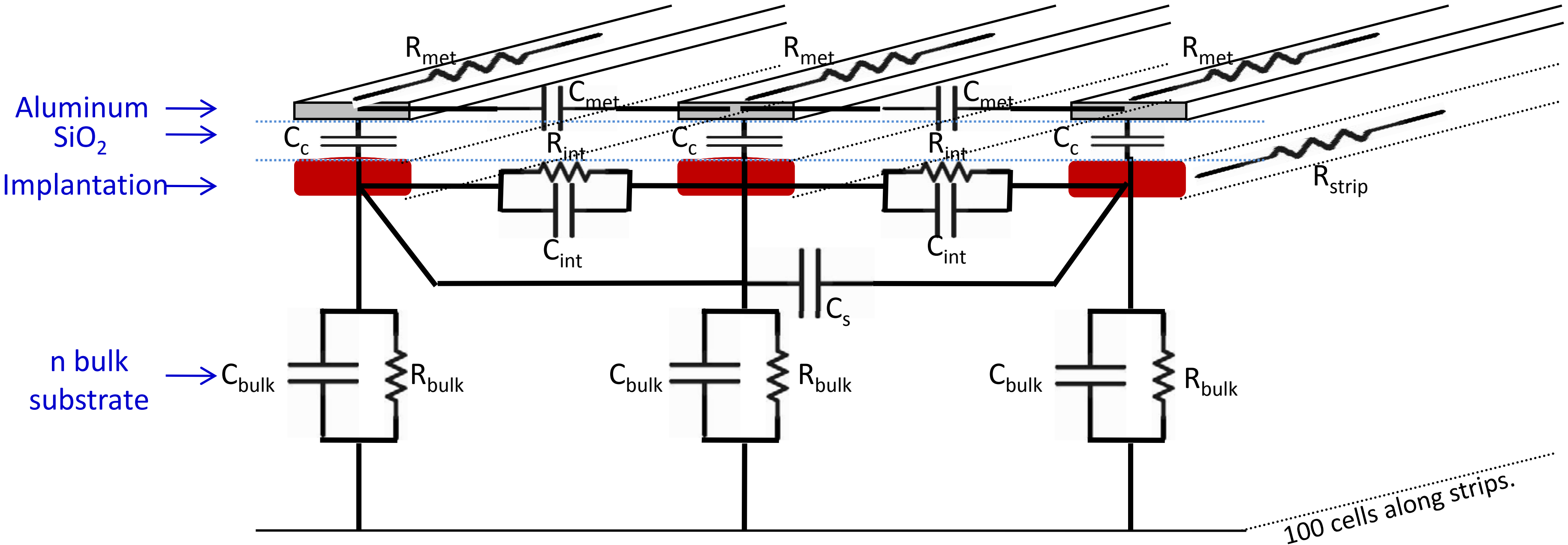


Fig.9 RC network of the strip sensor

- 10 parameters: $C_{bulk}$, $R_{bulk}$, $C_{int}$, $R_{int}$, $C_c$, $R_{strip}$, $C_{met}$, $R_{met}$, $C_s$, $R_{bias}$
- In this simulation, 5 strips and 100 cells are used ~ 80 µm/cell
- Good description of capacitance and resistance ***frequency response – C(f) & R(f)***

# Achievements in the first year

Spice simulation for total bulk, interstrip and coupling impedances *):

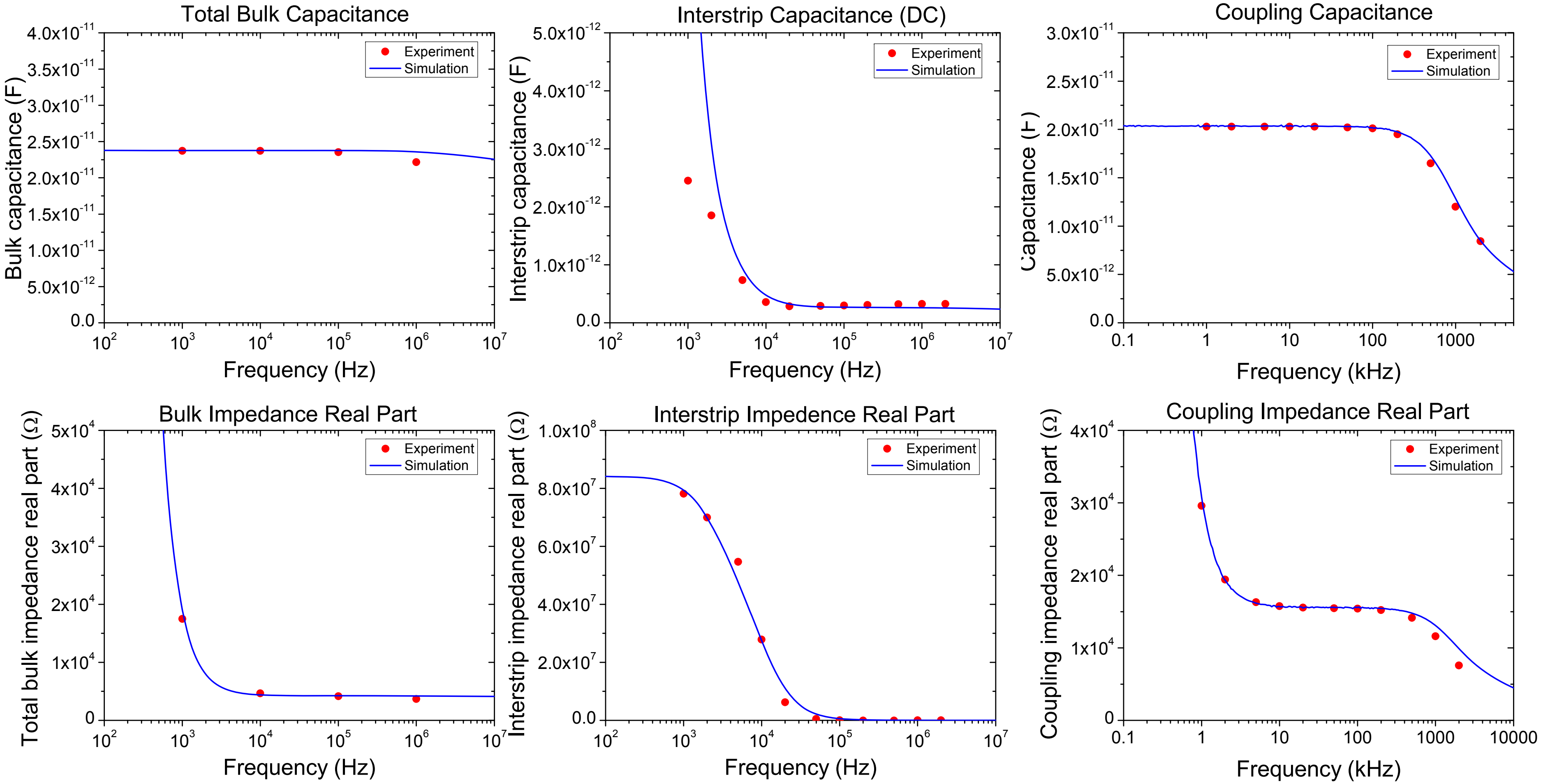


Fig.10 Comparison between spice simulation and experiment

***Because of the presence of interface traps, this simple model won't work for irradiated sensor.***

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*) Series mode

# Summary

- Benefit a lot from MC-PAD networks
- Work done:
  - i. Dose determination and successful irradiation for “large” area detectors
  - ii. Surface charges ($N_{ox}$ and $N_{it}$) extraction from MOS capacitors
  - iii. Reconstruction of CV and GV curves of MOS capacitors
  - iv. Characterization of segmented p+ on n sensor up to 100 MGy & Qualitatively understanding of irradiated n+ on n pixel sensor
  - v. SPICE simulation for unirradiated p+ on n strip sensor
- Further works (second year):
  - i. Modification of model calculation and optimize cross sections
  - ii. Development of SPICE model for irradiated sensor
  - iii. Dead layer study for irradiated p+ on n sensors
  - iv. Annealing study for irradiated sensors
  - v. Sensor mask design with Cadence

*Thanks for your attention!*

# Test sensor and photon irradiation

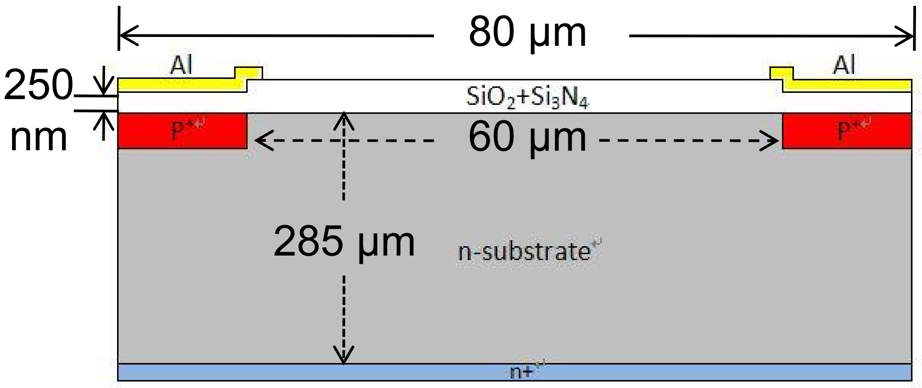

Fig 1. Side view of the test sensor

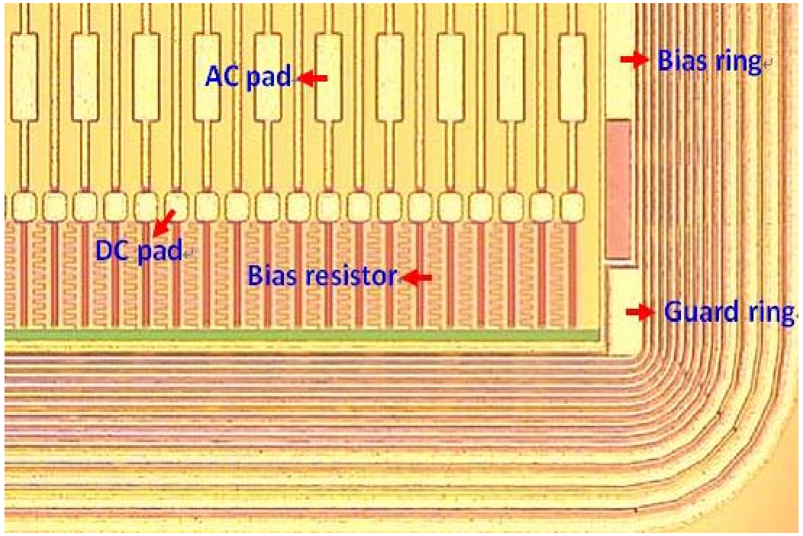

Fig 2. Top view of the test sensor

**$p^+$ on n Si strip sensor:**

- <100> n-substrate
- High resistivity: 2 - 5 kΩ·cm
- Thickness: 285 ±10 µm
- Active area: 0.62 $cm^2$
- "Oxide": 200 nm $SiO_2$+50 nm $Si_3N_4$
- Strip length: 7.8 mm
- Strip pitch: 80 µm
- Strip number: 98

**Photon irradiation:**

- @DESY DORIS III beamline F4
- ***Typical energy is 12 keV*** (Γ ~10 keV)
- Dose rate in $SiO_2$: 200 kGy/s
- ***Results for doses:***

***1 MGy, 10 MGy, 100 MGy***

# Macroscopic characteristics: Total capacitance

**CV curve analysis - three stages:**

① $\mathbf{V_{bias}} < \mathbf{V_{merge}}$ ( ≈ 6V), strips are depleted individually

② $\mathbf{V_{merge}} \leqq \mathbf{V_{bias}} \leqq \mathbf{V_{dep}}$, sensor partially depleted, $1/C^2$ increases linearly with $V_{bias}$

③ $\mathbf{V_{bias}} > \mathbf{V_{dep}}$, fully depleted, C ≈ constant.

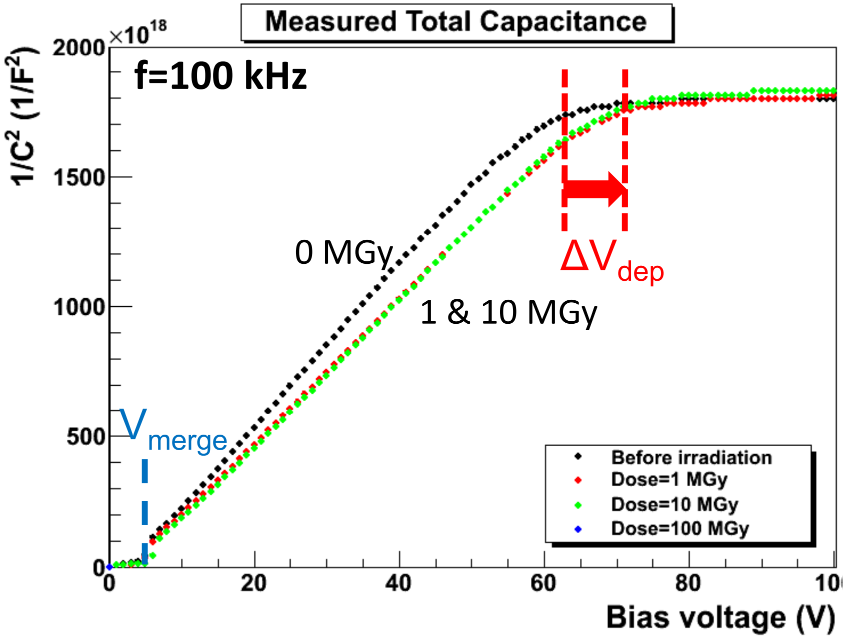

Fig 3. Measured CV curves for different doses

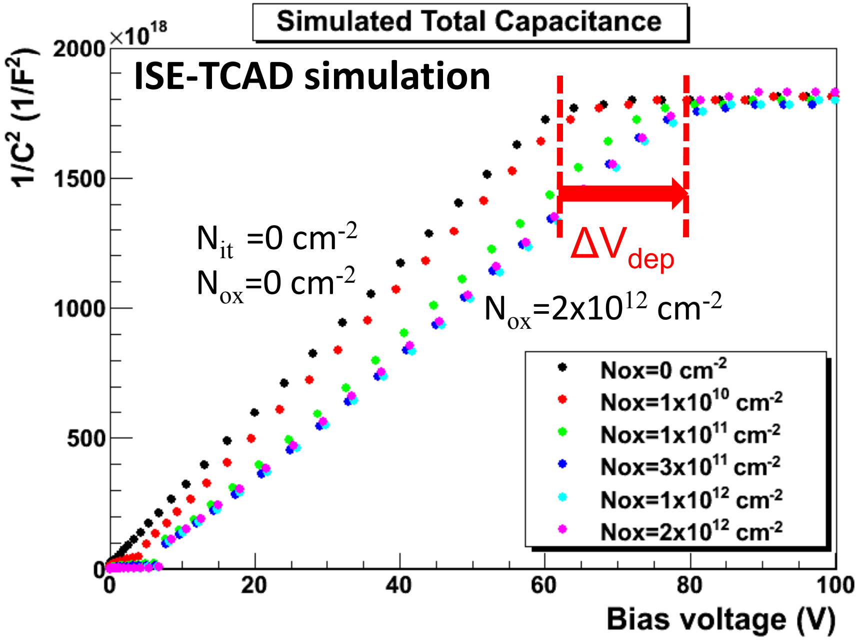

Fig 4. Simulated CV curves for different oxide charge densities

- ***Because of surface charges, $V_{dep}$ increases after irradiations!***
- From simulation, $V_{dep}$ changes with increasing oxide charge density $N_{ox}$

# Macroscopic characteristics: Total capacitance

Accumulated electrons delay increase of depletion depth.

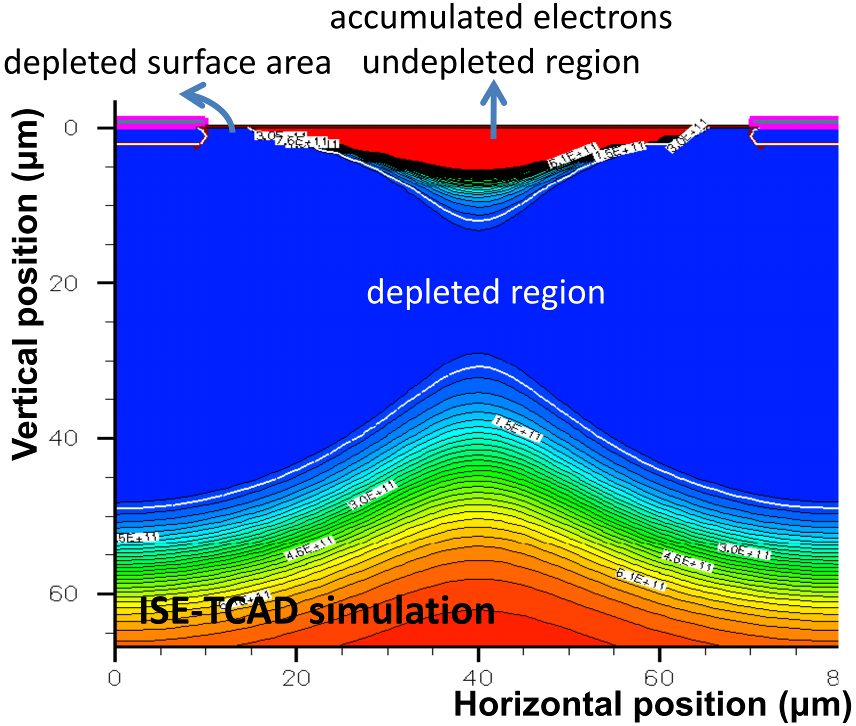

Fig 5. Simulated electrons density distribution

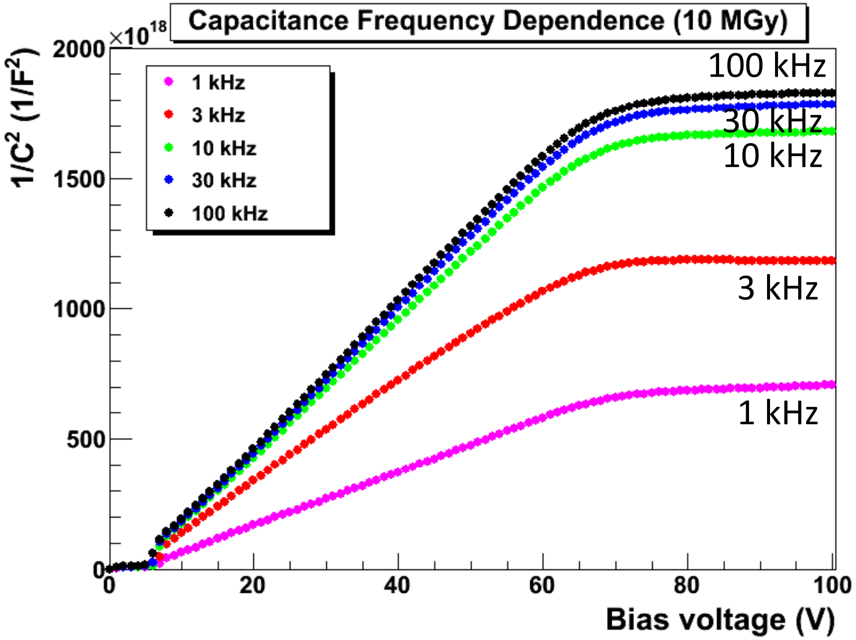

Fig 6. Measured CV curves frequency response

- High frequency → low capacitance
- ***Interface traps are responsible for the change of C with frequency***

# Macroscopic characteristics: Leakage current

$I_{leakage} = I_{bulk} + I_{surface}$ :

After irradiation → $\Delta I_{leakage} = \Delta I_{surface}$

$I_{bulk}$ depends on ***depleted volume*** of the sensor, and ***life time*** of charge carriers in bulk

***No change due to X-ray irradiation.***

$I_{surface}$ depends on ***interface trap density*** $N_{it}$, and ***Si-SiO₂ interface depleted area*** $S_{dep}$

***Changes with X-ray irradiation.***

# Macroscopic characteristics: Leakage current

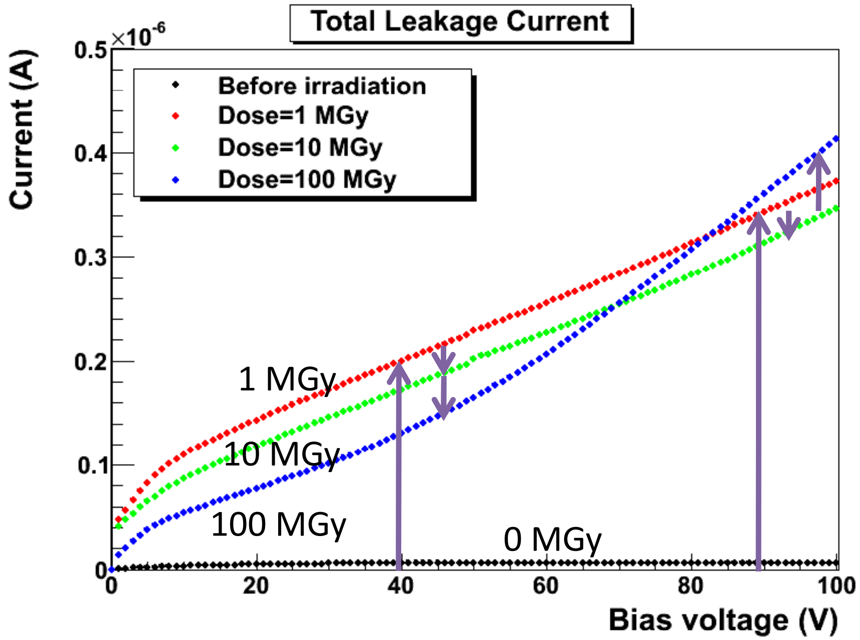

Fig 7. Measured IV curves for different doses

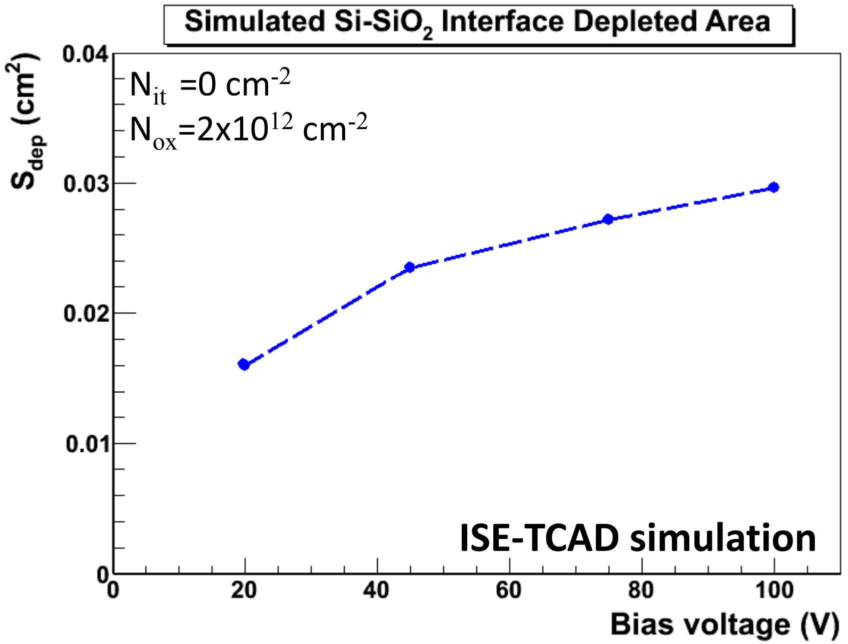

Fig 8. Simulated Si-SiO$_2$ interface depleted area

- Decrease of $I_{leakage}$ with dose → ***interface trap density $N_{it}$***
- Increase of $I_{leakage}$ with bias voltage → ***Si-SiO$_2$ interface depleted area $S_{dep}$***
- $I_{leakage}/S_{dep} \approx 10\ \mu A/cm^2$ agrees with measurements on gated diodes

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More details on TCAD simulation please refer to Ajay's talk.

# Summary

Summary:

- Detailed characterization of $p^+$ on n Si strip sensor for 0, 1, 10 and 100 MGy
  - — Data described by Spice model for 0 MGy
  - — Irradiation
    - ⇨ Increase of $N_{ox}$ → Change of depletion voltage
    - ⇨ Change of $N_{it}$ → Change of leakage current

  Changes can be described by ISE-TCAD simulation

- Tentative conclusion: $p^+$ on n sensor can work up to dose ~ 100 MGy

**Thanks for your attention!**

# <<Backup<<

# Macroscopic characteristics: Bias resistance

Bias “resistor” is made from low doped p+ implantation*).

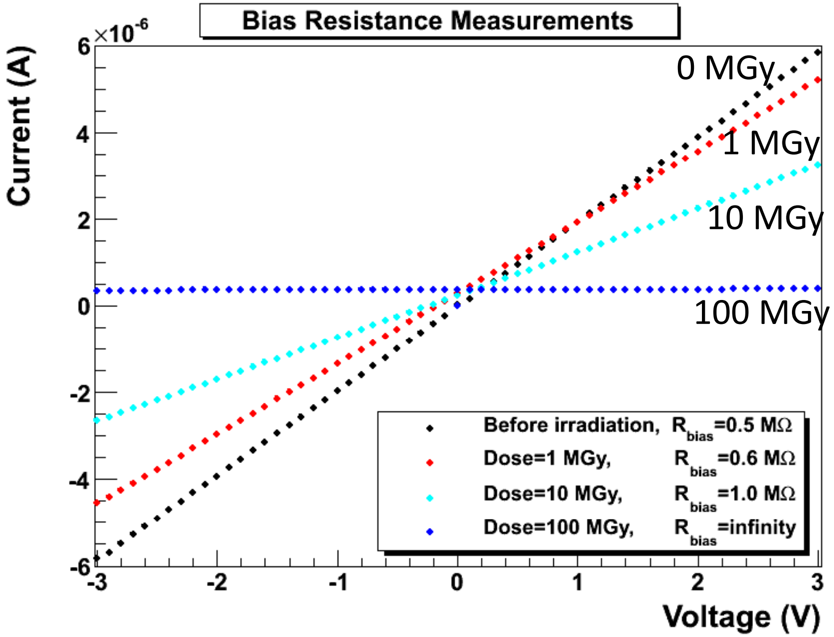

Fig 11. Measured IV curves for different doses

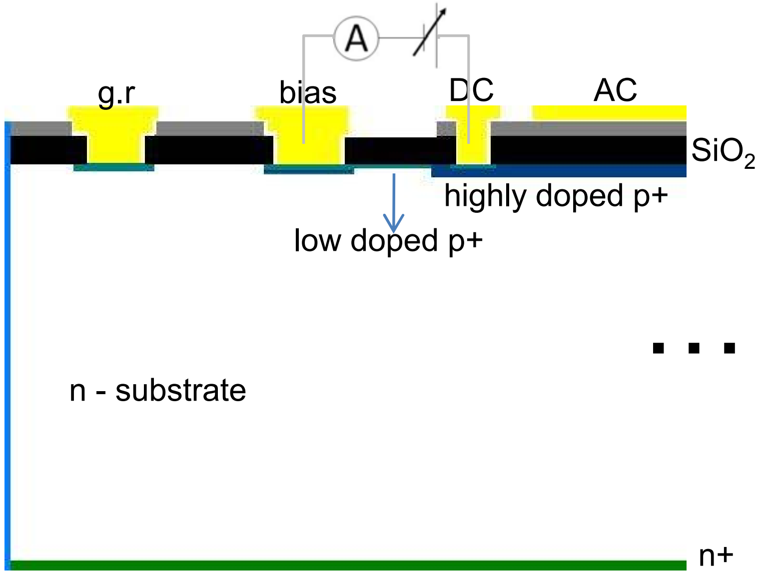

Fig 12. Cut of the strip sensor

- ***Accumulated electrons compensate holes → reduce the conductivity?***
  - ***→ Impact from both $N_{ox}$ and $N_{it}$***
- ***Problem: channel pinch off → voltage punch through → incomplete depletion***

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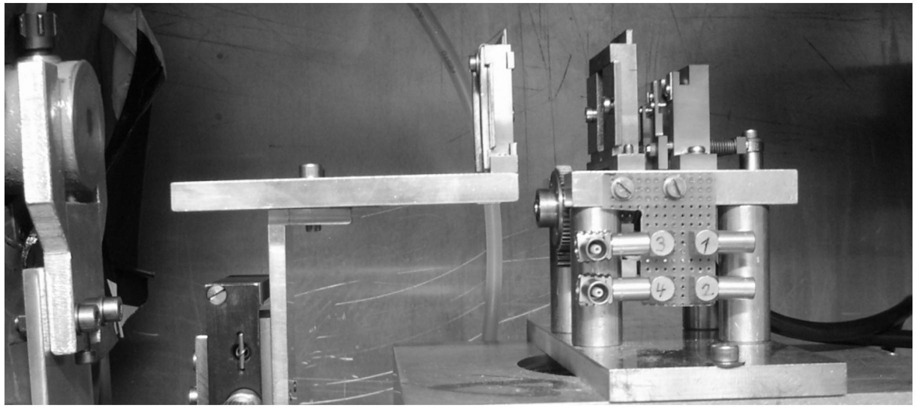
*) Poly-Si resistor is needed for radiation hard sensors

# Irradiation setup and spectrum

Irradiation setup – located at HASYLAB DORIS III beamline F4:



**At the beam centre:**

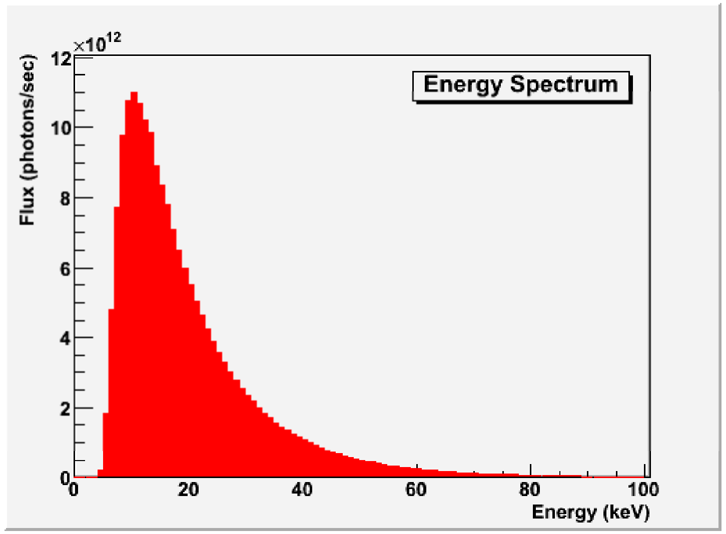
- ***Dose rate: 200 kGy/s***

**Beam scan:**

- Dose: depends on scanning speed, step width, detector size…
- ***Typical value: 500 kGy/scan***

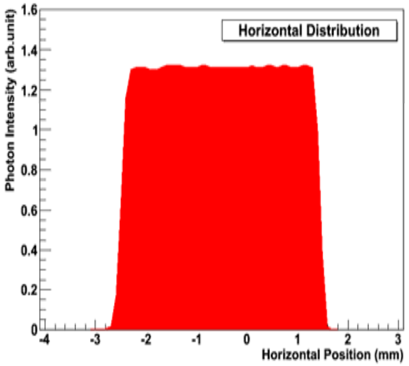
**Energy spectrum of photons:**

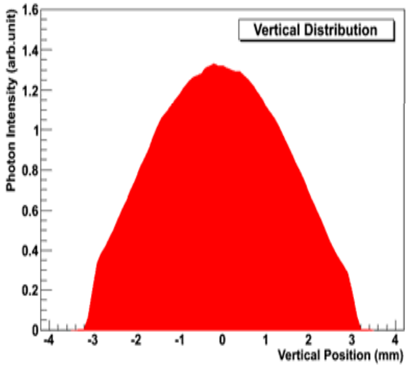
- ***Maximum possible energy: 11.5 keV***
- FWHM: 12 keV
- Average Energy: 20 keV
- ***Integrated flux: 2 × $10^{14}$ /s***



# Beam spot and profile

Beam profile at HASYLAB DORIS III beamline F4:





**At the beam centre:**

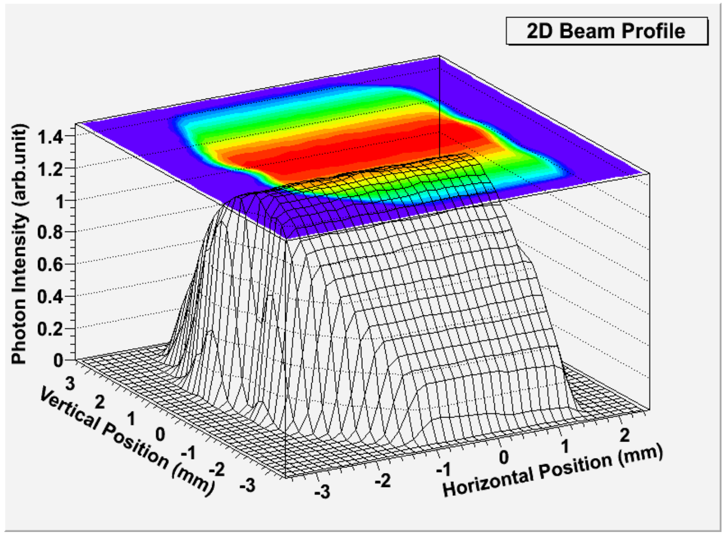
- ***Dose rate: 200 kGy/s***

**Beam scan:**

- Dose: depends on scanning speed, step width, detector size…
- ***Typical value: 500 kGy/scan***

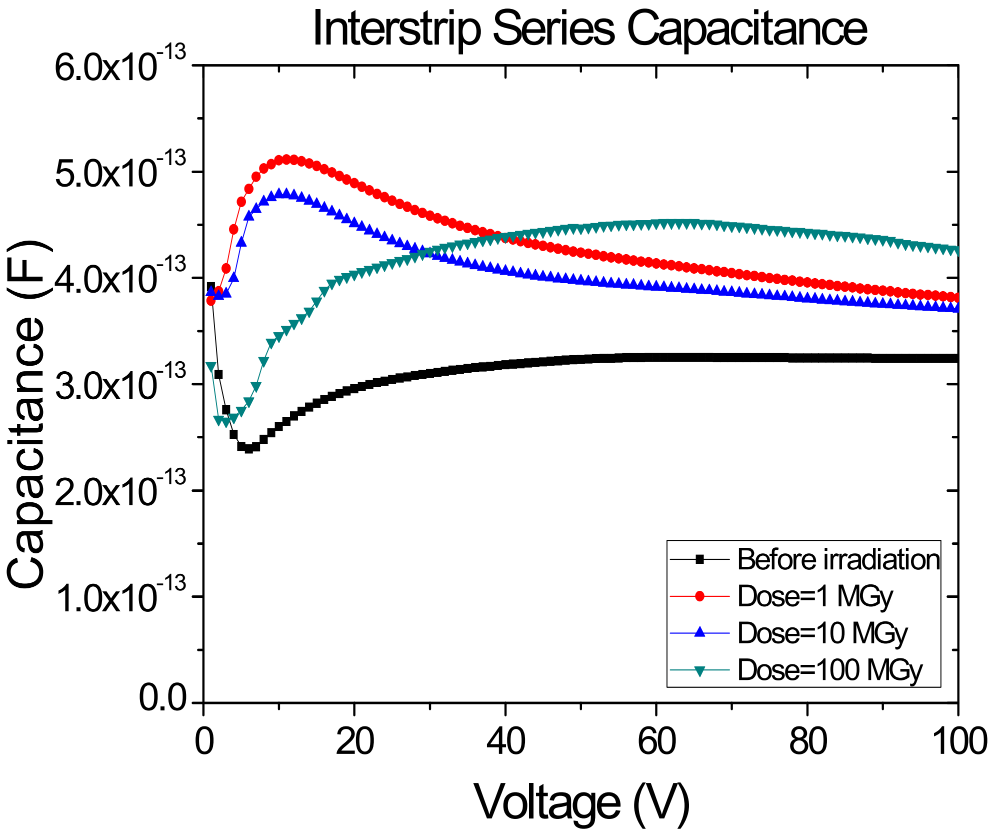
**Beam profile:**

- ***Beam spot: 4 mm × 6 mm***
- Horizontal: rectangle distribution
- Vertical: gaussian distribution



# Interstrip capacitance

Interstrip capacitance (between implantations):

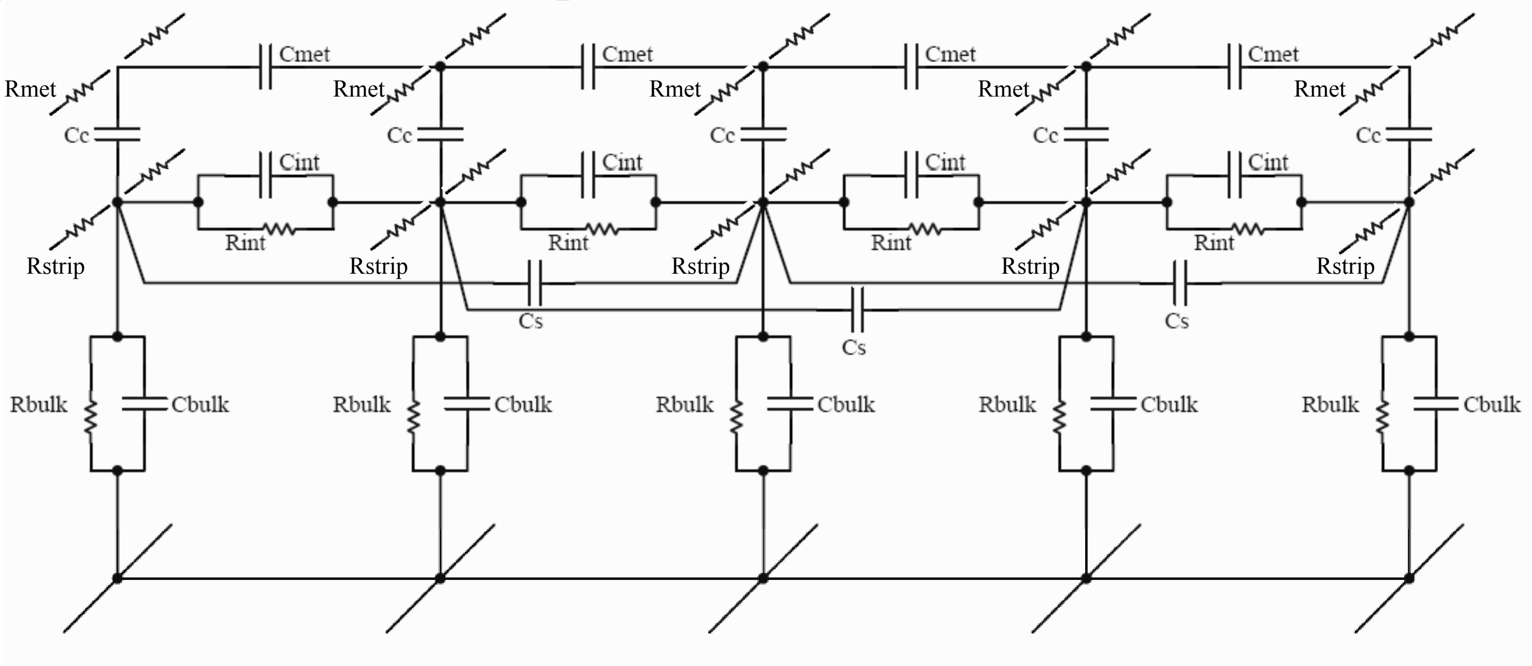


1 MHz plot:

- Above full depletion voltage, interstrip capacitance increases with doses because of the degradation of interstrip isolation
- Curve’s behaviors are complicate due to the accumulated electrons layer

# Complete spice model

Spice model: based on a 10 parameters' RC network 1)



- Able to simulate capacitance and resistance ***frequency response – C(f) & R(f)***
- In this study,100 cells are used ~ 80 µm/cell
- Determination of parameters: ① from direct measurements – Rmet, Rbias
  ② extraction from measurement results ③ from comparisons of sim and meas

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1) M.M. Angarano, et al. Nucl. Instru. & Methods, Vol. 428, No.2, 1999

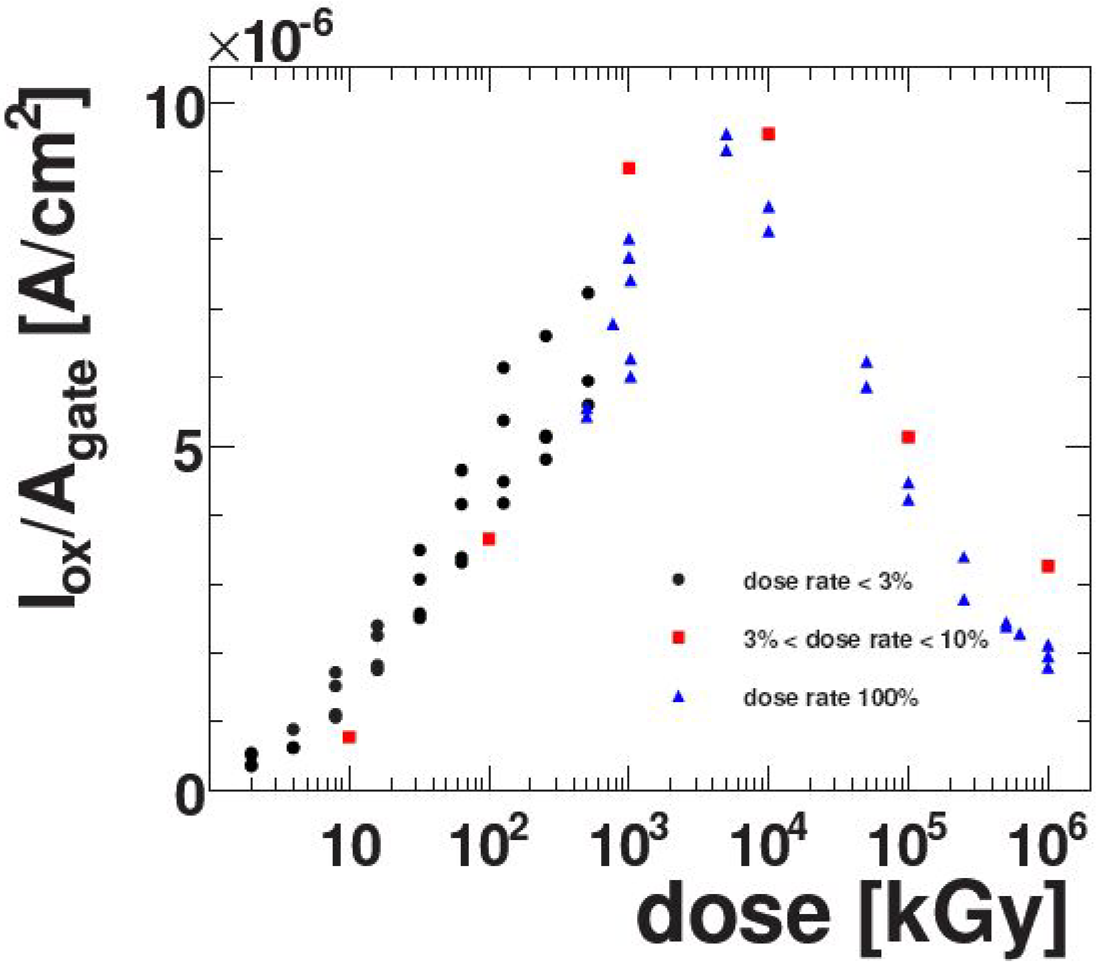
# Spice parameters and values

Spice parameters and their values:

| Parameter | Value | |
|---|---|---|
| Rstrip | 60 kΩ/cm | ☺ |
| Rbias | 0.5 MΩ | ☺ |
| Rmet | 0.05 Ω/cm | ☺ |
| Rbulk | 3.8 GΩ/cm | |
| Rint | 100 MΩ/cm | |
| Cc | 25 pF/cm | ☺ |
| Cbulk | 30 pF/cm | ☺ |
| Cint | 0.125 pF/cm | ☺ |
| Cmet | 0.125 fF/cm | |
| Cs | 6.25 fF/cm | |

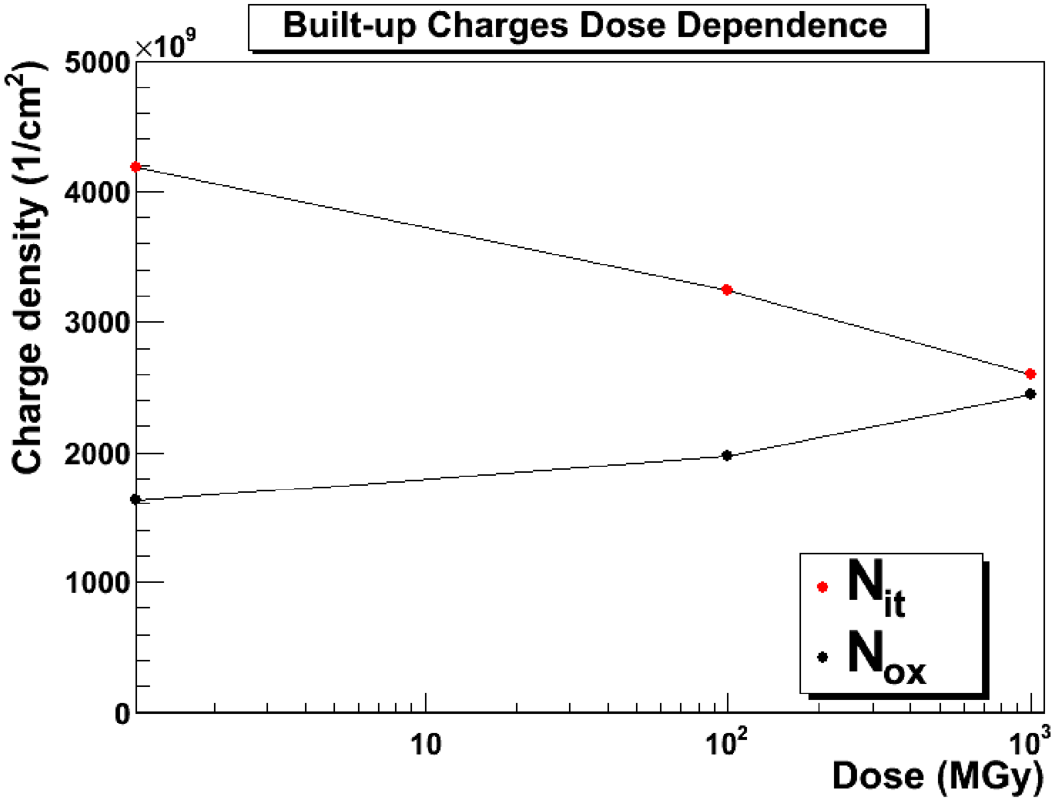
# Study on gated diodes

Surface current:

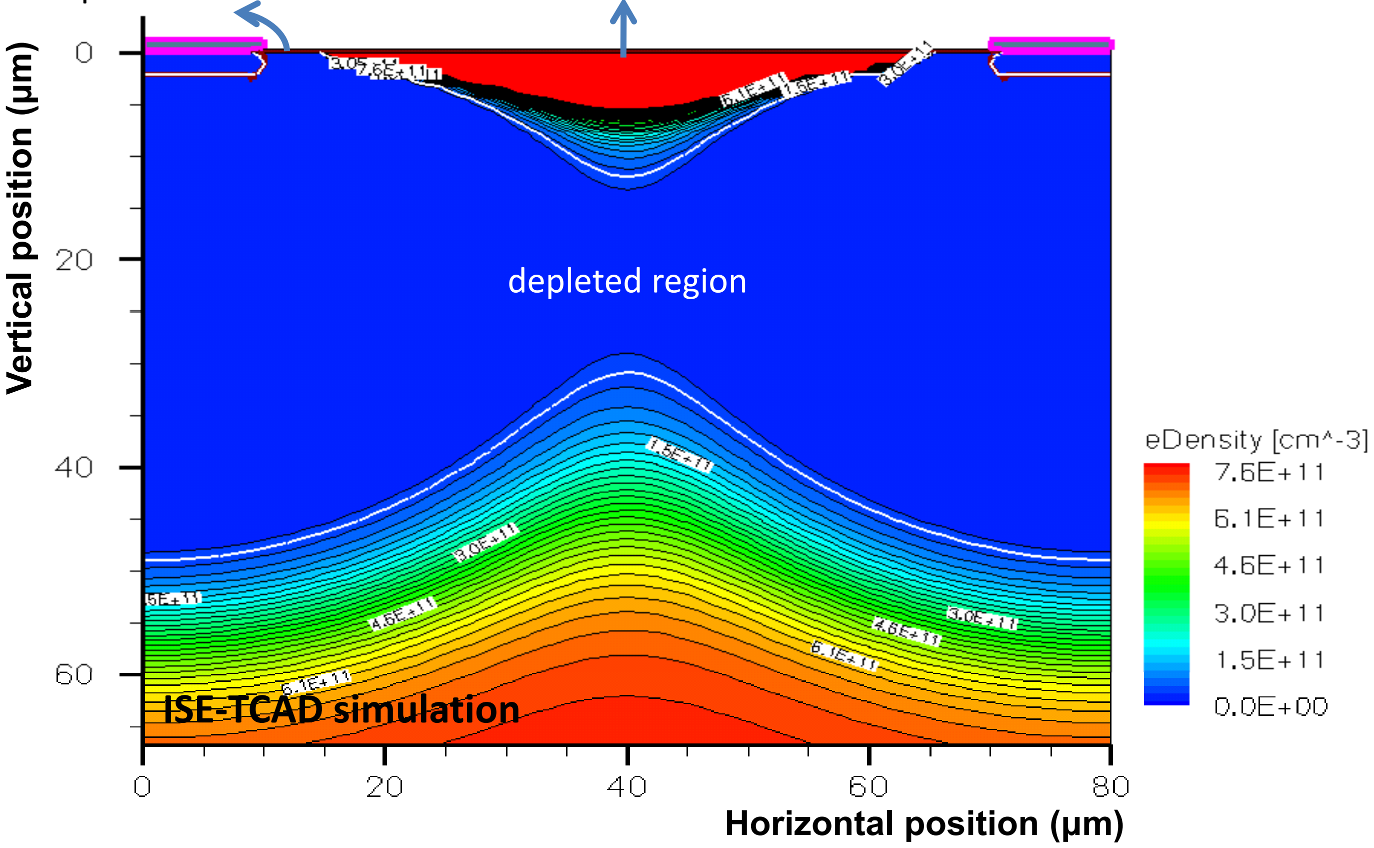


# Study on gated diodes

Oxide charges and interface state density:



# Detailed electron density from TCAD simulation



accumulated electrons
undepleted region

depleted surface area

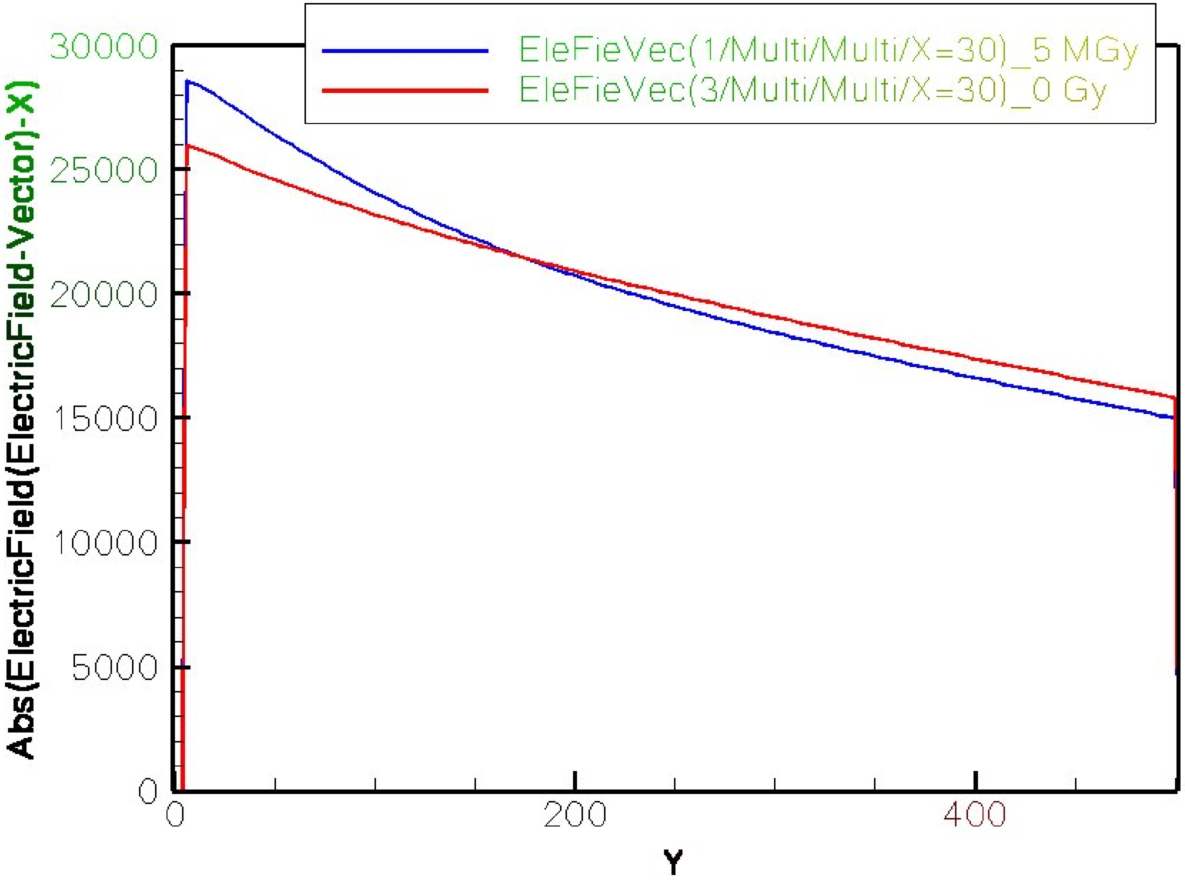
depleted region

ISE-TCAD simulation

# Optimization of sensor design for AGIPD

First multi-guard rings design for AGIPD $p^+n$ sensor:

- Electrostatic potential distribution in non-irradiated and irradiated Si Sensor

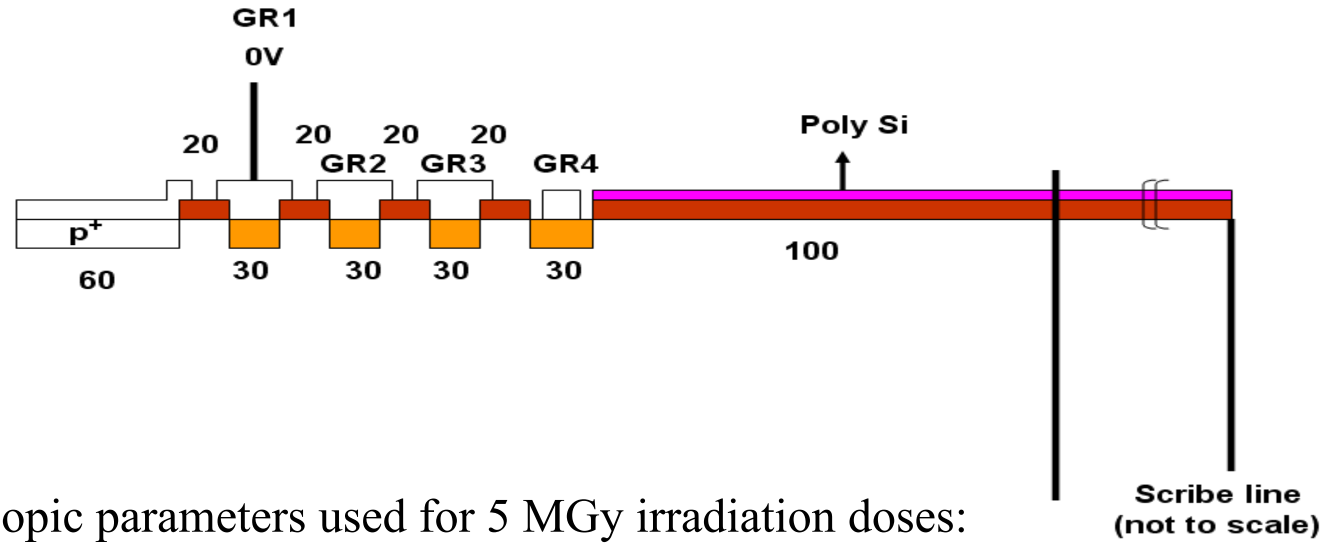


→ For the guard ring design sensor, electric field = 2.6-2.9kV/cm (below pixel) observed for 0 and 5 MGy irradiated dose

# Optimization of sensor design for AGIPD

First multi-guard rings design for AGIPD $p^+n$ sensor:

- Layout – 360 x 500 $\mu m^2$ and **no break down up to V= 1000V**
- The size of the p-implant is 120 x120 $\mu m^2$ with a pixel pitch of 200 x 200 $\mu m^2$ (80 μm pixel gap is used)



Microscopic parameters used for 5 MGy irradiation doses:

$N_{ox}$= $2x10^{12}$ $cm^{-2}$
- $E_c$ -$E_{it}$ = 0.354 eV (acceptor)

- Gauss with rms = 0.1016 eV
- $\sigma_{eff}$ = $1x10^{-16}$ $cm^2$
- $D_{it}$ (0.354 eV) = $5.861x10^{12}$ $cm^{-2}$ $eV^{-1}$

- $E_c$ -$E_{it}$ = 0.636 eV (acceptor)

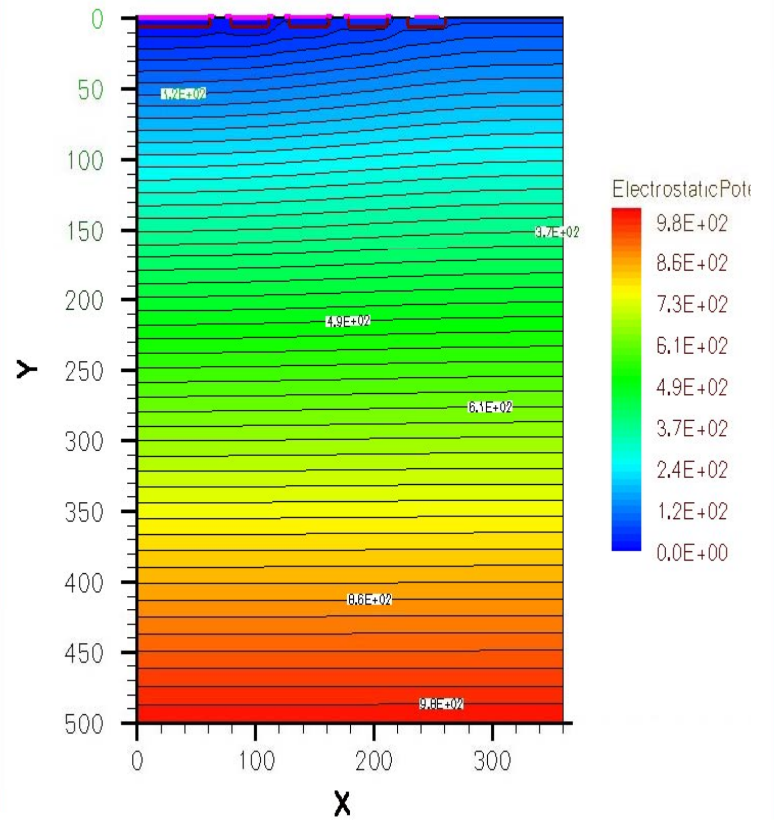
- Gauss with rms = 0.045 eV
- $\sigma_{eff}$ = $4x10^{-15}$ $cm^2$
- $D_{it}$ (0.636 eV) = $6.728x10^{12}$ $cm^{-2}$ $eV^{-1}$

# Optimization of sensor design for AGIPD

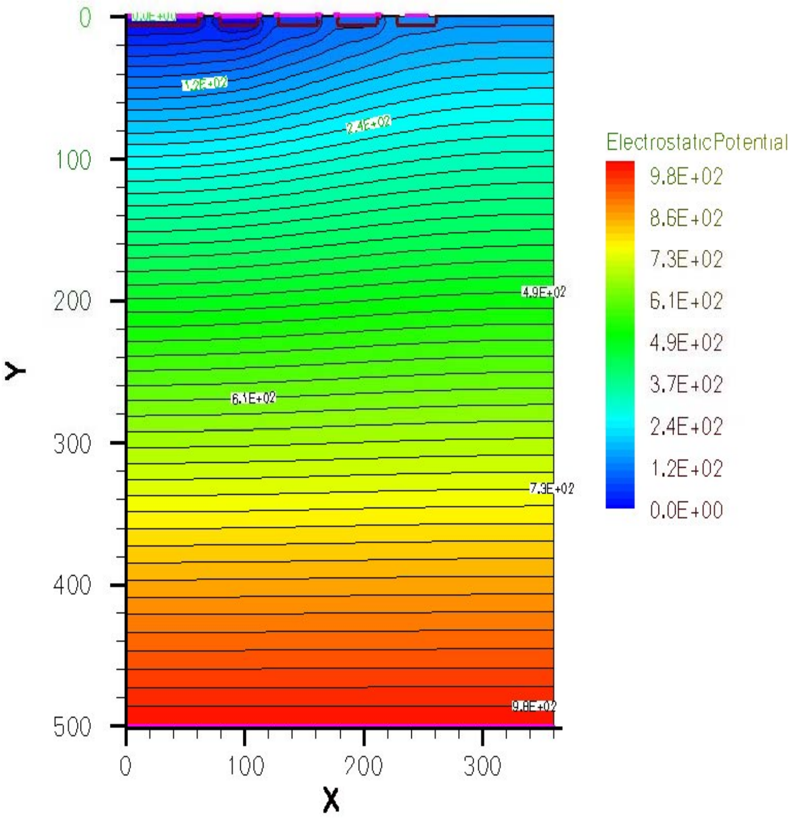
First multi-guard rings design for AGIPD $p^+n$ sensor:

- Electrostatic potential distribution in non-irradiated and irradiated Si Sensor

0 MGy
$N_{ox}=2.1\times10^{10}$ cm$^{-2}$



5 MGy

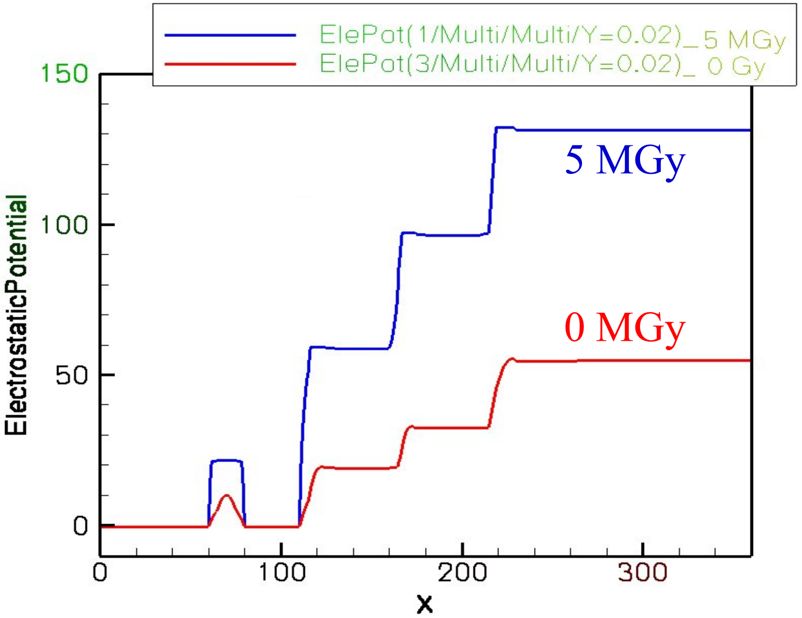


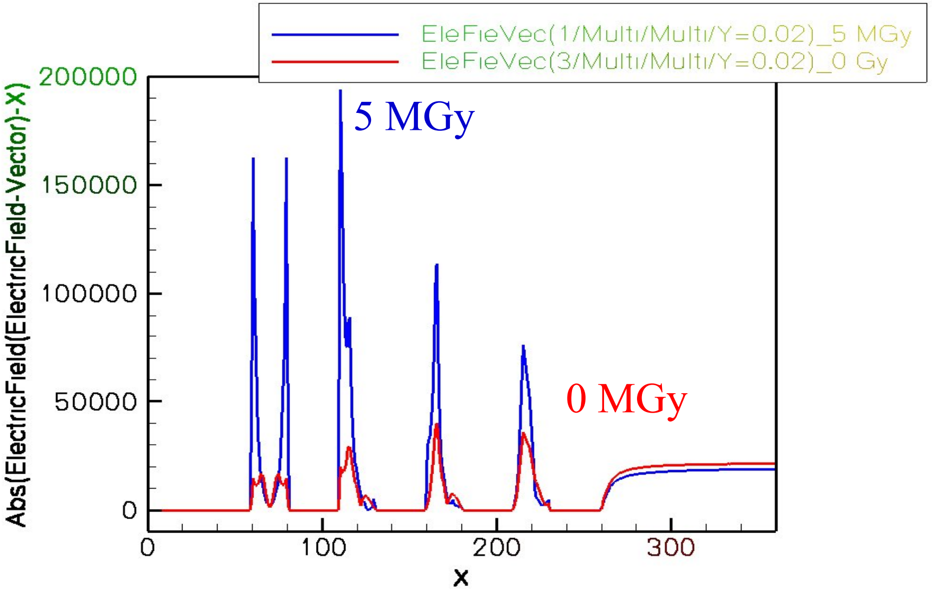
→ No breakdown observed up to 1000V for 0 and 5 MGy irradiated dose

# Optimization of sensor design for AGIPD

First multi-guard rings design for AGIPD $p^{+}n$ sensor:

- Electrostatic potential and electric field distribution in the Sensor





→ Surface charges ($N_{ox}$+$N_{it}$ ) change the potential distribution

→ Floating guard rings attained potential after punch-through ($V > V_{FD}$)

→ For the guard ring design, electric field < 200kV/cm ($E_{crit}$ for breakdown = 300kV/cm) observed for 0 and 5 MGy doses

# Summary on sensor design and simulation

Proposed $p^+n$ Si Sensor design parameters for 1000 V operation voltage:

→ **120x120 $\mu m^2$ p-implantation (80 µm pixel gap)**

→ $W_N$ = 500 µm

→ **Crystal orientation: <100>**

→ Oxide thickness: $t_{ox}$ ($SiO_2$)=1µm

→ Xj=5 µm

→ **Overhang: $W_{MO}$=5 µm**

→ Passivation – $SiO_2$ used ($SiO_2$+ $Si_3N_4$ preferred)
$Si_3N_4$ used to prevent physical damage on the surface of the sensor

→ Final passivation layer on top of the sensor – $Si_3N_4$ with a thickness of 2 µm for higher break down voltage
(**A. K. Srivastava**, A. Bhardwaj, Namrata, S. Chatterji, and R.K Shivpuri, “Two Dimensional Breakdown Voltage Analysis and Optimal Design of Silicon Microstrip Detector Passivated by Dielectric”, *Semicond. Sci. Technol.*, 17 427 (2002)

→ **4 multiple guard rings near to scribe line, with $W_{GS}$ (guard ring spacing) = 20 µm, $W_{GW}$ (guard ring width) = 30 µm; and first guard ring grounded**