Universität Hamburg
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12th AGIPD Consortium Meeting

Sensor Acceptance and Radiation Hardness of the AGIPD sensor

(for the first delivery of the AGIPD sensors)

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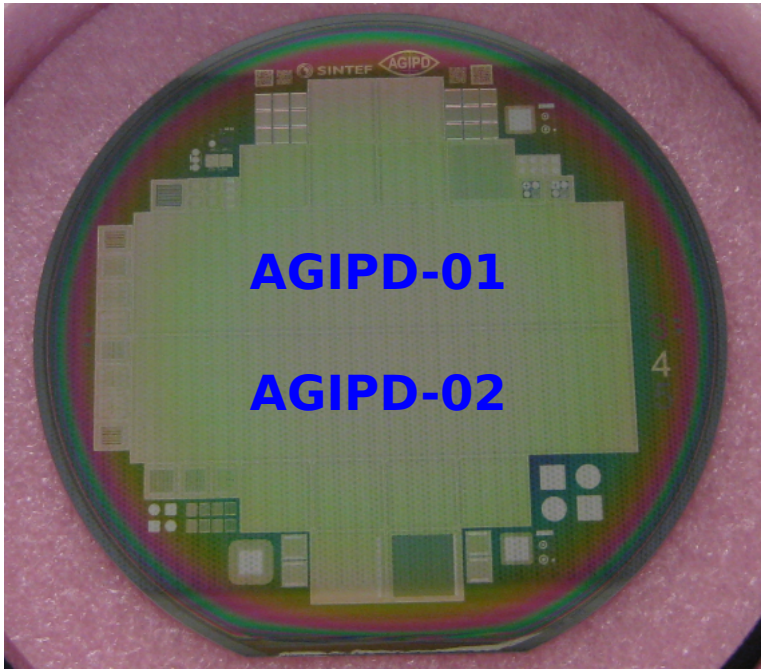
Outline

- Status of the AGIPD sensor → changes since Sept. 2012
- Summary of measurements at Sintef
- Measurements at Hamburg
- Properties of the AGIPD sensor
- Radiation hardness of the AGIPD sensor
  - Irradiation at the beamline P11 of PETRA III with 12 keV X-rays
  - Results
- Summary and future plans

Status of the AGIPD sensor

- 40 sensors (20 wafers) produced by Sintef [Sept. 2012 – Jan. 2013]
- J. Zhang @ Sintef for final measurements end of Jan.
- Sensors received in early February, packaged into two shipping boxes
- Information on doping concentration and dielectric received [OK for 1st order simulation]
- 1 wafer with two “bad” AGIPD sensors (V_{bd} < 900 V) has been cut and used for irradiation tests
- Other 19 wafers to be measured



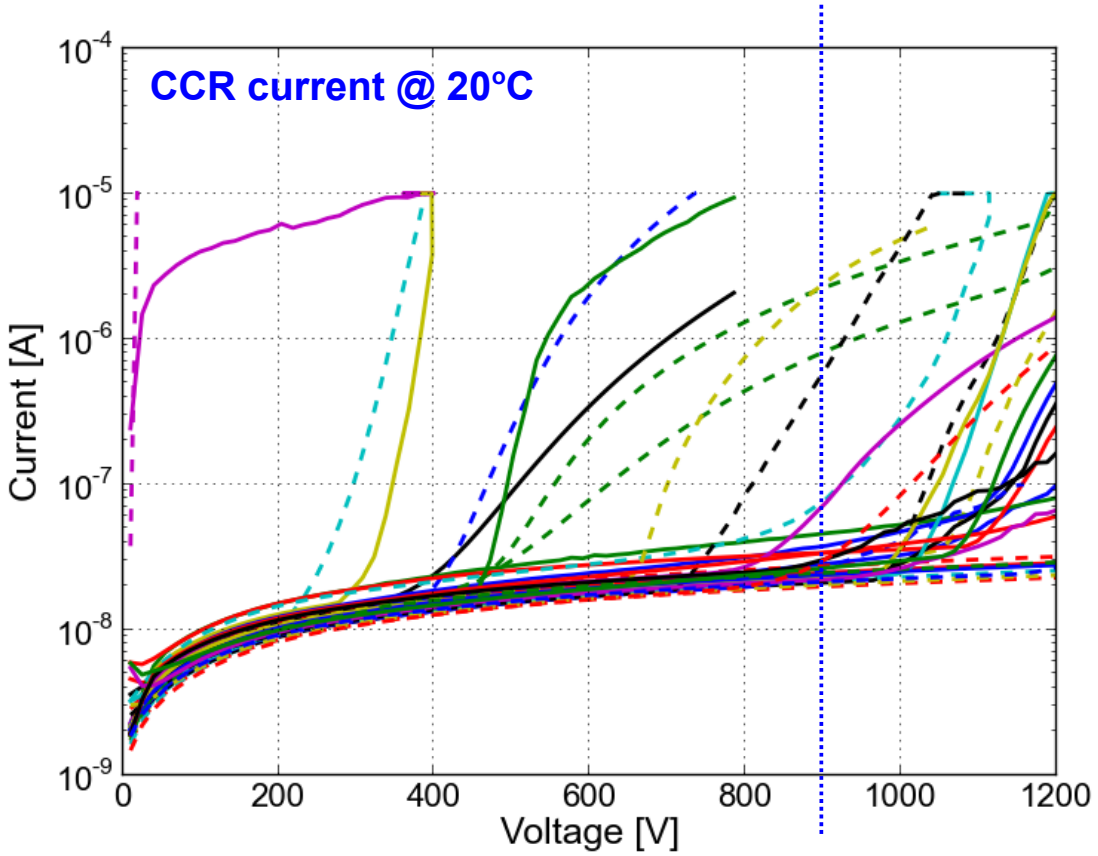
Specification of the AGIPD sensor @ 20°C:

V_{dep}	V_{bd}	I_{pixel} [nA] @ 500 V	I_{CCR} [µA] @ 500 V	C_{int} [pF] @ 500 V
< 350 V	> 900 V	< 20 & 50	< 0.2 & 20	< 0.5

Red: values after irradiation

Summary of measurements at Sintef

- IV measurements done by Sintef
  - all pixels floating
  - only CCR current
  - before & after “final” annealing (8 hours @ 275^{0}C)
  - Cat.1 & Cat.2 are considered good sensors: 70.0%

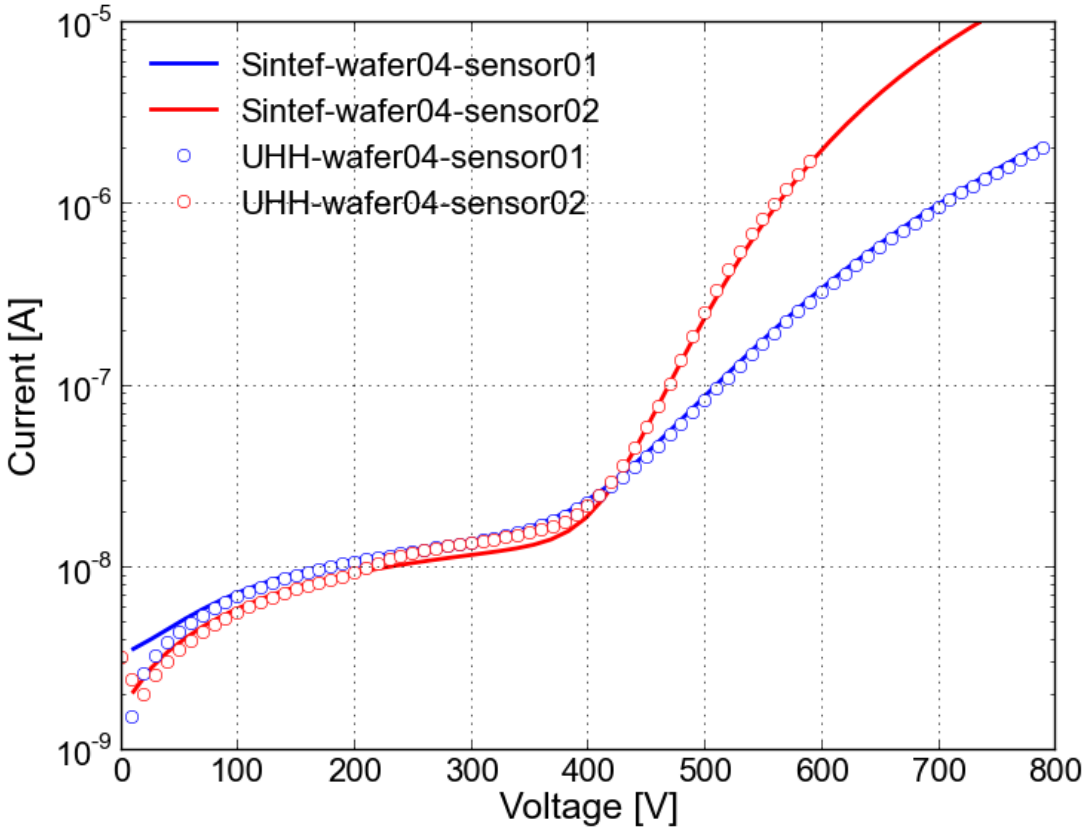


	Criterion	# sensor	Percent
Cat.1	(before + after) > 900 V	16	40,00%
Cat.2	(750V<before<900V)+(after>900V)	12	30,00%
Cat.3	(before<750V) + (after > 900V)	2	5,00%
Cat.4	after<900V	10	25,00%
Sum		40	100,00%

Measurements at Hamburg

To establish measurement procedures:

- One wafer with V_{bd} < 900 V for both sensors before and after “final” annealing



- I-V measurements at Hamburg reproduce results at Sintef

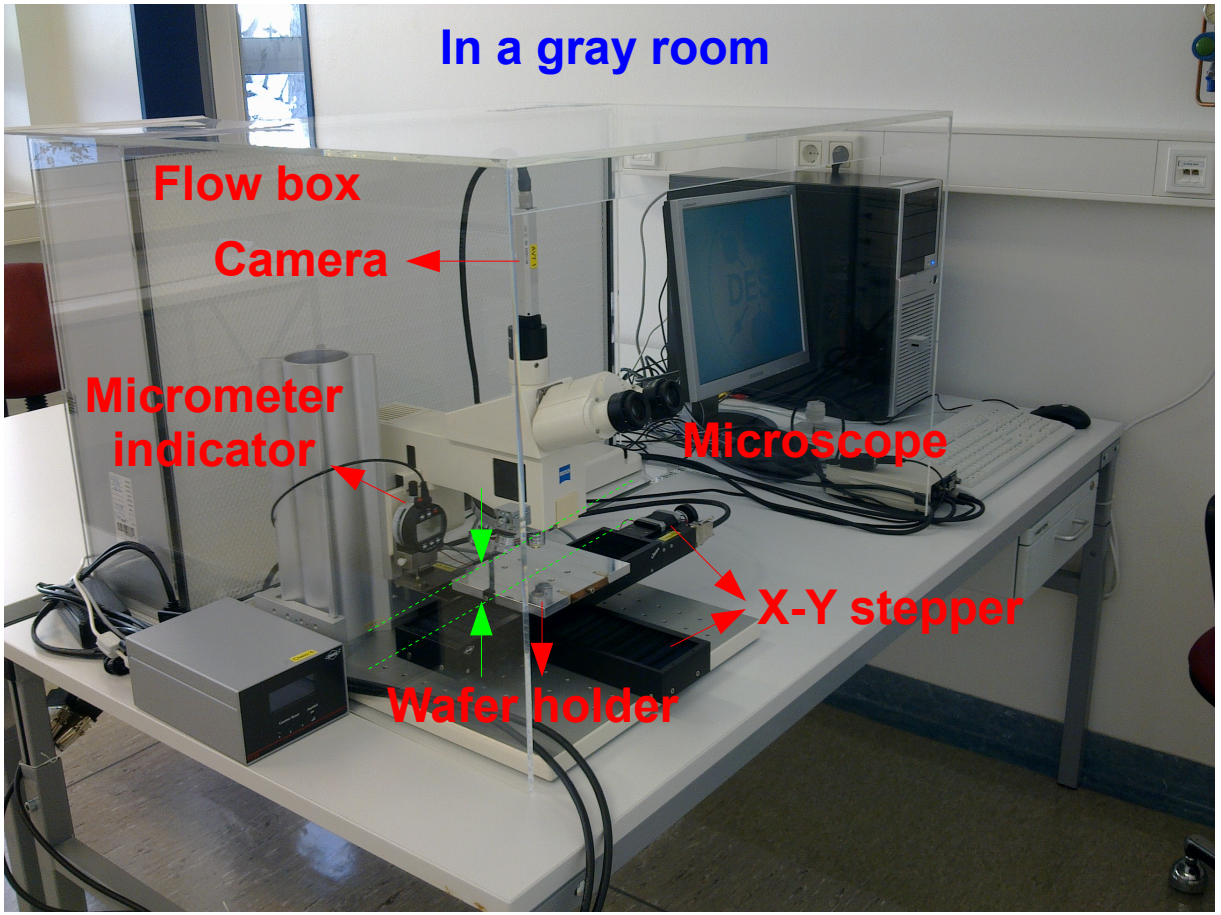
Measurements at Hamburg

To establish measurement procedures:

- Visual inspection of the AGIPD sensor
- Sensor flatness measurement

} set-up in a flow box in a gray room

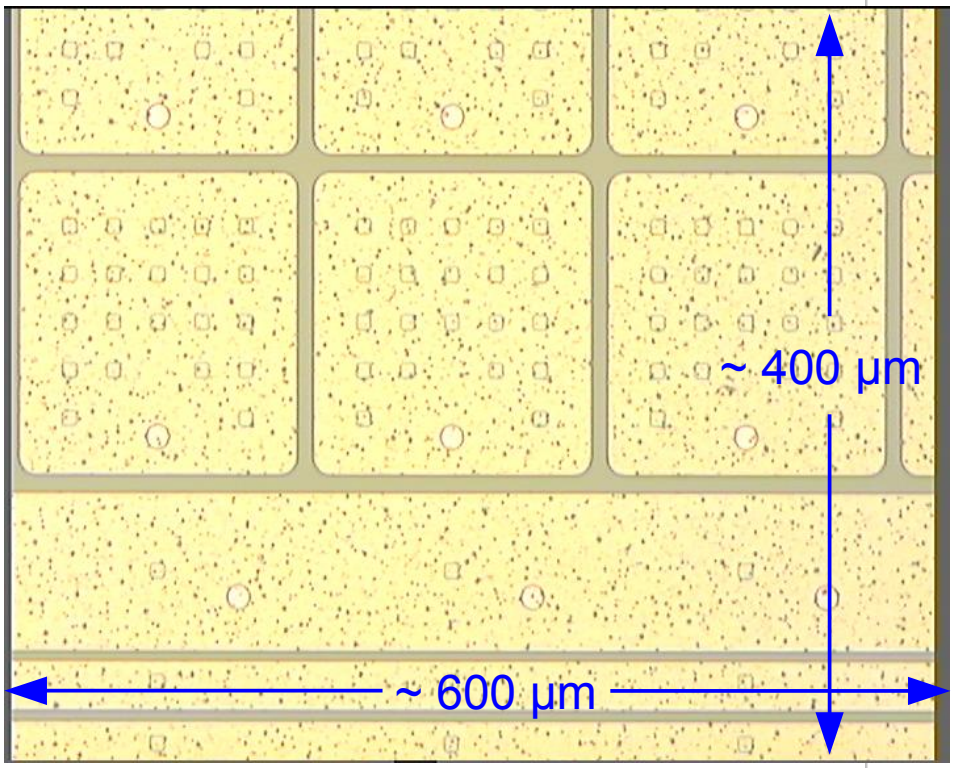
→ X-Y stepper
→ Microscope
→ Camera
→ Micrometer indicator

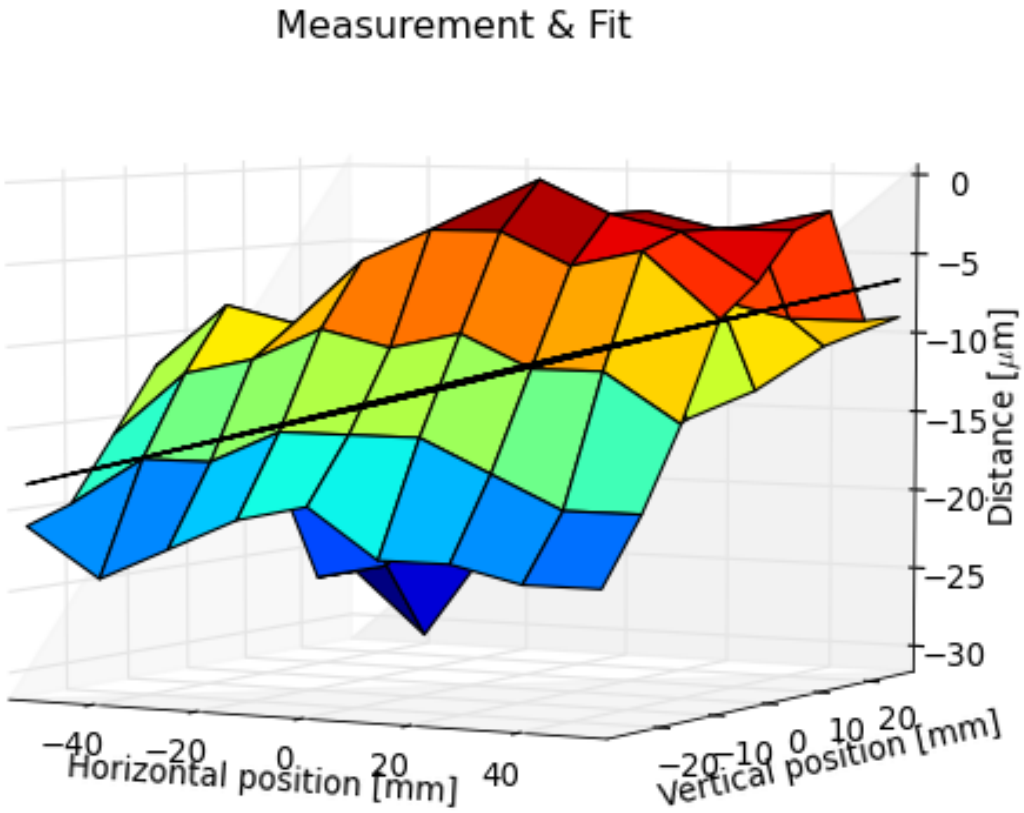


Measurements at Hamburg

To establish measurement procedures:

- Visual inspection: 12,000 pictures (600 µm x 400 µm) per sensor
- Sensor flatness of non-cut wafer: standard deviation of 8 µm from a fit to a plane



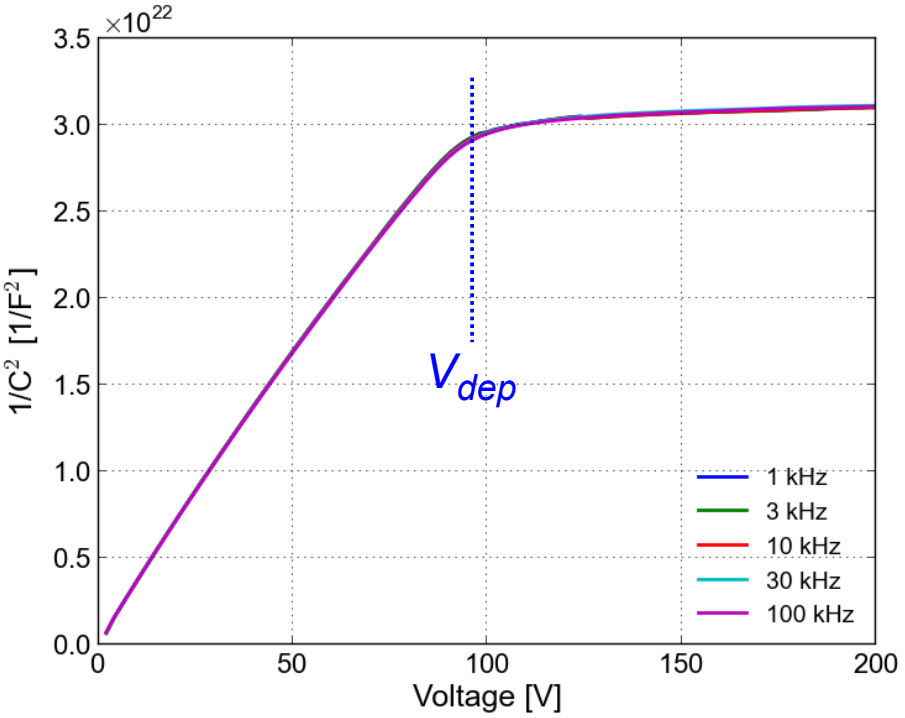


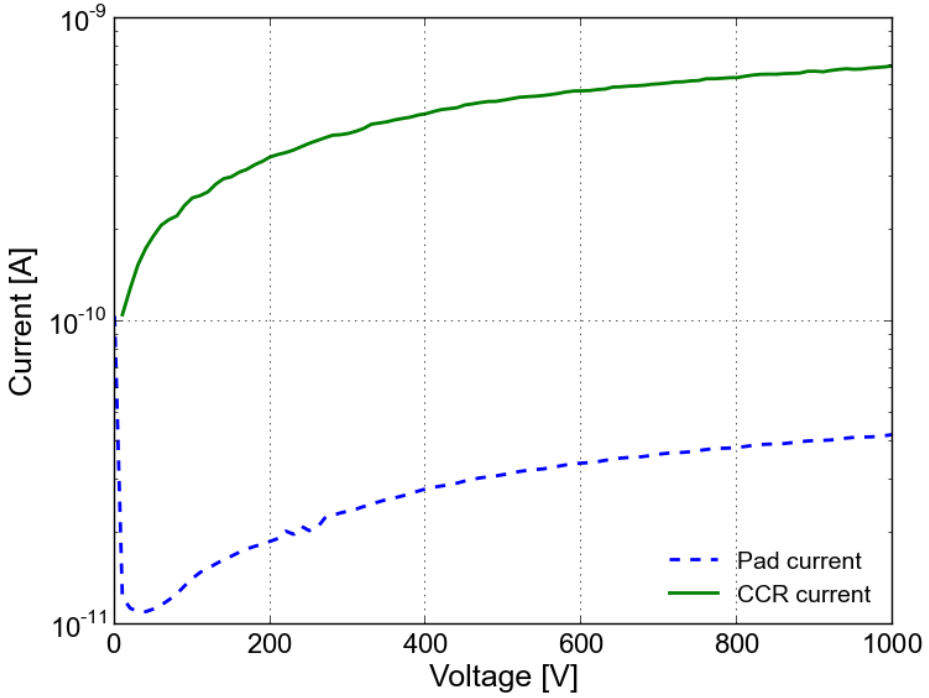
→ Cross check the sensor flatness after cutting the wafer

Properties of the AGIPD sensor

Full depletion voltage, doping concentration and leakage current

- Determination from a square diode (5 mm x 5 mm) with Sintef-12-GR structure





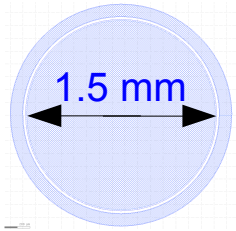
- $1/C^2$ vs. voltage: V_{dep} = ~ 95 V, N_d = ~ 5.3 x 10^{11} cm^{-3}, and ρ = ~ 7.8 kΩ•cm
- Leakage current: $I_{leakage}$ = 31.2 pA @ 500 V, corresponding to 0.12 nA/cm^2 (2.4 nA/cm^3)

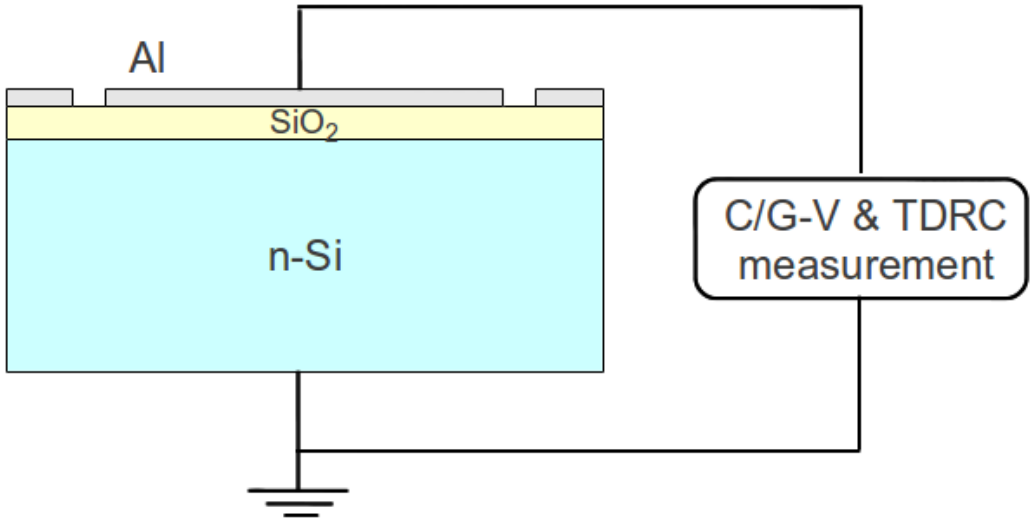
  → dominated by diffusion & bulk-generation current for the non-irradiated sensor

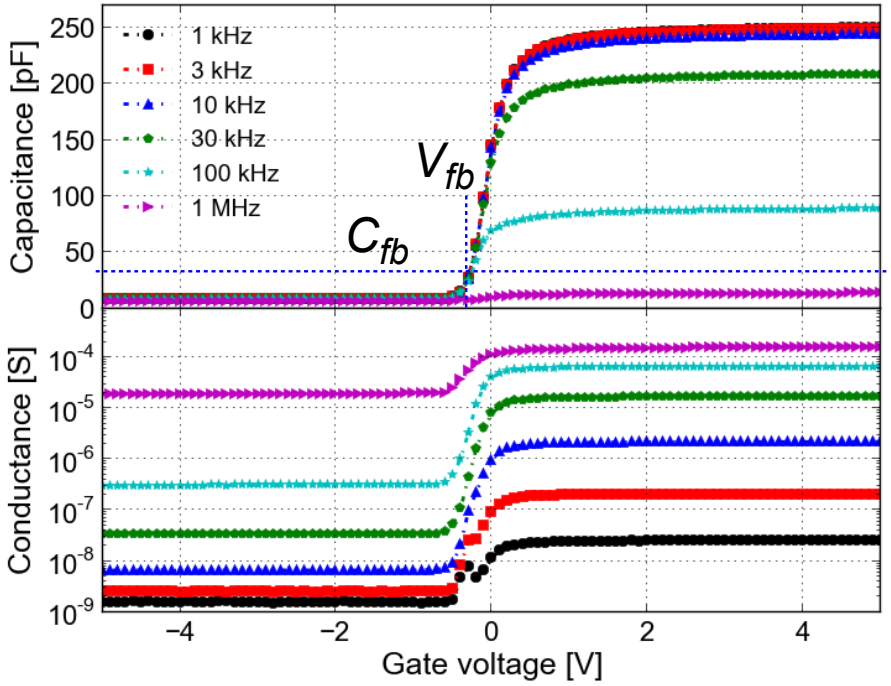
Properties of the AGIPD sensor

Flatband voltage and oxide-charge density

- Determined from a circular MOS capacitor (Φ = 1.5 mm)







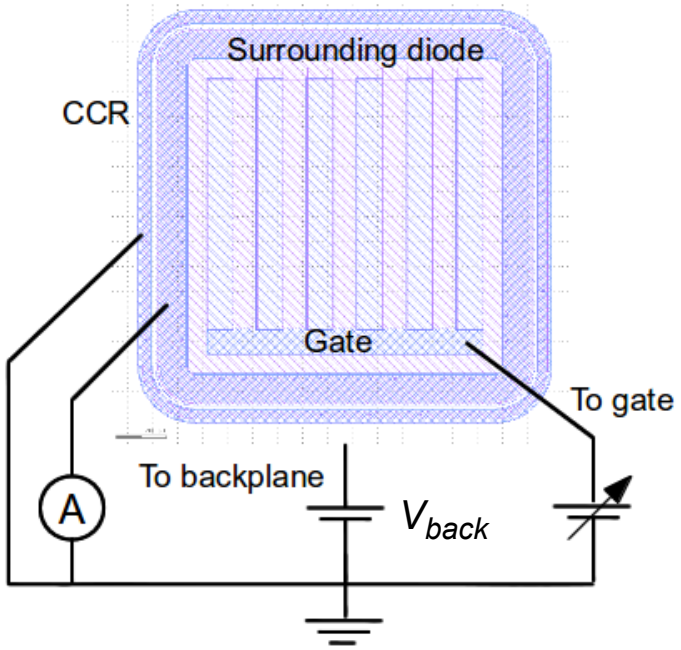
- Flatband voltage determined from C/G-V curves: V_{fb} = -0.39 V (C_{fb} = 29.3 pF)
- Oxide-charge density: $N_{ox} = -C_{ox} \bullet (V_{fb} - \Phi_{ms}^{*}) / (q_0 \bullet A_{gate}) = \sim 0$ cm^{-2} (2012: 2.8 x 10^{10} cm^{-2})

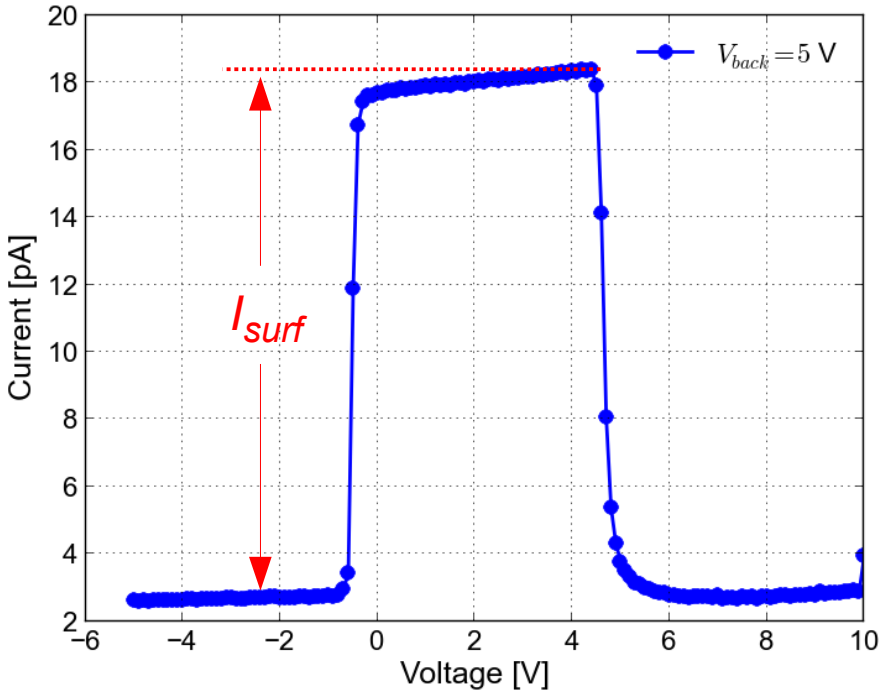
  → Extremely low oxide-charge density! Q_{ox}^{eff} negative? $^{*}\Phi_{ms}$ = -0.42 V

Properties of the AGIPD sensor

Surface-current density

- Determined from square gate-controlled diodes (GCD): A_{gate} = 7.1 x 10^{-3} cm^2





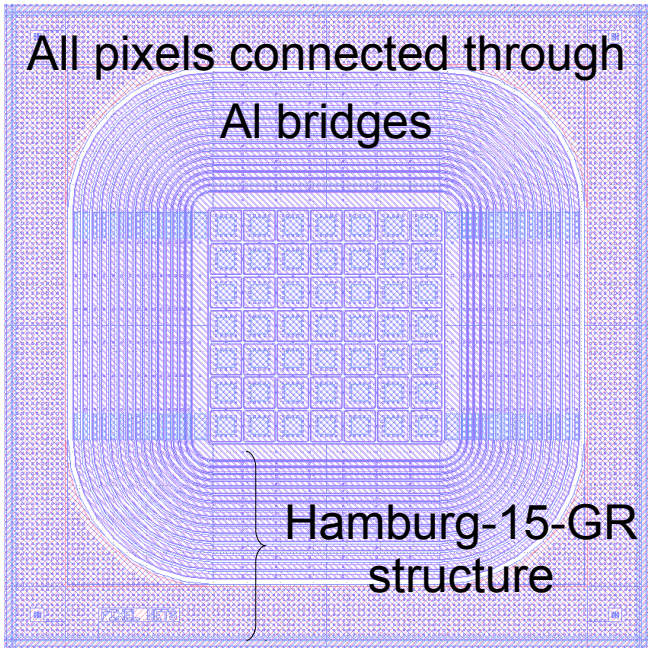
- Surface current @ RT: $I_{surf} = I_{dep} - I_{inv}$ = 16 pA
- Surface-current density @ 20°C: $J_{surf} = I_{surf}/A_{gate}$ = 1.9 nA/cm^2 (2012: 8.7 nA/cm^2)

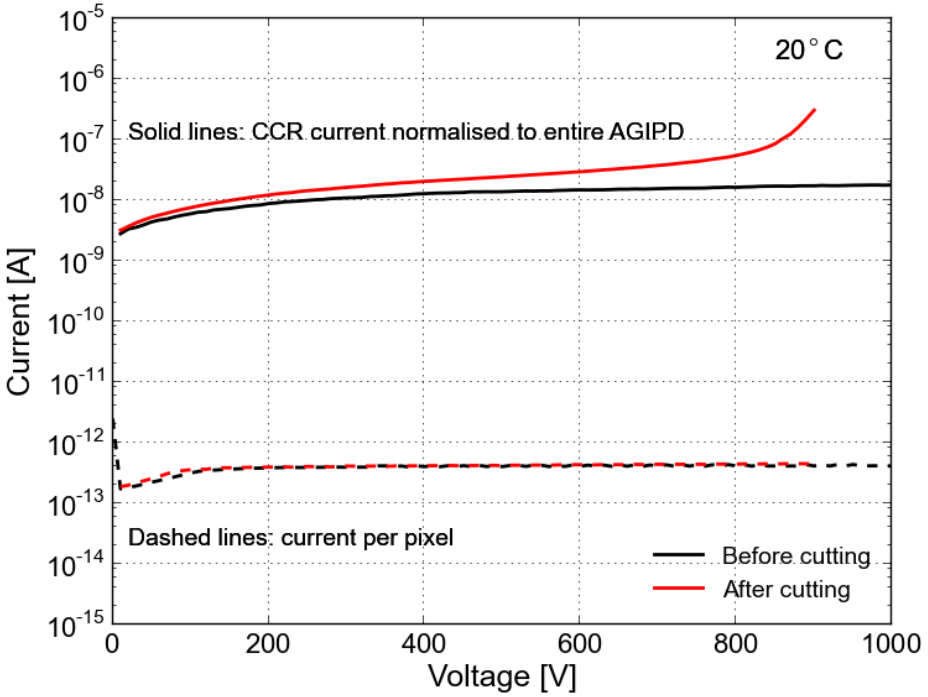
→ Low surface current for the non-irradiated sensor

Properties of the AGIPD sensor

Pixel current, sensor current and CCR current

- 7x7 inter-connected pixel sensors (all pixels connected) with standard AGIPD pixels and Hamburg-15-GR structure





- Pixel current @ 500 V: 0.42 pA/pixel → Current of AGIPD sensor = 28 nA
- CCR current @ 500 V normalised to entire AGIPD sensor: 21 nA

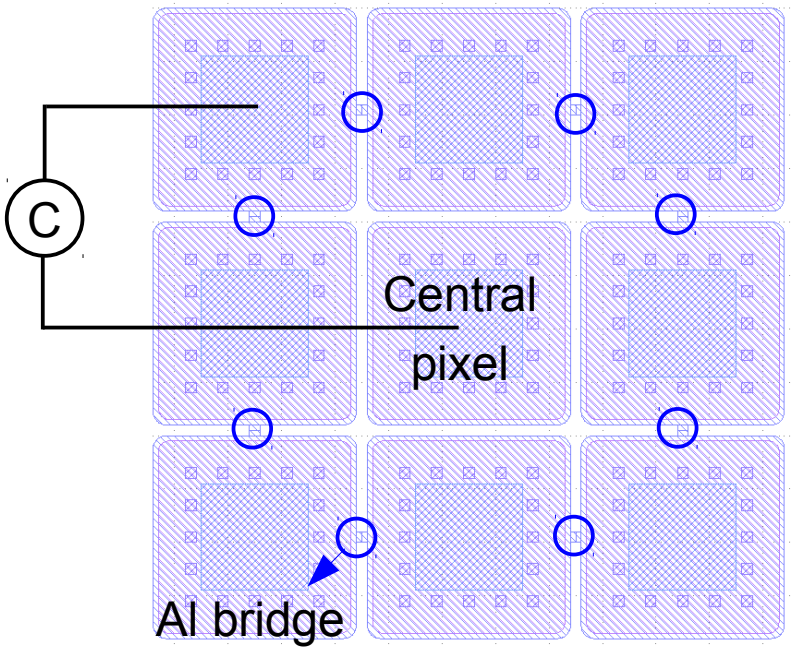
Within specification

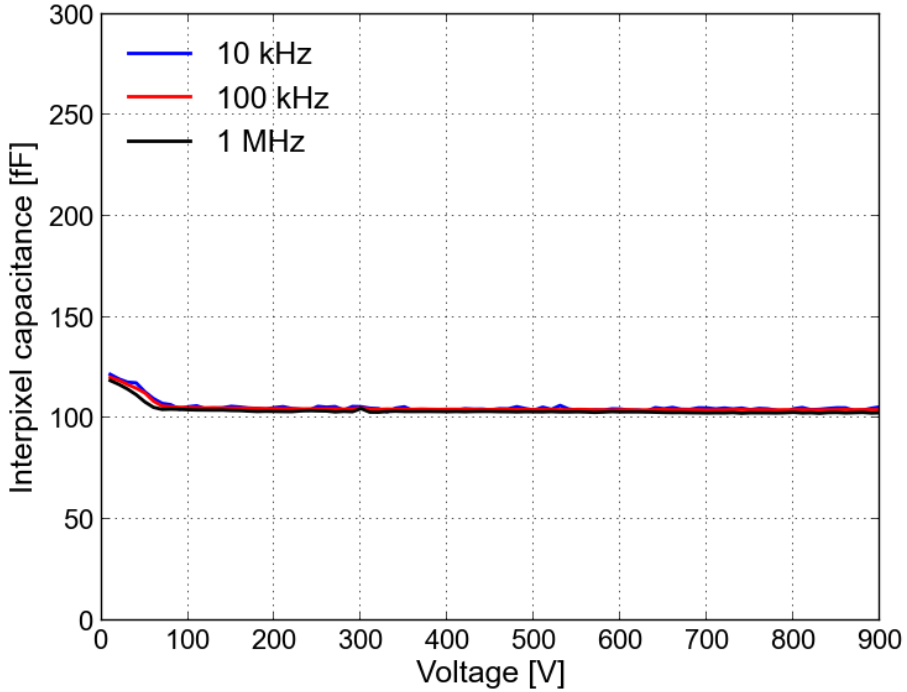
- V_{bd} reduced after cutting due to depletion boundary touching the cut-edge: ~ 850 V

Properties of the AGIPD sensor

Interpixel capacitance from 7x7 ring-connected pixel sensors

- 7x7 ring-connected pixel sensors with standard AGIPD pixels (3 rings of pixels surrounding the central pixel) and Hamburg-15-GR structure





- Interpixel capacitance measured between central pixel and its 8 neighbours:

  → C_{int} @ 500 V = 102 fF Within specification < 500 fF

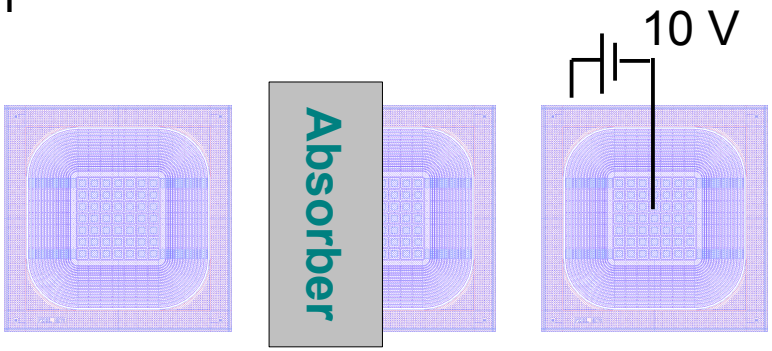
- Measurements confirm TCAD simulation result (98 fF): difference < 4%

Irradiation to the AGIPD sensor

Summary of irradiation at the beamline P11 of PETRA III (10, 100, 1000 kGy)

- Beamtime: evening of 27th March, 10:00 am 30th of March – 12:00 am 1st of April
  (2 days and a half)
- Properties of X-ray beam at P11:
  - Energy: 12 keV (tunable 6-12 keV)
  - Photon intensity: max. 1.7 x 10^{13} ph/s
  - Beam spot: 4 mm x 1.2 mm for a defocused beam (min. 60 µm x 250 µm)
  - Dose rate: max. 7.1 kGy/s for defocused beam
- Samples irradiated by scanning entire X-ray beam:
  - MOS capacitors
  - Gate-controlled diodes
  - Pad diode with Sintef-12-GR structure
  - Three 7x7 inter-connected pixel sensors*
  - Three 7x7 ring-connected pixel sensors*

  (*with Hamburg-15-GR structure)

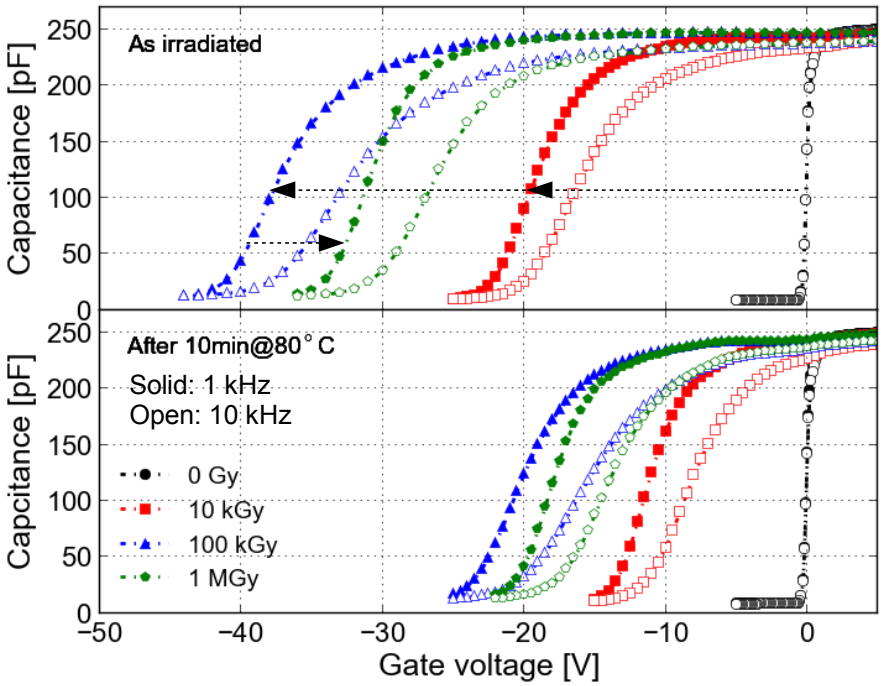


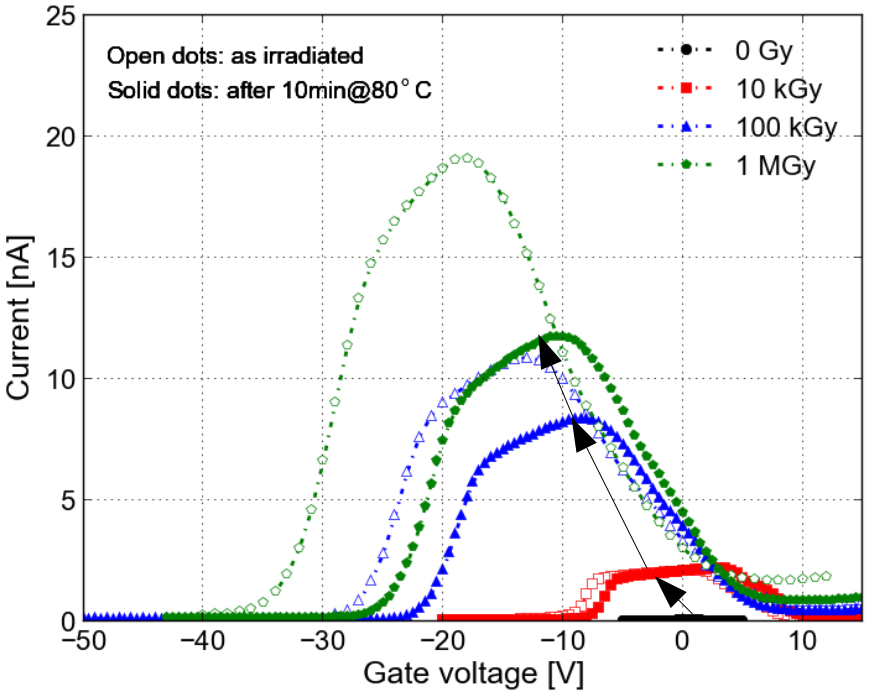
Irradiation methods of pixel sensors:
(1) Full sensor uniformly irradiated
(2) Half sensor uniformly irradiated
(3) Full sensor uniformly irradiated with 10 V

Results: C/I-V from MOS and GCD

C-V curves from MOS capacitors and I-V curves from gate-controlled diodes (GCD)

- C-V of MOS: (1) max. voltage shift @ 100 kGy → saturation of surface charges
  (2) after 10min@80°C, voltage shift reduced by 50%



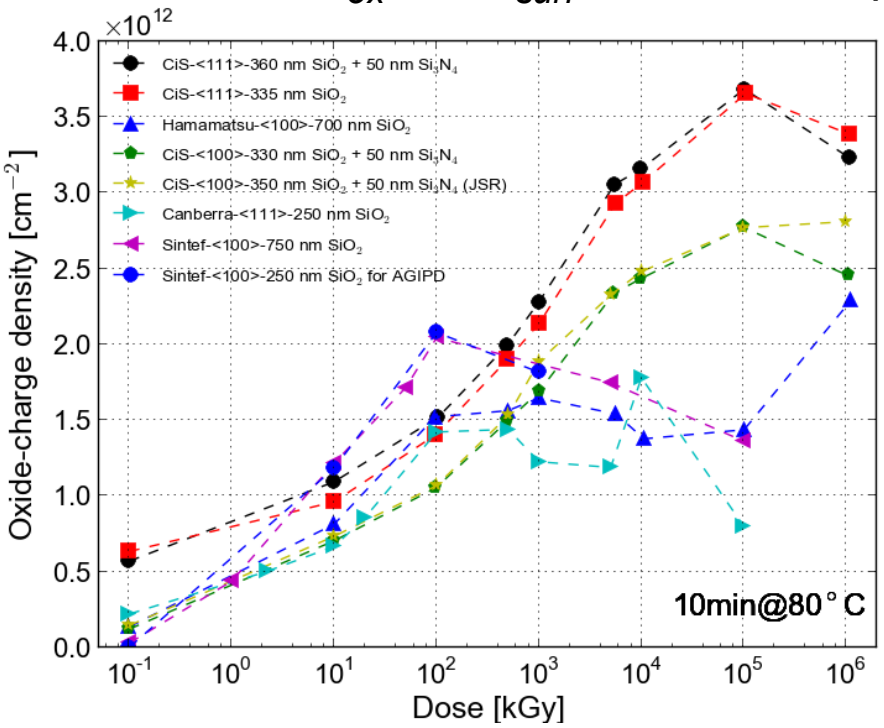


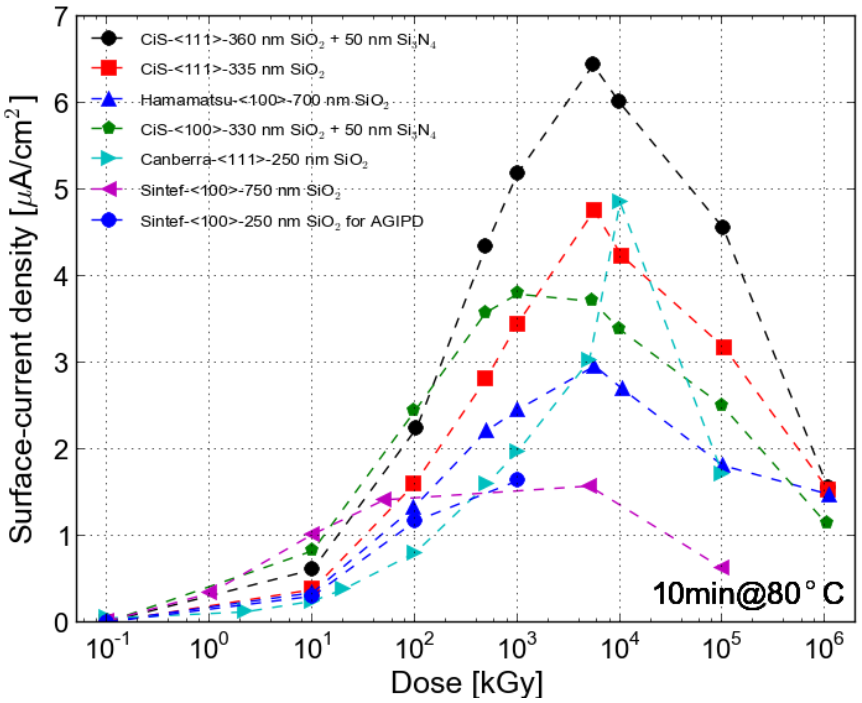
- I-V of GCD: (1) max. current @ 1 MGy → not saturate
  (2) fast annealing of surface current after 10min@80°C → ~ 35% reduced

Results: N_{ox} & J_{surf} vs. dose

N_{ox} and J_{surf} vs. dose

- Results of N_{ox} and J_{surf} vs. dose compared to previous results





- N_{ox} saturates at 100 kGy, N_{ox} ~ 2.1 x 10^{12} cm^{-2}
- N_{ox} consistent with the previous results of Sintef-<100>-750 nm SiO_2 (2012)
  → N_{ox} dose not depend on the thickness of SiO_2
- No saturation for J_{surf} up to 1 MGy → further irradiations!

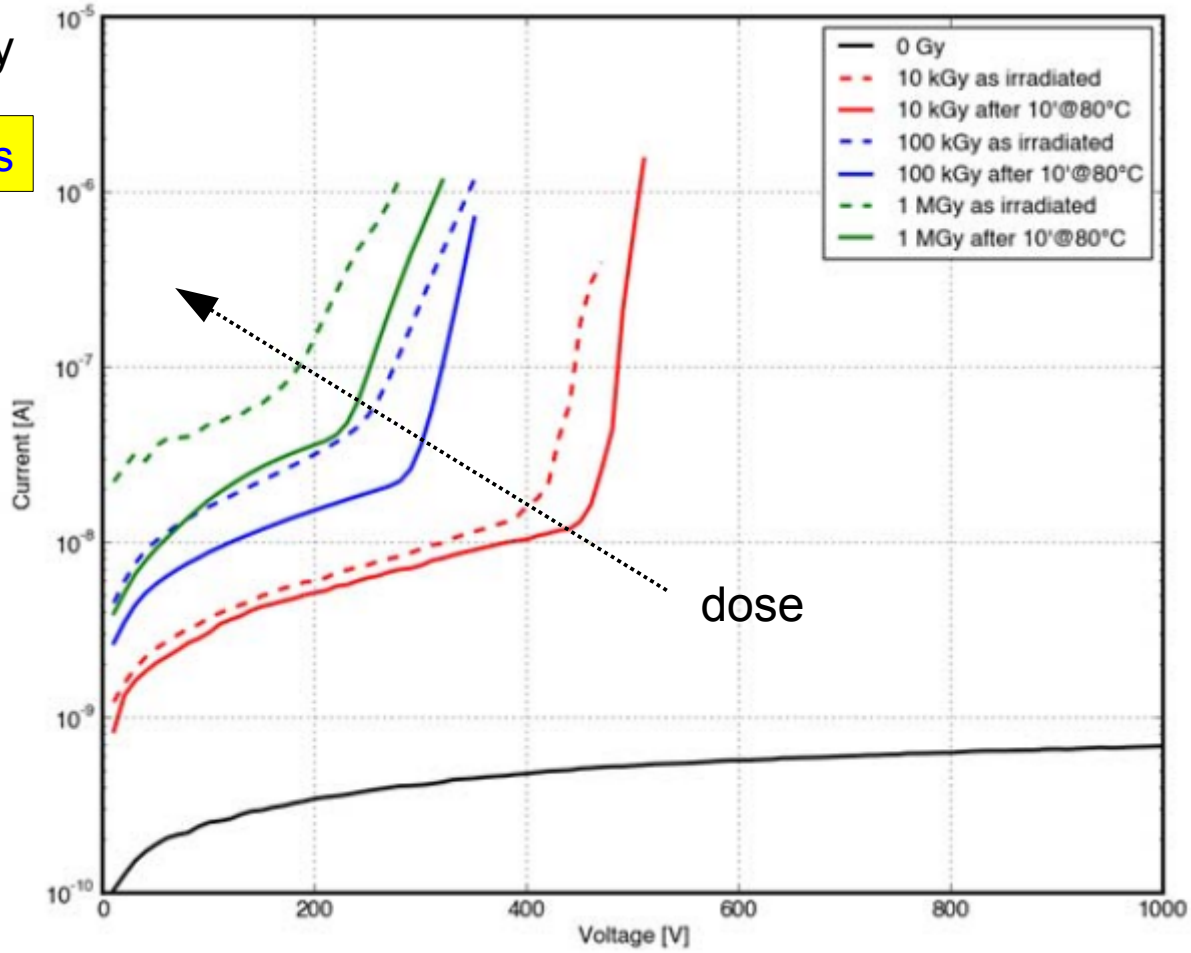
Results: V_{bd} vs. dose (Sintef-12-GR)

Breakdown voltage vs. dose from a pad diode with Sintef-12-GR structure

- No breakdown up to 1000 V before irradiation → looks good
- V_{bd} decreases with irradiation

  → V_{bd} < 250 V after 1 MGy

Not designed for radiation hardness

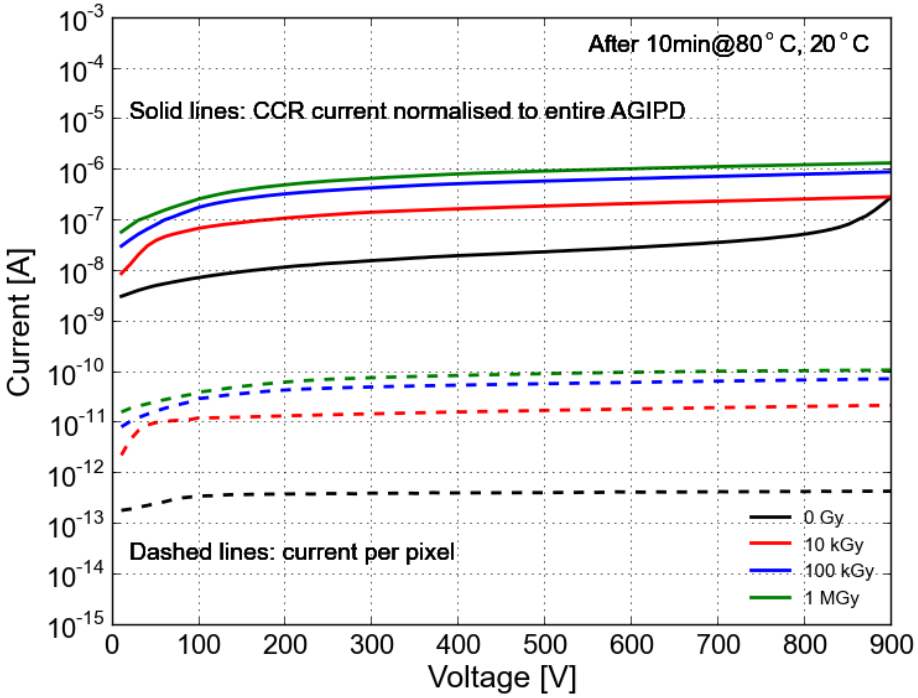


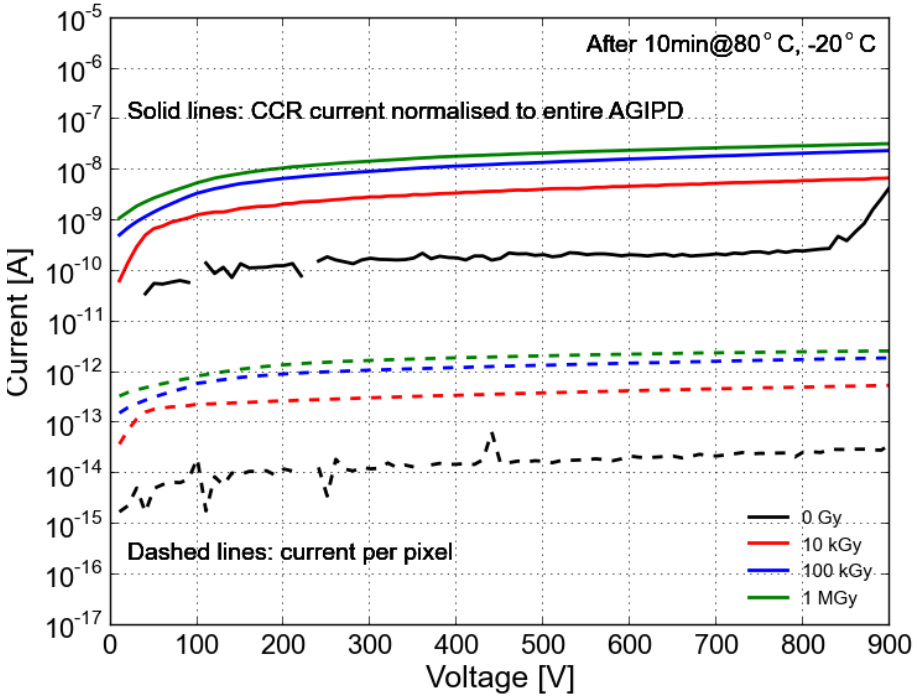
Results: $I_{leakage}$ & V_{bd} vs. dose

Pixel and CCR current vs. dose for 7x7 pixel + Hamburg-15-GR sensor (uniform irrad.)

- After 10min@80°C, pixel current < 0.2 nA/pixel, CCR current < 2 μA @ 20°C
- At -20°C, pixel and CCR current reduced by 2 orders of magnitude

Within specification





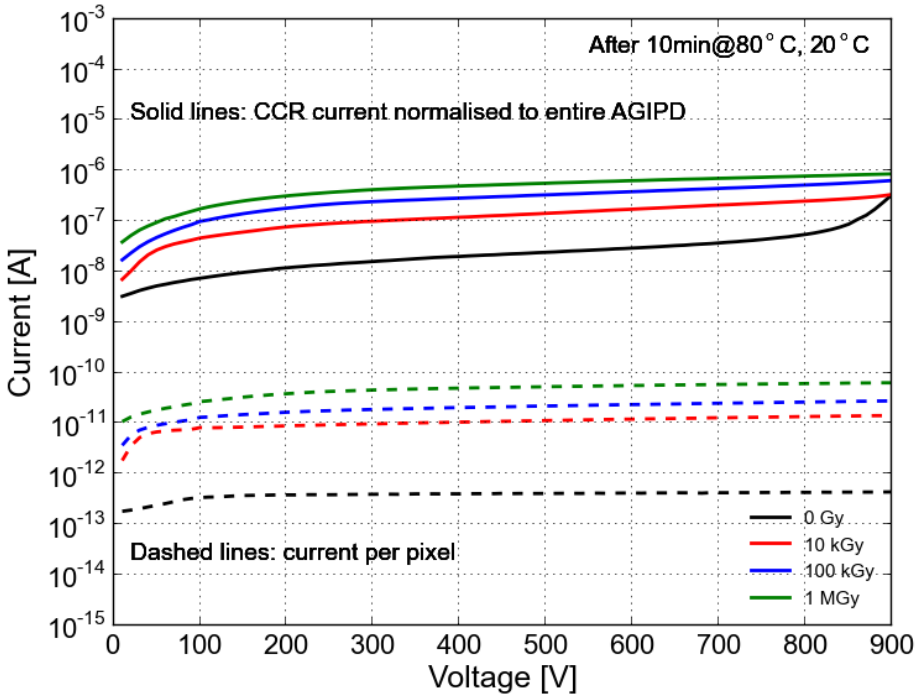
- Results as irradiated is a factor of 2 higher than after 10min@80°C annealing
- No breakdown up to 900 V! → The optimized AGIPD sensor is radiation hard!
  → TCAD simulation "predicted" the results.

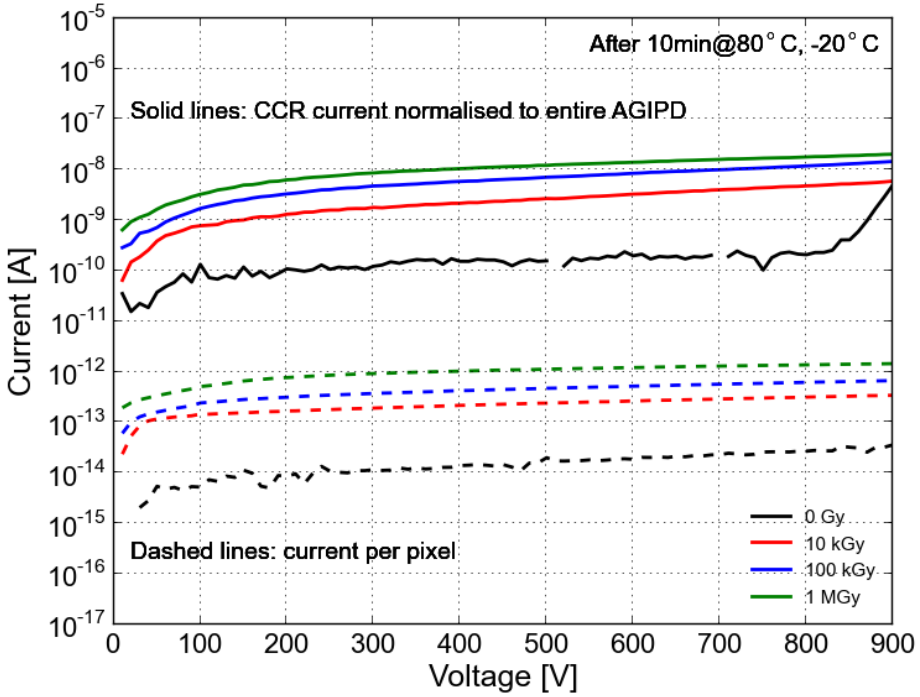
Results: $I_{leakage}$ & V_{bd} vs. dose

Pixel and CCR current vs. dose for 7x7 pixel + Hamburg-15-GR sensor (half irrad.)

- After 10min@80°C, pixel current < 0.1 nA/pixel, CCR current < 1 µA @ 20°C
- At -20°C, pixel and CCR current reduced by 2 orders of magnitude

Within specification





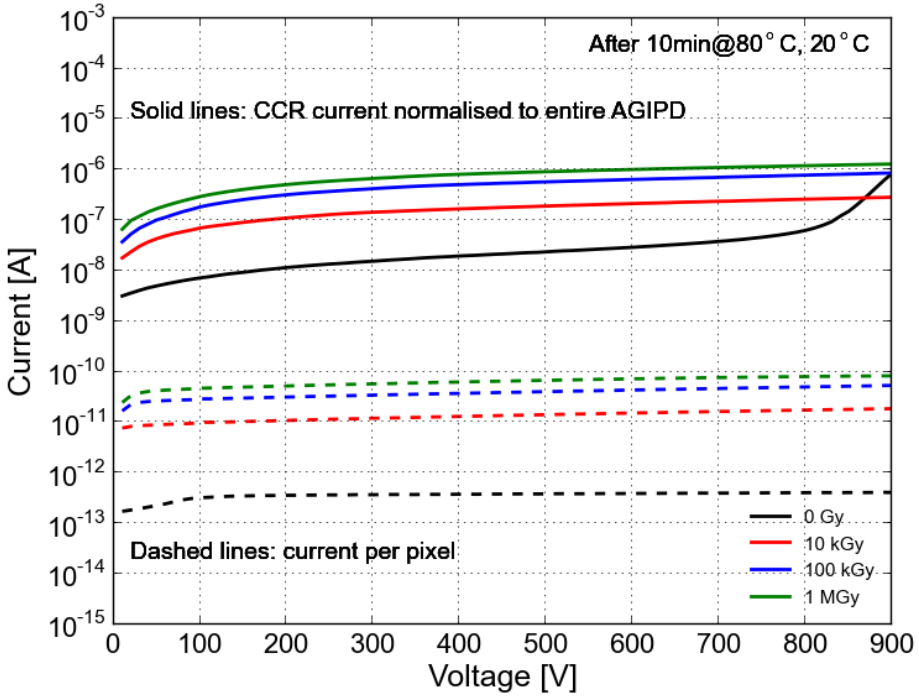
- No breakdown up to 900 V! (not a surprise now)
- More realistic case for the AGIPD → still works nicely!

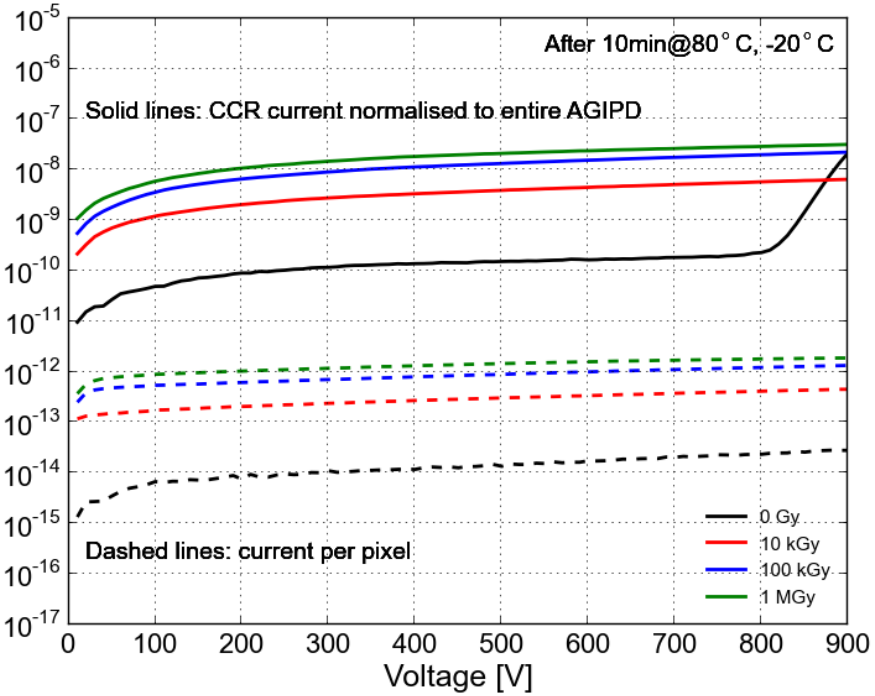
Results: $I_{leakage}$ & V_{bd} vs. dose

Pixel and CCR current vs. dose for 7x7 pixel + Hamburg-15-GR sensor (irrad. with 10 V)

- After 10min@80°C, pixel current < 0.2 nA/pixel, CCR current < 2 µA @ 20°C
- At -20°C, pixel and CCR current reduced by 2 orders of magnitude

Within specification



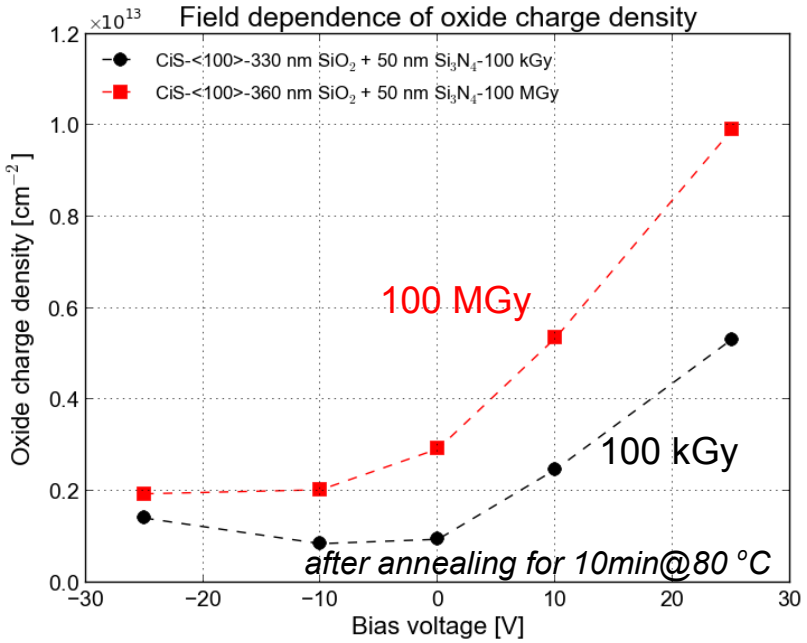


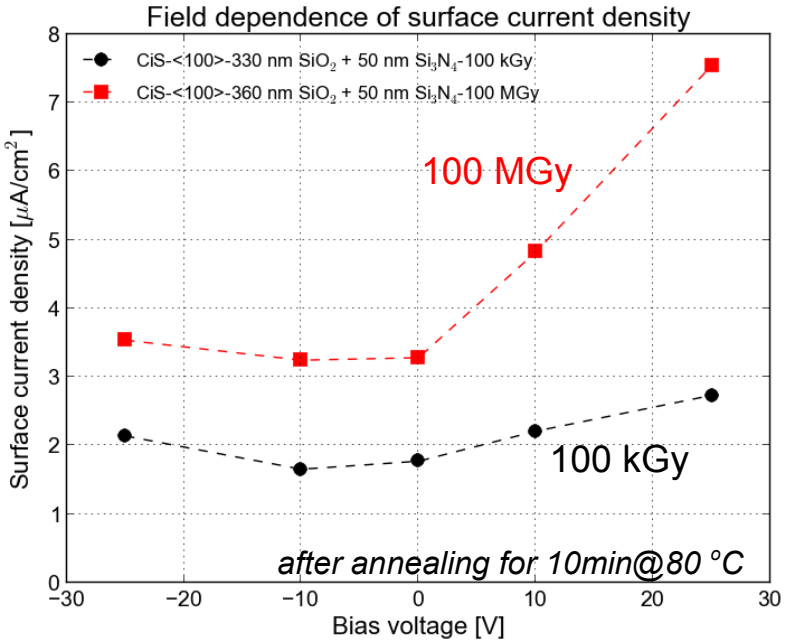
- No breakdown up to 900 V!
- No significant differences between irrad. with 10 V and uniform irradiation, as expected according to the study of gate-voltage dependence of N_{ox} and J_{surf}.

Reminder: N_{ox} & J_{surf} vs. E_{ox}

Investigations:

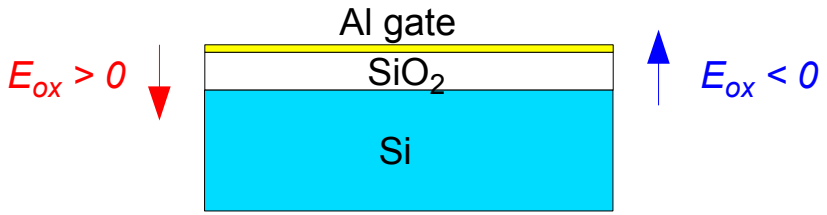
- CiS <100> MOS capacitor and Gate-Controlled Diode (~ 350 nm SiO_2 + 50 nm Si_3N_4)
- Electric field in the oxide E_{ox}: ~ (0 - 0.7) MV/cm [oxide breakdown: ~ 10 MV/cm]





Conclusions:

- N_{ox} and J_{surf} increase for $E_{ox} > 0$
- No strong E_{ox} dependence for $E_{ox} < 0$
- AGIPD p^+n sensor: $E_{ox} < 0 \rightarrow$ not a problem!



Results: C_{int} vs. dose

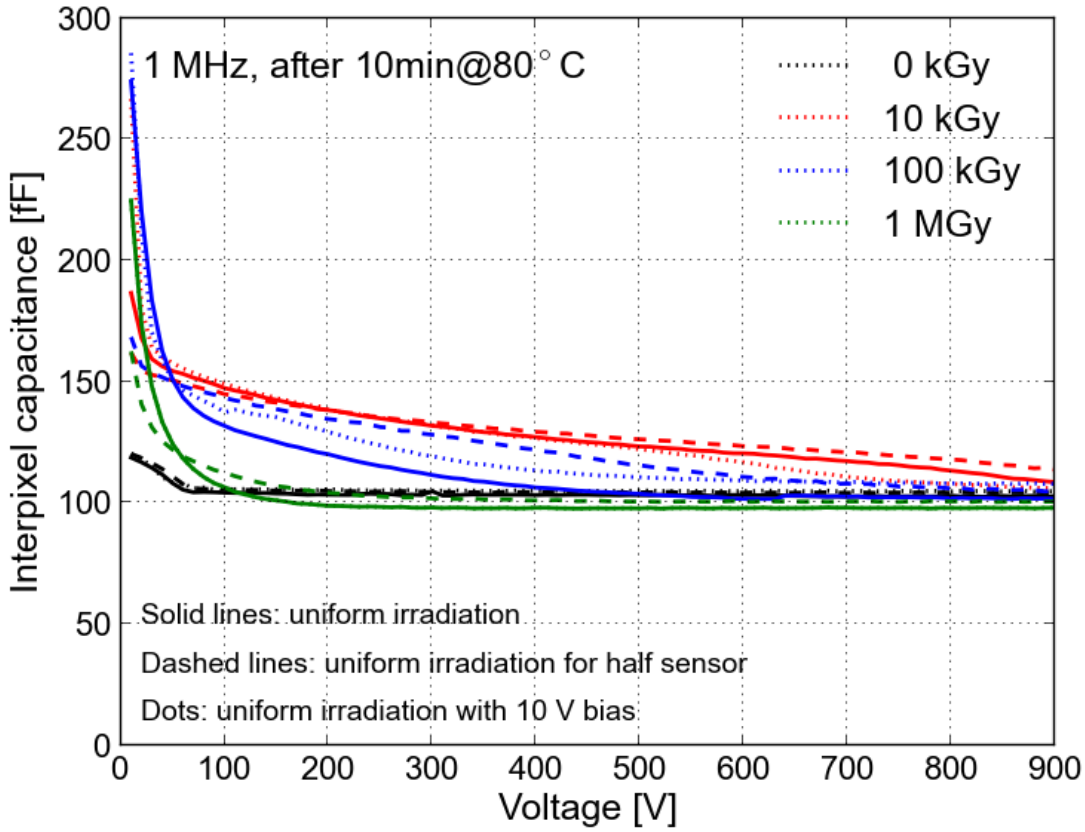
Interpixel capacitance vs. dose for 7x7 pixel + Hamburg-15-GR sensor

- Interpixel capacitance C_{int} measured after 10min@80°C annealing

→ Frequency dependence (< 30%)

→ C_{int} < 130 fF at 500 V

Within specification < 500 fF



TCAD simulation of C_{int} at 500 V:

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	98 fF	120 fF	346 fF
	300 nm	97 fF	123 fF	286 fF

→ Measurements confirm simulation results

Summary and future plans

Summary:

Measurements for AGIPD sensors

- Measurement procedures established
- Gray room and set-up for visual inspection and flatness measurements ready
- Low oxide charges and surface current
- Sensor breakdown ~ 850 V after cutting → solution to be found

} non-irradiated

- Sensor/pixel current, CCR current and interpixel capacitance within specification
- No breakdown up to 900 V after irradiation

→ The AGIPD sensor optimized by TCAD is radiation hard!

→ Measurements confirm the simulation results.

} irradiated

Future plans:

Improve the breakdown performance for the non-irradiated AGIPD sensor

Deliver first 4 wafers to PSI after a complete set of measurements (end of Apr.)

The other 15 wafers will follow

Ready for 2nd batch of delivery?