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Guard-ring design optimization in thin UFSD

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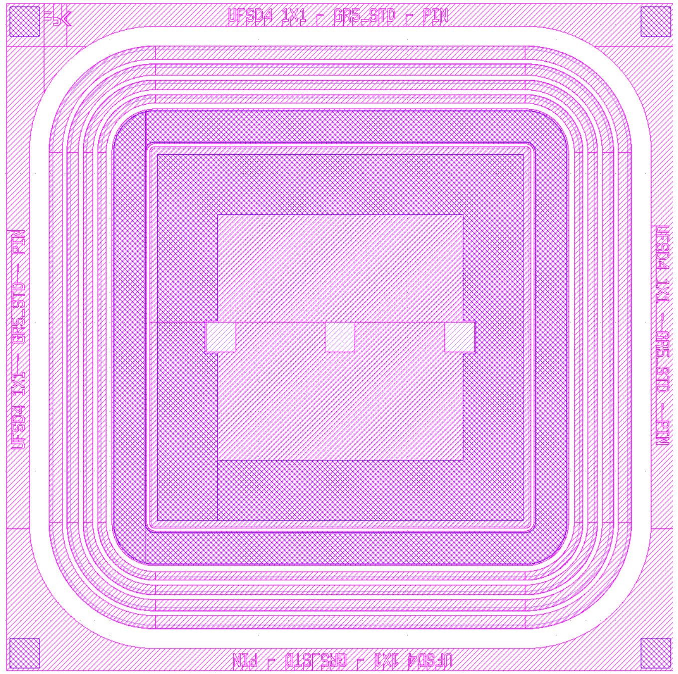
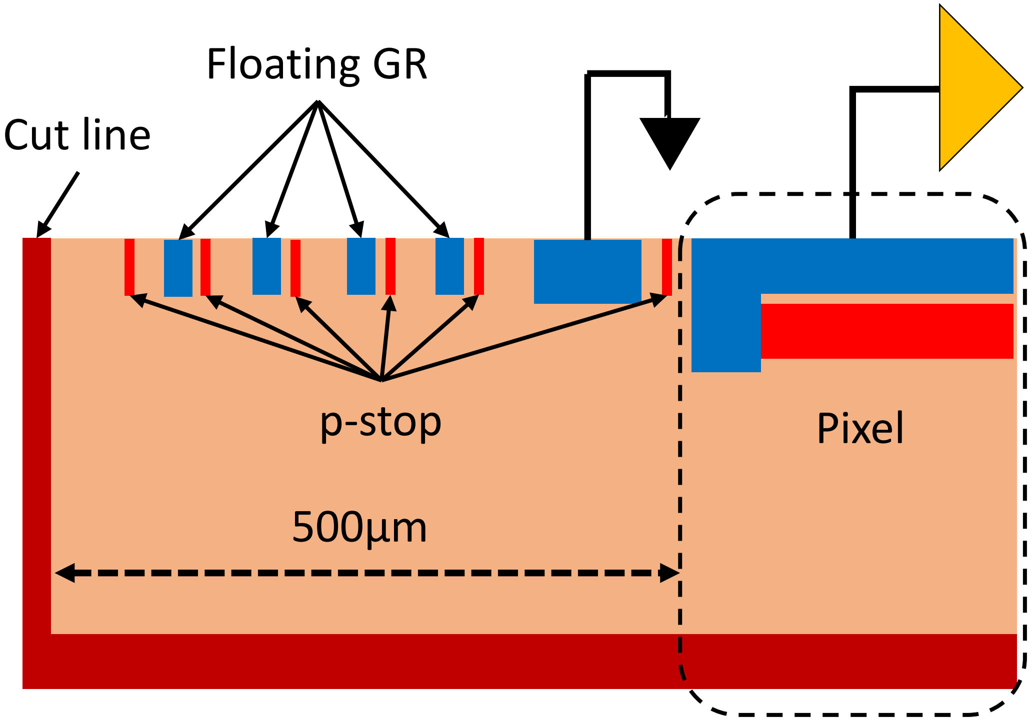
Outline

- Four Guard-Ring (GR) designs have been implemented in UFSD4 production by FBK
- Guard-ring designs investigated in simulation
- Characterization of new PiN diodes and irradiated LGAD (neutrons; Ø=$1.5\cdot10^{15}$ n_{eq}/cm^2)
  - PiN diodes: measurement of breakdown voltage
  - Irradiated LGAD: measurement of GR current
- Characterization of Noise due to different GR design in irradiated LGAD (neutrons up to Ø=$1.5\cdot10^{15}$ n_{eq}/cm^2)

Guard-ring and edge layouts

Design: GR5_STD
(Multi floating Guard-Ring)

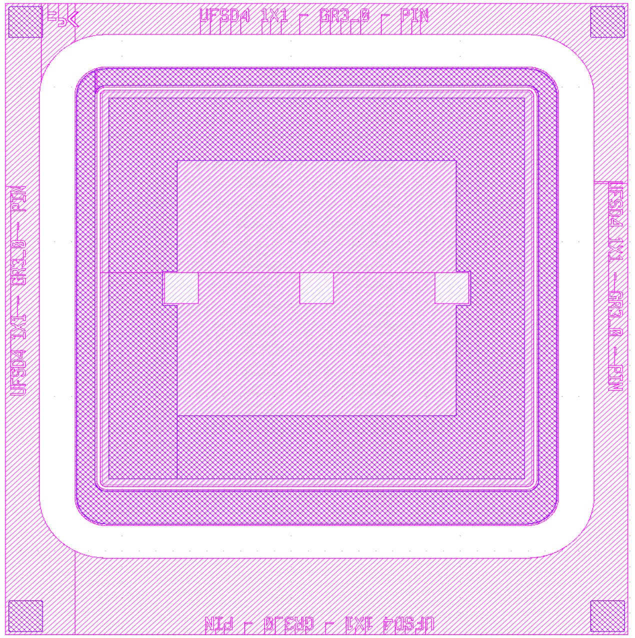


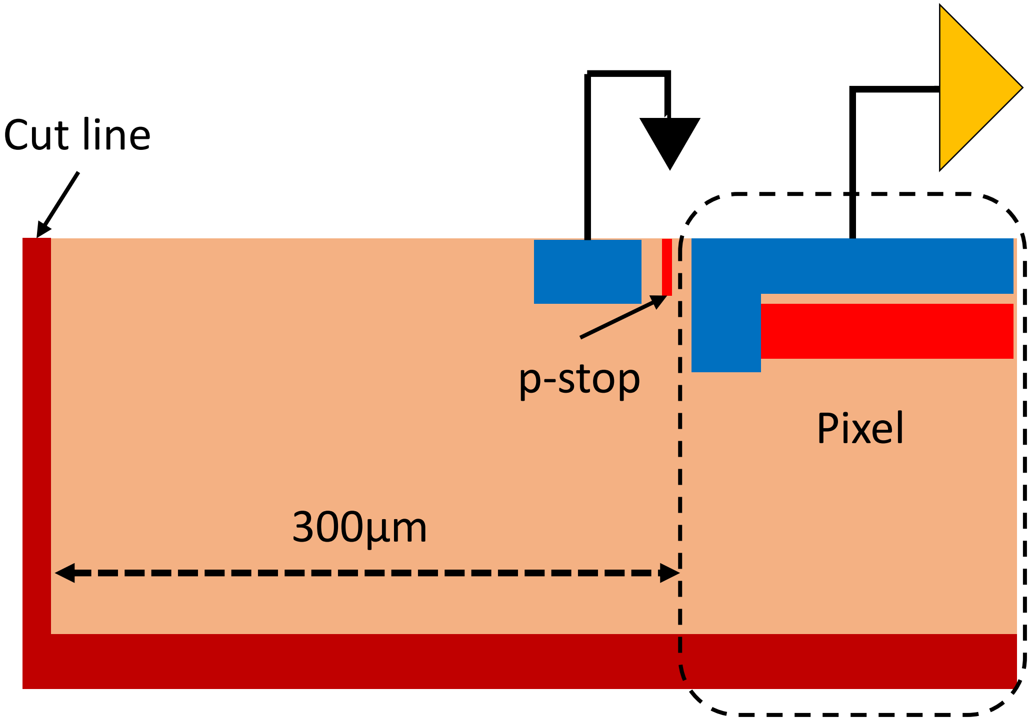


- ➢ Edge width of 500 µm
- ➢ One grounded Guard-ring
- ➢ 4 floating Guard-ring
- ➢ One p-stop between the last GR and the cut line

Guard-ring and edge layouts

Design: GR3_0
(Zero floating Guard-Ring)

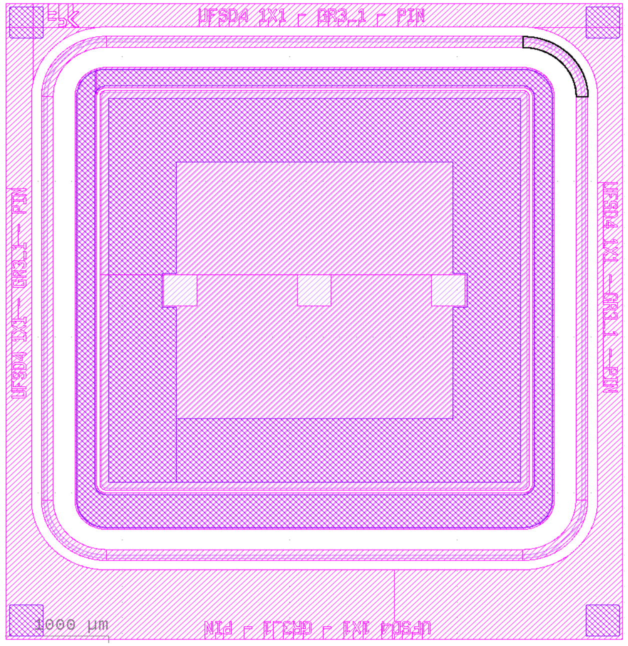




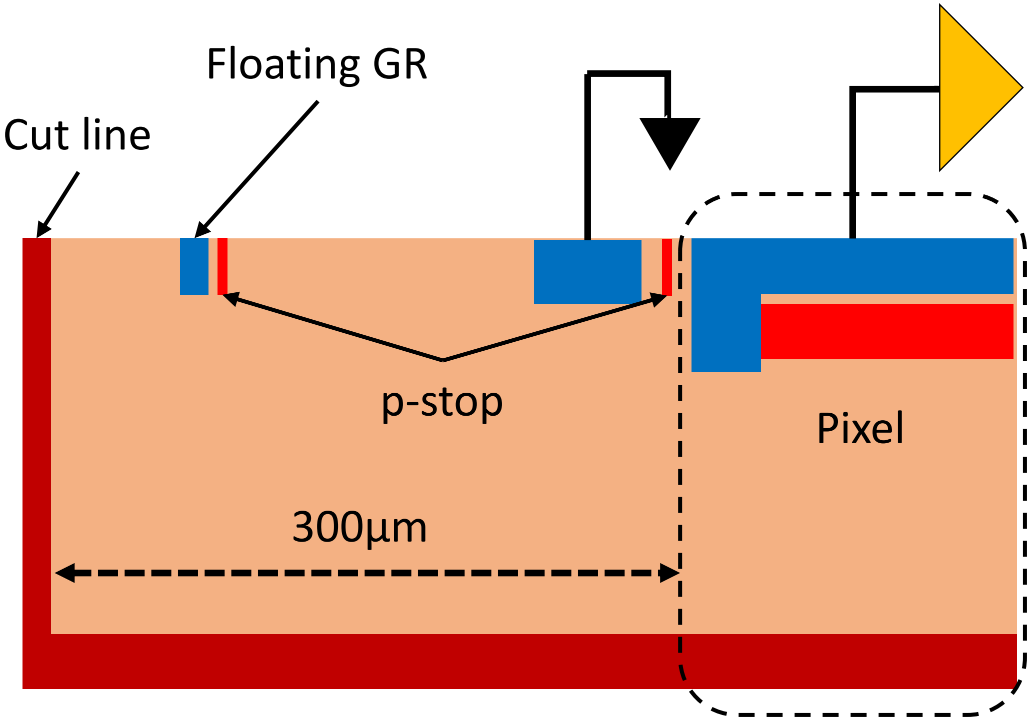
- Edge width of 300 µm
- One grounded Guard-ring
- No floating Guard-ring
- No p-stop between the GR and the cut line

Guard-ring and edge layouts

Design: GR3_1
(One floating Guard-Ring)

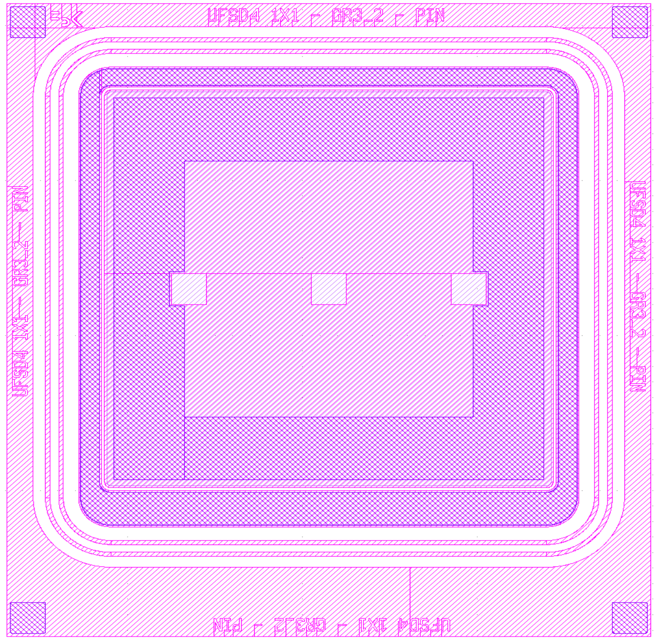


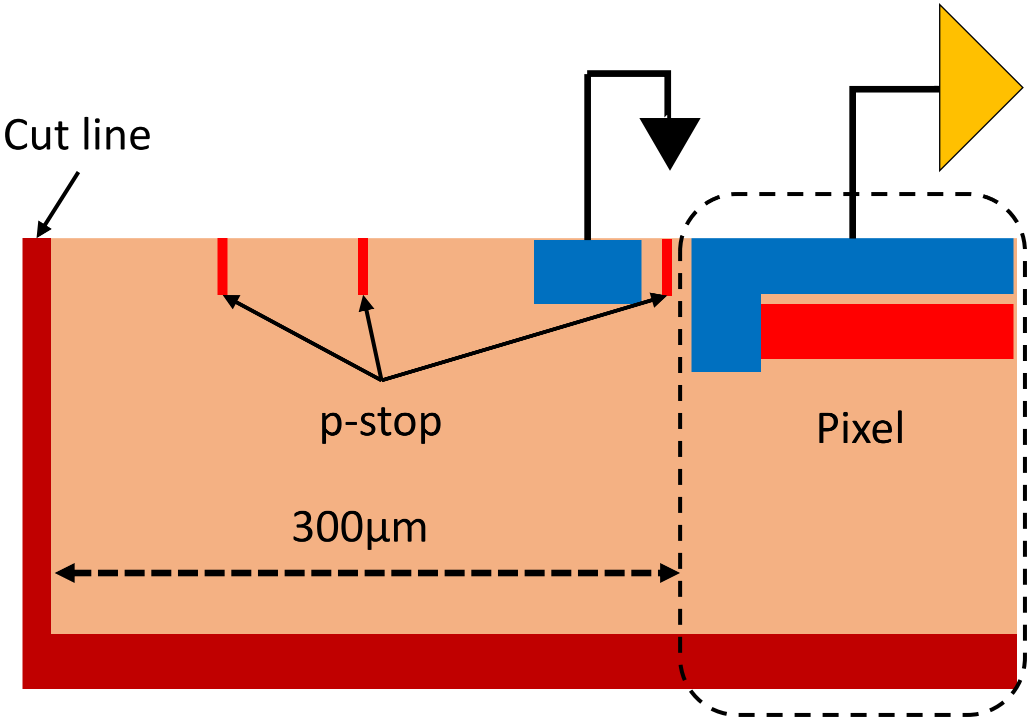
- ➢ Edge width of 300 µm
- ➢ One grounded Guard-ring
- ➢ 1 floating Guard-ring
- ➢ No p-stop between the floating GR and the cut line



Guard-ring and edge layouts

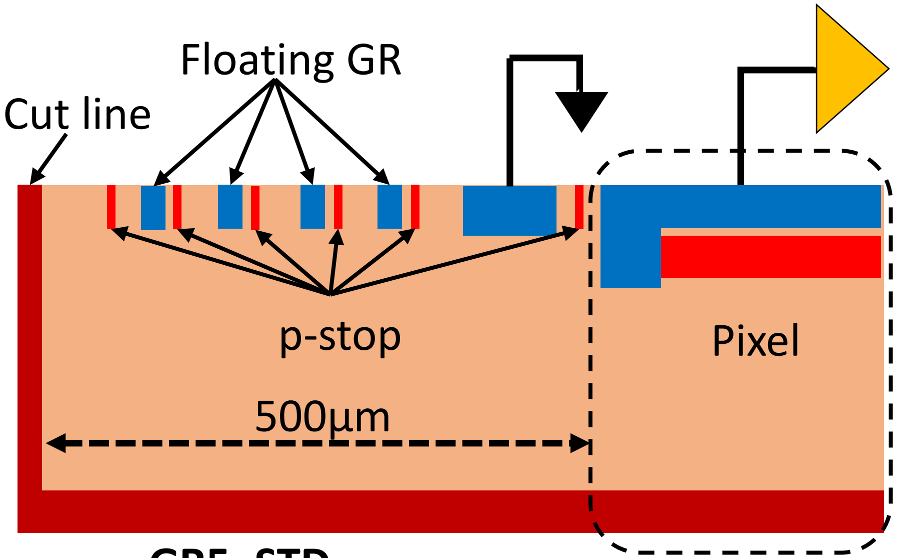
Design: GR3_2
(Zero floating Guard-Ring + double p-stop)



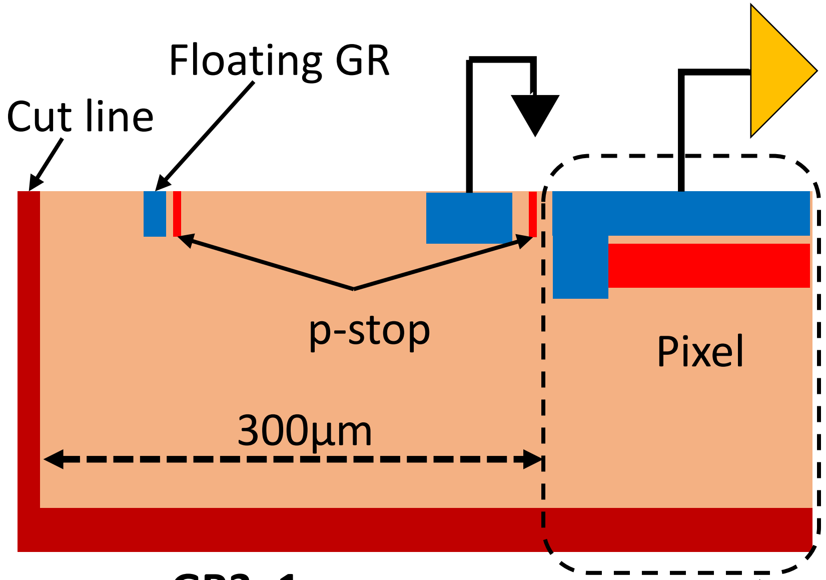


- Edge width of 300 µm
- One grounded Guard-ring
- No floating Guard-ring
- Double p-stop between the floating GR and the cut line

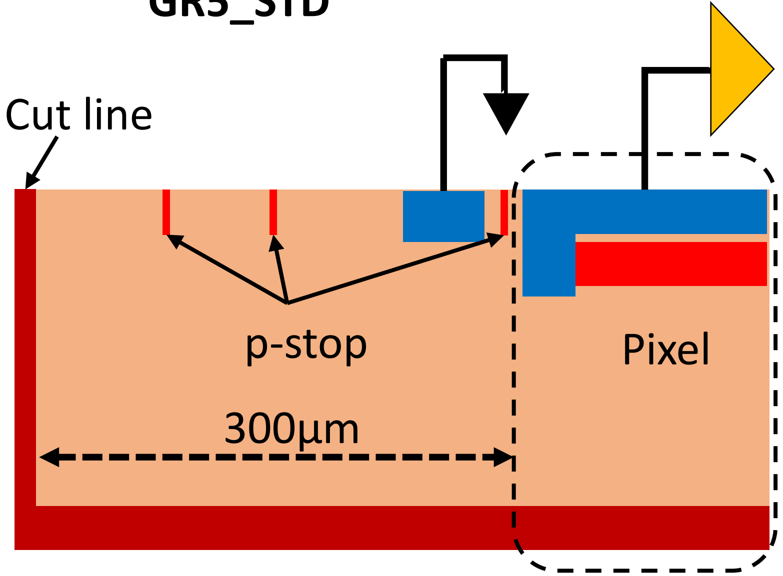
Summary of guard-ring tested



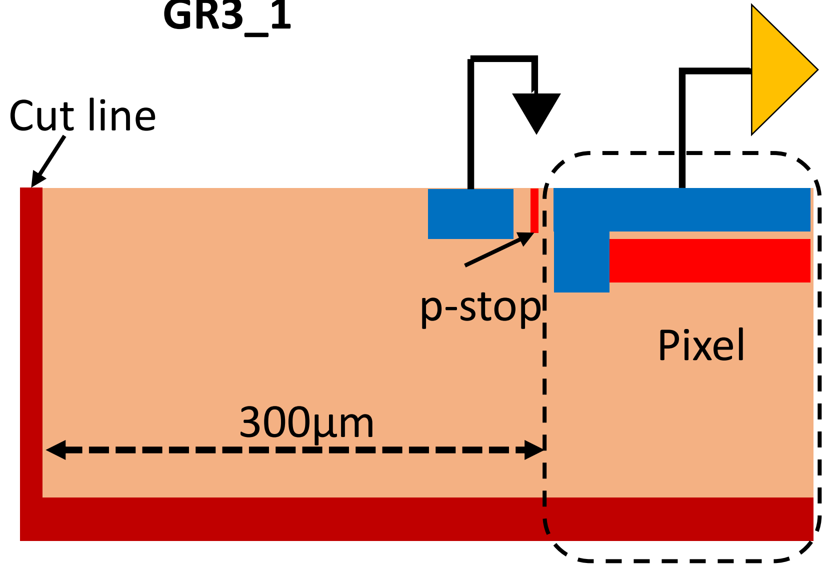
GR5_STD



GR3_1



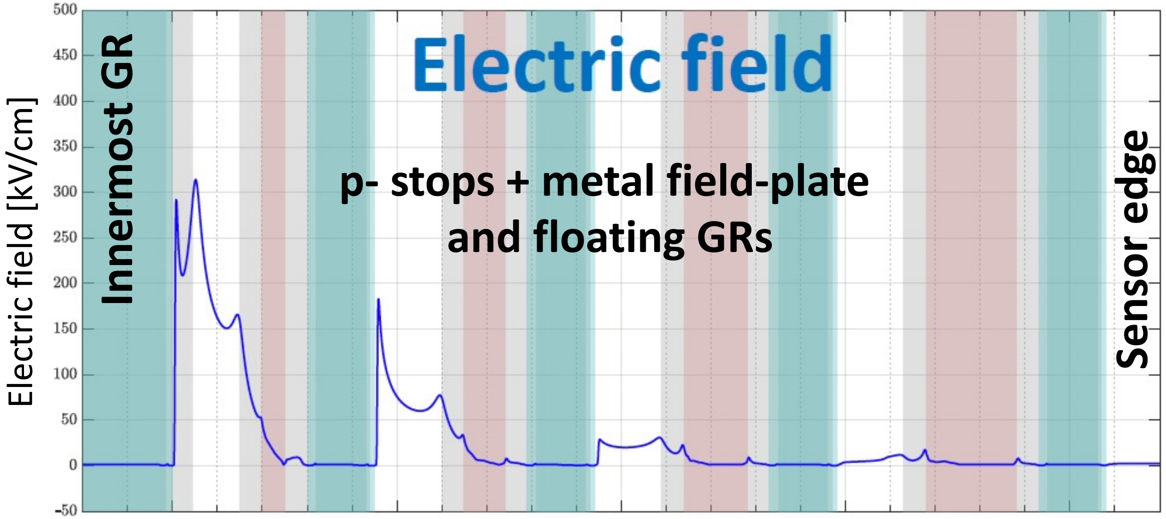
GR3_2



GR3_0

Simulations of different guard-ring designs in 45µm-thick LGAD

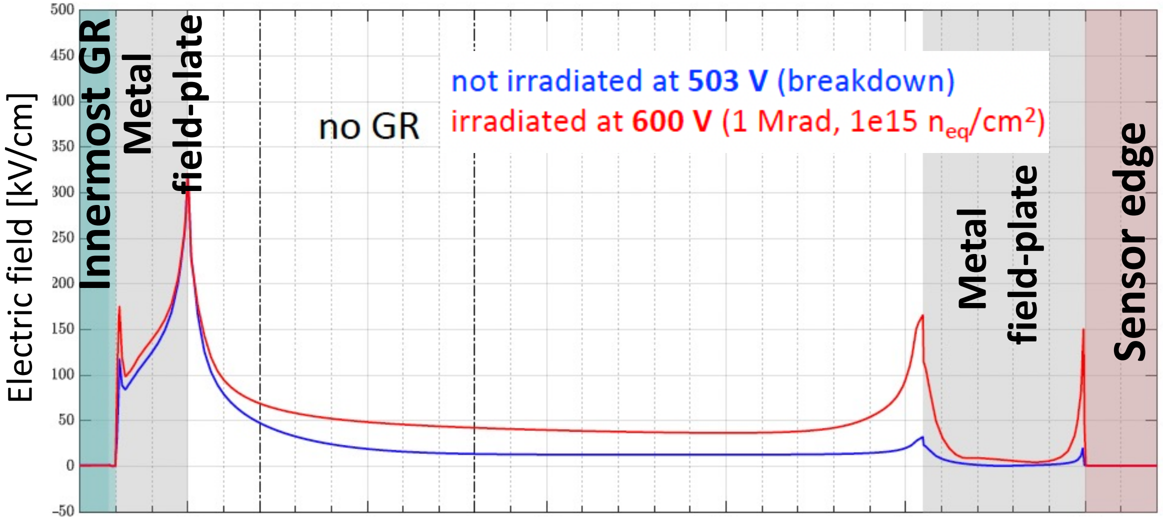
Multi guard-ring design



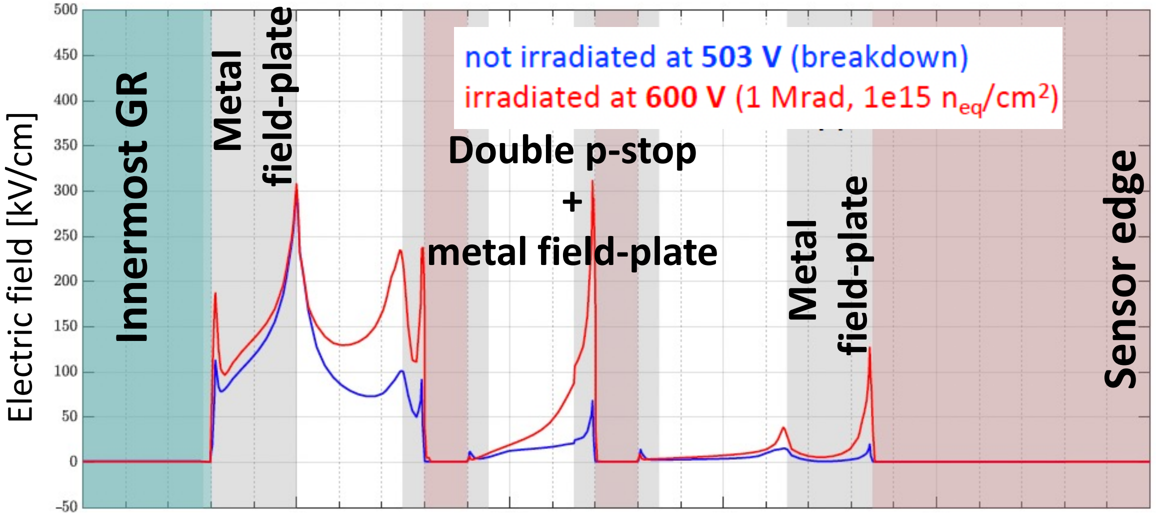
On the region between innermost GR and the sensor edge:

- ➢ Electric field drop localised between the innermost GR and the first floating one or first p-stop implant
- ➢ Negligible electric field drop in the region beyond the first floating GR
- ➢ Electric field drop smoother in design with no-floating GR than with floating one

No-floating guard-ring design



No-floating guard-ring + double p-stop design



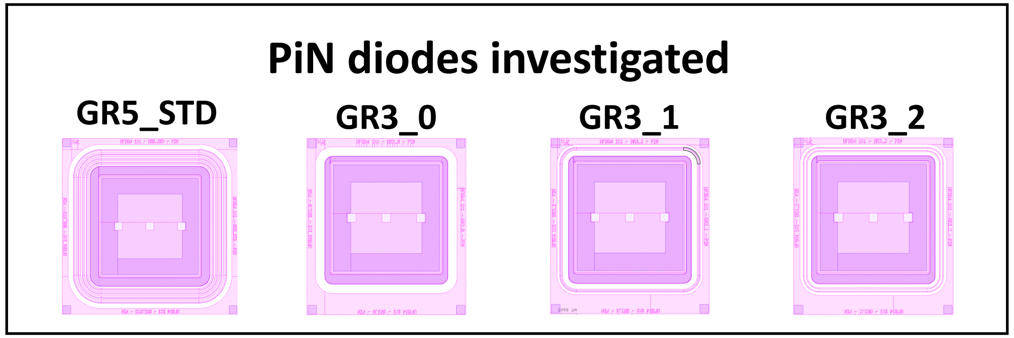
Evaluation method

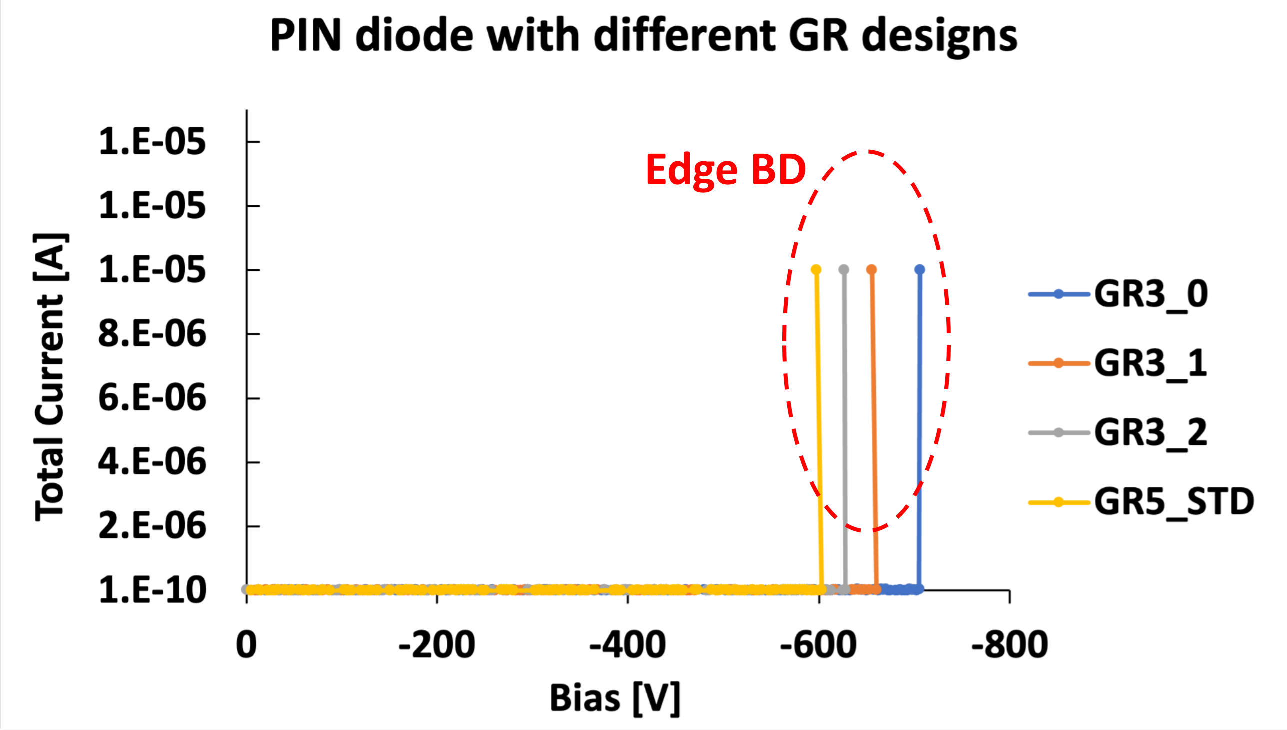
The different guard-ring structures have been tested using the following measurements:

- Breakdown of new PIN structures
- Current and breakdown in irradiated structures
- Presence of spurious signals (macro-discharges) due to guard-ring structure instability

Breakdown of PiN diodes with different GR designs

Breakdown measurement performed on PiN diodes unirradiated


PiN diodes investigated

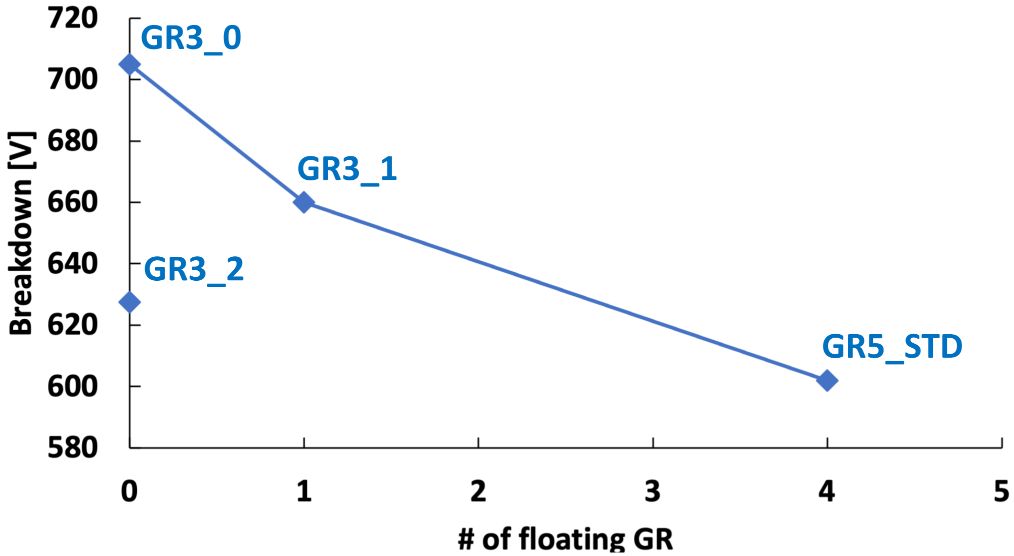

PIN diode with different GR designs

Breakdown:

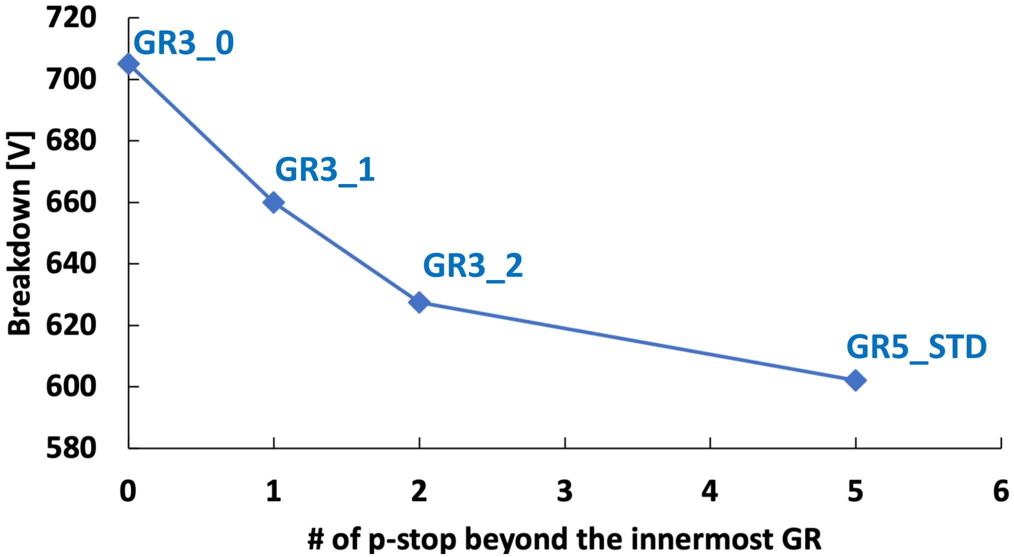
- ➢ Edge breakdowns between 600 V and 700 V
- ➢ Slight dependence on guard-ring design
- ➢ Designs with no floating GR are the most robust
- ➢ Design with multi-floating GR is the least robust
- ➢ The edge width does not affect the breakdown

Breakdown vs # of edge implants (guard-ring and p-stop)

Breakdown voltage
vs
# of floating guard-ring

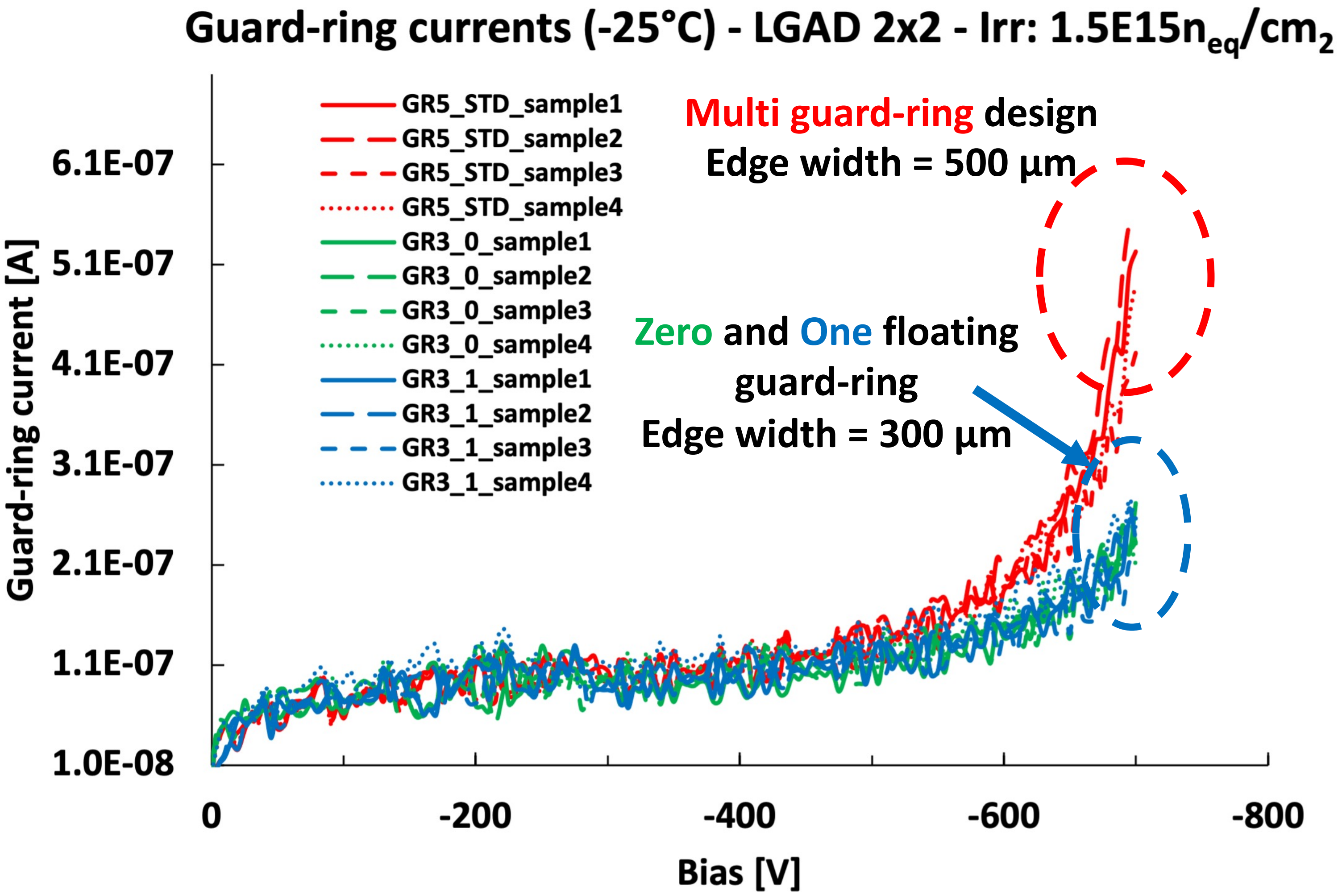


Breakdown voltage
Vs
# of p-stop beyond the innermost GR



Relationship between the breakdown voltage and the number of implants beyond the innermost guard-ring

Guard-ring currents in irradiated LGAD at Ø=$1.5\cdot10^{15}$ n_{eq}/cm^2

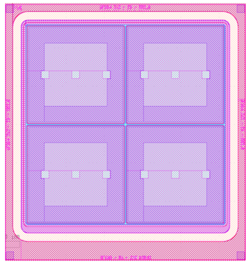

Guard-ring currents (-25°C) - LGAD 2x2 - Irr: 1.5E15n_{eq}/cm_2

Multi guard-ring design
Edge width = 500 µm

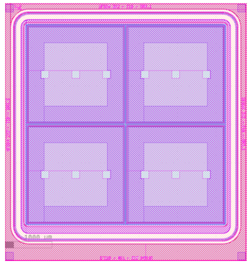
Zero and One floating guard-ring
Edge width = 300 µm

Guard-ring designs investigated on 2x2 LGAD:

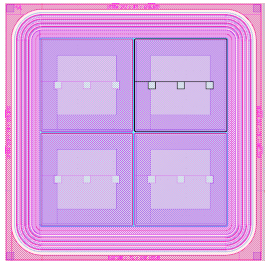
GR3_0



GR3_1



GR5_STD



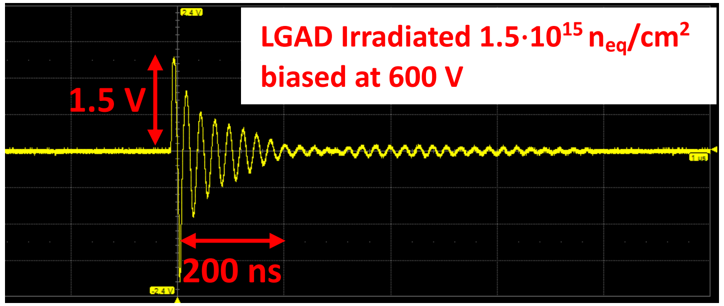
In presence of bulk damage:

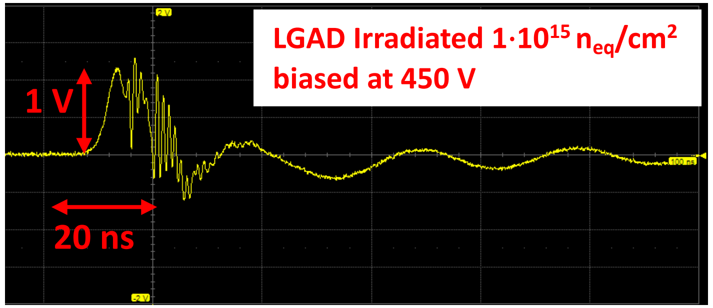
- Multi guard-ring design has a steeper increase of the edge current
- Zero and one-floating guard-ring designs are more robust than multi GR design

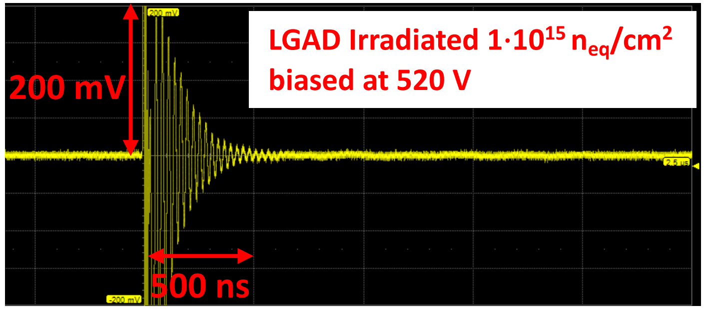
The effect of surface damage must be investigated

Characterization of Noise – Macro discharges

Macro Discharge (MD) phenomenon has been observed for the first time in multi guard-ring irradiated LGAD ($\emptyset > 1 \cdot 10^{15}\ n_{eq}/cm^2$), working at high bias (Bias > 450V)

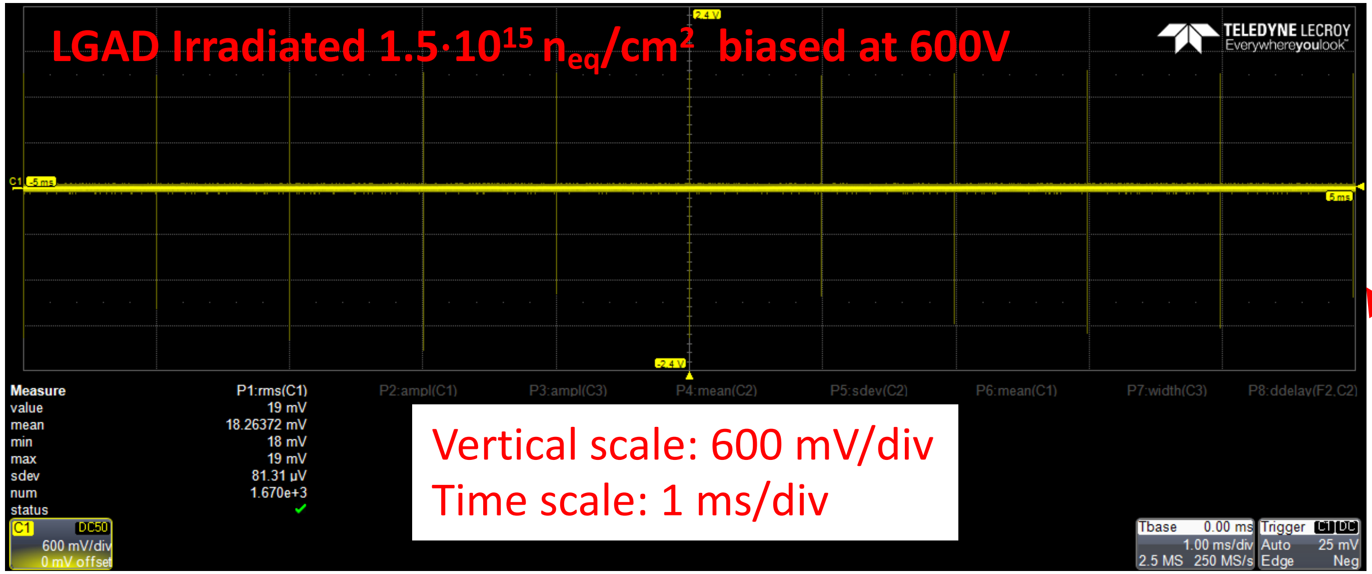

LGAD Irradiated $1.5 \cdot 10^{15}\ n_{eq}/cm^2$ biased at 600 V


LGAD Irradiated $1 \cdot 10^{15}\ n_{eq}/cm^2$ biased at 450 V


LGAD Irradiated $1 \cdot 10^{15}\ n_{eq}/cm^2$ biased at 520 V

- ➢ (MDs) were observed by triggering the sensor noise in absence of external source of signal (beta, laser etc…)
- ➢ Measurements were done in climatic chamber at -25°C with a readout chain based on SC-Board + a 20dB second stage amplifier (Cividec BroadBand)
- ➢ Macro discharge phenomenon, main characteristics:
  - Bias dependent
  - Irradiation level dependent
  - Discharges of different amplitude and time duration

Characterization of Noise – Macro discharges

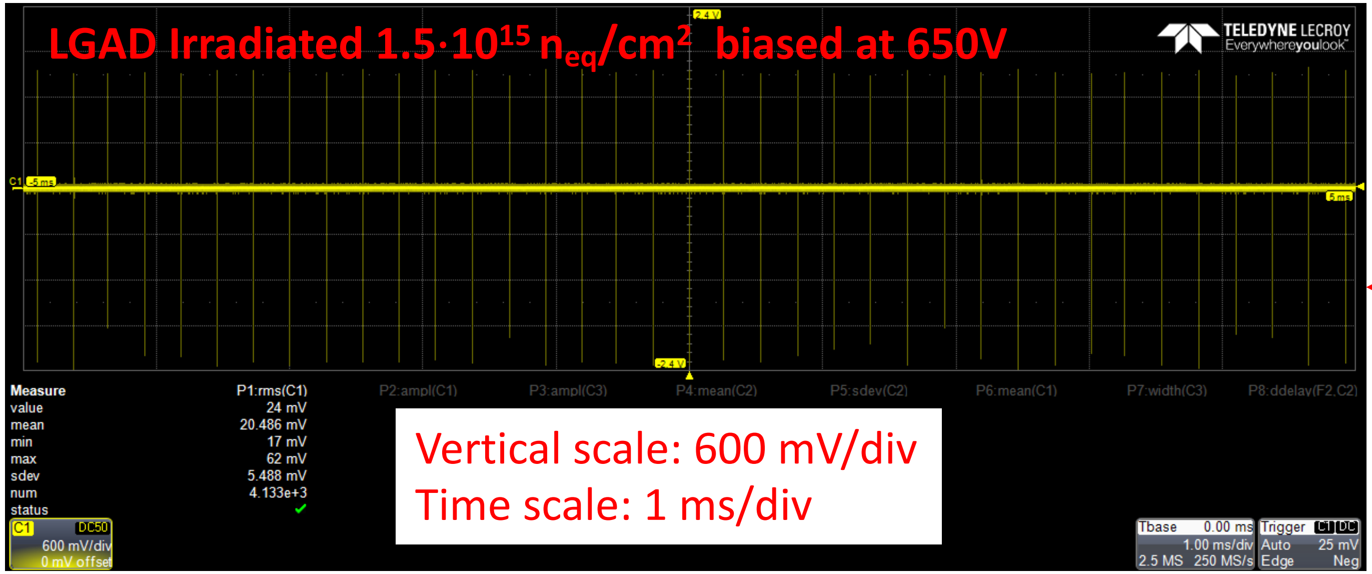


LGAD Irradiated $1.5{\cdot}10^{15}\ n_{eq}/cm^2$ biased at 600V

```
Measure   P1:rms(C1)     P2:ampl(C1)  P3:ampl(C3)  P4:mean(C2)  P5:sdev(C2)  P6:mean(C1)  P7:width(C3)  P8:ddelay(F2,C2)
value          19 mV
mean     18.26372 mV
min            18 mV
max            19 mV
sdev        81.31 µV
num         1.670e+3
status             ✓
```

```
C1  DC50   600 mV/div   0 mV offset
Tbase 0.00 ms   1.00 ms/div   2.5 MS   250 MS/s
Trigger C1 DC   Auto   25 mV   Edge   Neg
```

Vertical scale: 600 mV/div
Time scale: 1 ms/div



LGAD Irradiated $1.5{\cdot}10^{15}\ n_{eq}/cm^2$ biased at 650V

```
Measure   P1:rms(C1)     P2:ampl(C1)  P3:ampl(C3)  P4:mean(C2)  P5:sdev(C2)  P6:mean(C1)  P7:width(C3)  P8:ddelay(F2,C2)
value          24 mV
mean       20.486 mV
min            17 mV
max            62 mV
sdev        5.488 mV
num         4.133e+3
status             ✓
```

```
C1  DC50   600 mV/div   0 mV offset
Tbase 0.00 ms   1.00 ms/div   2.5 MS   250 MS/s
Trigger C1 DC   Auto   25 mV   Edge   Neg
```

Vertical scale: 600 mV/div
Time scale: 1 ms/div

Periodic Phenomenon (Hypothesis of a charge and discharge mechanism)

Time period dependent on sensor bias

Time period of 1 ms at 600V

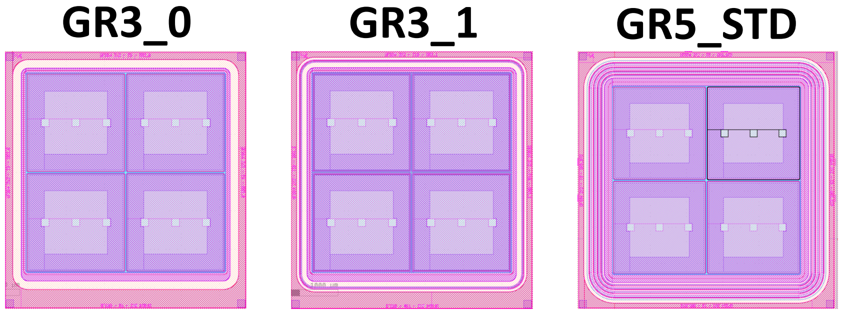
Time period of 250 µs at 650V

Macro discharges in different guard-ring devices

Macro discharges investigated in irradiated LGAD with different guard-ring designs

Guard-ring design investigated:

- Multi floating guard-rings (GR5_STD)
- One floating guard-ring (GR3_1)
- Zero floating Guard-ring (GR3_0)



Bias table at witch macro-discharges appear

	GR5_STD	GR3_1	GR3_0
$\emptyset = 1 \cdot 10^{15}\ n_{eq}/cm^2$	450–500 V	/	/
$\emptyset = 1.5 \cdot 10^{15}\ n_{eq}/cm^2$	450–500 V	550–600 V	/

Macro-discharge is guard-ring design dependent:

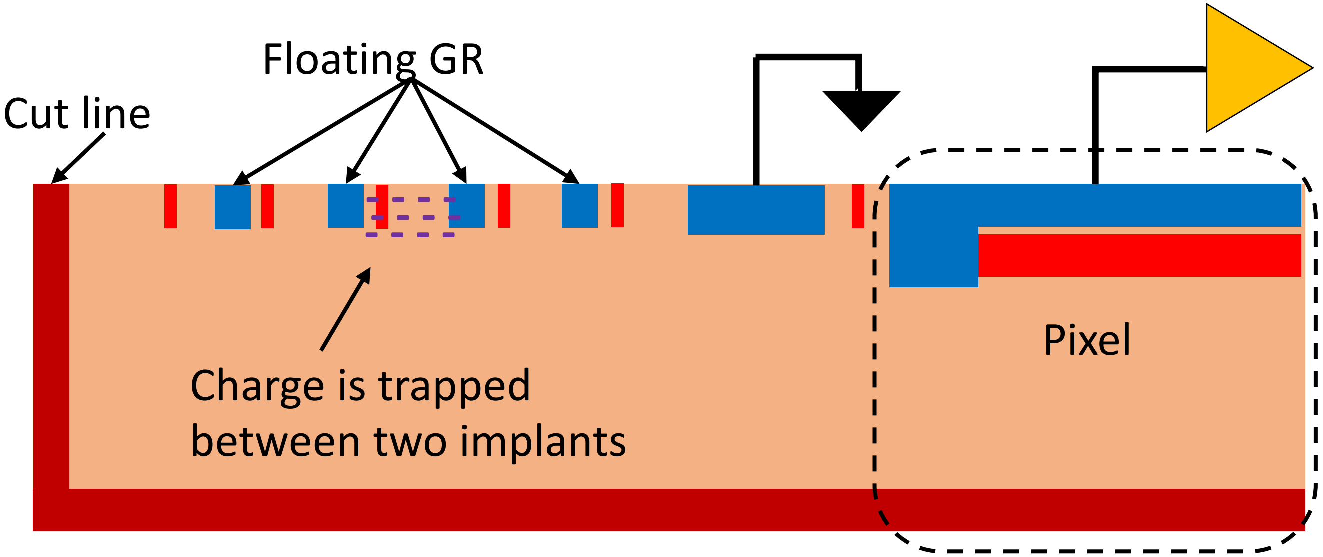
- GR5_STD design: Macro-discharges appear in the safe working bias (Bias < 500V) of sensors
- GR3_1 design: Macro-discharges appear above fluence of $1.5 \cdot 10^{15}\ n_{eq}/cm^2$, beyond the safe working bias (Bias>550V) of sensors.
- GR3_0 design: Macro-discharges do not appear

Possible source of macro-discharge

Pocket of area limited within two implants collect charge and increase their voltage, until they discharge

Consistent with evidence:

- Faster charge-up in more irradiated sensors
- Faster charge-up at higher bias



Summary

- Four Guard-ring designs have been investigated in simulation and implemented in UFSD4 FBK-production:
  - Multi floating Guard-Ring
  - One floating Guard-Ring
  - Zero floating Guard-Ring
  - Zero floating Guard-Ring + double p-stop

- From simulations and electrical characterizations pre and post neutrons irradiation, the designs with zero and one floating guard-ring are more robust than multi guard-ring design

- Noise characterization in irradiated LGAD showed Macro-Discharges correlated with the GR design:
  - In multi-GR design Macro-Discharges appear in the safe working bias (Bias<500V) range of sensors
  - In One-GR designs the Macro-Discharges appear beyond the safe working bias range (Bias>550V) of sensors
  - In Zero-GR designs the Macro-Discharges are absent up to 700V

Back up

Simulation parameters

- **45-µm-thick** active substrates with 0.81-µm-thick oxide
- **Edge contact** at the same bias of the back
- Horizontal **cutlines** at **100 nm** beneath the silicon/oxide interface
- **Radiation damage** models implementation (new Perugia, bulk damage)
- **Unirradiated** profiles plotted at **breakdown**
- **Irradiated** profiles plotted at **600 V**

Simulations of Zero floating guard-ring + double p-stop in 45µm-thick LGAD

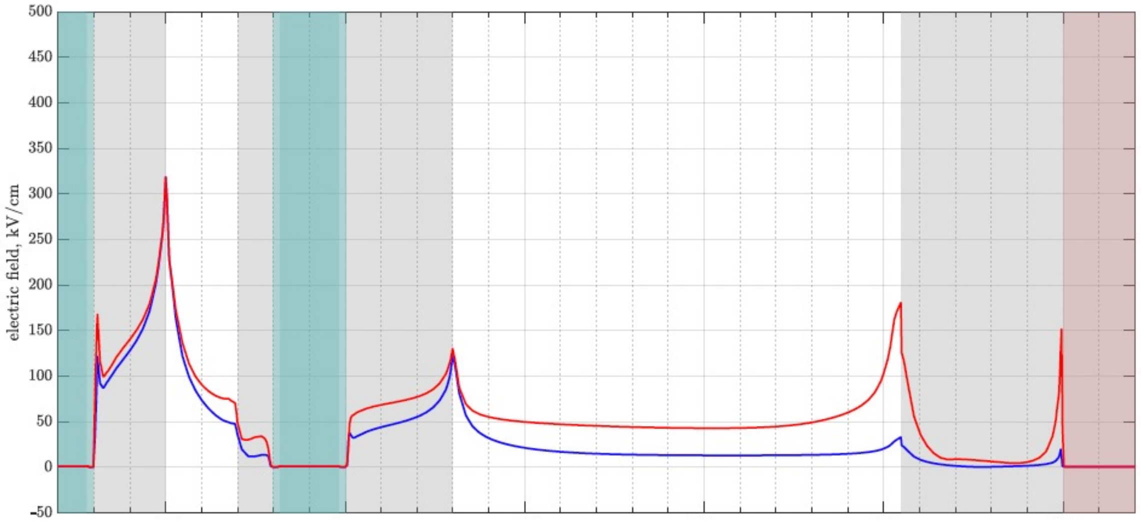
Innermost GR

not irradiated at **411 V** (breakdown)

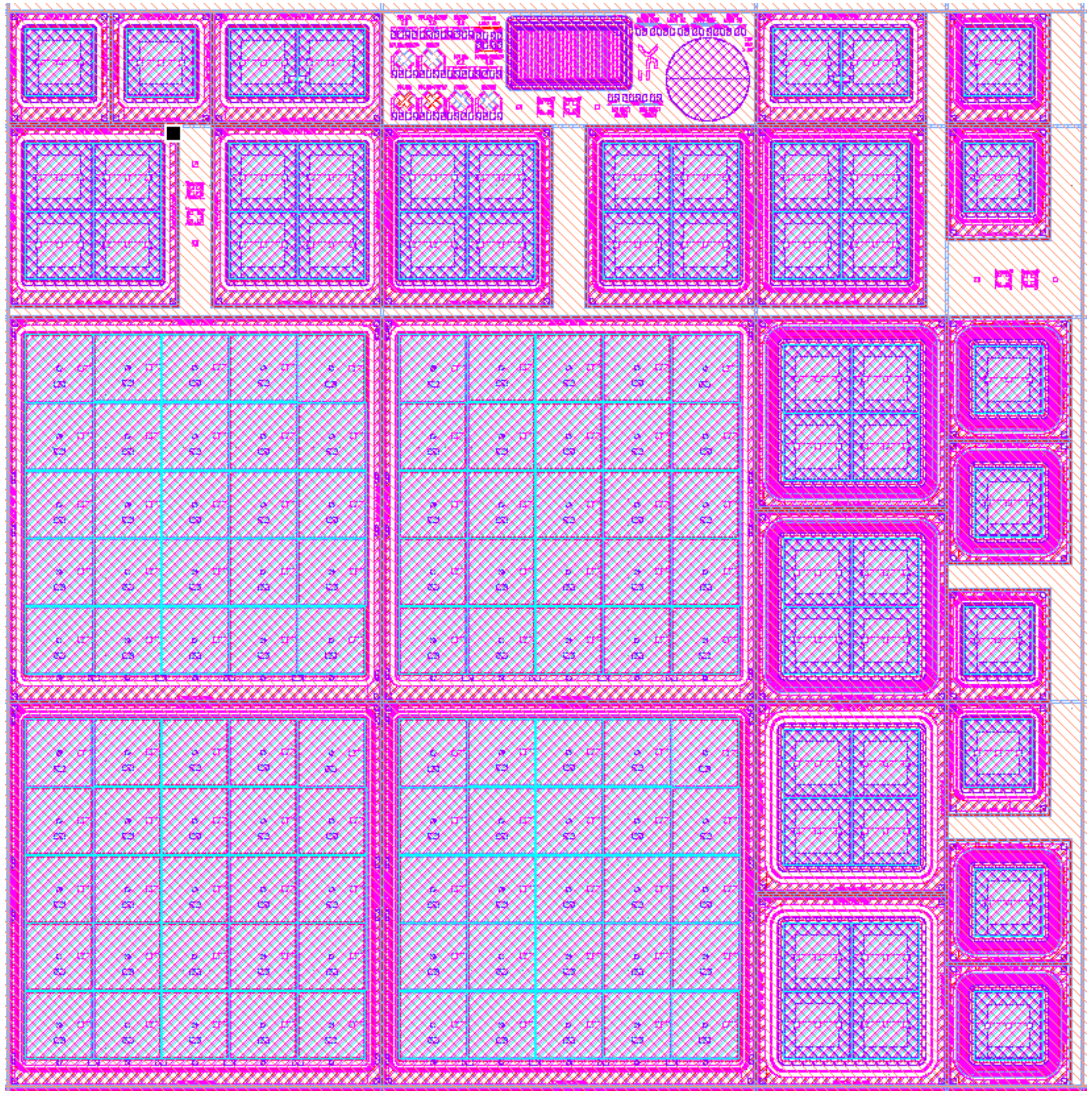
irradiated at **600 V** (1 Mrad, 1e15 n_{eq}/cm^2): ***I* ≃ 10 µA**

Double p-stop

Sensor edge



UFSD4 Reticle



Devices:

- Pair LGAD-PiN
- LGAD 1x2
- LGAD 2x2
- LGAD 5x5

Breakdown of irradiated LGADs