Enhancing guard-ring protection structures for the next generation of radiation-hard thin silicon particle detectors

T. Croci(1,*), A. Fondacci(4,1), R. White(5), A. R. Altamura(5), M. Durando(6), S. Galletto(6), G. Paternoster(7), M. C. Vignali(7), M. Boscardin(7), R. Arcidiacono(8,5), N. Cartiglia(5), F. Moscatelli(2,1), D. Passeri(3,1), M. Ferrero(5), V. Sola(6,5) and A. Morozzi(1)

1) Istituto Nazionale di Fisica Nucleare (INFN), Perugia, Italy.
2) Istituto Officina dei Materiali (IOM) CNR, Perugia, Italy.
3) Dipartimento di Ingegneria, Università di Perugia, Perugia, Italy.
4) Dipartimento di Fisica, Università di Perugia, Perugia, Italy.
5) Istituto Nazionale di Fisica Nucleare (INFN), Torino, Italy.
6) Dipartimento di Fisica, Università di Torino, Torino, Italy.
7) Fondazione Bruno Kessler (FBK), Trento, Italy.
8) Dipartimento di Scienze del Farmaco, Università del Piemonte Orientale, Novara, Italy.

(*) tommaso.croci@pg.infn.it

Motivations

- ✓ Developing high performing silicon detectors for particle tracking in the next generation of high-energy physics experiments at future colliders (e.g. HL-LHC, FCC) able to operate efficiently up to very high fluences, $\Phi \sim 1\times10^{17}$ 1 MeV n_{eq}/cm^2.
- ✓ To sustain high voltage values with minimum leakage current injection into the core region of the sensor, the design and optimization of the Guard-Ring (GR) protection structure is crucial, especially when small substrate thicknesses are used.
- ✓ In a recent R&D batch produced at FBK in the framework of the "eXFlu" project, different optimisation studies of GR structures for p-type thin substrates (45, 30, 20 and 15 μm) up to high fluences (2.5×10^{15} 1 MeV n_{eq}/cm^2) have been addressed.
  - ad-hoc advanced Technology CAD (TCAD) modelling of the different GR design strategies, accounting for the radiation-induced damage effects (bulk + surface);
  - extensive test campaign on these GR structures, both before and after irradiation.

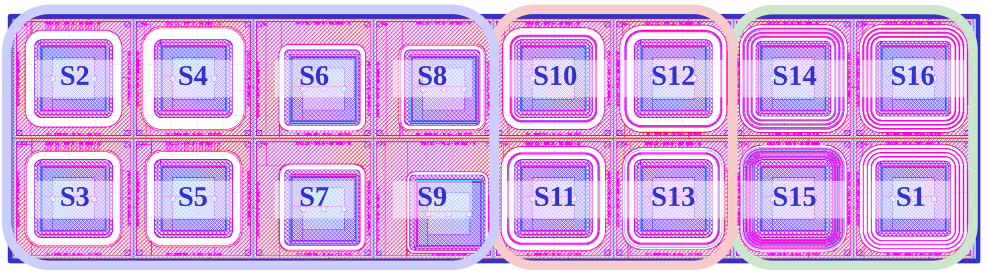
→ **Validation** of the development framework and **evaluation** of the impact of the various GR design options on their performance, both before and after irradiation.

Simulations: p-type substrate

DUTs

"EXFLU1" R&D batch, FBK

Shot with **GR designs** (i.e. **S1**, **S2**, etc…)

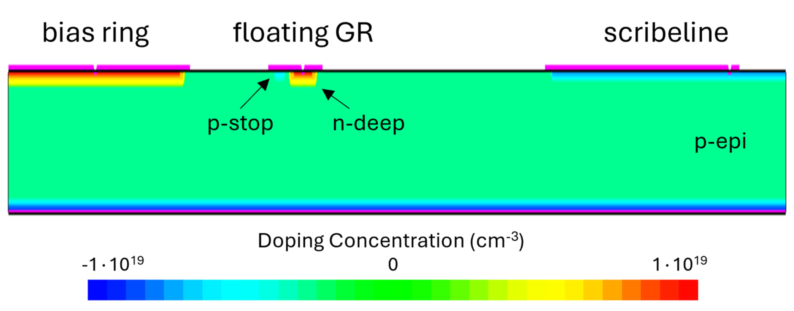


- ✓ **GR0: no floating GRs**, varying
  - *edge* region size
  - *void* region size (i.e., scribeline)
  - metal *overhang*
- ✓ **GR1: 1 floating GR**, varying
  - floating GR *position*
- ✓ **GR3: 3 floating GRs**, using one or both of:
  - single *n-deep* implant
  - single *p-stop* implant

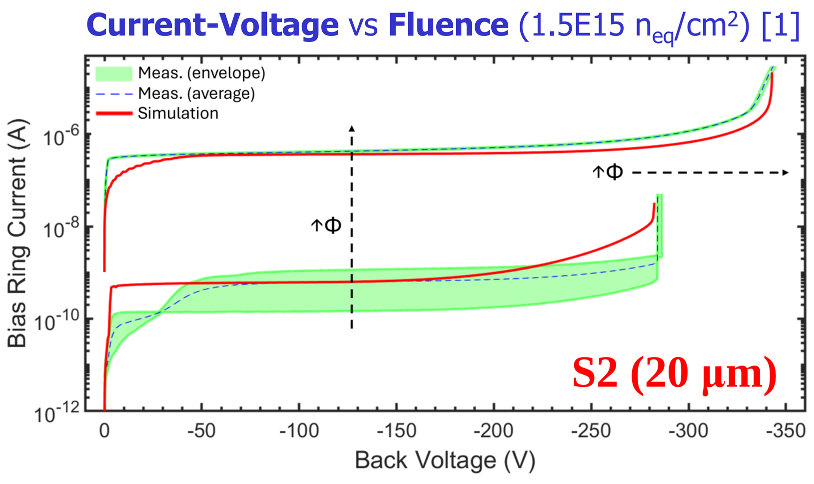
- ✓ Four substrate **thicknesses**: **45**, **30**, **20** and **15 μm**
- ✓ **Irradiation** campaign with **neutrons** at the JSI TRIGA reactor (Ljubljana, Slovenia), Fluences (Φ): **8-15-25E14 1 MeV n_{eq}/cm^2**

TCAD modelling

Layout of a GR structure (e.g. GR1)



Current-Voltage vs **Fluence** (1.5E15 n_{eq}/cm^2) [1]

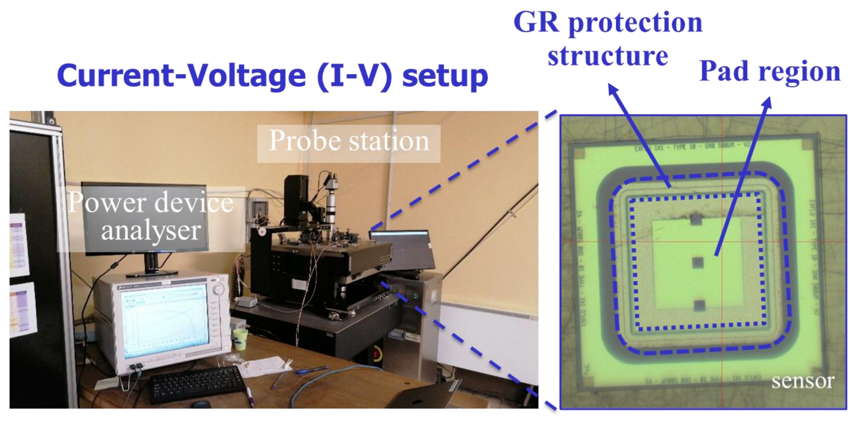


[1] T. Croci *et al.*, NIM, A 1069 (2024) 169801.
[2] P. Asenov *et al.*, NIM, A 1040 (2022) 167180.

Measurements: p-type substrate

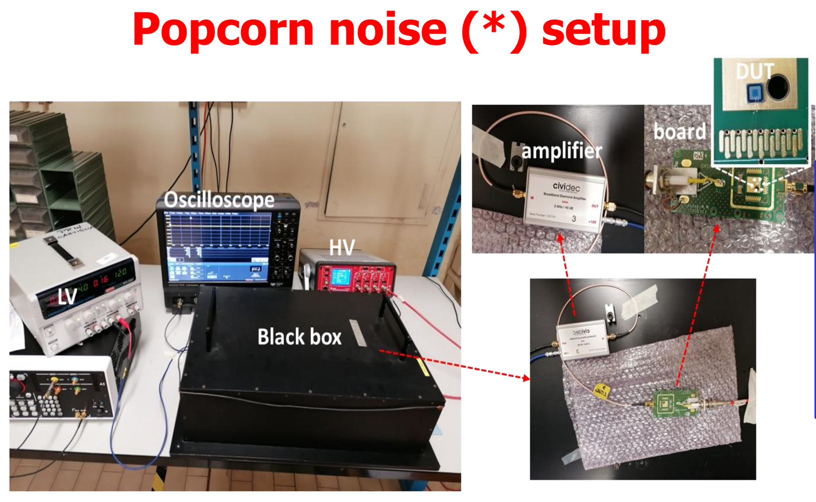
Setup

Temperature-controlled probe station



MPI TS200-SE, Thermal chuck -60/+300°C

Popcorn noise (*) setup

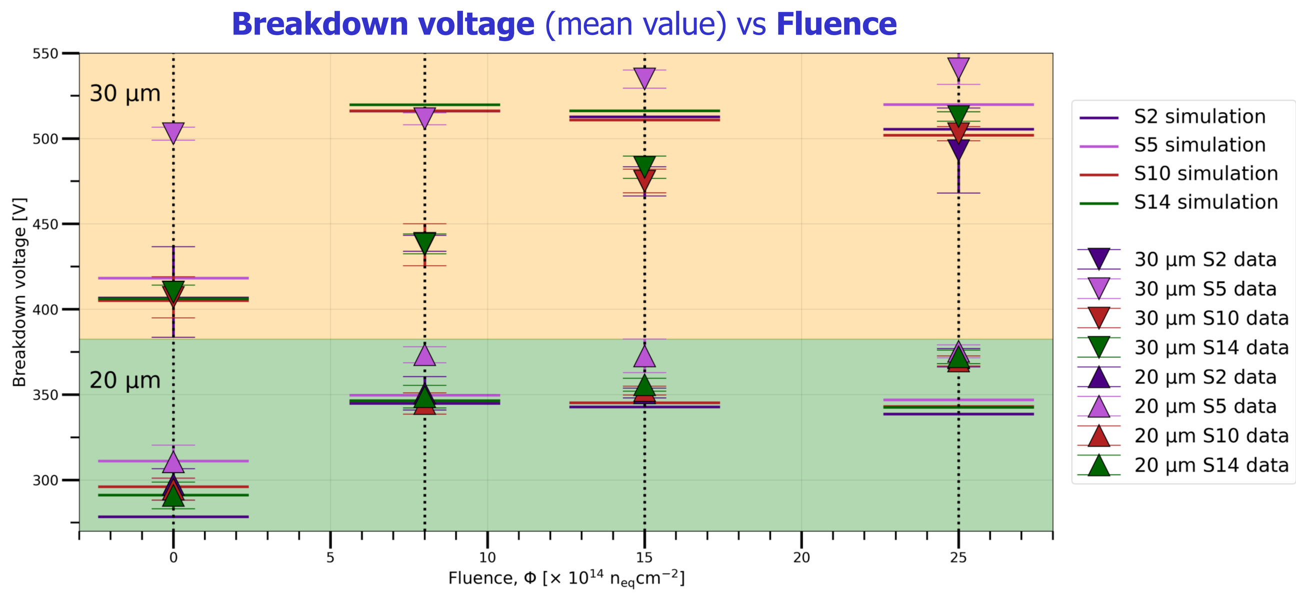


V$_{BD}$

"Perugia Modified Doping" TCAD radiation damage model [2]

GOOD AGREEMENT

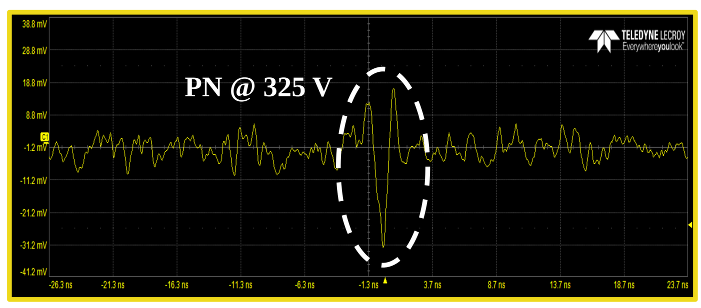
Breakdown voltage (mean value) vs **Fluence**

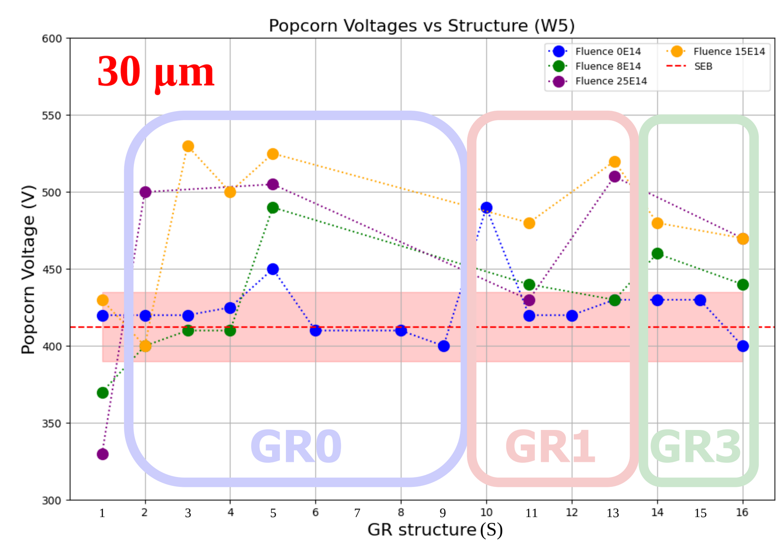


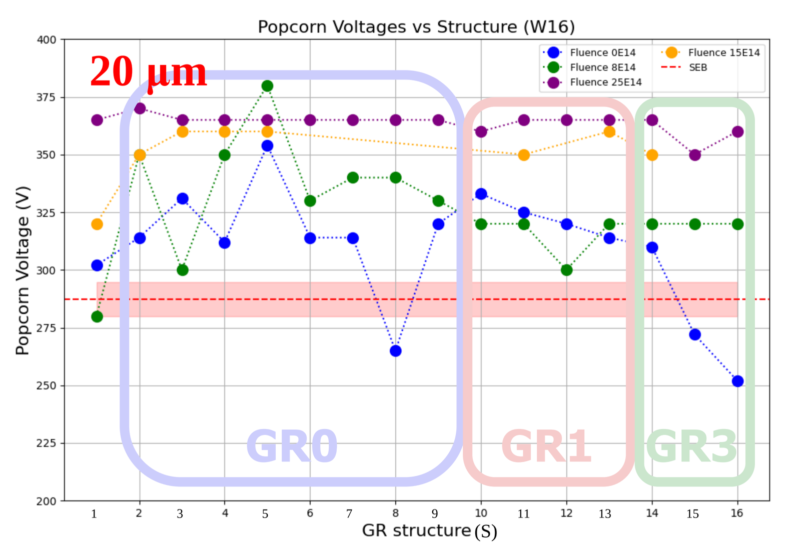
Popcorn noise

(*) Popcorn noise (PN):

type of noise in detectors characterized by random and sudden peaks in the output signal, which can exhibit significant amplitude in the absence of external stimuli.







when ↑Φ → ↑V_{PN} (≈V_{BD}) well **beyond** the **SEB limit** [3].
Not all the GR structures show PN (**S1** is typically the **worst** GR design).

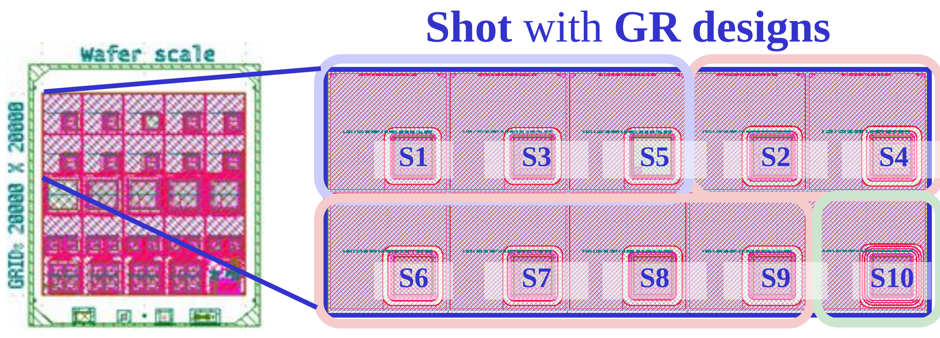
[3] M. Ferrero *et al.*, 43rd RD50 Workshop, CERN (2023).

Simulations: n-type substrate

DUTs

"NLGAD" R&D batch, FBK
(ongoing production)

Shot with **GR designs**

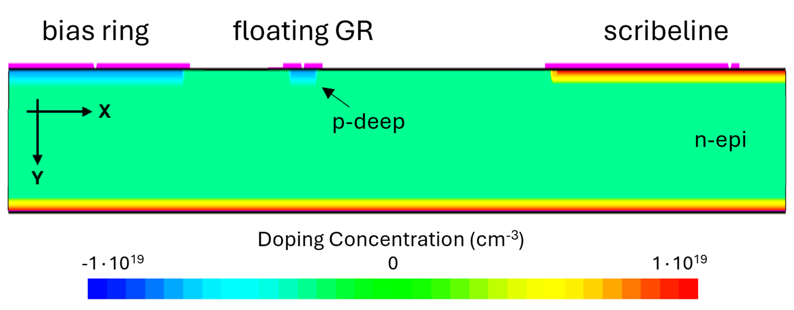


- ✓ **GR0: no floating GRs**, varying
  - metal *overhang*
- ✓ **GR1: 1 floating GR**, varying
  - floating GR *position*
  - metal *overhang*
- ✓ **GR3: 3 floating GRs**, using of:
  - single *p-deep* implant

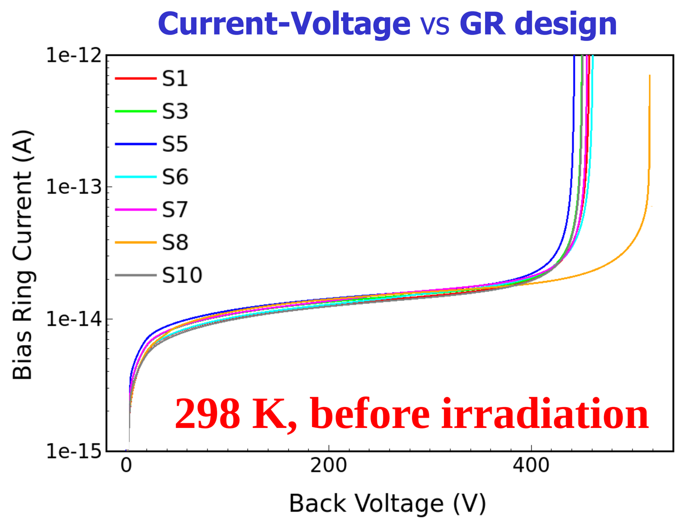
- ✓ Substrate **thickness**: **55 μm**

TCAD modelling

Layout of a GR structure (e.g. GR1)

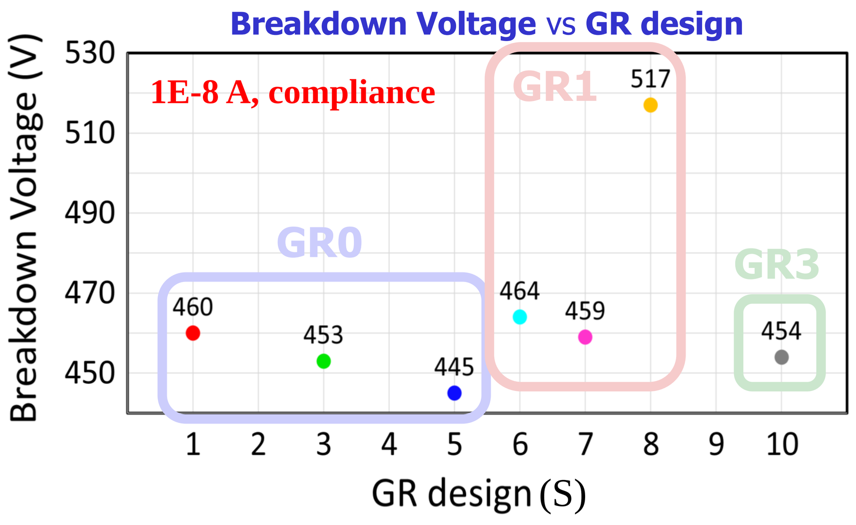


Current-Voltage vs **GR design**



V$_{BD}$

Breakdown Voltage vs **GR design**



$V_{BD,S3} \approx V_{BD,S7} \approx V_{BD,S10}$

$V_{BD,S1} \approx V_{BD,S6}$

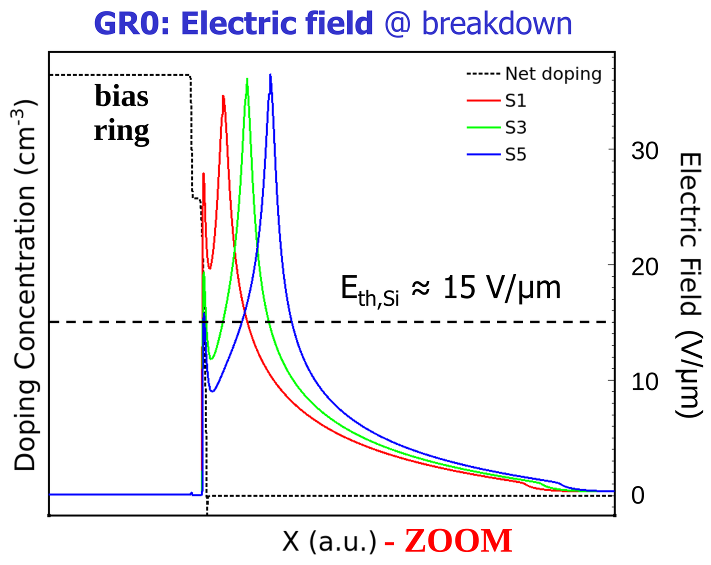
→ GR0 ≈ GR1 ≈ GR3

S5 worst GR design

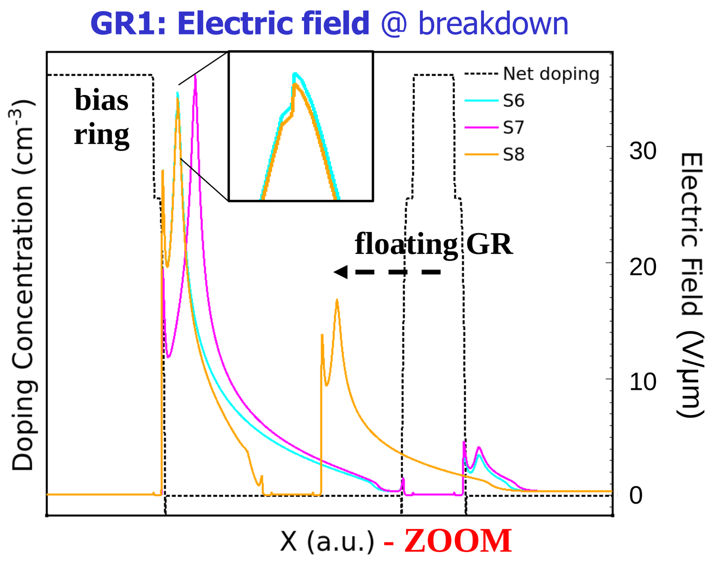
S8 best GR design

Electric field

GR0: Electric field @ breakdown



GR1: Electric field @ breakdown



Outcome

- ✓ The I-V characteristics and breakdown voltages of different Guard-Ring protection structures coming from the "EXFLU1" R&D batch (FBK) under different operating conditions (i.e. T and Φ) have been well reproduced in simulation [1].
- ✓ Use of the validated "Perugia Modified Doping" TCAD model [2] for a new series of simulations on different GR design strategies optimised for 55 μm-thick n-type substrates.
  → **Ongoing sensor production, "NLGAD" R&D batch (FBK).**
- ✓ The GR structures without any floating GR (i.e. GR0) have shown almost the same breakdown voltage of the GR1 and GR3 design options before and after irradiation
  → **GR structures without any floating GR are a viable design option.**
- ✓ P-type substrate:
  - ✓ An improvement of the breakdown voltage in GR0 structures has been obtained by increasing the overhang size of the metal contact over the bias ring.
  - ✓ Almost all the GR structures show popcorn noise near the breakdown voltage and beyond the SEB limit [3], both before and after irradiation.
- ✓ N-type substrate:
  - ✓ An improvement of the breakdown voltage in GR1 structures has been obtained by reducing the distance between floating GR and the bias ring.

Acknowledgement

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