TCAD optimization of LGAD sensors for extremely high fluence applications

T. Croci(1,*), A. Morozzi(1), P. Asenov(2,1), A. Fondacci(3,1), V. Sola(5,4), G. Borghi(6), M. Centis Vignali(6), F. Moscatelli(2,1), D. Passeri(3,1)

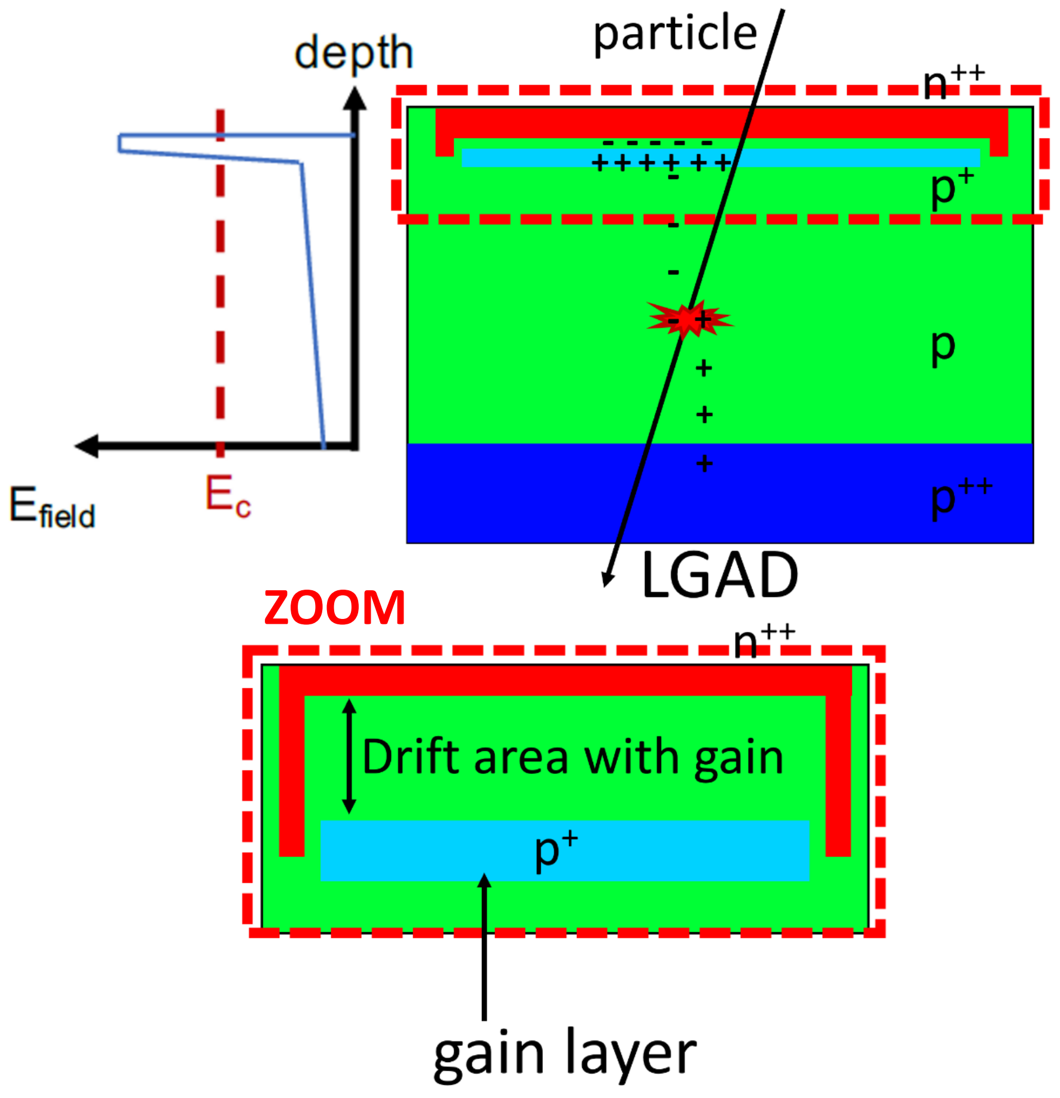
1) Istituto Nazionale di Fisica Nucleare (INFN), Perugia, Italy.
2) Istituto Officina dei Materiali (IOM) CNR, Perugia, Italy.
3) Dipartimento di Ingegneria, Università di Perugia, Perugia, Italy.
4) Istituto Nazionale di Fisica Nucleare (INFN), Torino, Italy.
5) Dipartimento di Fisica, Università di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

Motivations

- ✓ Developing radiation-resistant silicon detectors for particle tracking in the next generation of high-energy physics experiments (e.g. HL-LHC or FCC) able to efficiently operate in extreme radiation environments, $\Phi \sim 1\times10^{17}$ n_{eq}/cm^2.
- ✓ The Low-Gain Avalanche Diode (LGAD) technology helps to mitigate the radiation damage effects by exploiting the controlled charge multiplication mechanism [1].
- ✓ To maintain the desired gain (~ 10 - 20) and to prevent premature breakdown and large leakage currents at very high fluences, a careful implementation of the "multiplication" region and a proper design of the peripheral region are needed.
  - ○ ad-hoc advanced Technology CAD (TCAD) modeling of LGAD electrical behavior and its charge collection properties, before and after irradiation [2];
  - ○ massive test campaign on specifically devised LGAD structures both non-irradiated and irradiated ones.

=> Validation of the development framework and evaluation of the impact of several design strategies.

=> Sensor design and optimization before the large volume production.



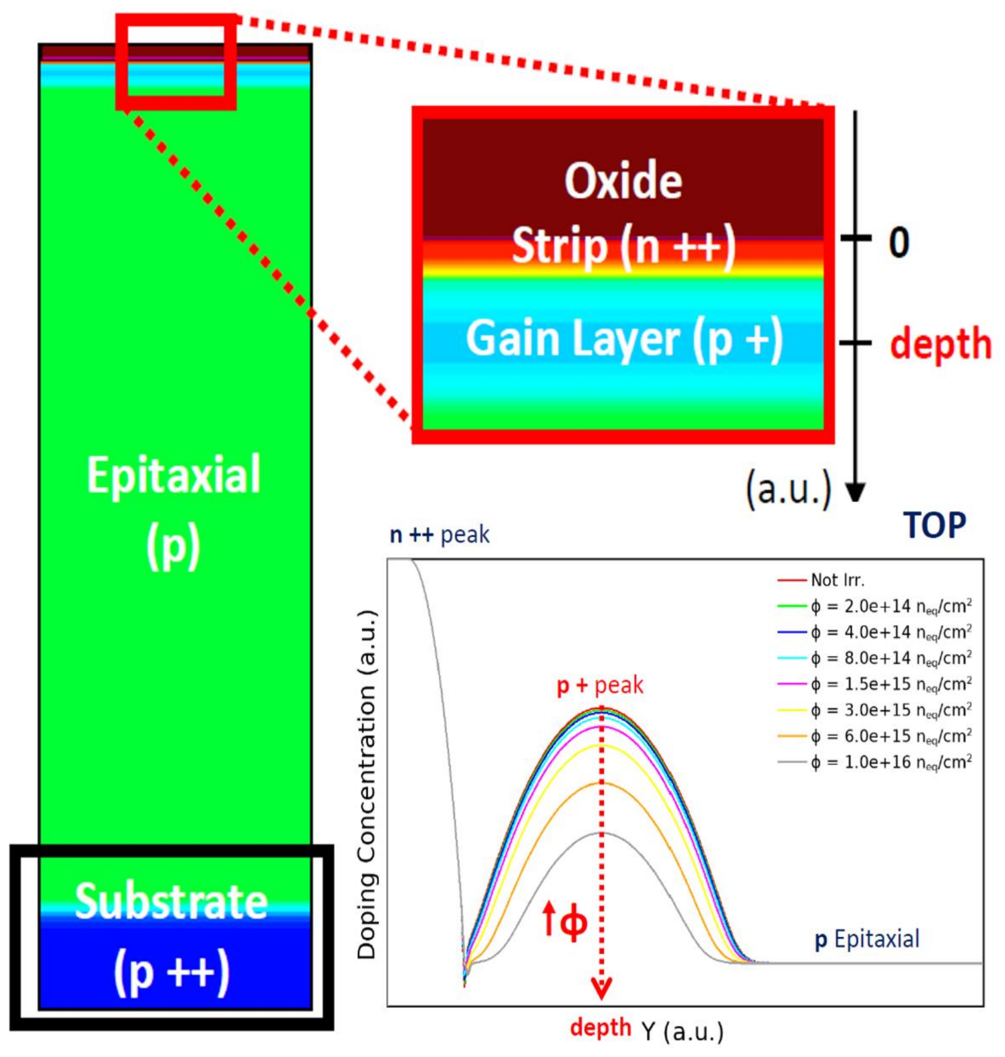
TCAD model for the numerical simulation of LGAD sensors before and after irradiation

- ✓ Focus on avalanche effect due to the multiplication layer (i.e. high electric field region, or gain layer) => stringent mesh requirements => "quasi-1D approach".
- ✓ Gaussian analytical profiles to model the highly doped n-type strip and the moderately doped p-type gain layer.
- ✓ Acceptor removal mechanism after irradiation modeled by the following analytical law:

$$N_{GL}(\Phi) = N_A(0)e^{-c\Phi}$$

where the *c* removal factor is calculated from the "Torino parameterization" [3].

[3] M. Ferrero *et al.*, An Introduction to Ultra-Fast Silicon Detectors, 1st ed., CRC Press (2021).

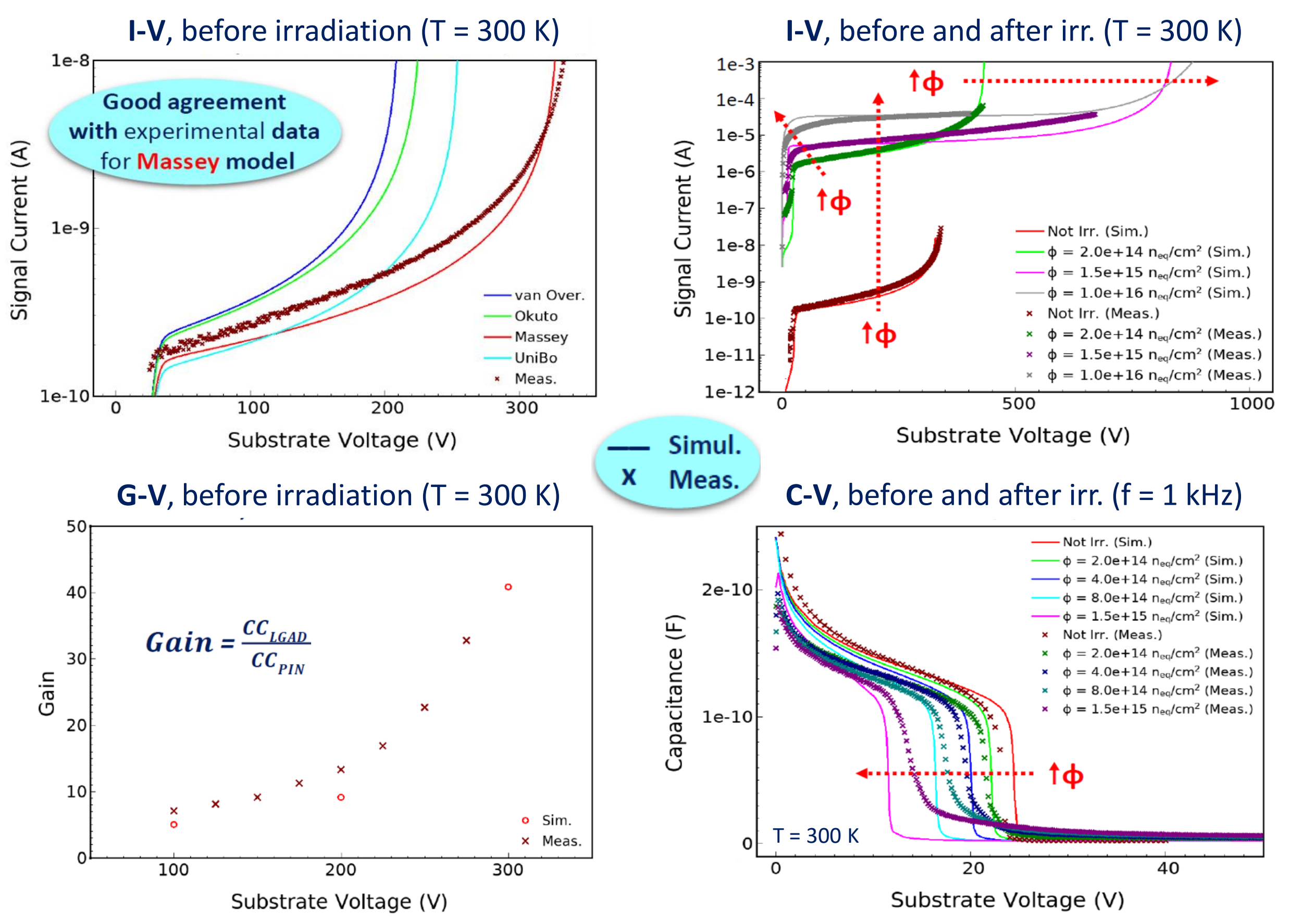


Comparative evaluation of different impact ionization models, among the embedded available ones (e.g. van Overstraeten-de Man, Okuto-Crowell and University of Bologna) as well as by extending the TCAD "portfolio" through the code library customization (e.g. Massey model).

By coupling the well-validated "New University of Perugia" radiation damage numerical model [4] with the acceptor removal analytical one => good reproduction of the experimental data.
=> reliable implemented simulation framework.

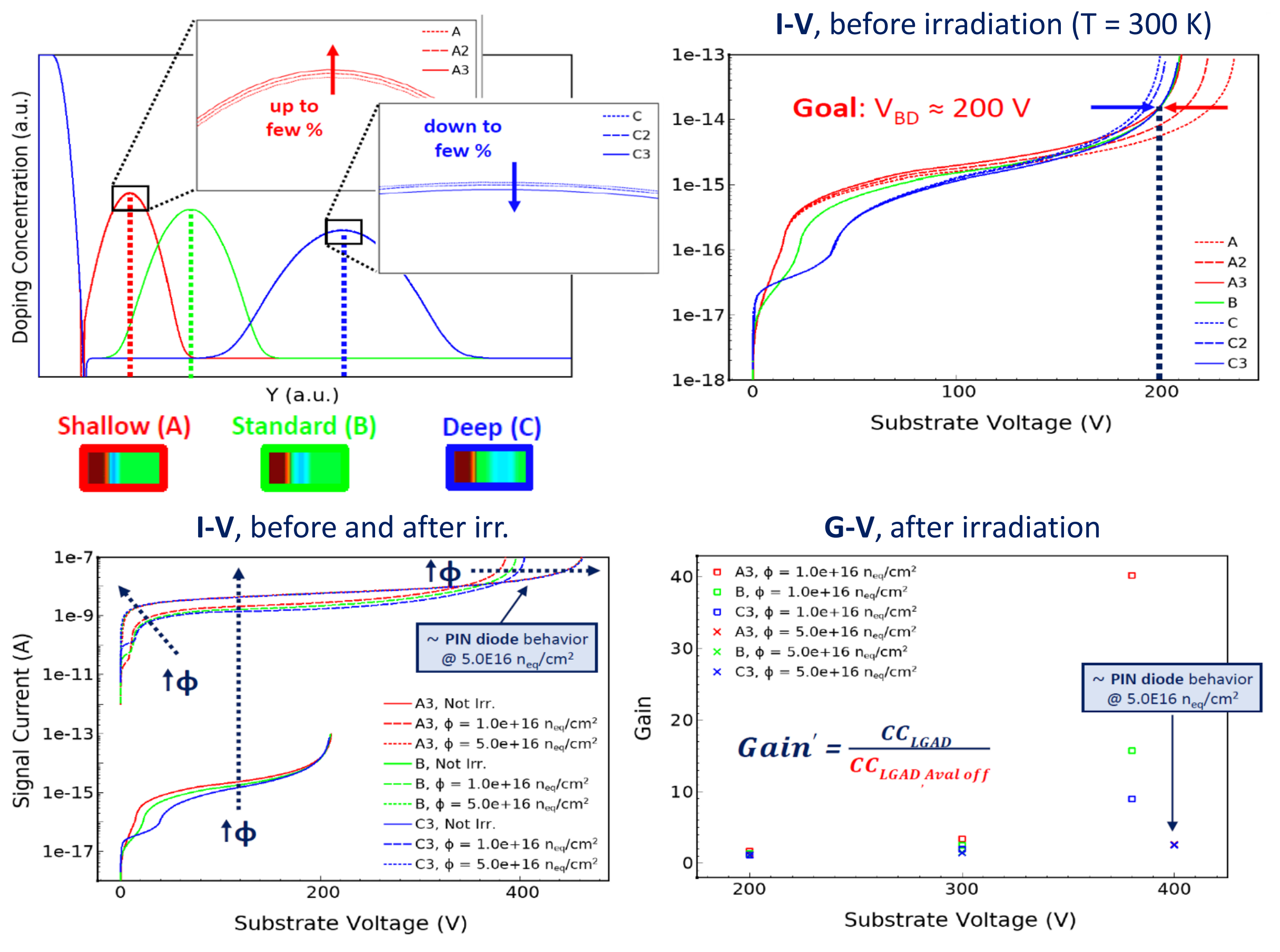
[4] A. Morozzi *et al.*, TCAD advanced radiation damage modeling in silicon detectors, PoS, Vertex2019 (2020).

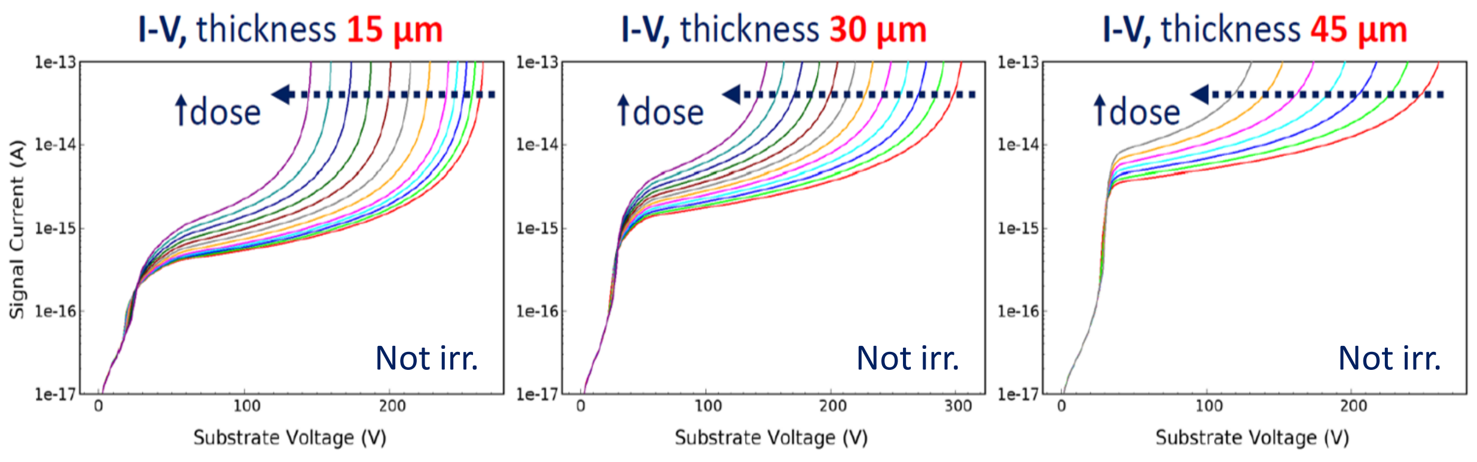
55 µm-thick device



Optimization of the gain layer implant

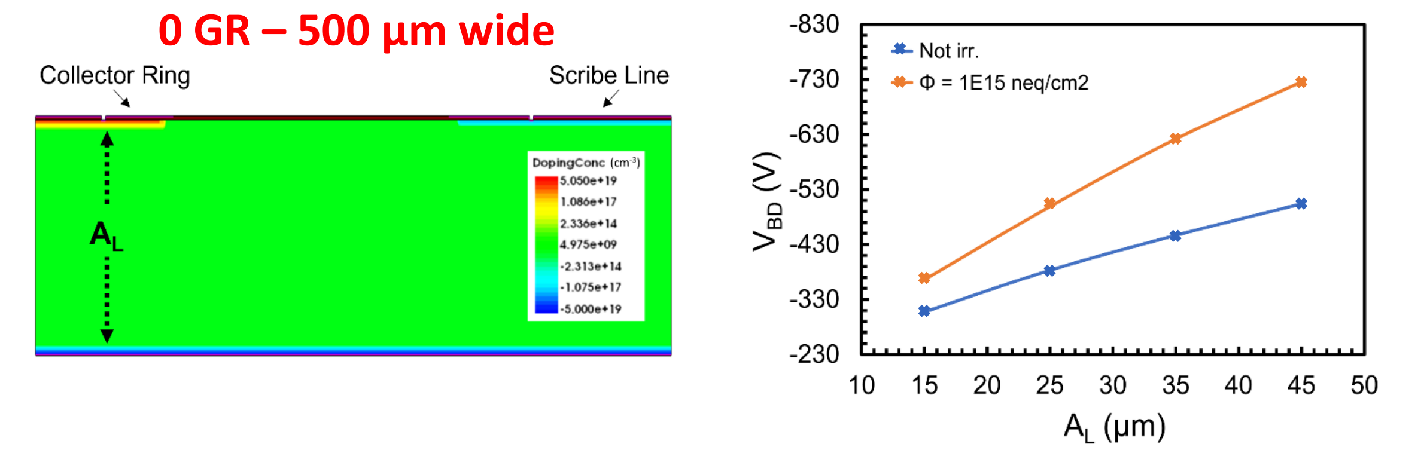
20 µm-thick device

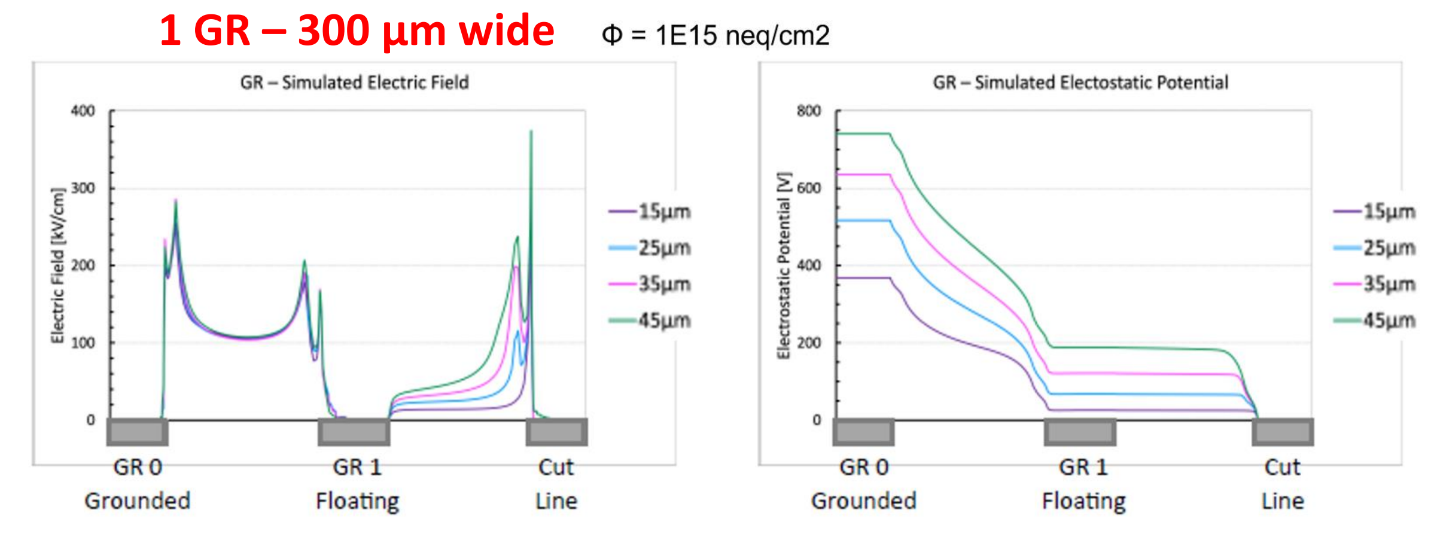


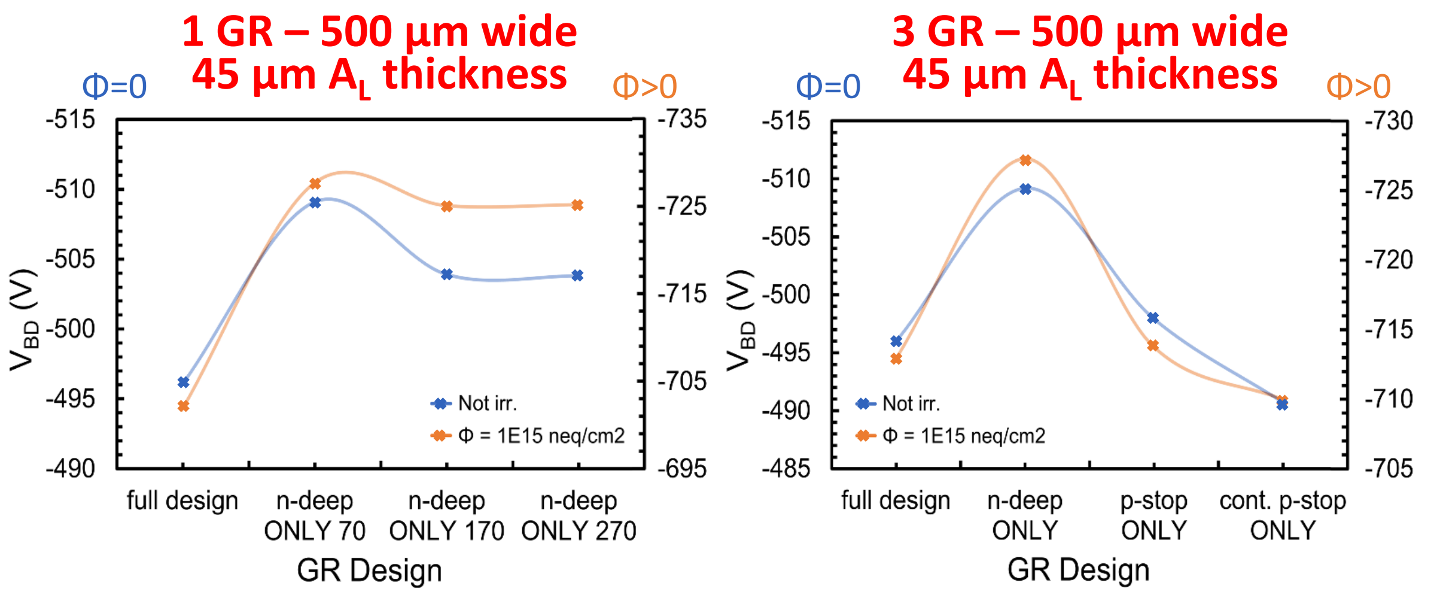


Analysis of the gain layer sensitivity for different combinations of doping profile and active substrate thickness => impact on the device electrical behavior, in terms of breakdown voltage (V_{BD}) and response after the passage of a charged particle, e.g. a minimum ionizing heavy ion, before and after irradiation.

Design of the sensor periphery







Several guard-ring (GR) design strategies for thin sensor substrates have been considered, to efficiently sustain high bias values (hundred of volts) over short distances. TCAD simulation shows the possible presence of dangerous high-electric-field peaks near the implants, which can trigger premature breakdown.

Outcome

- ✓ Design and preparatory studies of LGAD sensors for extreme fluence applications (e.g., future collider experiments)

  => Guidelines for a new production
  - ○ Substrate thickness: 15, 20, 30 and 45 µm.
  - ○ Gain layer implant doping profile: "Shallow".
  - ○ Periphery: 500 µm edge distance; 1 and 3 floating GRs without p-stops (only n-deep); different overhang sizes.
- ✓ Impact of several design strategies has been evaluated with the aid of TCAD simulations based on a recently proposed model for the numerical simulation of radiation damage effects on LGAD sensors.

References

[1] G. Pellegrini *et al.*, Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications, Nucl. Inst. and Meth. in Phys. Res. A, 12 765 (2014).

[2] T. Croci *et al.*, TCAD simulations of non-irradiated and irradiated Low-Gain Avalanche Diodes and comparison with measurements, J. Instrum. 17, C01022 (2022).

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