Development and test of innovative Low-Gain Avalanche Diodes for particle tracking in 4 dimensions

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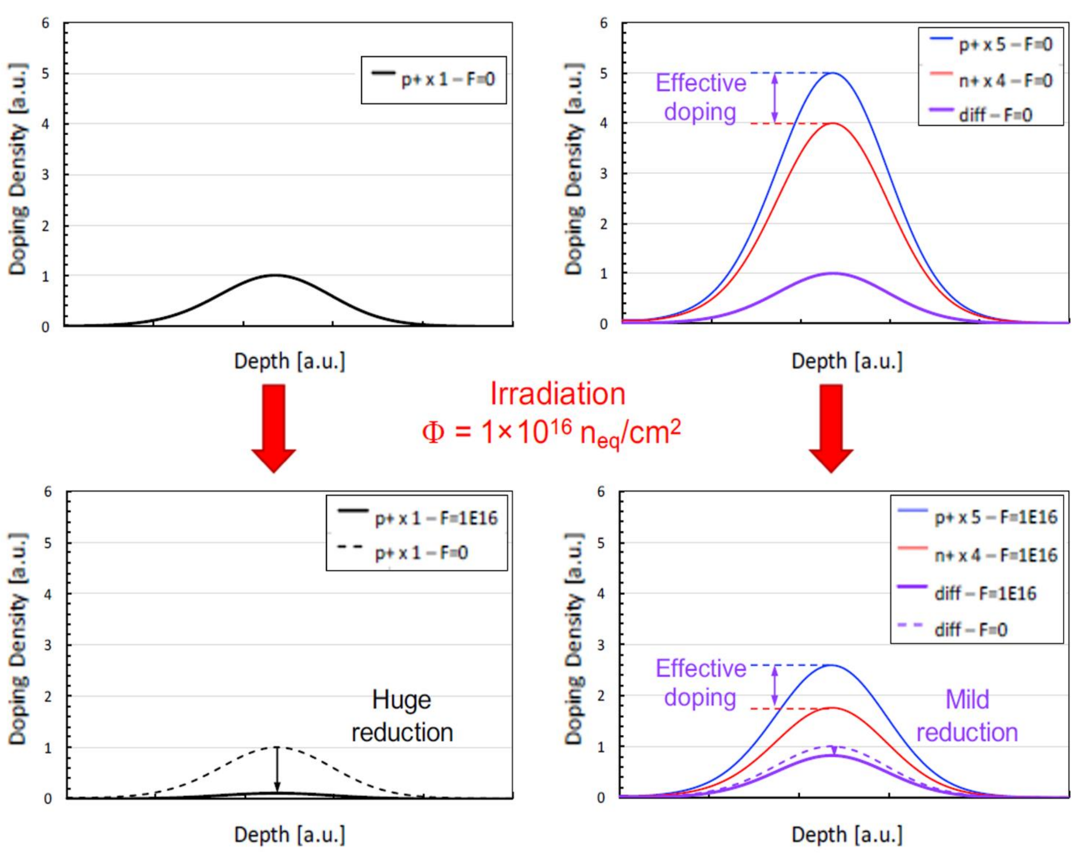
The 4DInSiDe (Innovative Silicon Detectors for particle tracking in 4Dimensions) project

- ✓ Developing the next generation of silicon detectors for 4D particle tracking in the future high energy physics experiments
  - able to deliver excellent time and position resolution - few tens of ps and μm, in harsh radiation environments, e.g. $\Phi \sim 1\times10^{17}$ n_{eq}/cm^2;
  - characterized by a *(i)* fully active detecting volume *(ii)* low material budget, and *(iii)* high radiation tolerance.
- ✓ Different areas of research have been identified, e.g. development, design, fabrication and test of radiation-hard devices
  - ad-hoc advanced Technology CAD (TCAD) modeling of Low-Gain Avalanche Diodes (LGAD) devices [1];
  - massive test campaign on specifically devised LGAD structures (UFSD2, UFSD3.2 and RSD1 productions by FBK foundry).

=> Validation of the development framework and evaluation of the impact of several design options => sensor design and optimization.

Extension of LGAD radiation hardness to fluences above 1×10^{15} n_{eq}/cm^2

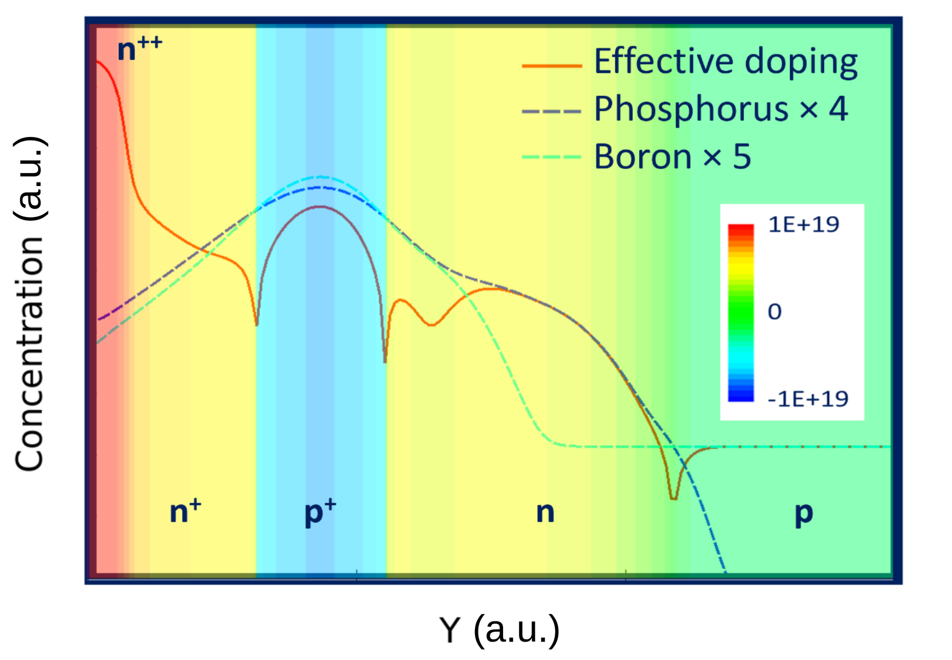
Acceptor removal limits the radiation resistance of LGAD-based sensors to about 10^{15} n_{eq}/cm^2. A gain implant based on doping compensation has the potentiality to extend the LGAD radiation resistance to much higher fluences [2]. Indeed, by using the interplay between radiation induced acceptor and donor removal, it is possible to keep a constant gain layer active doping density after irradiation.



Standard LGAD design | Compensated LGAD design

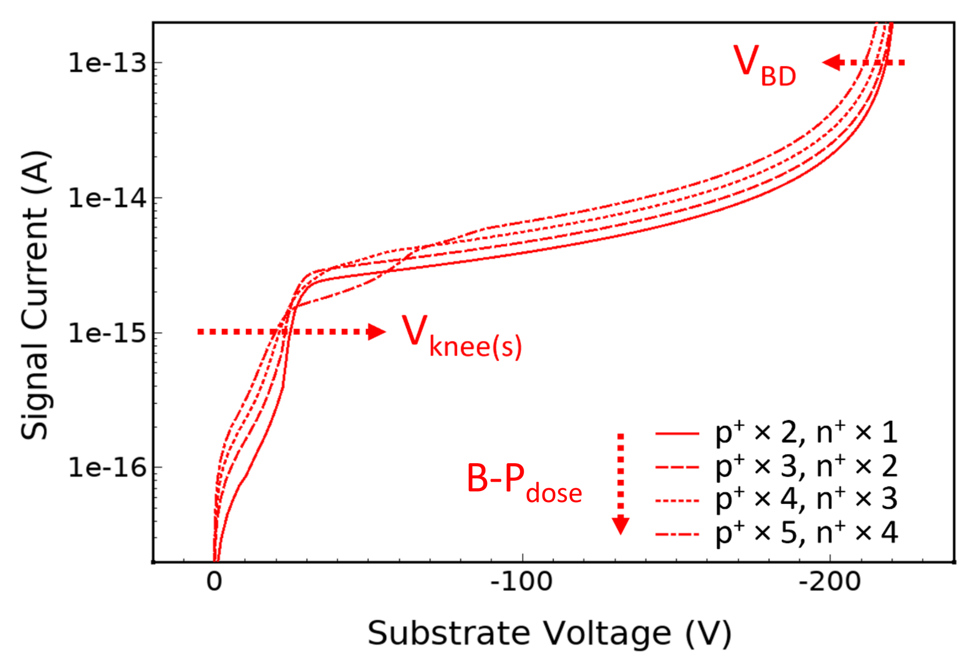
Process simulation of Boron (p^+) and Phosphorus (n^+) implantation and activation reveals the different shape of the two profiles (Silvaco TCAD) – e.g. higher tail of the n^+ implant with respect to the p^+ one.

Doping Profiles from Process Simulation



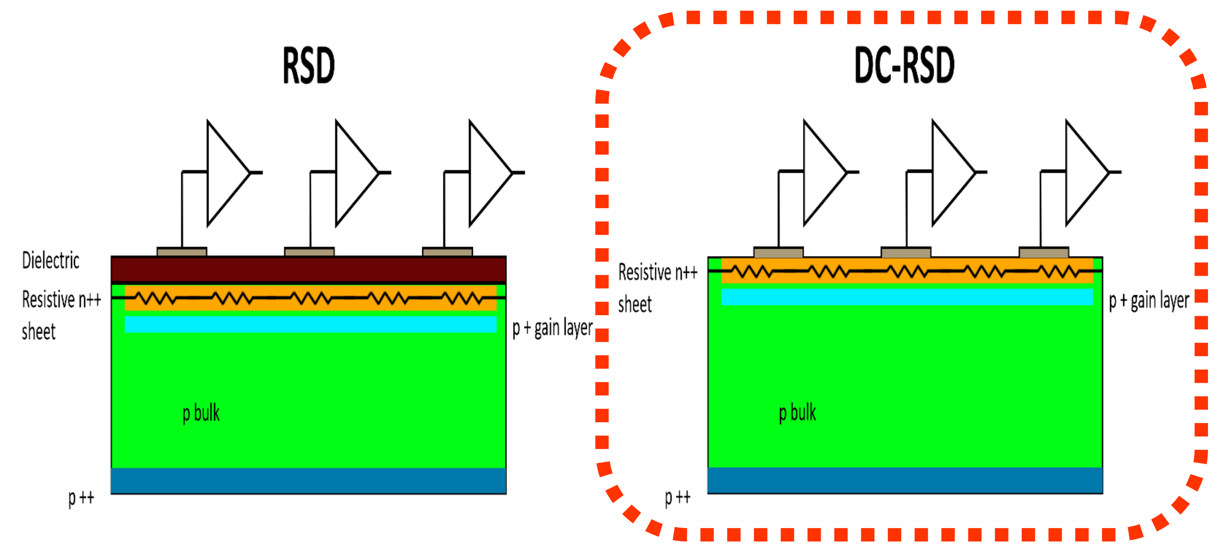
The simulation of the electrostatic behavior shows that even using different concentrations of Boron and Phosphorus, the compensated LGADs behave similarly to standard LGAD (Synopsys Sentaurus TCAD).

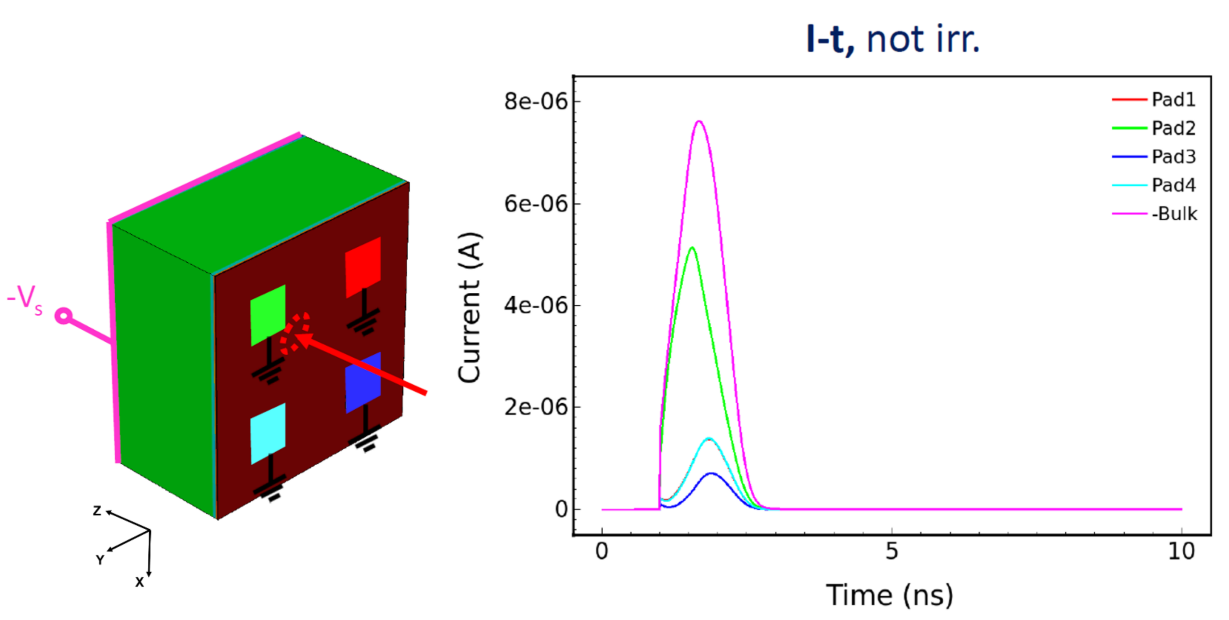
I-V from Device Simulation



A new design of resistive silicon detector: DC-RSD

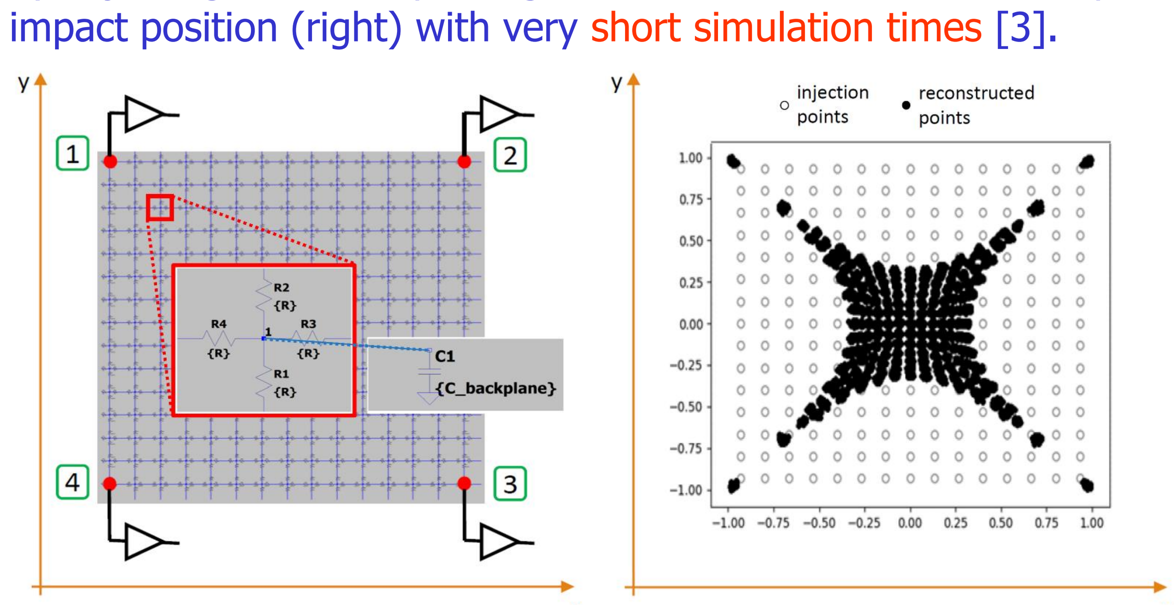
We propose a novel evolution of the Resistive Silicon Detector (RSD) design. By using a DC-coupled read-out, we eliminate uncontrolled signal spreading and position-dependent resolution. This allows also to overcome other known issues, e.g. the long tail-bipolar signals.

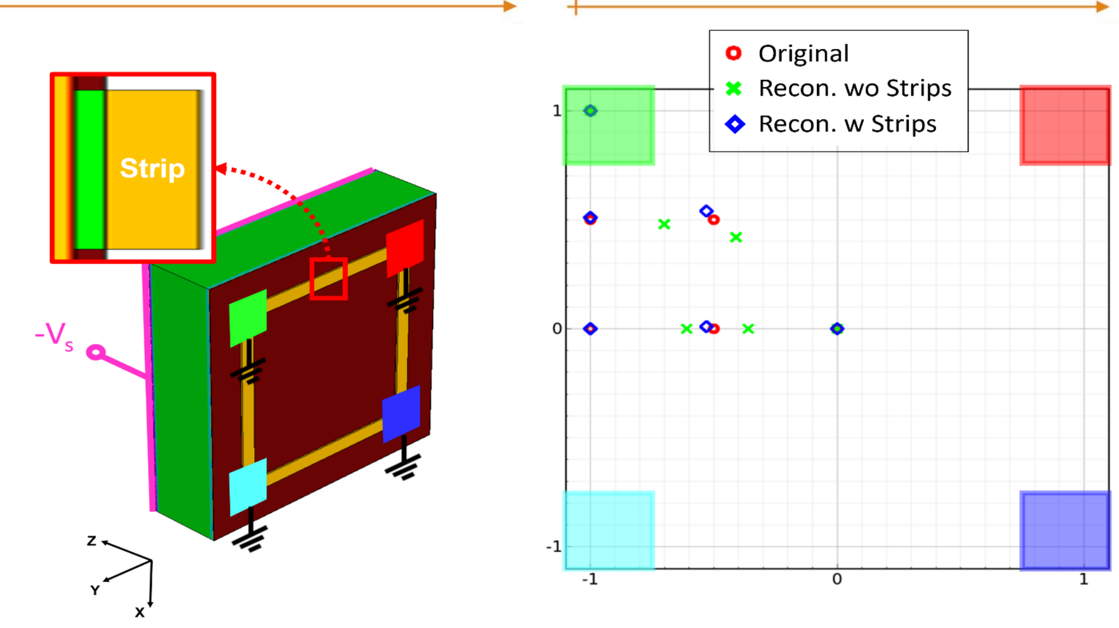




Step 2: full 3D TCAD simulation to characterize the device behavior in terms of response after the passage of a charged particle, e.g. a minimum ionizing heavy ion → the key features of the RSD' design, i.e. excellent timing and spatial resolutions (few tens of ps and μm), are maintained with the new paradigm of DC-RSDs.

Step 1: calculation of the output waveforms in Spice environment, accounting for an equivalent lumped-element electrical model (left), by injecting a test input signal → reconstruction of the particle impact position (right) with very short simulation times [3].





Optimization: the map of the reconstructed impact positions (right), obtained through the charge imbalance formula [3], shows a better accuracy of the position reconstruction in the case of DC-RSD flavor characterized by the strip-connected pads (left, blue cross markers - right), otherwise they tend to cluster in the center.

Conclusions

- ✓ Innovative paradigms for the design of LGAD sensors for 4D tracking have been proposed by the "4DInSiDe" collaboration:
  - Compensated LGAD as a new design of the gain layer implant;
  - DC-RSD as an evolution of the RSD design, i.e. DC read-out with low resistivity strip between collecting pads.
- ✓ The production of the compensated LGAD sensors is ongoing at the FBK foundry, while the first run of DC-RSDs is planned for Summer 2022.

References

[1] T. Croci *et al.*, TCAD simulations of non-irradiated and irradiated Low-Gain Avalanche Diodes and comparison with measurements, J. Instrum. 17, C01022 (2022).
[2] V. Sola *et al.*, A Compensated Design of the LGAD Gain Layer, Nucl. Inst. And Meth. In Phys. Res. A (submitted in April 2022).
[3] L. Menzio *et al.*, DC-coupled resistive silicon detectors for 4D tracking, Nucl. Inst. and Meth. in Phys. Res. A (submitted in April 2022).

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