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

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ABSTRACT

The MIUR PRIN 4DInSiDe collaboration aims at developing the next generation of 4D (i.e., position and time) silicon detectors based on Low-Gain Avalanche Diodes (LGAD) that guarantee to operate efficiently in the future high-energy physics experiments. To this purpose, different areas of research have been identified, involving the development, design, fabrication and test of radiation-hard devices. This research has been enabled thanks to ad-hoc advanced TCAD modelling of LGAD devices, accounting for both technological issues as well as physical aspects, e.g. different avalanche generation models and combined surface and bulk radiation damage effects modelling. In this contribution, it is reviewed the progress and the relevant detector developments obtained during the research activities in the framework of the 4DInSiDe project.

1. Introduction

In the future High Energy Physics (HEP) experiments, e.g. at the HL-LHC or the FCC, the number of pileup collisions will be extremely higher with respect to the present value at LHC. For this reason it will be a remarkable task to assign reconstructed particles to individual collisions. Present HEP experiments, such as CMS and ATLAS, are already building large timing layers ($\sim 20\,\mathrm{m}^2$) to be installed in their upgrades at HL-LHC to add to their experiment the capabilities of time tagging charged particles with a resolution of $\sim 40\,\mathrm{ps}$ per track. The development of detectors able to couple position resolution below $10\,\mu\mathrm{m}$ with a timing resolution of $\sim 10\,\mathrm{ps}$ will represent a key aspect in the design of future 4D silicon trackers in HEP experiments beyond the HL-LHC timescale.

Thanks to the introduction of controlled low gain and the optimization of the sensor design, the Low-Gain Avalanche Diode (LGAD) technology has become one of the choices for building 4D trackers. Indeed, it offers an intrinsic timing resolution of few tens of ps and, being a planar technology, it is accessible by many vendors. The major limit for its use is radiation damage manifested as initial acceptor removal, which causes the progressive loss of the signal multiplication capability.

The 4DInSiDe (Innovative Silicon Detectors for particle tracking in 4Dimensions) collaboration aims at developing the next generation of silicon sensors for trackers able to perform the concurrent measurements of the spatial and temporal coordinates with time and position resolutions of the orders of few tens of ps and μm, respectively, and in harsh radiation environments, e.g. $\Phi \sim 1 \cdot 10^{17}\,\mathrm{n_{eq}/cm^2}$. To this purpose, the design of innovative LGAD devices with the specific constrain of the radiation hardness has been tackled thanks to ad-hoc advanced Technology CAD (TCAD) modelling [1], accounting for both technological issues, e.g. sensitivity of the gain layer, as well as physical aspects such as different avalanche generation models and combined surface and bulk radiation damage effects modelling [2]. In this work it is reviewed the progress and the relevant detector developments obtained during the research activity in the framework of the 4DInSiDe project.

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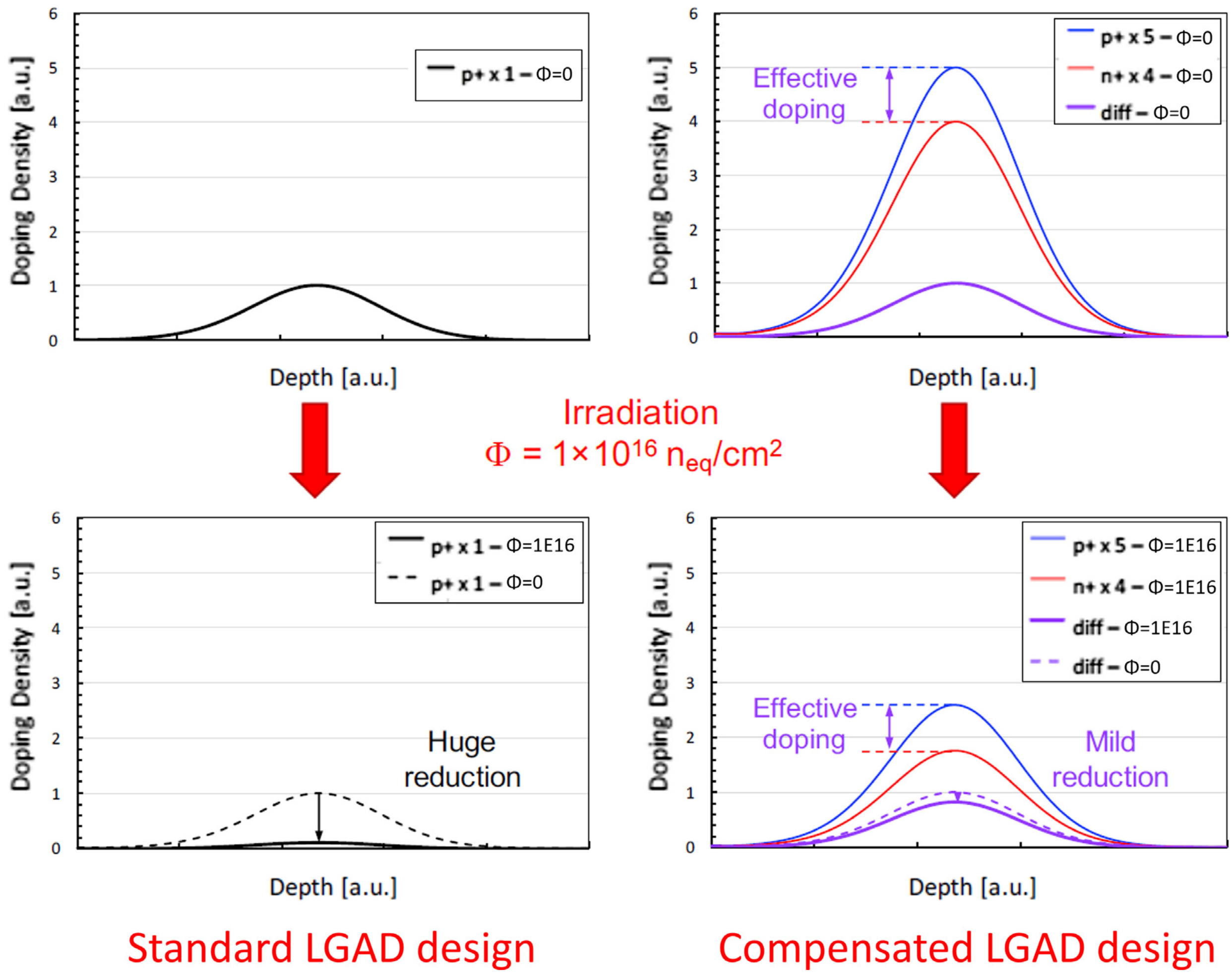

Fig. 1. Evolution with irradiation of a simulated gain layer profile (Gaussian) in standard (left) and compensated (right) LGAD, after a fluence of $1 \cdot 10^{16}\,n_{eq}/cm^2$. In the compensated design, four parts of an n^+-dopant are used to balance five parts of the p^+ one. Their difference (diff) results in an effective doping concentration similar to that of the standard LGAD before the irradiation, but in an almost unchanged one after the irradiation.

2. Extension of LGAD radiation hardness to fluences above $1 \cdot 10^{15}\,n_{eq}/cm^2$

Acceptor removal limits the radiation resistance of LGAD-based sensors to about $1 \cdot 10^{15}\,n_{eq}/cm^2$. Indeed, the LGADs lose their multiplication power and behave as standard sensors. In order to preserve internal signal multiplication to fluences above $1 \cdot 10^{15}\,n_{eq}/cm^2$, a new paradigm for the gain layer design is necessary.

To this purpose, a gain implant based on doping compensation has the potentiality to extend the LGAD radiation resistance to much higher fluences [3]. The gain layer in the standard LGAD design is obtained by implanting a certain dose of an acceptor material, typically Boron or Gallium, in the region below the n^{++} electrode. In our gain layer design, we propose a combination of a p^+-doped and an n^+-doped implant, that we called compensated LGAD design. As depicted in Fig. 1, the difference between acceptor and donor doping before the irradiation results in an effective concentration similar to that of the standard LGAD, and thus comparable gain values. Differently, the new design will be more tolerant to radiation, as both acceptor and donor atoms will experience removal by irradiation, but their difference will remain nearly constant, thus preserving the gain and hence the LGAD properties.

3. A new design of resistive silicon detector: DC-RSD

Resistive Silicon Detector (RSD) represents one of the emerging technologies for 4D tracking. It combines the excellent timing capabilities of LGAD with remarkable space resolution. The major peculiarity of the RSD paradigm is the use of a continuous n^+-resistive electrode and a continuous p^+-gain layer, thus avoiding segmentation that affects the fill factor. On the other hand, different drawbacks are linked to the nature of RSD paradigm, e.g. the bipolar behaviour of the signals, the baseline fluctuation, the uncontrolled signal spreading and the position-dependent resolution.

We propose a new design approach to resistive read-out sensors [4]. By eliminating the dielectric and using a DC-coupling to the electronics (Fig. 2 left), it is possible to cope with all these issues, while maintaining the advantage of 100% fill factor. Moreover, by simulating the passage of a charged particle, e.g. a minimum ionizing heavy ion, and by properly combining the signals read from the four pads, it has been proved that the accuracy of the reconstruction improves by more than a factor two if the read-out electrodes are connected with low-resistivity strips (Fig. 2 right).

4. Conclusions

Innovative paradigms for the design of LGAD sensors for 4D tracking have been proposed by the 4DInSiDe collaboration: compensated LGAD

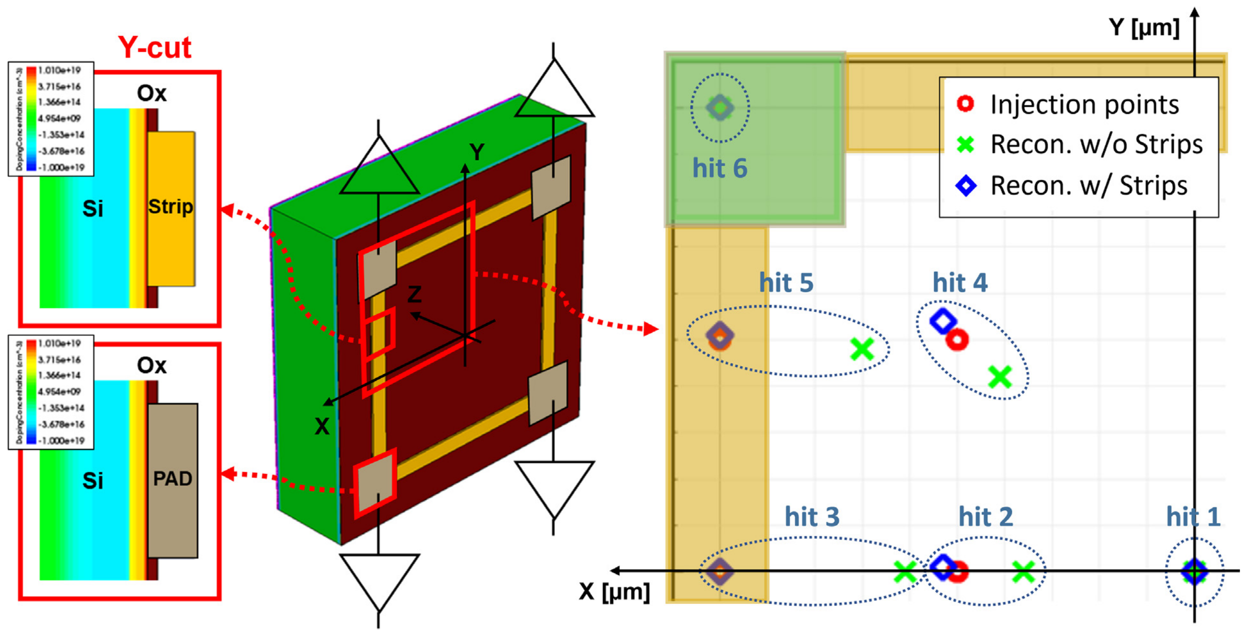

Fig. 2. Left side, layout of the simulated DC-RSD structure with strip-connected pads and cuts along the sensor depth (z-axis), which show the direct coupling of the resistive silicon layer to the read-out pads (grey) and the strips (orange). Right side, detail of the upper left quadrant of the map of the injected (red circular markers) and reconstructed (blue diamond and green cross markers) particle impact positions. Six injection points (hits) have been tested in the case of DC-RSD flavour without strips (w/o Strips) and with strips (w/ Strips).

and DC-RSD. The first is a new design of the gain layer implant that by combining p^{+} and n^{+} dopants has the potential to maintain a constant active doping density after irradiation, thus preserving the gain. The second is an evolution of RSD design that employs DC read-out with low resistivity strip between collecting pads. The first production of compensated LGAD sensors is currently in progress at the Fondazione Bruno Kessler (Trento, Italy), whereas a first batch of DC-RSD is planned for Summer 2022. An extensive test campaign has been foreseen on such structures, both not irradiated and irradiated ones, to confirm the feasibility of the design and to validate the selected design options.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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