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High-accuracy 4D particle trackers with resistive silicon detectors (AC-LGADs)

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Abstract: Future particle trackers will have to measure concurrently position and time with unprecedented accuracy, aiming at ∼5 µm and a few 10s ps resolution respectively. A promising good candidate for such a task are the resistive AC-LGADs, solid state silicon sensors of novel design, characterized by an internal moderate gain and an AC-coupled resistive read-out to achieve signal sharing among pads. The sensor design leads to a drastic reduction in the number of read-out channels, has an intrinsic 100% fill factor, and adapts easily to any read-out geometry. This report describes the design challenges, the signal formation and recent test results obtained with the first prototypes. A part is also dedicated to the reconstruction techniques that exploit the distributed nature of the signal, including machine learning. An outlook to a future development for optimized read-out electrodes and electronics is also presented.

Keywords: Particle tracking detectors (Solid-state detectors); Timing detectors; Solid state detectors; Electronic detector readout concepts (solid-state)

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2022 JINST 17 C03013

Contents

1 Introduction

Future accelerator designs call for trackers with extremely good (~5 μm) position and time (~10 ps) resolutions, very low material budget (less than 100 μm equivalent thickness per layer) and low power consumption (~0.1 W/cm^2). The suggested pixel size, of the order of 25 × 25 μm^2, is driven by the position resolution, not by the expected occupancy in the detector. Pixels of this size are technologically difficult to handle, and concurrent time measurement very challenging to achieve, especially with limited power budget.

When a particle induces a signal detectable in more than one pixel (signal sharing in presence of B field, or with floating electrodes), the position can be determined as an amplitude-weighted centroid of the involved pixels coordinates, leading to a position resolution that is typical smaller than the one obtainable with a single pixel read-out ($\sigma_x \ll \text{pitch}/\sqrt{12}$). The same σ_x can be obtained with larger pixels (more space available for the electronics).

Another way of achieving signal sharing among pads is the implementation of an AC-coupled resistive read-out, as implemented, for example, in the novel concept silicon sensors here described. They are based on the Low Gain Avalanche Diode (LGAD) technology, and achieve moderate signal multiplication and signal sharing among a few pads. The resistive AC-coupled LGADs (also called RSD, Resistive Silicon Detectors) have, by design, an 100% fill factor (ratio of particle-sensitive area of a sensor to total sensor area), enhanced timing performance and reduced material budget.

2 The Resistive AC-coupled Silicon Detectors (RSD)

The resistive AC-coupled LGADs (or RSD) are thin LGADs with the addition of a resistive n$^+$ layer and AC-coupled metal pads, whose shape and segmentation define the dimension of the matrix and the spatial resolution.

2022 JINST 17 C03013

The internal structure of an RSD is sketched in figure 1(A), where the key features of the device, the gain implant, the resistive n$^+$ electrode, and the AC-coupled read-out pads, are presented.

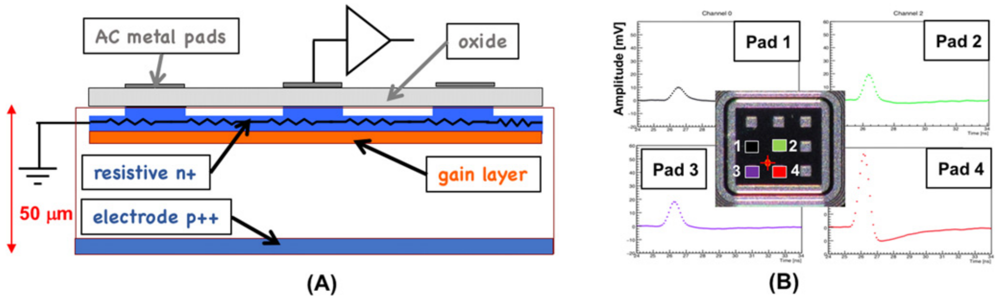

Figure 1. (A) Sketch of the internal structure of a resistive AC-coupled LGADs. (B) Amplitudes read out in four adjacent pads of an RSD matrix, when the laser is shot at the position indicated by the red spot.

The working principle of this device is the following: a charged particle traversing the sensor bulk induce a signal on the n$^+$ electrode, which spreads and generates signals on the AC read-out pads (fast process); the charges flow then to ground with a time constant that depends on the read-out input resistance, the n$^+$ sheet resistance, and the system capacitance. The pads surrounding the particle hit see a modified version of the original signal. During the propagation on the n$^+$ resistive surface, the signal becomes smaller, wider and delayed. Figure 1(B) shows how the signal, generated by a laser beam shot on the red spot, is shared among the read-out pads in a 50-micron thick AC-LGAD prototype. Each of the four pads sees a fast signal, with an amplitude that depends on its distance from the hit. The distributed nature of the signal in resistive AC-LGADs can be exploited to improve the position resolution of the reconstructed coordinates.

3 Resistive AC-LGAD prototypes: sensors characterization

The first prototypes of RSD, exploring the interplay between n$^+$ resistivity and dielectric thickness, have been produced by Fondazione Bruno Kessler (FBK) in 2019 [1].

Small pad matrices (3×3 or 4×4) with slightly different resistivity and dielectric thickness, and with different pitch and metal pad dimensions, have been tested with a picosecond laser TCT set-up (laser spot ~10 µm), in order to study the signal formation and to measure the performance. The data have been acquired shooting the laser in different locations within a grid on the surface of the device, recording the signals seen by four adjacent pads (only four pads were read out). The same data have been used to reconstruct the position and the time of the hit (laser shot). A few sensors have been also tested on a beam of 120 GeV/c protons, at Fermilab.

The resistive AC-LGADs inherit in first approximation the timing performances of the standard thin LGADs. The time resolution measured in the laboratory with the laser setup (jitter term), and at beam test, is very good and in line with the results obtained with LGADs of comparable gain. The time resolution, measured with protons, for two matrices with a 200 µm–pitch, 100 or 190 µm metal pad size, is $\sigma_t = 44$ ps and $\sigma_t = 42$ ps respectively, in line with the expectations (gain ~ 15) [2].

For what concerns the radiation resistance of that type of sensors, the radiation induced effects are expected to be similar to that of others LGAD devices: (i) decrease of charge collection efficiency due to trapping, (ii) doping creation/removal, (iii) increase of leakage current and shot noise, (iv) progressive de-activation of the gain layer. These devices will probably work well up to fluences of about 1–2 × 10^{15} n_{eq}/cm^2. Several RSD1 devices have been exposed to neutron fluences in the 4 × 10^{14} to 3 × 10^{15} n_{eq}/cm^2 range, and are currently under studies, to confirm the behavior of the irradiated bulk and gain layer, and to study the effect of enhanced oxide charges to the AC coupling mechanism.

3.1 Measurement of the position resolution

Three different analytic reconstruction methods, described in details in [2], have been studied for the measurement of the hits coordinates:

- MF (Main Formula) method. It allows to compute how the signal is shared among pads, assuming the sensor resistive sheet behaves as a current divider. The fraction S_i of the signal seen by one of the four read-out pad is given by:

$$S_i(\alpha_i, r_i) \approx \frac{\frac{\alpha_i}{\ln(r_i)}}{\sum_1^n \frac{\alpha_i}{\ln(r_i)}}, \tag{3.1}$$

  where r_i is the distance from the hit point to the pad i metal edge, and α_i is the pad angle of view. The hit position is given by the x-y coordinates that minimize the difference between measured and calculated amplitudes.

- LA (Linear Attenuation model) method. Conceptually similar to the MF method, it assumes that the fraction S_i decreases linearly with the distance hit-metal pad, and increases linearly with the angle of view (attenuation factor tuned with data)

- DPC (Discretize Positioning Circuit) method. In this case the position of the hit is determined by exploiting the charge imbalance between pairs of pads along the x and y direction (the maximum one-side charge imbalance needs to be measured experimentally).

Figure 2 shows the position resolution obtained analysing the laser setup data, using the three reconstruction algorithms above mentioned, for several devices characterized by different combination of metal pad-pitch sizes. The labels close to the data points (i.e. **100–200**) indicate the metal-pad size (**100**) and the pitch value (**200**) of the tested devices. The position resolution is shown as a function of the difference *pitch - metal*. Smaller pitch-metal distances yield a better spatial resolution. The three reconstruction models lead to similar results up to pitch-metal values of about 200 µm. The poorer resolution of the MF model indicates that the computation of the effective impedances deviates from reality over long distances [2]. Resolutions of less that 5 µm can be achieved with 200 µm-pitch sensor.

2022 JINST 17 C03013

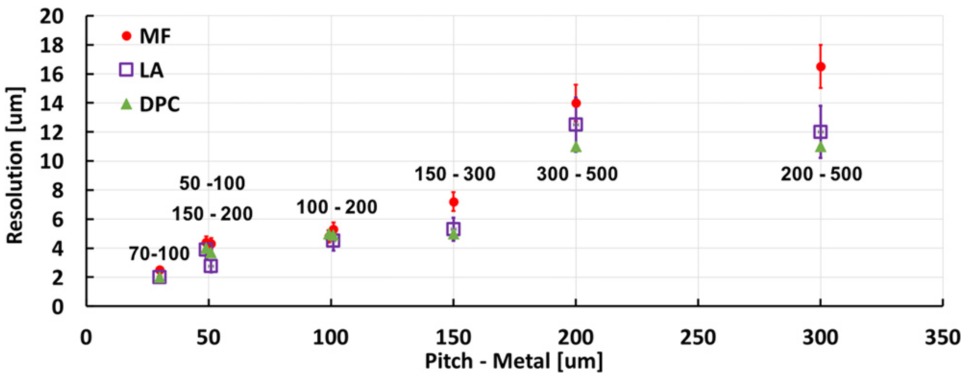

Figure 2. Position resolution of several RSD devices, obtained with laser data, using three different reconstruction algorithms, as a function of the distance between electrodes (pitch-metal size).

The lesson learned from the analysis of the signal behavior in RSD1 prototypes is: (i) if the sharing involves too many pads, some signals are too small (undetected) and the position reconstruction gets biased, (ii) the sharing should involve a fixed number of pads, over the whole surface of the device, in order to have an uniform response and performance, (iii) when the hit falls on the metal pad, it generates a signal only in that pad (no sharing, resolution is spoiled).

3.2 Machine learning applied to RSD

In resistive AC-LGADs, each of the signals read out in neighboring pads carries a lot of information (amplitude, derivative, width) that can be exploited to perform very accurate position and time measurements. Analytic laws used to predict the sharing between pads are not able to capture all this information, especially in devices with large geometries where attenuation laws are more difficult to be derived. Machine Learning algorithms are well suited to this type of task.

A multi-output regressor algorithm, trained with a combination of simulated and real data (laser setup data), has been implemented, leading to very promizing results. A spatial resolution of 2 µm for a sensor with a 100 µm pitch has been obtained. So far, only the signal amplitudes have been used as inputs, leaving room to improvements. In general this algorithm is able to replicate the performance obtained with the best of the analytic reconstruction methods [3].

4 Optimization of the RSD design

A second prototype production of resistive AC-LGADs from FBK (RSD2) has been mostly devoted to the study of the metal pad shape and its impact on the signal formation, and to the exploration/optimization of some parameters defining gain and signal sharing.

Several types of electrodes have been designed in order to obtain devices characterized by a signal sharing among a predetermined number of pixels (figure 3). The production has been completed in June 21 and the initial electrical tests conducted by the vendor are successful. Detailed laboratory tests (laser setup) to measure possible improvements to the position resolution and to the uniformity of the device, are currently ongoing.

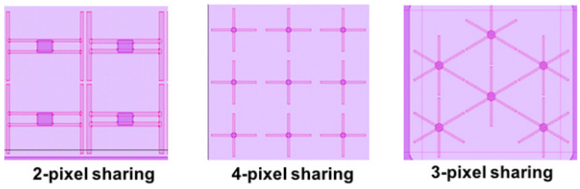

Figure 3. Examples of electrode shapes in RSD2.

5 Outlook

As an outlook for the future, figure 4 shows a possible signal processing line for further improvements towards high accuracy 4D trackers. To exploit the wealth of information carried by shared signals in resistive AC-LGADs, we envisage the use of front-end electronics able to sample the signals in multiple points in time (for example every 300–500 ps) so that many of its features — amplitude, area, width, slope of rising and falling edges, time of arrival — can be determined. Two points on the leading and trailing edges should be enough to achieve the goal. The samples are then sent to a data concentrator that runs a ML reconstruction code, a multi-channel time-varying regression task that uses many inputs to determine two outputs (position and time).

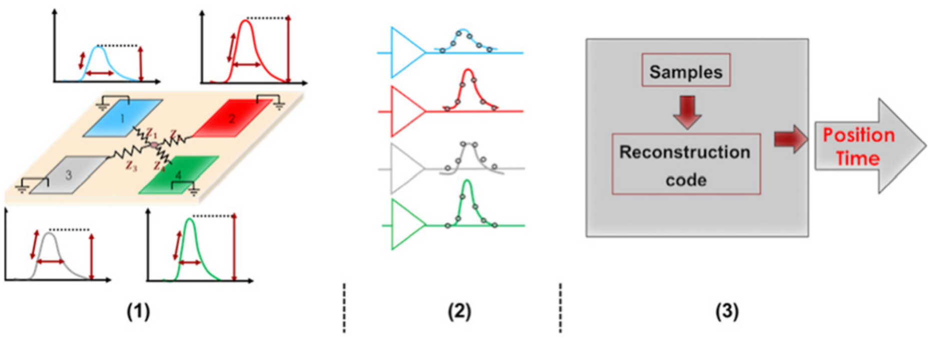

Figure 4. Conceptual design of read-out processing line: (1) RSD sensor providing signals sharing for every traversing MIP; (2) multiple sampling front-end (extraction of amplitude, ToA, ToT); (3) multi-inputs regression ML algorithm that outputs position and time measurements.

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2022 JINST 17 C03013

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