Abstract

This paper presents the principles of operation of Resistive AC-Coupled Silicon Detectors (RSD) and the results of the first combined laser - beam test analysis. RSDs are a new type of n-in-p silicon sensor based on the LGAD technology, where the n⁺ electrode has been designed to be resistive, and the read-out is obtained via AC-coupling. The truly innovative feature of RSD is the fact that the signal from an impinging particle is visible on multiple pads. In RSD, signal sharing is generated internally and it happens equally in both directions. It is obtained without floating electrodes or the presence of an external magnetic field. Careful tuning of the oxide thickness and the n⁺ doping profile is at the basis of the successful functioning of this design. Several RSD matrices with different pad-pitch geometries have been
extensively tested with a laser set-up in the Laboratory for Innovative Silicon Sensors in Torino, while beam test data have been obtained at the Fermilab Test Beam Facility with a 120 GeV/c proton beam with a smaller selection of devices. The resulting spatial resolution ranges between 2.5 µm for 70-100 pad-pitch geometry and 17 µm with 200-500 matrices, a factor of 10 better than what is achievable in binary read-out (bin size/√12). Beam test data show a timing resolution of ∼ 40 ps for 200-µm pitch devices, in line with the best performances of LGAD sensors.

Keywords: 4D tracking, AC-coupled detectors, LGAD

1. Introduction

AC-Coupled Low Gain Avalanche Diodes (AC-LGADs) are a new generation of silicon devices optimized for high-precision 4D tracking and conceived for experiments at future colliders. They are n-in-p sensors based on the Low-Gain Avalanche Diode (LGAD) technology with two additional key features: the AC-coupling of the read-out, occurring through a dielectric layer, and a continuous resistive n+ electrode. Given the presence of the resistive n+ layer, AC-LGADs are called Resistive Silicon Detectors (RSD). RSD devices are thus provided with one continuous gain layer and the readout segmentation is obtained simply by the position of the AC pads; therefore, this design allows reaching 100% fill-factor.

![Figure 1: Cross-section of RSDs internal structure: their properties are based on the combination of a resistive n+ layer and a dielectric oxide, allowing a local AC-coupling.](image)

The remarkable feature of the AC-LGAD design is that it leads naturally to charge sharing among pads. Internal signal sharing, in combination with internal gain, changes everything about high precision tracking: the position resolution achievable combining the signals from several pads (∼ 5 µm
with 200-µm pitch) cannot be matched by any other design. With RSD, instead of focusing on how to design the smallest possible pixel, the design focuses on how to maximize the uniformity of charge sharing and to find the right balance between signal sharing, gain, noise, precision, electronics, and reconstruction.

The first RSD production [3, 4] has been manufactured in 2019 by the Fondazione Bruno Kessler. The batch includes 15 wafers, 12 float-zone and 3 epitaxial, with varying \( n^+ \), gain and p-stop doping profiles, and different oxide thicknesses. Each wafer contains several devices with different geometries; the ones used for the measurements presented in this paper are square matrix sensors with a varying number of pads, pitch and pad size.

2. RSD signal properties

Signal formation in RSDs happens in three phases [2]. (i) In the first one, the drifting e/h pairs produce a direct charge induction on the \( n^+ \) electrode, similar to a standard LGAD, that can be described by Ramo’s law; there is no direct signal induction on the metal AC pads. (ii) The signal spreads laterally along the \( n^+ \) layer, which behaves like an RC transmission line, where \( R \) is the \( n^+ \) sheet resistance and \( C \) depends upon the bulk thickness and the AC metal pad capacitance. The AC pads act as pick-up electrodes and record a signal, smaller and delayed as the distance from the metal pad to the impinging point increases. This second phase generates the first lobe of the signal, identical to the one created in an equivalent DC LGAD, as shown in figure 2.

![Figure 2](image_url)

**Figure 2:** A typical signal generated by an RSD device, characterized by a first fast negative lobe, identical to the signal of an equivalent DC LGAD, and a slow positive lobe by which the AC pad discharges.
(iii) In the last step, the AC pads discharge, generating the second lobe of the signal, with opposite polarity with respect to the first one. The shape of this lobe depends on the read-out $RC$ time constant: systems with a small $RC$ will have signals with a larger and shorter positive lobe since they need to discharge the same amount of charge in a shorter time. The value of the $RC$ time constant affects also the first lobe: if the $RC$ is too short, the first lobe will be smaller due to ballistic deficit.

![Figure 3](image.jpg)

Figure 3: Sketch of the three phases of RSD signals formation (A); signal sharing phenomenon (B): four AC pads see a signal for a hit position corresponding to the red point on the RSD picture.

Figure 3 in (A) shows a sketch describing the three phases of signal formation, while in (B) the signals seen on 4 pads for a laser signal shot at the red position.

### 3. RSD Reconstruction Models

Extensive laser studies have been performed in the Laboratory for Innovative Silicon Sensors in Torino with several RSD matrices, with varying pitch and pad size. The main objectives of these measurements were the study of the signal formation and the measurement of the spatial and temporal resolutions as a function of the RSD pitch and pad size.
3.1. RSD Master Formulas: Logarithmic Attenuation Model

In RSD, a hit generates signals on multiple pads. This can be explained by comparing an RSD to a current divider: in a current divider, the current in a given branch is:

\[ I_i = \frac{1}{\sum_{1}^{n} \frac{1}{Z_i}}, \tag{1} \]

where \( I_i \) is the current in the branch \( i \) and \( Z_i \) the impedance. In an RSD, the situation is very similar, as represented in figure 4 (left): the signal is shared among the pads depending on the value of the resistance of the paths between the hit point and each of the pads. The value of the resistance \( Z_i \) in RSD does not simply scale with distance: as the signal travels from the hit point to the pad, it spread over a larger area. It follows that the impedance \( Z \) seen by a signal does not increase linearly with distance (figure 4 right).

Figure 4: Sketch of an RSD representing the impedances a signal sees while propagating.

The impedance per unit distance decreases as the increase of the arc of the circle given by the angle of view \( \alpha \) at a certain distance \( r \) from the hit position:

\[ Z \propto \frac{1}{\alpha} \frac{1}{2\pi r}. \tag{2} \]

Therefore, the expression for the impedance seen by a signal propagating up to a distance \( d \) is:

\[ Z \propto \frac{1}{\alpha} \int_{1}^{d} \frac{1}{2\pi r} = \frac{ln(d)}{\alpha}. \tag{3} \]

Combining equation (1) with equation (3), it is possible to calculate how a signal is shared among pads:

\[ F_i(\alpha_i, d_i) = \frac{\alpha_i}{\sum_{i}^{n} \frac{\alpha_i}{ln(d_i)}}, \tag{4} \]
where $F_i$ is the fraction of the total signal seen on the pad $i$, $d_i$ the distance from the hit point to the pad $i$ metal edge, and $\alpha$ the pad $i$ angle of view. Remarkably, this formula predicts without any free parameter how a signal is shared among pads for every RSD geometry, $n^+$ resistivity, and dielectric thickness.

This formulation allows to highlight some properties of signals in RSDs:

- the signal seen by a pad depends on how many and how close the other pads are,
- the number of pads that record a signal depends on the hit location
- if the hit is located on a metal pad, the signal is almost completely absorbed by a single pad since the impedance to reach that pad is zero,
- a floating pad does not contribute to charge sharing, as the resistance to ground is infinite,
- the sum of all the recorded signals is constant.

Since the $n^+$ layer is resistive, there is a delay between the hit time and when the signal is formed on the pad. This delay is proportional to the value of the resistance, evaluated by equation (3), and to the value of the system capacitance. Equation (5) defines the expression for the time of a signal generated by a particle impinging at a distance $d$ with an angle of view $\alpha$:

$$t(d, \alpha) = t_0 + \gamma \frac{\log(d)}{\alpha},$$

where $t(d, \alpha)$ is the time of the signal on the pad, $t_0$ is the hit time, and $\gamma$ is the delay factor that can be extracted from experimental data.

We call equations (4) and (5) the RSD Master Formulas (MFs): they allow to calculate for all the pads nearby a hit the fraction of the signal seen and its delay.

3.2. Linear Attenuation Model

In order to assess the validity of the MFs, we also developed a second model. This model, the linear attenuation model (LA), assumes that the signal on a pad decreases linearly with the distance from the hit point and
increases linearly with the angle of view [7]. In the LA model, the fraction of the total signal seen by a pad is given by:

\[ F_i(d_i, \alpha_i) = \frac{[1 - \beta * d_i] \cdot \alpha_i}{\sum_i [1 - \beta * d_i] \cdot \alpha_i}, \tag{6} \]

where \( d_i \) is the distance from the pad metal edge, \( \alpha_i \) the angle of view, and \( \beta \) is the attenuation factor. In the LA model, there is a tunable parameter, \( \beta \), that is determined from data. The LA model equation for the time delay also has a linear dependence on the hit distance:

\[ t(d) = t_0 + \zeta * d, \tag{7} \]

where \( \zeta \) is the delay parameter for this model.

In the studies presented in this paper, the LA model will be tuned for each geometry to obtain the best possible RSD performances and it will be used to benchmark the MF model.

Figure 5 illustrate an example of this comparison. For the 100-200 geometry, the plot shows the fraction of the amplitude seen in a pad as a function of its distance from the hit position as predicted by the MF (in blue) and by the LA model (in red). Remarkably, the MF and the LA-tuned predictions are very similar.
3.3. Position reconstruction

The RSD MF and the LA models allow predicting how a signal is shared among several pads considering the distance of the hit point to each of the pads. In this way, a point on the RSD surface is uniquely identified by the relative amplitudes seen by the nearby pads. Exploiting this remarkable property, the location of the hit point can be identified very accurately using the signals measured on several pads. Figure 6 shows an example of the amplitude seen in a given pad as a function of the hit position according to the RSD master formulas.

![Amplitude map for one AC pad calculated with the RSD Master formulas.](image)

Figure 6: Amplitude map for one AC pad calculated with the RSD Master formulas.

The reconstruction of the impinging particle position follows these steps:

- The total signal $A_{\text{tot}}$ amplitude is calculated as the sum of the amplitudes $A[i]$ seen in all active pads, $A_{\text{tot}} = \sum_i A[i]$;
- The fraction of the total amplitude seen in each pad is calculated as $(A[i]/A_{\text{tot}})_{\text{Meas}}$;
- This set of fractions is compared with the predicted fraction (using either MF or LA) in each x-y point. The hit position is the bin that minimizes the following chi-square:

$$
\chi^2 = \sum_i \left[ \left( \frac{A[i]}{A_{\text{tot}}} \right)_{\text{Meas}} - \left( \frac{A[i]}{A_{\text{tot}}} \right)_{\text{Calc}} \right]^2 ;
$$

(8)
The accuracy can be increased by performing a local interpolation around the minimum.

This iterative procedure locates the particle impinging point, according to the MF or LA model, as the position of the bin that best reproduces the measured share of amplitudes among pads.

3.4. Design optimization

As seen in the previous paragraph, signal sharing is germane to the RSD design, and this property is used in the location of the hit position. However, how the signal is shared depends upon many factors such as the hit position, the RSD geometry (metal and pitch size), and the pad geometrical distribution. All these factors influence the spatial resolution.

For any given geometry, it is possible to identify how many pads see a signal. Figure 7 (left) shows an example of these calculation for a $3 \times 3$ 100-200 matrix. The orange and yellow areas indicate the locations where hits can be reconstructed with three or four pads respectively: information from at least three pads allows to uniquely identify the hit position and reach a very good spatial resolution. However, this geometry shows two shortcomings:

- When the pads are positioned at the corner of a square, as they are in this example, the reconstruction with three pads is less accurate since the hit tends to be reconstructed closer to the three active pads than it should.
In the green area, only two pads record a signal and it is no longer possible to determine the hit position.

In order to obtain a detector with a very good and uniform spatial resolution, it is important to maximize the areas where the reconstruction is more precise. To this end, it is possible to optimize the disposition and shape of the metal pads. One such study is shown in figure 7 (right): here, the AC pads are placed in a triangular geometry. This geometry has two advantages: the distance between every two pads is the same, and the optimum precision is obtained with only 3 pads.

3.4.1. Design of the metal pad

Both designs indicate that there is no signal sharing when the particle hits a metal pad. This property was measured with the laser by shooting the signal in a narrow slit without metal placed inside the metal pad. The measurements also showed that signal sharing happens when the hit is within $\sim 10 - 20 \mu m$ from the metal edge. With this information, it is possible to redesign the metal pad to always have signal sharing.

Figure 8: Present metal pads design in a $3 \times 3$ RSD matrix (1) and a possible optimization of the pads shape and disposition (2) considering there is no signal sharing when particles hit metal pads.

However, the new design should include two important aspects:

- The angle of view in equation (4) should not be too small
- The capacitance of the metal pad should be large enough to prevent ballistic deficit.

Combining these aspects, figure 8 proposes an optimization of the metal pad disposition.
4. Laser studies

The properties of the RSD sensors have been studied using the Transient Current Technique (TCT), which exploits the signal induced in the sensor by a laser. The TCT employed in this study, manufactured by Particulars, is equipped with an IR picosecond laser, with a minimum spot size of \( \sim 10 \mu m \), and with a micro-metrical x-y moving stage. The intensity of the laser was set to reproduce the amount of ionization typical of a MIP in a sensor of the same active thickness, about 0.5 fC.

![Figure 9: One of the sensors employed in the TCT set-up. The red dots represents the locations of the laser shots.](image)

Several RSD matrices, with different combinations of pitch and pad sizes, have been characterized with the TCT setup. Each sensor has been tested at bias voltages corresponding to values of gain between 8 and 25. For each matrix, the laser is shot in multiple points in the area among the pads, as shown in figure 9. The four AC pads closest to the hit points have been read out simultaneously and their signals recorded using a 40Gs/s, 4 GHz BW oscilloscope. In every position, \( \sim 500 \) waveforms are acquired \[8, 9, 11\]. For each laser shot, the hit position is reconstructed using the method described in section 3.3. The spatial resolution at each position is evaluated as the sigma of the difference between the laser known coordinates and the reconstructed position \((x, y)_{\text{reco}} - (x, y)_{\text{laser}}\). Given that only four pads are read-out, only positions in which the whole signal is completely contained in these pads are considered. These positions are marked by the blue square in figure 9. Points between two pads, like the ones in the green and orange squares marked on the left side of figure 10 are poorly reconstructed.
For these areas, the 4 read-out pads miss part of the information and two more pads would be needed for a complete reconstruction. For this reason, as shown in the right plot of figure 10, the $(x, y)_{\text{reco}} - (x, y)_{\text{laser}}$ distributions for these positions are wider and shifted.

Signals shot inside the metal opening of the pads suffer from even greater uncertainties, as the only information is the amplitude recorded by the only active pad. For this type of events, the spatial resolution corresponds to the case of binary read-out, $\text{pad size}/\sqrt{12}$.

4.1. Study of signal sharing among pads

TCT studies have also been used to verify the predictions of equation (4). Figure 11 (a) displays the positions and the numbers of the laser runs included in the analysis for the 100-200 pad-pitch geometry. For each of these runs, the measured and predicted amplitudes are compared in the plots (c)-(f) of figure 11. On these 4 plots, the black points represent the calculated signals while the red points the measured values.

As an example, we consider run #6, highlighted with an orange circle in the figure. For this run, the amplitudes in both pads 1 and 3 are $\sim 25 \text{ mV}$, as the laser is shot halfway between them, while pads 2 and 4 register smaller signals, $\sim 10 - 15 \text{ mV}$, since they are farther from the run position. In contrast, in run #10, pad 2 sees most of the amplitude as the laser is shot as close as possible to its metal pad.
Additionally, in figure 11 (b), the sum of the amplitude of the signals from the four read-out pads is plotted as a function of run number. This plot shows two interesting features: (i) the predicted and measured points are in agreement and (ii) the signal total amplitude is constant, regardless of the run position.

Overall, the RSD Master formula shows a very powerful predicting power, allowing to understand the dynamic of signal sharing.

Figure 11: Map with positions of the laser runs for the 100-200 pad-pitch geometry (a); sum of the amplitude of the signals from the four read-out pad for each run (b). Plots (c)-(f) show the amplitude seen by each AC pad as a function of the laser run number. Black points represent the predicted values obtained with the master formula, while the red ones are the measured amplitudes.

4.2. Spatial resolution

Using the method explained in section 3.3, the spatial resolution as a function of the interpad distance has been computed for many geometries for both the MF and LA models. The results are shown in figure 12. Several features are shown in the figure:
Figure 12: Spatial resolution for different RSD pad-pitch geometries as a function of the interpad distance obtained by reconstructing hit positions with both the MF (red points) and LA (purple squares) models.

- The spatial resolution is extremely good, less than 5 \( \mu m \) in both \( x \) and \( y \) direction for interpad distances up to 100-150 \( \mu m \).

- Smaller interpad distances yield better spatial resolutions.

- The MF and LA-tuned models yield similar results up to interpad of about 200 \( \mu m \).

- For interpad distances above 200 \( \mu m \), the LA-tuned model yield better resolution. This discrepancy has been studied in detail, and the result confirmed. One possible explanation of this fact is that the MF assumes that the signal propagates on a cone: for larger distances, this fact might not be true anymore, leading to a degradation of its predictive power.

The results of the LA model shown in figure 12 have been obtained after a careful tuning of the parameter \( \beta \) (equation (6)). For each measured pad-pitch geometry, the attenuation factor has been chosen as the one that minimizes the spatial resolution. The \( \beta \) parameters used in this analysis are presented in figure 13 as a function of the interpad distance. The optimized \( \beta \) values have a logarithmic dependence on the quantity \( \text{pitch - metal} \): this fact demonstrates that the attenuation with distance is logarithmic, as implemented in the MF.
The dependence of the spatial resolution upon the signal amplitude has been studied for several pad-pitch geometries and it is shown in figure 14. As expected, the resolution improves with amplitude, and the improvement is much stronger in larger geometries. For small geometries, the resolution remains almost constant for a large range of amplitudes, showing that for these geometries even at low gain the performances are excellent.

Figure 13: Optimum value of the attenuation factor $\beta$ as a function of the interpad distance.

Figure 14: Spatial resolution represented as a function of signals amplitude for three pad-pitch geometries: 50-100, 100-200 and 200-500.
One interesting point is to understand why smaller geometries perform better. In smaller geometries, the signal seen on a pad changes more rapidly with position than in larger structures. This fact limits the position smear introduced by the electronic noise: a 3 mV noise in the geometry 50-100 corresponds to a position smear of about 3 µm while in 200-500 corresponds to a smear of about 15 µm. Therefore, in the absence of electronic noise, all geometries will have the same spatial resolution, while for any non-zero noise values, smaller structures are bound to have better performances [10].

4.3. Temporal resolution

Once the hit position has been reconstructed, the time of the hit is evaluated in a 2-step process. First, the time measured in each pad is corrected by the propagation delay from the hit position to the pad metal edge using equation (5). The value of the γ parameter of equation (5) is tuned to obtain the best resolution. The left part of Figure 15 shows how the temporal resolution of a single pad changes as a function of the delay parameter for 3 different geometries from the same wafer. As the right side of Figure 15 shows, the optimum delay parameter depends linearly on the ratio \( (\frac{\text{metal}}{\text{pitch}})^2 \). This fact is an indication that the geometrical properties of a given design, and not just the \( n^+ \) resistivity, play a role in the delay.

![Figure 15: Left side: Single pad temporal resolution as a function of the delay parameter for three pad-pitch geometries: 50-100, 70-100 and 200-500. Right side: Optimum delay parameter as a function of the ratio (metal/pitch)^2.](image)

Then, the time of the event is defined as the amplitude-weighted time average of the active read-out pads. The temporal resolution is obtained as the sigma of the \( t_{\text{trigger}} - t_{\text{reco}} \) distribution. An example of these steps is shown in figure 16: the left side shows the resolution of each of the 4 active pads for the 100-200 geometry, while on the right the combined resolution.
The resolution of the single channel is about $\sim 45$ ps, while the combination of the 4 channels yields to about $\sim 22$ ps, as expected from a situation without correlated noise ($22 \text{ps} \sim 45/\sqrt{4}$).

Figure 16: On the left: single-channel timing resolution for the four read-out pads for laser data. On the right: total timing resolution obtained combining the four pads timestamps.

The temporal resolution as a function of the interpad area is shown in figure 17. The resolution increases up to $\text{pitch} - \text{pad} = 100$. For interpad larger than 100 $\mu\text{m}$ the trend flattens, stabilizing around $25 - 30$ ps.

Figure 17: Temporal resolution for different RSD pad-pitch geometries as function of the interpad distance.
4.4. Summary of laser results

The spatial and temporal resolutions obtained for each geometry are summarized in table 1. The temporal resolution is in line with the best LGAD results, demonstrating how the RSD design does not degrade the LGAD performances. The RSD spatial resolution is extremely good for all geometries as the reconstruction method is able to exploit the power of internal signal sharing.

| pad-pitch geometry | spatial resolution [µm] | temporal resolution [ps] |
|--------------------|-------------------------|-------------------------|
| 50-100             | 4.3                     | 14.7                    |
| 70-100             | 2.5                     | 11.5                    |
| 100-200            | 4.8                     | 25                      |
| 150-200            | 4.4                     | 19                      |
| 150-300            | 7.2                     | 24                      |
| 200-300            | 5.3                     | 25                      |
| 200-500            | 16.5                    | 32                      |
| 300-500            | 14                      | 25                      |

Table 1: Spatial and temporal resolutions from TCT measurements for different RSD pad-pitch geometries. These results refer to studies where the laser has been shot in the interpad region of the sensors, as shown in figure 9.

5. RSD simulation in Weightfield2

Weightfield2 is a simulation program that has been extensively used in the design and characterization of the LGAD properties [12]. WF2 emulates the passage of a particle in a silicon detector and generates the output current, including the effect of non-uniform ionization, gain, geometry, and acceptor removal. The RSD principle of operation has been added to the WF2 program by implementing the prediction of the RSD master formulas, equation (4) and equation (5). In WF2-RSD it is possible to select a given pad geometry and to simulate the current signals in the nearby pads as a function of the hit position. Figure 18 shows on the left an example of geometry, and indicated by the purple circle the position of the hit. The number near each pad is the fraction of signal seen in that pad. On the right side, the

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2Shareware at http://cern.ch/nicolo
shape of the DC current, of the total AC current, and the currents in each of the pad is shown. The program allows generating many events in batch mode and writing the events to a file for offline analysis.

Figure 18: An example of pad geometry and of the current signals simulated by WF2-RSD.

6. Test Beam measurements

Two 3×3 RSD matrices from the same wafer, with 100–200 and 190–200 pad-pitch geometry, operating at -430 V were measured at the Fermilab Test Beam Facility. In this facility, 120 GeV/c protons are delivered every minute in 4 seconds spills, each containing 50-100k particles. RSDs were mounted inside an environmental chamber kept at a constant temperature of ∼22°C. The DUTs box was preceded on the beamline by a tracking telescope with 14 layers of strips and 4 layers of pixels, and followed by two additional strips layers. The tracker provides a spatial resolution of ∼45 µm. Additionally, the setup was instrumented with a Photek 240 micro-channel plate detector, placed inside the environmental chamber after the DUTs, with a timing resolution better than 10 ps [13].

The data were acquired with a Keysight MSOX92004A 4-channels digital scope with 40 GS/s and 20 GHz analog bandwidth. Given that only 4 signals could be recorded simultaneously, different types of datasets were recorded:

- 4 AC pads,
- 3 AC pads and the Photek [14],
- 2 AC pads, the DC pad and the Photek.
The following quality cuts were required in the analysis:

- the presence of only one isolated proton per event in the tracking system; its track must have hits at least in 14 layers of the tracking telescope and in one of the two downstream strip layers.

- the signal on each RSD read-out pad has to be larger than 15 mV,

- the signals should not saturate the scope

- the sum of the AC signals has to be larger than 80 mV (60 mV) when read with 4 (3) pads.

6.1. 100 – 200 geometry: 4-pads configuration studies

The 4-pads dataset has been used to evaluate the quality of the reconstruction using either the MF or LA model. Using the selection cuts above, figure [19] reports the hit position using the tracker (left), the MF (center), and LA (right) models.

![Hit maps for the 100-200 geometry](image)

Figure 19: Hit maps for the 100-200 geometry represented using the tracker coordinates (left) and reconstructed with the analytical method using the MF (center) and LA (right) models.

Given the uniform beam illumination during the beamtest, the density of hits as a function of position in the two right plots of figure [19] should be constant. This is shown in figure [20] where the events in the y-range 23255 \( \mu m < y < 23345 \mu m \) are plotted versus the x-axis. These plots show a good spatial uniformity for reconstructed events, demonstrating that the analytical method works well, especially for the MF model.
The comparison between the tracker and the RSD reconstruction can be done by measuring the tracker mean value when the events are selected in an x-y interval using the RSD. Figure 21 shows, for three x-y intervals, how the tracker reconstructed positions (red points) cluster around the RSD position (blue points).

This study is further investigated in figure 22, where $y_{RSD}^\text{mean}$ is plotted as a function of $y_{\text{tracker}}^\text{mean}$. For each point, the events are selected by requiring their RSD position to be within an x-y square of $30 \times 30 \mu m^2$. Both MF (left) and LA (right) models work very well, the correlation factors $R^2$ and the fit slope are close to 1.

This result proves that the MF model can accurately reproduce experimental data despite the absence of tunable parameters. In the LA model, it is instead necessary to optimize the attenuation factor $\beta$, whose best value in these studies is $\beta = 0.003/\mu m$. 

21
6.1.1. Spatial resolution using signals from 3 or 4 pads

In the dataset used for timing measurements, only 3 AC pads can be used for hit reconstruction. The analysis presented in the previous section is thus repeated including only 3 pads to compare 4- and 3-pads spatial resolutions. If we consider events in a triangular area near the included pads, the spatial resolution for the 3-pads dataset is equal to the 4-pads one. Moving to the total device area, instead, the spatial resolution worsens since the information from the missing pad would be needed to define the hit positions more accurately.

6.2. 100 – 200 geometry: timing studies using the 3 AC pads and the Photek dataset

The first step in the timing analysis is to measure the propagation delay, from the hit point to the read-out pads. The hit positions are reconstructed using the MF model.

Two methods are used to extract the best time delay parameter $\gamma$ (equation \([5]\)).

- In the direct method, the time of arrival is plotted as function of $\frac{\log(d)}{\alpha}$ and fitted linearly: the fit slope represents the time delay parameter, that is here $\gamma_{\text{dir}} = (19 \pm 1) \text{ ps}$ (figure \(23\)).

- The second method finds the time delay indirectly by minimizing the timing resolution as a function of the delay parameter, as shown in figure \(24\). For each pad, the best $\gamma$ parameter is the one that minimizes...
timing resolution: the resulting values are $\gamma_{CH0} = (12.1 \pm 0.6)\ ps$, $\gamma_{CH1} = (17.0 \pm 0.1)\ ps$, and $\gamma_{CH2} = (19.5 \pm 0.2)\ ps$. Combining the three channels, the parameter that minimizes the total time resolution is $\gamma_{ind} = (16.4 \pm 0.2)\ ps$.
The delay value used in the analysis is the weighted mean of the results from the two methods, $\gamma = (16.46 \pm 0.04) \text{ ps}$.

6.2.1. Timing resolution results

Once the delay parameter has been evaluated, the signals from the 3 pads can be combined to form $t_{RSD}$, defined as the arithmetic mean of their times of arrival. The timing resolution is measured as the sigma of the distribution of $t_{RSD} - t_{Photek}$. Figure 25 shows the three single-channel resolutions (top) and the combined one (bottom), $\sigma_{tot} = (51.9\pm0.5) \text{ ps}$. In contrast to the laser results (figure 16), this value is higher than the one calculated by combining the three single-channel resolutions assuming uncorrelated pads ($\sim 34 \text{ ps}$). This is caused by the presence of a correlated noise due to non-uniform ionization.

![Figure 25: Top: single channel timing resolution for the three read-out pads at test beam. Bottom: total timing resolution obtained as the arithmetic mean of the three pads timestamps.](image)

Timing resolution is defined as the sum of two terms, one depending on the non-uniform ionization [15] and the other due to jitter.

$$\sigma_{tot}^2 = \sigma_{Jitter}^2 + \sigma_{ionization}^2$$
The only contribution to the laser timing resolution is \( \sigma_{\text{jitter}} = \frac{N}{dv/dt} \), where \( N \) is the electronics noise of each read-out channel, that is uncorrelated. In the test beam, \( \sigma_{\text{tot}} \) also includes the contribution of non-uniform ionization. This contribution is fully correlated among pads: in RSDs, the signals spread from the hit point to the AC pads, and each pad sees a copy of the same signal. As a consequence, the jitter term is reduced by combining RSD signals, but the non-uniform ionization is not since it depends on the shape of the initial signal.

The reconstruction of the hit position thus greatly benefit from signal sharing among pads, whereas timing resolution does not improve using multiple pads as the shapes of the signals are 100% correlated.

In the \( t_{\text{RSD}} - t_{\text{Photek}} \) in figure 25 (bottom), \( t_{\text{RSD}} \) is calculated as the arithmetic average of the three RSD timestamps. This result can be improved if \( t_{\text{RSD}} \) is calculated as an amplitude-weighted average, yielding to a timing resolution of \( (44.4 \pm 0.3) \) ps (figure 26). This value is in line with the best LGAD performances obtained at the same gain.

![Combined timing resolution - weighted mean](image)

Figure 26: \( t_{\text{RSD}} - t_{\text{Photek}} \) distribution with \( t_{\text{RSD}} \) calculated as the amplitude-weighted mean of the three pads timestamps.

### 6.3. 190-200 geometry: 3 AC pads and the Photek

The 190-200 geometry was used to study the effect of large metal pads and floating electrodes on the signal reconstruction.

#### 6.3.1. Position reconstruction

The normalized density maps for pad 1 (left) and 2 (right) are shown in figure 27. The interesting comparison here is between the effect of floating
or grounded pads in the readout. Pad 1, shown on the left side of figure 27, has 4 floating neighbours, pads A, B, C, and D and four grounded neighbours, pads 0, 2, 3, and 4. Clearly, when the particles hit a floating pad, the signal is well visible in pad 1. In contrast, when particles hit a ground pad there is not signal sharing. The right side of figure 27 shows the same situation for pad 2: here all neighbours are grounded, and hits are visible only when they directly hit the pad.

Figure 27: Normalized density maps for pad 1 (left) and pad 2 (right) of the 190-200 geometry. The red square is the read-out pad, black squares indicate grounded pads, while the white ones represent the floating pads.

For the same two AC pads, figure 28 shows the signals amplitude as a function of x-coordinates. Pad 1 (left) is amidst a grounded pad and a floating one, while pad 2 (right) is placed between a grounded pad and the device edge. Amplitude attenuation is steeper next to grounded pads than underneath the floating ones.

These plots highlight how RSD signals with large metal pads work differently with respect of RSD with small metal pads:

- Most of the events are seen by only one pad
- Signal sharing is limited in a very narrow region between pads.
- RSD with large metal pads are similar to traditional LGAD, benefitting from a design that provides 100% fill factor.

For this reason, in this dataset, the large majority of events is seen only by one of the read-out pads, and 2- and 3-pads events are very few. Hit reconstruction is thus not applied to the 190-200 matrix, and the spatial resolution is estimated as \( \text{pad size}/\sqrt{12} \) (~55 \( \mu \text{m} \)).
6.3.2. Timing resolution

As a consequence of very limited signal sharing, the timing resolution of this geometry is very good for 1-pad events (very small jitter since the signal is large) and slightly worse for the 2-pads events. For the timing analysis, the selection cuts are:

- the sum of the AC signals is required to be larger than 80 mV,
- the signal on each pad should be larger than 15 mV,
- the tracker coordinates of the events need to have $x > 17.05 \text{ mm}$ and $y < 23.45 \text{ mm}$.

With this selection, the following timing resolution was obtained:

- 1-pad events: $(\sigma = 32 \pm 1) \text{ ps}$
- 2- and 3-pads events: $(\sigma = 42.1 \pm 0.6) \text{ ps}$.

6.4. 100-200 geometry: DC pad studies

The properties of the DC signal have been studied by concurrently reading 2 AC pads and the signal from the DC contact. The comparison between the DC and AC signals has identified two different families of events, depending on where the signal hit the RSD (figure 29):
Figure 29: Signals recorded by the DC pad (blue) and the closest AC pad (red) in the external DC frame (left) and in the inner DC region (right). The solid lines represent a single pulse, while the dashed ones are the average on few tens of waveforms.

- When the particle hits the RSD in the external frame between the edge of the DC contact and the first metal AC pads, both the DC (blue) and AC (red) signals have a fast component.

- In contrast, when the particle hits the RSD anywhere among AC pads, the DC signal does not show a fast component. This difference happens because the fast component always follows the path with the lowest high-frequency impedance to ground: when the particle hits among AC pads, this is represented by the AC ground. However, when the particle hits near the edge, the DC contact is sufficiently low impedance to absorb part of the fast signal.

In both regions, the falling edge of the pulse depends on the AC discharge current. The RC time constant of the DUT can be obtained by fitting the falling edge of DC signals with the exponential function \( e^{-\frac{t}{RC}} \) (figure 30). The resulting RC value for this geometry is \((5.08 \pm 0.03) \text{ ns}\).

The amplitude of the DC signal as a function of position is displayed in the 2D map in figure 31 (left): pulses near the edge, due to the presence of the fast component, have a much larger amplitude. Figure 31 (right) shows instead the pulse area, that remains constant.

6.5. 100-200 geometry: timing properties of the DC pad signals

Figure 32 shows that signals in the center of the DC pad are recorded with a time delay compared to the ones on the external frame. This delay...
Figure 30: The average of a hundreds of DC signals (dashed line) selected in the DC pad inner region and fitted with an exponential function to measure the RC time constant (red line). An example of a single pulse is represented in a solid blue line.

Figure 31: On the left, the amplitude map for the DC pad shows a difference in amplitude between the inner region and the external frame, while the map on the right shows a constant behaviour for signals area.

represents the signals propagation time towards the DC contact.

Given that only the signals near the edge have a fast component, the timing resolution can be obtained only for that specific region. These signals are selected applying a cut on the amplitude of at least 60 mV. The timing resolution for this region is $(45.1 \pm 0.7) \text{ ps}$, in agreement with the values obtained combining the AC pads resolutions presented in the previous sections.
7. Conclusions

This paper presents the principle of operation of Resistive AC-Coupled Silicon Detectors, a new type of LGAD characterized by a continuous gain layer and an AC-readout design. RSDs are the first silicon detector with internal signal sharing. Thanks to the RSD design, signals are spread among the neighbouring pads, allowing for a very precise determination of the hit position. The paper presents laser and beam test analyses to determine the RSDs performances. A spatial resolution of less than 5 $\mu m$ is achieved with large pixels ($\sim 100\mu m$) with a temporal resolution of $\sim 40$ ps.

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