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2D position sensitive microstrip sensors with charge division along the strip: Studies on the position measurement error

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ABSTRACT

Position sensitivity in semiconductor detectors of ionizing radiation is usually achieved by the segmentation of the sensing diode junction in many small sensing elements read out separately as in the case of conventional microstrips and pixel detectors. Alternatively, position sensitivity can be obtained by splitting the ionization signal collected by one single electrode amongst more than one readout channel with the ratio of the collected charges depending on the position where the signal was primary generated. Following this later approach, we implemented the charge division method in a conventional microstrip detector to obtain position sensitivity along the strip. We manufactured a proof-of-concept demonstrator where the conventional aluminum electrodes were replaced by slightly resistive electrodes made of strongly doped poly-crystalline silicon and being readout at both strip ends. Here, we partially summarize the laser characterization of this first proof-of-concept demonstrator with special emphasis on the study on how the different noise sources are affecting the device position error along the strip.

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1. Introduction

The resistive charge division method has been frequently used in gaseous detectors with resistive anodes [1–4] and studied for silicon pad detectors [5], but it has never been implemented to determine the position along the strip of an actual microstrip detector. Radeka, in his seminal paper [6], formulated for the first time the basic characteristic of the charge-division concept for resistive electrodes. Recently, the use of the charge-division method in very long microstrip sensors with a length of several tens of centimeters, has been proposed as a possible tracking technology for the International Linear Collider detector concepts [7].

In an initial study [8], the feasibility of the charge division concept was demonstrated on fully fledged microstrip sensor with resistive electrodes where the ionization signals were induced by a near-infrared laser. An electrical simulation of the sensor's equivalent circuit, including the amplifying and filtering stages, was developed and benchmarked against the experimental data. The simulation accounted for the major systematic effects degrading the response linearity; mainly, the nonconstant ballistic deficit due

to the attenuation of the signal pulse during its propagation along the dispersive electrode.

For the follow-up study presented here, the same microstrip detector with resistive electrodes made of a thin layer of highly doped polycrystalline silicon was tested in laser-based test stand and in a test beam. The prototype consists of 384 p⁺ strips (20 μm wide) with a pitch of 80 μm on a 285 μm thick n-type substrate. The resistive electrodes have a total length of 2 cm with linear resistance $R/\mu\text{m} = 12.2 \Omega/\mu\text{m}$. Fig. 1 shows a picture of the actual prototype attached to the sensor carrier.

We will report here on the estimation of the error on the measured position defined by Eq. (1), following Fig. 2 notation with A_1 and A_2 the amplitude of S_1 and S_2 signal respectively and L the length of the microstrip.

$$x = L \times \frac{A_2}{A_1 + A_2} \quad (1)$$

2. Noise sources and the position measurement error

As in a standard silicon sensor, the noise of our prototypes, read out by an analog front end consisting in a charge sensitive amplifier followed by a shaping stage, depends both on the sensor itself and on the signal processing electronics. The most important noise sources are:

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Fig. 1. Picture of one of the detectors mounted on the PCB sensor carrier. The two Beetle chips are identified by the white circles. Each one is connected to one side of 128 consecutive strips of the detector in order to provide double-sided readout.

Fig. 2. Schematic lateral cross-section of the microstrip sensor (not to scale). It is possible to distinguish the Aluminum elements and the resistive electrodes on the strips. The Aluminum pads at the two ends of the microstrip are connected to two opposite channels of the read-out electronics. When an ionizing particle crosses the detector, two signals (S_1 and S_2) are read out by the opposite electronic channels. The position along the strip, the x coordinate, is reconstructed comparing the collected charges at the ends of each strip according to Eq. (1).

- Noise from the input transistor of the amplifier σ_a . The actual incarnation of this noise varies with the kind of amplifier input transistor. The most relevant point for this discussion is the fact that this error is *uncorrelated* between the two ends of the sensor.
- Thermal noise σ_R from the resistive electrode. This noise, originating from thermal fluctuations of the current in the electrode, is expected to be *anti-correlated* between the two ends of the sensor.
- Shot noise produced by the statistical fluctuation of the sensor's leakage current. Due to the external origin of this noise contribution generated in the silicon bulk, the noise must be fully correlated between the two ends of the sensor.

Even though we can not consider it as a source of noise intrinsic to the detector, we will also discuss here the effect on the position error of the laser intensity fluctuations σ_L when the 20,000 pulses are recorded at a given scanning position. These laser fluctuations introduce fully correlated noise excursions at the opposite readout channels.

Using Eq. (1), by error propagation, we derive the following expression for the position uncertainty (standard deviation) σ_x , where its explicit dependence with position x , noise amplitude and correlation are shown:

$$\sigma_x^2 = \frac{1}{(A_1 + A_2)^2} [(L-x)^2 \sigma_2^2 - 2x(L-x)\rho\sigma_1\sigma_2 + x^2\sigma_1^2] \quad (2)$$

Using this Eq. (2) we can investigate the effect of three different correlation scenarios: fully anti-correlated ($\rho = -1$), as in the case of the thermal noise contribution; fully correlated ($\rho = +1$) due to laser intensity fluctuations and shot noise; and uncorrelated ($\rho = 0$) as it is the noise originating from amplifier noise.

2.1. Thermal noise

For this type of noise due to the electrode resistivity, the noise excursion at both ends of the electrode have the same magnitude but opposite sign, that is

$$\Delta A_1 = -\Delta A_2; \quad \sigma_{A1} = \sigma_{A2} \equiv \sigma_A; \quad \rho = -1 \quad (3)$$

Therefore accordingly to Eq. (2) the thermal noise effect on σ_x is independent of the position and it is fixed by the SNR ratio as it is given by the following expression:

$$(\sigma_x^{Therm})^2 = \frac{1}{(A_1 + A_2)^2} [(L-x)\sigma_A + x\sigma_A]^2 = \frac{L^2 \sigma_A^2}{(A_1 + A_2)^2} \quad (4)$$

2.2. Amplifier noise

As we said before this noise is associated to the input transistor of the amplifier therefore it is uncorrelated and not necessary of equal magnitude although one should expect that when using the same electronics at both ends, the amplifier noise should be similar, under this assumptions this noise parameters are

$$\sigma_{A1} \approx \sigma_{A2}; \quad \rho = 0 \quad (5)$$

And in combination with Eq. (2) we get

$$(\sigma_x^{Amp})^2 = \frac{1}{(A_1 + A_2)^2} [(L-x)^2 \sigma_{A2}^2 + x^2 \sigma_{A1}^2] \quad (6)$$

That is, the position resolution due to the amplifier noise depends quadratically on the distance. If we assume that $\sigma_{A1} \approx \sigma_{A2} \equiv \sigma_A$ we obtain a symmetric quadratic dependence:

$$(\sigma_x^{Amp})^2 = \frac{L^2 \sigma_A^2}{(A_1 + A_2)^2} \left(1 - 2\frac{x}{L} + 2\frac{x^2}{L^2} \right) \quad (7)$$

Thus the position error induced by the amplifier noise is a square root of two larger at the ends of the strip than at the center of the strips.

Additionally, the common noise, induced by external parasitic electromagnetic fields will appear as a correlated contribution to the amplifier noise. Fortunately, the common noise is suppressed by the hit finding algorithm.

2.3. Intensity fluctuation of laser pulses

This contribution is obviously fully correlated and its noise parameters are given by

$$\sigma_{A1}^{Laser} = \beta A_1; \quad \sigma_{A2}^{Laser} = \beta A_2; \quad \rho = 1 \quad (8)$$

where β is a positive constant which characterize the laser stability. Applying these parameters to Eq. (2) we get

$$\begin{aligned} (\sigma_x^{Laser})^2 &= \frac{\beta^2}{(A_1 + A_2)^2} [(L-x)A_2 - xA_1]^2 \\ &= \beta^2 [(L-x)x - x(L-x)]^2 = 0 \end{aligned} \quad (9)$$

as a result, we conclude that the laser intensity fluctuation does not have any contribution to the position measurement error.

2.4. Shot noise

The statistical fluctuations of the leakage current is the cause of this noise contribution, as in the case of the laser, this noise has to be fully correlated if we assume that both ends should sense the same increase or decrease of the leakage current. Besides, the current excursions at both end should be the same by symmetry. Under these two assumptions we get the following noise parameters:

$$\frac{\sigma_{A1}}{\sigma_{A2}} = 1; \quad \rho = 1 \quad (10)$$

Applying these parameter to Eq. (2) we get

$$(\sigma_x^{\text{shot}})^2 = \frac{1}{(A_1 + A_2)^2} [(L-x)\sigma_{A2} - x\sigma_{A1}]^2 = \frac{\sigma_{A1}^2}{(A_1 + A_2)^2} (L-2x)^2 \quad (11)$$

Thus, as in the case of the amplifier noise, the shot noise introduces a quadratic dependence with the position, in this particular case being zero at the center of the electrode and maximal at the edges.

3. Measured noise in prototypes

The experimental results presented along this section were carried out in the laser test stand described in detail in [8]; for each detector, we performed a longitudinal scan moving the focused laser beam spot along the midline of a polysilicon electrode. Contrary to the aluminum, polycrystalline silicon is transparent to IR light. We scanned the whole electrode length (20 mm). For each scanning point, 20,000 laser pulses were recorded.

3.1. Noise without signal

We have measured the noise in absence of laser or other signal (defined as the width of the pedestal) obtaining a Gaussian distribution with a sigma of 1.83 ADU and 1.8 ADU respectively for the noise of A_1 and A_2 amplitudes. The lack of correlation ($\rho \approx 0.03$) implies that the uncorrelated noise component (amplifier noise) dominates.

3.2. Noise during the laser scan

Fig. 3 shows the noise value for channel A_1 when doing the laser scan along the strip length. As expected, the further we move

Fig. 3. Noise values for the A_1 signal along the strip scanning points.

the laser spot away from the A_1 end, the further the noise is reduced, that is, the laser contribution to the noise is reduced linearly as x/L increases until the other noise components (amplifier, leakage and thermal) start to be dominant, reaching a final noise figure at the far end of the electrode very similar to the previously quoted pedestal width.

The change in the relative contribution of each of the noise components is also shown in the dependence of the correlation coefficient with the laser scan position, as it is shown in Fig. 4

3.3. Estimation of the measured position error vs. the position

Finally, we have estimated the position measurement error in two ways:

- In a direct way, taking as error the width of the distribution of variable x/L (defined in Eq. (11)) obtained at each scanning point from the 20,000 laser pulses.
- In an indirect way, using Eq. (2) and propagating the uncertainty on the measurement of the signal amplitudes and taking into account the measured correlation at each scanning point.

The resulting position errors are given in Fig. 5. As expected, we observe a minimum of the error around the center of the electrode with maxima near the ends. As a consistency test and a proof of

Fig. 4. Correlation coefficients ρ at the different laser scan points. The change in ρ for each point is due to the change in the relative contribution of the different noise sources.

Fig. 5. Fractional position measurement error at each scanning point.

the gaussianity of the uncertainty distributions we see that the two ways of estimating the error yield almost identical values.

4. Summary

We have carried out a study of the error position achieved by the charge-division method implemented in semiconductor microstrip sensors. Doing an analytical error propagation, we have derived the contribution to the error of the measured position of the different noise sources and the dependence of this error with the measured distance. The analytical extrapolation shows an excellent agreement with the measured error determined at the laser test stand.

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