NOISE PERFORMANCE MODELING OF SILICON MICROSTRIP DETECTORS AND OF THEIR READOUT AMPLIFIERS

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ABSTRACT: The noise performance of a silicon microstrip detector and of its readout amplifiers is crucial to the spatial resolution of particle detection. We describe an electrical model of the detector, suitable for computer simulations of the noise performance. A high level model of a readout amplifier, based on a few well known parameters only, is also presented. Both models can be combined to describe complete detection channels and simulated using a SPICE simulator. These models were used to examine the sensibility of the output signal-to-noise ratio to changes of detector parameters. We also present a comparison of the simulated noise performance with the corresponding measurements.

INTRODUCTION

A single-sided microstrip detector, schematically shown in figure 1, consists of an n-type silicon substrate with built-in long diffusion strips, forming semiconductor junctions. Between these strips and the metallized silicon backplane surface an electric field is created by means of a bias voltage, depleting this region. A particle passing the detector creates electron-hole pairs, which are separated in the electric field. In the detector with p-type strips holes are collected upon a few nearest strips and delivered to charge-sensitive readout amplifiers through integrated coupling capacitors, built up from diffusion strips, insulator film and metal strips. Readout amplifiers change these charges into voltages, which can be used to calculate the position of the particle.

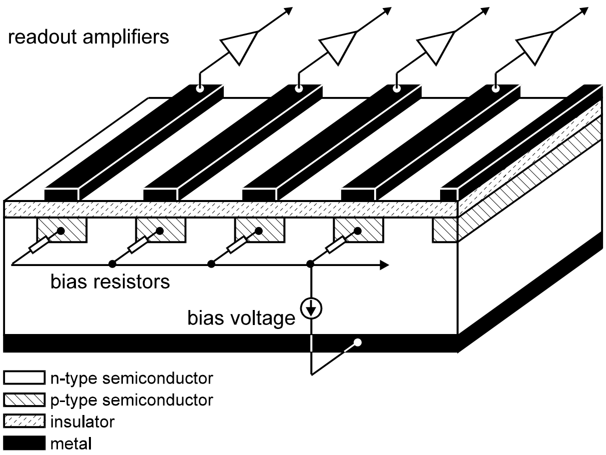

FIGURE 1 – *Simplified view of a single-sided silicon microstrip detector.*

The spatial resolution of the detection depends in particular on the distance between strips and the signal-to-noise ratio (SNR) at the outputs of amplifiers. The smallest distance between adjacent strips is limited by the minimum size needed for a single amplifier. A possible way to increase the spatial resolution of microstrip detectors is to optimize the noise performance of detectors themselves and of their readout electronics.

Microstrip detectors are often joined to form large detector systems, needing a lot of developing and prototyping effort. Such systems are expensive because of a large amount of applied silicon. Figure 2 shows a photograph of the DELPHI Silicon Tracker [1], which is an example of such a system.

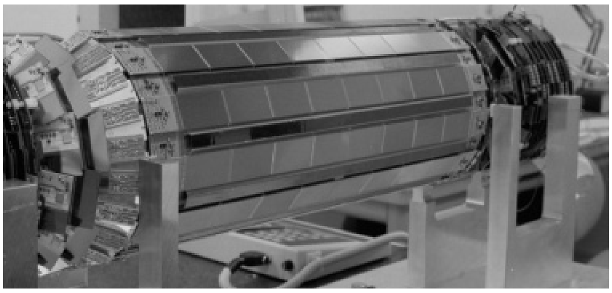

FIGURE 2 – *Silicon Tracker of the DELPHI experiment, CERN, Geneva. It consists of three barrel layers of modules build up from silicon microstrip detectors. Visible modules have length of about 50 cm and active silicon area of the whole system is bigger than 1.3 m^2.*

Because the final system resolution is determined also by the noise performance, all methods that allow predicting it before the detector prototype has been manufactured reduce the research and development time and costs. In this paper we describe such methods. They allow simulating SNR at outputs of the channels consisting of a microstrip detector and readout amplifiers, by means of SPICE – an electronics circuit simulator. We also show simulation results obtained applying these methods.

MICROSTRIP DETECTOR MODEL

To simulate charge transport and losses as well as noise generation in a microstrip detector, a distributed model of the detector was applied. The model takes into account all important detector elements responsible for the signal transfer from the point of its generation to the readout amplifiers:

- the resistance of diffusion strips (denoted as Rd);
- the coupling capacitance between diffusion strips and metal strips (Cc);
- the resistance of metal strips (Rm).

Charge loses are simulated by the following elements:

- the capacitance to the backplane (Cb);
- the capacitance to the adjacent strip in the diffusion layer (Ci_d);
- the capacitance to the second neighbour strip in the diffusion layer (Ci2_d);
- the capacitance to the adjacent strip in the metal layer (Ci_m);
- the capacitance to the second neighbour strip in the metal layer (Ci2_m);
- the resistance to the backplane (Rb).

The cross-sections of the detector model, perpendicular and parallel to the strips are presented in figure 3. To reflect distributed character of the detector its strips are modeled as transmission lines.

The noise contribution from the leakage current of the junctions is simulated by resistors connected in parallel with model elements Cb/Rb. The resistors, not shown in figure 3, give the same amount of thermal noise as the leakage current shot noise. Their resultant resistance R_{lk} per strip is:

$$R_{lk} = \frac{2kT}{q\,I_{lk}} \tag{1}$$

where: I_{lk} – leakage current per strip,
T – absolute temperature,
k – Boltzmann constant,
q – elementary charge.

The charge generated by a passing particle can be simulated as current sources connected between the affected diffusion strips and the backplane, in parallel with elements Cb/Rb. As a first approximation, also used by us, only one current source is applied, assuming that the whole charge was collected upon one strip.

In order to take into account the noise of bias resistors, they are put in the model between each diffusion strip and the backplane.

The presented model can be also used to simulate detectors with two metal layers. In this case, parasitic capacitors introduced by the second metal layer can be considered in capacitors of the first metal layer. Series resistors on the inputs of readout amplifiers may simulate the second metal strip resistance.

SPICE simulations of such detector models connected to the models of the readout amplifiers have shown that it is enough to simulate detector model equivalent networks of 9 strips divided into 20 sections in order to

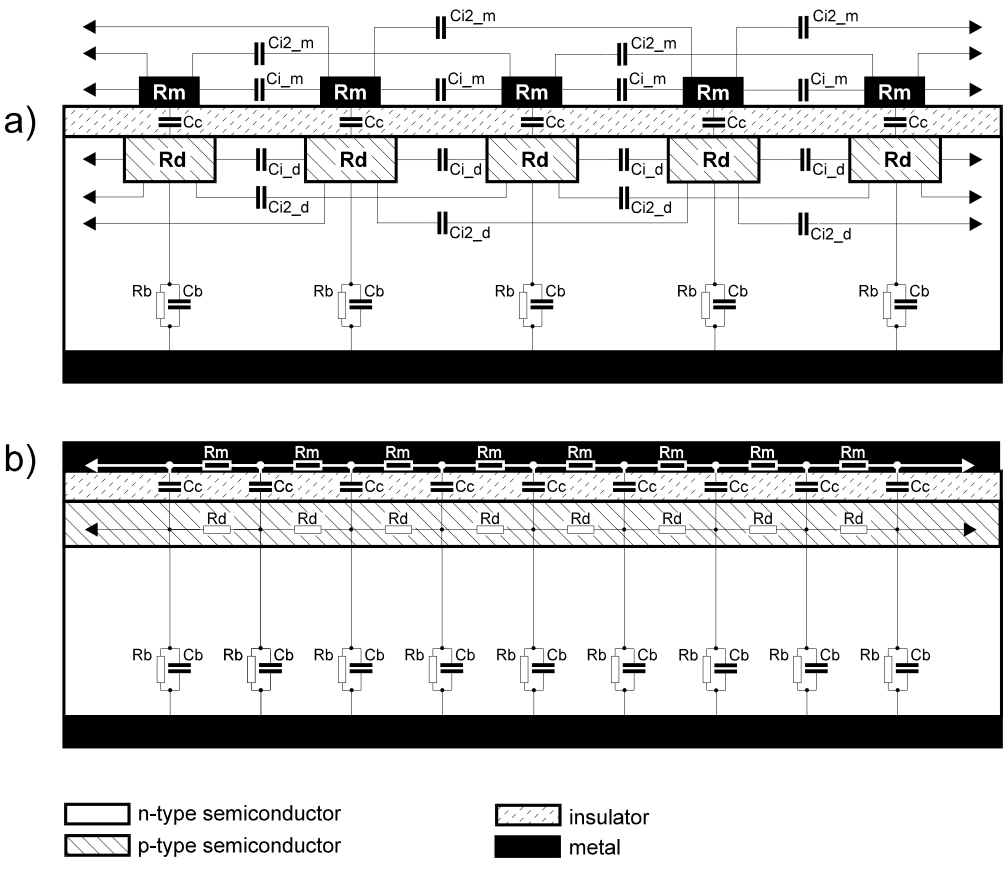

FIGURE 3 – The *silicon microstrip detector model and its elements. a) Cross-section perpendicular to strips. b) Cross-section parallel to strips. Not shown elements: resistors simulating leakage current, bias resistors, the current source simulating a generated charge by a passing particle.*

keep good simulation accuracy. Since such circuits have more than a thousand of elements, a special program was written to generate automatically the detector model networks in the SPICE simulator format, according to the model description in a text file.

READOUT AMPLIFIER MODEL

Charge amplifiers with shaping filters are used for the readout of silicon microstrip detectors. We built a model of such an amplifier upon following assumptions:

- the noise performance of the amplifier is described by means of an equivalent noise charge (ENC) which depends linearly on the detector capacitance:

$$ENC = \alpha + \beta C_d \tag{2}$$

where C_d is a detector capacitance seen from the amplifier input;

- the response of the amplifier with a shaping filter is similar to the response of the CR-RC filter.

The charge amplifier with such filter is shown in figure 4. Its elements are:

- I_d – the current induced by a passing particle in the detector strip connected to the amplifier input;
- C_d – the detector capacitance seen from the amplifier input;
- C_{in} – the input capacitance of the amplifier;
- *Ampl.1* – the ideal inverting voltage amplifier with gain k_u;
- C_f – the feedback capacitance;
- I_N, V_N – the noise of the amplifier brought to the input; both sources are frequency independent, i.e. they generate white noise.

The CR-RC shaping filter is connected to the amplifier output. It consists of the high-pass section C_h, R_h and the low-pass section R_l, C_l. Their time constants are the same, and amount to τ, i.e. $C_h R_h = R_l C_l = \tau$. In this particular case the filter peaking time is also τ. The sections are separated by an ideal voltage amplifier *Ampl.2* with gain of e, where e is the base of natural logarithm, compensating the filter attenuation; with such gain the filter attenuation of the unit step is fully compensated at the filter peaking time.

We aim at obtaining values of the noise sources I_N and V_N as well as the amplifier input capacitance C_{in}, assuming the noise of the circuit as in equation (2). Since the CR-RC filter transmittance is:

$$K_f(j\omega) = \frac{e\, j\omega\tau}{(j\omega\tau + 1)^2} \tag{3}$$

the noise mean square voltage at the output of the whole circuit can be expressed as:

$$\overline{(V_{of}^N)^2} = \frac{1}{2\pi}\int_0^\infty \frac{d\overline{(V_o^N)^2}}{df}\left(\frac{e\,\omega\tau}{\omega^2\tau^2 + 1}\right)^2 \tag{4}$$

where $\frac{d\overline{(V_o^N)^2}}{df}$ is the mean square voltage spectral noise density at the *Ampl.1* output.

The foregoing density can be calculated from the equation:

$$\frac{d\overline{(V_o^N)^2}}{df} = \frac{\frac{1}{\omega^2}\frac{d\overline{I_N^2}}{df} + (C_f + C_d + C_{in})^2 \frac{d\overline{V_N^2}}{df}}{\left(C_f + \frac{(C_f + C_d + C_{in})}{k_u}\right)^2} \tag{5}$$

where the spectral noise mean square density $\frac{d\overline{I_N^2}}{df}$ of the current noise source I_N and the spectral noise mean square density $\frac{d\overline{V_N^2}}{df}$ of the voltage noise source V_N transfer to the amplifier output as appropriate sources.

Inserting equation (5) into equation (4) and calculating the integral, one gets the noise voltage at the circuit output:

$$\overline{(V_{of}^N)^2} = e^2 \frac{\tau \frac{d\overline{I_N^2}}{df} + \frac{(C_f + C_d + C_{in})^2}{\tau}\frac{d\overline{V_N^2}}{df}}{8\left(C_f + \frac{(C_f + C_d + C_{in})}{k_u}\right)^2} \tag{6}$$

Now let us assume that the ENC given by equation (2) is delivered to the circuit input, i.e. on the circuit output there is its assumed noise. The attenuation of the filter is compensated at the filter peaking time by means of

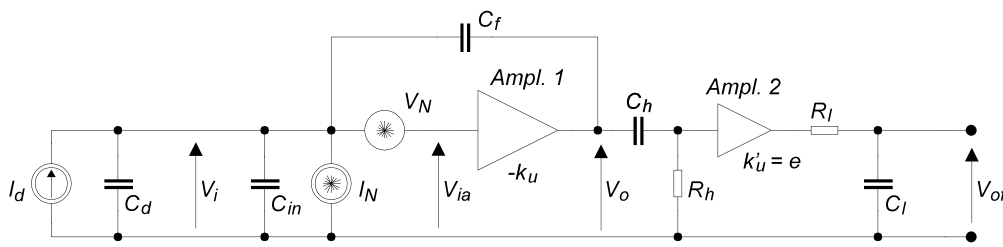

FIGURE 4 – *The charge amplifier structure with the CR-RC shaping filter. Main elements: I_d – the current generated in the detector; C_d – the detector capacitance seen from the amplifier input; C_{in} – the input capacitance; V_N and I_N – respectively noise voltage and noise current representing amplifier noise brought to the input; Ampl.1 – inverting amplifier with gain k_u; Ampl.2 – the amplifier separating low-pass and high-pass sections of the shaping filter and compensating its attenuation.*

Ampl.2, so that the ENC gives the same voltage at the amplifier *Ampl.1* output and at the filter output:

$$\overline{(V_o^N)^2} = \overline{(V_{of}^N)^2} = \frac{(\alpha+\beta C_d)^2}{\left(C_f + \frac{(C_f + C_d + C_{in})}{k_u}\right)^2} \qquad (7)$$

since the ENC transfers to the *Ampl.1* output like an input charge.
When comparing right hands sides of equations (6) and (7), one gets:

$$(\alpha+\beta C_d)^2 = \frac{e^2\tau}{8}\frac{d\overline{I_N^2}}{df} + \frac{e^2(C_f + C_d + C_{in})^2}{8\tau}\frac{d\overline{V_N^2}}{df} \qquad (8)$$

Expanding the squares and treating both sides of this equation as functions of variable C_d, one can compare coefficients upon the same C_d powers and get the following set of equations:

$$\begin{cases} \alpha^2 = \frac{e^2\tau}{8}\frac{d\overline{I_N^2}}{df} + \frac{e^2(C_{in}+C_f)^2}{8\tau}\frac{d\overline{V_N^2}}{df} & (9a) \\ \alpha\beta = \frac{e^2}{8\tau}\frac{d\overline{V_N^2}}{df}(C_{in}+C_f) & (9b) \\ \beta^2 = \frac{e^2}{8\tau}\frac{d\overline{V_N^2}}{df} & (9c) \end{cases}$$

Now treating $\frac{d\overline{I_N^2}}{df}$, $\frac{d\overline{V_N^2}}{df}$ and C_{in} as unknowns and the rest as data, one gets the result:

$$\begin{cases} \frac{d\overline{I_N^2}}{df} = 0 & (10a) \\ \frac{d\overline{V_N^2}}{df} = \frac{8\beta^2\tau}{e^2} & (10b) \\ C_{in} = \frac{\alpha}{\beta} - C_f & (10c) \end{cases}$$

Thus the noise of the circuit shown in figure 4 may be simulated by means of only the white noise voltage source V_N with the mean square spectral density given by equation (10b) and the input capacitance C_{in}, quantified in equation (10c). The noise current source I_N is redundant.
The noise source V_N can be easily modeled by a resistor R_N having the same spectral noise density:

$$R_N = \frac{2}{e^2 kT}\beta^2\tau \qquad (11)$$

where: β – ENC slope coefficient as in equation (2),
τ – time constant of the CR-RC filter and its peaking time,
T – absolute temperature,
k – Boltzmann constant,
e – natural logarithm base.

Note, that for building up a charge amplifier model according to presented method, only a few of its well known parameters are necessary: ENC, feedback capacitance, open loop gain of the inverting amplifier and the peaking time of the shaping filter.
By applying the above method, models of two charge amplifiers: MX6 and TRIPLEX [2] [3], used in the Silicon Tracker of the DELPHI experiment [4] [5], were constructed. Their schemes are shown in figure 5a and 5b.

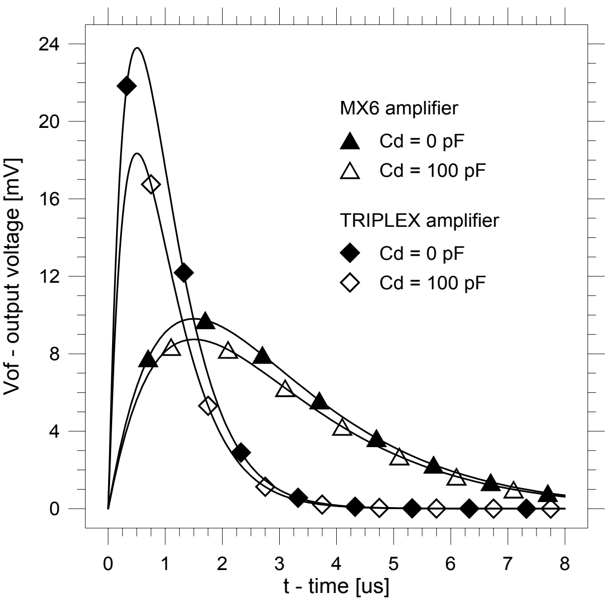

FIGURE 6 – *Simulation results: responses of MX6 and TRIPLEX amplifiers to the pulse input charge of 4 fC. They had two values of detector capacitance C_d connected to theirs inputs. Models of the amplifiers are shown in figure 5a and 5b.*

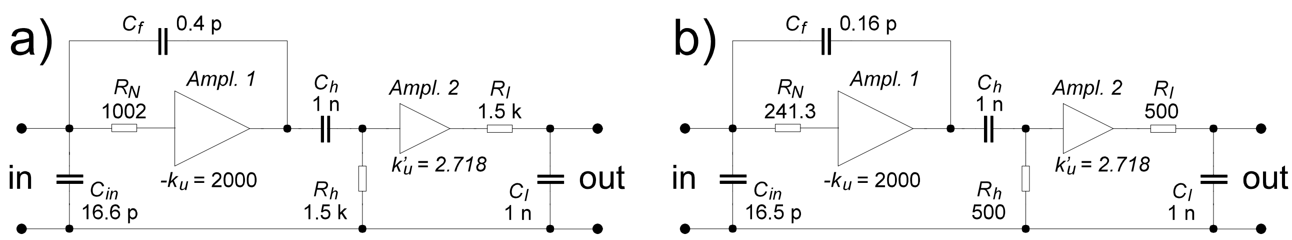

FIGURE 5 – *Models of charge amplifiers build according to the method presented in the paper. a) MX6 amplifier with parameters: α = 340 elementary charges, β = 20 elementary charges per 1 pF of the detector capacitance, τ = 1.5 μs [4]. b) TRIPLEX amplifier with parameters: α = 283 elementary charges, β = 17 elementary charges per 1 pF of the detector capacitance, τ = 500 ns [4].*

The models were simulated by means of SPICE, in order to obtain ENC dependence on C_d and to compare it to assumed one upon calculation of the models. For C_d ranging from 0 to 200 pF in 10 pF steps, we obtained ENC regression lines for MX6 and TRIPLEX amplifiers with α and β differing from the assumed ones by not more than 0.1% and 0.15% respectively.
These models can be also used to simulate the signal generation. Responses of the MX6 and TRIPLEX amplifiers to a pulse charge of 4 fC, corresponding to the charge generated by a minimum ionizing particle (MIP) on 300 µm path in silicon, are shown in figure 6.

SIMULATION RESULTS

An exemplifying detector model with the average values of parameters listed in table 1, equipped with the MX6 or TRIPLEX amplifier model, was simulated in order to examine the output signal-to-noise ratio sensibility to changes of detector parameters. The detector model included 9 strips, each divided into 20 sections. A charge of 4 fC, corresponding to the detector thickness of 300 µm and the perpendicular track of the MIP was injected into the central diffusion strip. Some of the results are presented in figures 7, 8, 9 and 10. The

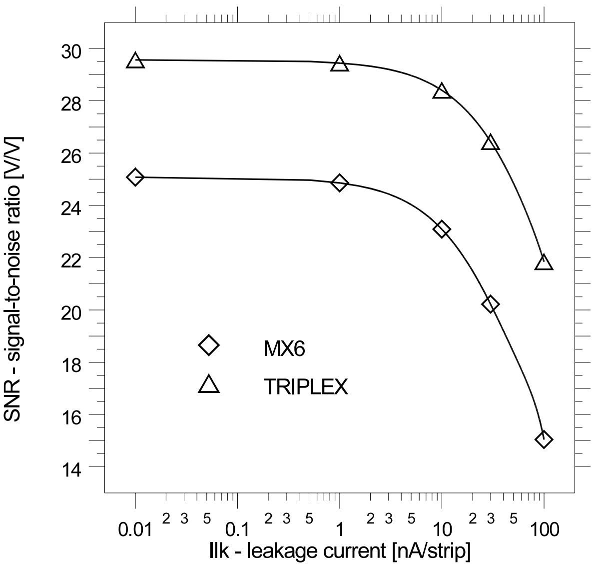

FIGURE 7 – *Simulation results of the signal-to-noise sensibility to changes of the leakage current of the exemplifying detector with MX6 and TRIPLEX amplifiers. Other model parameters as in table 1.*

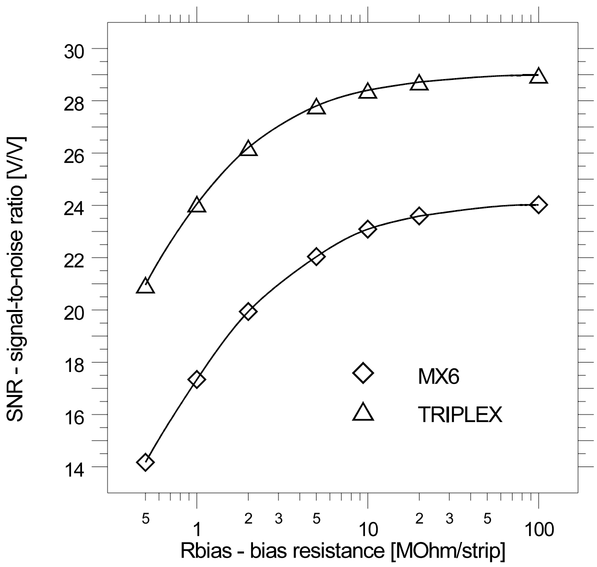

FIGURE 8 – *Simulation results of the signal-to-noise sensibility to changes of the bias resistance of the exemplifying detector with MX6 and TRIPLEX amplifiers. Other model parameters as in table 1.*

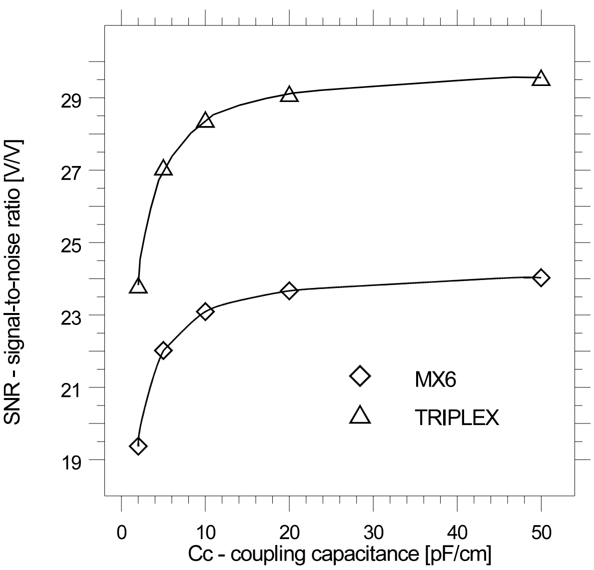

FIGURE 9 – *Simulation results of the signal-to-noise sensibility to changes of the coupling capacitance of the exemplifying detector with MX6 and TRIPLEX amplifiers. Other model parameters as in table 1.*

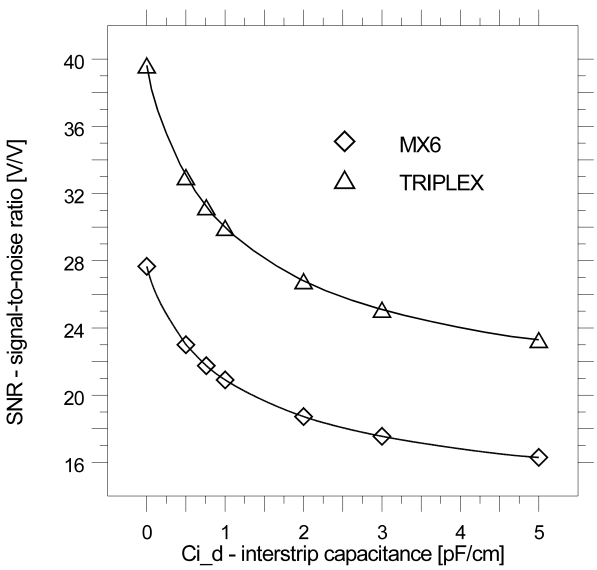

FIGURE 10 – *Simulation results of the signal-to-noise sensibility to changes of the diffusion layer interstrip capacitance of the exemplifying detector with MX6 and TRIPLEX amplifiers. Other model parameters as in table 1.*

signal-to-noise ratio is understood as the highest amplitude at the output of the amplifier connected to the strip on which the signal is generated, divided by the output noise voltage.

Detector parameter	Value
detector thickness	300 μm
strip length	10 cm
leakage current	10 nA/strip
bias resistance	10 MΩ/strip
capacitance to the backplane (Cb)	0.1 pF/cm
coupling capacitance (Cc)	10 pF/cm
diffusion layer interstrip capacitance (Ci_d)	760 fF/cm
metal layer interstrip capacitance (Ci_m)	240 fF/cm
diffusion layer 2nd neighbour capacitance (Ci2_d)	152 fF/cm
diffusion layer 2nd neighbour capacitance (Ci2_m)	48 fF/cm
backplain resistance (Rb)	10 GΩ/cm
diffusion layer resistance (Rd)	20 kΩ/cm
metal layer resistance (Rm)	30 Ω/cm

TABLE 1 – *Parameters of the exemplary detector model used in the sensibility simulations. Names in parenthesis refer to the model parameters in figure 3.*

The measured signal-to-noise ratios [4] [5] were compared with the simulation results. We examined models of the DELPHI Silicon Tracker modules, combined with the models of the readout amplifiers. As an example, the model parameters of the Rϕ side of the simulated outer layer module are listed in table 2.

Detector parameter	Value
detector thickness	290 μm
strip length	23.3 cm
leakage current	4 nA/strip
bias resistance	10 MΩ/strip
capacitance to the backplane (Cb)	90 fF/cm
coupling capacitance (Cc)	20 pF/cm
diffusion layer interstrip capacitance (Ci_d)	417 fF/cm
metal layer interstrip capacitance (Ci_m)	83 fF/cm
diffusion layer 2nd neighbour capacitance (Ci2_d)	83 fF/cm
diffusion layer 2nd neighbour capacitance (Ci2_m)	8.3 fF/cm
backplain resistance (Rb)	10 GΩ/cm
diffusion layer resistance (Rd)	20 kΩ/cm
metal layer resistance (Rm)	30 Ω/cm

TABLE 2 – *Parameters of the model of the CERN DELPHI Silicon Tracker outer layer Rϕ module. Names in parenthesis refer to the model parameters in figure 3.*

The model included 9 strips, each divided into 20 sections. Every second diffusion strip had the corresponding metal strip to which the TRIPLEX amplifier model was connected. To the central diffusion strip of the model a charge of 3.87 fC was injected, corresponding to the detector thickness and the perpendicular track of the MIP. The model simulation gave the output signal-to-noise ratio of 29.7 as compared to the measured value of 30 [5].

CONCLUSIONS

An electrical model of the silicon microstrip detectors, suitable for noise performance SPICE simulations, has been built. It takes into account all the important detector elements, responsible for the generated charge transport and for the internal noise. High level model of the readout amplifier has been also presented. The model uses only the feedback capacitance value, the open loop gain, the peaking time of the CR-RC shaping filter and the noise performance given by equation ENC = $\alpha + \beta C_d$, where C_d is the detector capacitance seen from the amplifier input. Simulations of the models of the MX6 and TRIPLEX amplifiers have shown that their noise performance agrees with the assumed one with very good accuracy.

The model of the chosen microstrip detector with average values of parameters has been combined with the models of the MX6 or TRIPLEX amplifiers. Such detection channels have been simulated to determine the influence of the detector model parameters to the output signal-to-noise ratio.

The detectors used in the DELPHI Silicon Tracker have been simulated applying these models. As an example we have presented the model of the outer layer Rϕ module equipped with the models of the TRIPLEX amplifier. The signal-to-noise ratio obtained in the model simulation agrees with the measured value within one percent.

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