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Noise Determination in Silicon Micro Strips

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Abstract

We report the study of amplifier noise on silicon micro strip detectors. We have used a fast, low noise amplifier-comparator VLSI chip with 22ns shaping time developed for the LHC to determine the noise at the pre-amp as a function of strip length and strip geometry, i.e., interstrip capacitance and ohmic strip resistance. In addition, we have tested the noise in irradiated detectors. We have compared the results with simulations using SPICE.

I. INTRODUCTION

In proposed silicon tracking detectors at future large hadron colliders like the LHC, the front end electronics has to be efficient and has to limit the noise background from the large number of channels. Efficiency and noise can be controlled via a threshold setting, either implemented in software in analog schemes, or in hardware in the so-called binary system. This threshold is set at a multiple of the noise sigma (σ_n), for example at four times σ_n in large systems like the silicon trackers for the LHC, to insure a tolerable noise occupancy in the system. In the planned LHC detector ATLAS [1], the noise occupancy has to be far below 0.1%. For planning of these large systems of more than 5 million channels, a prediction, and measurement, of the anticipated noise is necessary.

In a typical LHC detector system, the shaping of the front-end electronics (FEE) is much faster than 10 MHz, and the noise contribution from inter-strip capacitance is large, but it is not the only effect. A prediction of noise values based only on the measured total capacitance (C), and the noise slope of the amplifier measured with discrete capacitors will fail. In addition to the capacitance, the ohmic resistance of the strips (R), the coupling from the next neighbor amplifier and the shot noise from leakage currents (i_L) in the detector have to be included. Furthermore, possible changes due to radiation should be considered.

II. METHOD OF NOISE DETERMINATION

The noise measurements were performed on silicon strip detectors read out by fast-shaping FEE. The detectors are double-sided, AC-coupled, with 50µm pitch and narrow implants to minimize the inter-strip capacitance and hence, single channel noise [2]. Their depletion voltage is about 70V before irradiation, and we have varied the bias voltage as part of our test to explore sensitivity to the voltage settings. The detectors are 6cm long and 3.4cm wide. For some studies we have bonded two detectors end-to-end to make a single 12cm module in which case the FEE were mounted either close to the center across the strips, or alternatively off the detector, at the end. We used a binary read-out, where only the address of channels with pulse height exceeding a common threshold is recorded. It consists of a bipolar amplifier-comparator ASIC (LBIC) [3], and a CMOS 40MHz Digital Pipeline (CPD) [4]. Details of the FEE systems can be found in Refs. [3] and [4], here we give only the essential properties; the rise time is 22ns, the double hit resolution is 60ns, and the input noise charge as a function of external capacitance C is $\sigma_n = 700 + 32 * C\ [e^-]$. These detector modules were successfully used in a beam test at KEK to determine the sigma-to-noise ratio [4].

We employed two methods to determine the noise sigma, one was a calibration procedure, and the other was measuring the noise occupancy as a function of threshold.

As described in Refs. [5,6], the FEE can be calibrated by applying a pulsed voltage signal to the calibration capacitor of 84fF at the input of every channel, which injects a known charge into the channel. By measuring the occupancy as a function of the threshold voltage for several calibration inputs (Q_{in}=0.6,1.1,1.5,2.1,3.1,4.5 fC), the gain and input noise of the amplifier-comparator are determined: We fit the occupancy curves to error functions, which are characterized by the threshold voltages at 50% occupancy, which we call the response, and the output σ_n, which is related to the width of the curves (the difference between 88% and 12% occupancy points is $2.37 * \sigma_n$ = FWHM) In Ref. [6], it was shown that the calibration is as good as 3.5% in the response, given that the calibration circuits are carefully measured.

The noise occupancy is determined as a function of the threshold voltage, where we measure the occupancy per channel per time bucket of 25ns. It was shown in Ref. [6], that the noise occupancy is well described by an error function of (V_{th}/σ_n) which for large arguments can be approximated by a gaussian. We have found good agreement between the two methods, with the noise extracted from the occupancy being systematically 10% lower. We prefer the measurement of noise occupancy because it is a parameter of primary interest for the performance of the detectors and is sensitive to effects which contribute to the occupancy below the 10^{-3} level.

In double-sided detectors (DSSD), the capacitances are different on the two sides and we expect to measure different noise values. We have also measured an irradiated detector to assess the performance. This detector was used in a subsequent beam test [7].

III. PARAMETRIZATION of NOISE

The observed noise σ_n can be parametrized in term of several contributions:

$$\sigma_n^2 = [(\sigma_o + \beta_c)^2 + \sigma_R^2 + \sigma_I^2] + ... \quad (1)$$

where

σ_o = noise of the bare amplifier = 700 e^-

β_c = noise slope = 32 e^- / pF

C = total parasitic capacitance

σ_R = noise due to resistance of metal trace (R = 400 Ω for 6cm)

σ_I = shot noise due to leakage current

In addition, the noise is increased by about 15% due to coupling of the noise of the neighboring channels [8], In the following, we will investigate the size of the different contributions to the total noise. Smaller order effects, such as due to the biasing resistors, will not be included.

IV. RESISTANCE and CAPACITANCE

We investigated the dependence of the noise on resistance and capacitance on un-irradiated detectors, where the contribution from the shot noise is negligible. The ohmic resistance R of the metal trace contributes a noise charge of

$$\sigma_R^2 = 0.5 * kT * R * C^2/\tau * 2.71 \quad (2)$$

where τ = peaking time of the amplifier. Due to the fact that the amplifier is not connected to a discrete resistor and capacitor, but a network of distributed resistors and capacitors, the resistance noise term contributes less than that indicated in eq. (2). We studied this function by measuring the total noise of a 6cm detector alone, and of two 6cm detectors bonded together to form a 12cm long detector, which was either read out at the end or in the center, i.e. at the place of bonding of the two detectors, or at the end. The capacitance seen by the amplifier is the same in both cases, but the resistance is different. Fig. 1 shows the measure noise for the three cases for both the n-side and p-side of the double sided detectors, which were biased at about 60V. At that voltage, the capacitance is 1.5pF/cm for the p- (junction-) side and 3.7 pF /cm for the n- (ohmic-) side. In all cases, the contribution of the resistance to the noise is reduced to about 30% of that calculated from eq 2., due to the distributed network. Compared to the case where the readout is at the end, the noise for the center read-out is decreased by 11% for the n-side, and by 16% for the p-side. A SPICE simulation, including a distributed R-C network and neighboring channels found a reduction of between 10 and 15%, in agreement with our measurement (see Table 1). For ATLAS we will make use of this reduction and read out 12cm modules at the center, locating the electronics across the detectors ("center tapped"). Initial beam tests are encouraging as to the pick-up immunity of this arrangement [8].

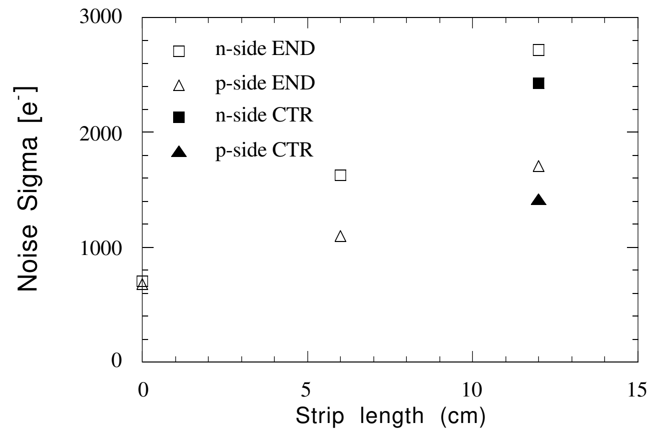

Fig. 1 Noise sigma's as function of strip length for both n- and p-side of the DSSD. The 12cm long detector was measured with both center and end connection of the FEE.

We have investigated the bias voltage dependence of the noise. The depletion voltage is about 75V and thus, the detector is just barely depleted at 80V. While the p-side capacitance is independent of bias voltage, the n-side capacitance continues to decrease with increased bias [9]. Hence the noise on the n-side continues to decrease with increasing bias. This is shown in Fig. 2, where the noise is shown for a 6cm and 12 cm, center tapped, n-side detector as function of bias voltage. In comparison, the noise of the 6cm long p-side is shown, which is much lower.

In Table 1, we prsent the measured capacitances and the predicted noise sigma's together with the measured noise sigma's. The agreement is good on the 10% level.

Side	L [cm]	FEE End/Cnt	V_{Bias} [V]	C_{tot} [pF]	σ_{pred} [e^-]	σ_{meas} [e^-]
P	6	End	60	8.9	1159	1100
P	12	End	60	16.9	1699	1700
P	12	Center	60	16.9	1458	1417
N	6	End	60	22.5	1853	1625
N	12	End	60	43.5	2907	2718
N	12	Center	60	43.5	2446	2428
N	6	End	100	12.4	1331	1370
N	6	End	200	9.4	1183	1180
N	12	Center	100	21.1	1615	1860
N	12	Center	200	16.3	1436	1550

Table 1. Comparison of noise sigmas obtained with the occpancy method (σ_{meas}), and SPICE simulations ($\sigma_{pred.}$).

V. IRRADIATION

We would conclude from the data in Fig. 2, that the n-side has much worse performance than the p-side. However, this is not true after irradiation to fluences of more than 10^{13} p/cm^2 of displacing particles (hadrons). At that point, the nbulk detectors invert, and the n-side becomes the junction side and the p-side the ohmic side [10]. Basically, all properties of the junction side, i.e. low capacitance and good charge collection, move to the n-side, while the p-side receives the higher capacitance and bad charge collection of the ohmic side. The bias voltage dependence of the p-side after inversion is not as extreme as on the pre-irradiation n-side. We show in Ref. [11], that the efficiency to collect charge is much better on the n-side than on the p-side after inversion. While the p-side is efficient only when the detector is over-depleted, the n-side is efficient even at half the depletion voltage. Given that the depletion voltage increases due to radiation, this makes the n-side the preferred side for operations long time after inversion.

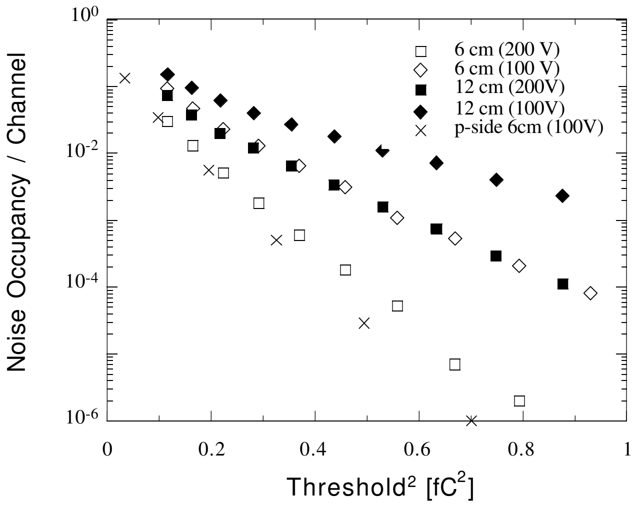

Fig. 2 Channel noise occupancy for 6 cm long and 12 cm long n-side detectors at two different bias voltages. A 6cm long p-side detector at 100V bias is shown for comparison.

In Fig. 3. we show the occupancy as a function of threshold for both the n-side and p-side for 6cm long detectors before and after irradiation. We saw in Fig. 2 that the n-side, before inversion, has to be biased to about 150V to reach our goal of 10^{-4} occupancy. After irradiation, the n-side of the 6cm detector has a noise occupancy slope which is smaller than the p-side before irradiation (while the p-side is a little worse). We can predict, that after irradiation, the n-side noise of 12 cm long detectors will be below 1500 e^-.

The shot noise from the leakage current (i_L) can be described as:

$$\sigma_L{}^2 = 2 * i_L * \tau / e * F \tag{3}$$

which amounts to $\sigma_I = 524 * (i_L/\mu A)^{0.5}\ e^-$ for $\tau = 22$ns, approximating the shaping constant F = 1. We have measured the leakage current at 100V and find $i_L(100V) = 1.6\ \mu A$. Note that this leakage current is of the same size as expected at the LHC after 10 years of operation, assuming cooling at 0^oC. Using eq. (3), we expect a noise contribution of about 20%, which is consistent with the measured noise of about 1100e^- on the irradiated detectors.

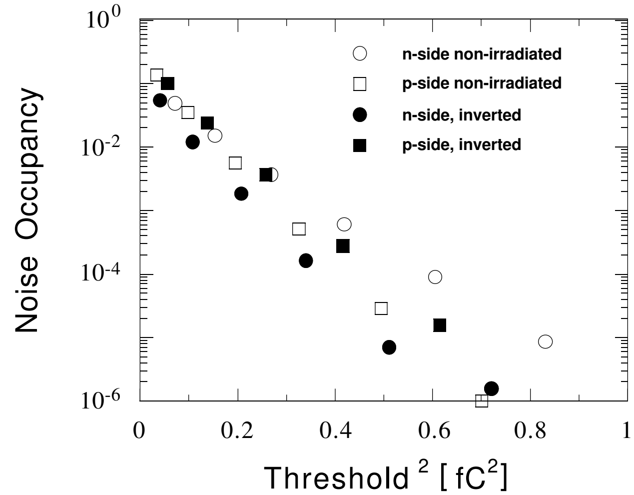

Fig. 3 Channel noise occupancy for 6cm detectors at 100V bias. Both the n-side and p-side are shown, before and after inversion.

VI. CONCLUSIONS

We have determined the noise in double-sided silicon micro strip detectors. We find the contribution from the resistance reduced due to the distributed R-C network, and obtain an 11-17% reduction in noise occupancy of a 12cm long detector with read-out in the center instead of from the end.

The noise on the n-side is bias voltage dependent for un-irradiated detectors and satisfies our goal of 10^{-4} noise occupancy of 12cm long detectors at bias above 150V. In the future we will use detectors with 75µm pitch, where we expect reduced noise because of reduced capacitance and strip resistance.

Irradiated detectors exhibit reduced noise on the n-side. The leakage current contribution to the noise is as expected.

The dependence of the noise on capacitance, strip resistance and leakage current is as expected from SPICE simulations.

VII. ACKNOWLEDGMENTS

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