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Quality Assurances for double-sided silicon microstrip sensors in the Silicon Tracking System of the CBM Experiment at FAIR

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The Silicon Tracking System (STS) is the central detector system of the future Compressed Baryonic Matter (CBM) experiment [1] at the Facility for Anti-proton and Ion Research (FAIR) [2], Darmstadt, Germany. STS faces numerous challenges [3] including the design constraints, tracking in high magnetic field, high precision in momentum resolution of $\triangle p/p \approx 1\%$, high radiation load $\approx 1\times 10^{14} n_{eq}/cm^2$ for SIS-300 energies, up to 1000 charged particles/interaction at rates of $\approx 10\ MHz/cm^2$ and to run a self-triggered front end electronics (FEE) to read 2 million channels (or strips). These constraints and severe conditions makes it significantly important to have a systematic quality assurance (QA) to investigate, test and exclude the silicon sensors on the basis of acceptance criteria determined by the experimental operational requirements. In this paper, all significantly important and mandatory tests required for QA test of the double sided microstrip sensors are discussed in detail. QA test includes all visual/optical test, pinhole test, bulk measurements, coupling capacitances and some interstrip parameters effecting the viability, operational ability and performance. Results have been shown for each QA test with an explanation of their significance, derived parameter from the test, frequency of the test and how many sensors have to be tested for the same.

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1. Silicon Tracking System at the CBM experiment

The Silicon Tracking System (STS) project is realized in cooperation with institutes from Germany, Poland, Russia and Ukraine. The detector system will be constructed and installed into the CBM experiment for the start of FAIR operation in the year 2018. The STS is main detector system in the CBM experiment at FAIR and responsible for reconstruction of the trajectories and momentum of all the charged particles originating from the interaction of heavy ion beam and the target. Up to 1000 charged particles are produced per interaction, at rates up to 10 MHz to enable CBM physics with rare observables. The track reconstruction has to be achieved with 95% efficiency and a momentum resolution 1%. These requirements can be fulfilled with a tracking system of 8 low-mass layers of silicon microstrip sensors located at distances between 30 cm and 100 cm downstream of the target inside the dipole magnetic field. Fig. 1 and Fig. 2 shows a latest version of CAD design of the STS in the CBM experiment and a schematic representation of ladder structures of the stations in the STS project.

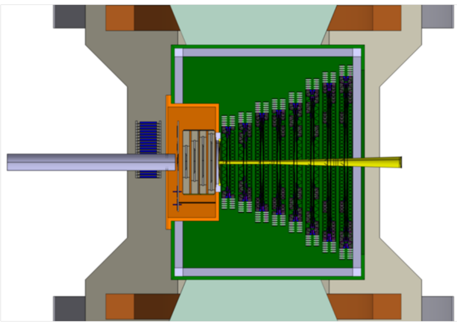

Figure 1: Silicon Tracking System at the CBM Experiment (indicated in green).

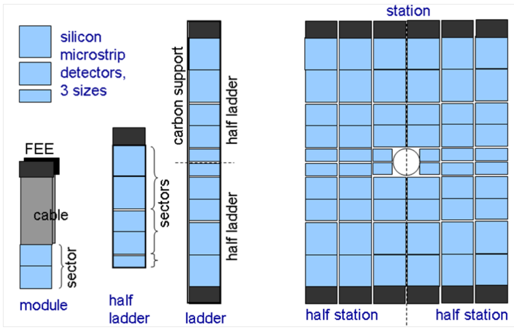

Figure 2: Ladder and station scheme for the STS project.

2. Silicon strip sensors

The STS will be populated with double-sided silicon micro-strip sensors. Those will be mounted onto a low-mass mechanical support structure made from carbon fiber beams and will be read out through low mass multi-line fine-pitch flat cables by front-end electronics located outside of the physics acceptance at the periphery of the stations. Presently the STS project is considering three types of double sided silicom microstrip sensors. These sensors are 300 μm thick and are of area 6.2 cm $\times$ 6.2 cm, 6.2 cm $\times$ 6.4 cm and 6.2 cm $\times$ 2.2 cm. The double sided sensors have 1024 strip per side per sensor to be read by FEE. The strip pitch for all the sensors are 58 μm and strips width is about 18 μm. Moreover, Sensor prototypes with smaller dimensions (1.5 cm $\times$ 1.5 cm) have been produced alonside large sensors for electrical characterization and testing. For the moment we have been producing sensor prototypes from CiS Forshungsinstitute, Erfurt-Germany [4] and Hamamatsu Photonics, Japan [5].

3. Quality Assurance

Double sided silicon sensors are one of those sensor types which need utmost care in production. There are still some areas where one has to investigate to make its performance better,

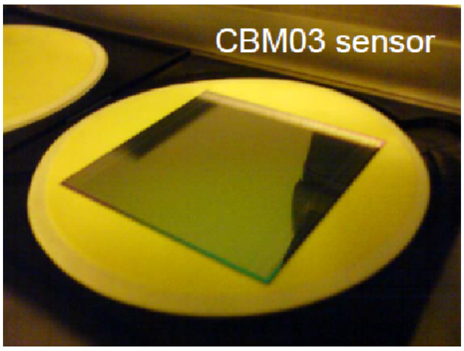

Figure 3: CBM03 prototype double sided silicon microstrip sensor.

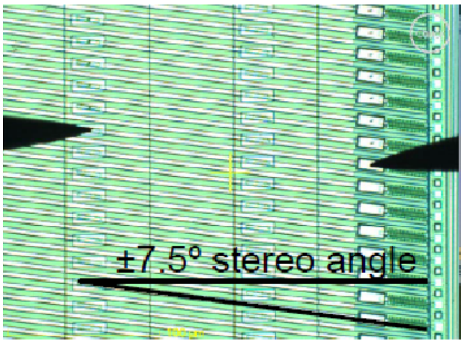

Figure 4: ±7.5 degree Orientation of strips in prototype sensor

since these sensors are still evolving and commercial production of these sensors is not so very popular except in some high energy physics experiments. The sensor needs tough characterization and investigation to understand their behavior and evaluate the operating condition for the same. At Detector Laboratory in GSI Darmstadt, one of our prime focus is to prepare systematic QA test procedures for our silicon sensors before the mass production phase which is scheduled now to 2016.

Quality Assurances for silicon microstrip sensors in our view can be divided into three main cat-

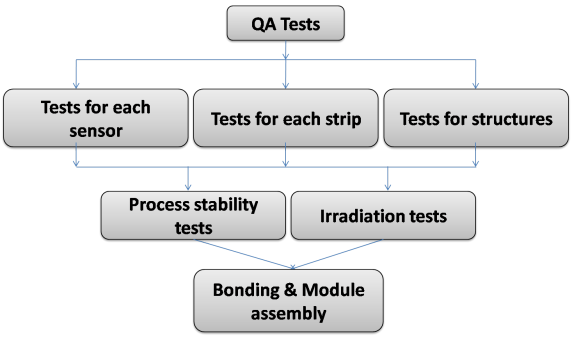

Figure 5: Philosophy and steps in Quality Assurance tests in STS project.

egory namely, (a) Tests for each sensor because we need to know the overall health of the sensor, (b) Tests for each strip on 10% of all sensors because these test involves physical interaction of probing needles and surface of sensors and it can damage the sensors so it is recommended to test only 10% of total for key interstrip parameters and (c) Tests for structures only 1 wafer/production line as it provides all information of the production process for the whole wafer. Then we need to perform the process stability tests and irradiation tests for radiation hardness. Finally, after these tests we could send suitable sensors for bonding and module assembly. The point of interest is to decide the number tests and frequency of these test needed. The QA tests include visual/optical test, pinhole test, bulk electrical test, coupling capacitance, interstrip resistance and interstrip capacitance. QA also includes test of sensor performance with readout electronics using Laser tests and LED for operational and performance tests. In this paper we restrict only to QA with electrical characterization for microstrip sensors. All these tests are discussed in following sections.

4. Visual inspection

Visual inspection is first and the foremost test which needs to be performed for each and every sensor that has been received or delivered from the manufacturer. This provides a first insight to the quality of the sensor handling and one can immediately decide if the sensor has to be tested or it is already broken. Broken sensor here means not even good for bulk tests. These test can be performed over a traveling microscope (high magnification for eg. 2X or 10X) or Wafer Prober.

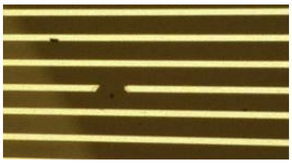

Figure 6: Loss in strip integrity.

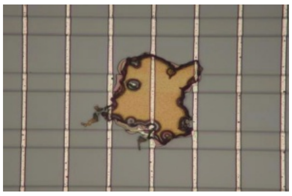

Figure 7: Scratch on the sensor surface.

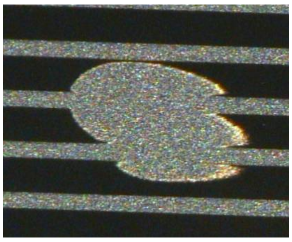

Figure 8: Strip shortening.

Wafer Prober can provide detail investigation about any common strip failures which could have been the result of inefficiency of the production cycle, etching etc. The Common strip failures are namely, open strip, shorted strip with the neighboring strip, open implant, open implant at via, open bias resister, shorted bias resistor with neighboring strip resistor etc. Some of these are shown in Fig. 6, 7 and 8 [6].

5. Pinhole Test

Total charge produced by the incoming particles in the sensor bulk material is collected by the strip and with the help of these coupling capacitance which has to be read out over the front end electronic (FEE). The significance of the pinhole test is to get the idea of the isolation of the oxide layer between the AC pad and DC pad. Each prototype sensor has 4 AC pads and 1 DC pad per strip. A schematic representation of a pinhole is described in the Fig. 9. Pinhole test is performed

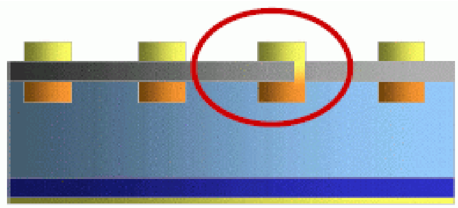

Figure 9: Schematic representation of pinhole in the implant.

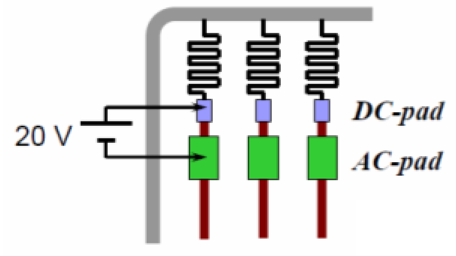

Figure 10: Circuit daigram for the pinhole test or isolation test.

by a simple test by connecting the AC pad and DC pad with the help of two probe needles from the Wafer Prober of the same strip to a test voltage and observe the current Fig. 10. A very low current around fA is observed if the oxide layer is intact and isolation is perfect. If small current of about tens of pA or more flows through the strip while testing shows that the strip has pinhole or the oxide layer is not perfect. In other words, the AC pad and the DC pad is not isolated.

6. Bulk electrical test

Bulk measurements test are the one of the significant tests that is to be performed to all sensors as it gives overall sensor health including effect of ambient temperature, depletion voltage and operational voltage range.

6.1 Leakage current

Leakage current is measured as a function of reverse-bias voltage applied across the silicon sensor using a voltage source (Keithley Model 2410 picoammmeter). This is one of the bulk measurements that have to be performed before actual mounting of the sensor to a module. This measurement gives us overall health of the sensor [7]. The sensor is considered to be healthy and not abnormal if the average leakage current per strip is less than 5 nA. In our case we set an acceptance of 2 nA per strip. Measurement of one such leakage current for CBM03' non irradiated prototype sensor is shown in Fig. 11.

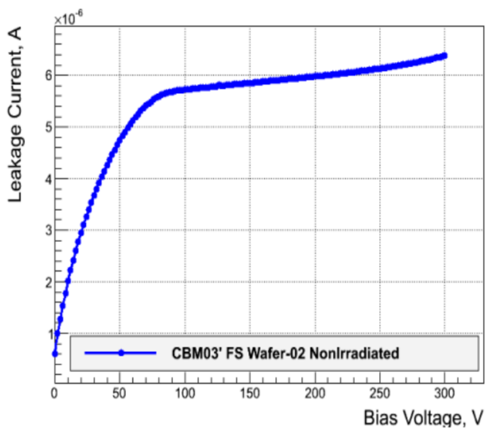

Figure 11: Leakage current measurement for CBM03' prototype sensor.

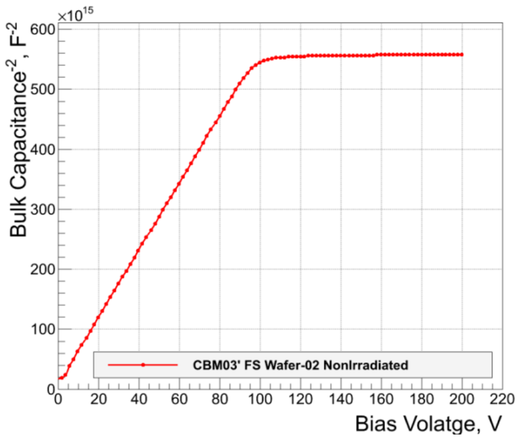

Figure 12: Depletion voltage measurement for CBM03' prototype sensor.

6.2 Depletion voltage

Silicon microstrip sensors require a reverse bias potential to create a region free of mobile carriers between the p-side and n-sides. This region is called the depletion layer. Depletion voltage is the bias voltage that extends the depletion layer in the entire depth of the bulk material of the sensor. This allows the charge liberated by an ionizing particle which has to be collected. To obtain the maximum charge collection efficiency, the silicon micro-strip sensors are operated in over depleted mode. Bulk capacitance measurement of an over depleted sensor using a coupled Kiethley voltage source and a QuadTech LCR meter. Depletion voltage (V_{fd}) is obtained from the knee point of inverse square capacitance as a function of biased voltage (Fig. 12). From the depletion voltage we also get the operational voltage V_{op} range, normally it is recommended to operate sensor at V_{fd} = $V_{fd} + 20\ V$.

7. Coupling capacitance

Measurement of the coupling capacitance is significant because it provides insight to the sensor performance. The value of coupling capacitance allows to judge about the transmission of the signal. The ratio of coupling and interstrip capacitances affects the value of the signal transmitted to the read-out electronics. Coupling capacitance measurements were performed at the clean room environment using a wafer prober from Züss, voltage source from Kiethely and LCR meter from QuadTech. A small voltage is applied to the AC pad and the DC pad of the same strip of a over depleted sensor to get coupling capacitance. The measurement is done a low frequency (i.e., 10 kHz) knowing the fact that coupling capacitance is frequency depended at higher frequencies. Neighboring strip were connected to a virtual ground to avoid field distortions on the surface of the sensor. These test are performed only at a maximum of 10% sensors as this test is categorized under test of strips.

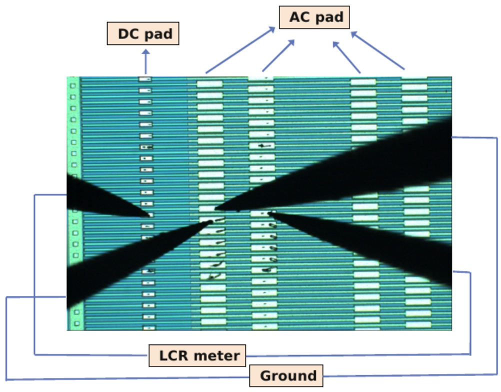

Figure 13: Coupling capacitance measurement: Positioning of needles in the setup

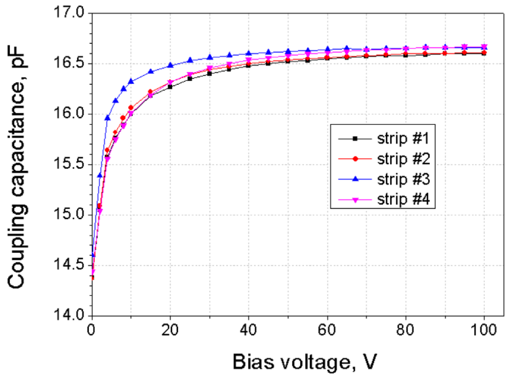

Figure 14: Coupling capacitance measurement at different strips for CBM02 prototype sensor.

8. Interstrip resistance

The value of the interstrip resistance along with the interstrip capacitance determines a number of strips over which the charge produced by an ionizing particle in distributed (clusters) and consequently, describing the spatial resolution of the detector. Conclusions that can be drawn from the value of the interstrip resistance and its variation while a detector is affected by different factors on the state of its surface, defect content in the bulk silicon. shows the quality of performance of the p^+-stop structure. The measurement of interstrip resistance is not trivial. In principle the interstrip resistance varies from sensor to sensor but is in the order of 100 M Ohms. As in the previous section, it was mentioned that these following test can only be performed with the biased sensor and preferably in an over depleted mode. A test voltage is introduced between two neighboring strips ranging from (-2 V or +2 V) and the interstrip current is measured. The value $\triangle$V/$\triangle$I from the graph gives us the interstrip resistance (Fig. 15). During the measurement of such kind, one should try to avoid the risk of distorting the electrostatic fields within the interstrip region of the sensor being under the total depletion voltage. These test are performed only at a maximum of 10% sensors as this test is categorized under test of strips.

9. Interstrip capacitance

In double-sided, AC-coupled silicon microstrip detectors, the signal to noise ratio is a function of detector capacitances: the coupling capacitance influences the signal strength and the interstrip and body capacitances the noise level. In addition, the resistance of the metal strip can influence the signal strength for fast shaping [14]. The parameter that determines the capacitances is the geometrical shape (width and length) of the strip. The interstrip capacitances can be lowered by reducing the width of the strips. As in STS we have a strip width of around 18 Âţm and strip pitch of 58 Âţm. Interstrip capacitances is the main contribution to the noise level. One of the measurements for the interstrip capacitance for CBM03 sensor prototype is shown in Fig. 16. These test are performed only at a maximum of 10% sensors as this test is categorized under test of strips.

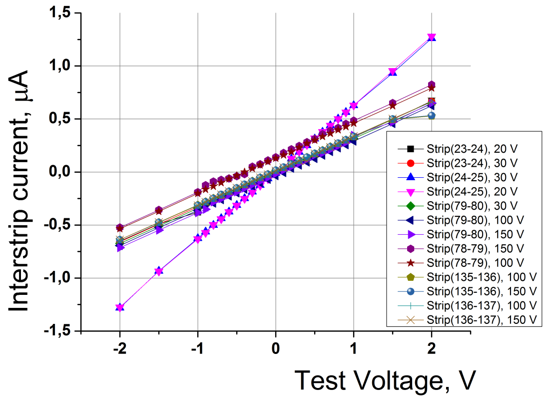

Figure 15: Interstrip resistance measurement.

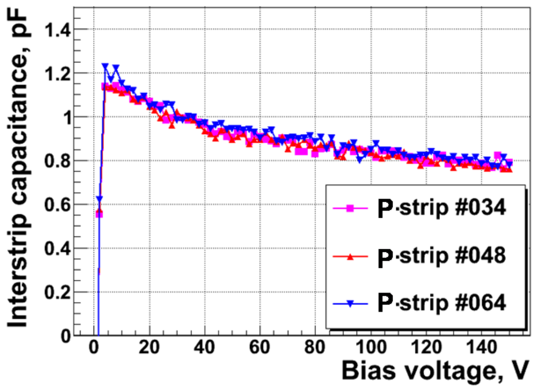

Figure 16: Interstrip capacitance measurement.

10. Radiation Hardness test

As all our sensors have to be operational in the high fluence(radiation) environment. It is obvious to investigate and test the radiation hardness of these prototype sensors. The basic post irradiation effect is seen as increase in leakage current and change in depletion voltage due to defects formed by the irradiation. Fig. 17, shows how leakage current in the prototype silicon

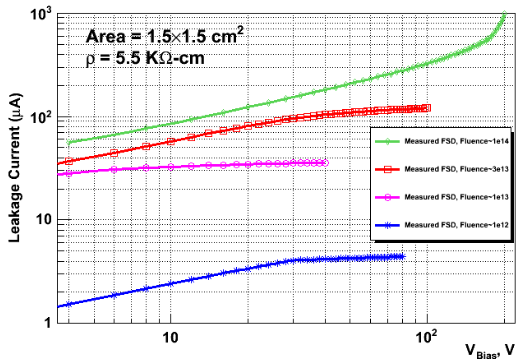

Figure 17: Leakage current measurement for radiation hardness.

sensors irradiated with neutron at TRIGA III reactor in Ljubljana, Slovenia. increases from nm for the non irradiated 11 to range to μm and even more depending upon the fluence (fluence is represented in terms of 1 MeV neutron equivalent) and also the change in depletion voltage which first gradually decreases and then after a minimum full depletion voltage it again increases with increasing fluence called Type inversion.

11. Laser test

The band gap of the silicon is 1.12 eV and infrared light of wavelength $\lambda = 1060$ nm has an energy of 1.17 eV, the photons are absorbed in the thin silicon material and produce charge in the medium. The absorption depth of the infrared light in silicon is around 500 μm [8] and our silicon microstrip sensor is 300 μm thick. So laser beam deposits the same energy like a particle beam which passes though the medium. The idea here is study the response of the sensor at different location on the surface of the sensor and figure out the discrepancy in the response if there is any. Testing the sensor module which is a sensor plus front-end electronics (FEB) is an important QA procedure This test qualifies the sensor for preparation of much bigger unit for the STS which included ladders made up of sensor modules and then to half stations. The setup is shown schematically in Fig. 18 A customized infrared laser from Sacher Lasertech [9] with

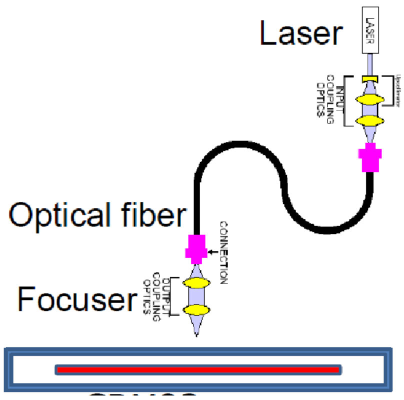

Figure 18: Schematic representation of Laser test setup.

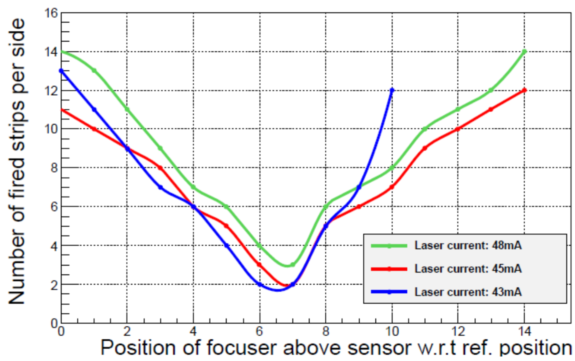

Figure 19: Calibration of focuser at diferent laser currents.

maximum power < 5 mW is used in a pulsed mode coupled to optical fiber beam delivery system. The fiber is then coupled with a multi lens focuser [10] which provides a 13 μm spot size of beam at a working distance of 10 mm above the sensor surface. Calibration of focuser was done before proceeding to the measurements. From the calibration curve Fig. 19, we conclude the best position in z direction of the focuser above the sensor surface and by tuning the laser current we can achieve charge collection only from one strip per side of the sensor. Operating the pulsed laser at 40 mA current to inject charge of about 24000 electrons, which is equivalent to 1 minimum ionization particle (MIP) and investigate the response. The Fig. 20. shows the distribution of total digital amplitude from each side of the sensor. From this distribution one observe only one strip cluster which confirms we collect charge from one strip per side.

Then we move from the one strip to other in one direction (x or y) to scan the sensor which has 256 strips on each side for the strip integrity, bonding failures, channel gain and also investigate response at different geometrical location on the sensor surface. Fig. 21 shows the hit position in one such measurement exercise from the laser measurement.

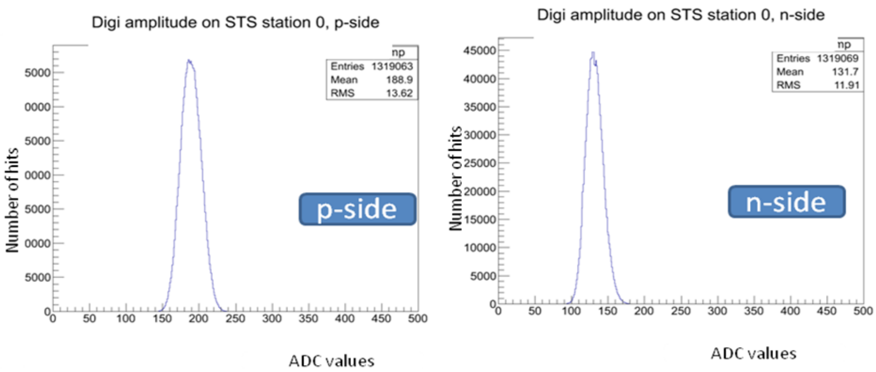

Figure 20: ADC distribution for the p and n-side of the sensor.

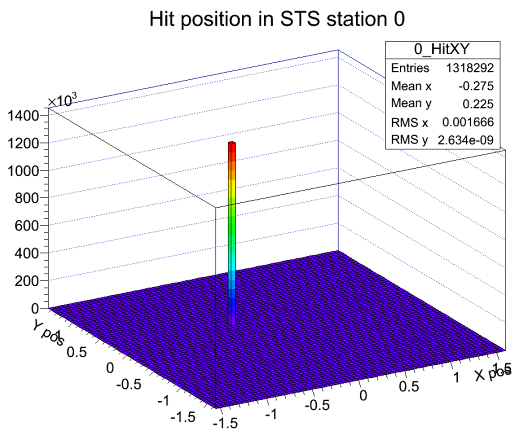

Figure 21: Hit position of the laser beam on the sensor surface.

12. LED test

The most common way to check the whole sensor + FEB module is by using radiation sources like Am-241 and Sr-90, the Infrared LED test is the fastest test for a boarded sensor on a PCB and bonded to read over the n-XYTER electronics. Also, it is free from radiation sources and shielding requirements in the former case. The test can be used to investigate or gain knowledge about following features of the sensor: (1) Bonding stability of the strips or number of broken bonds in the sensor. (2) Number of dead strips (if any) or in other words, strips integrity. (3) Gain variation in the channels of the sensor. (4) Noise in the channels when the sensor is biased and (5) Overall health of the sensor when connected to the front-end electronics and performance.

Fig. 22 show first results from the LED test station in our laboratory. This test is performed by inducing collimated beam ($\sim$5 mm) of photons on an over depleted silicon sensor using Infrared LEDs (λ = 1060 nm) in a pulsed mode of 10 ns to create charge particles in the silicon sensor and detect them by our n-XYTER based readout system. In Fig. 22, we could easily obeserve the shape of the collimated LED on the sensor surface and the dead strips in the middle of the illuminated area. it also explains that charge is collected not only by one strip but multiple strips at a given instant. The amplitude not been similar can be explained on the fact that due to collimation the

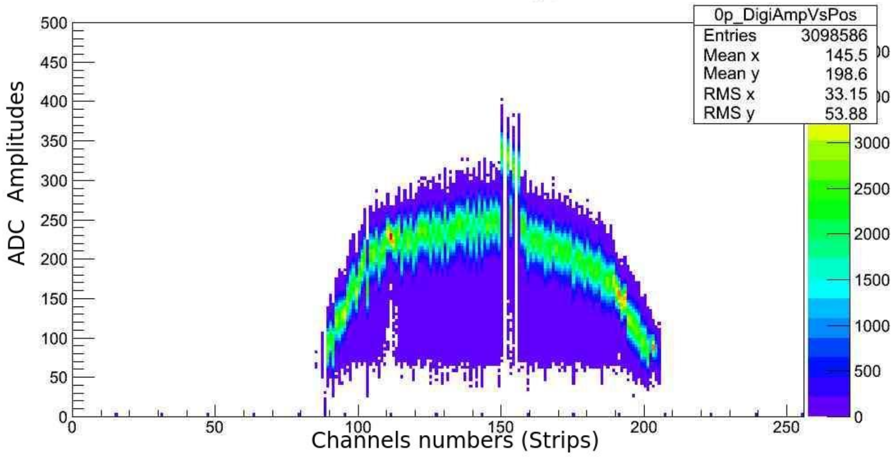

Figure 22: Results from the LED tests on silicon microstrip sensors.

length of strip exposed to infrared beam is not same for all corners strip which results in such shape. The results from the LED test proves that we can can enough information of dead strips, bonding failures, noise and sensor performance efficiently and quickly without using radiation source.

13. Conclusions

From the systematic studies of the silicon microstrip sensors we have now identified important parameters and test which needs to be performed on the sensors for the Quality Assurance. This study also gives and information about the number of test and frequency of the tests. Visual and Bulk measurements to all sensors. Coupling capacitance, Bias resistance and Interstrip measurements on 10% of sensor. Radiation hardness, Current and process stability to one sensor per wafer and Laser scanning and LED test to a few sensor to check the noise performace with the electronics.

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