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CONSTRUCTION AND PERFORMANCE OF SILICON DETECTORS FOR THE SMALL ANGLE SPECTROMETERS OF THE COLLIDER DETECTOR OF FERMILAB

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The manufacturing process of a series of position sensitive silicon detectors is described together with the tests performed to optimize the performance of the detectors. The detectors are Schottky diodes with strips on the ohmic contact which allow to determine the position of the incoming ionizing particles by charge partition.

Four detectors were assembled in a telescope and tested inside the vacuum pipe of the Tevatron Collider at Fermilab. The system is a prototype of the Small Angle Silicon Spectrometer, designed primarily to study p–p̄ elastic and diffractive cross sections, and is a part of the Collider Detector of Fermilab (CDF).

Several tests were performed to check the efficiency and the linearity of response of various regions of the detectors. Scans of the beam halo were also done both in high and low β optics to check how close to the beam the detectors could be operated. Finally, the dependence of the detector response on temperature and integrated radiation dose was investigated.

1. Introduction

Position sensitive silicon detectors look very attractive for colliding beam experiments. Until now, implementation of these detectors was considered mainly for heavy flavour tagging by means of microvertex detectors [1]. As a matter of fact the high spatial resolution coupled with the possibility of operating under vacuum make such devices very promising tools also in experiments of elastic and diffractive scattering, since they would allow to reach very small t values.

The Small Angle Silicon Spectrometer of the Collider Detector of Fermilab (CDF) will consist of seven stations of silicon detectors covering the full azimuthal angle and polar angles between ~0.2 and ~15 mrad. By exploiting the bending power of dipoles and quadrupoles of the machine they allow to measure p–p̄ elastic scattering down to very small t-values ($0.04 \leq |t| \leq 2$ GeV/c^2), as well as the total cross section. Diffractive dissociation will also be measured up to masses as large as physics will provide (hundreds of GeV) [2,3].

To study the performance of a prototype insertion, four position sensitive silicon detectors were manufactured and assembled in a telescope which was installed and tested inside the Tevatron beam pipe at Fermilab. We report here on the results of these tests.

2. Manufacturing process of the silicon detectors

The raw material was high purity n-type silicon with nominal resistivity ($\rho \sim 10\,000\ \Omega$ cm) and a thickness, ranging between 820 and 950 μm. After lapping and mirror finishing of the surfaces the wafers were cut to a petal-like shape by a diamond wire saw. Particular care was taken in surface treatment and in curing edge

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effects in order to reduce leakage currents and to minimize dead regions. A smooth lapping of the edges and a short etching of the exposed surfaces resulted in a strong reduction of the edge component of the leakage current.

The diode structure was obtained through evaporation of aluminum and gold, providing an ohmic contact and a Schottky barrier respectively. The strips were produced with a lithographic process on the aluminum side in a clean room. A 4 μm thick positive photoresist layer was deposited with a spinner on the ~1000 Å thick aluminum film. After carefully aligning the substrate with respect to the Ni–Cr glass mask, the wafers were exposed to a 200 W UV lamp on a Kasper Mask Aligner. After development, etching of the aluminum and stripping of the residual photoresist the detectors were mounted on laser cut alumina sheets. The silicon crystals were glued to the alumina boards by a vacuum compatible epoxy.

By ultrasonic bonding the detector strips were connected to the printed circuit on the alumina board by 20 μm aluminum wires. Coated copper thin wires were used to connect the pads on the alumina sheets to the pins of the vacuum feedthroughs (fig. 1).

Two petal-shaped detectors have circular θ-strips, two others have approximate φ-strips. The φ detectors have 40 parallel 100 μm wide strips, 1 mm apart from each other, while the θ detectors have 35 arch-shaped strips with the same width and separation, such that the full system allows to measure the $r-\phi$, $r-\theta$ coordinates of the incoming particles. A guard ring structure was used to prevent residual edge leakage current.

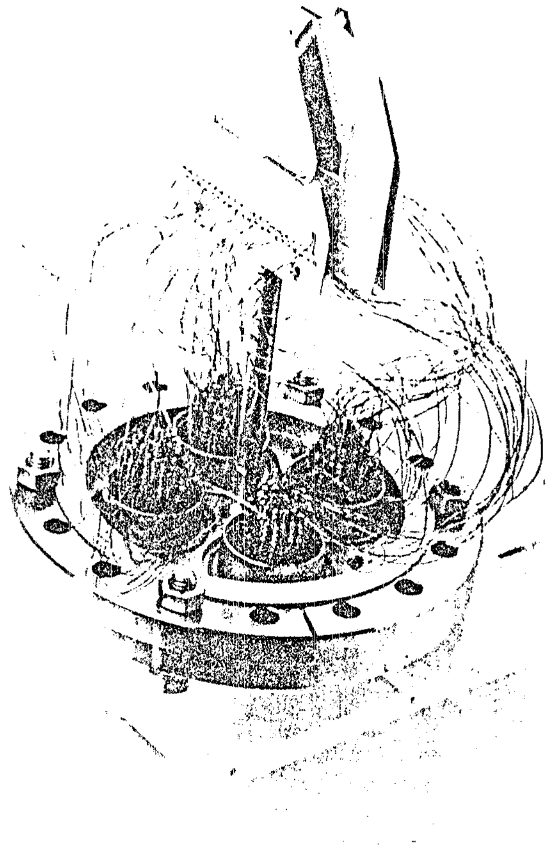

Fig. 1. The prototype telescope assembled on the vacuum flange.

3. Measurements performed on the detectors

The current vs voltage characteristics of some detectors are shown in fig. 2; the arrows indicate the adopted working points. The solid lines correspond to measurements of the inverse current after subtracting the contribution of the current from the guard ring, while dashed lines represent the overall current including the guard ring. For three detectors the two curves perfectly overlap, showing that the procedure adopted to prevent this source of current was fully effective. Only in one case the residual edge leakage current is appreciable. The depletion voltage was studied through the capacitance vs voltage curves which show the typical $V^{-1/2}$ behaviour (fig. 3), and then checked with minimum ionizing particles crossing the detectors.

A systematic study involving several prototype detectors was devoted to understand the behaviour of the different strips. For each electrode we plotted the dependence on bias voltage of the interstrip resistance and strip capacitance. The first one shows a sharp increase when the depletion region extends until the ohmic contact and injection starts. The second one shows a flat plateau when all the ionization produced in the diode is collected by the electrodes (fig. 4).

This systematic work allowed to choose the operating bias for each detector of the test telescope and to reach an improved understanding of the performance of each electrode. By setting the voltage just below full depletion, most of the charge produced in the diode is collected and, with reasonable values of reverse current, it becomes possible to exploit the resistance in the interstrip region to share the charge between the electrodes in proportion to the conductance.

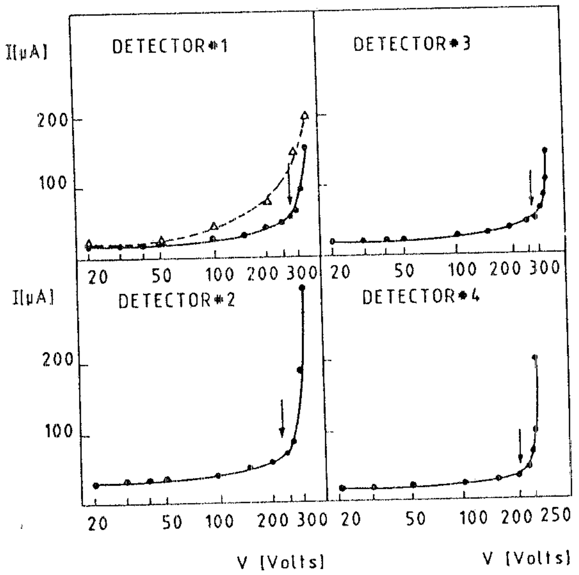

Fig. 2. I–V characteristics of the four detectors.

By increasing the voltage the depletion layer becomes thicker and the interstrip resistance R, which is due to the resistive layer of undepleted silicon at the ohmic contact, increases too. Since this resistance is a series resistance at the input of the amplifier, higher values of R would be preferable. However, when the voltage is increased, the reverse current increases too and some compromise must be made. We found that a good working point was a reverse current per strip of

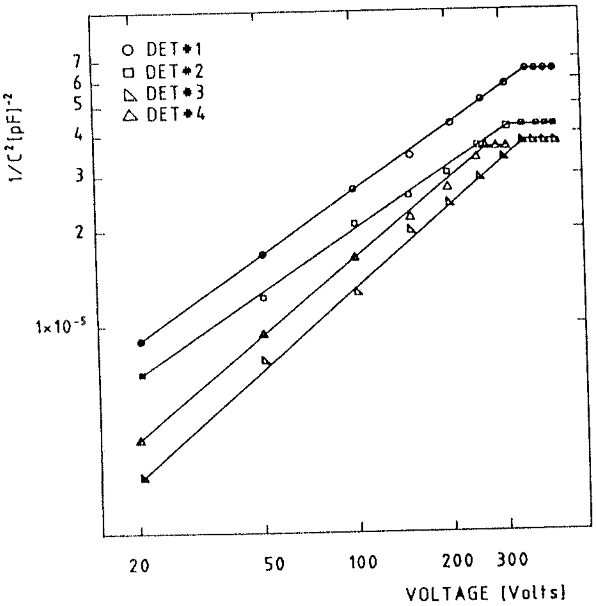

Fig. 3. C–V curves for the same detectors; all the strips are connected in parallel.

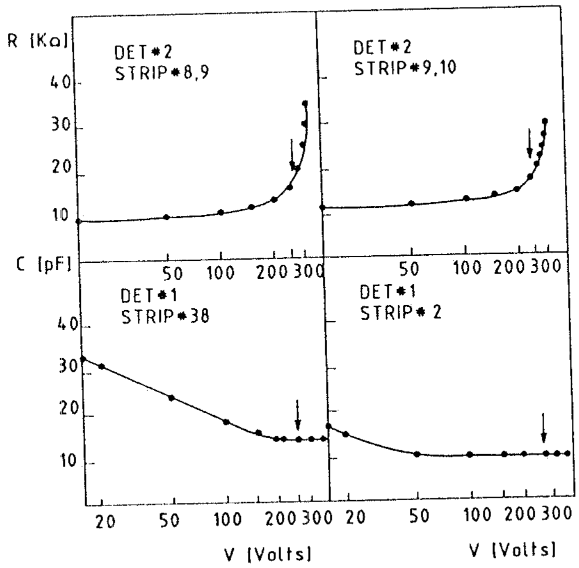

Fig. 4. Interstrip resistance and strip capacitance versus voltage for some typical electrodes.

the order of 500 nA and a corresponding interstrip resistance larger than 10 kΩ.

4. Test results

In order to test the performance of the detectors in their working environment, four detectors were inserted inside the Tevatron beam pipe. The silicon detectors were mounted on a supporting rod held on a movable flange-bellow system which was remotely controlled. This allowed us to vary the distance of the detectors from the beam, depending on beam conditions, to study how close to the beam one could set them in the small angle scattering experiment.

The signals from the strips were amplified by a set of commercial charge sensitive amplifiers (LeCroy HQV 820) located outside the vacuum feedthroughs, and were digitized by the "Rabbit" system of CDF and read out on an IBM-PC.

Different measurements were performed with minimum ionizing particles in the beam halo and the sharing of charge between adjacent strips was carefully tested. When a particle crosses the interstrip region both strips are fired, and on each electrode a pulse height distribution is produced similar to those shown in fig. 5. A simple sum of the two distributions produces a clean Landau peak. The signal to noise ratio is 13 to 1 in the case of fig. 6. A typical value for this ratio was 12 to 1. In these conditions it becomes possible to determine the position of a crossing particle by interpolating the charge collected by two adjacent electrodes [4]. The accuracy in reconstructing the impact point with this method is in principle limited only by the signal to noise ratio. This limit corresponds, in our case, to ~80 μm. The response of some strips to a uniform flux of particles is shown in fig. 7; the flatness of this plot can be taken as a test of the linearity of response of the different regions of the detector.

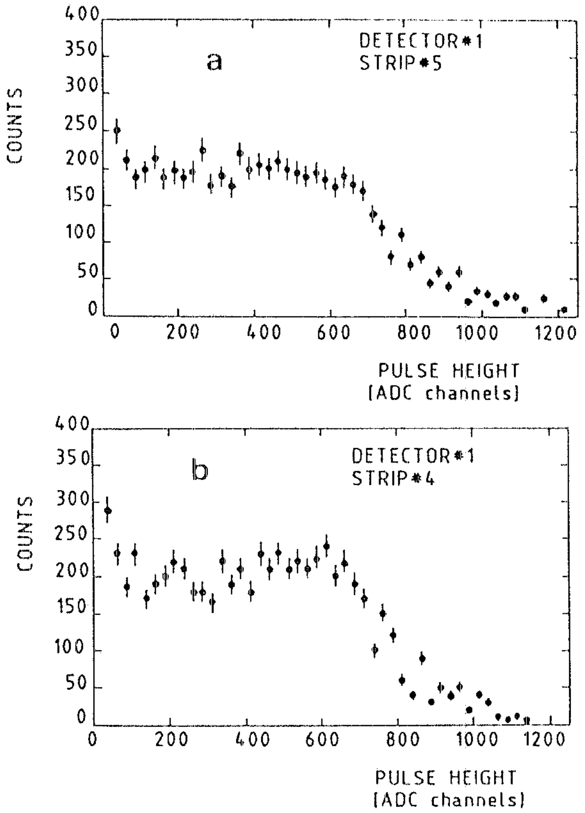

Fig. 5. (a) and (b): Pulse height distributions of two adjacent strips when mip cross the interstrip region.

Different scans of the beam halo were performed in order to understand the minimum distance from the beam at which the detectors can work. Fig. 8 shows the detectors placed in a working position. Limiting

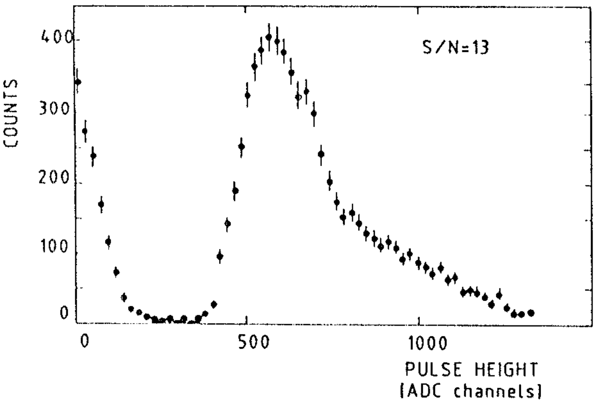

Fig. 6. Sum of the pulse height distributions of two adjacent strips.

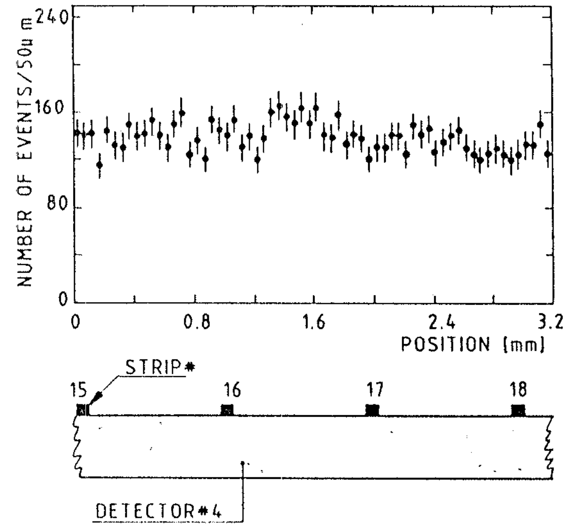

Fig. 7. The response of detector 4 to a uniform flux of particles.

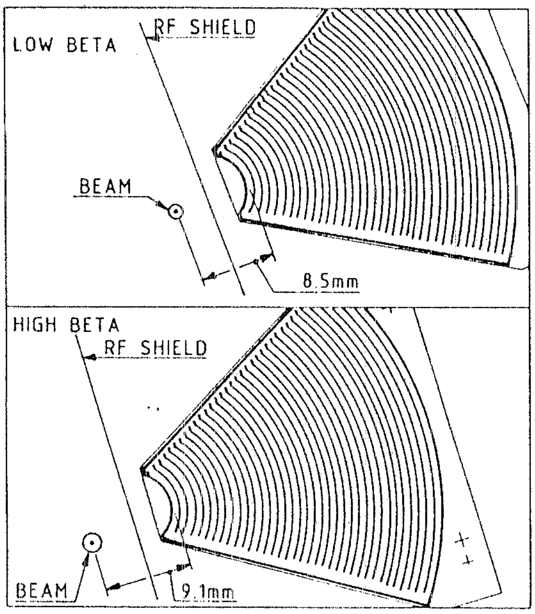

Fig. 8. Sketch of the relative position of the telescope with respect to the beam in low and high β optics. The quoted distance is the distance between the centre of the beam and the first active strip of the detectors.

the rates of the incoming particles to reasonably low values (30–40 kHz), distances of 9.1 and 8.5 mm were reached in high and low β optics respectively, without any special beam manipulation.

5. Temperature and radiation dependence

A worrying phenomenon was noticed a few days after installation of the detectors. A steady increase in the reverse current of all detectors was monitored. Vacuum or radiation effects could not account for it by any means. This effect has been traced later as being due to heat transfer from the beam pipe and from the preamplifiers sitting on the flange. A forced ventilation or some other cooling system of the supporting flanges is foreseen in the final installation in order to remove this source of heat.

The overall dose integrated during the test was about 500 rad corresponding to ~15 rad/day. From previously performed measurements we know that up to a total irradiation dose of 10^4 rad no effect on the performance of our detectors can be expected. Therefore, we can foresee that during the experiment the detectors will operate comfortably for at least one full year.

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