



# Characteristics of irradiated silicon microstrip detectors with $\langle 100 \rangle$ and $\langle 111 \rangle$ substrates

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## Abstract

In a program of developing radiation-hard silicon sensors for the LHC-ATLAS experiment, we have irradiated various types of silicon sensors with 12 GeV protons at KEK. Among the other properties, we made a comparative study of characteristics of the sensors with two wafer planes  $\langle 111 \rangle$  and  $\langle 100 \rangle$ . The studied sensors are p-on-n type, which satisfy the ATLAS-SCT specifications. Possible dependence on the substrate orientation could result from different dangling-bond configurations. The compared characteristics are the charge collection efficiency, interstrip capacitance, and noise levels. The noise levels were measured with a real ATLAS-SCT electronics system. A substantial difference is observed in the interstrip capacitance at  $\sim 10$  kHz, while the difference is small at  $> 1$  MHz. The differences in the charge collection efficiency and in the noise levels appear to be small. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Silicon microstrip detectors will be extensively used for tracking in the ATLAS experiment at the LHC. The ATLAS SCT (Semiconductor Tracker) system is described in detail in Ref. [1]. The sensors

are AC-coupled and single sided with dimensions of  $63.56$  (width)  $\times$   $63.96$  (length)  $\times$   $0.28$  (thickness)  $\text{mm}^3$ . The electrode strips of  $12 \mu\text{m}$  width are made on the  $p$  side at a pitch of  $80 \mu\text{m}$ . The number of readout strips is 768. Two of such sensors are wirebonded together, constructing a readout strip length of  $\sim 12$  cm. The radiation tolerance is one of the key issues to operate silicon microstrip detectors in ATLAS, where the radiation

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Table 1

Tested silicon microstrip sensors. \* is either 0, 17 or 42, denoting the proton fluence in unit of  $10^{13} \text{ cm}^{-2}$

Sensor name	Maker	Resistivity	Wafer plane	Fluence ( $\text{cm}^{-2}$ )
Hp4k-*	Hamamatsu	4 k $\Omega$ cm	$\langle 111 \rangle$	$0, 17 \times 10^{13}$
Hp1k-*	Hamamatsu	1 k $\Omega$ cm	$\langle 100 \rangle$	$17, 42 \times 10^{13}$
Sp4k-*	SINTEF	4 k $\Omega$ cm	$\langle 100 \rangle$	$17, 42 \times 10^{13}$

environment is estimated to correspond to  $3 \times 10^{14}$  multi-GeV proton equivalent per  $\text{cm}^2$  in 10 years of operation.

In a program of developing radiation-hard silicon sensors, we have fabricated various types of silicon sensors and irradiated them with 12 GeV protons at KEK. The irradiations were performed for two separate sets of sensors to  $1.7 \times 10^{14}$  and  $4.2 \times 10^{14} \text{ cm}^{-2}$ . The present measurements were made 6–12 months after the initial annealing was completed. The details of the irradiation conditions and performance tests which include the leakage current increase, change in the full depletion voltage and drop in the charge collection are reported elsewhere [2].

In this report, we examine the possible difference between the sensors with the two wafer planes,  $\langle 100 \rangle$  and  $\langle 111 \rangle$ . The compared sensors are summarized in Table 1. All the sensors are the p-on-n type, satisfying the ATLAS-SCT specifications. Comparative studies are made on the charge collection efficiency, interstrip capacitance, and noise performance. As pointed out in Ref. [3], different behaviors between these wafer orientations could result from the different amount of the dangling bonds at the Si–SiO<sub>2</sub> interface.

## 2. Charge collection

The charge collection could degrade due to trapping and recombination centers created by intense radiation. The surface charge accumulation could also modify the electric field around the strips and hence the charge collection efficiency. If the influence associated with the wafer orientation emerges itself only at the Si–SiO<sub>2</sub> interface and not

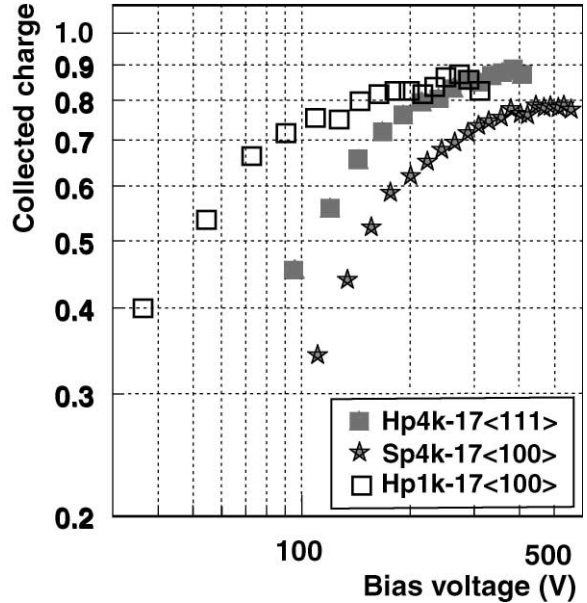


Fig. 1. Charge collection curves of the three sensors irradiated to  $1.7 \times 10^{14} \text{ protons cm}^{-2}$ . The vertical axis is normalized by the charge collection plateau of an Hp4k-0 sensor.

in the bulk, we expect small difference at least in the former effect.

The charge collection curves were measured using penetrating  $\beta$ -rays from a  $^{90}\text{Sr}$  source [2]. The sample sensor was sandwiched between a pair of  $A\ell$  slits with a scintillation counter set underneath, which created gate signals to an ADC. Three adjacent strips were read out separately. The peak ADC count of the summed signals is plotted as a function of the bias voltage. Fig. 1 is an excerpt from Ref. [2], which shows the charge collection curves of the three types of the sensors irradiated to  $1.7 \times 10^{14} \text{ cm}^{-2}$ . The ordinate is normalized by the charge collection plateau of a non-irradiated Hp4k sample.

We note that the shapes of Hp4k-17 and Sp4k-17 sensors are similar whereas the Hp1k-17 curve remains high at lower voltages. This difference can be attributed to the initial resistivity difference.

In Fig. 2 we plot the charge collection values at plateau for various samples we tested. Typically there are measurements for two samples at the same condition (only one for SINTEF), which are

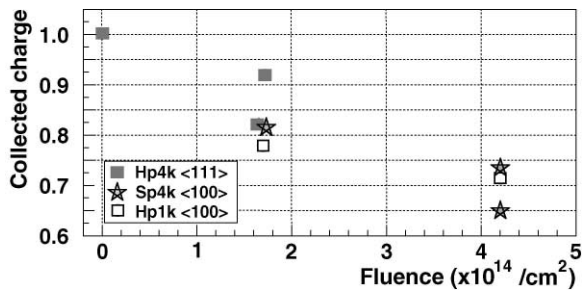


Fig. 2. The charge collection of three types of the sensors as a function of proton fluence.

plotted by the same marks in the figure. Although the set of samples is not complete, there seems small difference between  $\langle 111 \rangle$  and  $\langle 100 \rangle$  wafer orientations. As is pointed out in Ref. [2], though, n-on-n sensors are superior to p-on-n sensors in the charge collection, since the junction side of irradiated n-on-n sensors is on the strip side and the electric field becomes preferable for charge collection.

### 3. Interstrip capacitance

The characterization of the interstrip capacitance was based on an HP4192A LCR meter. Several Al strips were wire-bonded to a printed circuit board, which provided the connection to the LCR meter through Lemo cables. Hereafter we define the interstrip capacitance as that between two neighboring strips with the adjacent strips being at floating.

Fig. 3 shows the frequency dependence of the interstrip capacitance. The bias voltages were set on the plateau in the charge collection curves. Non-irradiated sample exhibits a cutoff at a few kHz, which is due to existence of bias resistors parallel to the interstrip capacitance. The irradiated Hp1k  $\langle 100 \rangle$  sensors show a small deviation at a frequency lower than 10 kHz. The curves of Sp4k-17 and Sp4k-42 (not shown in the plot, which behaves similar to Sp4k-17) show a larger deviation than Hp1k sensors. However, these curves are essentially similar in shape, if we take into account that the cutoff of SINTEF sensors resides in a smaller frequency region. On the

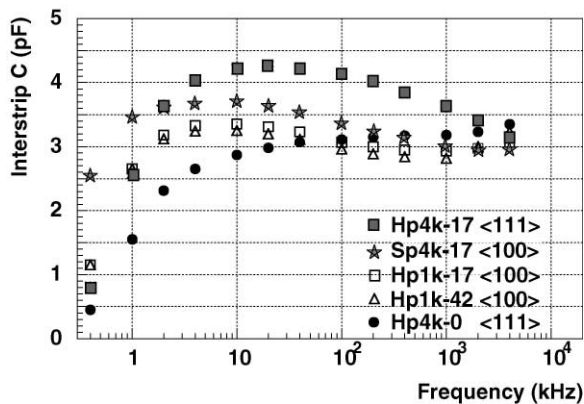


Fig. 3. Frequency dependence of the capacitance between neighboring strips. The bias voltage is set on the plateau in the charge collection curves.

contrary, the irradiated  $\langle 111 \rangle$  sensors show an enhancement of  $\sim 30\%$  in a wider frequency range below  $\sim 100$  kHz. They all, however, tend to become identical above  $\sim 5$  MHz. It can be concluded that the frequency dependence of the interstrip capacitance is not dependent on the proton fluence in the range we investigated. Since a major difference in the curves is observed between  $\langle 100 \rangle$  and  $\langle 111 \rangle$  sensors, the wafer orientation should be attributed to the changes.

We evaluated the bias voltage dependence of the interstrip capacitance at 10 kHz, where the difference appears to be most distinctive. The results are shown in Fig. 4. While the interstrip capacitance at lower bias voltages seems different between Hp1k-17 and Sp4k-17 sensors, it converges into a similar value at the full depletion voltage of  $\sim 300$  V. The different behavior at lower voltages should be related to the difference in the wafer resistivity. On the other hand, the interstrip capacitance of Hp4k-17 is high at lower voltages and continues to decrease across the full depletion voltage, resulting in the interstrip capacitance being higher than the others even at 300 V.

It is reported in Ref. [3] that the interstrip capacitance is influenced more by irradiation if the frequency is decreased (from 1 MHz to 100 kHz) and the bias voltage is lowered (from 500 to 300 V) for  $\langle 111 \rangle$  substrate with resistivity of  $6 \text{ k}\Omega \text{ cm}$ . It also reports that there is essentially small change for  $\langle 100 \rangle$  substrate with resistivity of  $1 \text{ k}\Omega \text{ cm}$ .

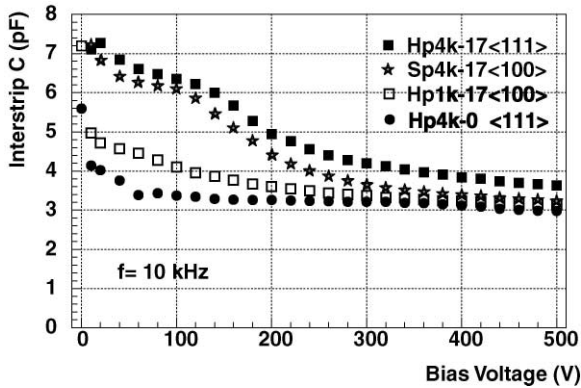


Fig. 4. Interstrip capacitance at 10 kHz as a function of bias voltage.

The present results are qualitatively consistent with their measurements.

#### 4. Contribution to the electronics noise

The interstrip capacitance contributes dominantly to the detector capacitance. The actual contribution to the electronics noise may not be substantial since the increase is small in the range above 1 MHz which is the frequency range responsible for the electronics.

The contribution to the electronics noise was evaluated by using a non-irradiated real SCT readout system based on ABCD2T front-end chips [4]. One ABCD2T chip (128 readout channels) was mounted on a flexible Kapton-based hybrid. Consecutive 6 cm long 16 strips were wire-bonded to the ABCD2T chip through a pitch adapter. Another consecutive 16 strips were also wire-bonded to the same chip inputs, thereby simulating 12 cm long strips in the real SCT configuration. The sample was placed in a thermostat chamber with the temperature being kept at  $-10^{\circ}\text{C}$ . The same input channels of the same ABCD2T chip are used in order to compare the noise levels of the different sensor types.

The ABCD2T is a binary readout system, therefore the noise was evaluated from the sigma of the error function which was fitted to the efficiency vs injected charge relation at a given comparator threshold voltage. The threshold

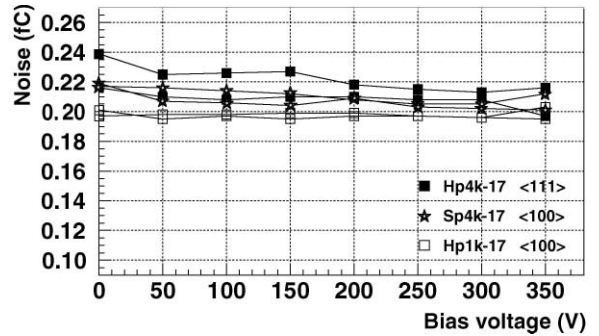


Fig. 5. Noise as a function of the bias voltage for the three types of irradiated sensors, two sensors for each.

voltage was adjusted to correspond to 2 fC of the charge injection. Although the noise values of the connected 16 channels are consistent to each other, we calculated the average of the central channels in order to avoid the possible influence from the unconnected strips. We plot the averages in Fig. 5. Two sensors were measured for each of the three types irradiated to  $1.7 \times 10^{14} \text{ cm}^{-2}$ . The noise levels at 300 V, where all the sensors are on the full depletion plateau, show that Hp4k-17  $\langle 111 \rangle$  tends to be somewhat larger than Hp1k-17 and Sp4k-17  $\langle 100 \rangle$  by 5–7%. The significance is, though, weak compared with the systematic uncertainty of  $\sim 3\%$ . Note that the noise level for a non-irradiated sensor is 0.20 fC.

In the figure we show the noise levels up to 350 V. Above this voltage the noise level was found to increase. The sensors we used in this study are based on “1997 design” where a substantial micro-discharge is observed around the guard rings. The current design (“1998 design”) has modified the layout and such an increase is not observed [5].

#### 5. Summary

We have evaluated the characteristics of silicon microstrip sensors irradiated with protons and compared the results in view of  $\langle 111 \rangle$  and  $\langle 100 \rangle$  substrate orientations. The comparison was performed on the charge collection, interstrip capacitance, and the contribution to the electronics

noise. Although an increase of 30% was observed for  $\langle 111 \rangle$  in the interstrip capacitance at  $\sim 10$  kHz, there are small differences in other characteristics. The noise levels measured with a real SCT electronics system agreed to each other to a level of 5–7%.

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