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Silicon sensor probing and radiation studies for the LHCb silicon tracker

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On behalf of the LHCb Silicon Tracker group[1]

Abstract

The LHCb Silicon Tracker (ST) will be built using silicon micro-strip technology. A total of 1400 sensors, with strip pitches of approximately 200 μm and three different substrate thicknesses, will be used to cover the sensitive area with readout strips up to 38 cm in length. We present the quality assurance program followed by the ST group together with the results obtained for the first batches of sensors from the main production. In addition, we report on an investigation of the radiation hardness of the sensors. Prototype sensors were irradiated with 24 GeV/c protons up to fluences equivalent to 20 years of LHCb operation. The damage coefficient for the leakage current was studied, and full depletion voltages were determined.

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Keywords: Silicon detector; LHCb

1. Introduction

The LHCb experiment [2], at present under construction at the LHC at CERN, has been designed to perform high-precision measurements of CP violating phenomena and rare decays in the B meson systems. A vertical cross-section of the detector is shown in Fig. 1. It is a single-arm magnetic spectrometer, exploiting the large and strongly forward peaked $b\bar{b}$ production cross-section at the LHC.

The ST is part of the tracking system of LHCb and consists of two sub-detectors that will be built using silicon micro-strip technology: the Trigger Tracker (TT) station, located upstream of the spectrometer magnet; and the Inner Tracker (IT), which covers the innermost region of tracking stations T1–T3 downstream of the magnet. Each tracking station consists of four detection layers. In two of the layers readout strips are vertical, in the other two they are rotated by a stereo angle of $\pm 5^\circ$. The design of the IT and the TT station has been described in Refs. [2–5].

The TT station is entirely built using silicon micro-strip technology and covers the full LHCb acceptance. The layout of a detection layer in the TT station is shown in Fig. 2. It makes use of sensors that were developed for the outer barrel of the CMS ST [6]. Sensors have a thickness of 500 μm and measure 9.4 cm in length and 9.6 cm in width. The strip pitch is 183 μm. The basic detector unit is a seven-sensor long module that is functionally split into a four-sensor long outer readout sector and a three-sensor long inner readout sector. These long modules require the use of thick sensors to ensure good enough signal-to-noise performance. All front-end readout electronics are located at one end of the module, the inner readout sector being connected to its front-end readout chips via a 40 cm long kapton interconnect cable.

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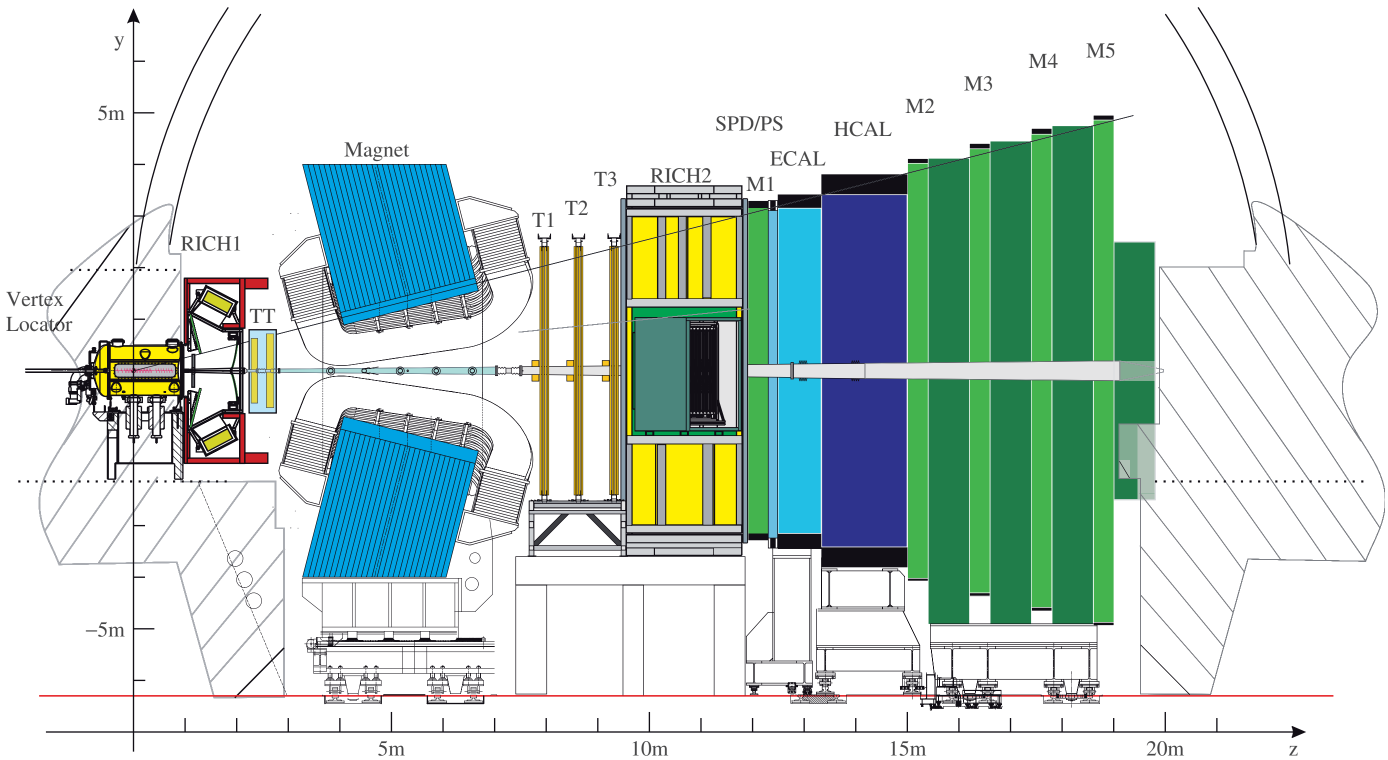

Fig. 1. Vertical cross-section of the LHCb detector. The TT station is located upstream of the spectrometer magnet. The IT covers the innermost region of tracking stations T1–T3 downstream of the magnet.

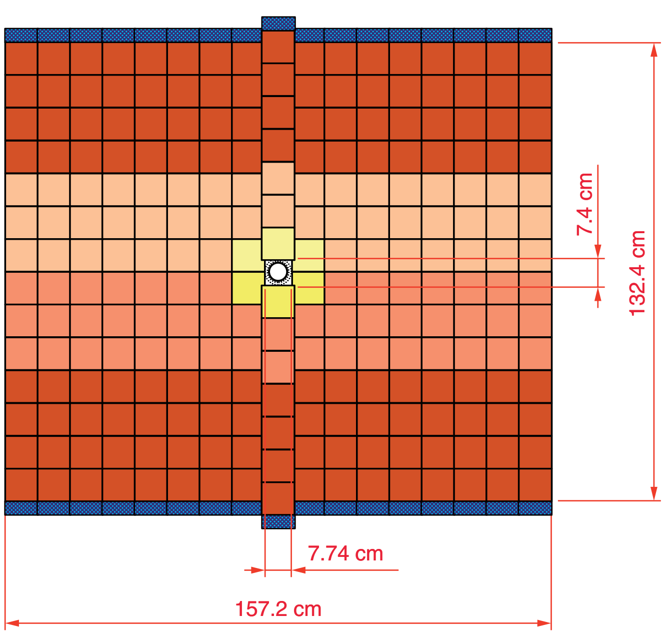

Fig. 2. Layout of a detection layer in the TT station. Readout sectors are indicated by different shadings. All silicon sensors are 500 μm thick.

Stations T1–T3 are constructed using two detector technologies: the inner region of these stations (IT) is covered by silicon micro-strip detectors, whilst the outer region is covered by straw-tube drift chambers. The shape and dimensions of the IT active area have been optimized to ensure sufficiently low occupancies in the surrounding detector [3]. The layout of one detection layer in the IT is shown in Fig. 3. Two types of rectangular silicon sensors of different thickness but otherwise identical design will be employed. All sensors measure 11 cm in height and 7.8 cm in width and have a strip pitch of 198 μm. In order to minimize material budget, 320 μm thick sensors will be used for the single-sensor ladders above and below the beam pipe, whilst 410 μm thick sensors are required to ensure good enough signal-to-noise performance for the two-sensor long ladders to the left and to the right of the beam pipe.

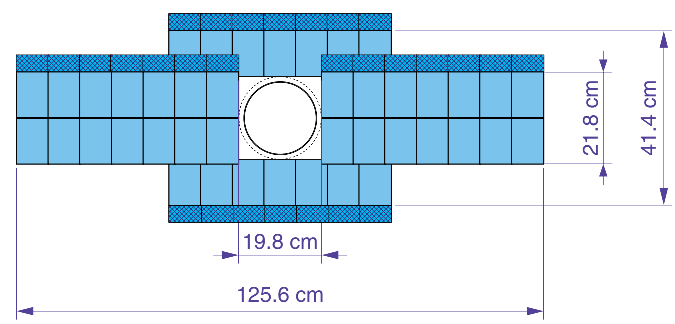

Fig. 3. Layout of a Inner Tracker station. The cross-shape and dimensions are optimized to ensure sufficiently low occupancies in the surrounding detector. Two-sensor long modules use 410 μm thick sensors, whilst one-sensor long modules use 320 μm thick sensors.

A total of 1400 sensors will be used in this project. All sensors are single-sided, p-on-n type, produced from 6″ wafers. The p^+ strips are AC-coupled and connected through polysilicon resistors to a common bias ring.

Surrounding the bias ring there is one floating guard ring. All sensors will be produced by Hamamatsu Photonics (HPK), Japan.

In this article, we present our silicon sensor quality assurance (QA) program. Details of the acceptance and test procedures are explained, and we give results from the first batches of production sensors consisting of 14 320-μm-thick sensors (HPK-320), 35 410-μm-thick sensors (HPK-410), and 98 500-μm-thick sensors (HPK-500). Furthermore, an irradiation study with IT prototype sensors was performed, and the results on the damage coefficient for the leakage current are presented. Full depletion voltages were determined from total sensor capacitance measurements and were compared to the values obtained from studies of the charge collection using a laser.

2. QA procedure and results from sensor pre-series production

To ensure the desired performance of the detector modules, a rigorous QA of the sensors is required. Our QA program [7] consists in two stages: tests performed by HPK prior to shipment, and tests performed by our group after reception. HPK provides us with the results of their tests, which include measurements of total leakage currents up to 500 V bias voltage, full-depletion voltages, individual strip currents, and sensor thickness on every sensor. On a wafer lot basis we receive information on the values of polysilicon resistors, coupling capacitances, the breakdown voltage of capacitors, and implant resistances.

After reception, we perform the following tests and measurements:

- visual inspections,
- leakage current and total sensor capacitance as a function of the bias voltage,
- leakage current dependence on humidity, temperature and mechanical strain,
- long-term behaviour and repeatability of currents,
- coupling capacitances, and
- metrological measurements.

Visual inspections, leakage current, total sensor capacitance and metrological measurements are performed on all sensors, whilst the remaining tests are performed on a randomly selected sample of ~10% of the sensors.

Until May 2005 we received a total of 147 sensors (≈ 10% of the total), including sensors of all three types that will be used in the ST. Table 1 summarizes the types and quantities of the delivered sensors, together with the total quantities that will be produced.

Our QA program starts with a visual inspection on all sensors, to search for macroscopic defects like scratches, chipped edges and pad contamination, as well as to judge the overall sensor cleanliness. In general, sensors were found to be of very good quality in this visual inspection. No deep scratches or big defects were found during this test. About 60% of the sensors were found to be free of any defects, and the remaining sensors present only small defects. All sensors can be used in detector ladders.

During the electrical characterization, we measured the leakage current as a function of the bias voltage. An excellent uniformity of the currents from sensor to sensor was found. As an example, the currents measured for three sensors of each type are shown in Fig. 4. The distribution of the leakage currents measured at 500 V is shown in Fig. 5. They are typically below 400 nA and none of the sensors failed the acceptance criteria (see Table 2).

Table 1
Sensors delivered until May 2005 and total quantities to be produced

Sensor type	Delivered sensors	Total production
HPK-320	14	194
HPK-410	35	386
HPK-500	98	1000

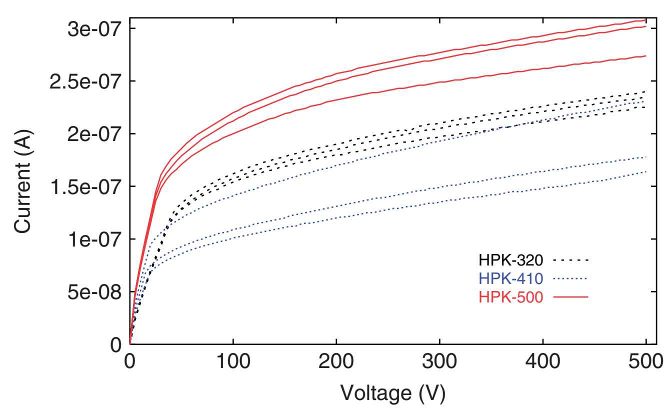

Fig. 4. Typical IV curves measured on the three types of sensors. No breakdown is observed below 500 V.

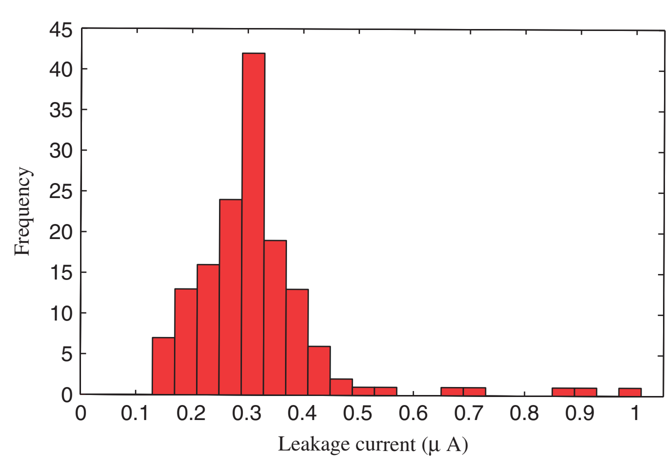

Fig. 5. Distribution of the leakage currents measured at 500 V on the three types of sensors. All sensors fulfil the specifications.

Table 2
Specifications and acceptance criteria for the measurements performed during the QA program. The numbers for HPK-320 and HPK-410 are identical, whilst HPK-500 sensors have different specifications

	HPK-320 and HPK-410	HPK-500
Total leakage current	$<1\,\mu$A at $V_{depl}+100$ V	$<5\,\mu$A at $V_{bias}=300$ V $<10\,\mu$A at $V_{bias}=450$ V
Breakdown voltage	>500 V	>500 V (mini-sensor)
Full depletion voltage	50–140 V	100–300 V
Coupling capacitance	>60 pF/cm	>55.2 pF/cm
Total strip capacitance	<1.6 pF/cm	<1.3 pF/cm
Polysilicon resistors	1.5 ± 0.5 MΩ	1.5 ± 0.5 MΩ
Bad strips per sensor	<1%	<1%

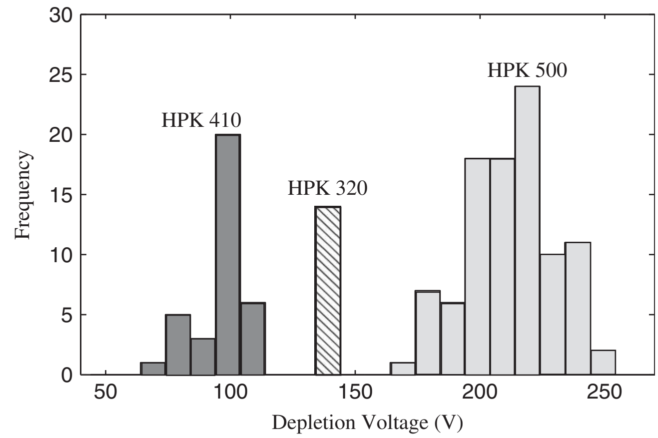

Fig. 6. Distribution of the measured full depletion voltages. All sensors fulfil specifications: HPK-320 and HPK-410 sensors deplete between 70 and 140 V, and HPK-500 sensors deplete between 160 and 250 V.

The full depletion voltage was determined for all sensors from the measurement of the total sensor capacitance as a function of the bias voltage. The measurements were taken at a signal frequency of 1 kHz. Fig. 6 shows the distribution of the obtained full depletion voltages. All HPK-320 and HPK-410 sensors are between 70 and 140 V, and all HPK-500 sensors deplete between 160 and 250 V, fulfilling the specifications.

Other features of the leakage current were studied for $\sim$10% of the sensors. Given the convex shape of the sensors (see Fig. 8), the application of vacuum to hold the sensors to the chuck of the probe station, by pulling the sensor flat against the chuck, produces a strain of the sensor. Therefore, a possible dependence of the leakage current on the application of vacuum to the sensors was investigated. No differences between the currents obtained with and without chuck vacuum were observed for any of the sensors. The repeatability of the IV curves under stable conditions (same temperature and relative humidity (RH)) was checked and the curves were found to be reproducible. Moreover, the current stability of the sensors was investigated and verified in a $\sim$30 h long biasing test, while temperature and RH were monitored. In Fig. 7, the time dependence of leakage current and temperature is shown for one sensor of each type. Only small drifts in current were observed that were fully correlated to temperature. Measurements were made in a dry atmosphere (RH $\lesssim$20%), chosen on the basis of similar measurements made on prototype sensors, where currents were found to be independent of the RH for values up to 60%. The leakage currents were reproducible and stable against long term drifts.

Coupling capacitance measurements were performed on about 20% of the sensors to check for metal opens, metal shorts or pinholes in the dielectric layer of the coupling capacitor. None of the inspected sensors failed the requirement of <1% bad strips.

All sensors were characterized on an optical metrology machine (Mahr OMS 600) in order to verify the mechanical specifications. Several parameters like flatness, overall length and width of the sensor, distance between the edge and the first strip, and parallelism between edges and strips were measured. As an example of these tests, a typical warp profile of a HPK-320 sensor laying freely on a flat surface, with the strip side facing upwards, is shown in Fig. 8. The specifications for the HPK-320 sensors require a warp of less than 50 μm. As seen in Fig. 8, the sensors have a convex shape with typical warps around 75 μm. On the basis of the fact that, as mentioned above, flattening the sensors does not affect the currents, we proceeded to the assembly process, where no problems related to the warp arose. Therefore, this specification was considered unnecessarily tight and was not taken into account for the mechanical grading. Thicker sensors have smaller warps and are within specifications. With these observations, all sensors were mechanically classified as good.

3. Irradiation tests

The expected particle fluence in the innermost region of the IT detector is approximately $1.8\times10^{13}\,\mathrm{cm}^{-2}$ 1 MeV neutron equivalent fluence after 10 years of operation at nominal luminosity [3]. In order to investigate the radiation hardness of the sensors, we performed an irradiation study on IT prototype sensors. In this section, we present measurements of full depletion voltages and leakage currents, as well as total strip, inter-strip and coupling capacitances for the irradiated sensors.

Three LHCb Multi-Geometry prototype sensors (called LHCb 1, LHCb 5, and LHCb 8 in the following) and one CMS OB2 test-structure were irradiated. The LHCb prototype sensors contain five regions with different strip geometries, i.e. different strip widths and pitches. Otherwise, the sensors have the same thickness, dimensions, and material specifications (in particular, a resistivity in the range 2.5 to 7 kΩ cm) as the HPK-320 sensors. Further details on these sensors and the CMS OB2 test-structure Refs. [8,6], respectively. The electrical characterization of

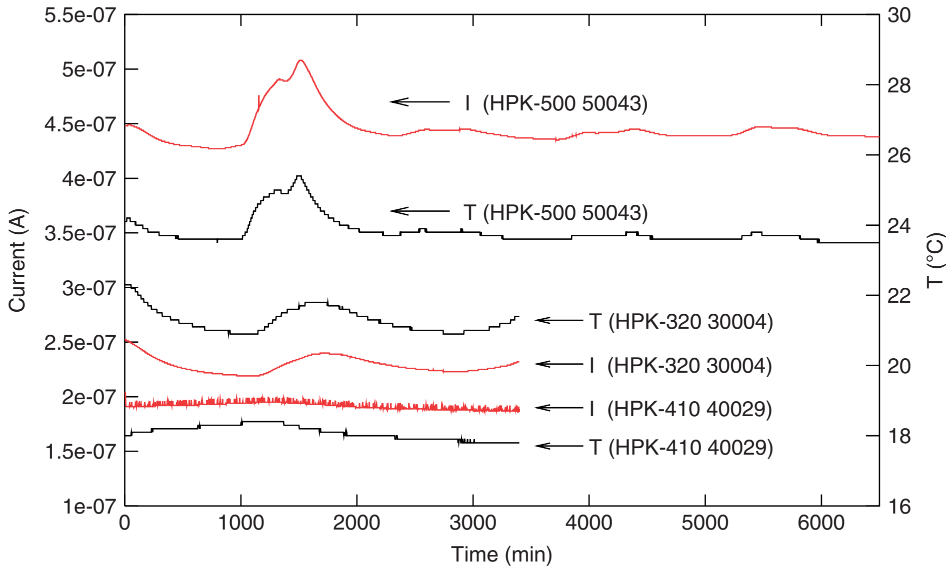

Fig. 7. Current stability test for one sensor of each type. The sensors were biased at 450 V for 58 or 110 h. Drifts in current are fully correlated to ambient temperatures (T).

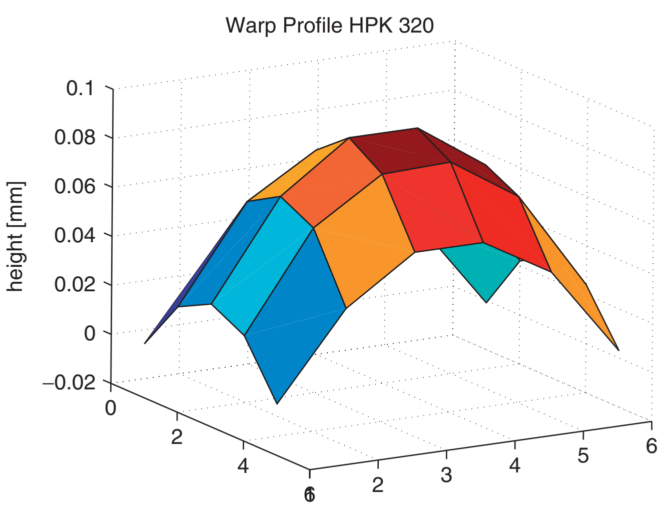

Fig. 8. Warp profile of a HPK-320 sensor. The measured points are connected by surface grid lines. The z-coordinates were recorded on a regular grid of 6×6 points covering the full surface of the sensor.

the LHCb prototype sensors before irradiation has been described in Ref. [9].

The irradiation was carried out using 24 GeV/c protons at the T7 irradiation facility at the PS at CERN [10]. One of the sensors was irradiated to a fluence of $1.9 \times 10^{13}\,\mathrm{p/cm^2}$ while the remaining sensors and the CMS test-structure were irradiated to a fluence of $6.3 \times 10^{13}\,\mathrm{p/cm^2}$. Assuming a hardness factor $k = 0.6$ for 24 GeV/c protons [12], this corresponds to 1 MeV neutron equivalent fluences of 1.2×10^{13} and $3.8 \times 10^{13}\,\mathrm{cm^{-2}}$, respectively, or roughly 7 and 20 years of operation in the innermost part of the IT. The irradiation was performed in two steps. First, all sensors were irradiated up to the lower fluence. The box was then moved out of the beam, but stayed in the irradiation facility until the next access. Meanwhile, the sensors were kept at a temperature of $-4\,^{\circ}\mathrm{C}$ to avoid annealing effects. Sensor LHCb 5 was then removed from the box and the remaining sensors were irradiated up to the higher fluence. The average fluences received by each sensor, obtained from activation measurements on aluminium foils, are summarized in Table 3.

After the irradiation, the sensors were annealed for 80 min at $60\,^{\circ}\mathrm{C}$ in order to accelerate the effects of short-term annealing [13]. The electrical characterization was performed directly after this heat treatment. The measurements were performed at room temperature, between 24.5 and $27\,^{\circ}\mathrm{C}$. Between the tests, the sensors were stored in a freezer at $-20\,^{\circ}\mathrm{C}$ in order to suppress reverse annealing effects.

To determine the full depletion voltage, the total sensor capacitance was measured as a function of the bias voltage. The estimated full depletion voltages are shown in Table 3. The full depletion voltages measured before irradiation are about 60 V for the sensors and 140 V for the diode. Details have been reported in Refs. [8,9,11], respectively. After the lower fluence, the depletion voltage is 40 V, which is lower than the initial depletion voltage and gives a large safety margin for over-biasing the sensors.

We measured total leakage currents for the three irradiated LHCb sensors and the diode on the test-structure. The leakage currents measured before irradiation for the sensors were below $1\,\mu\mathrm{A}$ at the full depletion voltage. Details have been reported in Refs. [8,9]. The diode current before irradiation was about 5 nA at 300 V. The obtained leakage currents after irradiation measured at the full depletion voltage and at 500 V and normalized to $T = 20\,^{\circ}\mathrm{C}$, are given in Table 3.

The leakage current increase due to radiation scales linearly with the received fluence ϕ and is proportional to

Table 3
Average fluence of 24 GeV protons per cm^2 received by the sensors and measurements performed after irradiation

Sensor	Fluence (p/cm^{-2})	$V_{depl.}$ (V)	I at $V_{depl.}$ (mA)	I at 500 V (mA)
LHCb 5	1.9×10^{13}	40	1.24	1.50
LHCb 8	6.3×10^{13}	130	3.61	4.72
LHCb 1	6.3×10^{13}	130	4.14	4.82
Diode	6.3×10^{13}	115	0.043	0.065

Leakage currents are normalized to $T = 20\,^{\circ}C$. The active area of the diode is $0.49\,cm^2$ and the thickness is 500 μm.

the depleted volume V of the detector: $\Delta I = \alpha V \phi$. The proportionality factor α is the current related damage constant, which depends on the particle type and energy.

We calculated α using the leakage current of the detectors measured at the full depletion voltage and normalized to $T = 20\,^{\circ}C$ and the fluences from the activation measurements of the aluminium foils. We obtained a mean value of $\alpha = 2.8\times10^{-17}\,A/cm$ for the current related damage constant [11], in good agreement with the value of $2.54\times10^{-17}\,A/cm$ for 24 GeV protons given in Ref. [15], which was obtained after annealing for 4 min at 80 °C, equivalent to our annealing for 80 min at 60 °C [16].

In order to normalize the particle fluence ϕ to the equivalent 1 MeV neutron fluence we calculated the so-called hardness factor, k_α. Comparing the α parameter from this irradiation to the value for 1 MeV neutrons, $\alpha = 4.56\times10^{-17}\,A/cm$ quoted in Refs. [14,15], we obtain a hardness factor of $k_\alpha = 0.61$ for 24 GeV protons. This value is in excellent agreement with the value of 0.62 given in Ref. [17].

In addition, we performed several strip tests for the irradiated sensors. Inter-strip capacitances and coupling capacitances were found to be essentially unchanged after irradiation. The total strip capacitances for the sensors irradiated to the higher fluence showed an increase of about 15% compared to unirradiated sensors. No significant increase was observed after the lower fluence.

Two detector modules were constructed using two of the irradiated sensors and were equipped with a readout hybrid carrying three Beetle 1.3 front-end readout chips [18]. A detailed study of the charge collection was performed on these modules using an infrared laser system. The model presented in Ref. [19] was found to give a reasonable parameterization of the data. The full depletion voltages were extracted from the fit and, after allowing for the effect of reverse annealing, are in agreement with those found in the C–V measurements presented above [20].

4. Summary

A QA program for ST silicon sensors has been defined and applied to a first batch of 147 sensors received from HPK. The results from these sensors are very satisfactory. The sensors have excellent quality, with leakage currents below 1 μA at 500 V and the remaining electrical parameters within specification. All sensors passed the acceptance criteria and can be used for detector module production.

We performed an irradiation study on three LHCb IT prototype sensors and one CMS test-structure, that were exposed to 24 GeV/c protons up to fluences of 1.9×10^{13} and $6.3\times10^{13}\,p/cm^2$. The standard annealing scheme of 80 min at 60 °C was followed. The proton fluence was obtained from activation measurements on aluminium foils.

It was found that the sensors fully depleted at about 50 V after irradiation to the lower fluence. This depletion voltage is lower than the initial depletion voltage and gives ample safety margin to sufficiently over-bias the sensors. A current related damage constant $\alpha = 2.8\times10^{-17}\,A/cm$ has been extracted from the leakage current measurements, corresponding to a hardness factor $k_\alpha = 0.61$ for 24 GeV protons. Inter-strip capacitances and coupling capacitances remain essentially unchanged after irradiation. Total strip capacitances show no significant variation after irradiation to the lower fluence.

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