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ELSEVIER Nuclear Instruments and Methods in Physics Research A 531 (2004) 238–245
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

The silicon sensors for the Inner Tracker of the Compact Muon Solenoid experiment

Manfred Krammer*

Institute for High Energy Physics, Austrian Academy of Sciences, Nikolsdorfergasse 18, Vienna 1050, Austria

On behalf of the CMS Tracker Collaboration

Available online 21 June 2004

Abstract

The Inner Tracker of the Compact Muon Solenoid (CMS) experiment, at present under construction, will consist of more than 24 000 silicon strip sensors arranged in 10 central concentric layers and 2×9 discs at both ends. The total sensitive silicon area will be about 200 m^2. The silicon sensors are produced in various thicknesses and geometries. Each sensor has 512 or 768 implanted strips which will allow the measurement of the position of traversing high-energy charged particles. This paper gives a short overview of the CMS tracker system. Subsequently, the design of the silicon sensors is explained with special emphasis on the radiation hardness and on the high-voltage stability of the sensors. Two companies share the production of these sensors. The quality of the sensors is extensively checked by several laboratories associated with CMS. Important electrical parameters are measured on the sensors themselves. In addition, dedicated test structures designed by CMS allow the monitoring of many parameters sensitive to the production process. By August 2003 about 5000 sensors were delivered and a large fraction of these sensors and test structures was measured.

PACS: 29.40.Wk; 29.40.Gx; 06.60.Mr

Keywords: LHC; CMS; Silicon microstrip detectors

1. The CMS experiment

At CERN, the European Laboratory for Particle Physics in Switzerland, the large proton–proton collider LHC is under construction. The accelerator will be housed in the previous LEP collider tunnel, 27 km in circumference, and will consist, among other components, of more than 1200 superconducting dipole magnets allowing the particle beams to reach an energy of 7 TeV/c^2. To exploit this machine four experiments are being constructed. Two of these experiments, ATLAS and CMS, are multipurpose experiments designed to study the constituents of matter and the associated forces.

*Tel.: +43-1-544-7328; fax: +43-1-544-7328-54.
E-mail address: krammer@hephy.oeaw.ac.at (M. Krammer).

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doi:10.1016/j.nima.2004.06.011

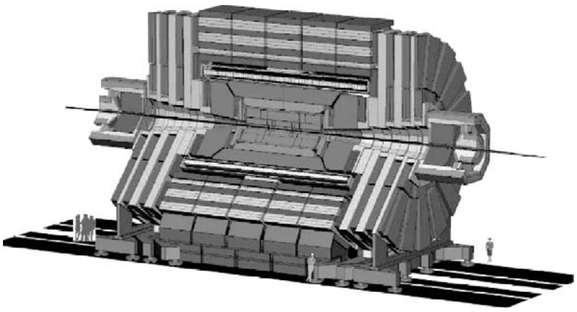

Fig. 1. An artist's view of the CMS experiment.

The acronym CMS stands for 'Compact Muon Solenoid' and indicates one of the key features of this experiment, the precise measurement of muons. The CMS detector will consist of several shells of different detector elements (see Fig. 1). Particles created in the high-energy collisions in the very centre of the detector will first traverse the 'Inner Tracker' a system of silicon sensors designed to detect charged particles. The arrangement of these sensors is such that the trajectories of charged particles can be measured with as little interference as possible with the detector material. Outside of the Inner Tracker is the electromagnetic calorimeter, a detector consisting of about 80 000 scintillating crystals, whose purpose is to absorb electrons and photons and to measure their energy. Further out is a shell of hadronic calorimeters measuring the energy of hadrons, e.g. pions, protons, etc. Just outside the hadronic calorimeter is a superconducting solenoid magnet which will create a magnetic field of 4 T. All charged particles traversing this field are deflected with a track radius depending on the particle charge and momentum. The outside shell of CMS is formed by the muon chamber system, a gas detector system designed to measure the tracks of through going muons. Combined with the muon tracks measured in the Inner Tracker the momentum of the muons can be determined with high precision.

The complete CMS detector will be 21.6 m long, with a diameter of 15 m and with an overall weight of 12 500 tons. The construction of the CMS detector is well advanced and it is scheduled to be finished in the first-half of the year 2007 when the LHC accelerator will start its operation.

2. Layout of the Silicon Inner Tracker

The CMS Inner Tracker [1] is divided into five substructures: the pixel detector very close to the interaction point [2], which is not discussed in this paper, the inner barrel detector (TIB), the inner discs (TID), the outer barrel (TOB) and the two end cap detector systems (TEC). The overall length of the inner tracker will be 5.4 m with a diameter of 2.4 m. The total weight will be about 3 tons. The temperature inside the tracker will be adjusted such that the maximum temperature of the silicon sensors will not exceed -10°C. The total electrical power dissipation is expected to be about 45 kW.

Fig. 2 shows a cut through a quarter of the Inner Tracker. The solid lines in this sketch represent the silicon sensor modules. The modules of the TIB are mounted on four and the TOB modules on six concentric shells. The supporting structures for the TID and TEC are discs, two times three discs for the TID and two times nine discs for the TEC. The basic construction element of the Inner Tracker is a module (see Fig. 3). The supporting frame of a module is made of carbon fibre or graphite. Glued onto the frame is a Kapton layer to isolate the frame from the silicon and to provide the electrical connection to the silicon backplane. A ceramic multilayer hybrid holds the readout chips and the auxiliary chips. A glass pitch adapter is mounted between the hybrid and the first silicon sensor to match the different pitches of the chip input pads and the sensor strips. Wire bond connections between the individual channels of the readout chips and the pitch adapter, between the pitch adapter and the first sensor and between the two sensors make the electrical connections. The modules of the TIB, the TID and the four inner rings of TEC will consist of only one silicon sensor, whereas the modules of the TOB and the three outer rings of TEC will hold two sensors. All barrel modules are rectangular. The disc modules have a wedge shape in order to form rings. Fig. 3 shows a final module of the sixth ring of the TEC.

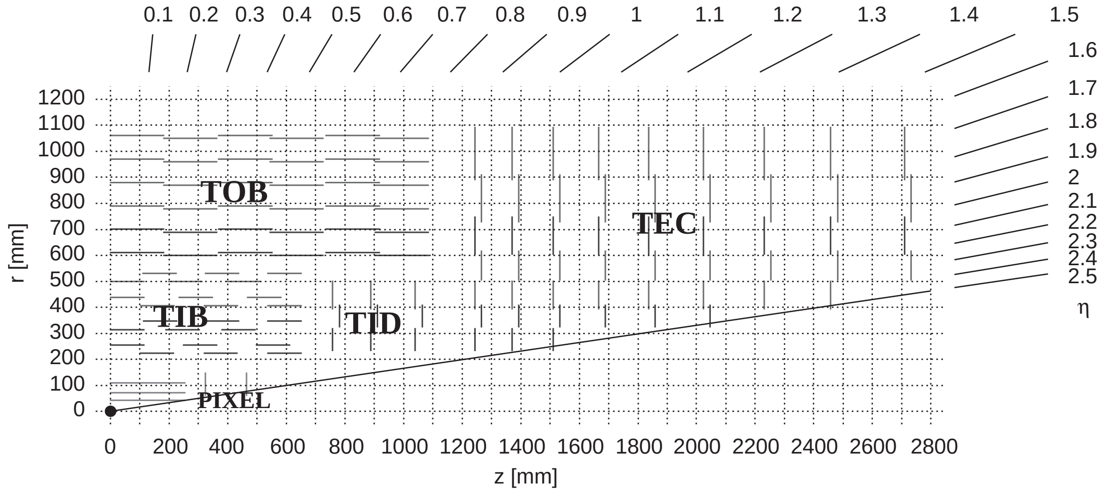

Fig. 2. The CMS Inner Tracker layout.

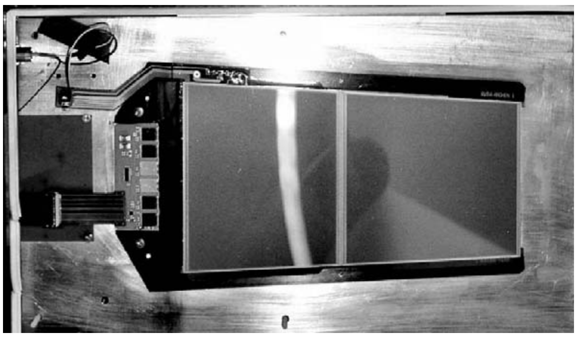

Fig. 3. A ring 6 module for the TEC.

The first two layers in TIB and TOB, the first two rings in TID and rings 1, 2, 5 in TEC are instrumented with double-sided modules. These are made of two independent single-sided modules, mounted back to back and rotated by 100 mrad with respect to each other.

Table 1 lists some numbers illustrating the overall dimension of this project.

Table 1
Some key numbers from the Inner Tracker construction

Area of active silicon	$\approx$200 m^2
Number of silicon sensors	24,244
Different sensor designs	15
Number of modules	15,232
Number of strips	$\approx$9,600,000
Number of electronics channels	$\approx$9,600,000
Number of readout chips	$\approx$75,000
Number of wire bonds	$\approx$25,000,000

3. Design of the silicon sensors

3.1. General design considerations

To build such a large silicon system as the Inner Tracker of CMS, the influence of the design of the silicon sensors on the mass production was studied first. In close collaboration with industry the basic parameters of the sensors were defined to reach maximum efficiency for the mass production. The result was a rather simple design compared to previous projects in high-energy physics [3]. In this respect, it was decided to use only single-sided sensors.

A second criterion driving the design was to optimize the use of the wafer area as the silicon sensor price is determined by the number of wafers rather than the actual sensor surface. The 15 different sensor types were designed to make maximum use of the area available on 6 in. wafers as most of the manufacturers use 6 in. fabrication lines for the sensor production.

Concerning the silicon material standard high-resistivity n-type silicon wafers are used. The potential advantage of oxygenated material with respect to radiation hardness was neglected in favour of the safety of using well-understood material.

3.2. Radiation hardness

The proton–proton collisions inside the LHC detectors will create an enormous radiation background which will damage every detector material. The innermost layers of the silicon strip detector will receive an estimated fluence of 1.6×10^{14} neutrons cm^{-2} (1 MeV neutron equivalent) during 10 years of LHC operation. The fluence is gradually lower for sensors mounted further away from the interaction point. Although silicon is inherently radiation hard compared to other detector technologies, the silicon sensors will nevertheless be modified and damaged. The two most important macroscopic effects of the irradiation are the increase of the leakage current which is linear with fluence, and the conversion of the n-type bulk into p-type with ever increasing carrier concentration. A consequence of the second effect is the need for increasing bias voltage after the type inversion which eventually leads to detector breakdown. For the long-term operation of the sensors in the Inner Tracker, it is therefore essential that the sensors can sustain very high bias voltages up to 400–500 V.

An appropriate choice of the resistivity of the original silicon wafers is important to influence the evolution of the depletion voltage. CMS has decided to use different material for the inner part of the tracker compared to the outer part. The inner four barrel layers (TIB), the inner discs (TID) and the four innermost rings of the forward discs (TEC) are fabricated using silicon of relatively low resistivity (1.25–3.25 kΩ cm) with a thickness of 320 μm. The outer six barrel layers (TOB) and the three outermost rings of the end-cap discs (TEC) will be made of silicon with high resistivity (3.5–7.5 kΩ cm), using wafers of 500 μm thickness.

The low-resistivity sensors for the inner part of the detector will require a high bias voltage at startup (up to 330 V), however the type inversion will occur at a higher fluence and hence later in time. At the end of the foreseen lifetime of 10 years, the sensors which are exposed to the highest fluence will require a bias voltage which is not much higher than the one at startup. For the sensors in the outer part the choice of high-resistivity material allows the use of thicker wafers with still manageable depletion voltage.

Another choice related to the radiation hardness was to use silicon wafers with a lattice orientation of $\langle 1\,0\,0 \rangle$. CMS studies have shown that this material has advantages compared to material with a lattice orientation of $\langle 1\,1\,1 \rangle$. The interstrip capacitance remained nearly unchanged after irradiation for sensors produced on $\langle 1\,0\,0 \rangle$ material, but increased significantly if $\langle 1\,1\,1 \rangle$ material was used [4].

3.3. Sensor design details

In order to cover the barrel layers and the end-cap discs with silicon sensors, 15 different designs are needed: four different rectangular designs for the barrel and 11 different wedge shaped designs for the inner discs and the end-caps. Tables 2 and 3 show an overview of the different sensor types, their dimensions, the strip pitches and the number of sensors needed for the particular type.

The principal design parameters are identical for all designs. Fig. 4 shows a corner of a wedge-shaped sensor. The sensors have p^+ strips on n-type bulk material. The strip pitch varies from 80 μm up to 205 μm. The ratio strip width to strip pitch is 0.25 for all types. The strips are AC coupled and the coupling insulation is formed by two thin layers of SiO_2 and Si_3N_4. The thickness of the aluminium readout lines is required to be at least 1.2 μm. An array of polysilicon resistors

Table 2
Inner barrel 320 μm thick sensors and outer barrel 500 μm thick sensors, geometrical dimensions and multiplicities

Type	Length (mm)	Height (mm)	Pitch (μm)	Strips	Multipl.
IB1	63.3	119.0	80	768	1536
IB2	63.3	119.0	120	512	1188
OB1	96.4	94.4	122	768	3360
OB2	96.4	94.4	183	512	7056

Table 3
Geometrical dimensions and multiplicities for 320 μm thick (W1–W4) and 500 μm thick (W5a–W7b) wedge sensors for TID and TEC: W1 has two different versions for TID and TEC, whereas the TID shares identical W2 and W3 sensors with the TEC

Type	Length 1 (mm)	Length 2 (mm)	Height (mm)	Pitch (μm)	Strips	Multipl.
W1 TEC	64.6	87.9	87.2	81–112	768	288
W1 TID	63.6	93.8	112.9	80.5–119	768	288
W2	112.2	112.2	90.2	113–143	768	864
W3	64.9	83.0	112.7	123–158	512	880
W4	59.7	73.2	117.2	113–139	512	1008
W5a	98.9	112.3	84.0	126–142	768	1440
W5b	112.5	122.8	66.0	143–156	768	1440
W6a	86.1	97.4	99.0	163–185	512	1008
W6b	97.5	107.5	87.8	185–205	512	1008
W7a	74.0	82.9	109.8	140–156	512	1440
W7b	82.9	90.8	90.8	156–172	512	1440

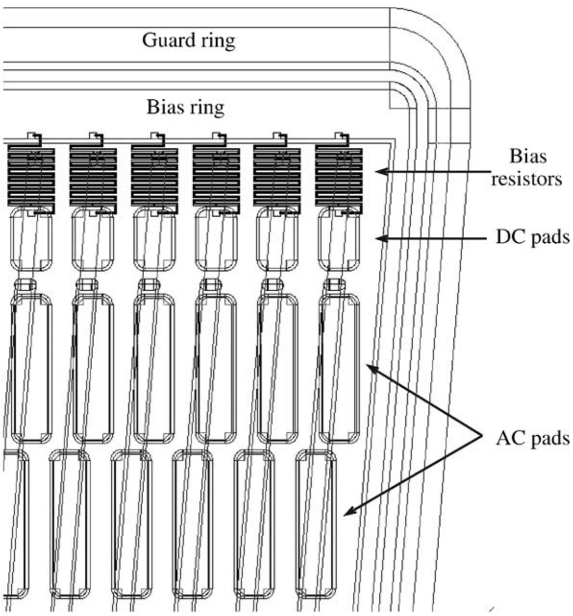

Fig. 4. View of the corner region of a wedge-type sensor.

($1.5 \pm 0.5\,\mathrm{M\Omega}$) is implemented to connect the individual strips to a common p^+ bias ring. To enable the sensors to be operated at a bias voltage of up to 500 V the aluminium readout strips are wider than the p^+ strip implants (4–8 μm metal overhang). For each strip two aluminium pads are foreseen for bonding. The DC pad is in direct contact with the p^+ strip implant for testing. The active sensor area is surrounded by the p^+ bias ring and one floating p^+ guard ring. Metal field plates on top of the guard ring also extend beyond the guard ring p^+ implant. An n^+ implant is realized along the sensor edges.

Outside of the sensor area a set of standardized test structures is implemented, identical for all 15 wafer types, which is used for the CMS quality control.

The contract for the production of these sensors was awarded to two companies. Hamamatsu Photonics K.K. (Hamamatsu-City, Japan) is producing all the sensors for the inner part of the tracker (TIB, TID and rings 1–4 of TEC). The second company, ST Microelectronics (Catania, Italy), is producing all the sensors for the outer part (TOB and rings 5–7 of TEC).

4. Quality assurance and progress in sensor procurement

The procurement of the silicon sensors for CMS is done in several stages. The first step was a research and development programme together with several companies to establish the optimal design. This was followed by the official market survey and the tendering procedure. After the contracts were negotiated and signed the two selected companies had to deliver a so-called pre-series for each type of sensor. This pre-series was about 5% of the total number of sensors. Using the pre-series production the design, correct implementation of the design and each company's process was checked. The delivery of the pre-series for all sensors was essentially finished by the end of 2002. At the beginning of the year 2003 the series production started. By August 2003 about 5000 sensors had been delivered. The delivery is scheduled to finish by the end of 2004.

To perform the acceptance test for more than 24 000 sensors in about two years is a very challenging task. The CMS sensor group has therefore developed a comprehensive procedure to qualify the sensors [5]. This quality assurance program contains four parts

- *Tests performed at the companies prior to shipment*: The contract with both companies lists a set of measurements and acceptance criteria. These measurements are, for example, tests of the leakage current, the determination of the depletion voltage and a check for pinholes and broken or shorted aluminium lines. Only sensors passing these tests are delivered to CMS.
- *Quality control on sensors*: This is an exhaustive test of the sensors. The total sensor leakage current and the total sensor capacitance is scanned as a function of the bias voltage and, at a bias voltage of 400 V, several parameters for each strip are measured in a strip scan.
- *Process control on test structures*: Using the specially designed set of test structures more than 10 parameters are measured. These parameters allow monitoring of the production process and provide data which cannot be measured on the sensors themselves.
- *Irradiation tests*: Using a neutron and a proton irradiation facility, test structures and sensors are checked for the required radiation hardness.

The goal of the CMS quality assurance procedure is to deliver 99% good sensors to the module assembly centers where the sensors, readout hybrids, etc. are glued to mechanical frames. A failure of a sensor at this stage will cause significant additional costs due to the lost material and working time. Furthermore the tests have to make sure that the sensors will be sufficiently radiation hard for the expected 10 years of operation in CMS.

In the following the quality control, process control and irradiation tests are explained and the experience with the already delivered sensors is given.

4.1. CMS quality control

The quality control is carried out in five CMS centres (Karlsruhe, Rochester, Perugia, Pisa, Vienna) and consists of an optical inspection and an electrical characterization. During the optical inspection the sensor is checked by eye for obvious damage, the edges of the sensor are scanned using a microscope to check for defects introduced during cutting and the dimensions are measured. The electrical characterization is done using fully automatic systems which measure the bias current and the detector capacitance as a function of the bias voltage up to 550 V and subsequently measure on each strip the values of the single strip leakage current, the resistance of the polysilicon resistor, the coupling capacitance and the leakage current of the dielectric. This strip scan is done with the sensor kept at a bias voltage of 400 V. This measurement takes several hours and is therefore only done on a sample of sensors.

The optical survey has revealed serious problems with the quality of the cut edge and for one company also problems with scratches. After appropriate interventions both problems have been solved. The leakage current characteristic is very important for CMS as the sensors will be operated at high bias voltages. Figs. 5 and 6 show the distribution of the total leakage current at 450 V for thin and thick sensors, respectively. The majority of all sensors have a leakage current of about 200 nA (sensors from HPK) and 1 μA (sensors from STM). For the thick sensors a small percentage exceed our acceptance criterion of 10 μA at 450 V and are rejected (not shown in the figure). The CMS criterion for the number of single strips with failures is less than 1% of the total number of strips, i.e. five for a sensor with 512 strips and seven for a sensor with 768 strips.

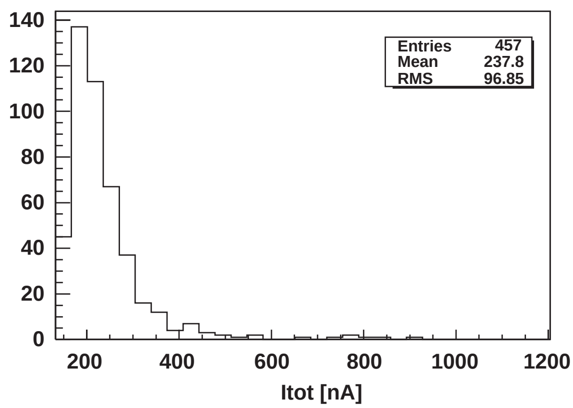

Fig. 5. Distribution of the leakage current for thin sensors (produced by HPK).

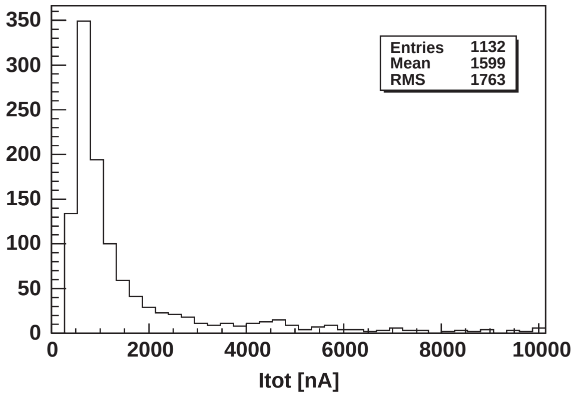

Fig. 6. Distribution of the leakage current for thick sensors (produced by STM).

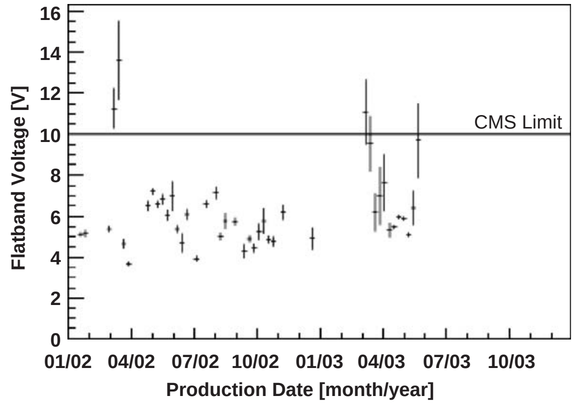

Fig. 7. Measured flat band voltage versus production date for thick sensors (produced by STM). Each point represents the average value for sensors produced within a particular week.

The agreement between the measurements made by the companies and by CMS is excellent. The strip failure rate for thin sensors is about 0.1% and for thick sensors it is about 0.4%. At the beginning of the production of the thick sensors the rejection rate of sensors failing the strip criterion was not negligible. However, this has improved for recent deliveries. The strip failures were mainly correlated with scratches and were detected as bad values of the coupling capacitance.

4.2. CMS process control

The process control is done in three CMS centres (Florence, Strasbourg, Vienna) [6]. A set of standard test structures, identical for all 15 sensor designs and for both producers, is used to perform 10 measurements in an automated way: $C(V)$ on a MOS structure, $C(V)$ on a diode, interstrip resistance, $I(V)$ on a mini-sensor, interstrip capacitance, $I(V)$ on a gate-controlled diode, resistance of the polysilicon resistors, the aluminium lines and the p^+ implants, coupling capacitances, and the breakdown voltage of the decoupling capacitor. The results of these measurements are compared to the specifications and then are also used to monitor possible changes in the production process of the companies.

In general, the measured parameters are well within the CMS specifications and are very stable in time. There are two exceptions. From the measurement of the capacitance as a function of the bias voltage on a MOS device the so-called flat band voltage can be deduced. The flat band voltage is a measure of the oxide quality. A high flat band voltage indicates the presence of many trapped charges in the interface region of the silicon oxide and the silicon bulk. The production process for the thick silicon sensors usually results in a flat band voltage of about 5 V. However, for several batches a dramatic increase up to 35 V was observed. Fig. 7 shows the measured flat band voltage as a function of the production date of thick sensors. The sensors corresponding to batches with high flat band voltage did not show any problem while measured by the quality control centres. Only after receiving a significant irradiation dose was there an increase in the interstrip capacitance and as a consequence a decrease in the signal-to-noise ratio for these sensors. This is a serious problem and the sensors had therefore to be rejected. An investigation at the company revealed a contamination of apparatus used during the production of these sensors.

A second problem detected by the process control was the use of wafer material with too high resistivity for the thin sensors. As explained earlier, the thin sensors used in the inner layers are built on rather low-resistivity material to delay the inversion point and to ensure sufficiently low bias

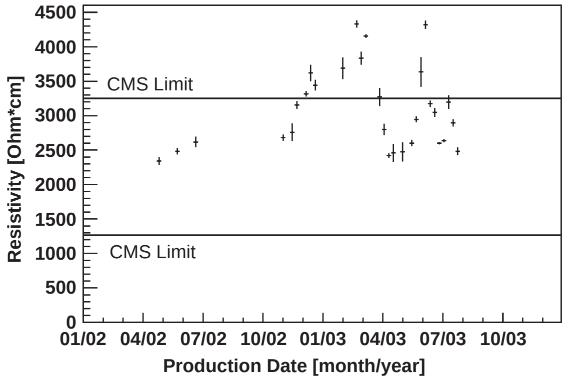

Fig. 8. Measured wafer resistivity versus production date for thin sensors (produced by HPK). Each point represents the average value for sensors produced within a particular week.

voltages throughout their lifetime. As shown in Fig. 8 the resistivity for thin sensors has been within the agreed limits, except for some batches. After intervention with the company the selection of the material was again within the CMS specifications.

4.3. Irradiation tests

The irradiation tests for a small number of sensors and test structures are done by two laboratories: a neutron irradiation facility in Lovain-la-Neuve and a proton irradiation facility in Karlsruhe. The irradiations are performed at a temperature of $-10°C$ up to the fluence expected in CMS for the particular sensor type. After irradiation and a short period at room temperature to allow for beneficial annealing the structures are re-measured at $-10°C$. The tests before and after irradiation consist of the measurement of the leakage current, the determination of the depletion voltage and the measurement of several single strip parameters: the values of the strip capacitance, the interstrip resistance, the polysilicon resistor value and the coupling capacitance.

The irradiations performed so far have confirmed the required radiation hardness of the silicon material as well as of the production process by both companies [5]. All measurements are in agreement with the CMS calculations for the leakage current and for the change of the depletion voltage. Hence, none of the sensor batches had to be rejected after the irradiation tests.

5. Summary

The procurement of the CMS silicon sensors is well under way. The quality assurance program implemented by CMS is in full operation and has proven to be very effective. During the start-up of the series production the quality tests on the sensors have given important feed back to the companies for the optimization of their processes. The CMS process control monitors the production process and the material used, and has identified some irregularities and non-compliances. The irradiation tests have verified the radiation hardness of the delivered sensors.

The sensor delivery is scheduled to finish at the end of 2004. According to the construction schedule of CMS the Inner Tracker will be installed in CMS in Spring 2006. The data taken during the sensor quality assurance is very promising and the CMS sensor group is certain that the sensors for the Inner Tracker will perform as required for the projected lifetime of the experiment.

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