SILICON SENSORS FOR THE COMPACT MUON SOLENOID EXPERIMENT AT THE LARGE HADRON COLLIDER, CERN

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Introduction

A specific research and development programme was undertaken by BARC, to develop the technology for 32-strip silicon sensors, for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC), CERN. These sensors will be used as Preshower sensors in the Electromagnetic Calorimeter of CMS for π/γ rejection and will cover an area of ~40,000 cm² in the CMS. Developing silicon sensors with very stringent electrical specifications and uniformity over a large area of ~40 cm² has been a challenging task, as such technology did not exist in our country. This R&D has been carried out in various phases such as prototype development, preproduction and production. Figs. 1, 2 and 3 show wafers fabricated during various phases of this project.

In view of expected radiation damage, the technology development was targeted to produce sensors with high breakdown voltage and low leakage currents, for ensuring ten years of operation without failure, in the high neutron and gamma radiation environment of LHC. The production of a thousand sensors has been recently completed and these sensors in the form of micromodules have been delivered to CERN. Fig. 4 and Fig. 5 show the silicon sensor after wafer dicing and the silicon sensor micromodule. The micromodule has the front end hybrid bonded to the 32 strips. The front end hybrid incorporates the PACE chip which has a 32-channel preamplifier, amplifier, shaper, 192-channel analog memory along with control logic. This chip is a radiation hard chip developed by CERN and has been fabricated by CERN in a 0.25 micron technology at IBM.

The micromodules are assembled in the form of ladders which comprise of 7-10 micromodules and

Fig. 1: Prototype

Fig. 2: Seven guard-ring design (Preproduction)

Fig. 3: Four guard-ring design (Preproduction & production)
these are then connected to a system motherboard which controls the micromodules and also acquires the signals from the micromodules. Fig. 6 & Fig. 7 show the ladder before and after integration of system motherboard.

The technology development of the silicon sensors and their production involved several important activities such as detector design and layout, process and device simulations for optimization, development of characterization setups and performance evaluation, fabrication process development and optimization, quality control during production and assembly of sensors into micromodules. The prototype development for the silicon sensors was carried out with a sensor geometry of 60 mm x 60 mm using standard silicon technology. The 4” integrated circuit fabrication facility of Bharat Electronics Limited (BEL), Bangalore was used for the development of the technology for fabrication of the sensors. Several batches of silicon wafers were fabricated at BEL for optimizing the fabrication process so as to meet the required specifications. After successful development of prototype sensors and demonstration of technological capability, BARC was qualified for the production of 1000 sensors and micromodules for the CMS experiment. A set of common specifications were decided in a meeting held at CERN during May 2000, in which all the countries (India, Greece, Taiwan and Russia) involved in the production of preshower silicon sensor, participated. As per the specifications finalized in this meeting, the production of the silicon sensors was carried out for the modified geometry of 63 mm x 63 mm. In order to evaluate the performance...
of the sensors, a great deal of effort was also taken to develop various automated setups for characterizing sensors and probe-jigs for making simultaneous contacts to the 32 strips. A test and assembly facility was setup at the production center (BEL) for carrying out all specified sensor qualification tests during the production phase. The present document describes in detail various aspects such as the design of the sensors, processing issues and sensor characterization. The results of various tests performed during the technology development and production phase, are also presented. In order to qualify the sensors for radiation hardness, the sensors were irradiated at CERN using the 24 GeV proton beam and in a nuclear reactor at BARC and Dubna, Russia. The results of these irradiation tests have also been presented.

**Specifications and design of the sensor**

The technology for sensor fabrication and its design were targeted to meet the following electrical and geometrical specifications:

- Full depletion voltage of the strips ($V_{FD}$): $55 < V_{FD} < 150V$
- Breakdown voltage ($V_{BD}$) of each strip: $> 300V/500V$
- Total leakage current of the sensor: $< 5 \mu A$ at $V_{FD}$ and $< 10 \mu A$ at $300V/500V$
- Uniformity of leakage current for the strips: at most one strip with leakage current $> 1 \mu A$ at $V_{FD}$ and $> 5 \mu A$ at $300V$
- Length of sensor: $63 \text{ mm} \pm 100 \mu m$
- Width of the sensor: $63 \text{ mm} - 100 \mu m$

As shown in Figs.1-3, three types of mask layouts incorporating 32-strip silicon sensor along with other test structures were designed during various phases of technology development, preproduction and production. Test structures such as PIN diodes of various geometries, MOS capacitors, gated diodes, etc. have been incorporated in the mask design, for carrying out process diagnosis and process optimization during fabrication. In addition to this, several other types of detectors such as PIN diodes of various geometries, pixel detectors, virtual pixel detectors, small area strip detectors, photodiodes, etc. were incorporated, to utilize the space around the silicon sensor. These detectors were designed for applications involving physics experiments and radiation monitoring instrumentation applications involving measurement of $\alpha$, $\beta$ and other charged particles, $\gamma$ radiation, X-rays and neutrons.

The first version of the design used during the prototype development phase, incorporated a silicon sensor with a geometry of $60 \text{ mm} \times 60 \text{ mm}$ (Fig.1). The sensor comprised of 32 $P^+$ strips having a width and pitch of 1.69 mm and 1.81 mm respectively. The strips were enclosed in seven $P^+$ guard-rings and an $N^+$ guard band was used in the scribe line region. However, it was later removed as it was found to deteriorate the performance of the sensor. The geometric design parameters of the sensor were the same as specified by the Preshower group, CERN. The sensor is passivated and has windows in the passivation for the purpose of bonding. A four layer mask was used for fabricating the sensors. In the initial batches, the performance of the sensors fabricated using this design, was quite poor. However, after continuous modifications of the process parameters, in subsequent batches, sensors having very low leakage, high breakdown voltage and uniformity could be realized.

As the sensor geometry was modified later from $60 \text{ mm} \times 60 \text{ mm}$ to $63 \text{ mm} \times 63 \text{ mm}$, the mask was redesigned during the pre-production phase (Fig. 2 and Fig. 3). The main design considerations for the design of the silicon sensors for production are as follows:
Not only performance, but yield also was an important issue for production of sensors.

Due to radiation damage, the operating voltage of the sensors would progressively increase with time, during the operation in the LHC environment. The sensors would be operated at a much higher voltage after a period of 7-8 years requiring the breakdown voltage of the sensors to exceed 300V/500V.

In order to realize sensors with high breakdown voltage, the following design strategy was incorporated in the final design of the sensor:

- Floating field guard rings to reduce the peak electric fields at the surface via punch through mechanism. As shown in Fig. 2 and Fig. 3, two types of guard ring designs with seven and four guard rings were designed.

- Since the breakdown field in the oxide is higher than avalanche breakdown field in the silicon, metal overhangs were incorporated over the P+ strips to distribute the voltage dropping across silicon and oxide so as to increase breakdown voltage of the strips.

Process and device simulations were carried out to finalize the design parameters such as width of the guard rings, spacing, length of the metal overhang, etc. As shown in Fig. 2 and Fig. 3, wafers with two types of guard ring designs i.e. four and seven guard rings, were fabricated during the preproduction phase and the yield of the batches were compared. Since the four guard ring design gave better yield, this design was used for the production of sensors. The same mask is being used for the production of sensors. The schematic cross section of the sensor showing various layers and geometric dimensions is as shown in Fig. 8. The magnified view of the layout of the sensor showing guard rings is seen in Fig. 9.

**Fig. 8: Cross section of the preshower silicon sensor (all dimensions are in microns)**

**Fig. 9: Magnified view of the corner of the sensor**

**Characterization setups and sensor test facility at BEL**

During technology development phase, static current vs voltage (I-V) and capacitance vs voltage...
(C-V) measurements were used to evaluate the performance of the sensor i.e. leakage current, breakdown voltage and full depletion voltage. A great deal of effort was taken to develop characterization setups in order to carry out automated and simultaneous measurements of all 32 strips of the sensors. Probe jigs with microscopic X-Y-Z positioning to simultaneously probe all 32 strips of the unpassivated/passivated sensor were designed and fabricated at BARC.

A complete test facility for carrying out sensor qualification tests was setup at the production center (BEL), so as to avoid transport of sensors and also because further assembly of sensors in to micromodules was to be carried out at BEL. The test facility was setup in a class 10,000 clean room environment and included the equipment for I-V and CV characterization as described above. In addition to electrical characterization setups, measurement jigs for measurement of geometric parameters such as length, width and thickness were used to verify that the dimensions of the sensors were within the specified tolerance. The sensors were visually inspected from front and back using high magnification microscope for checking the dicing quality at the edges and mechanical defects on the surface, as these are important factors determining the long-term reliability of sensors. The data of all measurements was entered in to the CRISTAL data base at CERN.

Fabrication technology for sensors

The sensors were fabricated by the silicon IC fabrication facility of BEL, Bangalore as per the process outline provided by BARC. The development for the preshower silicon sensors was challenging as compared to the standard ICs or ASICs because of the following reasons:

- The sensor fabrication required a custom process to be developed starting from virgin silicon wafer, while ICs/ASICs mostly use a standard well established process available at the foundry.
- The geometry of the sensor is very large as compared to the silicon ICs/ASICs. Hence realizing an acceptable yield of 50% was much more difficult as yield decreases sharply with increase in the die size.
- The preshower sensor required very low leakage currents of the order of nA at high voltages of the order of few hundred volts, while usually ICs have low current at low operating voltages and high current at high operating voltages.
- The process uniformity over a large area of the order of few hundred mm² was required for silicon sensors while in the case of standard ICs the die size is quite small and is of the order of few mm².

Considering the specifications of sensors such as full depletion voltage, total capacitance of the strips, breakdown voltage, etc., high purity silicon wafers were used as the starting material for fabrication of sensors. The sensor technology was developed using N-type, FZ, <111>, 3-5 kΩ-cm or 5-10 kΩ-cm wafers supplied by TOPSIL and WACKER. These wafers had specified zero defect density and high life time of the order of a few milliseconds. This is an important specification as the quality of the wafers is a critical factor for sensor fabrication and even a single defect occurring over the sensor area, which is quite large, would result in a bad strip giving non-acceptable performance. Fabrication of sensor was carried out using a complex process sequence involving more than 25 process steps. The process used for fabricating the sensors at BEL is shown schematically in process flowchart 1.

The process parameters used for the above processes were optimized so that, there is no degradation of the wafer quality and there is no generation of defects during processing, which could increase leakage and reduce breakdown voltage. Extensive process simulations were carried out to finalize the process.
parameters such as implantation energy and dose for boron and phosphorus, temperature and time for drive in cycles, intrinsic and extrinsic gettering cycles, etc. High temperature cycles were properly optimized and the contamination was strictly controlled during fabrication. The process optimization for meeting the desired specifications, carried out in several batches, has been discussed in detail in the subsequent section of this note.

**Process optimization**

The technology development was carried out in a short span of about one year, by systematically optimizing various processes involved in sensor fabrication. During the initial fabrication runs, the sensors were fabricated without surface passivation and scribing. After realizing sensors with acceptable performance, surface passivation and scribing were introduced and optimized in the later phase. The following important points were considered to decide the initial process parameters such as quality of the oxide, boron and phosphorous implant dose and energy, the screen oxide thickness, the drive-in temperatures and time subsequent to implantation:

- Excess positive oxide charge would give rise to low breakdown voltages at the junction edges at the surface, due to accumulation of negative charge; better quality oxide with a lower defect density is required.
- Junction curvature effects strongly affect the breakdown voltages. Process parameters for ion implantation and drive-in need to be selected, to tailor the junction curvature and reduce the thermal budget, which cause defect generation.
- The temperature cycles should be optimum so that the thermal budget is low and also problems related to the warping of wafer should be prevented as the wafer is thinner i.e. 300 μm instead of 500 μm which is the standard thickness for a 4” wafer.

The technology development for the Preshower sensor was initiated using a process which involved a few process steps such as initial oxidation, metallization, etc. The dose and energy of boron implantation was varied. The performance of the sensors was evaluated using IV measurements to see the leakage currents and breakdown voltage. The typical IV characteristics of the sensor fabricated in the second batch is as

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**Flowchart 1: Sensor fabrication process**

- Initial oxidation
- P⁺ lithography
- Screen oxidation
- Boron implantation for P⁺ strips & guard rings
- P⁺ implant anneal & drive-in
- Backside N⁺ implant
- N⁺ implant anneal & drive-in
- Contact lithography
- Front metallization
- Metal lithography
- Passivation
- Passivation lithography
- Back metallization
- Scribing
shown in Fig.10. As can be seen, the sensors have higher leakage currents of the order of few microamps and breakdown voltages for most of the strips are as low as 10-50 V. Though the silicon sensor performance was poor, the diodes on the same wafer could withstand high voltage up to 1000 V without breakdown and the leakage currents were low of the orders of nAs (Fig.11). This indicated that the main cause for the poor performance of the sensor could be generation of bulk and surface defects over the sensor area and which could be prevented by tuning critical process steps.

**Test structures for process diagnosis**

The fabrication process for the sensor was monitored during various stages using dummy wafers. The parameters like oxide thickness, sheet resistivity of P⁺ and N⁺, metal thickness, junction depth, etc. were measured, to ensure that each process step was carried out consistently and there were no problems during fabrication of a particular process step. The layout of the sensor incorporated various test structures in order to measure surface and bulk defects. These structures incorporated MOS capacitors, gated diodes, diodes with different perimeter to area (P/A) ratio, diodes with different guard ring designs, etc. Baby strip detectors were also incorporated to test the radiation hardness of sensors in fast neutron and gamma background. To debug the problems causing lower breakdown/ higher leakage currents, PIN diodes of different geometries were tested to find out their leakage and breakdown voltage. MOS capacitors were fabricated separately to check the quality of the oxide at various stages of processing e.g. initial oxidation, drive-in of P⁺ after implantation, etc. by inserting test wafers. These capacitors were characterized to obtain the fixed oxide charge and interface state density to ensure that these parameters were within reasonable limits.

**Process modifications for improvement of the performance of sensor**

During initial batches, sensors with desired specifications could not be produced by only varying process parameters such as implant dose and energy. Three types of processes having various combination of process steps were used to identify a set of process parameters for obtaining desired performance of the sensor. These processes were targeted to see the effect of the following parameters:

- Starting material or wafer quality
- Quality of the surface of the wafer
- Effect of implantation in the scribe-line region
- Reduction in defect generation due to gettering
- Independent control of N⁺ and P⁺ doping.
Wafers from two manufacturers (WACKER and TOPSIL) with two ranges of resistivities (3-5 kΩ·cm and 5-10 kΩ·cm) were used, to see the effect of starting material. A number of wafers were fabricated using various combination of process steps such as sacrificial oxide, Argon implant for extrinsic gettering, combined or separate drive in cycles for N⁺ and P⁺ implantations, with/without implant in scribe line, etc. Best results were obtained for wafers which were processed with sacrificial oxidation, Argon implant on the back side, separate drive-in cycles for N⁺ and P⁺ implantations and no implant in the scribe-line region.

Fig. 11 shows the reverse IV characteristics of a sensor fabricated in the fourth batch using this optimized process. Comparison of Fig. 10 and Fig. 12 clearly show the remarkable improvement in the performance of sensor in terms of leakage and break down voltage. The leakage currents have become very uniform and except for two, all strips could withstand 300V without breakdown. After optimizing the basic process for sensor fabrication in four batches, in the fifth batch, passivation was carried out on the front-side of the sensor. The best results were obtained for a PSG passivation layer. During this batch, measurements were carried out on all wafers after successive process steps such as after front metallization, after front passivation, after back metallization and after scribing. These measurements were carried out to check whether the process of passivation and scribing degrades the performance of the sensor or not. The leakage current per strip was significantly reduced by an order due to passivation from about 100 nAs to about 5-10 nAs and it was confirmed that there is no degradation of sensor quality due to passivation and scribing. Using the optimized process of batch 5, a few sensors meeting CERN specifications of leakage and breakdown (no strip with break down for < 300 V) could be fabricated in the sixth batch (Fig. 13).

Though about 70% of the sensors fabricated in batch 6 were found to have more than 90% good strips (≤ 2 bad strips out of 32 strips), the yield of the process was less than 30%. The problem was thought to be related to the injection of the carriers from the back side as several sensors showed the increase of strip currents around full depletion voltage. A double N⁺ implant was incorporated at the back side of the wafer in the seventh batch to reduce back injection. The implantation dose, energy and drive-in temperature and time were decided, based on the simulations carried out to

![Fig.12: IV characteristics of a sensor fabricated in the fourth batch](image)

![Fig.13: IV characteristics of a sensor fabricated in the sixth batch](image)
obtain a thick N$^+$ layer at the back side. By incorporating this process, the yield of the process improved significantly to about 50%. The typical CV and IV characteristics of all 32 strips of the sensor fabricated using the final optimized process are as shown in Fig.14 and Fig.15 respectively. As can be seen from the plots, sensors with very low leakage currents, high breakdown voltage and uniformity have been realized using the optimized process.

obtaining reasonable yield, twenty prototype sensors were delivered to CERN for demonstrating their performance. The data of IV and CV measurements was analyzed to obtain the parameters such as full depletion voltage of the strips, total leakage current, breakdown voltage, etc. The summary of these parameters obtained for twenty prototype sensors is plotted in Fig. 16. As can be seen, the sensors have very low leakage and the total leakage current at 300 V is by one order less than the required total leakage current specification of 10 μA. The full depletion voltage of sensors is also quite uniform and is as expected considering the substrate resistivity of 3-5 kΩ·cm.

### Production of sensors and quality control

Sensors with very good uniformity and at a production yield of 50% were produced at BEL and the production of a thousand sensors was completed using the optimized process as discussed earlier. The production was carried out using 300 μm thick, <111>, FZ, 2-4 kΩ·cm wafers manufactured by WACKER. During the production of silicon sensors, a test facility was setup at BEL for carrying out all tests in a class 10,000 environment with controlled humidity and temperature. The sensors were subjected to several quality control tests as outlined by CERN. These tests mainly involved electrical (IV and CV) and mechanical measurements (length, width and thickness). Each sensor was subjected to visual inspection from the front and backside for ensuring that the surface was free of any defects such as scratches and chipping at the edges. The breakdown voltages, leakage current and capacitance of individual strips, full depletion voltage, mechanical dimensions of the sensor (thickness, length and width), dicing quality, etc. were some of the main parameters which were monitored during quality control. The data of measurement was analyzed using a LabView programme to find various parameters for individual strips of each sensor. As shown in Fig.17, this data is plotted in LabView and was used to qualify or reject the sensors.
The stability of the sensor was tested by measuring the total leakage current of the sensor at different stages such as after fabrication, before micromodule assembly, after micromodule assembly, etc. The statistical distribution of various parameters such as $V_{BD}$, $V_{FD}$, total leakage current at $V_{FD}$ and at 300 V for thousand sensors are plotted in Fig. 18 a-d. As can be seen, the breakdown voltage exceeds 500 V for majority of the sensors. The total leakage current of the sensor is of the order of 200 nA at $V_{FD}$ and is less than 1.0 μA at 300 V for most of the sensors though this tolerance is 10.0 μA.

![Fig. 16: Electrical specifications of the prototype sensors](image)

![Fig. 17: Electrical parameters obtained for 32 strips of a sensor using IV & CV data](image)
Reliability of sensors

Considering the operation of LHC for ten years in high radiation background, reliability requirements were very stringent, as the sensors are expected to operate without failure, once the LHC is commissioned. In view of the fact that the sensor production was started in the year 2002 and the actual commissioning of the sensors in the LHC will be done in 2008, it was also necessary to have a high shelf life. The stability of the sensors with time was verified by measuring the total leakage of the sensors with time at no bias conditions. In order to test the stability under bias condition, few sensors were kept at 300 V and the total leakage current was monitored with time. In order to test the radiation hardness of sensors, a few sensors were irradiated using the 24 GeV proton beam at CERN and in the nuclear reactors at BARC and Dubna, Russia. The variation of $V_{\text{BD}}$ to neutron damage was investigated by irradiating sensors in APSARA reactor at BARC. As can be seen, after irradiation to a neutron fluence of $2 \times 10^{14} \text{ n/cm}^2$, $V_{\text{BD}}$ increases to about 300 V which is as expected (Fig. 19). Fig. 20 shows the total leakage current variation with time for four sensors after irradiation to a proton beam at CERN. The variation of temperature at the time of measurement is also indicated in the same plot. This plot shows that sensors have a stable behavior even after a long time of more than 300 days after irradiation and the leakage current increase due to irradiation, is within the limit of 1 mA.

Fig. 18: Distribution of (a) $V_{\text{BD}}$, (b) $V_{\text{FD}}$, (c) $I_{\text{FD}}$, and (d) $I_{\text{300}}$ for 1000 sensors. The tolerance for $I_{\text{FD}}$ is 5.0 $\mu$A and for $I_{\text{300}}$ is 10.0 $\mu$A.
Summary

Demanding technology and the capability for large scale production of silicon sensors with good uniformity, low leakage currents and high breakdown voltage has been demonstrated and developed by BARC, for the first time in our country. The sensors produced have very good uniformity in terms of parameters such as full depletion voltage, breakdown voltage and leakage current of strips. The individual strip leakage is of the order of few nA/cm² and the strip and total leakage currents are quite well below the specified limits. Irradiation tests carried out have shown that the sensors meet the stringent specifications for reliable operation in the high radiation environment of LHC. Subsequent to the development of technology, the production of a thousand sensors has been recently completed. The sensors assembled in the form of modules are being installed in the CMS preshower at LHC, CERN. The R&D carried out over the past few years has given us the technological capability for large scale production of large area sensors. Though the R&D was targeted for the development of sensors for the international experiment at CERN, this R&D triggered the indigenous development of a wide variety of high performance sensors, for nuclear instrumentation and radiation monitoring instrumentation applications at BARC.

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Publications


