TECHNOLOGY DEVELOPMENT OF SILICON SENSORS FOR THE COMPACT MUON SOLENOID EXPERIMENT AT THE LARGE HADRON COLLIDER, CERN, FOR PHYSICS EXPERIMENTS AND FOR RADIATION MONITORING

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Introduction

In recent years, silicon sensor technology has become the most preferred technology, for building detector systems of ambitious high energy physics experimental research facilities such as the LHC. Silicon sensors are being increasingly used, for detection of particles in high energy physics experiments, due to their superior performance such as fast response, good signal-to-noise ratio, compactness and their suitability to build multidetector systems, involving thousands of sensors having millions of channels. High position resolution in 1D or 2D can be easily obtained, by segmenting the sensors into strips, microstrips or pixels. Moreover, application of the well established silicon integrated technology for sensor fabrication, has enabled realization of sensors with very good uniformity and low cost. In the past few years, the Electronics Division has carried out R&D to develop the technology for various types of silicon sensors, using the fabrication facilities of the silicon foundries in our country. This programme has focused on developing the following types of sensors:

- Large area sensors for international high energy physics experimental facilities- CMS Experiment at LHC, CERN and PHENIX Experiments at RHIC, BNL, USA
- Sensors with high energy resolution for measurement of position and energy of particles in nuclear physics experiments at BARC
- Sensors for compact, low power radiation monitoring instrumentation.

A specific research and development programme was carried out, to develop the technology for 32-strip silicon strip sensors for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC), CERN [1-8]. These sensors are used as Preshower sensors in the Electromagnetic Calorimeter of CMS for \( \pi/\gamma \) rejection and cover an area of \( \sim 40,000 \text{ cm}^2 \) in the CMS end caps. Developing silicon sensors with very stringent electrical specifications and uniformity over a large area of \( \sim 40 \text{ cm}^2 \), has been a challenging task. 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 in the high radiation environment of LHC. The design of the sensors, the complete mask layout and process parameter optimization was carried out by the Electronics Division. The fabrication of the sensors...
was carried out using the IC fabrication facility of Bharat Electronics Limited (BEL), Bengaluru as per the process outline provided by BARC. Eleven hundred silicon detector micromodules have been delivered to CERN. The silicon sensors activity was further expanded, to develop a wide variety of silicon sensors, suitable for various applications involving nuclear physics experiments and radiation monitoring [9-15]. Advanced silicon sensors such as silicon microstrip sensors with a geometry of 62 x 62 mm$^2$ incorporating 128 strips have been developed, for the PHENIX Experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), USA. The pitch of the strips is 470 μm and the spacing between the strips is 15 μm. Several types of silicon sensors such as silicon PIN diodes, silicon pad sensors, high energy resolution sensors for alpha and charged particle spectroscopy, large area PIN detectors for low activity counting, single and multielement silicon PIN photodiodes, radiation sensitive MOSFETs - ‘XRFETs’, etc. have been developed, as an outcome of R&D activity. An overview of this technology development activity is presented in the subsequent sections of this paper.

**Various types of sensors developed**

Silicon sensors find wide range of applications in several fields involving measurement of radiation such as charged particles, neutrons, photons, etc. The applications involve high energy particle physics, nuclear physics and astrophysics experiments, personal dosimeters, medical dosimetry, low energy X-ray spectroscopy, high resolution α and charged particle spectroscopy, detection of low activity radiation such as plutonium in air and radon monitors, contamination monitoring, area monitors, X-ray imaging, tomography, etc.

Considering the above applications, the silicon sensor R&D was targeted, to develop a wide range of sensors having different specifications in terms of sensor geometry, area, segmentation, energy resolution and dead layer. The silicon sensors developed as a result of this R&D are listed below:

- 32-strip silicon strip sensors for the CMS Experiment at LHC, CERN. These sensors are also being used for nuclear physics experiments at BARC
- 128-strip silicon microstrip sensors for the PHENIX Experiment at BNL, USA
- Silicon pad sensors with a 2 x 2 matrix and energy resolution of 18 keV for energy and position measurements of charged particles, for the ‘Charged Particle Array’ at BARC
- Single element silicon sensors with area ranging from 100 mm$^2$ to 400 mm$^2$ for charged particle identification and alpha spectroscopy applications

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**Fig. 1 : Wafers designed and fabricated during various phases of CMS silicon strip sensor development**
Figs. 1-3 show fabricated wafers incorporating various types of silicon sensors.

After fabrication at wafer level, the sensors have been packaged using the facility of Bharat Electronics Limited, Bengaluru. Custom packages on ceramic substrates have been developed for this purpose. The sensors have been wire bonded using 1mil diameter aluminum wire, using wedge bonding machines. Fig. 4 shows some of the packaged sensors. An overview of the silicon sensor technology development and their performance is presented in the subsequent section of this paper.

Fig. 2: Fabricated wafer showing silicon pad sensors for Charged Particle Array

Fig. 3: Fabricated wafer showing silicon sensors for charged particle spectroscopy and low activity counting

Fig. 4: Packaged silicon sensors
Preshower silicon sensors for the CMS Experiment at LHC, CERN

The R&D for the development of technology for Preshower sensors, was carried out in various phases such as prototype development, preproduction and production. Figs.1(a)-(c) show wafers fabricated during various phases of this project. Fig. 5 and Fig. 6 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 32-channel preamplifier, amplifier, shaper, 196-channel analog memory along with control logic. This 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 have 7-10 micromodules and are then connected to a system motherboard which controls the micromodules and also acquires the signals from the micromodules. Fig. 7 show the ladder before integration of system motherboard.

The technology development of the silicon sensors and their production, involved several important activities such as sensor design and layout, process and device simulations, development of characterization setups and performance evaluation, fabrication process development and optimization, quality control during production and assembly of sensors into micromodules. The 4" integrated circuit fabrication facility of BEL, Bengaluru has been used, for development of the technology for fabrication of the sensors. Eight batches of silicon wafers were fabricated at BEL for optimizing the fabrication process, so as to meet the specifications. After successful development of prototype sensors and demonstration of technological capability, BARC was qualified for the production of 1000 sensors for the CMS experiment. In order to evaluate the performance of the sensors, a great deal of effort was also put in, to develop various automated setups for characterization of sensors and probe-jigs for making simultaneous contacts to the 32 strips. Various aspects such as the design of the sensors, processing issues and sensor characterization and performance of the sensors are described in the subsequent sections of this paper.
Design of the Preshower sensor

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., were incorporated in the mask design for carrying out process diagnosis during fabrication. In addition to this, several other types of sensors such as PIN diodes of various geometries, pixel sensors, virtual pixel sensors, small area strip sensors, photodiodes, etc. were incorporated in the designs, to utilize the space around the silicon sensor.

The first version of the design used during the prototype development phase incorporated a silicon sensor with a geometry of 60mm X 60mm having 32 P+ strips (Fig.1 (a)). 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. After continuous modifications of the process parameters, in subsequent batches, sensors having very low leakage, high breakdown voltage and uniformity could be realized. As shown in Fig. 3(c), the final version of the sensor was designed for the geometry of 63mm x 63mm, with strips of width of 1.78 mm and pitch of 1.9 mm. This has been used for the production.

Features such as floating field guard rings, metal overhang over the P+ strips and rounded corners have been incorporated in these designs, to increase breakdown voltage of the strips. All the 32 P+ strips are enclosed by four floating field guard rings. The last guard ring is located at a safe distance from the dicing edge, so that, mechanical defects due to dicing do not affect the leakage currents.

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. 1(b) and Fig. 1(c), 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 designs gave better yield, this design was used for the production of sensors.

Characterization of Preshower sensors

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 put in, 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 set up in a class 10,000 clean room environment at the production center (BEL), so as to avoid transport of sensors and also because the further assembly of sensors into micromodules was to be carried out at BEL. The data of all measurements was entered in to the CRISTAL data base at CERN. The IV and CV data was used, to qualify the sensors for specifications such as full depletion voltage (V_{FD}) of the strips (55<V_{FD}<150V), breakdown voltage (V_{BD}) of each strip (>300V), total leakage current of the sensor (,<5\mu A at V_{BD} and <10\mu A at 300V) and uniformity of leakage current for the strips ( only one strip with leakage current >1 \mu A at V_{BD} and >5\mu A at 300V). 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 are within the specified tolerance of 100\mu m.

In order to ensure that the sensors would operate reliably in the radiation environment of LHC, the radiation hardness of the sensors was tested by irradiating them with fast neutrons up to a neutron fluence of 2x10^{14}n/cm^2 in a reactor (at BARC, India...
and at Dubna, Russia) and using a 24 GeV proton beam at CERN. As leakage currents increase excessively due to neutron radiation damage, the measurements after neutron irradiation were carried out at lower temperatures.

**Fabrication technology for Preshower sensors**

The development for the preshower silicon sensors was challenging as compared to the standard ICs or ASICs, because of nonavailability of standard technologies, much larger chip area causing decrease of yield and specifications requiring very low leakage currents at high operating voltages exceeding 500V.

The sensor technology was developed using high purity silicon wafers (N-type, FZ, <111>, 3-5 kΩ-cm or 5-10 kΩ-cm) supplied by TOPSIL or 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 the sensor was carried out, using a complex process sequence involving more than 25 process steps. Extensive process simulations were carried out to finalize the process parameters such as implantation energy and dose for boron and phosphorus, temperature and time of drive in cycles, intrinsic and extrinsic gettering cycles, etc.

The technology has been developed in a short period of about one year, by systematically optimizing various processes involved in sensor fabrication, in eight batches. During initial batches, sensors with desired specifications could not be produced by only varying process parameters such as implant dose and energy. Hence, various suite of processes were investigated, to optimize the process parameters.

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 the starting material. A number of wafers were fabricated using various combinations 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. 8 shows the reverse IV characteristics of a sensor, fabricated in the sixth batch, using the optimized process. The characteristics clearly show the remarkable improvement in the performance of the sensor in terms of leakage and break down voltage. The leakage currents have become very uniform and all strips could withstand 300V without breakdown. 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 on the basis of simulations, carried out to obtain a thick N⁺ layer at the back side. By incorporating this process, the yield of the process significantly improved by 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.9 and Fig.10 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.

![Fig. 8 : IV characteristics of a sensor fabricated in the sixth batch](image-url)
Production of sensors

Sensors with very good uniformity and production yield of 50% have been produced at BEL and production of eleven hundred sensors has been completed, using the optimized process as discussed earlier. The production was carried out using 300μm thick, <111>, FZ, 2-4kΩ-cm wafers manufactured by WACKER.

During the production of silicon sensors, the sensors were subjected to several quality control tests as outlined by CERN. 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.

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 300V for one thousand sensors are plotted in Fig. 11. As can be seen, the breakdown voltage exceeds 500V for the majority of the sensors. The total leakage current of the sensor is of the order of 200nA at $V_{FD}$ and is less than 1.0 μA at 300V for most of the sensors, though this tolerance is 10.0μA.

Considering the operation of LHC for ten years and high radiation background, reliability requirements were very stringent as the sensors are expected to operate without failure, once the LHC is commissioned. In order to test the stability under bias condition, few sensors were kept at 300V and the total leakage current was monitored with time. The radiation hardness tests carried out on the sensors proved, that the sensors could withstand the radiation environment of LHC.

Silicon microstrip sensors for the PHENIX Experiment at BNL, USA

After the successful development of large area silicon strip sensors for the CMS Experiment, this development activity has been taken to the next level, by developing advanced microstrip sensors for the PHENIX Experiment at BNL, USA. These sensors were designed to have 128 strips with a pitch of 470 μm and strip spacing of 15 μm. The strips will be read by a 128 channel readout.
Fig. 11: Distribution of (a) $V_{BD}$, (b) $V_{FD}$, (c) Total current at $V_{FD}$ ($I_{FD}$) and (d) Total current at 300V ($I_{300}$) for 1000 sensors. The tolerance for $I_{FD}$ is 5.0 $\mu$A and for $I_{300}$ is 10 $\mu$A.

Chip, developed by BNL. A silicon pitch adapter to match the strip pitch of the sensor with 48 $\mu$m pitch of the readout chip has been also designed and fabricated with these sensors.

Fig. 12 (a) shows the 128-strip microstrip sensor and Fig. 12 (b) shows the magnified view of the corner of the sensor. The microstrip sensors have been fabricated on 4-6 $k\Omega$-cm, <111>, TOPSIL wafers with a thickness of 300 $\mu$m. An automated test setup incorporating a 128 pin probe card for probing the strips, a channel multiplexer and low current and capacitance measurement instruments has been developed, for the characterization of the sensor.

Fig. 12 (a): Silicon microstrip sensor – Geometry - 62mm x 62mm, 128 strips with separation of 15 microns.
The typical capacitance and leakage current characteristics for the 128 strips at different bias voltages are shown in Fig. 13 and Fig. 14 respectively. These microstrip sensors have been delivered to BNL for the PHENIX Experiment.

**Silicon sensors for nuclear physics experiments and radiation monitoring**

As shown in Fig. 2-4, various types of sensors have been designed and fabricated, for nuclear physics experiments, such as ‘Charged Particle Array’ at BARC and radiation monitoring instrumentation applications. These sensors have been designed to have circular and square geometries, with area ranging from 100 mm$^2$ to 400 mm$^2$. The design has been carried out, so as to reduce the leakage currents and improve breakdown voltage of the sensors. The pad sensors have four pads each of geometry 10 mm x 10 mm and total area of 25 x 25 mm$^2$. These sensors have ion implanted junctions and oxide passivation. The process parameters have been initially optimized, using process simulations and then further tuned by carrying out fabrication runs in several batches. The dead layer of the window and leakage current minimization were of prime concern, in order to get the best energy resolution for charged particles. The sensors have been characterized by leakage current and capacitance measurements and by carrying out energy resolution measurements, using an alpha source of $^{239}$Pu and $^{241}$Am. A setup comprising of a charge sensitive preamplifier, spectroscopy amplifier, HV and MCA has been used, for energy resolution measurements. The measurements have been carried out by mounting the sensor and the source in a vacuum chamber. The leakage current characteristics of the sensors show, that the leakage currents are quite low (<10nA/cm$^2$ at 100V). The pulse height spectrum obtained for the four pads of the pad sensor is shown in Fig. 15. The pads show energy resolution of about 20-22 keV for $^{241}$Am alpha particles of 5.486 MeV. The energy
resolution of the sensor with area of 300mm$^2$ is about 18keV (Fig. 16).

**Silicon PIN photodiodes**

Silicon photodiodes coupled to a scintillator are used, for the measurements of X-rays or $\gamma$-radiation and charged particle spectroscopy, involving long range particles encountered in nuclear studies, laser based instrumentation, physics research and X-ray imaging. Considering the large numbers of applications of silicon photodiodes, the technology development of silicon PIN photodiodes has been carried out. Several types of photodiodes with area ranging from 0.5mm$^2$ to 100mm$^2$, quadrant detectors and 16-element array of photodiodes have been designed, using a four layer mask (Fig. 17).

The photodiodes have been fabricated using high resistivity silicon wafers, by a custom-developed low leakage current process. The dark current and capacitance of the diodes for various bias voltages has been measured up to full depletion voltage using automated setups. The dark current has been observed to be about 3-5 nA/cm$^2$ and the capacitance at full depletion voltage is about 45 pF/cm$^2$. The response of these diodes has been evaluated at different wavelengths using laser/LED and compared with a commercial photodiode having comparable area [16]. The typical responsivity of PIN photodiode of geometry...
6mm x 6mm (marked as ED) is shown in Fig. 18. The responsivity is about 0.66 A/W at 940 nm wavelength and falls to 0.24 at 453.5 nm. The performance is comparable to that of commercial photodiodes (UDT).

Summary

Demanding technology and capability for large scale production of silicon sensors with good uniformity, low leakage currents and high breakdown voltage have been developed by BARC, for the CMS Experiment at LHC, CERN. 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. Eleven hundred sensors supplied by us in the form of micromodules, have been installed in CMS preshower at LHC, CERN. The R&D carried out in 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 physics experiments and radiation monitoring instrumentation applications at BARC. Development of new types of sensors such as silicon photomultiplier and integrated ΔE-E silicon detector telescope are underway [17].

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References


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