Sensors for the CDF Run2b silicon detector


This paper is posted at Purdue e-Pubs.
http://docs.lib.purdue.edu/physics_articles/403
Sensors for the CDF Run2b Silicon Detector


Abstract—We describe the characteristics of silicon microstrip sensors fabricated by Hamamatsu Photonics for the CDF Run 2b silicon detector. A total of 953 sensors, including 117 prototype sensors, have been produced and tested. Five sensors were irradiated with neutrons up to $1.4 \times 10^{14} \text{ cm}^{-2}$ as a part of the sensor quality assurance program. The electrical and mechanical characteristics are found to be superior in all aspects and fulfill our specifications. We comment on charge-up susceptibility of the sensors that employ a (100) crystal structure.

I. INTRODUCTION

The CDF collaboration has designed a new silicon tracker system [1], [7] for Tevatron Collider Run 2b. The system is a six-double-layer device located between 2.1 and 17 cm radius, consisting of about 2300 single-sided silicon microstrip sensors. The whole detector is divided into an inner layer (L0) with 144 axial sensors and five outer layers (L1 to L5) with 1512 axial and 648 1.2-degree stereo sensors. In the following, we report on the outer sensor results. The inner sensors are similar, although smaller in size (78.5 × 15 mm) and have a finer pitch (25 μm with alternate readout strips). Details of the L0 design can be found in [2].

The outer layers are built out of compact stave structures [3], [8], [9]. Each stave consists of 12 silicon sensors. Layers 1 and 5 have axial sensors on both sides, while layers 2 to 4 have axial sensors on one side and stereo on the other side. The double axial layers, L1 and L5, provide efficient and unambiguous anchor hit points that can be used for L0 hit search and for track extrapolation to the outer tracking system. The silicon sensors are glued to a rohacell structure sandwiched by carbon-fiber (CF) sheets and internal bus cables. The readout hybrids are glued directly on the silicon sensors. The cooling tube, embedded in the rohacell, efficiently sinks the heat generated in the sensors after receiving radiation and in SVX4 ASIC chips on the hybrids. The innermost sensors are designed to operate at $-5^\circ$C with ethylene glycol coolant at $-15^\circ$C. The staves are installed in a 66-cm long cylindrical barrel structure with each end supported by a CF bulkhead. Fig. 1 shows an end view of the barrel. Two barrels, each containing 90 staves, are arranged along the beam-line (in z) covering the interaction region to $||z| < 2$ with...
The system requires 1512 axial and 648 stereo sensors. We report on characteristics of 953 delivered sensors. First, we describe the electrical properties of the sensors. Five axial sensors were irradiated with neutrons up to $1.4 \times 10^{14}$ n/cm$^2$. The characteristics of these sensors are also given. We observed some charge-up susceptibility and investigated its characteristics. Mechanical properties were also studied. Finally, we summarize the results.

II. Electrical Properties

A. General Quality Assurance (QA) Procedure

Hamamatsu Photonics performed intensive QA tests: $I$–$V$, $C$–$V$, ac-pad scan, and dc-pad scan. The ac-pad scan classifies defective strips as “ac open” (the aluminum strip has a break), and “ac short” (neighboring aluminum strips are shorted). The dc-pad scan reports “open” (the implant strip has a break), “short” (neighboring implant strips are shorted), “leaky” (the strip current is large), and “bad isolation” (the interstrip resistance is too small).

We have performed additional tests in order to verify the HPK test results and to evaluate the electrical characteristics in further detail. The tests are as follows.

1) $I$–$V$ curve: Total leakage current was measured up to 1000 V bias at a step of 10 V.

2) $I$–$V$ curve stability: $I$–$V$ curves were measured every 100 min at least ten times, and typically 30 times. The bias voltage between the $I$–$V$ measurements was set at 500 V.

3) $C$–$V$ curve: Total capacitance was measured as a function of bias voltage. The curve was used to extract the full depletion voltage.

4) AC scan: Oxide coupling capacitance, and equivalent series resistance (implant and bias resistance) were measured for each readout strip with an LCR meter. Also, the leakage current was measured when 100 V was applied across the oxide.

5) DC scan: The leakage current of individual strip was measured for the sensors that showed a rapid increase in leakage current, or micro-discharge [4]. The bias was set above the micro-discharge onset voltage.

6) Interstrip isolation: The interstrip resistance was measured with applying voltages ($-1$ to $+1$ V) to the neighboring intermediate dc pads and measuring the current emerging from the readout dc pad under test

7) Interstrip capacitance: The capacitance between the neighboring ac pads was measured. Other strips were floating.

We measured $I$–$V$ and $C$–$V$ characteristics for all the sensors (except for some prototype sensors). The ac scan and $I$–$V$ stability tests were performed on a sampling basis. The rest of the tests were made less frequently. In particular, they were performed to diagnose the sensors that showed results which deviated from the expectations.

B. $I$–$V$ Characteristics

The $I$–$V$ curve is relatively easy to measure and provides an overall view of the sensor quality. In Fig. 3, we show typical $I$–$V$ curves of a subset of the sensors. The measured leakage
current values were normalized at 20 °C while the test bench temperature was in the range of 26 °C to 30 °C. The humidity was in the range 35% to 60%. The leakage current is quite small and most of the sensors do not show any significant micro-discharge up to 1000 V we measured. There are two sensors in this sample of 116 sensors, which show micro-discharge with onset voltages of around 800 and 900 V. The leakage currents at 500 and 950 V are shown in Fig. 4 for all 953 sensors.

The leakage current is typically 0.1 μA. We set our leakage current requirement to be less than 2 μA at 500 V in order to insure that no single readout strip has a leakage current exceeding ~1 μA, as this would degrade the noise performance. All the sensors fulfilled this specification. In addition, 97% of the sensors showed leakage current below 0.5 μA, even at 950 V. HPK has realized this superior performance by employing a single guard-ring structure with 1-mm distance between the scribed edge and the sensitive area (see Fig. 2).

For the sensors that show micro-discharge, we have verified that the micro-discharge is caused at a single or a few strips by measuring the individual strip leakage (dc scan). It would be also possible to use these sensors if such strips are disconnected from the readout.

C. Stability of I–V Curves

We measured the I–V stability for 42 sensors, including all the sensors that show degraded I–V characteristics. Between the I–V measurements, the sensors were biased at 500 V for 30 min. The results can be categorized into four types. For most of the sensors (35 sensors), the I–V curves were consistent and stable, as in Fig. 5(a). Two sensors showed stability as in Fig. 5(b), where small micro-discharges developed above 900 V. We found four sensors that had significant micro-discharge as shown in Fig. 5(c). Out of these four, two sensors showed bad micro-discharge in the initial I–V measurement: The onset voltage increased gradually with time. The other two were good to 1000 V initially, but the onset voltage of 600 V showed up within 1 h. The onset voltage then increased with time, reaching 800 V or higher at the last measurement.

An exceptional behavior was observed for one sensor. The I–V stability is shown in Fig. 5(d). The I–V, initially good to 1000 V, started to become chaotic after 8 h and finally went into breakdown at 800 V after 10 h. We investigated the cause with an IR camera, and found a discharge hole on the bias-ring. Since

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Axial</th>
<th>Stereo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer</td>
<td>&lt;100&gt;</td>
<td>320±15μm thickness; &lt;130μm warp</td>
</tr>
<tr>
<td>Dimensions</td>
<td>40.55 x 96.392 mm</td>
<td>41.10 x 96.392 mm</td>
</tr>
<tr>
<td>Full depletion voltage</td>
<td>100 V &lt; Vdep &lt; 250 V</td>
<td></td>
</tr>
<tr>
<td>Leakage current</td>
<td>&lt; 2 μA at 20°C and at 500 V</td>
<td></td>
</tr>
<tr>
<td>Number of strips</td>
<td>512 readout and 513 intermediate strips</td>
<td></td>
</tr>
<tr>
<td>Strip widths</td>
<td>8 μm implant and 14 μm Al electrode</td>
<td></td>
</tr>
<tr>
<td>Readout strip pitch (angle)</td>
<td>75 μm (0°)</td>
<td>80 μm (1.2°)</td>
</tr>
<tr>
<td>Coupling capacitor</td>
<td>capacitance &gt; 120 pF; breakdown voltage &gt;100 V</td>
<td></td>
</tr>
<tr>
<td>Interstrip capacitance</td>
<td>&lt; 1.2 pF/cm</td>
<td></td>
</tr>
<tr>
<td>Poly silicon resistance</td>
<td>1.5±0.5 MΩ</td>
<td></td>
</tr>
<tr>
<td>Defective strip fraction</td>
<td>&lt; 1%</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Typical I–V curves (curves for 116 sensors are overlaid).

Fig. 4. Leakage currents at 500 and 950 V for all 954 sensors. The numbers exceeding 0.5 μA are given in extremely right bin.

1Although our specification is 500 V, we investigated the possibility of operating the same sensor at higher voltages for future applications. Since our initial results were promising up to 1000 V, we chose 1000 V as the maximum to apply.
we recognized no hint of discharge bridging to nearby structures, the discharge must have occurred toward the bulk substrate probably via some defect in the wafer. The sensor did not recover, indicating the creation of a permanent junction breakdown.

In summary, most sensors are good to 1000 V, but some created micro-discharge after a time scale of 1 h. In any case, operation below 500 V should be safe.

D. Full Depletion Voltage

We measured the $C-V$ curves of 908 sensors using an LCR meter with test pulses at 400 Hz and 1 V. We extracted the full depletion voltage as the intercept of two straight lines in a $C^{-2}-V$ plot. The full depletion voltage is distributed from 87 to 165 V, as shown in Fig. 6.

Our depletion voltage specification of 100 to 250 V is based on the resistivity range from 1.25 to 3.25 kΩcm, a wafer class employed by HPK. Some fraction, 7.7%, of the sensors are out of specification: It is explained by HPK as a nonuniform wafer resistivity and the sampling, three points per wafer, was not enough. Since the requirement, minimum of 100 V, is to delay the type inversion, such sensors are safely usable if we place them in the outer layers.

E. AC Scan and Number of Defect Strips

The strip integrity was intensively evaluated by an ac scan where the measurement was performed in two steps. First, the capacitance and series resistance were measured by probing between the ac pad and bias-ring with the LCR meter set at Cs-Rs mode and at 400 Hz. Second, a 100-V pulse was applied across the oxide and the leakage current through the oxide was measured 1 s after. The capacitance represents the oxide coupling capacitance and the resistance represents the sum of the bias resistance and implant electrode resistance. The implant resistance contributes approximately 0.3–0.5 MΩ.

AC scan was performed for 49 sensors. The coupling capacitors and resistors were found to be very uniform and defective strips can be easily identified: An example plot is given in Fig. 7 for a stereo sensor, where the first 25 strips starting from -256 are shorter due to the stereo angle. The leakage current in this plot, about 10 nA, is due to the leakage through the CMOS relays that we used in the apparatus to isolate the LCR inputs from 100 V pulses. This is larger than the leakage through genuine coupling capacitors, but is much smaller than the leakage when the oxide has a punch through, 10 μA, as defined by protection resistors in the system.

With HPK’s ac scan, they evaluate various defects by injecting step pulses into the bulk from the backside contact and measuring the signal emerging from the ac pad, thus eliminating use of an LCR meter. No bias is applied in this measurement. One of the purposes of our ac scan is to verify the HPK results.

The 49 sensors we selected have defects reported by HPK. Except for some leaky strips and bad isolation strips, we suc-
A. Neutron Irradiation

Radiation damage of silicon sensors has been studied intensively for the application to, e.g., LHC experiments. Although radiation in CDF is composed of various hadrons, we irradiated five sensors with neutrons at MNRC Irradiation Facility at the University of California, Davis, in order to verify that our sensors are radiation hard as expected from previous results [5].

Three of the sensors received 1.4 x 10^14 n/cm^2 and sensor (2) at 1.40 x 10^14 n/cm^2. The irradiation time was 69 min in total. No sensor bias was applied and no temperature control was attempted during the irradiation.

Right after the irradiation, the sensors were stored at −7 °C. The sensor temperature was then increased for certain periods.
so that the beneficial annealing is almost complete hence the full depletion voltage is at the minimum.

B. Total Leakage Current and Full Depletion Voltage

Fig. 8 shows the I-V curves of the irradiated sensors. The current is normalized at 20 °C. The sensors do not have any micro-discharge up to 1 kV and show clear shoulders indicating that the leakage current through the bulk dominates.

The measurement of full depletion voltage is strongly affected by high leakage current and therefore was performed in the environmental chamber at −25 °C. The full depletion voltages derived from $C^{-2}-V$ plots ranged from 128 to 130 V for the sensors irradiated to $1.4 \times 10^{14}$ n/cm$^2$, and about 50 V for the sensors irradiated to $0.7 \times 10^{14}$ n/cm$^2$. These values are consistent with previous measurements [5], which predict that the full depletion voltage be around 120 and 40 V, respectively.

The damage constant $\alpha$ is expressed by $\alpha = \Delta I/(V \phi_{eq})$, where $\phi_{eq}$ is the 1-MeV neutron equivalent fluence, $\Delta I$ the increase in the total leakage current measured at the full depletion voltage, and $V$ the volume of the sensor. Previous studies show that the leakage current of irradiated sensors decreases (anneals) with time. Because of this feature and temperature dependence of the leakage current, $\alpha$ is calculated after the short-term annealing is almost completed and at 20 °C. Systematic study of the annealing phenomena is available such as from the Rose Collaboration [5]. At room temperatures, the current decreases substantially within a month, with $\alpha$ reaching $3 \times 10^{-17}$ A/cm.

Instead of evaluating the damage constant, we use our results to evaluate the neutron fluence. The evaluated neutron fluence is $1.1 \times 10^{14}$ n/cm$^2$ for $1.4 \times 10^{14}$ n/cm$^2$, and is $(0.33-0.64) \times 10^{14}$ n/cm$^2$ for $0.7 \times 10^{14}$ n/cm$^2$. The present results prefer somewhat smaller neutron fluence but are in reasonable agreement.

C. Bias Resistance and Interstrip Resistance

The resistances of various sensor components are key properties to evaluate the radiation effect on silicon sensors. The oxide layer accumulates the positive charges created by radiation, which degrades among others such as effective bias resistance and interstrip resistance. In the following, we evaluated the degradation using real sensors instead of using test pieces, thus the results represent the effective changes.

Fig. 9(a) shows the bias voltage dependence of the bias resistance of a particular strip before and after irradiation. Although the resistance saturates below about 100 V before irradiation, much larger bias voltage, about 350 V, is required to reach the asymptotic value.

Fig. 9(b) shows the bias dependence of the interstrip resistance. The resistance is substantially degraded: it was greater than 50 GΩ before irradiation. In order to keep the resistance above 1 GΩ, a bias of 250 V is required at −10 °C.

Although the data are shown for a particular strip (pair), we found that the degradation is very uniform among the strips both for the bias resistance and interstrip resistance.

D. Interstrip Capacitance

Fig. 10 shows the bias dependence of the interstrip capacitance measured for a particular set of neighboring strips for the two sensors irradiated to $1.4 \times 10^{14}$ n/cm$^2$. The LCR test signals were at 1-MHz frequency and 5-V amplitude. Although the curves at small bias voltages behave differently due to individual difference, the shoulders around 130 V are consistent with the full depletion voltage. The interstrip capacitance decreases gradually with bias voltage, approaching asymptotic values consistent with those of nonirradiated sensors. We notice, though, that the bias should be substantially larger than the full depletion voltage to reach the asymptotic value.

E. Charge Collection

The two sensors irradiated to $1.4 \times 10^{14}$ n/cm$^2$ were used to construct a module, with a real readout hybrid [3], [8], [9] attached. This module was illuminated with Nd:YAG laser to in-
investigate the charge collection. The laser wavelength 1064 nm corresponds to the energy slightly above the energy gap of silicon, hence the laser is absorbed almost uniformly along its trajectory. This simulates well the passage of charged particles.

Fig. 11 shows the collected charge as a function of the bias voltage. Since the laser spot spreads over a few strips, ADC sum of neighboring strips is plotted. The same curve measured for a nonirradiated module is superimposed in the figure.

The voltage dependence of the charge collection is almost as expected from the $C-V$ curve of the same sensor, which is shown in the inset in the figure. We notice that the charge collection of the irradiated module increases even above the full depletion voltage. The deficit in the collected charge can be explained as follows: Defects caused by irradiation act as trapping centers for the drifting charge. As the integration time of the SVX4 chips, 112 ns, is shorter than the detrapping times of these defects, the deficit in collected charge is observed as shown in Fig. 11. This effect can be mitigated by raising the bias voltage. Higher electric field reduces the drift time of the charge and by that also the probability for the drifting charge to get trapped.

IV. SENSOR SUSCEPTIBILITY OF CHARGE UP

In the early stage of testing, we often observed the sensor to show degraded performance in a region spreading over about 30 to 50 strips. The symptom is that the coupling capacitances are larger, the series (implant and poly-silicon) resistances are smaller, and interstrip resistances are smaller, which implies that the strip isolation is degraded in the region. After investigation, it turned out that the vacuum tweezers used to pick up the sensor caused the charge-up phenomenon. The phenomenon disappears if the sensor is placed back to the envelope provided by HPK.

The wafer orientation we employed is $\langle 100 \rangle$. Because the positive charges trapped at the SiO$_2$–SiO$_2$ interface and in the oxide layer are fewer in $\langle 100 \rangle$ than in $\langle 111 \rangle$, they attract fewer electrons underneath the interface. Thus, external potentials can more easily create a p$^+$ inversion layer between the p$^+$ strips, degrading the strip isolation. MOSFET devices usually use $\langle 100 \rangle$ wafers for this reason.

We observed that the charge-up phenomenon could remain for at least a week if the sensor surface is isolated. In our practical sensor application, though, the wire-bonds to the amplifiers stabilize the Al electrode potential, which should eliminate the inversion layer. In order to verify this hypothesis, we performed the following study.

We created a charge-up sample and wire-bonded three ac pads in the charge-up region to ground, simulating the connection to the amplifiers. We repeated the ac scan to monitor the recovery. The results are given in Fig. 12. The initial charge-up, as visible in Fig. 12(d), almost recovered 20 h after wire-bonding [Fig. 12(e)]. The recovery seems to be somewhat slower at the mid-point between the wire-bonded strips; see the distribution 1 h after [Fig. 12(b)]. Therefore, we can conclude that charge-up phenomena, if it exists, will disappear once the sensors are assembled to modules.

From our experience, we are able to diminish the creation of charge-up if we eliminate use of vacuum tweezers. Also we find that the charge-up susceptibility degrades with time: we tried to charge-up the sensors intentionally, but it was hard for the samples one month after the delivery. Our hypothesis is that the sensor accumulated positive charge in the oxide layer in this period and became resistive to the creation of an inversion layer.

V. MECHANICAL PRECISION

The following mechanical properties were measured for a sample of sensors with a microscope, which has a reproducibility of about 2 $\mu$m horizontally and 3 $\mu$m vertically.
Fig. 12. AC scan results for charge-up study. (d) Initial distribution where strips 105 to 135 show irregular coupling capacitance (100 pF nominal) and series resistance (1.4 MΩ nominal). (a) Expanded plot of the charge-up region. (b) Enlarged plot 1 h after where strips 109, 110, and 120 are wire bonded. (c) Expanded and (e) entire distributions 20 h after. LCR frequency is 1 kHz.

A. Wafer Thickness

The wafer thickness was measured for 78 sensors at the center of shorter sides. The sensors were placed vertically on a stage under the microscope. The central value was 320.4 μm, with the distribution shown in Fig. 13. The spread is much smaller than the precision quoted by HPK, 15 μm. The thickness difference at the two shorter sides of the same sensor was a maximum of 5 μm.

B. Edge Cut Precision

The distance between the fiducial marks to the edge was measured at the four corners of 44 sampled sensors. The nominal distance is 330 μm. The distances were distributed from 323 to 335 μm along the longer side and from 326 to 335 μm along the shorter side. The edge cut precision was better than 7 μm, while the precision quoted by HPK is 20 μm.

C. Sensor Planarity

The sensors tend to be bowed due to different thermal expansions between SiO₂ and Si: They are flat at high temperature when processed. The bow is more significant for single-sided sensors than for double-sided sensors.

The planarity was measured on 1 cm grids. A typical profile is given in Fig. 14, where three corners are used to define the reference plane and the deviations to it are plotted. Positive deviations mean that the sensor is bowed with the strips on the convex side. The profile is generally universal among the different sensors.

In order to increase the statistics, the height at the sensor center was measured with the microscope with respect to the height of the fiducials at the four corners. The deviations are distributed from 80 to 100 μm for 11 axial sensors and 55 to 90 μm for 11 stereo sensors. The differences can be attributed to the fact that the stereo sensors are wider than axial sensors. The twists, deviations of the 4th fiducial height which was not used to define the reference plane, are distributed from 6 to 21 μm for the 22 sensors.

VI. Conclusion

We evaluated the electrical and mechanical properties of microstrip sensors designed for the CDF Run2b silicon detector. The leakage current is small (0.1 μA typically) and most sensors show no breakdown up to 1000 V. The fraction of defective readout channels is estimated to 0.04%. The coupling capacitance, bias resistance, and other electrical values are found to be quite uniform.
We have characterized various electrical parameters of the sensors irradiated with neutrons up to $1.4 \times 10^{14}$ cm$^{-2}$. The evolution of the full depletion voltage and increase of the leakage current are consistent with previously known values. Many parameters such as interstrip capacitance, interstrip resistance, and bias resistance are apparently degraded due to charge accumulated in oxide layer and type inversion. We observed that it requires a bias of 250–300 V to reach the asymptotic values while the full depletion voltage is evaluated to be around 130 V.

The mechanical precision, wafer thickness uniformity, edge cut precision and sensor bowing, were measured. All are found to be within our specifications.

ACKNOWLEDGMENT

The authors would like to thank K. Yamamura of Hamamatsu Photonics for useful discussions. They would also like to thank MNRC for neutron exposure and D. Newell and H. Ben Liu for providing fluence calibration information.

REFERENCES

[6] The 1-MeV equivalent fluence was calculated based on ASTM E722 report on “KERMA” (the total kinetic energy release in silicon matter) factors for silicon.