UC Santa Cruz

UC Santa Cruz Previously Published Works

Title

Design and performance of silicon strip sensors with slim edges for HPS experiment

Permalink

<https://escholarship.org/uc/item/0v15m0f6>

Authors

Fadeyev, V
Bassignana, D
Bravo, C
et al.

Publication Date

2020-07-01

DOI

10.1016/j.nima.2020.163991

Peer reviewed

Design and performance of silicon strip sensors with slim edges for HPS experiment

V. Fadeyev^{a*}, D. Bassignana^b, C. Bravo^c, M. Christophersen^d, M.
Diamond^{ce}, M. Graham^c, J. Jaros^c, R.P. Johnson^a, F. Martinez-
5 Mckinney^a, T. Maruyama^c, A. Moreno^b, O. Moreno^c, T. Nelson^c, M.
Solt^c, A. Spellman^a, M. Ullan^b

^a Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064,
USA

10 ^b Centro Nacional de Microelectronica (IMB-CNM, CSIC), Campus UAB-Bellaterra, 08193
Barcelona, Spain

^c SLAC National Accelerator Laboratory, USA

^d U.S. Naval Research Laboratory, Washington DC, USA

^e Department of Physics, University of Toronto, Toronto, Ontario, Canada

15 Abstract

We report on design and performance of new strip sensors for the Heavy Photon Search (HPS) experiment. The sensors feature a slim edge implementation using the Scribe-Cleave-Passivate (SCP) method. The slim edge design has allowed the introduction of a new layer closer
20 to the target, which increased the tracking acceptance and vertex precision, improving physics reach of the experiment. We describe the production, testing, and operational experience with the new sensors.

Keywords: Silicon strip sensors, slim edge, fixed target, silicon tracker

25 1. Introduction

The HPS experiment is searching for a heavy photon particle in the mass range between 19 and 500 MeV/c² and coupling constant between

* Corresponding author, E-mail address: fadeyev@ucsc.edu

such a photon and the electromagnetic current in the range $e \sim 10^{-2} - 10^{-5}$. This particle is postulated to mediate interactions with Dark
30 Matter and is of cosmological importance. The experiment itself has a fixed target geometry [1]. It is operated at Jefferson Lab's CEBAF electron accelerator. Electrons with energy of several GeV impinge on the thin tungsten target and can produce heavy photons in a process similar to bremsstrahlung. The heavy-photon subsequently decays into
35 an electron-positron pair which can then be detected [2].

HPS can use several search strategies. One of them relies on displaced vertex identification requiring a precision tracking and vertexing system. HPS was originally built with a 6-layer Silicon Vertex Tracker (SVT) placed in 0.25-0.5 T vertical magnetic field.
40 Each layer had 2 strip sensors at a small crossing angle. The sensors were originally made by HPK[†] for the D0 Run2b upgrade. They have 30 μm strip pitch, but half of the strips are floating. The readout pitch is 60 μm . The effective positional resolution of each layer is 6 μm in the vertical plane and either 60 μm or 120 μm in the horizontal (bending)
45 plane, depending on the layer. The sensors are placed side by side with the hybrids to minimize multiple scattering in the acceptance region defined by their active area. Only sensors themselves and a thin support layer of carbon fiber are present in the tracking volume, resulting in 0.7% radiation length per layer.

50 The last HPS data taking run took place during the summer of 2019. For this run the SVT was upgraded with an additional layer, called layer-zero (L0), placed at 5 cm distance from the target, half of the

[†] Hamamatsu Photonics K.K., <http://www.hamamatsu.com>

original first layer (L1) distance. In order to improve the physics reach and avoid beam scattering, the new sensors' active region was designed to be 750 μm away from the beam. This required slim edge sensor technology, with the goal of having a 250 μm wide inactive sensor periphery. The old design with the standard edge would have inserted the peripheral region of the sensor into the beam path, as illustrated in Figure 1.

L1 position was the closest to the beamline in the previous tracker configuration. Availability of slim edge devices allowed the active area in the replaced L1 to be brought closer to the beam, increasing the tracking acceptance. Layers 2 and 3 were brought closer to the beam to keep the projectile geometry of the active area with respect to the target. They did not require replacing sensors or modules. The combined effect of these changes is a factor of two improvement in the vertex resolution along the beam line. Additional details of the physics reach enhancement with the reconfigured tracker are described in reference [3].

Figure 1. A sketch of the first few layers of the tracker geometry relative to the target and beam line. (A) The previous layout with the old sensors, which does not allow an efficient placement of L0 due to the interference of the

inactive edge with the beam. (B) The new layout with the new sensors in L0 and L1 allows an increased tracking volume acceptance while maintaining 0.5 mm distance from the physical sensor edges to the beamline.

80

In the rest of this article, we explain the new sensor design in Section 2, describe sensor production experience in Section 3, summarize module production in Section 4, and report on operational experience during the data taking run in Section 5.

85 **2. HPS sensor design**

The new sensor design was significantly different from the Run2b sensors due to the experimental requirements and manufacturability considerations:

- Thinner silicon is desirable to limit track scattering in L0,
90 which affects vertex resolution. The reduced thickness of 200 μm was chosen as the smallest value that does not require wafer processing with an additional (“handle”) wafer support.
- The strip length was reduced in order to maintain a high
95 signal-to-noise ratio with thinner sensors and smaller signal. This was possible due to proximity to the target, which limits the track occupancy area.
- The hit density in the first layers is higher than in the rest of
100 the tracker. In order to keep the occupancy low, the strips were split in the middle of the sensor. This resulted in two rows of 1.5 cm long strips (Figure 2).

- The same p-in-n sensor type was used, with AC-coupled strips and polysilicon biasing in order to keep a uniform design and architecture of readout electronics.

105 A summary of geometrical parameters for both sensor types is shown in Table 1.

110 Figure 2. Wafer layout in the vicinity of one sensor, including guide marks for both horizontal and vertical cleaving lines shown in the inserts. An area near the edge in the center is zoomed in in another insert, showing the boundary of the two strip rows.

115 Table 1. Design parameters for strip sensors used in the HPS experiment. The HPK sensors were used for the original 6-layer tracker. The CNM sensors were used for the upgrade in L0 and L1.

	HPK for D0 Run2b	CNM for HPS
Dimensions	4.0 cm x 10.0 cm	1.6 cm x 3.4 cm
Thickness	300 μm	200 μm
Number of strip rows	1	2
Number of readout	639	256

strips		
Strip length	9.8 cm	1.5 cm
Strip pitch	30 μm (physical), 60 μm (readout)	55 μm
Inactive edge width	1000 μm	250 μm

120 The slim edge was implemented as a post-processing step using the SCP method [4][5]. SCP creates a sensor sidewall with high surface quality to help control the voltage gradient between the top and bottom of the sensor. In order to create such a surface, cleaving along the sensor lattice is employed, followed by sidewall passivation. Different
125 bulk types require different passivations. For the n-type used in this work, Plasma Enhanced Chemical Vapor Deposition (PECVD) of silicon oxide or silicon nitride, and an atomic layer deposition (ALD) of a nanostack of $\text{SiO}_2/\text{Al}_2\text{O}_3$, can be used as options [6]. One can also take advantage of native oxide formation on the freshly cleaved surface,
130 which could be improved by either UV exposure or thermal cycling [7].

The sensors were laid out and fabricated to the HPS design on 4-inch wafers by CNM Barcelona. The wafer layout had 6 sensors with provisions for a 3-step singulation process:

- Saw dicing was done first, leaving over 5 mm of space
135 around the long sensor side targeted for the slim edge implementation and one of the short sides.
- The short side was cleaved next using special alignment marks far from the active area. This step was meant to verify the wafer orientation relative to the sensor layout.

140 • Last, the long-side cleaving created the slim edge. It has a similar alignment mark as the short side cleaving (Figure 2). The control of the physical edge placement on this side was expected to be more challenging due to its larger size, characteristic for a strip sensor.

145 The layout featured a narrow bias ring on the slim edge side in order to keep the edge structures compact. The ring was wider on the opposite (non-slim) side to accommodate a wirebonding pad.

3. HPS sensor production

150 The total of 12 wafers were processed by CNM at the same time, resulting in 72 sensors. Since each tracker layer needs 4 sensors, the minimum set for L0 and L1 is 8 devices. However, we anticipated yield losses due to device performance, SCP application, and module construction. The overall strategy was to produce more sensors and modules than we need, and then to select the best performing ones to include in the tracker, leaving the rest as spares.

160 The SCP application was done in several batches, starting from the sensors with low breakdown voltages. The first such batch indicated an issue with cleaving. The first cleaving step (along the short side) made an edge well aligned with the sensor orientation. However, the subsequent cleaving along the long side resulted in an inconsistent edge orientation with a large spread (Table 2). As a consequence, a slim edge that starts at a nominal position at one corner significantly deviates from that position as the crack propagates along the sensor side (Figure 3). The leading hypothesis for the reliability difference between the two

165 sides is the proximity of the guard rings to the target edge position on
the long side. The guard ring area might have a built-in mechanical
stress that interferes with the control of the cleaving process.

170 Table 2. Geometry of the first set of cleaved samples. The cleaving line
angle relative to the nominal orientation was measured.

Detector	Short side cleaving angle	Long side cleaving angle	Edge distance
R11622W01S4	-0.20°	0.26°	326 μm
R11622W01S6	-0.13°	0.24°	320 μm
R11622W02S2	-0.16°	0.43°	375 μm
R11622W03S1	-0.16°	0.43°	375 μm
R11622W03S2	-0.16°	0.43°	375 μm
R11622W04S2	-0.18°	0.36°	355 μm
R11622W04S4	-0.16°	0.51°	400 μm
R11622W04S5	-0.20°	-0.13°	212 μm

Figure 3. Edge region at the sensor corners for a sample cleaved during
the first test. The cleaving plane is at the nominal position on the right side. It
175 has deviated by 150 μm on the left side.

There are several methods to scribe the sensor surface with varying
degree of sidewall damage and control of the cleaving line [5][6]. As a
test of the alternative to the relatively gentle diamond scribing, laser

180 scribing was used at varying laser power to test the cleaving reliability
and sensor performance at scribe depths of 27 μm and 50 μm (Table 3).
Although these depths are significant, they are much smaller than the
total thickness of 200 μm . The edge placement was at the target
distance or less, with small variability along the sensor. The post-
185 cleaving leakage-current levels were higher than before the singulation.
A subsequent “baking” (exposure to 170 C for 63.5 hours) brought
them back to the levels approaching the initial performance (Figure 4).
This observation is consistent with the thermal cycling facilitating the
native oxide improvement [7].

190 The laser-scribing test indicated that one can control the edge
placement well while maintaining a good breakdown behavior of the
slim edge sensors. For logistical reasons, this test was performed
relatively late in the production flow. Due to the project schedule
constraints, the other sensors were cleaved using the diamond scribe
195 despite the edge width variability.

Table 3. Edge distances at the sensor corners and the center for two devices
laser-scribed to the indicated depths.

Sensor ID	Scribe Depth [μm]	Edge left [μm]	Edge center [μm]	Edge right [μm]
W07-S4	27	265	246	222
W08-S1	50	184	208	219

Figure 4. IV characteristics for two sensors laser-scribed at NRL at 3 processing stages: after fabrication at CNM, after cleaving, after post-cleaving baking.

205

The first one third of good sensors had silicon nitride deposited after cleaving. The deposition was done in a PECVD chamber with the back side of the sensor facing upward. A portion of the backside was protected from the deposition with a mask. The resultant nitride layer covered the side walls and the exposed back surface. The coating complicated the backside connection during module assembly and may have led to a reduced adhesion to gelpacks used for transportation. The silicon nitride deposition was not used for the remaining sensors.

210

The sensors with relatively low breakdown voltages were subjected to the “baking” step. It improved the performance in some cases even for devices coated with silicon nitride (Figure 5).

215

Figure 5. IV characteristics for a set of sensors before and after “baking” at 170 C for 23 hours. The breakdown performance of the best sensors in this set was significantly improved. All sensors shown in this plot, except for W04-S5, had silicon nitride passivation.

A major complication was a relatively high rate of pinholes affecting a few percent of the strips. Their locations were mapped during electrical sensor tests at CNM. The nominal HPS geometry projects maximum track occupancy in the 50 (100) strips closest to the edge in L0 (L1). Therefore the pinholes in such regions affect tracking efficiency. They were counted as one of 3 main criteria for sensor selection, the other two being the breakdown performance and slim edge width.

4. HPS module production

The 22 best sensors were used to build modules with APV25 ASICs originally developed for the CMS experiment [8]. Electrical characterization assessed their signal level using built-in charge

235 injection circuitry and evaluated the noise for each channel. Pinholes
 showed up in such tests as channels with low noise, especially at low
 sensor bias voltage (Figure 6). Their locations did not always coincide
 with the bad channel list from the sensor tests. Therefore a new list was
 composed. Wirebonds were plucked from such channels to avoid
 240 APV25s being influenced by the DC current on the input channels.

Figure 6. Readout noise as a function of channel number for a module for 0 V
 245 sensor bias. The two strip rows (sectors) are mapped to have the channels
 closest to the slim edge numbered as 0 and 511. The channels with artificially
 low noise indicate a presence of pinhole defects.

Due to the changed pinhole list, the constructed modules were re-
 prioritized using the same criteria of pinhole counts near the slim edge
 250 of the sensor, breakdown voltage, and the slim edge width. The total of
 10 modules were chosen for deployment, covering the needs of the L0
 and L1 assembly and leaving 2 spares (Table 4). First 4 layers of the
 new tracker and a portion of a module with the slim edge sensor are
 shown in Figure 7.

Table 4. The list of modules selected for the tracker upgrade, their location in the system, and the sensor performance properties. The location abbreviation includes layer number (L0 or L1), the tracker halves (T for “top”, B for “bottom”), and strip orientation (A for “axial”, S for “stereo”). The edge width given in parenthesis is for the bottom surface of the sensor in cases where it is different from the top side.

Sensor ID	Module Number	Tracker Location	Vfd [V]	Vbd [V]	Edge width [μm]	N(pinholes for first 50 strips)	
						Strip row A	Strip row B
W11S2	22	L0TS	32	420	337 (358)	0	2
W10S1	19	L0TA	30	270	298 (338)	3	0
W11S1	16	L0BS	32	330	352 (398)	0	0
W11S3	17	L0BA	32	340	318	0	2
W11S6	18	L1TS	32	370	377 (425)	1	0
W09S2	7	L1TA	30	300	360 (399)	2	0
W10S3	15	L1BS	30	290	395 (442)	0	0
W10S4	3	L1BA	30	200	366	0	1
W4S3	9	Spare 1	25	370	349	1	2
W10S6	20	Spare 2	30	340	274	3	0

265 Figure 7. First 4 layers of the upgraded tracker, with the 2 layers composed
270 from the new modules (left). A section of a new module with a slim edge
sensor (right).

5. SVT commissioning and operations

During the 2019 data taking run the SVT was cooled to -9 C. The
270 currents measured at the beginning of the run were rather low, and there
was a large range of bias values available above the typical full
depletion voltage of 30V (Figure 8). The operational bias was set to
60 V.

275 Figure 8. IV characteristics of 4 HV channels servicing the 8 sensors used in
the first 2 layers of the upgraded tracker. Each HV channel powers 2 sensors.

Prior to the data taking, the tracker position had to be calibrated
280 relative to the beam with so-called wire scans. Thin wires had a fixed
position relative to top/bottom halves of the tracker, which were moved
closer to the beam while monitoring the scattered beam with
scintillators. The maximum scintillator counts corresponded to the wire
being centered in the beam. Due to a lack of absolute reference from
285 the beam position diagnostics, the initial wire location was out of range.
Approaching the beamline with the bottom tracker half resulted in
beam going through one of the sensors' peripheral regions for the total
of about 10 seconds.

The motion controllers moved in effective steps of 20 μm during this
290 time, and the projected beam profile was 25 μm by 167 μm . The
exposed area extended about 80 μm inward from the edge, forming a
nearly continuous area (Figure 9). The abnormal condition was
recognized as the sensor current was 1 μA , which was the power
supply limit, at which time the tracker half was moved away from the
295 beam.

The exposed region had 1-MeV neutron-equivalent fluence of
3.6x10¹⁴ neq/cm² assuming the nominal NIEL factor for electrons
[9][10]. It received ionization dose of 119 Mrad. As a result of this
accident, the leakage current at 200 V for the corresponding HV
300 channel increased by a factor of 7, to 0.60 μA . This is the channel
labeled as "L1B_H0" in Figure 8. The current at 150 V bias was
consistent with other channels, and no other consequences of the
accident were observed.

305

Figure 9. Illustration of the beam location in the inactive area of the sensor during the beam-finding accident.

The initial misalignment was found and corrected. When data
310 taking started, all sensors exhibited a temporary current increase, by a
factor of 2, rising gradually over 1 hour of the beam time. A similar
effect was observed with previous test runs for HPK sensors, but at a
smaller magnitude, of about 10%. At first we adopted the operational
strategy of shutting off the beam and sensor HV for 10 minutes for
315 every hour of run time. This stabilized the currents but resulted in a loss
of data collection time. The origin of this phenomenon was deemed to
be due to X-ray production off the 4 μm tungsten target and slow
surface charge redistribution in the sensors. To avoid the beam time
loss, an alternative strategy was implemented. The target was replaced
320 by 20 μm thick one, with a corresponding reduction in the beam current
to maintain the same trigger rate. The thicker target self-absorbed a
significant amount of the X-ray flux, and the beam downtime was no
longer necessary.

325 By the end of the almost 3-month long data taking run, the sensor
current levels went up to the range of 2-5 μA , indicating radiation
damage. The origin can be due to two different effects:

- Particle flux in the experiment, which has a non-uniform
distribution across the sensors (Figure 10).
- Neutron showers from the beam hitting upstream collimators
330 during position tuning, which should result in a nearly uniform
distribution.

It is possible to disentangle these effects by studying properties of
the sensors used in the tracker. We measured strip implant potentials in
a device from a previous test run. Such potentials are due to the bulk
335 currents collected by the implants, which flow through the bias
resistors. They represent an average irradiation fluence along the strip.
The non-uniform potential profile near the edge (Figure 11) indicates
that the irradiation was not uniform, implying that the tracks
contributed a significant portion of the total fluence.

340 At the end of the run, a dedicated sensor bias scan was performed
to assess the sensor properties. Despite the radiation damage, the
signal-to-noise ratio remained within 10% of the initial value of about
22.

345 Figure 10. Number of hits per channel of one of the new modules from a data taking run. The channel map is the same as in Figure 6.

350 Figure 11. Strip implant potential as a function of channel number, measured for different biases on HPK sensor used in a previous test run.

6. Further work

Another data taking run may take place in 2021. The sensors can be re-fabricated and modules rebuilt on this time scale in order to further
 355 improve the tracker performance and to avoid further irradiation

damage effects. In such a refabrication we will be able to address the two most significant issues from the past experience:

- An alternative technology for making AC capacitors has already been found. It was shown to have a much lower pinhole rate.
- 360 • Other scribing options should lead to a more reliable slim edge placement.

7. Conclusions

We have designed, fabricated, and deployed new strip sensors in the HPS experiment. They have slim edges implemented with the SCP
365 method. Pinhole presence and slim edge position variation near guard rings affected the device yield. Nonetheless, the initial plan to over-produce the devices still allowed for insertion of a new L0 layer and replacement of the L1 layer, resulting in an improved physics reach of the experiment. The problems encountered can be addressed in a future
370 run with different technology options.

The upgraded tracker was successfully commissioned despite the alignment accident resulting in beam briefly going through one of the sensors' peripheral region. There was an onset of radiation damage, but the tracker maintained its high efficiency throughout the data taking
375 run.

Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council of Canada. The work was supported in

part by the U.S. Department of Energy, Grant DE-SC0010107. We
380 would like to thank the Institute for Nanoscience (NSI) at the U.S.
Naval Research Laboratory (NRL) and the NSI staff. The work done at
NRL was sponsored by the Office of Naval Research (ONR).

References

- 385 [1] M. Battaglieri *et al*, Nucl. Instrum. Meth. A777 (2015) 91-101
- [2] P. H. Adrian *et al*, Phys. Rev. D98 (2018) no.9, 091101
- [3] C. Bravo, DPF 2019 Proceedings, arXiv:1910.04886v1
- [4] M. Christophersen *et al*, Nucl. Instrum. Meth. A699 (2013) 14-
17
- 390 [5] V. Fadeyev *et al*, Nucl. Instrum. Meth. A731 (2013) 260-265
- [6] M. Christophersen, V. Fadeyev, B. Philips, H. F.-W.
Sadrozinski, Proceedings of Science, Vertex 2012 (2013) 20
- [7] J. Wright *et al*, IEEE Nuclear Science Symposium Conference
Record (2010)
- 395 [8] M.J. French *et al*, Nucl. Instrum. Meth. A466 (2001) 359
- [9] G.P. Summers *et al*, IEEE Trans. Nucl. Sci. NS-40 (1993) 1372
- [10] A. Vasilescu and G. Lindstroem, Displacement damage
in silicon (on-line compilation),
<https://rd50.web.cern.ch/rd50/NIEL/default.html> , last accessed
400 February 8, 2020