Design and Fabrication of a Highly Integrated Silicon Detector for the STAR Experiment at Brookhaven National Laboratory

Benjamin Buck\textsuperscript{c,*}, Eric Anderssen\textsuperscript{b}, Jason Bessuille\textsuperscript{c}, Mario Cepeda\textsuperscript{b}, Thomas Johnson\textsuperscript{b}, James Kelsey\textsuperscript{c}, Gerrit van Nieuwenhuizen\textsuperscript{c}, Gerard Visser\textsuperscript{a}

\textsuperscript{a}Indiana University, Bloomington, IN, USA
\textsuperscript{b}Lawrence Berkeley National Laboratory, Berkeley, CA, USA
\textsuperscript{c}Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract

We present the design of a detector used as a particle tracking device in the STAR experiment at the RHIC collider of Brookhaven National Laboratories. The “stave,” 24 of which make up the completed detector, is a highly mechanically integrated design comprised of 6 custom silicon sensors mounted on a Kapton substrate. 4608 wire bonds connect these sensors to 36 analog front-end chips which are mounted on the same substrate. Power and signal connectivity from the hybrid to the front-end chips is provided by wire bonds. The entire circuit is mounted on a carbon fiber base co-cured to the Kapton substrate. We present the unique design challenges for this detector and some novel techniques for overcoming them.

Keywords: Electrical and Mechanical Integration; Hybrid Substrate; Nuclear Physics; Carbon Fiber Reinforced Polymer

1. Introduction

The Intermediate Silicon Tracker (IST) is a silicon based particle detector installed at Brookhaven National Laboratory (BNL) in the Relativistic Heavy Ion Collider (RHIC). The detector is located in the central region of the Solenoidal Tracker at RHIC (STAR) experiment and makes up the third tracking layer in a 4-layer vertex detector upgrade. It is comprised 24 staves, each of which is a flexible PCB wrapped around a carbon fiber core. Attached to each stave are 6 silicon sensors which can detect energetic particles which pass through them. These silicon sensors are read out by 36 analog front-end chips which are connected to an external data acquisition system.

2. Hybrid design

Each stave holds the electrical substrate known as a “hybrid.” The hybrid is the flexible circuit onto which the silicon sensors, analog front-end chips, and passive components are mounted. The hybrid is permanently bonded to the stave during the stave manufacturing. The hybrid is broken up into 2 areas, the sensor area and the connector area. In the sensor area we desire as little mass as possible to reduce interactions with passing particles. For this reason, the sensor area, which makes up most of the hybrid, is made of 2 layers of 0.5 oz. copper on a 1 mil Kapton substrate. The connector area is made of the same 2 layers of 0.5 oz. copper but with an additional 1 oz. copper layer and 1 mil Kapton layer. Over both
areas is a 1 mil Kapton coverlay attached with 1 mil of adhesive. This coverlay has no cutouts on the bottom layer and acts as insulation between the copper and the structural material in the stave. On the top layer large areas of this coverlay are cut out around any area with bonding pads or component pads. Conventional solder mask is applied to this area as shown in figure [1]. The hybrids are finished with ENEPIG for compatibility with both wire bonding and conventional soldering. In order to keep the copper weight down, all vias are selectively plated through. This selective plating can be seen in figure [8].

![Figure 1: Image showing one of the IST hybrids. 'A' marks a sensor placement site, 'B' marks an APV placement site, 'C' marks a connector placement site.](image)

Each hybrid provides the electrical connection from the APV chips to the connector site on one end of the stave. Electrically the hybrid is broken up into three separate circuits which share a common ground. Each circuit serves 12 APV chips and 2 sensors. The APV chips require power, analog output, and control signals to be routed to each chip. The sensors require a bias line which must withstand up to 200 V.

In the sensor area we require as little mass as possible. Because of this, the sensor area has only two routing layers, so careful routing was needed to optimize the power net distribution and signal distribution. The power nets are distributed as three large busses per section for 1.25 V, −1.25 V, and ground. The power supplies for the staves operate on a remote regulation scheme, so a sense net from each bus is routed locally away from the APV chips in each section and back to the connectors. For the analog output signals, a differential pair from each APV chip is routed to the connectors. The analog output is a 100 Ω differential current mode signal. Source termination is provided at the board which plugs into the stave. In addition, the APV chips use I2C for slow controls to set various parameters of the chip. These nets are also routed as a bus to each of the chips in a section. Finally, two differential pairs provide a clock and a trigger to each APV chip. These are routed as a bus to each of the chips in a section.

The hybrid has 36 APV placement sites where APV chips are attached and 6 sensor placement sites where sensors are attached. The APV chips generate nearly all of the heat in the stave so an aluminum cooling tube is embedded in the stave directly beneath the APV chips as shown in figure [2]. To reduce the thermal resistance, 14 vias are placed on the APV placement sites to conduct heat through the Kapton core. The 6 sensors do not produce any appreciable thermal load.

3. Stave design

Each hybrid was assembled into a stave at the Lawrence Berkeley National Laboratory (LBNL) Composites Shop in Berkeley, California. Two carbon fiber cover sheets were co-cured to a hybrid and then a carbon fiber honeycomb was glued to one side. A block of carbon foam with a channel cut in it for cooling was also glued on. The carbon foam has a lower radiation length but is homogeneous unlike the carbon fiber honeycomb. This uniformity
makes it more suitable for wire bonding, so the carbon foam is located underneath any area where wire bonding will be performed.

Each stave nominally generates about 12 W of heat. Cooling is provided by flowing a synthetic heat transfer fluid, 3M™ Novec™ 7200 Engineered Fluid, through the aluminum tube which runs through the carbon foam. Because the IST is installed in the central region of STAR, we needed a cooling fluid which would not damage the other detectors surrounding it in the event of a leak. Novec has a very low vapor pressure, leaves no residue when it evaporates and has a very high resistivity, making it a good candidate. Novec was chosen because it has a lower ozone-depletion potential than other engineered fluids with similar properties. Other detectors using a similar design have observed galvanic corrosion between the carbon foam and the aluminum tube [3]. In order to prevent this, the carbon foam channel was coated with epoxy before the tube was laid in to provide a barrier. The target running temperature is 25°C which is above the dew point in the experimental hall; this will prevent moisture from condensing on the detector which could facilitate galvanic corrosion. In addition, all parts of the stave and cooling system are electrically grounded.

Two end pieces called “closeouts” were then attached on either end of the stave. One is made of carbon filled PEEK and the other of aluminum. The closeouts have holes and slots to provide a way to mount the stave to the finished detector. The aluminum closeout is electrically bonded to the carbon face sheets, the carbon fiber honeycomb, and the carbon foam. This provides a means to ground the materials in the stave since they are electrically isolated from the hybrid.

Once everything was bonded to one of the face sheets, glue was applied to the other side and it was folded over 180° to complete the stave. Figure 3 shows the stave right before this step. Fully cured staves were inspected and then sent to MIT for further assembly.

4. Sensor design

The IST sensors were designed by MIT and manufactured by Hamamatsu. The sensors are 300 μm silicon with 2 metallization layers. The backside has a sputtered aluminum coating to provide the bias voltage. This voltage reverse biases the PN junctions in the sensor which form the individual sensing elements (see figure 4). Particles passing through the sensor will interact with the silicon lattice and produce charge pairs which will drift apart. A capacitor above each sensing element AC couples the signal and routes it to a bonding pad located on one edge of the chip. This is a proven, standard technology for particle detection.
Figure 3: Top image shows the hybrid, ‘B’, with the two carbon fiber face sheets, ‘A’, attached. The bottom image shows the same hybrid now with the carbon fiber honeycomb, ‘D’, and carbon foam, ‘C’, attached. The PEEK closeout, ‘E’, and aluminum closeout, ‘F’, can also be seen.

Figure 4: A simplified schematic of the silicon sensor. Charge pairs produced in the sensing elements are detected on the output pads.

Each sensor has 6 groups of sensing elements with 128 sensing elements in each group. A bond pad for each one of the sensing elements is grouped at one edge of the sensor and is arranged in a pattern which mirrors the bonding pattern for the APV chip (see figure 5). This allows for much simpler bonding between the APV and the sensor, especially useful because the bonding pitch is so small. The sensing elements are arranged in a grid at a pitch of 6275 µm × 596 µm in 64 rows and 12 columns. The bonding pads are arranged in 2 rows of 64 pads. The pads are 58 µm × 136 µm with 30 µm between each pad and 80 µm between the 2 rows.

5. APV chip

The APV25-s1 chip is the readout and pre-amplifier ASIC for the sensors. It has 128 channels each with a charge sensitive pre-amplifier, shaper, and 4 µs long pipeline. Events are read into the pipeline at 40 MHz. Events in the pipeline are selected by triggers and marked for readout. A single differential pair per chip reads out each of the 128 channels in series for a selected event.

This ASIC was designed by the Imperial College in London for the Compact Muon Solenoid (CMS) running at the Large Hadron Collider (LHC) [4]. It was designed for the high radiation environment present in the middle of a physics experiment and used an IBM
Figure 5: APV bonding pads on top and silicon sensor bonding pads on bottom.

Figure 6: APV chip showing input bonding pads on the top, power bonding pads on the left and right, and control bonding pads on the bottom.

0.25 μm radiation hard process. Detailed information about the APV chip can be found in [2] and [4]. Figure 6 shows the APV chip bonded to a stave.

6. Passive attach

In addition to the sensors and APVs, a few passive components are needed on the stave. Each stave has 195 additional components, mostly 0402 sized capacitors for bypassing the APV chips. In addition, there is a small temperature sensor, termination resistors for the clock and trigger lines, protection resistors for the sensor bias lines, and a connector for each section.

The connectors used were the Samtec TEM and SEM series. They provide a low mating height and high pin density which is ideal for our application. The pins are extremely fragile, however, so extreme care had to be taken during testing and assembly to reduce the number of mating cycles and prevent any connectors from being damaged.

The temperature sensor used was a Texas Instruments TMP102 which shares the same I2C bus as the APV chips in one of the sections. A computational fluid dynamics (CFD)
study was done to determine the location of the hottest spot on a stave assuming nominal operating conditions (see figure 7). The temperature sensor is placed in this location.

![CFD study showing two staves which make up a single cooling loop.](image)

The passives were soldered onto the hybrids after stave assembly. Because the hybrid was already attached to the carbon fiber parts of the stave, it could not be put into a solder oven and had to be hand-assembled. Proxy Manufacturing in Methuen, Massachusetts assembled all of the staves. The assembly process was further complicated because there is no silk screen legend for most of the components on the board. Because the bypass capacitors are located so close to the APV chips there was no space for a silk screen legend (see figure 8). Instead, the pattern of component placement was made the same for all APV placement sites and detailed documentation was produced to prevent any parts from being incorrectly placed. A visual inspection at MIT after the passives were attached to the staves provided an additional quality check for such an error.

During production one stave was found to have a short between two power nets on the hybrid, away from any solder areas. Using a thermal camera we were able to determine the location of the short (see figure 9). Until that point in production, the staves were not electrically tested after receipt from LBNL or after passives were attached. After this incident, the power nets were electrically tested for shorts. We found no additional problems during production.
7. APV attachment

During production we performed separate assembly steps for the APV chips and the silicon sensors. Our production volume was limited by the silicon sensors as they were the single most expensive component to purchase and also had the longest lead time. Running out of sensors late in production would have delayed installation of the full detector. To increase the overall yield, the APV chips were installed on the staves first, wire bonded, and tested to make sure they were fully functional. Only after all APV chips on a stave were verified to be working properly were silicon sensors attached.

The APV chips were glued directly to the hybrid using a conductive epoxy, TRA-DUCT 2902. A pneumatic dispenser was used to apply a uniform amount of glue for each APV chip. The glue is both thermally and electrically conductive and acts as a means to connect the back side to VSS and as a means to conduct heat away from the chip.

It is important that the alignment of the APV chips is precise. Since there are bonding pads on all sides of the chip, both “x” and “y” alignment are important. To achieve good alignment we made custom tooling which would allow the technician to align each chip manually. The tooling provides an edge which all APV chips are pressed against to set the “y” alignment. Then the technician aligns the bonding pads on the APV chip with copper features on the hybrid to ensure a precise alignment in “x”. The tooling used for this is shown in figure 10. This alignment step was most important because the mounted APV chips would then have to match exactly the location of the output pad sites on the silicon sensors. Misalignment would make the bonding process more difficult and increase the likelihood of shorts between wire bonds. All of the alignment was done by hand under a microscope by a skilled technician.

8. APV bonding and testing

Staves with APV chips attached were sent to the Instrumentation Division at Brookhaven National Laboratory for wire bonding and testing. Wire bonding was done on a Hesse & Knipps Bond Jet 815 bonding machine using 1 mil aluminum wire. A program for the bonding machine was written to wire bond each APV chip automatically, but inspection was done by a bonding technician during the bonding process to ensure the operation went smoothly. Example images from the inspection are shown in figure 11. During this operation 31 control nets were bonded from the hybrid to the APV chip and 21 power nets are bonded from the hybrid to the APV chip. There were a total of 1872 wire bonds for this operation. The stave was held down using only the stock vacuum chuck on the bonding machine. No additional fixture was needed.
Bonded APV chips had to be tested before silicon sensors could be attached. In an experimental assembly building located next to the STAR detector we set up a clean room with a testing station for the IST. The testing station consists of a rack to hold detectors with a cosmic ray trigger inside a light-tight box (ambient light will create noise on the sensors due to the photoelectric effect.) The staves were attached to a data acquisition system (DAQ) (see [1] for more information) which provided power and control signals and digitized the data from the APV chips. To test each stave, it was attached to the DAQ and operated. Noise and pedestal levels were recorded over many events and then analyzed.

All staves were then sent back to MIT for further work. Staves that had APV chips on them which did not pass the noise and pedestal level tests had those chips removed and replaced and then sent back to BNL. The replaced APV chips were bonded and then re-tested before they were sent back to MIT. Staves with fully functioning APV chips then had the silicon sensors installed.

9. Silicon sensor attachment

The silicon sensor attachment was the final assembly step done at MIT. Before the process began, all tooling and staves were cleaned with isopropyl alcohol to ensure that no contaminants were transferred onto the sensors. Staves were placed in MIT-made tooling which held the stave in place. An adjustable blade at the top edge of the stave was moved until it marked the top edge of where each sensor would sit. The blade was fastened in position and then the sensor attach began.
The sensors are held down with two different types of epoxy as shown in figure 12. The first is a conductive epoxy needed to make a good contact between the aluminized back side of the sensor and the traces below, which carry the bias voltage. We used the same TRA-DUCT 2902 adhesive for this. The second epoxy is EPON 828 resin with VERSAMID 140 hardener. We used this epoxy for mechanical strength and stability since the conductive epoxy is not very strong. A single line of conductive epoxy was put down and then several lines of conventional epoxy were applied to make a strong bond. We found that the working time after applying the glue was about 30 minutes after which it would be much more difficult to get the sensor to lie flat.

Figure 12: Left shows the silicon sensor attach tooling. The right two photos show a sensor being placed and highlight the two different types of epoxy used.

The silicon sensors were aligned in a similar way to the APV chips. The tooling provided a stop in the “y” direction so the technician needed only focus on alignment in the “x” direction. Under a microscope, a technician would align the sensor bonding pads with the APV bonding pads checking all 6 APV chips for each sensor. An example view through the microscope during this alignment procedure is shown in figure 13. After all sensors were aligned, weights were applied to the sensors. In early prototypes we found that the sensors would drift during the curing process. Adding weights to the tops of the sensors prevented the sensors from drifting. After the weights were applied, the alignment was rechecked and adjusted if necessary. Staves would be allowed to cure for 24 hours before they would be packaged and transported.

Figure 13: The reticule in the microscope is used to align the bonding pads between a sensor and the APV chips which serve it.
10. Silicon sensor bonding and testing

The bonding of the silicon sensors took place at the same Instrumentation Division at BNL on the same bonding equipment. Again 1 mil aluminum wire was used. An automatic bonding program was used but we required close supervision by the technician. Because of the size and pitch of the bonding pads it was important to catch any error and repair it before bonding continued. The bonding process put down 128 bonds between each APV chip and each silicon sensor for a total of 4608 wire bonds. In addition, 24 bonds were put down between each sensor and the hybrid as part of the biasing circuitry for a total of 144 bonds. Depending on the amount of technician intervention, this process would take between 1 and 2 hours. The end result can be seen in figure 14 and figure 15.

![Figure 14: Closeup of a sensor on a completed stave. The encapsulant is difficult to see because of its transparency.](image)

Fully bonded staves were brought back into the IST clean room and tested again. Using the DAQ system, we were able to identify any shorted bonding wires and determine if it was possible to repair them. In addition, baseline noise and pedestal information was again recorded. We found very few errors with the bonding done at BNL and nearly all of the staves produced are in use in the final detector. Fully functioning staves then had an encapsulant applied to the bonding wires to protect them during handling and installation. The first prototypes used Dymax 9001-E-V3.1 cured with a Dymax 5000-EC series ultraviolet curing lamp. We found that, after exposure to the UV light source, some APV chips would no longer function or have higher input noise. While the exact cause of this was unknown, we suspect that the silicon was damaged by the UV treatment. For production staves, Dow Corning Sylgard 186 elastomer was used. This encapsulant has a room temperature cure and did not affect the performance of the APV chips. A fully completed stave, ready for installation, is shown in figure 15.

![Figure 15: A completed stave ready for installation.](image)

After the encapsulation the staves were tested extensively and optically surveyed before being installed.
11. Optical survey

The structure which the staves are mounted to has a mechanical alignment accuracy of about 200$\mu$m. However, once installed we require knowing the position of the detector to a higher degree of accuracy. We are able to do this by aligning tracks which pass through the IST as well as other detectors. We can reduce the number of tracks needed to do this alignment by knowing very precisely how the sensors on a single stave are located relative to each other. Before installation each of the staves was placed on an optical survey station and measured. The survey station, a Nikon VM-150, was used to measure each of the staves. We estimate the accuracy of these measurements to be about 5$\mu$m in the plane of the detector and 50$\mu$m out of plane. We combine this information along with the “rough” position of each detector inside the experiment and will be able to align the detector from tracks generated in this and other detectors (see figure 16).

![Figure 16: Left shows a stave on the survey station. Right shows a computer reconstruction of tracks going through the IST (red layer) and other detectors which surround it.](image)

12. Installation

Fully functional staves were installed on a carbon fiber support structure arranged to have full azimuthal coverage. As seen in figure 17 The silicon components are facing into the support structure which protects the silicon from damage during the full installation process. Electrical connections were laid on the tube and connected to each of the detectors. We were able to run the detectors in place to ensure that all electrical connections were sound. Data was taken to establish the baseline noise and pedestal data before final installation. Finally, cooling lines were attached to the cooling tubes running through the staves and were tested with a helium leak checker. Two staves were found to have leaks inside the cooling tube. These staves were not installed and the cause of the leaks is currently being investigated.

Once the entire IST was assembled the support structure was mated with a larger detector support system and inserted into the central region of STAR. The detector was then hooked up to electrical and cooling services and run in place again to ensure that all detectors are working properly.

13. Summary

The IST for STAR is made of 24 staves, each of which carry 6 silicon sensors read out by 36 APV chips. The detectors are designed to operate in a high radiation environment with as little mass as possible to reduce the chance of interactions with particles. The staves were
designed and manufactured at MIT and LBNL. Passive assembly as well as APV readout chip and silicon sensor attachment took place at MIT while bonding, testing and installation took place at Brookhaven National Laboratory. The finished detector was installed into STAR and is currently taking data with 95 percent of channels working properly.

14. Acknowledgements

The fabrication of the IST was split between MIT and University of Illinois at Chicago. Dr. Zhenyu Ye at UIC coordinated with the Silicon Detector Lab at Fermi National Accelerator Laboratory to complete all steps in production after the passive attach. Their assembly process was very similar to the assembly process used at MIT but not identical; it is outside the scope of this paper to detail the two separate assembly processes.

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