Development of the Hybrid Structure for the Barrel Module of the ATLAS Silicon Microstrip Tracker

T. Kohriki[1], Y. Ikegami[1], T. Akimoto[2], K. Hara[2], Y. Iwata[3], Y. Kato[2], T. Kondo[1], I. Nakano[4], T. Ohsugi[3], S. Shimma[2], R. Takashima[5], R. Tanaka[4], S. Terada[1], N. Ujiie[1] and Y. Unno[1]

***Abstract*--A novel hybrid structure for the barrel module of the ATLAS Semiconductor Tracker (SCT) is developed. The hybrid carries 12 bare readout chips totaling 1536 channels. A flexible copper-polyimide 4-layer lamination is used as a basic circuit. The circuit is reinforced by two carbon-carbon bridges coated with Parylene polymer. The hybrid staffed by resistors, capacitors and pitch adaptors undergoes heat cycling and quality inspections. The hybrid after chip mounting and wire bonding is placed over the top and bottom sides of the module assembly with no direct contact to silicon sensors. The electrical, mechanical as well as thermal performances of the module are proven to be excellent.**

I. INTRODUCTION

Aiming at the experiment start in 2005, construction of the ATLAS detector [1] for the Large Hadron Collider (LHC) project at CERN is in progress. LHC accelerates protons up to the center-of-mass energy of 14 TeV and collide them at 40 MHz with a luminosity goal of 10^{34} $cm^{-2}s^{-1}$.

Three sets of large aperture super conducting toroids generate the magnetic field for the muon chambers. Inside the muon system, there are scintillation-tile hadron calorimeters, LAr electromagnetic calorimeters and Inner Detectors (ID) [2]. A central solenoid generates a magnetic field of 2 T in the ID volume. The ID is built up by the pixel detector, the Semiconductor Tracker (SCT) of silicon micro strip sensors, and the straw transition radiation tracker.

The ATLAS SCT [3] covers the region from 300 to 520 mm in radius from the beam line. It consists of the barrel part with 4 cylindrical layers and the forward part with 9 disks on each side. The total area of the silicon strip sensors is 61 m^2. For a 10-year operation of the innermost sensors at r = 300 mm, the total radiation dose is $2x10^{14}$ n_{eq}/cm^2 with an estimated uncertainty of ±50%. The ATLAS SCT system is designed with a minimized amount of material and to tolerate large radiation doses.

The design and prototyping of the barrel SCT modules has been successfully progressed to the stage of mass production. One important element of the module is the hybrid structure. This article describes the design, the components, and the fabrication procedures of the hybrid structure.

II. BARREL SCT MODULE

The module is a basic detector unit providing stand-alone mechanical rigidity as well as electrical and thermal functionalities. A picture of the module is shown in Fig. 1. The total number of barrel SCT modules is 2,500.

The module has four identical silicon strip sensors of single-sided AC-coupled p-on-n type [4]. Two such sensor pairs, forming a stereo angle of 40 mrad, are glued on the top and the bottom of the central baseboard. Strips of two sensors are wire-bonded to form 126 mm long strips. The sensor has 768 readout strips with a pitch of 80 µm

The baseboard acts as a mechanical core and also as a thermal conductor to transfer the heat generated in the sensors to the cooling pipe. The baseboard is made of thermalized pyrolytic graphite TPG (or VHCPG: Very High

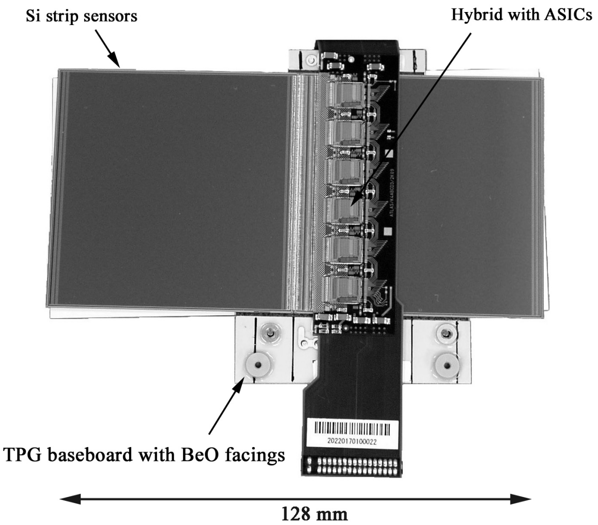

Fig. 1. A picture of the barrel SCT module.

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[1] IPNS, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

[2] Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki, Japan

[3] Department of Physics, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan

[4] Department of Physics, Okayama University, Okayama, Okayama 700-8530, Japan

[5] Department of Education, Kyoto University of Education, Fushimi, Kyoto 612-0863, Japan

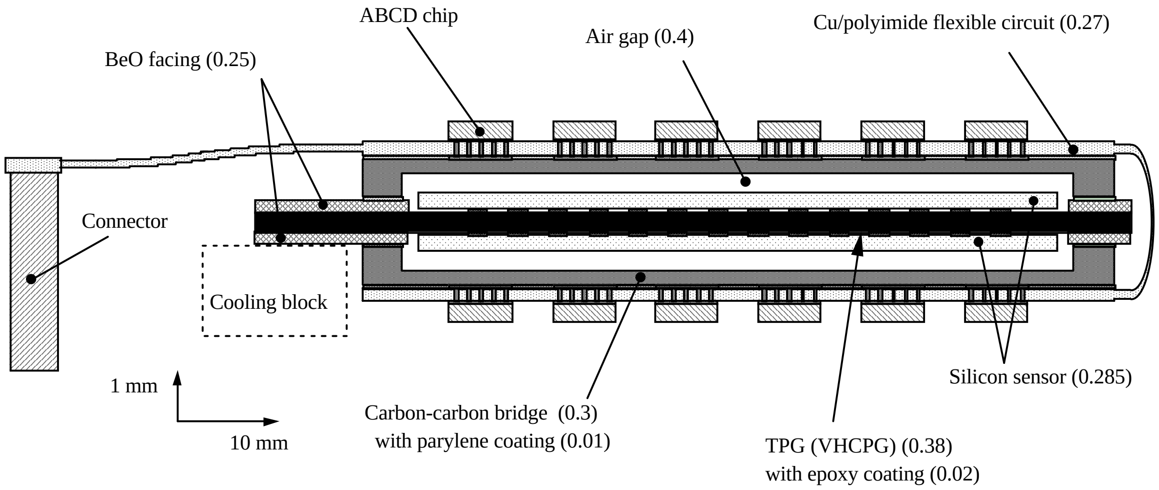

Fig 2. Cross section of the module at the location of the hybrid. Note that the vertical direction is magnified by 5. The numerals are thickness in unit of mm.

thermal Conductivity Pyrolytic Graphite). Its thermal conductivity is 1450-1850 W/m/K in plane and 6 W/m/K out of plane. The baseboard is encapsulated by 20 µm thick epoxy. Four small spots of epoxy are removed from each side to provide openings for electrical HV connection to the rear side of the silicon sensors. Two BeO facings are attached to the VHCPG baseboard at each protruding end. The facing has precision holes for precision module mounting and also has gold plated pads for HV connection.

In order to satisfy the combined electrical, thermal and mechanical requirements, the optimized design is a hybrid placed near the center of the module, above and below the sensors, and connected to the strips near the middle of their total length. This configuration minimizes the space conflict with neighboring modules. It also made it possible to pick up signals near the central part of the strips, thus minimizing the spread resistance of metal readout strips seen by the front-end circuits.

Two hybrid circuits using Cu/Polyimide laminates with a flexible wrap-around connection in between make a single-piece construction of the hybrid possible. Fig. 2 shows the cross section of the module with magnification in vertical direction. It is noted that the hybrid ‘bridges over’ the sensors with an air gap of 0.4 mm. Thus no material (except bonding wires) is in contact with the sensor surfaces.

TABLE I. MAJOR PARAMETERS OF THE ATLAS BARREL SCT MODULE

Number of sensors	2 in top, 2 in bottom
Dimensions of strip sensor [mm]	63.96 x 63.56 x 0.285
Strip pitch / stereo angle	80 µm / ±20 mrad
Sensor operating temperature	< 0°C, optimum -7°C
Number of ABCD chips	6 in top, 6 in bottom
Hybrid power consumption	6W nom., 8.1 W max.
Thermal runaway heat flux	> 240 $\mu W/mm^2$ at 0°C
Thickness (sensor/hybrid part)	1.15 / 3.28 mm
Radiation length averaged	1.17 % X_0/module

Since the flexible circuit itself does not have enough rigidity, it is reinforced with a Carbon-Carbon bridge. The bridge must be strong enough to make the ultrasonic wire-bonding possible. In addition the bridge provides a thermal path with its high thermal conductivity as well as an additional electrical functionality for ground connection. In this configuration, the thermal path for the ASIC heat is largely decoupled from the thermal path for heat generated in the sensor bulk, keeping the strip sensors as cold as possible. The bridge is supported by the protruding edges of the baseboard via BeO facings.

Twelve ABCD chips dissipate a power of 6 W for nominal operating conditions and nominal process parameters, up to a maximum of 8.1 W for the worst case. As the dose accumulates, the heat generation in the sensor bulk becomes 120 $\mu W/cm^2$ (at the sensor temperature of 0°C). A thermal simulation shows that, with the present module configuration, thermal runaway occurs at 220 $\mu W/mm^2$ with coolant temperature of -14°C.

The overall weight of the module is 25 g and the radiation length averaged over the silicon sensor area is 1.17% X_0. Table I lists up the major parameters of the module.

III. HYBRID COMPONENTS

A. *Readout ASIC*

The readout ASIC, ABCD3TA [5], has a binary architecture comprising all functions for signal processing from 128 strips. It is implemented with 0.8 µm BiCMOS DMILL technology. Its amplifier with a gain of 50 mV/fC integrates the signals by unipolar shaping with a peaking time of 20 nsec. The equivalent noise charge with 12 cm strips connected is about 1500 e at room temperature before irradiation and expected to be 1800 e at about 0°C after 10 years of operation. The threshold for hits is set to 1 fC. Three consecutive clock buckets are readout to identify genuine signals. For uniform threshold setting, the threshold is adjusted by a 4-bit DAC attached to each channel and its full-range is selectable from 60, 120, 180 and 240 mV to cover increased threshold spreads by radiation. The hit patterns are stored in 132 bit deep pipeline buffers until being accepted by the Level 1 trigger.

B. Cu/Polyimid flexible circuits

The technology of flexible multi-layer circuits of Cu/Polyimide(Kapton) has been now widely used in industry [6]. The layer structure of the Cu/Polyimide circuits is shown in Fig.3 together with thickness of the layer component. The starting core is a double-sided Cu/Polyimide sheet, to which a single-sided sheet is built up on each side. All Cu/Polyimid sheets used are of adhesive-less type. The top and bottom copper layers are entirely etched out in the flexible sections for the I/O connector and for the wrap-around part. Electrical connections across different layers are realized by either through-holes, drilled through all 4 layers, or laser-cut via-holes between layers L1 and L2. The diameters of the through- and via- holes are 0.3 and 0.15 mm, respectively. The circuit pattern is formed with a minimum line width of 100 +0/-20 μm and a minimum spacing of 80 -0/+20 μm between lines. All transitions from metal pads/rounds to metal lines are done via tear drops to prevent possible cracks. The bonding pads are plated by gold with 3 μm thick nickel backing.

Fig. 4 shows the actual layout patterns. The top layer L1 has bonding pads and branch traces while the second layer L2 contains most of the longitudinal bus lines between chips as well as the HV line for sensor biasing. The third layer L3 carries analog and digital grounds while L4 supplies the digital and analog powers. These L4 power planes are meshed by removing 50% of copper. In the flexible 2-layer parts, these power lines are raised to L2.

The L1 areas right underneath the ASIC chips and the glass pitch adaptors are covered by bare meshed grounds for better ground connection to the chip substrates. Seventeen through-holes (300 μm in diameter) are added underneath the analog part of each ASIC, which will be filled with thermally and electrically conducting glue in assembly stage. This ensures thermal and electrical connections between chips and the Carbon-Carbon bridge. Fig. 2 shows these pillars. The effective thermal conductivity of this pillar is 40 W/m/K.

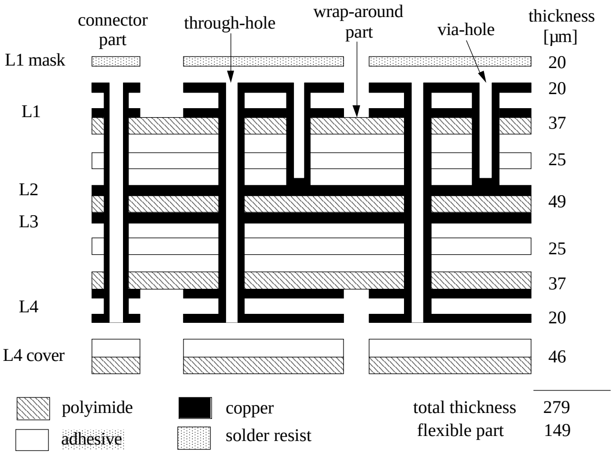

Fig. 3. Layer structure of the Cu/Polyimide(Kapton) laminate. In this figure, the layer components are separately drawn, but actually they are in contact in the product. A build-up method is used starting with the central L2-L3 adhesive-less laminate. Two types of holes, thru and via, are made for vertical connections. Copper layers of L1 and L4 are etched out for flexible parts. Thickness of each layer component is given in terms of μm.

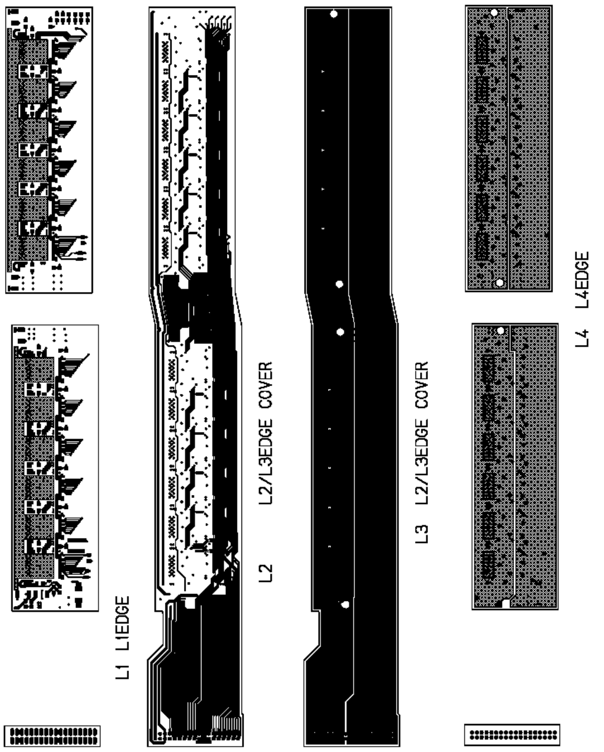

Fig. 4. Layout of the Cu/PI flexible circuit. The first and second top layers L1 and L2 are used for signal circuits, L3 is for digital and analog grounds, and L4 supplies the power plane.

All the surface of L1 is covered by solder resist except spots for wire bonding and component soldering. The back plane is covered by a polyimide layer with openings for pillar sections.

The digital and analog grounds and powers are completely separated in the layout design. However, we found that the electrical stability of the module is better when the analog and digital grounds are connected at 12 spots aside the chips in layer L1.

Along the fabrication of the circuits, quality assurance (QA) tests will be carried out by vendor: (1) visual inspection for all products, (2) specimen tests for mechanical tolerance on outer dimensions, bonding pad/gap widths, plating thickness, and (3) integrity test of lines: disconnection/short-cut tests for all products, and resistance measurement for samples.

TABLE II . PROPERTIES OF THE CARBON-CARBON

Thermal conductivity	(// fiber)	700 ± 20	W/m/K
	(⊥ fiber)	35 ± 5	W/m/K
Density		1.9	g/cm^3
Young's modulus	(// fiber)	294	Gpa
Tensile strength	(// fiber)	294	Mpa
Thermal expansion coefficient	(// fiber)	-0.8	ppm/°C
	(⊥fiber)	10	ppm/°C
Resistivity	(// fiber)	2.5×10^{-6}	Ωm

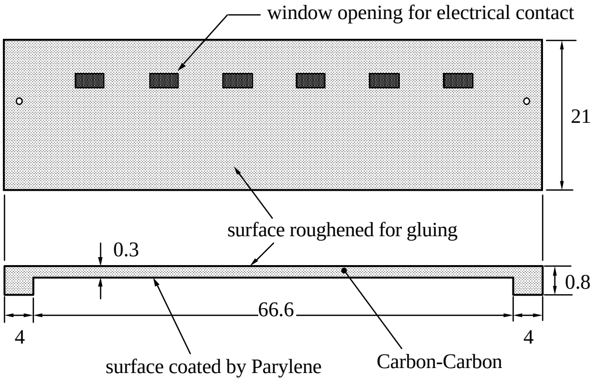

Fig. 5. Design of the carbon-carbon bridge. The scale unit is in mm.

C. *Carbon-Carbon bridge*

The bridge material is required to have high Young's modulus and low radiation length. We have surveyed various materials and concluded that Carbon-Carbon made of carbon fibers with carbon binder turned out to be best suited for the current application. Beryllium is another candidate but it is poisonous and its machining is difficult. Carbon-Carbon provides high thermal as well as electrical conductivities. We used unidirectional Carbon-Carbon for minimum thickness. Its properties are summarized in Table II [7]. The thermal conductivity in fiber direction is nearly twice of that of copper. Its young's modulus in fiber direction is as strong as that of ceramics.

As shown in Fig. 5, the Carbon-Carbon bridge is machined to a thickness of 300 µm with legs on both ends 500 µm high. Two small holes are made for guides in assembly steps. To prevent any fluff coming off, the surface of the bridge is coated with 10 µm thick Parylene polymer [8], which can be grown uniformly on the surface by gas vapor deposition. The coated surface is roughened with laser where adhesion is required. In addition the coating is partially removed to open windows for thermal and electrical contact to the bottom side of the ASICs via pillar holes through the Cu/Polyimide laminate.

QA is made on: (1) mechanical tolerance of outer dimensions, (2) Young's modulus and tensile strength for samples to be greater than 90% of specified values, (3) thermal conductivity to be greater than 600 W/m/K, and (4) electrical resistivity to be less than 25 mΩ between the two farthest windows.

D. *Glass pitch adaptor*

The basic pitch of input pads of the readout ASIC is 48 µm, while that of the silicon strip sensor is 80 µm. In order to make parallel wire bonding possible, a pitch-adaptor is introduced in front of the ASICs. The pads and traces are fabricated with an aluminium deposition of 1-1.5 µm thickness on a glass substrate. QA items are: (1) for all products, visual inspection of the mechanical finish, tolerance, and interruptions/short-cuts of the traces, and (2) for samples, tape-peel test of the aluminum traces and (3) wire-bond pull test. The wire-bond breaking strength is to be greater than 6 grams for a height/distance setting of 0.3.

E. *Passive electrical components*

All passive electrical components are of surface mount type 1608 (or 3216) with a length/width of 1.6/0.8 (or 3.2/1.6) mm. All chip capacitors are of X7R type with a capacitance change of < 5% between –20 and +40°C. The resistor type is thin metal film with a 0.5% tolerance. Two thermistors are mounted to monitor the hybrid temperature.

IV. HYBRID ASSEMBLY

The hybrid assembly is performed as follows. Firstly, Cu/Polyimide flexible circuits and Carbon-Carbon bridges are glued together. Then the passive components as well as a connector are soldered and two pitch-adaptors are adhered. The assemblies are subject to thermal cycling followed by quality analysis. About 2,500 hybrids with passive components loaded are to be delivered to the module assembly clusters, UK, Scandinavia and U.S. Each cluster completes hybrids by mounting ASICs and then assembles them into complete modules.

A. *Gluing the Carbon-Carbon bridge and Cu/PI laminate*

Two epoxy adhesive sheets are used: one thermally conductive and another electrically conductive. A piece of thermally conductive adhesive sheet, ABLEFILM 563K-.002, 50 µm thick with alumina filler, is punched out to the bridge size with six openings for pillars. Each pillar opening is covered with a piece of electrically conductive sheet, ABLEFILM 5025E-.002, 100 µm thick, silver loaded. The electrically conductive film is thicker so that it fills up the pillar holes in the Cu/PI laminate. Both adhesive films require an elevated temperature curing at 125°C for two hours. A special jig is used to press the assembly of the Carbon-Carbon bridges, adhesive sheets and the Cu/PI laminate on a curved surface under the pressure of 4 kg/cm^2 during its 2 hr curing. This is to compensate the difference in thermal expansions between Cu/PI and Carbon-Carbon so that the hybrid becomes nearly flat at room temperature.

QA is made for all products: (1) visual inspection for excess adhesives, residuals on the surface, and mechanical

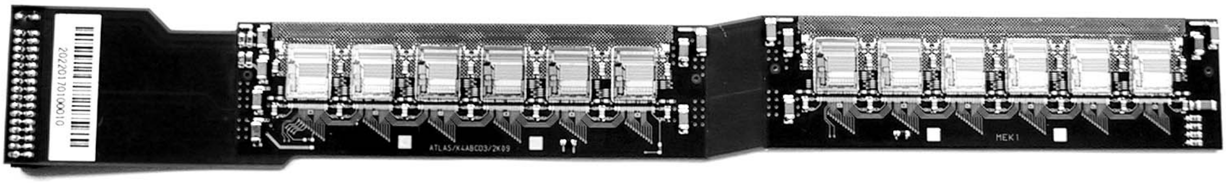

Fig. 6. A picture of the staffed hybrid. The Cu/Polyimide flex circuit is reinforced with carbon-carbon bridges on the back side. All the passive components, glass pitch-adaptors and 12 ABCD3T chips are mounted.

tolerance for the alignment and thickness, and (2) bows of the hybrid section at the room temperature, which are to be less than 75 µm both in the long and short directions.

B. Soldering the passive components

Since high temperature application is not recommended after the Cu/PI and the bridges are glued, the solder reflow technique is not applicable. Firstly, the hybrid surface is covered by a protection sheet with spot openings at soldering pads. Using a 3-axis dispensing workstation, a dot epoxy is applied to the spot of each passive component. Then an automatic robot places the components. After half a day for curing, a drop of liquid solder flux is applied for each soldering spot and then one(two) soldering balls of 0.4 mm in diameter are placed at each end for the type 1608(3216) component. Solder balls are heated manually (or by laser in future) for soldering. The protection sheet is removed after washing with water and alcohol.

QA is made for all hybrids: (1) visual inspection of component placement, solder fillet, surface contamination and residuals, (2) electrical measurement of the termination resistors at the connector, the impedance of the filter network and the capacitances between analog/digital power lines and ground, and (3) a wire-bond pull test at the test pads to be greater than 6 grams.

C. Gluing glass pitch-adaptors

Two glass pitch adaptors are glued onto the hybrid with the room temperature curing epoxy Araldite-2011. Its low viscosity makes the glue layer thin and bubble free. The pitch-adaptor is aligned under a microscope to the fiducial marks within ±50 µm. QA is made for all hybrids by visual inspection of component placement, crack in glass and adhesive squeeze-out.

D. Thermal Cycle test

In order to eliminate initial failures and/or marginal products, the passive component loaded hybrids are thermal-cycled between -30 and +60°C for 5 times. The transit and hold times are 0.5 and 1 hour, respectively. QA is made for: (1) visual inspection for component loss, cracks, (2) mechanical tolerance for thickness and bows and (3) electrical performance of resistance, capacitance, and leakage currents in the low voltage lines at 10 V and HV lines at 500 V. The flatness of the hybrid at 25°C was measured on the backside of the Carbon-Carbon bridge with a 3D measuring device. The results showed a bowing distributed from -20 to -75 µm peaked at -50 µm along the length. The minus sign means a dent near the center as seen from the circuit side. The values are less than the maximum allowance of 75 µm.

The hybrids that passed the QA procedure will be delivered to the module assembly clusters.

E. Stuffing ASICs

The ASIC chips are glued on the hybrid with electrically conductive epoxy, Eotite p-102. Four fiducial marks on the hybrids are used for aligning the chip. The epoxy is cured at 50°C for 2 hrs. Nearby bonding pads are masked during gluing. After all (but for bonding to the sensors) wire bonds are made, an electrical test is done to ensure that all ASICs perform properly and that all wire bonds are effective. Bad chips are replaced using a simple jig that applies heat locally. In addition, a 100 hours long test at an elevated temperature of 37°C is performed under the nominal Level 1 trigger rate at 100 kHz. This is in order to catch infant mortality problems of the ASICs. Experience to-date has shown no such failures. The temperature and duration will be adjusted during the production phase in the light of experiences gained.

Fig. 6 is a photo picture of the hybrid with all the components mounted including ASIC chips.

V. MODULE ASSEMBLY

The hybrid with ASICs thus completed and inspected will be mounted onto the sensor-baseboard assembly [9] which is fabricated in parallel to the hybrid assembly. This process is comparatively simpler using special jigs which carry wrapping-around motions over the sensor-baseboard assembly. Great care must be paid not to touch the surfaces of both objects. The required accuracy of positioning is ±50 µm. The long pot life of the adhesive allows ample time for repositioning. After curing and visual inspection, the assembly is mounted into a special protection box for storage as well as for interim performance checks including HV application.

There are in total 4608 of these wire-bonds per module. Particular care is required in wire-bonding between pitch adaptor and sensors for 1 mm difference in height. Typically one module can be bonded and inspected in 4 hours. Fig. 7 is

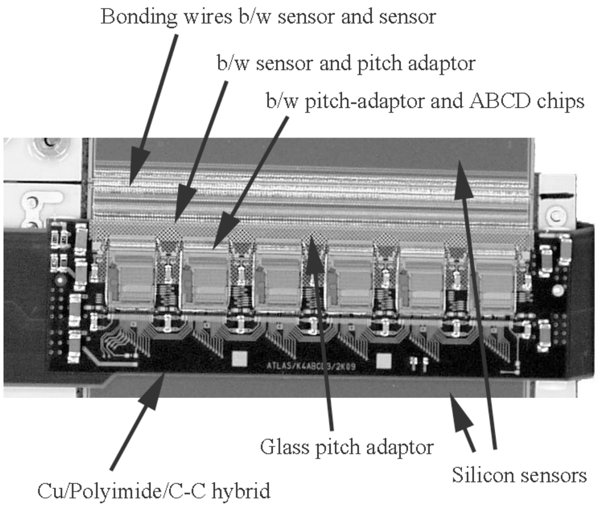

Fig. 7 A magnified picture of the central part of the module.

a magnified picture of the central part of the module completed.

VI. PERFORMANCE OF THE PRE-SERIES PRODUCTION MODULES

A total of about 50 passive components loaded hybrids were made as for pre-series production.

About thirty modules have been constructed with various sets of components including chips and hybrids at the developing stages. Ten modules are assembled with the final chips ABCD3TA and the hybrids of final design. Their average gain and ENC are summarized in Table III. The gain and equivalent noise charge (ENC) distribution of a typical module is shown in Fig 8. A fairly good uniformity over all channels is seen. All modules satisfied the criteria, the gain being greater than 50 mV/fC and ENC less than 1500 e.

Several modules with the present hybrids have been irradiated up to 3 x 10^{14} protons/cm^2 with no indication of mechanical as well as thermal deteriorations.

TABLE III
AVERAGE GAIN AND ENC OF THE MODULES MADE AT JAPAN CLUSTER

Module ID	Gain [mV/fC]	ENC [e]
0170100020	57.7	1291.4
0170100035	53.0	1399.9
0270100036	54.3	1412.0
0170100037	56.4	1332.3
0170100044	54.2	1458.3
0170100046	56.1	1493.3
0170100047	54.8	1449.8
0170100049	55.8	1377.3
0170100050	56.3	1450.3
0170100052	55.0	1392.5
Average	55.4	1405.7

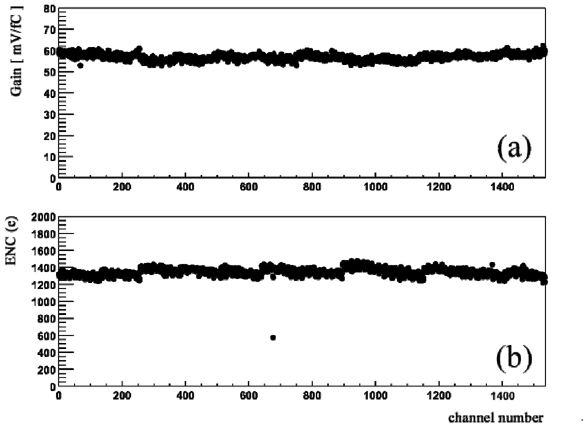

Fig. 8. Gain (a)and ENC (b) as a function of the channel number in a typical module.

VII. SUMMARY

The hybrid for the ATLAS barrel SCT module is designed and developed. A 4-layer Cu/polyimide lamination is used for the top and bottom circuit parts, together with a 2 layer lamination for the flexible parts. The Cu/polyimide ciucuit parts are reinforced by thin Parylene-coated carbon-carbon bridges. The hybrids are mounted with passive components and pitch-adaptors before delivery to module production clusters.

The specifications of each component as well as assembly procedures of the hybrid are described with quality assurance at various stages.

Some thirty barrel modules including ten modules with the final chip version (ABCD3TA) have been assembled with the hybrids showing its good performance including its radiation hardness.

VIII. ACKNOWLEDGMENT

The authors would like to thank all the collaborators belonging to the ATLAS SCT group led by M. Tyndel. The work of design, prototyping, tests and construction of the barrel SCT system is a joint effort among these people. The hybrid part described in this paper resulted from concentrated work developed in Japan, in tight collaboration and consultation with people involved in various components of the barrel SCT modules. Among others, we would like to give our special thanks to R. Apsimon, A. Carter, J. Carter, W. Dabrowski, M. Gibson, A. Grillo, C. Habor and N. Spencer for their useful suggestions.

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