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

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***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 re-enforced 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. Some twenty full-fledge modules with active silicon strip sensors were assembled. Their 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 Large Hadron Collider (LHC) project [1] is advanced at CERN. LHC can accelerate protons up to the center-of-mass energy of 14 TeV and collide them at 40 MHz providing a luminosity of 10^{34} $cm^{-2}s^{-1}$.

Three sets of large aperture super conducting toroids generate toroidal 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 magnetic field of 2 T in the ID volume. From the interaction point, the ID consists of the pixel detector, the Semiconductor Tracker (SCT) of silicon micro strip sensors, and the straw transition radiation tracker. Its overall dimension is 2.3 m in diameter and 7 m in length.

The ATLAS Semiconductor Tracker (SCT) [3] covers the region from 300 to 520 mm in radius from the beam line. It consists of the barrel part of 4 cylindrical layers in the central region and the forward part of 9 disks in each side. The total area of the SCT silicon micro strip sensors is 61 m^2. The position resolution is achieved with a strip pitch of 80 μm, a pair of sensor layers within a module arranged to have a stereo angle of 40 mrad. At design luminosity of 10^{34} $cm^{-2}s^{-1}$, the annual fluence at the innermost sensors at r = 300mm is about $1.8x10^{13}$ n_{eq}/ cm^2 expressed in terms of equivalent 1MeV neutron flux. Thus 10-year operation at LHC requires the radiation tolerance up to $2x10^{14} n_{eq}/cm^2$ in 10 years including 50% uncertainty. The SCT is a precision that is capable of identification 40 MHz bunch crossing identification and that can tolerate large radiation doses with minimal possible material.

II. BARREL SCT MODULE

The barrel SCT system consists of 4 cylindrical layers where are mounted exactly the same modules. A picture of the module is shown in figure 1. The module is a basic detector unit providing stand-alone mechanical rigidity together with electrical and thermal functionalities. The total number of barrel SCT modules is 2,500 sets.

Two 6.4 cm square p-on-n sensors are aligned to form a 12 cm strip unit. Two such pairs are aligned and glued on the top and the bottom of the central core, the baseboard, forming a stereo angle of 40 mrad. The baseboard acts as a mechanical core and also as a thermal conduction to transfer the heat of the front-end electronics and the sensors to the cooling pipe, which is fitted to one edge of the baseboard. The baseboard is also used as an electrical conductor to provide bias voltage to the back plane of the sensors.

The front-end readout ASICs are mounted on a hybrid set which bridges across the sensors. A single hybrid is wrapped around to readout top and bottom sensors, and the connection to the external world is provided at the cooling end. The hybrid is not glued to the surface of sensors but to protruding edges of the baseboard (called as facing).

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The cooling of the module is provided by a thermal contact over an area of $420mm^2$ between the lower BeO facing of the module and an aluminum cooling block. Two spring clips compress two pieces together. The grease for thermal contact is Dow Corning 340, which has demonstrated both good thermal conduction and high radiation tolerance. The cooling block encapsulates a CuNi cooling tube that carries the evaporative fluid of C_3F_8.

The overall weight of the module is 25 g and the radiation length averaged over the silicon sensor area is 1.17% X_0.

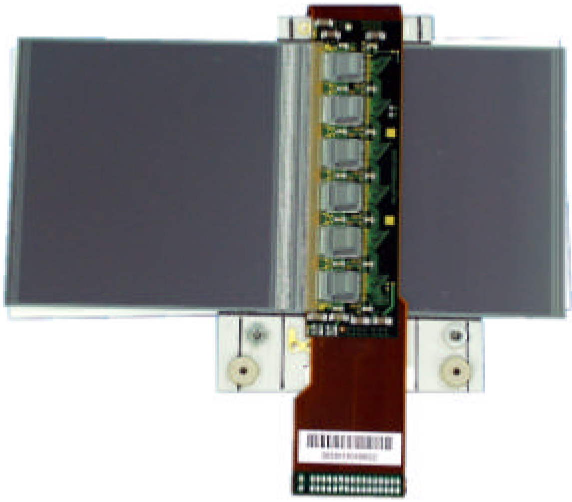

Fig. 1. A picture of the barrel SCT module

A. Sensor

The SCT collaboration decided to use single-sided p-on-n type of silicon micro-strip sensors for its radiation tolerance and cost. The barrel SCT module is made of four identical sensors. Its size is 63.96 mm x 63.56 mm (cut-edge to cut-edge) and the thickness is 285 µm [4]. Two sensors are aligned to form a 128 mm long unit. Strips of the two sensors are wire-bonded to form 126 mm long strips by aluminum wire with a diameter of 25 µm. The sensor has 768 readout strips with a pitch of 80 µm. AC coupled readout is adopted. A positive bias voltage is applied to the n-type bulk from the rear side of sensors. The initial full depletion voltage is less than 150 V.

B. Baseboard

The baseboard substrate is thermalized pyrolytic graphite VHCPG (Very High thermal Conductivity Pyrolytic Graphite). Its thermal conductivity at room temperature is 1450-1850 W/m/K in plane with -0.4%/C and typically 6 W/m/K out of plane. Its thickness is 380 µm. The encapsulation is typically 20 µm thick. Four small spots of epoxy are removed from each side to provide openings for electrical connection to the rear side of the silicon sensors with conducting epoxy. In consequence, the VHCPG substrate is kept at the positive high voltage. Four BeO facings are attached to the VHCPG sheet. The facing has precision holes for precision module mounting and also has gold plated pads for high voltage connection to the readout hybrid via wire bonding.

C. Hybrid

In the minimum amount of substances, a binary readout scheme is adopted in SCT in order to make 40 MHz bunch crossing identification possible. Intensive tests revealed that strengthening of ground planes was very important for stable operation. The SCT group adopted a Copper/polyimide flexible multi-layer circuit, which is widely used commercially.

Since flexible circuit itself does not have rigidity, it is reinforced with a Carbon-Carbon bridge. It is a mechanical support for Cu/Polyimid flexible circuits as well as providing for high thermal conductivity and for functions electri cally as a ground plane.

The basic pitch of input pads of the readout ASIC is 48 µm, while that of the silicon micro strip sensor is 80 µm. In order to make parallel wire bonding possible, a glass pitch-adaptor is placed in front of the ASICs.

III. HYBRID COMPONENTS

A. Readout ASIC

The readout ASIC, ABCD3TA [5], has the binary architecture comprising all functions for signal processing from 128 strips in a single chip. It is implemented in 0.6 µm BiCMOS DMILL technology. Its amplifier with a gain of 50 mV/fC integrates the signal charge from the strip. The output signal is formed by unipolar shaping with a peaking time of 20 nsec. The input equivalent noise charge is 1500 e. Pulses exceeding the threshold of typically 1 fC are stored as 1-digit hits. Three consecutive clock buckets are readout to identify genuine signals. To make the thresholds as uniform as possible, the threshold is adjusted by a 4-bit DAC attached to each channel. The full-range of the DAC is selectable from 60, 120, 180 and 240 mV to cover the increased spread of the threshold offsets caused by radiation. The hit patterns are stored temporally in 132 deep pipeline memory buffers. When the Level 1 trigger is asserted, the compressed hit information is send to the next data buffer. The chip also has an internal calibration pulser.

B. Cu/Polyimid flexible circuits

The technology of flexible multi-layer circuits of Cu/Polyimide has been now widely used in industry [6]. The layer structure of the Cu/Polyimide circuits is listed in Table I. The starting core for build-up is a double-sided Cu/ Polyimide sheet, where a pair of single-sided sheets is glued on both sides. All Cu/Polyimid sheets are made with an adhesive-less technology. The top and bottom copper layers are removed in the cable section to the I/O connector and in the wrap-around section. The power plane (L4) is meshed by removing 50% of copper. Electrical connections across different layers are realized by either through-holes, drilled through all layers, or laser-cut via-holes between the top and second layers. The minimum diameters of the holes are 0.3 and 0.15 mm for through-holes and via-holes, respectively. This fine via-hole technology makes the hybrids small and light. The circuit pattern is formed by etching with a rule of the minimum width of 100 µm and the minimum gap of 80 µm. The bonding pads are gold-plated with 3 µm-thick nickel backing.

TABLE I. LAYER STRUCTURE OF THE CU/POLYIMIDE

Layer	Material	Thickness [µm]
Top cover	solder resist mask	20
Through-hole plating	Cu	20
Single-sided	Cu (12µm)/PI	37
Adhesive		25
Double-sided	Cu (12µm)/PI/Cu (12µm)	49
Adhesive		25
Single-sided	Cu (12µm)/PI	37
Through-hole plating	Cu	20
Cover film	PI/adhesive (33µm)	46
Total (circuit part / cable/wrap-around part)		279 / 149

As shown in Fig. 2, the top layer L1 has bonding pads, branch traces, the second layer L2 contains most of longitudinal bus lines between chips and the sensor HV line, L3 carries analogue and digital grounds, and L4 is the power supply plane with copper meshes. The digital and analogue ground connection is made on the hybrid aside of every ASICs. Seventeen through-holes are added underneath the analog part of each ASIC, which are filled with thermally and electrically conducting glue. This ensures thermal and electrical connections between each chip and the carbon-carbon bridge. The effective thermal conductivity of this pillar is 40 W/m/K.

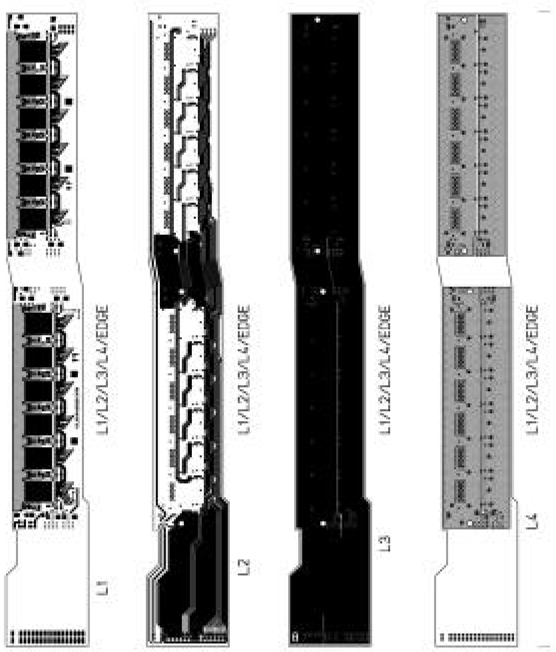

Fig. 2. A layout of the Cu/ Polyimide flexible circuit

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

C. *Carbon-Carbon bridge*

Since the Cu/Polyimid flexible circuits itself is not rigid enough, it must be reinforced with carbon-carbon bridges. The bridge is required to have high Young's modulus and low radiation length. It provides high thermal and electrical conductivities, since it functions also as a ground plane. The bridge is made of unidirectional carbon fibers with carbon binder (carbon-carbon). Its properties are summarized in Table II [7].

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 coeff.	(// fiber)	-0.8	ppm/°C
	(⊥ fiber)	10	ppm/°C
Resistivity (along fiber direction)		2.5×10^{-6}	Wm

The thermal conductivity in the fiber direction is nearly twice of Cu, and the young's modulus in the fiber direction shows that it is as strong as ceramics. The bridge is machined to a thickness of 300 µm with pedestals on both ends 500 µm high. The surface of the bridge is coated with Parylene polymer of 10 µm thick, which can be grown uniformly on the surface by gas vapor deposition technique. The coated surface is roughened with a laser where adhesion is required. Coating is partially removed to open windows to make a thermal and electrical contact for ASICs.

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*

In order to enable parallel wire bonding, a pitch-adaptor is introduced in front of the ASICs. Since a fine pitch of 48 µm is required, the pads and traces are fabricated on a separate piece with aluminum deposition of 1-1.5 µm in thickness on a glass substrate.

QA items are: (1) for all products, visual inspection of the mechanical finish, tolerance, and open/short of the traces, and for samples, (2) tape-peel test of the aluminum traces and (3) wire-bond pull test. The wire-bond breaking strength is to be greater than 6 g for a height/distance = 0.3 setting.

E. Passive electrical components

All passive electrical components are of surface mount type. Its size is 16 x 8 or 32 x 16 in mm. All chip capacitors are 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 and the connector are soldered and two pitch-adaptors are adhered. 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 assembles them into complete modules.

A. Gluing the Carbon-Carbon bridges

Two epoxy adhesive sheets are used: thermally conductive and electrically conductive. A set of small windows has been cut out on the surface of the bridges in order to improve the thermal and electrical contact between the carbon bridge and the ASICs. The area other than the windows is covered with the thermally conductive adhesive sheet, ABLEFILM 563K-.002, 50 µm thick, alumina-filler filled, and at the windows with the electrically conductive sheet, ABLEFILM 5025E-.002, 100 µm thick, silver loaded. The electrically conductive film is thicker so that the adhesive will fill up the through-holes of 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 on a curved surface at 4 kg/cm^2 during its curing. This is to compensate the difference in thermal expansions between Cu/PI laminate and carbon-carbon plate 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 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 a high temperature application is not recommended after the flexible circuits and carbon-carbon bridges are glued, the solder reflow technique is not applicable. First, the hybrid surface is covered by a protection sheet with openings only for 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 cure, a drop of liquid solder flux is applied for each soldering spot and then one(two) soldering balls are placed at each end for the type 1608(3216) component. Solder balls are heated manually (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 from the connector for the termination resistors, the impedance of the filter network and the capacitances of V_{cc}-GND and V_{dd}-GND, and (3) a wire-bond pull test at the test pads to be greater than 6 grams.

C. Gluing the Glass pitch-adaptors

Two glass pitch adaptors are glued onto the hybrid with a 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 10V and high voltage 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 instrument. The results showed a bowing distributed from -20 to -75 µm peaked at -50 µm along the length. The minus sign

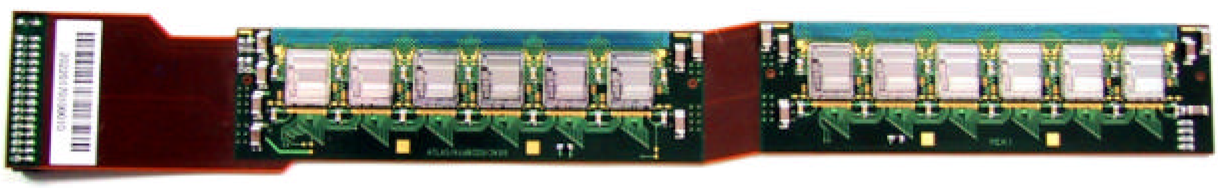

Fig. 3. A picture of the Cu/Polyimide flex circuits with carbon-carbon reinforcement bridges on the back side. All the passive components, glass pitch-adaptors and 12 ABCD3T chips are

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 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 elevated temperature of 37°C is performed with the nominal Level 1 trigger frequency of 100 kHz, in order to catch infant mortality problems of the ASICs. It is noted that 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. 3 is a photo picture of the hybrid with all the components mounted including ASIC chips.

V. PERFORMANCE OF THE PRE-SERIES PRODUCTION MODULES

A total of about 50 passive components loaded hybrids were made as for pre-series production. The gain and equivalent noise charge (ENC) distribution of a typical module is shown in Fig 4 in which fairly good uniformities over entire channels are seen.

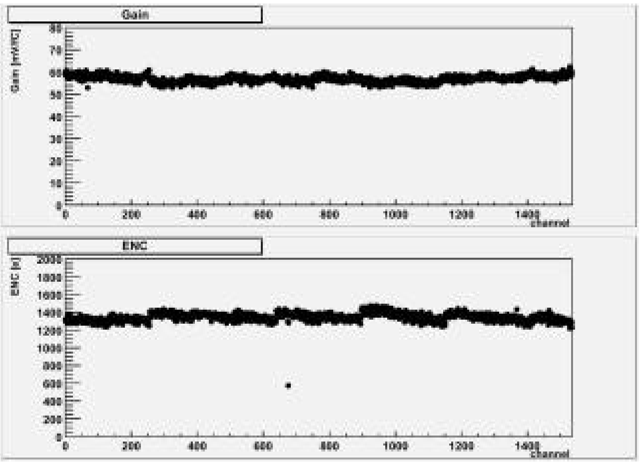

Fig. 4. Gain and ENC as a function of the channel number in a typical module.

The Japan cluster made 10 modules with full set of ABCD3TA chips mounted. Their average gain and ENC are summarized in Table 3. All modules satisfied the criteria, namely, the gain is greater than 50 mV/fC and the ENC is 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

VI. SUMMARY

The hybrid for the ATLAS barrel SCT module is designed and developed. A 4-layer copper-polyimide lamination is used for the top and bottom circuit parts, together with 2 layer lamination for flexible parts. The copper-polyimide ciucuit parts are reinforced by thin Parylene-coated carbon-carbon bridges. The hybrids are mounted with passive components and pitch-adopters 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 have been constructed with the hybrids showing its good performance including its radiation harness.

VII. REFERENCES

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