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Application of Cu-polyimide flex circuit and Al-on-glass pitch adapter for the ATLAS SCT barrel hybrid

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Abstract

We applied the surface build-up Cu-polyimide flex-circuit technology with laser vias to the ATLAS SCT barrel hybrid to be made in one piece from the connector to the electronics sections including cables. The hybrids, reinforced with carbon–carbon substrates, provide mechanical strength, thermal conductivity, low-radiation length, and stability in application-specific integrated circuit (ASIC) operation. By following the design rules, we experienced little trouble in breaking the traces. The pitch adapter between the sensor and the ASICs was made of aluminum traces on glass substrate. We identified that the generation of whiskers around the wire-bonding feet was correlated with the hardness of metallized aluminum. The appropriate hardness has been achieved by keeping the temperature of the glasses as low as room temperature during the metallization. The argon plasma cleaning procedure cleaned the contamination on the gold pads of the hybrids for successful wire bonding, although it was unsuccessful in the aluminum of the pitch adapters.

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Keywords: Hybrid; Flex circuit; Al-on-glass; Pitch adapter; Wire bonding

1. Introduction

ATLAS detector is under construction and will be placed at the large hadron collider (LHC) at the European Organization for Nuclear Research

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(CERN) [1]. Among various detector components, a charged particle tracking system, named Semiconductor Tracker (SCT) and composed of silicon microstrip detectors, will be positioned near the interaction point and inside the 2 T solenoidal magnetic field [2]. The SCT is made of the barrel and the endcap sections where 2112 and 1976 detector units are disposed on cylinders and disks, respectively.

The detector unit in the barrel section is the ATLAS SCT barrel module. It is composed of four silicon microstrip sensors, two on the top and two on the bottom side, together with the electronics for providing electrical power to and reading out signals from the sensors [3]. The pair of sensors, on the top and the bottom, is connected strip by strip with Al-wire bonding to make 768 strips on the top and another 768 strips on the bottom side. These strips are then connected to 12 application-specific integrated circuits (ASIC, ABCD3T [4]): 6 for the top and 6 for the bottom on an electronics carrier the hybrid.

Due to a large number of particles generated at the collisions, the silicon microstrip sensors will be damaged by radiation and biased up to 500 V after 10 years of operation. The power dissipation of the sensors will be 2 W total and that of electronics will be 5 W. The heat, especially of ASICs, has to be released to the cooling element efficiently. The hybrids must have good heat conduction and little radiation length.

We designed the hybrids for the ATLAS SCT barrel modules by applying Cu-polyimide flex-circuit technology. We fabricated 2600 hybrids to make 2112 barrel modules.

2. Design and construction of the hybrid

The Cu-polyimide flex-circuit technology has been applied in industry to numerous commercial products, such as digital cameras. The vendor [5] had the capability to make an object as large as 300 mm × 300 mm and multiple layers from single to any number of layers. The size and flexibility in layer construction allowed realizing the hybrid in one piece from the connector to the end of electronics. The electronics section is made of four layers and cable section of two layers. The electronics sections were reinforced with a carbon material to be rigid and to have good thermal conductivity. The carbon substrates, together with the organic material of insulator, polyimide, enabled the hybrid to have low-radiation length.

2.1. Circuit diagram

The circuit diagram of the ATLAS SCT barrel hybrid is shown in Fig. 1. The chart is specific for the ASICs used however, common general features can be seen in the chart: multiple bus lines running along the hybrids for multiple ASIC chips. There are also communication lines connecting adjacent chips and connecting alternative chips for bypassing a chip in case of failure. There are 17 bus lines and 16 communication lines at a cross section.

2.2. Cu-polyimide flex-circuit construction

The fundamentals in the flex-circuit design are the layer construction. From the circuit diagram of the ATLAS SCT barrel hybrid, the minimum number of layers required and designed at the electronics section was four. The metal layers were, from the top, L1—traces to the chips, L2—bus and communication traces, L3—power planes for analog and digital circuits, and L4—analog and digital ground planes. Since the section of four metal layers was not flexible enough, the cable section was reduced to two metal layers.

A cross-section of the flex-circuit at four layers is shown in Fig. 2. The two Cu layers in the middle, sandwiching a polyimide sheet of 25 μm thick, formed a core layer. The Cu sheets were joined to the polyimide sheet without an extra adhesive. This double-sided core layer was extended to the cable sections. Two single-sided layers were added, one on the top and the other on the bottom, glued to the core layer with an adhesive. The basic thickness of Cu sheets was $\frac{1}{3}$ oz (12 μm thick). The top and bottom Cu layers were covered with relatively thick Cu layers after metallizing the via and through-holes. In order to reduce the amount of Cu in the top and the bottom layers, both Cu sheets were etched to a half thickness before the through-hole metallization.

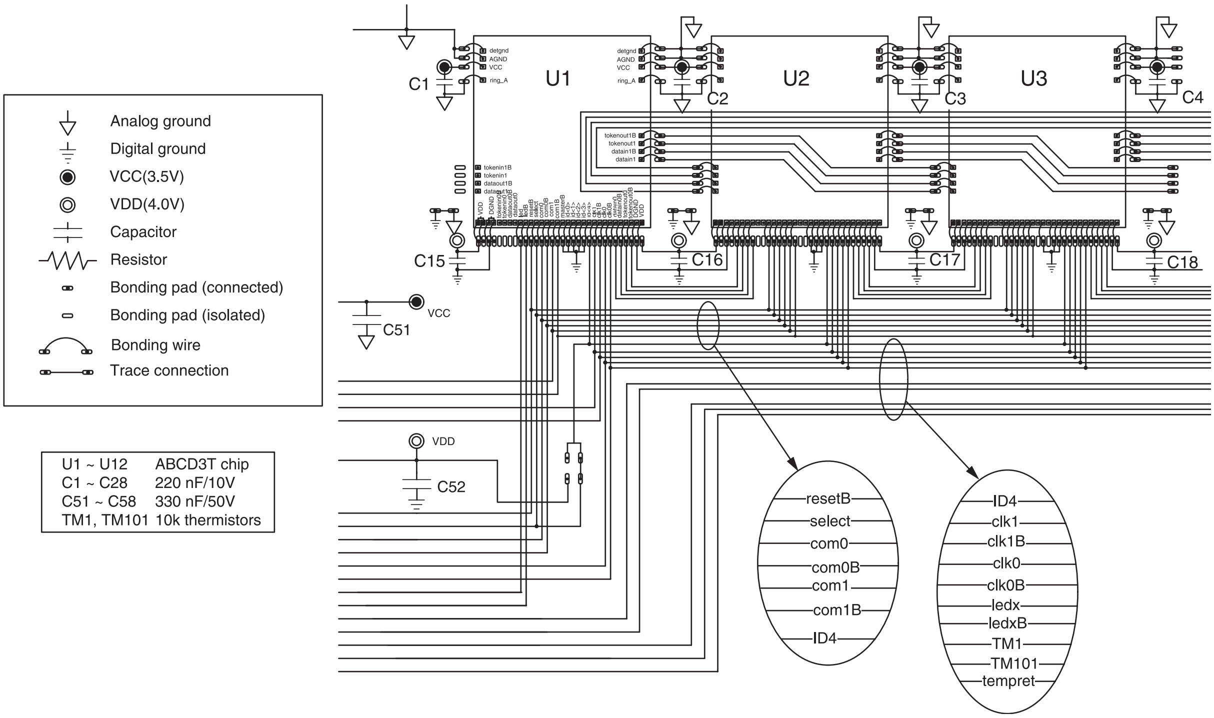

Fig. 1. Excerpt of circuit diagram of the ATLAS SCT barrel hybrid. A section of only the first three chips is shown in the figure.

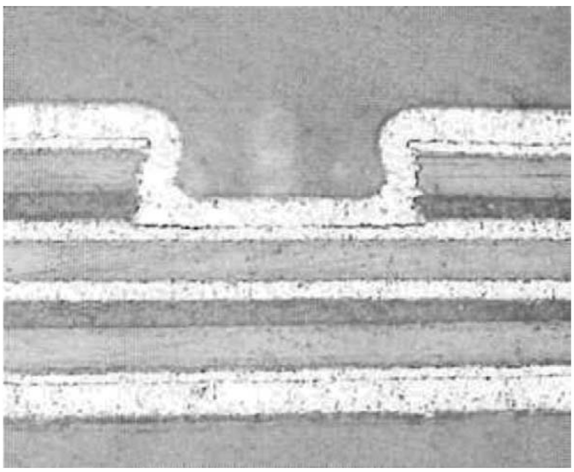

Fig. 2. A cross-section of Cu-polyimide hybrid with the surface build-up technology. A cross-section of via is also shown between the top and an inner layer.

The top and bottom layers, after the through-hole metallization, were etched to a mesh of 50% opening, effectively reducing the thickness by half.

In order to make connections between the top or bottom and the inner layers, holes (called ‘‘via’’) were made while processing the top or bottom single-sided layers. The vendor uses a laser for drilling vias. The diameter of the via was 150 μm, and the diameter of the metal area around the via, called ‘‘land’’, was 300 μm. Constructing a layer-over-layers with via holes is called ‘‘surface build-up’’ technology. The connections between the top and the bottom layers through the inner layers were also made with through-holes realized with mechanical drilling. The diameters of the through-hole and its land were 300 and 500 μm, respectively. The narrow land size of the vias allowed to lay out the multiple bus and communication traces in high density, thus reduced the width of hybrid and ultimately the radiation length.

2.3. Flex-circuit design rules

The vendor provided its design rules of flex-circuits [6]. The design of ATLAS SCT barrel hybrid followed their critical design rules. However, we asked for tighter tolerances for some patterns that they could provide ultimately: the minimum metal trace width of 100 μm and the minimum distance between the traces (i.e., gap) of 80 μm.

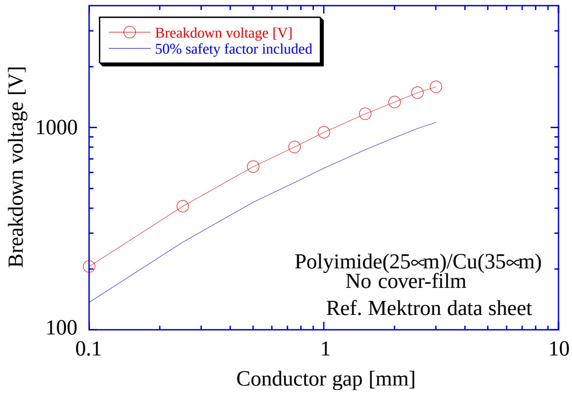

Fig. 3. Breakdown of high voltages in two conductors as a function of conductor gap, without a cover film. The line with an open circle is the measurement and the line without markers is the recommended values that include a 50% safety factor.

Unlike usual commercial products, the hybrid was required to connect a high voltage of 500 V. The vendor had a datasheet of the breakdown of high voltages as a function of conductor gaps, as shown in Fig. 3. The curve with open circles is the measured breakdown voltages and the line without markers is the recommended values including a 50% safety factor. From the curve, a gap distance of 700 μm from other traces was chosen for the traces carrying the 500 V high voltage.

There are detailed design rules to adopt in order to reduce the risk of breaking the traces. These are shown in Fig. 4 and reproduced from the document in Ref. [6]. The top three patterns show the so-called "tear-drop" designs where narrow traces join larger patterns. The rule is to smooth the transitions with a larger radius (R) to avoid abrupt transitions of metals. The bottom two figures are to reinforce the possible bending points. These design rules are important as the flex circuits are bent, often unintentionally. Besides, CAD

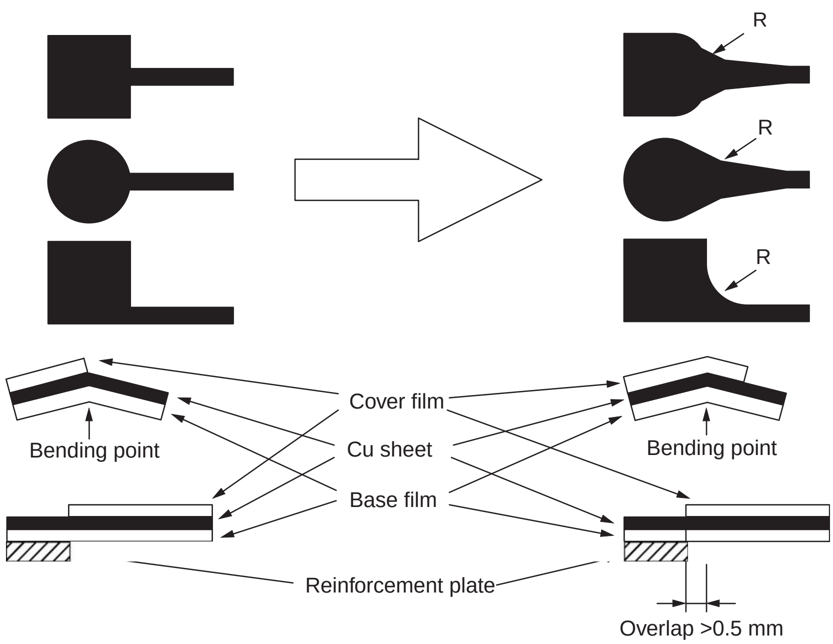

Fig. 4. Design rules for reducing the risk of trace breaking. The left patterns shall be modified to the right patterns. The top three are to avoid abrupt transitions and the bottom two figures are to reinforce possible bending points.

programs for rigid printed circuit board may draw patterns as in the left side.

2.4. Mechanical and thermal design

The electronics sections of the Cu-polyimide flex-circuits were reinforced for mechanical and thermal reasons by gluing the flex-circuit to a support substrate. Mechanically, ATLAS SCT barrel hybrid was designed to "bridge" over the silicon sensors so as to influence them minimally. The electronics sections were also to withstand the wire bonding in the hybrid. Thermally, the heat of the electronics was to be transported efficiently from the ASICs to the cooling element.

In order to fulfill the above requirements, a material called "carbon–carbon" with the carbon fibers running along the direction of the hybrid was adopted as support substrate. The uni-directional carbon–carbon material had Young's modulus as strong as ceramics and the thermal conductivity of 700 W/m/K longitudinally. The details of the design can be found elsewhere [7].

2.5. Cu-polyimide ATLAS SCT barrel hybrid

The overall design of the hybrid is shown in Fig. 5. Two electronics, two cables, and one connector section were made into one continuous piece, thus eliminating vulnerable external connections between the sections. Two electronics sections were displaced by 1.67 mm vertically to match the stereo angle of 40 mrad of the top and the bottom sensors when the hybrid was wrapped around. Due to the use of organic and carbon materials, it was light in weight (6.2 g + 1.0 g (ASICs)), and low in radiation length (0.30% + 0.06% (ASICs) Xo, averaged over the module area of 128 mm × 64 mm). The carbon substrates were not only providing good mechanical strength and thermal conductivity but also reinforcing the ground plane as they were connected electrically to the ground plane with a conductive epoxy. The thick ground planes of Cu and carbon substrates helped to make the hybrid robust against electrical instability in the ASICs. The cost of one hybrid was relatively inexpensive due to the low cost of Cu-polyimide flex-circuit.

A section of the first three chips corresponding to the circuit diagram in Fig. 1 is shown in Fig. 6. The top shows the first (L1) and the bottom, the second (L2) layer. The bus traces were laid in L2 in a pitch of 300 μm where the metal and gap widths were 200 and 100 μm, respectively. In L2, the communication traces along which digital signals are transmitted, were positioned under the LSI chips. The LSI chips were shielded from the communication traces through the ground plane including the chip pad areas. In a section of the chip pads, there were bunches of through-holes connecting the ground planes in the L1 layer and

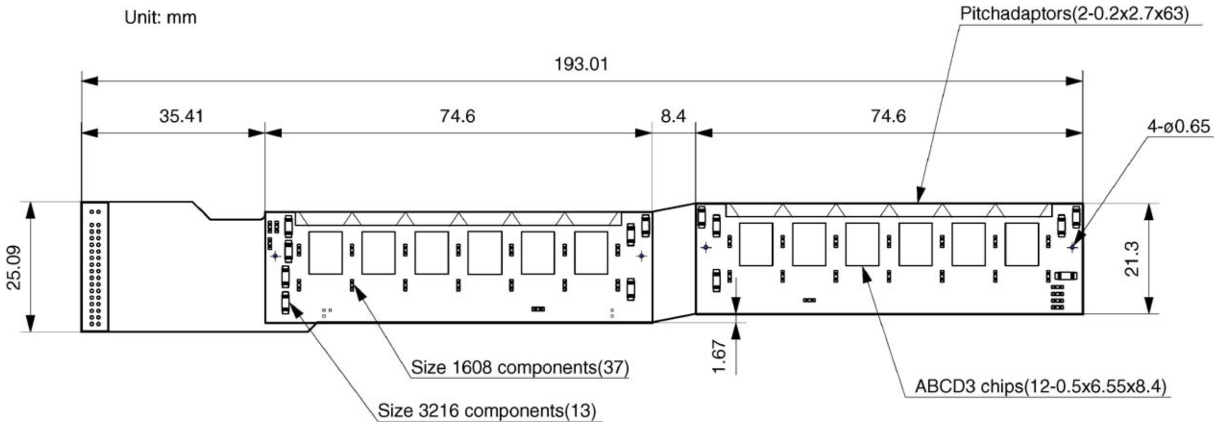

Fig. 5. The overall design of the ATLAS SCT barrel hybrid. The sections where LSI chips are mounted are the electronics sections with four layers and reinforced with carbon–carbon substrates. The leftmost section is the connector section with four layers for reinforcement reason. The remaining sections are the cables with two layers.

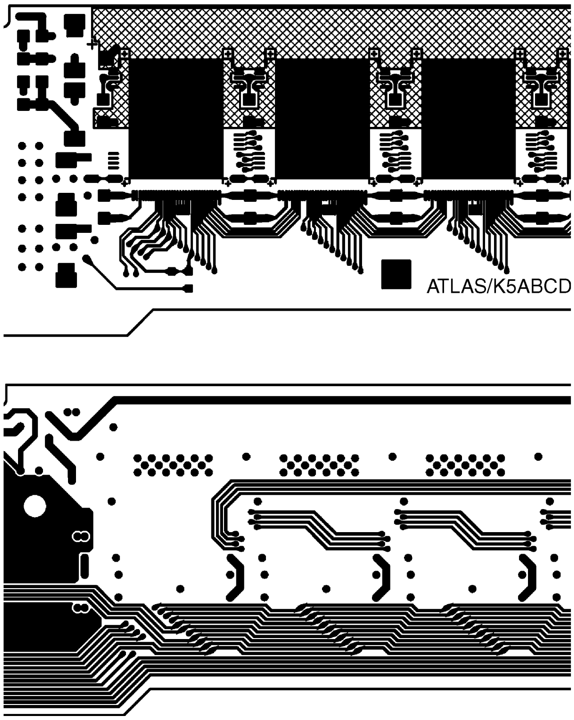

Fig. 6. Metal patterns in the first (L1) (top figure) and the second (L2) (bottom figure) layers at the first three LSI chips corresponding to the section in Fig. 1. The L1 layer is meshed except for the chip pads and traces.

the main ground planes in the L4 layer. The through-holes were then filled with conductive epoxy when the flex-circuit was glued to the carbon–carbon substrates. The through-holes also helped to transmit the heat of the chips to the carbon–carbon substrates.

The electrical continuity and short circuit in the flex-circuits were tested in the flex vendor before delivery. About 5% of hybrids were set aside due to various damages in the assembling stages.

3. Al traces-on-glass pitch adapter

The pitch of the ASIC chips input pads was 48 μm, while that of the silicon microstrip sensors was 80 μm. In order to make the wire bonding straight, a pitch adapter (PA) was designed and placed in front of the chips on the hybrid as shown in Fig. 5. The pitch in the ASICs was too fine to integrate the PA in the L1 layer. The PA was produced in thin aluminum (1 μm thick) on a glass substrate (200 μm thick). The dimensions of the PA and the aluminum trace patterns are shown in Fig. 7.

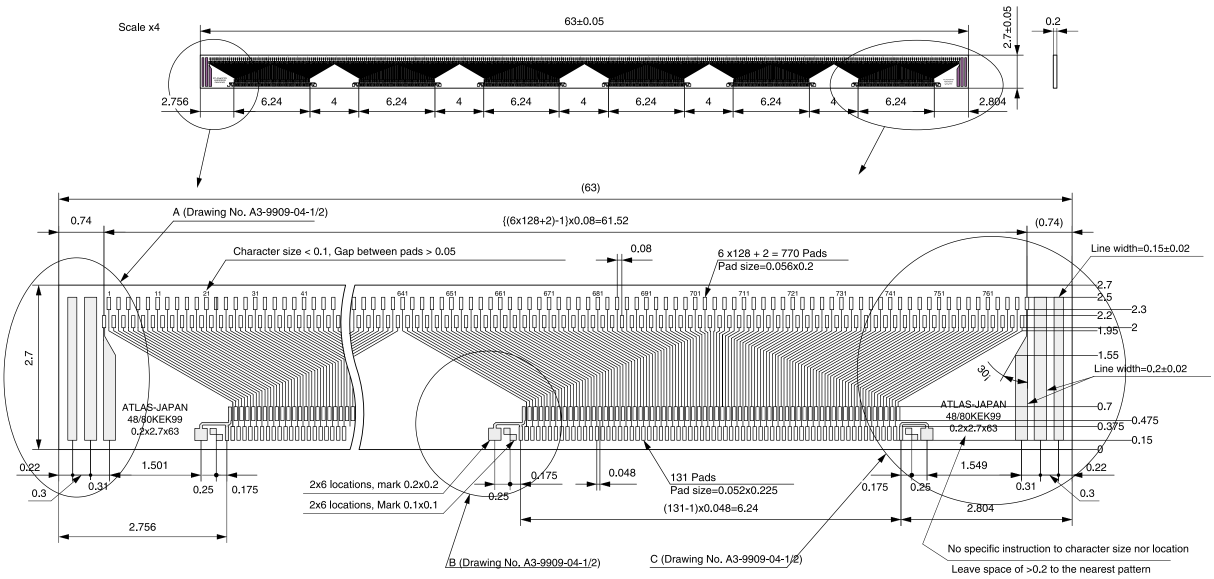

Fig. 7. The dimensions of the pitch adapter (top figure) and the trace patterns (bottom figure). The traces were aluminum of 1 μm thickness and the substrate was a glass of 200 μm thickness.

3.1. Whiskers in PA wire-bonding

Although the PA is a simple construction, pure aluminum on a glass substrate, this has been the most difficult object in the whole hybrid fabrication. The difficulty was associated with wire bonding. In some products of the PAs, a splash of metal, ''whiskers'', was observed around the feet of wire bonding, as shown in Fig. 8. In the figure, the wire was Al with 1% Si of a diameter of 25 μm and wire bonding was made with a supersonic wedge-bonding machine. In a batch of PA, the whiskers were narrow like hairs, and in other batches thick as seen in Fig. 8. In some PAs, the whiskers were seen at the sides of and in other at the ends of the feet. The length of whiskers varied from little to a few tens of microns, and varied depending on the bonding machines.

Although the whiskers were also observed in the wire bonding on the ASIC chips or on the silicon microstrip sensors, their amount and length were generally less. For a comparison, silicon wafers were metallized with aluminum simultaneously with the glass substrates. The wire bonding on the Al-metal on silicon wafers confirmed less generation of whiskers in amount and in length.

Changing Al-metallization on PAs from pure-aluminum to Al + 1% Si did not make much difference. Other metallization, e.g., Al + 0.5% Cu, gave a better result and the metallization of Al + 0.5% Cu elsewhere has given a satisfactory result [8]. However, we have not adopted Al + 0.5% Cu metallization mainly because of availability of the process to us in the industry in Japan and a potential corrosion issue when the Cu content is high [9].

After numerous investigations, it appeared that the generation of whiskers was most plausibly correlated with the hardness of metallized aluminum. The window of hardness for having a reduced amount of whiskers seemed narrow. When it was too soft, it generated whiskers; when it was too hard, it became difficult to make the wire bonds stick. The window seemed also dependent on machines in wire bonding. Unfortunately, we failed to measure the hardness of a thin metal, such as 1 μm thick, reliably.

The difference of the finish of the metallized surfaces: uniform in the silicon wafers and non-uniform in the glass substrates implied that the temperature is a critical factor. In the metallization chamber, a wafer or a substrate had been held with its fringe to the metal blocks. The non-uniformity in a glass could be caused by the low thermal conductivity of glass, which induced higher temperatures toward the center of the glass. The generation of whiskers indicated that the temperature had to be as low as room temperature.

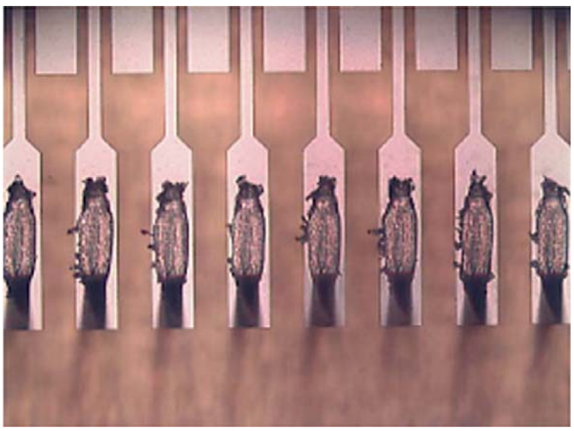

Fig. 8. Whiskers observed around the feet of the wire bonds on a pitch adapter made of Al-on-glass substrate.

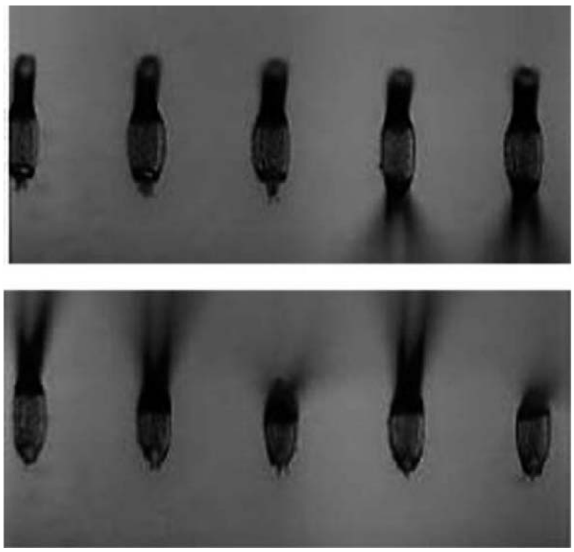

Fig. 9. Improved aluminum metallization where few whiskers were generated.

Having understood the fundamental factors, the metallization vendor modified the process and delivered much improved and consistent products over the production batches. As shown in Fig. 9, few whiskers were generated when the process of metallization was improved.

The yield of PA due to the whiskers had increased from about 75% to about 95% after the improvement. Because of improper finish of traces due to dusts and scratches, the overall yield of the PA was the yield due to the whiskers times about 80%.

4. Other issues in hybrid fabrication

4.1. ASIC chip replacement

The ASIC chips were attached on the chip pads of the L1 layer with an electrically conductive epoxy adhesive. The epoxy adhesive had silver powders for electrical conduction and could be cured in room condition, e.g., reaching 90% of ultimate hardness after 24 h at 23 °C [10]. The electrically conductive epoxy helped not only to have the ground plane as close to the chips as possible but also to transport the heat of the chips to the hybrid with its higher thermal conductivity. The epoxy was softened at a temperature around 80 °C and the chips could be removed by twisting them with a tool.

4.2. Surface contamination and plasma cleaning

The surface of the flex-circuit was cleaned with argon plasma cleaning at the vendor. When the flex-circuits were glued on the carbon–carbon substrates, with heat pressing at 120 °C and 4 kg/cm^2, the surface of the flex-circuits was protected with a film with weak adhesion. Similarly, when the PAs were glued on the hybrids, while no heat-press was applied, the surface of the PAs was protected with the same film.

Occasionally, we observed surface contamination by residues of adhesives coming from the protection film. The residues were only visible with a microscope; however, the quality of wire bonding was degraded: the pull strength was lowered and spread wider. Without contamination, the pull strength in the gold pads of the hybrid and the aluminum pads of the PA was about 10 g with a spread (one standard deviation) of a gram or so.

The residues on the surface of the hybrids were cleaned with argon plasma cleaning, e.g., 500 W power and a few 10 seconds. Although the residues on the PAs surface could be cleaned with the plasma cleaning, the surface of the aluminum became unbondable afterward such that the wire bonds did not stick. The reason for this has been under investigation. Because of the unbondability, the residues on the PAs surface were cleaned with alcohol-dipped cotton tips.

5. Summary

We applied the Cu-polyimide flex-circuit technology that is widely used in commercial products to the ATLAS SCT barrel hybrid. The surface build-up technology with laser vias provided flexibility in the layer construction and allowed high-density layout of multiple traces. The flexibility in layer construction and availability of a large size of flex-circuit enabled the ATLAS SCT barrel hybrids to be constructed in one piece from the connector to the far-end section of electronics including the cable sections. The high-density layout enabled the width of the hybrid to be narrow and with less material. Reinforcement with the carbon–carbon substrates at the electronics sections gave strong mechanical construction, good thermal conductivity, and stability in the ASIC operation. By following the design rules of the vendor, little trouble in breaking the traces was experienced.

The pitch of input pads of the ASICs required pitch adapters between the sensors and the ASICs to be made of aluminum traces on glass substrates. The condition not having whiskers around the wire-bonding feet required an appropriate hardness of metallized aluminum. The range of hardness seemed to be narrow but it was achieved by keeping the temperature of glass as low as room temperature and as uniform over the entire glass area, during the metallization.

Argon plasma cleaning process cleaned the contamination on the gold pads of the hybrids for successful wire bonding. The surface of the pitch adapters was cleaned separately with alcohol-dipped cotton tips as the argon plasma cleaning made the aluminum of the pitch adapter unbondable.

Acknowledgements

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