Laser Micromachining and Characterization of Metal-on-Glass High Density Pitch Adapters

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Abstract— Pitch adapters (PAs) are passive electronic components widely used to adapt different pitches between silicon strip detectors and readout electronics. This paper presents an optimized process to fabricate high-density pitch adapters using laser ablation of metal-on-glass layers. Minimum pitch sizes of 40 μm for the pads and 25 μm for the conductive traces were achieved. The resolution of the method allowed the cutting of traces as narrow as 15 μm . Different prototypes and small production series have been successfully manufactured and tested for electrical parameters, bondability and metrology. Ageing tests were also performed to ensure long-term reliability. The production yield reached 80%. Fully functional particle detectors for high-energy physics have been assembled using these pitch adapters, characterized and tested with lasers and radioactive sources.

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Index Terms—High energy physics instrumentation, laser ablation, laser applications, silicon devices, laser materials processing, laser machining.

I. INTRODUCTION

MICROELECTRONICS PAs are adopted extensively in modern high-energy physics and astrophysics as the interconnection between silicon strip detectors and readout electronics [1]. The channel-density of strip detectors is continuously increasing and induces further developments on the different technologies for pitch adapter fabrication.

To date, high-density PAs are produced by industry through photolithography [2] of a metal layer previously deposited on a ceramic or glass substrate.

Nowadays, several Printed Circuit Boards (PCBs) and MicroElectroMechanical Systems (MEMS) commercially employed are fabricated by laser micromachining [3-5]. Thus, the aim of this work is to design and produce PAs through laser ablation following a novel technique developed by the authors [6].

The standard photolithography fabrication process implies the manufacturing of one or more masks and several steps, including at least resin deposition and chemical etching. As a result, photolithography is an expensive, slow and complex fabrication method.

In comparison, laser ablation allows to manufacture devices in a single step. On average, the time needed for a single unit is 10 minutes. In addition, This new method is fast and versatile allowing the machining of multiple variations of the design and therefore speeding up the R&D phases of detector construction in high-energy physics and astrophysics.

Comprehensive electrical tests proved that laser ablation devices meet the specifications of high quality photolithography units. Furthermore, samples with the most challenging designs and a pitch of 40 μm , equivalent to those currently used at CERN experiments were machined.

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Initially, devices with a minimum pitch of 60 μm [6] were fabricated. Eventually, two 40 μm pitch different PAs were designed and produced in small series since detector prototypes were needed for the on-going LHCb vertex detector (VELO) upgrade program R&D [7].

The versatility and the multiple set-ups of the laser technology [8] allow improving the resolution and the

minimum pitch size as it was remarked before. Currently, trace widths of 15 μm and pitches of 40 μm for the pads and 25 μm for traces have been achieved. Besides the production yield reached 80%. As part of the acceptance quality assurance procedures extensive tests have been performed on the bondability and electrical properties of the manufactured PAs. The electrical properties meticulously studied are the insulation, the resistance and inter-trace capacitance. Moreover, ageing tests were performed to guarantee a reliable functioning of at least 10 years in the harsh LHC environment. Particle detectors were assembled using these PAs. Their performance was carefully studied in terms of the electronic noise added to the readout signal due to the PAs.

II. FABRICATION PROCESS

The combination of a 300 μm thick commercial borosilicate glass (Desag263T from Schott [9]) with a Cr+Al (0.2+1.0 μm thick) metallic layer as substrate was found to be the optimal choice [10]. The metallization technique involves the deposition by evaporation of one layer of Cr and three layers of Al. The Cr layer increases the adherence of the Al to the glass [11]. The deposition was performed using a commercial coating system (BALZERS BAE 250) (Fig. 1). Soon after the last evaporation an annealing process is completed to homogenize the surface of the coating and to improve the quality of the wire soldering at a subsequent time.

Fig. 1. Scheme of PVD process steps.

The custom designed PAs were produced by laser ablation of the metal-on-glass substrates with a quasi-perpendicular nanosecond Nd:YVO₄ laser (Powerline E, RoFin) emitting 9.90 J/cm² with a repetition rate of 100 kHz at a wavelength of 1064 nm. The laser apparatus is fitted with a galvanometer beam steering system and a flat-field lens of 100 mm focal distance. The use of this lens allows increasing the resolution of the laser cutting respect to the lens of 160 mm employed in previous work [6]. The paths followed by the laser during the ablation were carefully optimized and finally separated as far as possible in space to minimize the heating of the substrate. For the same reason no overlap was allowed.

Laser ablation is a very flexible and fast technique for this purpose, allowing testing improvements in ten minutes for a 60x10 mm² standard size PA. An illustrative scheme of the apparatus and the method described here is shown in Fig. 2.

Following the format requirements of the laser CAD-like software, DXF (Drawing Exchange Format) files have been generated using an external program that provides an easy tool

to draw a pitch adapter composed of several hundred channels with the design needed (Fig. 3). The pattern coordinates are accurately computed inside the program and the output DXF file is filled. Introducing changes in the design is very fast and simple, it only implies to execute the program with new parameters. This is very convenient in the prototyping phase of the pitch adapter manufacturing. As a result, up to 6 different standard size design patterns were produced spending little time (≈ 10 minutes each) in the production enabling us to focus on the inspection and testing of the prototypes.

Fig. 2. Photography of the laser apparatus and experimental setup.

Fig. 3. Pitch adapter CAD-like design (top) compared with a micrograph (bottom) obtained with a Nikon MM-400/L (50x) optical microscope.

III. CHARACTERIZATION AND TESTING

The pads and traces pitch and width of the traces for the 40 μm PAs produced were measured by image treatment of micrographs obtained with a Nikon MM-400/L optical microscope (Fig. 4). This microscope is coupled to a Nikon DS-Fi2 high-definition colour camera head controlled by a

DS-U3 unit with NIS-Elements D software that allows the image treatment of the micrographs obtained with a magnification range from 50x to 1000x. The resolution of the camera depends on the lens and on the magnification level employed, being 1.34 $\mu\text{m}/\text{pixel}$ and 0.07 $\mu\text{m}/\text{pixel}$ for the 50x and 1000x magnifications, respectively.

The average pad pitch size ($40\pm 1.5\mu\text{m}$), trace pitch size ($25\pm 1.5\mu\text{m}$) and trace width ($15\pm 1.5\mu\text{m}$) of the PAs fabricated

Fig. 4. Micrograph (50x) of the inner pads and traces (in blue) and the laser-cleaned inter-traces regions (in black) for one produced PA.

is in agreement with the CAD-like designs. This optical study confirms a big improvement in the resolution in PA fabrication with respect to former works [6, 10]. A higher density of traces obtained in the later work is clearly seen to the naked eye (Fig. 5).

Fig 5. PAs with 60 μm (top) and 40 μm pad pitch (bottom).

The optical study was completed and notably enhanced through the microstructural characterization of the PAs by a FESEM Ultra Plus (Field Emission Scanning Electron microscope, Zeiss) operating at 3 kV and equipped with an EDS (Energy Dispersive X-Ray Spectroscopy, EDX) analyzer. Moreover, a transversal cutting of the samples allows observing the homogeneous channel structure of the PA produced, the adhesion between metal layers and the glass substrate. Fig. 6 shows how laser ablation reproduces accurately the CAD-like designs. The edges of the pads are not straight; even some structures were elevated and broken due to the sample preparation. The cutting of these samples was done through a scribing and cleaving method. Furthermore, the effect of the shape of the laser beam is clearly shown observing this micrograph. The channels are not straight due to the laser beam movement and its elliptical shape (the spatial beam profile) [12]. Nevertheless, this fact

does not affect the electrical properties of the devices as we tested in previous works [6, 10] and as we confirm in this study.

Fig. 6. Micrograph (200x) of the inner pads and traces.

The inter-traces regions after the laser cutting are clearly visible when increasing the magnification of the microscope. Despite of the debris originated from the ablation process there are no short-circuits between the traces (Fig. 7).

Fig. 7. Micrograph (1000x) of the pads, traces and the laser-cleaned inter-traces regions.

This micrograph shows melted structures at the border of the pads, which correspond to a debris area detected in our previous work [6]. The SEM study confirms that they are debris due to the laser ablation [12]. However, after the annealing process, the shape of the structures obtained at the border of the pads is favorable to insulate traces between them. In fact, this round-wall structure seems to favor the electrical conductivity of the traces (Fig. 8). Moreover, the optimal metal-erasing of the laser-cleaned inter-traces regions promoted by laser ablation is observed. The surface of the traces presents dust particles without significative modification of its homogeneity.

The EDX analysis of these areas was also carried out. This study confirms again the suitability of the laser ablation to fabricate high-density PAs. The compositional map shows the laser-cleaned inter-traces regions practically free of metal layers. Only blue signals corresponding to Si, i.e. the glass

Fig. 8. Micrograph (5000x) of the borders of the traces and the laser-cleaned inter-traces regions.

substrate, are observed at these areas (Fig. 9). Some isolated metal particles can be present as we can observe in previous figures, but they are not enough to produce short-circuits between traces. It is clearly observed that metal particles of aluminum (grey color) and chromium (green color) are limited to traces. Fig. 9 shows another effect of the laser treatment due to the filling of material. Observing the borders of the traces and analysing quantitative results seems to exist a little higher amount of chromium there. Starting from the electrical point of view, the electrical resistivity of chromium ($12.5 \times 10^{-8} \Omega m$) is higher than the aluminium ($2.65 \times 10^{-8} \Omega m$) [13]. This fact could favours to enhance insulation between traces and consequently, favours conductivity through themselves.

Fig. 9. Micrograph and corresponding EDX compositional map of traces. Blue color corresponds to Si signals (glass substrate), while aluminum and chromium signals are depicted by bright-grey and green colors, respectively.

The adhesion between metal layers and glass substrate was also analyzed by SEM. Fig. 10 shows the good adhesion between materials. However, in Fig. 11 a detached trace at the edge of the PA is illustrated. The cutting of the PA using the scribing and cleaving method caused this detachment, as already seen in Fig. 6-7. Under the metallic trace there is a glassy material torn from the substrate of the PA. The amount of this material is higher at the edge with respect to the inner part of the trace. This is due to the melting of materials in this

region during the laser ablation, enhancing the adhesion between them [12].

Fig. 10. Micrograph (2000x) of a PA cross section.

Fig. 11. Micrograph (5000x) of the edge of a PA showing a detached trace.

Subsequently, two prototype modules were assembled in the first half of 2013, one in Santiago and another in Glasgow with these PAs. Both have micro-strip sensors manufactured by Hamamatsu, and the readout is based on Beetle ASIC [14].

Beetle chip pads layout is quite complex, each one has 128 readout channels, being these pads grouped in 4 columns, with 32 pads each one and showing a constant pitch of 40 µm.

The quality assurance procedure consists of different stages. Firstly, an optical inspection is performed to discard the PAs with major defects. Afterwards, groups of traces in different regions of the PA were tested in the clean room with a SUSS PM5 probe station looking for shortcuts and open circuits. Finally, all the traces are measured for the PAs passing the two previous checks. Our acceptance criterion was less than 1% defective channels per PA, leading to an 80% yield.

Furthermore, ageing tests were performed on two prototypes, with 100 bonded wires each, to ensure both metallization and wire bonding long-term stability [15]. Two different tests were completed to mimic an average lifetime of 10 years at the LHC. A 50% safety factor was applied. The pull strength was measured in half of the wires before the tests and in the other half just after.

1 The first prototype was thermal cycled 15 times from -25
2 to 75 °C to simulate the thermal stress induced by the usual
3 annual detector shutdowns for maintenance. Each cycle lasted
4 12 minutes. The difference between average wires pull
5 strength tested before and after cycling was shown to be 0.42
6 grs. This test was accomplished placing the prototype on a
7 thermal driven aluminium chuck. The chuck is cooled or
8 heated by means of a 128 W water-cooled Peltier module. A
9 dedicated Labview [16] program automates the whole process,
10 controlling the Peltier module power supply and recording the
11 temperature probes readings.

12 The second prototype went through and accelerated ageing
13 test equivalent to 15 years, simulating an electromigration
14 failure mechanism. The standard acceleration factor for
15 chemical processes derived from the Arrhenius model assumes
16 for electromigration an activation energy of 0.6 eV. As a
17 result, 15 years at an ambient temperature of 20 °C are
18 equivalent to 15.5 hours at 200 °C. In this case the difference
19 between average wire pull strengths tested before and after
20 cycling was 4.61 grs. This was expected because there is a
21 well known annealing effect on the aluminium wire itself from
22 the heating at 200 °C [15]. To make the test the prototype was
23 placed in an oven at the before mentioned 200 °C for 15.5
24 hours.

25 In summary, considering the ageing tests results, our
26 devices proved to withstand well beyond the average 10 years
27 life-expectancy of a high energy physics experiment. An
28 average wire pull strength of 4.85 grs (SD: 0.34) was
29 measured after the ageing in the worst case. No changes were
30 observed in the Cr+Al metallic layer.

31 Trace length ranges from 10 to 21 mm, while width varies
32 from 15 to 25 µm. These traces were electrically tested to
33 determine their resistance, insulation and inter-trace
34 capacitance. Minimum and maximum measured resistance
35 values were 9.4 and 41 Ω respectively, whereas inter-trace
36 insulation was always bigger than 1 GΩ, in agreement with
37 high quality PAs produced through photolithography [2].
38 Special attention was paid to the inter-trace capacitance
39 determination, because the electronic noise observed in our
40 readout system is proportional to this parameter. The inter-
41 trace capacitance was measured in two final PAs for the
42 shortest and longest pair of traces at frequencies from 1 KHz
43 to 1 MHz (upper limit of our LCR meter). It was shown to be
44 almost constant in the whole frequency range for a chosen
45 trace length as can be seen in Fig. 12. Minimum and
46 maximum values of 0.64 and 1.29 pF were measured at 1
47 MHz for the shortest and longest traces respectively.
48 Furthermore, considering these traces pairs measured we got
49 and average value of 62.09 ± 0.96 fF/mm.

50 In order to check the uniformity of this parameter all over
51 the PAs area, 10 pairs of short and long traces were measured
52 for both designs at 4 discrete frequencies: 1, 10, 100 and 1000
53 KHz, having in the worst case scenario a deviation of 3.5%.

54 To assess good pad bondability, tests were performed on a
55 final pitch adapter with a Kulicke&Soffa 8060 wedge-bonding
56 machine using a 25µm Al/Si (1%) alloy wire. Bonding
57 parameters and wedge specifications are listed in Table 1.

Fig. 12. Inter-trace capacitance as a function of sampling frequency and trace length.

TABLE I

BONDING PARAMETERS

Parameter	Value	Parameter	Value
Time	30 ms	Feed angle	45°
Current	50 mA	Hole diameter	2 mils
Current Profile	Square	Bond length	2.5 mils
Force	26 gr	Material	Tungsten carbide
Hold force	27 gr	Surface finish	Matte
Wedge	0.2 mps	Manufacturer	Kulicke&Soffa

Wire bond pull tests were performed following standards [17] by pulling the wires at their centre with a Dage 3000 series pull tester obtaining an average force of 8.99 grs (SD: 0.38).

As part of the VELO upgrade program [7], 12 n-on-p micro-strip sensors were purchased from Hamamatsu and were delivered on the second half of 2012. Each micro-strip sensor has 2560 strips, which are read out by a total of 20 Beetle chips.

The sensors were designed following two geometries (r,φ), to provide radial and angular coordinates of the hits. A fully working module was built in Santiago with a 200 µm thick radial sensor wire bonded to a hybrid instrumented with 4 Beetles. A custom made PA was needed to connect the sensor strip's pads (with a 40 µm pitch and grouped in 4 blocks separated by 9.04 mm) to the hybrid's pads (with a 112 µm pitch). The readout of the module was carried out using an ALIBAVA system [18]. A photograph of the detector prototype is shown in Fig. 13. The PA is at the centre inside a dotted line rectangle.

Initially only one Beetle was wire-bonded to the sensor, allowing comparison between bonded and non-bonded strips. The difference in noise can be appreciated in Fig. 14, and it is due to the capacitance of the strips.

Fig. 13. Pitch adapter after assembling and bonding on a detector prototype.

One question that arises when producing PAs is how much noise is introduced with these devices. In order to answer this question, an independent study was carried out to determine the increase of the electronic noise with the length of the PA traces. Following the same technique a new PA was designed and produced, having in total 30 traces with two different lengths and a ratio of $\approx 3:1$ (18.6 and 6.4 mm) (Fig. 15). Then it was wire-bonded to a micro-strip sensor with 3.9 mm strips length. The readout was carried out with the aforementioned ALIBAVA system. In Fig. 16 are shown the noise readings for a single Beetle chip where channels from 175 to 204 were wire-bonded to the PA and sensor. As it can be seen there is no clear difference for traces with different lengths, so we conclude that our PAs have a negligible impact on the total noise. The different noises appreciated in Fig. 14 are mainly due to the sensor strips capacitance.

Using a ^{90}Sr source, the Signal-Noise ratio (S/N) of the detector prototype shown in Fig. 13 was measured giving a value of 30. Such value is encouraging since the current VELO sensors, which are 100 μm thicker, achieved a S/N ratio of 20 during installation with the same front-end chip and amplification parameters [19]. However a direct comparison cannot be made until the sensor is tested in a test-beam environment.

Fig. 14. Wire-bonded strips (red line) vs. non-wired (blue line).

Fig. 15. Noise test PA (center) wired to a silicon strip detector (right) and readout electronics (left). It is clearly visible the different length of traces.

Fig. 16. Noise comparison for PAs traces with different length.

The bias voltage at which the sensor is fully depleted of free carriers (so-called Full Depletion Voltage or FDV) is a key parameter in the sensor characterization. Such voltage can be determined before the wire bonding by measuring the capacitance of the sensor as function of the bias voltage, or after the instrumentation by evaluating the S/N as function of the voltage. With this sensor, the S/N was measured using a ^{90}Sr source and two different lasers (660 and 1060 nm). In all cases the FDV obtained was -100 V, in agreement with the measurements before the instrumentation.

IV. CONCLUSION

Pitch adapters were manufactured by laser ablation of metal-on-glass substrates. The precision and the complexity levels attained are similar to those produced by the standard photolithographic method and currently used in the LHC experiments at CERN.

The lowest pitch achieved was 40 μm for the pads and 25 μm for the traces. The resolution of this method allowed traces 15 μm wide. Two different pitch adapters were produced in small series. The production yield attained 80%. Ageing tests were carried out to validate an usage of at least ten years at the LHC. Two detector prototypes were assembled using these pitch adapters. These modules were tested with a radioactive ^{90}Sr source and lasers. The electronic noise introduced by the pitch adapters was measured to be negligible.

This new technique is shown to produce pitch adapters with specifications meeting the photolithography standards in a faster, cheaper and more flexible manner.

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