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Hybrid Design, Procurement and Testing for the LHCb Silicon Tracker

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Abstract

The Silicon Tracker of the LHCb experiment consists of four silicon detector stations positioned along the beam line of the experiment. The detector modules of each station are constructed from wide pitch silicon microstrip sensors. Located at the module's end, a polyimide hybrid is housing the front-end electronics. The assembly of the more than 600 hybrids has been outsourced to industry. We will report on the design and production status of the hybrids for the LHCb Silicon Tracker and describe the quality assurance tests. Particular emphasis is laid on the vendor qualifying and its impact on our hybrid design that we experienced during the prototyping phase.

I. Introduction

The LHCb experiment [1] at the Large Hadron Collider LHC is a dedicated *B* physics experiment that is set up as a forward spectrometer. The experiment comprises a vertex detector (Velo), a tracking system, two Ring Imaging Cherenkov (RICH) counters, a calorimeter system consisting of pre-shower detector, electromagnetic and hadronic calorimeters and a muon system. Charged particle tracking is provided by the Velo and four detector stations: one station in front of and three behind the dipole magnet. The first tracking station (TT) in front of the spectrometer magnet consists entirely of silicon strip detectors that are arranged in four detection planes perpendicular to the beam pipe. In case of the other three tracking stations only the inner part (IT) is employing silicon strip devices in four detection layers while the outer area is covered with straw tubes. The two silicon trackers having together a total surface area of 10 m^2 of silicon are segmented in 336 (IT) and 280 (TT) readout units with about 300k channels. The production of the silicon detector modules is presently done at CERN/Lausanne (IT) and Zurich (TT).

Each detector module is read out by integrated circuits, the Beetle chips [2] that are located on front-end hybrids at the end of the detector modules. Data are then further shipped with low mass cables to service boxes located outside the detector acceptance. The Beetle chip is a 128-channel ASIC device for 40 MHz sampling and multiplexed deadtimeless readout that is manufactured in a 0.25 μm CMOS process and was irradiation tested up to 40 MRad. The chip features for each channel a low-noise charge-sensitive preamplifier, an active CR-RC pulse shaper with a minimum rise time (~13 ns) well below the LHC requirements and an analogue pipeline with a programmable latency of up to 160 sampling

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times. Upon a trigger the corresponding signals stored in the pipeline are readout within 900 ns.

The hybrid packages for the IT and TT detectors consist of the Beetle chips mounted together with passive electronic components on a flexible printed circuit board (PCB) and of ceramic pitch adapters to match the silicon sensor pitch to the pitch of the Beetle input pads. The complete package is attached to heat spreader substrates that provide a low thermal impedance path to further cooling plates.

The production of the pitch adapters and the full assembly of the hybrid packages including the ultrasonic aluminium wire bonding are done by a single company, RHe Microsystems, Germany [3]. So far, a pre-series of 15% of the total hybrid production quantity has been delivered recently and has been undergone numerous tests.

II. THE HYBRID DESIGN

A. General Layout

The two main hybrid types that are employed by the Silicon Tracker carry either three chips for the IT detector modules or four chips for the TT detector modules. The hybrid for the IT detector module has a ceramic pitch adapter that is attached to the component loaded flex circuit. This assembly is then glued with silver epoxy to an aluminium balcony providing cooling for electronics and a low impedance connection to a common ground. Wire bonds connect then the 384 silicon strips of the detector module via the pitch adapter to the three Beetle chips.

The TT silicon detector modules are 160 cm long silicon ladders that are longitudinally segmented in four or six independent readout units. The hybrid packages are located at both ends of a detector module. Therefore, a stack of up to three hybrids at each end is necessary for the readout. The stacked hybrid design of the TT detector requires the use of three different hybrid subtypes each having four Beetle chips. The hybrids for the TT detector differ in the overall length and in size and material of the heat spreaders.

Figure 1 shows a photograph of the three hybrid variants for the TT detector. The hybrid of the lowest level is the largest one and is laminated to a ceramic substrate. The four Beetle chips of the lowest level are connected through a separate pitch adapter to the silicon sensors. The two types of the upper levels are laminated to gold plated copper plates and have pitch adapters that connect the Beetle chips to polyimide interconnect cables, which are glued to the pitch adapters. The interconnect cables route the analogue signals from distant silicon sensors to the hybrid. Copper spacers with a height of 2.5 mm are used for separating the hybrid layers in the hybrid stack.

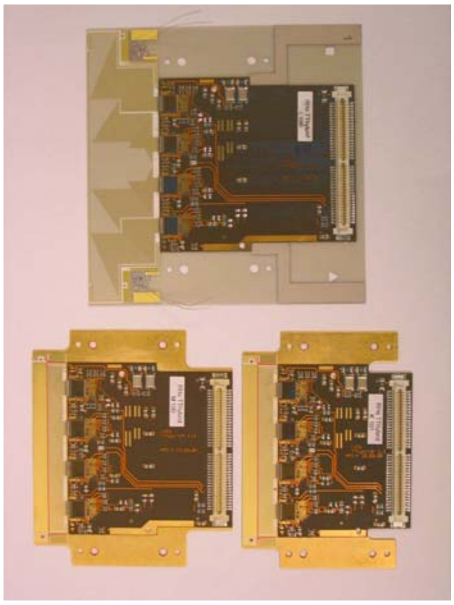

Figure 1: Photograph of the three hybrid subtypes for the TT detector. The hybrid at the top of the picture shows the lowest hybrid level.

B. Pitch adapters and ceramic base plate

The silicon sensors that are used for the LHCb silicon tracker have a pitch of about 200 µm and their strips are wire bonded through ceramic pitch adapters to the Beetle inputs. These 128 input pads per chip are laid out in a four-row staggered structure leading to an effective input pitch of 40.24 µm. Facing the side of the Beetle the pitch adapter features bond pads that are mirror images of this structure. The lines fan out to match then the pitch of the silicon sensors or in case of the upper two TT hybrids the pitch of the interconnect cables.

The size of the IT pitch adapter is 77 x 11 mm^2. The two types of TT pitch adapters have sizes of 94 x 24 mm^2 and 88 x 11 mm^2 respectively. All three types are produced with a single metal layer in thin film technology on 0.25 mm thick Alumina (Al_2O_3). The metal on the ceramic is TiW/Au with 50 nm TiW and 2 µm Au. The aluminium wire bonding on the metal layer was found to be very good reaching bonding strengths of more than 10 g. Accelerated aging tests at elevated temperatures showed no evidence for any significant bonding degradation. Additional pads on the TT pitch adapters that are used for solder connections for the HV supply lines to the silicon sensors are plated with NiAu (2 µm Ni and thin Au) and are surrounded by solder resist.

The typical trace width of the pitch adapter lines is 30 to 40 µm. To comply with the tight input pitch of the Beetle, the trace width and separation on the pitch adapter have to reach 10 µm or less in limited regions close to the Beetle. The ultra-fine trace width and separation on our pitch adapters represent even for thin-film industry a technological challenge.

The base substrate onto which the lowest level of the TT hybrid is mounted is a 95 x 96.4 mm large and 0.5 mm thick Aluminium nitride (AlN) plate. This ceramic is chosen due to its high thermal conductivity and its moderate coefficient of thermal expansion, which is reasonably well matched to that of silicon. The AlN ceramic piece provides a mounting surface and a large thermal contact area to cooling balconies once the silicon modules are installed into the detector station. The AlN plate carries alignment and mounting features that are necessary for an accurate detector module installation. It further has vias for HV connections to route HV lines with a flex cable to the silicon sensor backplanes. The AlN piece requires tight mechanical tolerances of ±10 μm and is processed in thick-film technology.

All types of pitch adaptors and the AlN carrier plate for the IT & TT detectors are produced at RHe Microelectronics, Germany [3].

C. Flexible PCBs

The flex-circuit board of the hybrid is manufactured from polyimide and has a size of roughly 67 x 60 mm^2 for the TT and up to 130 x 77 mm^2 for the IT. The layout features four conductive layers each with a copper thickness of 18 μm on 50 μm thick polyimide. The design uses blind vias technologies to cope with the dense (~115 μm) pitch of the Beetle backside bonding pads and the resulting routing density. There are two dedicated planes for analog and digital power and ground. The routing of the signal and control lines is done on the remaining two planes. Minimal trace width and separation for the flex PCBs are 75 μm each in the vicinity of the chips and typically 150 μm elsewhere.

Additional polyimide layers on the top and bottom layers act as solder stop masks and insulation of the flex-circuit. The total thickness of the flex circuit is then between 270 to 300 μm. The bond and solder pads for aluminium wire bonding and reflow soldering of passive components like capacitors and resistors for HV blocking have a surface finish of Au/Ni.

The output end of the flex-circuit is lay out to fit a 60 (80) pin single (dual) row board-to-board connector of 0.5 mm (1 mm) pitch for the IT (TT) hybrid. A flexible jumper cable which connects to the hybrid routes the signals to further patch panels. Although smaller miniature connectors with pitch of 0.5 mm or less are available this connector type was chosen due to its robustness.

Several prototypes of the flex-circuits for the IT and TT hybrids were successfully manufactured at Optiprint AG, Switzerland [4]. The company is presently producing the remaining flex-circuit PCBs for the series production.

D. Hybrid Assembly

The complete assembly of the IT & TT hybrids is done at a single company, RHe Microsystems. The assembly process starts with the lamination of the flex-circuits to the ceramic or copper base plate using an adhesive tape (3M 467MP) at elevated temperatures. Positioning holes in the base plates and the flex circuits aid to achieve an accurate positioning within 20 μm or better. The surface mounting technology (SMT) of the passive electronics components follows a standard reflow oven process. After that the pitch adapters are glued on the base substrates using again positioning pins. The die attach of the Beetle chips is done manually and aligned with respect to the pitch adapters where alignment marks aid in positioning. RHe Microsystems ensures a full documentation during the chip picking and placing process so that only accepted chip from the wafer tests are used and can be later tracked to a hybrid location.

Finally, the company does the ultrasonic bonding of the hybrids. The control and power lines between chips and flex-circuit are bonded with aluminium wires of 30 μm diameter, while 25 μm diameter aluminium wire is used for the pitch adapter to chip bonds. The aluminium wire bonding of the pitch adapter to chip is a challenging task since wire bonds have to be done at four different loop heights and with special fine pitch bonding tools only. No encapsulation of the wire bonds or glob-top is used.

III. EXPERIENCES FROM PROTOTYPING

A. Vendor Issues

During the prototyping phase of the hybrids we experienced several difficulties with vendors that led to delays in the project. Fortunately, all problems could eventually be solved to our satisfaction. The problems with vendors typically arise, if either the chosen technologies are at the cutting edge or the number of produced units is small compared to typical commercial orders.

Initially, we had planned to qualify two different companies for pitch adapter fabrication and hybrid assembly. Naturally, this caused some problems in coordinating quality control standards and common technical specifications among the companies like minimum pull strength values for pitch adapter-chip bonds. A more severe problem was certainly, that our vendor qualification process suffered significantly from one company who was manufacturing at that time AlN carrier pieces and pitch adapters that were repeatedly delivered with large delays and were of poor quality. In addition, the company designated for the hybrid SMT component loading and bonding lost suddenly interest in continuing the hybrid assembly after a successful round of prototyping. At a relatively late stage of the project we made the decision to move to one single company capable of producing thin/thick film ceramics, SMT and wire bonding. Fortunately, we could identify such a company who was able to produce successfully prototypes for us on a relative short time scale.

Our industry experience in the hybrid prototyping phase told us several lessons: First of all, it is very important to start a vendor qualification process as soon as possible. Additionally, it might not be sufficient to rely on only one vendor as a single source. If possible, a second vendor as a back up should be qualified in an early stage of the project. We had a very positive experience with a single company doing several production and assembly tasks in house, since it made the settlement on common specifications among different companies superfluous. Moreover, a good and open communication to the company has to be established. This includes also regular vendor visits.

Finally, in dealing with industry for small-scale projects that are technologically at the cutting edge, we believe that a suitable company has to show interest and motivation that go beyond pure commercial interests in order to make such projects a success.

B. Design Issues

The initial design of the lower TT hybrid had the pitch adapter structure integrated on the AlN ceramic. Due to the large area of the AlN plate, only one single carrier piece per 4'' raw ceramic substrate could be processed in thin film technology. The challenging fine trace structure of the pitch adapter made the AlN yield unacceptably low, so that a separation of AlN carrier piece now processed in thick-film technology and independent pitch adapter with thin-film metal became necessary.

Concerning the flex-circuit PCBs one of the main problems was due to shorts between GND and VDD that appeared when the PCBs were glued onto the aluminium balconies using electrically conductive silver epoxy. The flex-circuit design incorporates a cover layer of polyimide at the bottom of the hybrid to insulate the VDD power plane from the aluminium balcony. However, openings in the cover layer and vias to the GND plane underneath the chips provide a thermal contact and a GND reference connection. Several IT hybrids failed either due to lacking insulation, misplaced vias or too large opening windows.

IV. TESTING OF HYBRIDS AND ITS COMPONENTS

The testing of the IT & TT hybrids and its components is done in several steps that are carried out at different locations. The flex circuit vendor performs an automatic optical inspection and an electrical test for continuity of the traces. After receiving the flex circuits at the hybrid assembly site, a bonding test on a PCB lot basis is carried out.

The manufactured pitch adapters undergo an electrical needle card test and visual screening for shorted and open traces at the vendor. RHe Microsystems is able to perform laser repair of shorted traces. Initially we allow up to several defects (shorts) per pitch adapter ceramics prior to repair. The final specification for the pitch adapters after repair permits up to one short between two traces or for one interrupted trace after repair. About 70% of the pitch adapters delivered by the company were produced without any trace defect and the remaining pieces had at most two faults, which could all be recovered by laser repairs.

The tight mechanical tolerances on the produced AlN ceramics were verified on samples using an optical coordinate measurement machine at the University of Zurich.

We have provided for an electrical hybrid test station that is set up locally at the company. After SMT and bonding of chips to flex circuits an initial electrical functional test of the hybrids is carried out at the vendor. The functional test checks the basic digital and analogue functionality of all chips on the hybrid. If for some reasons a chip fails the test, a repair and/or replacement of a chip is still possible. After passing the functional test, a thermal cycling test follows, which consists of 10 cycles between –20ºC and +60ºC in a climate chamber. The hybrids are held for 5 minutes at each endpoint temperature. Afterwards, the electrical functional test is repeated. All 43 tested hybrids from the TT pre-series production passed this functional test and thermal cycling.

After receiving the hybrids from the vendor an extensive testing and burn-in program is performed at the Max-Planck-Institute in Heidelberg. The goal of these tests is to characterize, document and grade each received hybrid for later use in the detector modules. The testing program starts with a visual inspection and consists of a detailed readout test at the start, middle and end of a 48h long burn-in period. The detailed test verifies first the basic I2C addressing functionality of the chips. The total currents at default settings are measured through the sense lines and a pipeline scan with 1 MHz trigger rate is performed. Analogue tests include a mapping of the pipeline to determine the relative gain and find possible dead channels and/or dead pipeline cells. Moreover, pedestals and noise versus channel number are determined and pulse shape scans are performed using the Beetle internal test pulse at different operational settings. Figure 2 shows some histograms of the result of a hybrid test. The left upper plot shows raw and base line subtracted noise as a function of the channel number on a relative scale. The relative gain of the pipeline cells is mapped on the right upper plot with observed variations of less than 5%. The pedestal residuals of each pipeline cell for all channels are shown in the middle right plot. Typical pulse shapes of the Beetle chips for different operational settings are presented in the middle left graph and their timing characteristics are indicated in the lower left plot of Fig. 2. Finally, the lower right plot shows average peak amplitude versus channel number.

During the test high voltage of up to 600V is applied on the HV pads of the hybrid and any currents are monitored. A special counter is checking if sparking effects on the HV lines have occurred. Additionally, the functionality of the PT-1000 thermal probes on the hybrid is tested.

Up to 16 hybrids in any combination of IT and TT hybrids can be tested in parallel. All raw data and log files are stored to disk and linked into a hybrid database, which will be interfaced to the IT & TT production database.

So far, 84 out of 92 tested hybrids from the pre-series passed this quality program on the first go. The analysis of the failed hybrids is not yet completed. These failed hybrids are presently undergoing a thorough debugging phase.

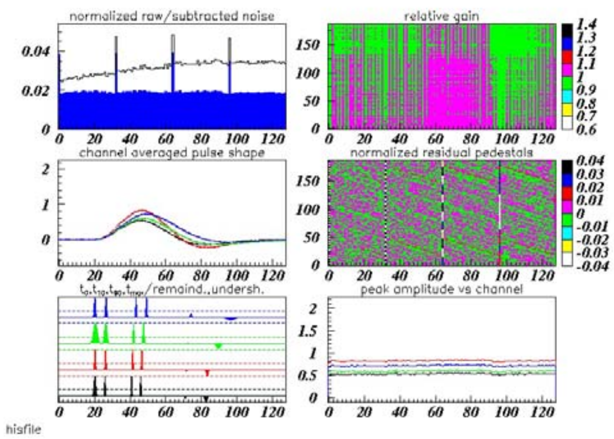

Figure 2: Example of the output of a hybrid test. The histograms show from left to right: raw and base line subtracted noise, relative pipeline cell gain, pulse shapes for different chip settings, timing characteristics and finally the average peak amplitude.

V. CONCLUSIONS

The design of the IT and TT hybrids for the LHCb Silicon Tracker was presented. The pre-series hybrid production at industry of almost 100 hybrids corresponding to 15% of the total series has been completed recently. This pre-series is presently undergoing an extensive testing program. As a preliminary result we found 84 out of 92 hybrids passing our tight quality assurance program. The reasons for the failures of the remaining eight hybrids are currently being investigated in detail.

The hybrid production and assembly of the Silicon Tracker project poses a number of technological challenges that are related to the ultra-fine pitch structure on the ceramics and to the complex wire bonding. Having encountered vendor-related problems during the prototyping phase, we were finally able to identify a company for hybrid assembly that could provide thin-film processing, surface mounting technologies and wire bonding capabilities in house. Fortunately to the LHCb Silicon Tracker project RHe Microsystems was very motivated to meet the technological challenges of our project and to develop solutions with us that were successfully applied in the pre-series production.

VI. REFERENCES

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