Front-End Hybrids for the CMS Silicon Tracker

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Abstract

A Front-End Hybrid for the readout electronics of the CMS silicon tracker has been developed in different technologies with the aim of a fully industrial production of the ca. 15 000 modules needed for the complete experiment. We present the development of the electrical design of the multi-layer board and its implementation in different technologies: thick-film on ceramic, advanced FR4-PCB, a combined Mixed-Flex Rigid multi-layer structure and a Full-Flex design in polyimide on a rigid carrier substrate. We will describe the impact of the technology on the design, test results of the various hybrids fabricated and discuss the possibilities of a cost-effective production in industry.

I. THE CMS FE-HYBRID

The CMS tracker consists of about 15000 silicon detector modules arranged in 10 cylindrical layers and 18 disk-like structures around the LHC interaction point in the central/barrel and end-cap region, respectively. Each detector is read out by four or six analogue integrated circuits, the APV25[1] chip. The FE-hybrids have been designed and developed by a team of two laboratories in Strasbourg[1,2]. An automatic test station for the industrial production has been built by a collaboration of two university laboratories in Louvain-la-Neuve[3] and Aachen[4].

A. Functionality of the FE-Hybrid

The main function of the FE-hybrids is to carry the APV read-out circuits and to provide the necessary environment: low impedance power supply lines, fast and slow control signals like the 40 MHz LHC clock, level_1 trigger and the I2C control bus and the differential analogue output lines. Three more ASICs have been integrated on the FE-hybrid as well. The PLL chip decodes the level_1 trigger from the 40 MHz clock signals and synchronises the phase of the clock. The MUX circuit multiplexes a pair of two 20 MHz APV analogue outputs onto a single differential line and transmits the signals at 40 MHz to the optical analogue link situated outside the detector module. The third ASIC, the DCU equipped with six 8-bit ADC channels, measures via several thermistors on the hybrid itself and on the detector modules the temperature and monitors also the APV25 power supply voltages and the leakage current of the silicon detector. For this purpose the current return of the detector passes through the FE-hybrid. However, no HV is present on the hybrid.

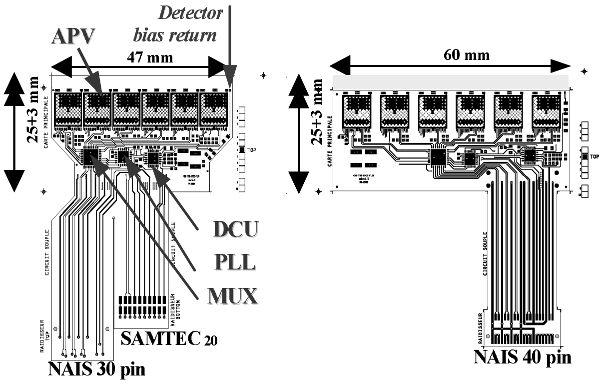

Figure 1: TIB and TOB/TEC Layout in the 2002 version on the left and right hand side, respectively. Clearly one can distinguish the positions of up to 6 APV read-out chips and the three auxiliary ASICs mounted as LPCC together with the SMD components.

The locations of the different ASICs are clearly visible in Fig. 1 showing the upper metal layer of the two different types of FE-hybrids. Only the readout chips are mounted as naked die, the other ASICs are packaged components, LPCC. A polyimide cable has been integrated into the layout of the hybrid. The connectors of this cable plug into an external interconnect card or cable. In this way no insertion forces are transmitted to the detector module. The cable has to be bent by 180° for the assembly of the detector module on the tracker structure and compensates possible mechanical tolerances. For an overview over the CMS-Tracker interconnections and the readout architecture see N.Marinelli's contribution to this conference[2].

The FE-hybrid has been realized as a high-density 4-metal layer board in different technologies.

Further requirements on the FE-hybrid include mechanical properties like sufficient flatness and rigidity for the automatic detector assembly, thermo-mechanical compatibility with the detector-module frames produced from carbon fibre or graphite material, efficient heat transfer to evacuate the up to 3 Watt electrical power of the ASICs and radiation hardness.

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B. *Modularity*

As shown in Fig. 1. two different geometries had to be developed: the very high-density layout for the very inner part of the CMS tracker (TIB and TID) with severe mechanical and geometrical constraints and a slightly larger circuit for the outer (TOB) and end-cap (TEC) regions. For the stereo modules the identical hybrids are used, but the position of the connectors on the cable is on its other side. There are hybrids with four and with six APV25. However, due to the large size of the tracker, for each type of hybrid at least 1000 objects will have to be produced. The precise numbers of each type are listed in table 1 demonstrating that the fabrication of the 15000 hybrids is well adapted for an industrial production.

Table 1: Different types of FE-Hybrids

	TIB/TID		**TOB**		**TEC**	
	R-Φ	**stereo**	**R-Φ**	**stereo**	**R-Φ**	**stereo**
6 APV	1056	1056	1680	-	1152	1152
4 APV	1428	-	2448	1080	4096	-
Total	**2484**	**1056**	**4128**	**1080**	**5248**	**1152**
	3540		**5108**		**6400**	
Total	**15048**					

II. TECHNOLOGY CHOICES

In Table 2. we summaries some parameters important for the technology choice:

Table 2: Material parameters relevant for the hybrid technology

	CTE	Thermal Conductivity	Xo
Material	ppm/°C	(W/mK)	(mm)
Al2O3	7.0	24.0	75.5
FR4/G10	12-16	0.2-0.3	194.0
Carbon Fibre	< 1.0	200-400 ‖ 1 ⊥	250.0
Graphite E779	7.4	65.	188.
Polyimide	45.0	0.2	286.0
Cu	17.0	390.0	14.3
Au	14.0	318.0	3.35

At the beginning of the project the choice of technology was determined by the wish to minimize the amount of radiation length in the tracker. However, very soon more technical criteria and the industrial availability of the technology determined the choice. The first proto-types were realised in a thick-film technology on a ceramic substrate. The metal layer had to be gold instead of silver, because the latter is heavily activated by neutron absorption. The Al_2O_3 substrate is also well adapted to evacuate the heat. Of concern was the CTE-mismatch to the CF-frames, however extensive testing and simulation demonstrated the validity of this technology. For some detector modules (TEC) the frames were modified replacing some part by graphite to match better the CTE of the ceramic.

Recently we worked with carbon fibre and FR4 substrates. Again the thermo-mechanical adaptation to the module frames becomes an important issue.

III. PROTOTYPES IN THICK-FILM TECHNOLOGY

The production of these first series was very complicated due to the very high density and small feature size of the via around one of the control ASICs. At that time the PLL and MUX chip were merged in a single die with very small pitch (115 µm). That meant that small via of 120 µm had to be placed very close to each other with 240 µm pitch. These small features are at the limit of this technology and after about 20 circuits had been produced successfully at the CERN workshop[3], only two industrial companies[4,5] agreed to produce circuits. One of them succeeded after a few months of R&D. Fig. 2 shows a photograph of such a hybrid produced by Dorazil-electronics, Berlin[4].

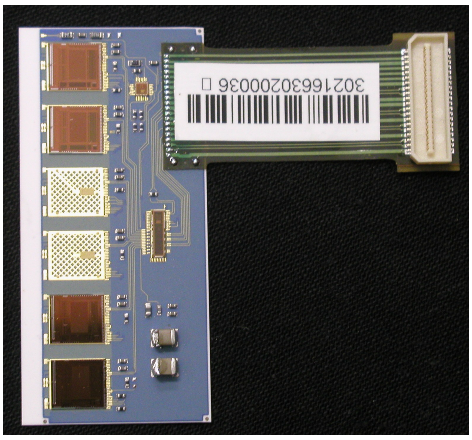

Figure 2: Ceramic hybrid of Dorazil-electronics

At the end of the production of 150 hybrids it was concluded that that layout was not suitable for high yield mass production on a large scale.

APV25 Biasing:

In the very first prototypes of our hybrids a peculiar sensitivity of the APV25 read-out chip to its powering scheme was discovered. The APV25 circuit has an inverter stage between the pre-amplifier and the shaper in order to adapt better the dynamic range to the signal polarity. Both, preamplifier and inverter are connected to the V125 bias line with separate lines inside the chip and two separate bonding pads. It is mandatory to power these two lines from independent sources, otherwise the common resistance in this power-line, which can never be extremely small, will introduce a coupling between the preamplifier and the inverter stage, leading to strong oscillations of the APV25 output base line, in our case in the order 80 kHz with 200 mV amplitude. For further discussion of this phenomenon see reference [6]. On the CMS hybrids the second V125 bias line is derived from V250 via a 50-100Ω resistor network, individually for each APV. This arrangement was tested up to a common resistance of 5Ω in the V125 power line.

Electrically the FE-hybrids worked very well and preserved well the quality of the read-out chips. In Fig. 3 we show the three stable analogue read-out traces from six APVs.

Mechanically the hybrids resisted repeated thermal cycling between –20° and +15° and proton radiation up to 2.7 10^{14}p/cm^2.

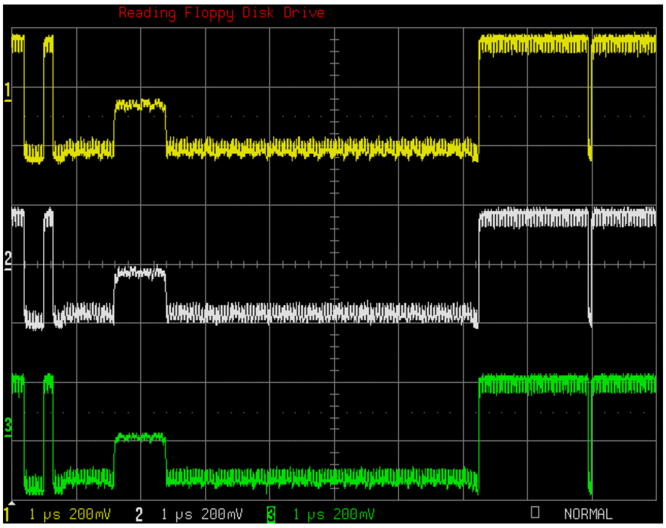

Figure 3: Output trace on an oscilloscope of six APV25 with a group of calibration signals read by a FE-hybrid.

IV. NEW TECHNOLOGY R&D

At the end of 2001 a new version of the control ASICs became available in the form of three packaged LPCC components with a 0.5 mm pitch. Now it was possible to revise the layout with larger via diameters of 100/300 µm and separations of more than 90 µm. These slightly relaxed parameters made it possible to produce the circuit in other advanced technologies.

A. Pure FR4 Circuit

A first batch of circuits was produced by French industry[7] in the beginning of 2002 using nearly standard printed circuit technology on rigid FR4. However, great difficulties were encountered to solder the polyimide cable on to the circuit putting this promising path to a halt. As a consequence the cable became an integrated part of the circuit in the next design in a combined technology.

B. Flex-Rigid(FR4) Technology

In this technology the two upper metal layers 1 and 2 are located on a double sided polyimide flexible foil of 25 or 50 µm thickness, whereas layers 3 and 4 are formed by a double-sided FR4 sheet. In this type of technologies the heat transport from the APV-read-out chips is a crucial issue. We installed generous thermal via to transmit the heat to the bottom of the hybrid to the cooled module frame. A photo of such a hybrid is shown in Fig. 4.

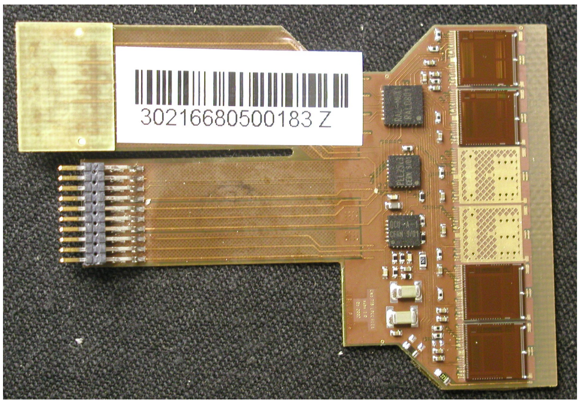

Figure 4: A flex-rigid polyimide-FR4 circuit, fabricated by Cibel[7], France

Electrically these hybrids had a similar good performance as the ceramic ones, however they are less rigid and planar. Typically, we measured deformations of up to one millimetre on different samples. These deformations are related to the asymmetric structure of the multi-layer board with different materials of un-matched CTE-coefficients and also possibly inappropriate handling. This mechanical imperfection represents an additional difficulty for the automatic assembly procedure of FE-hybrids and pitch-adapters. Much effort has been invested to obtain flatter and more rigid substrates. One key parameter is the thickness of the FR4 layer, which is limited by the minimal blind via diameter to about 150-200 µm. A new layer structure is under study in industry[8] to overcome this limitation.

C. Full-Flex Polyimide Circuits on Rigidifiers

In this variant the hybrids are fabricated as a four metal layer polyimide circuit, which is laminated on a rigid substrate. The thickness of the polyimide layers is 25 µm for our application, the Cu metal layer on average about 25 µm depending on the specific fabrication process used by industry. As a substrate to rigidify we use 500 mm thick carbon fibre or FR4 sheets. In the FR4 sheets large metallized through holes are implemented under the ASICs to transfer the heat to the frame of the detector module. First prototypes[9] have been received at the time of submission of this paper.

V. INDUSTRIAL PRODUCTION

The strategy for the supply of the required over 15 000 FE-hybrids is to rely fully on industrial capacities and standards. This is considered necessary in order to achieve a cost-effective production on a relatively limited time scale in the order of one year, which would be impossible otherwise. The large numbers for each variant of hybrid will ensure uniformity of each series. The production includes not only the substrate itself but also the loading with SMD components, connectors, ASICs (LPCC and naked die) and bonding. Prototype runs in the order of a hundred hybrids are used to qualify the companies. These prototypes have to be produced under identical conditions as the series and undergo intensive testing for qualification. These tests include electrical performance, temperature cycling and aging tests and verification of their radiation hardness. The supplier is not allowed to change the production process or components after this initial qualification.

The manufacturer is expected to deliver fully functioning hybrids. To test the functionality of each hybrid at the manufacturers premises before delivery, an industrial portable test station was developed by UCL-Louvain and RWTH-Aachen.

VI. THE FRONT-END HYBRID INDUSTRIAL TESTER (FHIT)

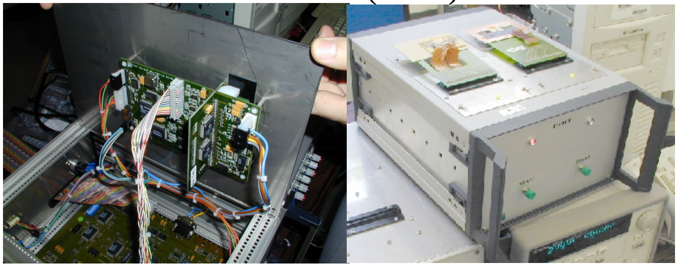

Figure 5: The closed and opened FHIT test station

Fig 5. presents two photos of the tester. It is equipped with two adapter boards and inputs in parallel, so one hybrid can be exchanged while the other one is being tested. The full test of a hybrid takes about 90 seconds. The second photo shows the different components and its mechanical structure: three boards with electronic circuits, active elements, fast controllers and switching matrices for the connectivity test and a connection to the ARC read-out board developed by the RWTH [11] located at the bottom of the box.

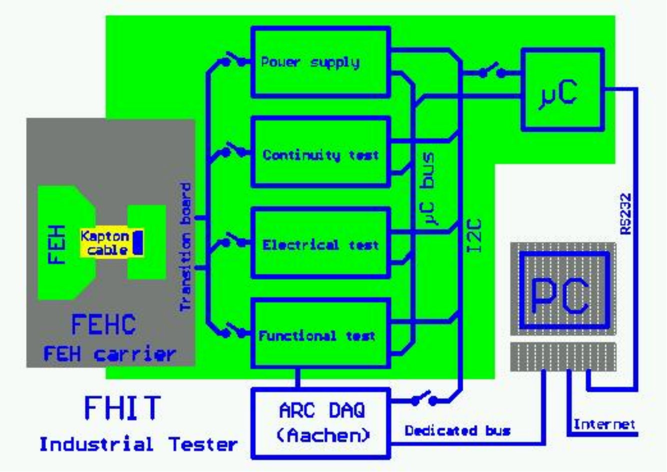

Figure 6: Block diagram of the FHIT test sequence

A schematic block diagram in Fig.6 demonstrates the program flow of the test sequence. First a bar-code scanner is used to register the individual hybrid and to recognise the type of hybrid followed by the continuity test for missing connections or shorts. The electrical test measures the power consumption and does a scan via the I2C protocol to verify the integrity of the control ASICs mounted as LPCC components and the control part of the APVs. The last step is the read-out test of the APVs, a measure of the electronic noise and the recording and discrimination of its response to calibration signals. A further important measurement is the calibration of the DCU ADCs performed at this stage. A protocol of the entire test is written to a log-file, which will accompany the hybrid and will be transferred to the CMS database.

VII. SUMMARY AND CONCLUSIONS

The successful development of the FE-Hybrids for the CMS tracker within two and a half years in different technologies has been presented. Many modifications have been integrated into the design of the layout to help the CMS detector-module integration.

The high density of the layout has a strong impact on the chosen technology. After a series of proto-types in thick film technology on ceramic substrates we have since 2002 turned to polyimide/FR4 circuits, which promise also to be more cost effective. A fully industrial production is foreseen for the over 15 000 hybrids to achieve constant high quality deliveries within approximately one year. As part of the preparation of this production an industrial test station has been developed and is operational.

VIII. REFERENCES

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