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Nuclear Instruments and Methods in Physics Research A 473 (2001) 102–106

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Multi Chip Modules technologies

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Abstract

In the past few years, impressive progresses in electronic devices and their packaging have been achieved. High energy physicists benefit from this, being able to minimise the amount of material in their Vertex-Detectors. Although the environment of Vertex-Detectors is much more controlled and stabilised than in the industry- or end-user-applications, the requirements of material-budget and device complexity are higher.

This paper tries to give a short overview of the existing Multi Chip Module technologies used in Vertex-Detectors and focuses on the prototyping results of an upcoming Multi Chip Module technology, called Multi Chip Module-Deposited (MCM-D), as it is planned to be used for the innermost part of the ATLAS Pixel detector. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: ATLAS; Bump bonding; Flip chip; MCM-D; Multi Chip Module; Thin film; Pixel; Vertex-Detector

1. Introduction

There are two developments that help a designer of a Vertex-Detector to implement an increasing number of features in the system. In the industry, the first is known as "System on a Chip" (SoC), meaning that all features are implemented in one integrated circuit. This is achieved by enhancing the manufacturing process (mixed signal, BiCMOS, embedded RAM, etc.).

The other way is to build the different functionalities in separate integrated circuits, using the appropriate process for each part (Bipolar, CMOS, PROM, RAM, NVRAM, etc.) and to build the specific device by mounting the parts needed in a single but complex package. This package provides the necessary connections between the parts and the outer world.

For Vertex-Detectors, the requirements on the modules are quite different to the normal industry ones. Cooling issues, for example, are well known in industry, but the temperature and power consumption ranges and the need for material reduction leads to completely different solutions. For the planned high energy physics experiments, additional requirements like radiation hardness have to be faced, which are more or less unknown in other fields. Protection against environmental impacts may be reduced to a minimum in Vertex-Detectors, causing one to talk about *hybridisation* instead of *packaging*.

Although encapsulation is not needed in Vertex-Detector environments, the number of hybrids to be built and installed in the planned high energy physics experiments are orders of magnitudes higher than in the existing ones. Here, the production process and handling issues become

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PII: S0168-9002(01)01128-7

crucial for the projects. In addition, the rising frequencies that were used require a defined behaviour of the connecting lines, meaning that the thickness of dielectrics and the width of signal lines have to be very well controlled. This leads to the challenge of improving all the connections within the module, the modules *intra-connections*, to a robust system with a high quality frequency behaviour.

2. Multi Chip Module techniques

There are two widespread MCM techniques well known in the industry, the MCM-Ceramic and the MCM-Laminated. Driven by the rising needs of telecommunication devices, a third one called MCM-Deposited is currently reaching a high volume production state.

2.1. MCM-Ceramic

The MCM-Ceramic (sometimes called MCM-Cofiered) provides the most robust modules, demonstrated by its usage in car-engine environments. Three types of this technology are used: Thick Film, High Temperature Cofiered Ceramic (HTCC) and Low Temperature Cofiered Ceramic (LTCC). As dielectric materials, Al_2O_3, AlN or glass and as conductors, Tg, Cu or Au are used. The main difficulty is the shrinkage of the material during the firing process, resulting in a difficult dimensional control and the impossibility of building ground-planes due to warpage. On the other hand, more than 50-layer substrates are built using this technique.

2.2. MCM-Laminated

Here, the layers are built separately and laminated together. This allows rigid and flexible modules to be built. Enhanced lamination steps allow through holes, to connect non-adjacent conductor layers. Copper is used as conductor and as dielectric materials Kapton[1] and Upilex[2] dominate the market; both are available in a plurality of mutants. Common to both is the absorption of moisture in the range of 1–2 wt%, resulting in a rising dielectric constant ε_r.

This advanced and flexible technique with a large number of manufacturers will be used in many planned high energy physics projects, as it may be found in these proceedings.

2.3. MCM-Deposited

The MCM-Deposited provides the highest connection density by depositing dielectric and conductor materials on a substrate. This is done using thin film processing techniques.

Al or Cu is used as conductor material. Copper may be deposited in two different methods. A subtractive method is to sputter the desired thickness of the layer. It is structured afterwards by masked etching. An additive method uses a thin sputtered seed-layer as plating base. The layer thickness is achieved by electro-plating the structures needed. Only the seed-layer has to be etched afterwards. The final metallisation of the top layer may be tuned to the mounting technique. As an example, for solder bump-bonding it may be Ni:P with an Au cover.

The three mainly available dielectric materials are shown in Table 1. Some of them are photosensitive, thus reducing the number of process steps.

As a summary, Table 2 shows a comparison of the Multi Chip Module techniques.

Table 1
Dielectric materials used for MCM-Deposited

Material	Trade name	Manufacturer	ε_r	Cure temp.
PI	Pyralin	DuPont	3.3	350–400°C
Epoxy	Probelec	Ciba	4.1	120°C
BCB	CYCLOTENE	Dow	2.65	250°C

3. The ATLAS MCM-D Pixel Detector Module concept

The ATLAS Pixel Detector will consist of two different types of hybrid pixel modules [1]. Following the current plans, the larger part will

[1] Kapton is a registered trade mark of Dow Chemical.
[2] Upilex is a registered trade mark of UBE.

consist of an MCM-L based hybrid. Details of this design may be found in Ref. [2]. The innermost barrel layer at a radius of 5 cm will be removable, so handling issues become more important. Taking this into account, a module concept based on the MCM-D technology was prototyped.

The main idea of the ATLAS MCM-D Pixel Detector Module concept is to use the sensor (see Ref. [11]) as substrate for the thin film structures. These structures provide all module intra-connections. As illustrated in Fig. 1, this allows the integration of the signal-lines and the power-supply connections within the module, using bump-bonding/flip-chip as the only assembly technique. The signal-lines are placed above a ground-plane in a micro-strip configuration, guaranteeing a defined impedance. All the module intra-connections are placed on an additional, insensitive area of the sensor, which is covered after flip-chipping by the data-buffering and collecting part of the electronic circuits (see Refs. [3,4,10]). Major requirements for the thin film technique are:

- highest process temperature below 300°C,
- 50 Ω micro-strip signal lines,
- low power-supply connection resistance,
- high inter-connection density.

The first item is caused by the sensitivity of the high resistive, oxygen-enriched silicon substrate. (Above 300°C the generation of thermal donors starts.) The second and third items are needed to ensure the proper functionality of the module. The last item is caused by the need for a connection between each sensor cell through the thin films towards the bump-bond connecting the corresponding electronic cell. These connections, called "feed throughs" in the following, have to be built with a 50 μm pitch in the ATLAS pixel geometry.

Feed throughs give an additional capacitive and resistive load to the electronics front-end. But they give the freedom to segmentise the sensor equally, determined only by the area and the number of channels provided by the electronics. In addition, the feed throughs may be used to connect the readout cells to a sensor segmented in a "bricked" way, improving the mean resolution in the long direction of the pixels.

To achieve the items given above, a process using Benzocyclobutene (BCB, see Chapter 2.3) and electro-plated copper was chosen. In collaboration with the *Fraunhofer Institut für Zuverlässigkeit und Mikrointegration* (IZM, Berlin, Germany) a successful prototype program has

Table 2
Exemplary numbers of the different Multi Chips Module techniques

	MCM-C	MCM-L	MCM-D
Max. no. of layers	> 50	20	5
Defined waveguides	Difficult	Possible	Easy
Min. line-width/space (μm)	75/200	75/75	10/20
Min. via-diam./pitch (μm)	90/200	50/100	20/50
Max. proc. temp. (°C)	850–1300	350	250
ε_r	7–10	3–4	2.65
Moisture absorption (wt%)	—	1–2	0.2

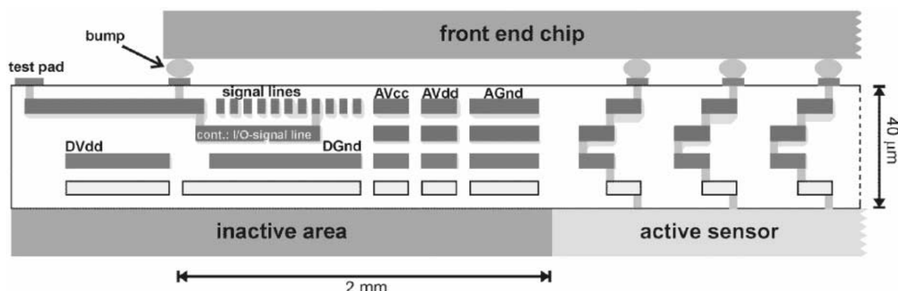

Fig. 1. Schematic cross-section of the four layer bus and signal system. On the right-hand side, the feed through connections from the detector to the read out chip are illustrated.

been carried out, showing that high performing modules can be built following this concept.

3.1. Prototyping results

To determine the influence of the thin film structures on the performance of the module, a comparison has been done with the results of the measurements of "conventional" hybrids. Here, only the results of the testbeam measurements of the charge collection and the spacial resolution are shown for the MCM-D hybrids. The results of the conventional hybrids can be found in Ref. [5] and detailed information about other measurements done with MCM-D hybrids in Refs. [6–9].

3.1.1. Charge collection

The increased coupling capacity between adjacent pixels may result in a reduced charge seen by each electronic cell individually. The charge seen may be reconstructed using the calibrated pulse height information given by the pixel unit cell [4].

Selecting the appropriate single and double hit events of a testbeam measurement, the Landau distribution can be reconstructed as shown in Fig. 2. The maxima of these distributions are at the expected value and not changed compared to "conventional" hybrids. The maxima of the single and the added double hit information is at the same value, meaning that there is no additional charge loss for double hits. The ratio between the number of single and double hits is also not changed.

3.1.2. Spacial resolution

The position of a hit pixel may be subtracted from the track position given by the testbeam set-up. This residual gives the spacial resolution of the pixel system. In Fig. 3, the resolutions in the short pixel dimension of 50 μm are shown. The single hit resolution, shown on the left-hand side, results in a plateau of 37.6 μm, representing the middle of the pixel. Here, single hits are most probable. The tails with a width of 5.2 μm are caused by the increasing charge sharing between the neighbouring pixels. Therefore, the number of single hits in this region decreases. For double hits, on the right-hand side of Fig. 3, the coordinates of the hit pixels may be weighted with the charge information, resulting in a resolution of 5.1 μm. Both the single and double hit resolutions agree with the ones measured with conventional hybrids [2,5].

4. Conclusion

The technologies developed in connection with electronic packaging (as MCM-D) may be adapted to the needs of Vertex-Detectors. But their specific requirements are not always covered by industry, i.e. there is still no flexible MCM-L using aluminium as commercially available conductor. The upcoming developments driven by the mobile telecommunication have the potential to integrate passive components in the modules intra-connection structures and new dielectric materials, and large area processing techniques will result in new ways of building Vertex-Detectors.

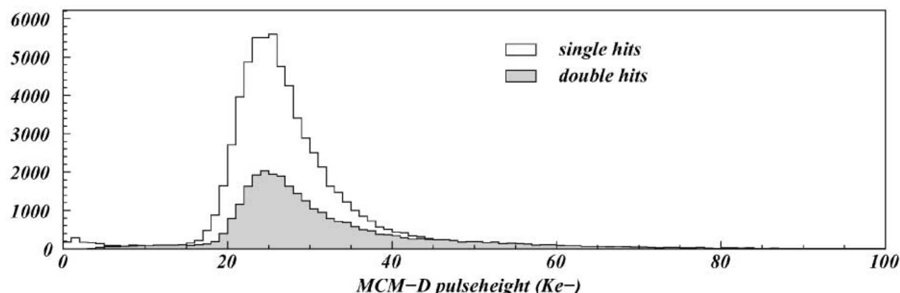

Fig. 2. Reconstructed energy deposition seen by an MCM-D Single Chip assembly.

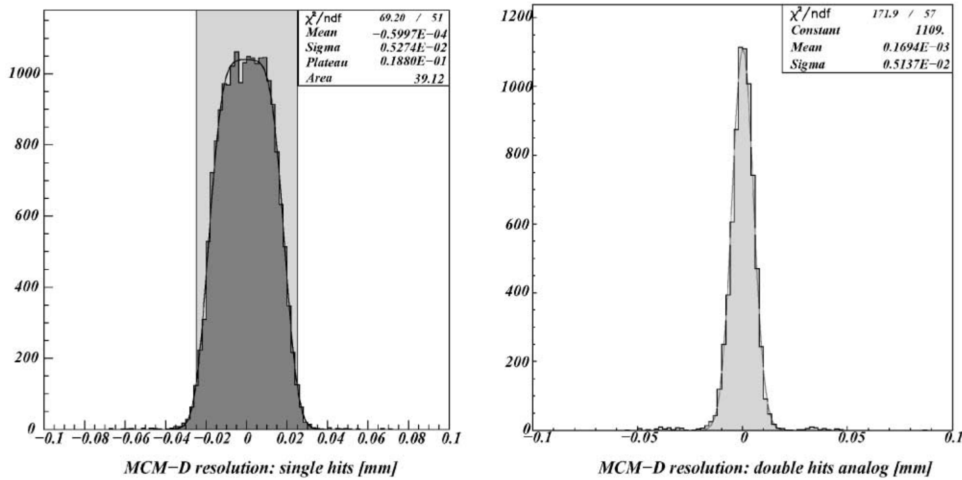

Fig. 3. Residuals expected—measured position of single hits and weighted double hits, with the latter resulting in a resolution of $\sigma = 5.1$ μm.

Acknowledgements

The prototyping program of MCM-D pixel detector modules has been done in the context of the ATLAS Pixel Project (CERN), in close collaboration with the *Fraunhofer Institut für Zuverlässigkeit und Mikrointegration* (IZM, Berlin, Germany).

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