State of the art technologies for front-end hybrids

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Abstract

The front-end hybrids for solid state and gas detectors will be crucial components of the next generation particle detectors. Requirements such as high-density and high-speed interconnects, low mass, radiation resistance, high-current and high-power dissipation capabilities are examples of the challenges to be solved concurrently.

The technologies for front-end hybrids developed at CERN are presented and future possibilities such as embedding active and passive circuits are described. Comments are made concerning the ability to use these technologies for large scale production by industry.

I. EXISTING TECHNOLOGIES

To make hybrid interconnection circuits there are many different technologies available on the market (Figure 1). They can be split in two families: organic and mineral. The most used is the Printed Circuit Board (PCB) technology. For cost reasons other technologies are often only chosen when a higher density is needed.

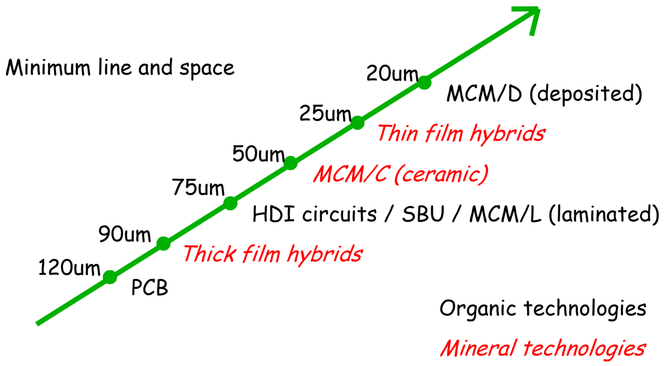

Figure 1: Hybrid circuit technologies

A. PCB

Printed Circuit Board technology is the one that has seen the largest improvements in the past ten years. The production process itself has not significantly changed but many new materials appear and automation equipment is now available to reduce the production time. The biggest interest in this technology is the low production cost and low to high volume capability.

PCB technology is limited by the mechanical drilling as the minimum hole size that can be obtained is around 0.15 mm. Minimum line width and spacing are around 100 µm depending on the supplier.

B. HDI

High Density Interconnect (HDI) technology is an improvement of PCBs were the mechanical drilling in the high density parts of a board has been replaced with laser drilling or plasma ablation. All the other processes stay similar to PCBs. It is clear that these circuits are interesting in many aspects for high-energy physics as it provides reliable high density circuits for a low cost. A further advantage is that HDI technology is available from many companies. The size of the via holes can be reduced down to 50 µm allowing a pad size of 150 to 200 µm. Small vias of this size are also known as micro-vias. Usually the boards are smaller than PCBs which permits to reduce the track width down to 40 to 70 µm. The thicknesses of the metal layers are also reduced down to 15 µm instead of the minimal 35 µm used in PCB technology.

C. Thick film and MCM/C

Thick film ceramic hybrids have been used in the past in physics because of the possibility to build circuits with a higher connection density than PCBs. With etched metals and photo-imageable dielectrics it still is possible to have a higher density than HDI circuits. The other advantages come from the fact that it is a full mineral technology allowing high operating temperatures with low degassing and the best long term stability of all technologies. However, the price, the difficulty to build in large volumes and the more complicated assembly process make that this technology is mainly used in vacuum and high temperature (e.g. power) applications.

D. Thin film and MCM/D

The use of vacuum metal deposition and liquid polyimide gives the possibility to make tracks down to 20 µm and micro-vias down to 25 µm in size. These technologies are used in very high density compact modules and are compatible with direct silicium chip bonding. The production costs are higher than the other technologies because of the use of glass masks and the need for special equipment for alignment. The dielectrics need a high temperature of around 300 °C to be properly cured.

II. PITCH ADAPTORS

In many physics applications silicon chips with a bonding pitch of 45 µm are used. This pitch needs tracks and spacing of 20 µm on the supporting circuit. The only technologies that can reach this density are thin film and MCM/D.

Thin film allows making even smaller lines but always with only a single layer on a glass or ceramic substrate. In this case the high density connection circuit should be added by gluing the pitch adaptor to an HDI or PCB substrate and then they should be wire bonded together. This assembly is delicate due to the precise positioning needed.

With MCM/D the pitch adaptor can be directly routed in the circuit. This solution is most of the time not cost effective because the full circuit area will be made with a very high density process.

A third solution consists in keeping a conventional thick film or HDI technology circuit and split the dense area in many layers. This is easily obtained with thick film were one can stack up to three layers at a pitch of 80 µm and make openings to reach all the contacts. With HDI circuits it is possible to do this with laser, plasma or chemical ablation. The principle is still the same: split the high density part in many layers to be compatible with the technology and open the dielectrics to make the contacts reachable by wire bonding. Figure 2 shows different examples of pitch adapters.

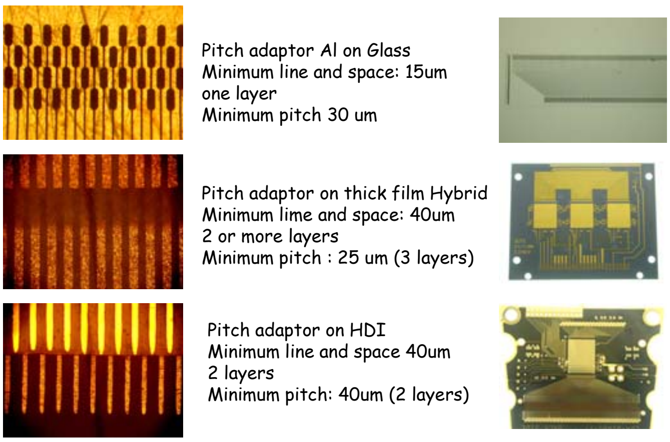

Figure 2: Pitch adapters made in different technologies

Other advantages to build the pitch adaptor in HDI technology are: lower cost, possibility to have thinner materials, better dielectrics and the possibility to cut the circuit in any shape, including round ones.

III. Trends of Future Circuit Materials

Many new materials are now available or in development to build PCBs and HDI circuits. For each new project five topics need to be addressed in order to make an optimal choice: manufacturability, reliability, environmental considerations and miniaturisation (Table 1).

Table 1: Circuit material selection criteria

Manufacturability	Reliability	Environmental	Functionality	Miniaturisation
Process compatibility Registration Drilling compatibility	Low CTE Fillers High TG CAF-resistant	Halogen free Lead Free	Low Dk Low Df Embedded components	Embedded component Metal core

A. *Manufacturability*

Woven glass epoxy composites such as FR4 are still the easiest materials to process. But with the introduction of laser drilling new concerns have appeared: shape of the micro-vias, difficulty to process anisotropic materials, cleaning of the micro-vias and the metal adhesion to the dielectrics.

Many developments have been carried out to find glass or Kevlar reinforced materials with the same laser drilling behaviour as can be obtained with homogeneous materials like pure epoxy or polyimide. As a result it is nowadays possible to drill these materials by laser as for example a homogeneous glass cloth has been developed.

The dimensional stability throughout the production processes is also an issue when density is increased. In conventional technologies a mismatch of 100 to 200 µm is still acceptable over a board of 400 mm x 400 mm in size. In HDI boards the alignment mismatch should be kept below 50 µm to fit with the photolithographic possibilities. This dimensional stability limits the use of existing materials. For example standard polyimide, which is one of the best materials for HDI processes concerning patterning and laser drilling, was one of the worst concerning large boards registration. New polyimides are now available with a better mechanical stability but on large boards it is still difficult to realise the full density potential of these materials.

B. *Reliability*

For the best reliability the materials should have a thermal expansion coefficient (CTE) that is in the X and Y axis as close as possible to the components attached to the board (4 ppm/°C for chip on board and around 15 ppm/°C for encapsulated components), and should have a well controlled CTE in the Z-axis. In most of the composite materials there is a matrix that constraints to a low CTE in the X and Y axis but it leaves the expansion in the Z-direction free. New materials have been developed with high Tg resins, with in some cases special fillers to avoid any cracks in the metalised holes. For long term stability the conductive anodic filament (CAF) resistance should also be taken in account in the material choice. CAF is a phenomenon of copper migration through the glass fibres in the circuit board [1].

C. *Environmental*

The regulations concerning the use of materials containing heavy metals and containing halogens have changed in 2006. Firstly the European Community RoHS regulation imposes to PCB manufacturers to remove all heavy metals like lead in circuits. In PCB production lead was fortunately only used to create the finishing layer and this problem was easily solved by using Ni/Au or Immersion Tin finishes instead of Tin/Lead. The biggest concern comes from assembly. The new lead-free alloys used to solder the components have a fusion temperature that is 50 degrees higher than classic Tin/Lead solders. The use of PCB materials with a higher Tg and controlled CTE are now mandatory to avoid board destruction during assembly [2].

Concerning halogen-free materials there is no formal obligation in the European Community to use them. However, to prevent toxic fumes to be generated during a fire in for example one of the tunnels, CERN's safety regulations impose the use of halogen free materials in electronics boards. Unfortunately not all PCB vendors can provide this type of material.

D. Functionality

The most important electric parameters in the choice of isolating dielectrics are the dielectric constant and the dissipation factor [3]. These two parameters define the impedances of a board and the quality of signal transmission and therefore the maximum reachable speeds.

Many producers of base materials are trying to build improved materials that can be processed with conventional production lines. We start to see for example glass epoxy materials with one order of magnitude reduction in the dissipation factor. For low dielectric constants only special materials such as PTFE and Polyimide can be used.

The functionality of boards can also be increased by the use of buried components such as embedded resistors and capacitors.

E. Miniaturisation

Miniaturisation can be increased by the use of embedded components. The area gain is clear with resistors while with capacitors the decoupling between power layers can save board space and routing area. However, increasing the miniaturisation increases the problem of thermal cooling. In many applications the power dissipated by the components cannot be removed by convection alone. Adding a thermally conductive core can often solve this problem.

IV. COOLING

Metals, carbon composites or graphite and ceramics are the three material families that can be used for thermal management in hybrids (Table 2). The perfect material should have a thermal expansion coefficient close to that of silicon (4 ppm/°C), a high isotropic thermal conduction, a high radiation length and should be easy to process and all this at a reasonable cost.

A. Metals

Metals are often used because of their price and the ease of processing. Some of them have very interesting CTE and thermal conductivity characteristics. CIC (copper/invar/ copper) is a composite that can be introduced directly in the hybrid circuit to reduce the CTE and functions as a thermal drain at the same time. It can also be used as a conductive layer. CIC is not used as a substrate as it is too flexible. Aluminium is more critical if one wants to embed it in the circuit: the CTE is too large to create a reliable structure. It should be used as a substrate onto which a hybrid can be glued with special elastic glues. Al/Si alloys have been developed to create a material that is stiff enough to be a substrate with a good thermal conduction and with a controlled CTE at the same time.

B. Carbon based materials

There are no materials with better properties than carbon for thermal management. Carbon is light and carbon fibre can be used as a stiff substrate while the CTE is low which is interesting for chip on board applications. Pyrolytic graphite can have a thermal conductivity of up to 1600 W/m°C which is about eight times the thermal conductivity of aluminium. The disadvantages of these materials are the price, the complexity of the processes to obtain a good adhesion and their anisotropic properties. The temperature range for structures containing carbon is often limited compared to metals or ceramics.

Table 2: Materials used for thermal management

	CTE [ppm/°C]	Thermal conductivity [W/m°C]	Process	*Price*
CIC	5	170	easiest	low
Aluminum	22	220	easy	low
Al/ Si	6-15	120	easy	medium
Carbon fibre	2	Up to 1000/ z 10	difficult	medium
Carbon carbon	2	600/z 300	difficult	high
PG	0	600/z 8	difficult	high
TPG	0	1600/z 8	Very difficult	Very high
Alumina	7	22	easy	low
Berylia	8	300	easy	high
AlN	4	100-230	difficult	medium

C. Ceramics

Ceramics have been widely used in thick film and thin film technologies. They can also be used as substrates for HDI hybrids. Their CTE can be closely matched with silicon which makes them the best type of substrate for high reliability applications. Alumina remains the most frequently used material but its thermal conductivity is the limiting factor. Berylia is not only used for its good thermal conductivity but also because the material has a very high radiation length which means it does not easily stop particles when used inside a particle detector. AlN (aluminium nitride) is the best material for high temperature and high reliability modules due to its perfect CTE match with silicon.

V. LOW MASS

High energy physics has a particular demand for low mass circuits. When used inside a particle detector, a circuit made of copper or heavy heat sinks can stop particles or create multiple scatterings which degrades the precision of the detector. Therefore at CERN a project was undertaken to develop a process to build low-mass circuits that are usable inside particle detectors [4].

Table 3 shows a few materials used in electronics with their principal characteristics concerning radiation transparency. Beryllium is the lightest metal but due to its toxicity it is impossible to use it. Aluminium is still close to 6.5 times more transparent than copper and offers the best compromise between transparency and conductivity. With dielectrics the difference is not so large depending on the type of material. The choice is driven more by the radiation resistance and in this field Polyimide is still one of the best materials.

Table 3: Some physical parameters of base materials

Material	Radiation length [cm]	Density [g/cc]	*Resistivity [µOhm*cm]*
Aluminium	8.9	2.7	*2.7*
Copper	1.4	9.0	*1.7*
Beryllium	35.3	1.9	*3.3*
Gold	0.3	19.3	*2.4*
Glass epoxy	19.4		
Polyimide	29.0		

The newly developed process converted the conventional HDI micro-via technology into a low mass technology with design rules and structures similar to copper HDIs. The main challenge was to replace the conventional copper layers by aluminium. Copper can be deposited chemically on dielectrics or electrochemically on metals. Unfortunately aluminium can only be deposited by vacuum deposition. After a long period of study and many trials we have been able to deposit in a reliable way a 15 µm aluminium layer on polyimide and also plate micro-vias at the same time.

The first application of such a low-mass circuit is the ALICE pixel bus. More than 120 buses have been produced. This 160 mm by 14 mm sized bus has five aluminium metal layers with lines and spacing down to 70 µm. The total thickness is less than 250 µm with two aluminium layers of each 50 µm thick for carrying the power and three 12 µm thick layers carrying the signals.

VI. BURIED COMPONENTS

Buried passive components are quite common in some technologies such as thick film and thin film. In thick film technology the resistors are obtained by screen printing ruthenium oxide pastes. These resistors are in fact made in the same way as SMD discrete resistors. For capacitors high dielectric constants materials with an ε_r of up to 10000 are used. With thin film technologies only resistors can be made easily. In this case a thin layer of Ni/Cr is vacuum deposited and patterned chemically. The thermal stability of these resistors is in the range of a few ppm/°C but the absolute value is limited compared to thick film. In thick film technology, resistors from milli-Ohms to Giga-Ohms can be obtained while in thin film technology the maximum value is around a few hundred Kilo-Ohm.

Producers of PCBs have tried to do the same with organic technologies (PCB, HDI). Since roughly ten years materials are now available to create buried resistors and capacitors, while developments are still in progress to embed active silicon. In all the technologies also inductors have been embedded but the use is more marginal. A successful application of buried components however is the integration of antennas in printed circuits.

A. Embedded resistors in PCBs

The principle of embedding resistors in printed circuit boards is close to that used in thin film technology. The resistive layer is deposited or chemically grown on a copper foil. Values up to 250 ohms per square can be obtained. This foil is then with the resistive part inside glued to one layer of a PCB (Figure 3, step a). Three steps of photolithographic processes are then following in order to create the resistor. Step b defines the tracks and the outside shape of the resistor, step c removes the non used resistive area and step d opens the real resistive area. The accuracy of these resistors is about ±10% after etching. The resistor can then be trimmed with a laser to reach ±1%. This trimming plus the special etching processes steps are the limiting factor for low and medium volume production.

The main advantages of these embedded resistors are the possibility to increase the board density, the reduction cost of the PCB assembly, an improvement in impedance matching, the reduction of series inductance, and a lowering of crosstalk and noise levels.

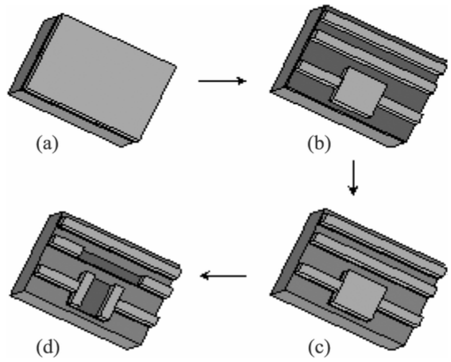

Figure 3: Process steps for embedding resistors

B. Embedded capacitors in PCBs

Embedding capacitors simplifies the assembly, gives the possibility to increase the board density and gives better high frequency properties to the board.

To embed capacitors in PCBs, the principle is the same for all technologies: create two electrodes facing each other in two successive layers. The value is defined by the area of these electrodes, the thickness of the dielectric and the dielectric constant. The dielectric thickness has been reduced to 10 µm by some producers which increases the capacity with a factor of five compared to standard dielectrics (e.g. ZBC2000 material from Sanmina corp). The other way to raise the value is to increase the dielectric constant. This is achieved by loading the dielectric with ceramic particles. For example the company OAK-MITSUI has developed a material with an ε_r of 30 which makes capacities of 1.7nF/cm^2 possible.

It is still difficult to create discrete capacitors but for power decoupling this technology is able to create capacitors in the µF range.

C. *Embedded active silicon in PCBs*

One can also embed silicium ICs in a PCB. The principle is to glue a thinned chip to a standard PCB and to glue on top of it a layer of resin coated copper (RCC) thicker than the chip using standard processes [5].

Figure 4 shows a 50 µm chip buried in a 100 µm RCC layer (build-up 2). The connections to the chip are created with laser micro-vias followed by a classical chemical copper metallization and electroplating reinforcement. The difficulty at this stage is to stop the laser ablation on the chip metallization.

Some tests have been performed on chips with reinforced copper metallization to avoid any destruction of the chip by the laser. The second problem comes from the thermal expansion mismatch between the chip and the RCC (60 ppm/°C for RCC and 4 for silicon). This problem can be avoided by using glues with fillers such as aramid epoxy.

The main advantage of this technology is that all connections to the chip are made directly inside the board, therefore eliminating the need for wire bonding. Chips even may be stacked and thermal management is easier as heat can be removed from both sides of the chip.

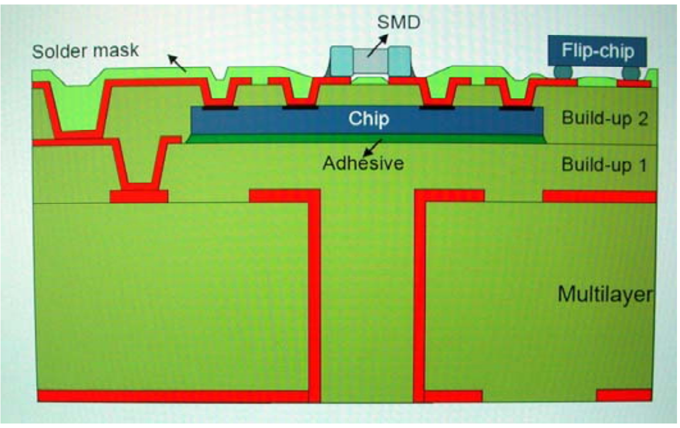

Figure 4: Embedded Si chip not needing wire-bonding

VII. Conclusions

The most appropriate technologies for front end electronics are HDI and SBU. These technologies offer a high enough density for a good price as many companies are now able to build these components in mass volume. In some applications the required density is higher than usual but even in these cases it is possible to increase the density locally so that the high precision alignments are only needed in a specific area.

Many materials are available for thermal management. The choice should be driven not only by the thermal characteristics of these materials but also by their processability. Simulation tools exist to test several options.

With the CERN developed process, low mass circuits with aluminium tracks and thin polyimide dielectrics are now available for low to medium volume production. The design rules and possible structures are close to conventional copper HDIs.

In order to increase the density or to improve the functionality it is possible to embed resistors, capacitors and more recently some companies have tried to embed even silicon in the PCBs.

VIII. References

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