Meeting Heat And CTE Challenges Of PCBs And ICs

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The electronics industry is facing issues with hot spots, solder joint stresses and Coefficient of Thermal Expansion (CTE) mismatch between PCB and IC substrate. Flip chip type packages for example have very low CTE compared to traditional PCB material. Thus it is necessary to have low CTE printed circuit boards in order to keep solder joint intact with such low CTE packages. There are currently several materials available in the market to address thermal and CTE challenges but each material has its own advantages and limitations. Ideal solution for the challenges would be a material that has the ability to do thermal management and CTE control, as well as increasing rigidity with no additional weight. Carbon fibre has very unique thermal and mechanical (CTE and stiffness) properties but it is not a dielectric like glass fibre. If we manage to use carbon fibre along with the glass fibre, we can address electrical, thermal and mechanical aspect of the functionality required by the industry.

The evolution of electronics is now reaching a threshold of design capability. The printed circuit board (PCB), the ground base of all electronics, is reaching limitations due to material functionality. High Density Interconnect (HDI) PCBs are facing high signal frequency, signal speed, thermal, and Coefficient of Thermal Expansion (CTE) issues. While traditional dielectric materials have very good electrical properties such as very low dielectric constant, low loss, high frequency and high speed characteristics, other materials can better address thermal and CTE issues. Some of these materials have the capability to solve one issue while sacrificing performance in other areas. Heavy copper, for example, has the ability to manage the thermal issues on a PCB, but has limitations in terms of CTE control, high density (weight) as well as manufacturability. Non-woven aramid materials have the ability to control CTE, but have limitations in thermal management, twice the z-axis expansion and a tendency to absorb moisture.

Thermal transfer rates of raw materials

There are several types of materials used for thermal management in printed circuit boards or semiconductor substrates. Thick copper, other metals, metal alloys and carbon composite materials each possesses its own unique thermal conductivity. Some of these materials can also contribute Coefficient of

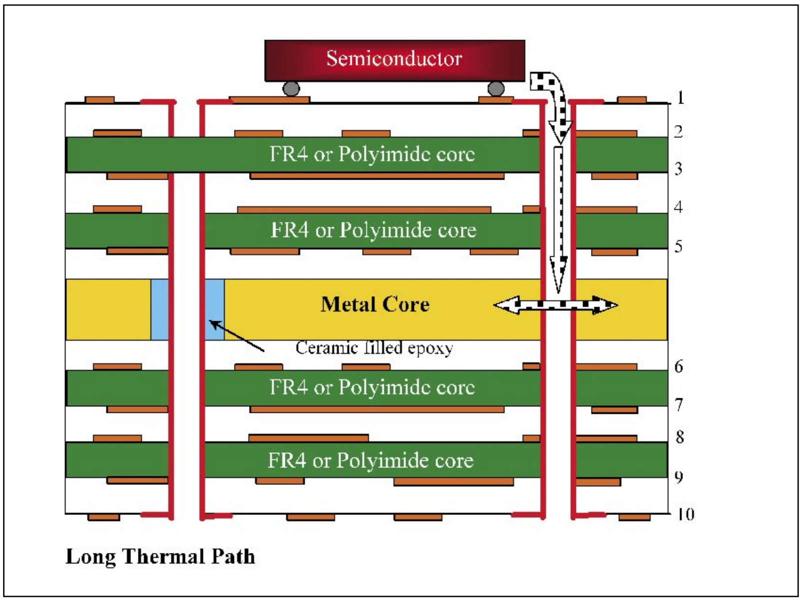
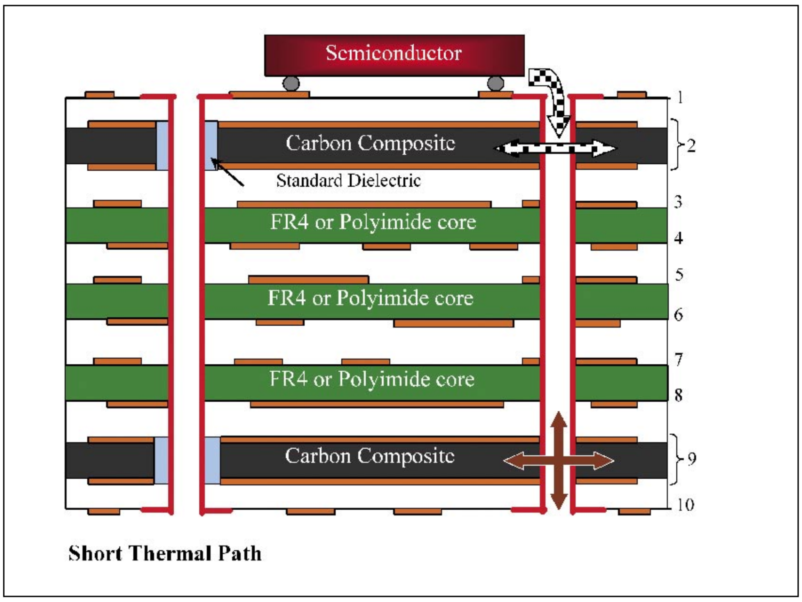
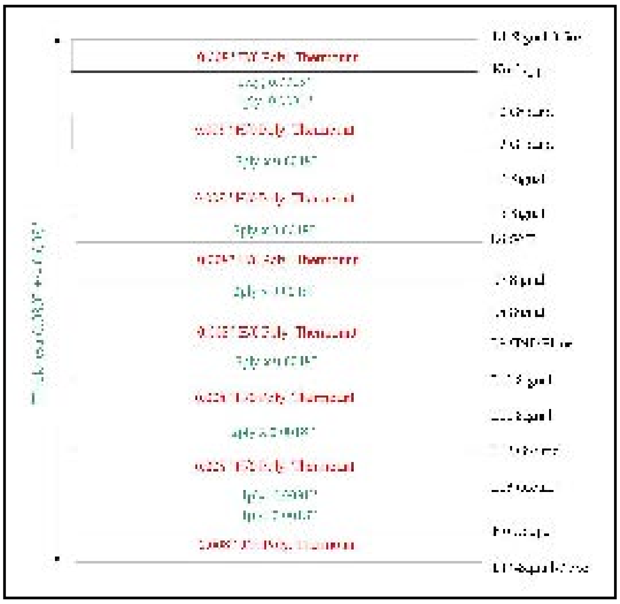


Figure 1 – Thermal path from heat source (IC) to the thermal plane





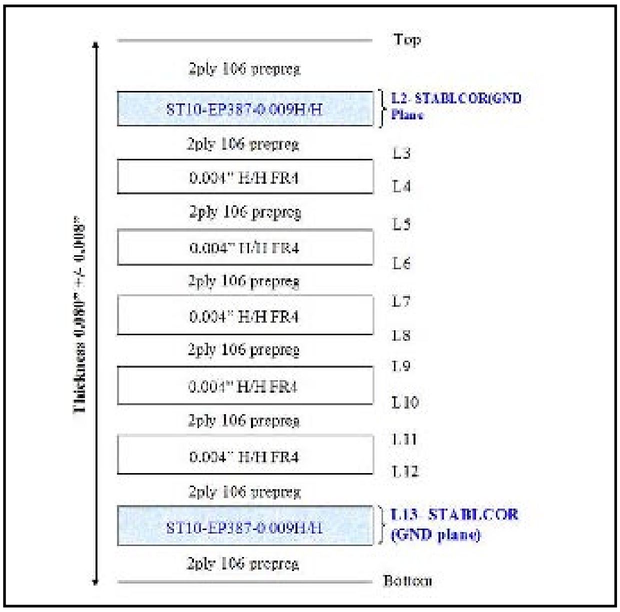


Figure 2 – 14-layer non-woven aramid PCB

Figure 3 – 14-FR4 with two layers of carbon composite PCB

Thermal Expansion (CTE), stiffness and weight benefits in addition to the thermal conductivity.

Common thermal management materials used in a printed circuit boards today are metals like copper, copper invar copper (CIC), copper molybdenum copper (CMC) and aluminium. Thermal conductivity of copper ranges from 385-400W/mK, CIC ranges from 20-30W/mK, CMC ranges from 180-220W/mK and aluminium is around 150W/mK. Normally metals are isotropic thermal conductors. Thick metal layers are used as an integral layer of a PCB. Most designers place heavy copper in the centre of the board, so as not to create expansion problems near the surface. However, a metal layer located at the centre of the PCB is quite far from the heat generating chips located on the surface. The trouble with having the heavy copper/metal at the centre is that the thermal path is much longer for the heat travelling from the chip to the metal core, as there are several layers of dielectric (non-thermally conductive) materials in between. Therefore, even though copper/metal can have a very high thermal conductivity its effectiveness is limited. In addition, the isotropic nature of the metal tends to spread heat around in a circular pattern, so the heat generating IC and does not utilise the entire PCB area for efficient cooling. Another limitation that designers face with thick metal layers is the limit to the fine features and connectivity of signals from one side of the metal core to the other side. This reduces the ability to use thick metal layers for thermal management in an HDI design.

The thermal transfer rate of carbon composite can range from ~75 to 175W/mK depending on the material selected. Carbon composite laminate is fibrous and is used as a plane layer, preferably in a ground plane of a PCB or substrate. It can be easily processed and easily placed in the second layer from the surface of the PCB. Multiple layers can be strategically placed throughout the PCB in symmetric manner in order to increase heat capacity. The thermal conductivity of this composite is directional (non isotropic) driven by the carbon fibre throughout the entire plane, thus enabling the PCB to act as a heat spreader. The composite laminate acts like a heavy copper layer without the high expansion and weight premiums. Carbon composites are easy to drill through, which could be advantageous in HDI designs. Designers can have fine features and connect all the necessary signals from one side of the composite layer to the other side without any limitations.

In carbon embedded PCBs, heat travels through the ground vias and thermal vias, and then through a very thin dielectric layer before reaching the carbon composite layer, thus embarking on a much shorter thermal path (with lower thermal resistance). The heat can also travel through the thin dielectric layer directly to the composite layer located on the second layer (right under the surface). Once the heat reaches the composite layer it travels quickly, in an anisotropic way, to a structure connected to the board, such as a wedge lock, chassis, frame or heat sink. Additionally, with the added carbon in the PCB the board acts like a heat spreader, thus, channelling the heat away from the ICs.

The limitation of carbon composite material in a printed circuit board is that it is an electrically conductive material, such as copper/metal. Copper can be patterned using chemical etching process but carbon composites are not compatible with the chemical etching process. Thus, there is know how required in order to successfully incorporate composite material within a PCB. The good news is that the manufacturer does not require any capital investment in equipment to process this material.

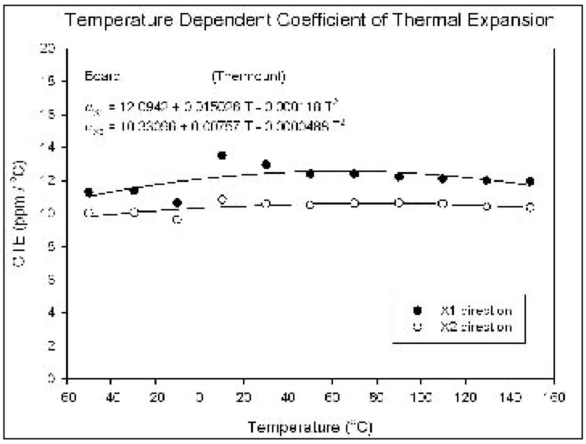


Figure 4 – In-plane CTE graph of a 14-layer Thermount PCB

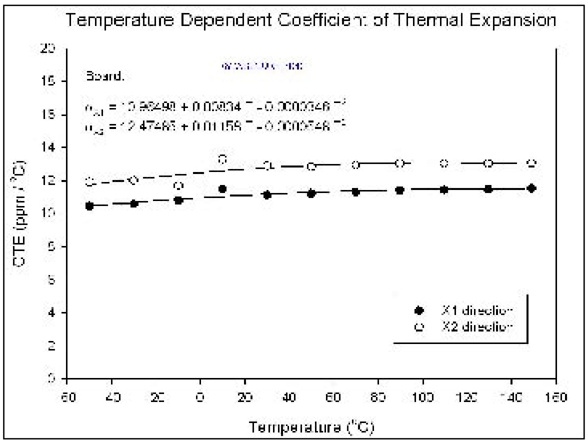


Figure 5 – In-plane CTE graph of a 14-layer FR4 + carbon composite hybrid PCB

Additional benefits of carbon composites

Carbon fibres have some great properties besides thermal conductivity, such as negative co-efficient of thermal expansion (CTE), high tensile modulus (stiffness) and low density (weight). Composites made from these carbon fibres bring unique benefits to the circuit industry beyond thermal management benefit.

Coefficient of Thermal Expansion (CTE) properties

Most printed circuit board materials are made from glass fibre composite (also known as organic materials) with different resin systems. Glass fibre based PCB composite materials have in-plane CTE ranging from +16.0 to +20.0ppm/°C. Carbon fibres have very low to negative CTE, (-0.41 to -1.5 ppm/°C). So, composites made using carbon fibres have very low in-plane CTE (+2.0 to +6.0ppm/oC).

Throughout the last few decades, wire bonds have been used between the die and the organic substrate to absorb the expansion mismatch, and then leads were added to carry the signals to the board. This process works effectively for expansion mismatch, but not for high signal speeds. As the world demands increased power and speeds in all areas of electronics, faster interconnect and packaging methods had to be invented, thus giving birth to the flip-chip, Ceramic Ball Grid Array (CBGA), Chip Scale Package (CSP) and Multi Chip Packages (MCP) of today. Plastic, ceramic and flip-chip packages have become mainstream in electronic packaging technology. Plastic packages expand during thermal cycling at a rate of 16-20ppm/°C, ceramic packages at 6-8ppm/°C and flip-chip at 2.5-4ppm/°C. Plastic packages can be mounted reliably onto standard printed circuit board because of matching CTE but mounting low CTE ceramic and flip chip packages on a high CTE printed circuit board causes tremendous stress at solder joint and leads to solder joint failure. With high I/O count chips such as ASICs, processing devices and even memory chips, the ability to place the bare die directly on an organic PCB is hampered by shear

Thermal Management, CTE Control, Stiffener Materials Comparison

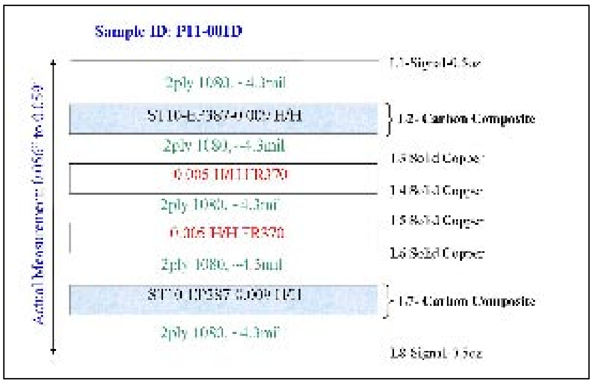
MATERIAL	Thermal Conductivity (W/m K)	In PLANE CTE (ppm/C)	Tensile Modulus (Msi)	Density (g/cc)
Low Modulus Carbon Fiber	9 to 12	-0.41	30 to 35	1.7 to 1.8
High Modulus Carbon Fiber	200 to 225	1.5	100 to 114	2.1 to 2.2
Copper Clad Carbon Composite	X & Y: 75 to 175*	3 to 6	10 to 26	1.65 to 1.7
Heavy Copper	385 to 400	17 to 18	7 to 16	8.9
Copper-Invar-Copper (CIC)	20 to 30	5 to 6	18 to 19	8.5
Copper-Molybdenum-Copper (CMC)	180 to 220	6 to 8	N/A	9.6 to 10
Non-woven Aramid Composite	0.2 to 0.3	9 to 12	2 to 2.1	1.35 to 1.3
Copper C11000 Full Hard	385 to 400	17	5.4	8.9
Aluminum 5052	160	23	3.75	2.7
Aluminum 6061 T6	180	23	3.75	2.7

*Theoretical Calculated Values

Table 1 – Thermal, CTE, rigidity and density properties of the various PCB materials

Table 2 – Stiffness improvement data at 10mm constant deflection

Sample Identification	Maximum force @ 5mm (N)	Force/N/mm	Stiffness Improvement (%)
P11-001D	163.9	37.6	134.2
P11-002D	117.9	31.69	134.7
P14-001	120.0	23.3	-



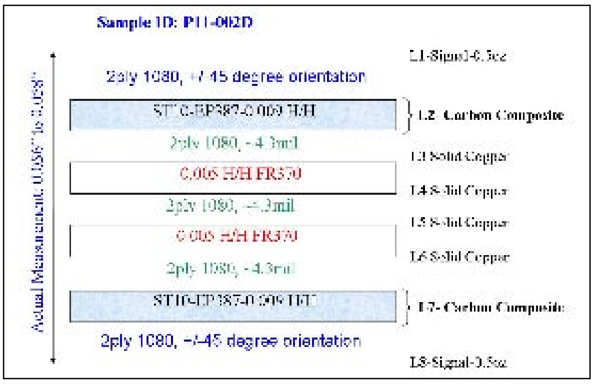
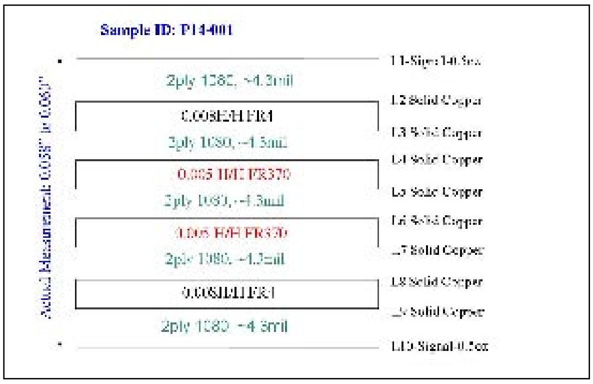
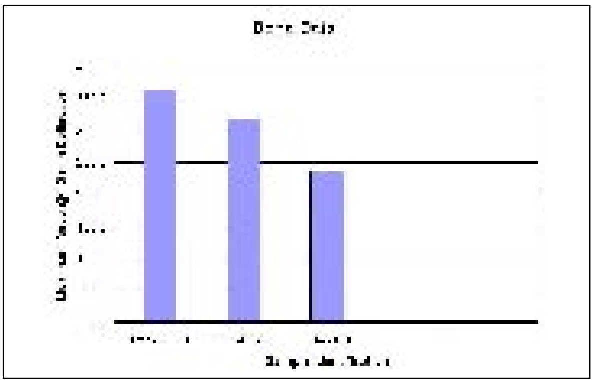


Figure 6 – Typical 8-layer carbon composite PCB (left) and special 8-layer carbon composite PCB (right)
Figure 7 – 10-layer FR4 PCB, 60mil thick (left) and load v/s deflection data comparisons (right)





stress caused by expansion mismatch at the tiny bump connections. The higher the connection count on a chip and the smaller the connection pads, the harder it is to attach and adhere to a radically expanding substrate or board. Thus, to mount a low CTE, high I/O packages reliably on a printed circuit board, a low CTE printed circuit board is required. To do so, a user can take low CTE carbon composite laminate and embed it into a PCB stack-up. This will tailor the surface CTE of a standard PCB from 4ppm/°C to 12 ppm/°C, enabling closer CTE match with ceramic or flip chip packages.

CTE/carbon composite case study

Non-woven Aramid (Thermount) material was very popular for its low CTE properties. Many defence and medical electronics companies were using aramid material to reduce coefficient of thermal expansion of a printed circuit board. About a year ago due to limited availability of aramid fibre, production of aramid composite material discontinued. A CTE study was done on an 14-layer aramid-based PCB and an FR4 board with two carbon fibre composite layers. Figure 2 shows the cross-sectional stack-up of the 14-layer aramid PCB. Figure 3 shows the cross-sectional stack-up of the 14-layer FR4 and carbon composite PCB.

Figure 4 shows in-plane CTE of the 14-layer aramid PCB. As you can see, in-plane CTE ranges from 10.3 to 12.1 ppm/°C in the temperature range from –50°C to +150°C, whereas the CTE of the same design manufactured with FR4 and two carbon composite layers measures 10.9 to 12.5 ppm/°C in the temperature range from –50°C to +150°C (Figure 5). As you can see, the CTE between two different material set is comparable. Thus, designers can use carbon composite within a multilayer printed circuit board to tailor the surface CTE. There are three main factors that affect the surface CTE: (1) volumetric ratio of the carbon composite versus rest of the material, (2) distance of the carbon composite layer from the surface and (3) type of the carbon composite.

In addition, the FR4 hybrid PCB does not have z-axis expansion as the aramid board has, the hybrid board is not as moisture sensitive as the aramid board, and finally the carbon composite makes the PCB thermally conductive and more rigid at higher temperatures.

Tensile modulus (stiffness/rigidity)

Tensile modulus of the carbon fibre ranges from 34 to 114msi (million pounds per square inch). The tensile modulus of the carbon composite ranges from 10 to 25msi, whereas the tensile modulus of the glass fibre is about 10-12msi and of glass composite 3.5-4.5msi (Table1). When carbon composites are embedded in an FR4 or polyimide board, the stiffness increases up to 3 times depending on the volume and type of the carbon composite vs. the volume of the dielectric material in the board.

A study was done to measure stiffness improvement using two layers of a carbon composite within an 8-layer, 0.060” (1.52mm) thick printed circuit board. Figures 6A, 6B and 6C show cross-sectional stack-ups of the test samples. All samples were laminated at the same time and kept at constant 60mil thickness. A three point bend test was performed by Accolade Engineering Solutions. Deflection remained constant at 10mm and the load necessary to achieve the pre-determined deflection was measured. Deflection versus load on all three samples was measured and recorded as shown in Figures 6D and Table 2. A carbon composite volume of only 26% produced a stiffness improvement of 154%.

Density (weight)

The density of the carbon fibre ranges from 1.7 to 2.2 g/cc. When fibre is combined with resin, the resulting composite density ranges from 1.65 to 1.70g/cc. Density of other thermal management materials such as copper (8.9g/cc) and CIC (9.9g/cc) are substantially heavier. In space applications where weight adds a premium cost to the project, the replacement of CIC or heavy copper is essential.

Stiffness to weight ratio

As can be seen from property chart, carbon composites deliver substantially higher stiffness to weight ratios compared to other thermal materials, thus increasing the shock and vibration reliability of the electronic devices. This is also an advantage for the mobile and aerospace electronics industries.

This article is based on a paper originally presented at the IPC Printed Circuits Expo, APEX and the Designer's Summit 2008

Cutting Sensitive PCBs The Gentle Way

According to LPKF, their no-touch laser process which replaces mechanical methods when cutting flexible and rigid PCBs protects sensitive components and solder connections from possible damage, improving reliability in the production of modern electronic subassemblies. The focussed laser beam produces very fine cuts. PCBs – assembled or unassembled – are not subjected to any mechanical stress and are not exposed to residual dust. This means that components can be placed closer to the cut line for more efficient use of the available space. PCB manufacturers use the LPKF MicroLine series laser systems either as stand alone work stations or integrated within production lines.

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Label Applicator For High-Mix Environments

Rohwedder Group, a leading global provider of complex system solutions for automation technology, has launched its JOT Automation J502-23 Label Applicator. JOT Automation offers standardized modular solutions with the latest processing technologies and capability for easy product-specific part modification.

The JOT Automation Label Applicator has been designed as a cost efficient solution for automatic, fast and accurate circuit board labelling, especially in medium-volume/high-mix environments. It offers flexible in-line operation as well as short product change time and with a connection to the factory database, there is also a wide range of traceability options. With software for quick label layout design and an easy to use graphical user interface, the J502-23 Label Applicator aims to combine efficiency with usability.

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