PCB FABRICATION

Carbon Composite For Tough PCB Design Specifications

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Carbon has emerged as a new way to constrain the core of a PCB or substrate, allowing a Silicon die that has CTE of 2.5ppm/°C to be placed on organic material that has a similar expansion rate (2-5ppm/°C). Decreasing or even eliminating thermally induced strains at the solder joint allows the electronic industry to attach Silicon without the need for underfill and adhesion material. We take a look at the properties of a Carbon core printed circuit board and see how the benefits of Carbon go beyond surface CTE expansion control and include high tensile modulus (rigidity), low weight, and high thermal transfer rates.

With flip chip technologies gaining acceptance in mainstream electronics, solutions for reliably connecting bumps are critical in order to maintain the integrity of a design. Until recently, the dielectric constant (13.36) of Carbon was considered too high for use in a PCB or substrate. Now, methods to isolate Carbon from signal carrying vias have been perfected and allow designers to capitalise on the benefits of Carbon while designing a printed circuit board filled with signals. Even blind and buried via structures now carry Carbon composite laminate layers, without requiring unsustainable capital equipment expenditures or other added costs. Sequential lamination is possible and practical, while still adding Carbon layers to the structure.

Coefficient of Thermal Expansion properties

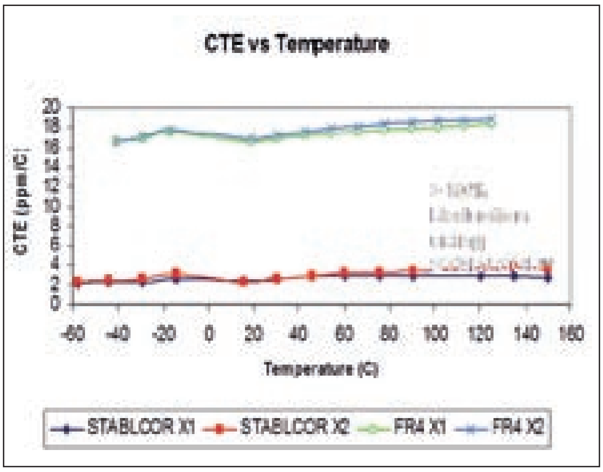
Plastic and ceramic have become the mainstream in electronic packaging technology. Silicon die expands during thermal cycling at a rate of 2.5ppm/°C, organic material at 17-19ppm/°C and ceramic at 6-8ppm/°C. Combining these materials without chip "packaging" has been a difficult task for designers because a die at 2.5ppm/°C can not effectively be attached to an organic substrate expanding at 17-19ppm/°C rate without being subjected to too much stress at the solder joints. Throughout the last few decades, first wire bonds between the die and the organic substrate were used to absorb the expansion mismatch, then leads were added to carry the signals to the board.

This process works well for expansion mismatch, but not for high signal speeds. As the market demands increased power and speeds in all areas of electronics, faster interconnect and packaging methods had to be developed, thus giving birth to the flip-chip, Ball Grid Array (BGA), Chip Scale Package (CSP) and Multi Chip Package (MCP) of today. In small CSP applications, efficient interconnections between signal bumps and the signal carrying board have been achieved, but large direct die attach applications have been less successful. 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 limited by the shear stress at the bump connections caused by the expansion mismatch. The higher the connection count on a chip and the smaller the pads, the harder it is to attach the die to a board.

With Carbon imbedded next to the surface layers of PCB, or in the centre of a thin substrate, the surface expansion rate of the material can be tailored to match or come close to the expansion rate of Silicon. Carbon composite laminate has a low expansion rate, generally 1.0 to 3.0 ppm/°C, depending on the type of Carbon material used, and dominates or "controls" the expansion rate of the other organic materials in the PWB.

Figures 1 & 2 - CTE test results of the composite laminate board vs. standard FR4

STABLCOR/FR4			FR406		
Board Temp (C)	CTE X1	CTE X2	Board Temp (C)	CTE X1	CTE X2
-57.79	2.05	2.27	-40.84	16.6	16.66
-44.12	2.2	2.45	-29.21	16.9	17.01
-28.97	2.29	2.63	-16.95	17.55	17.68
-14.24	2.61	3.11	18.68	16.54	16.84
15.73	2.38	2.22	30.56	16.94	17.28
30.66	2.68	2.65	42.41	17.21	17.57
45.61	2.87	2.97	54.26	17.43	17.9
60.46	2.96	3.18	66.08	17.61	18.13
75.37	2.98	3.33	77.95	17.79	18.31
90.39	2.92	3.36	89.77	17.95	18.49
120.2	2.87	3.53	101.49	18.08	18.62
135.11	2.86	3.66	113.35	18.2	18.77
150.01	2.75	3.65	125.03	18.3	18.85
Average	2.65	3.00		17.47	17.85



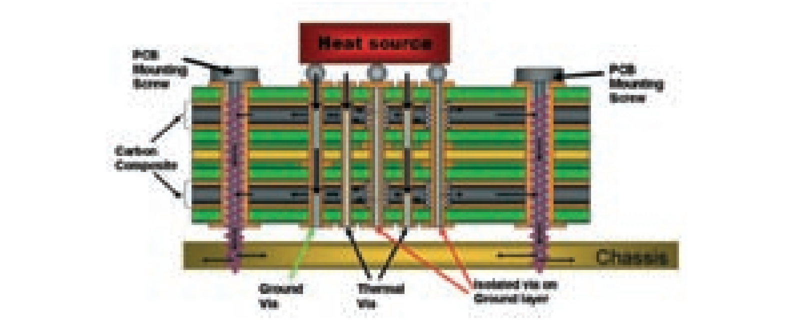


Figure 3 – Schematic diagram of a Carbon composite PCB showing heat path from the source to the chassis

The composite laminate material chosen and the layer of the board in which it is put determine the surface CTE rate of that board. To prepare a board or substrate with thermal expansion rates between 3 and 12 ppm/°C, a designer need only follow the design guidelines for laminate type and stack-up placement. This tailored expansion rate will remain close to a constant during the entire temperature range, up to the glass transition temperature of the resin system used. High temperature epoxy would have a Tg of 170°C and the glass transition temperature of ultra high temp epoxy or materials such as polyimide would have Tg of 235°C. Tests done on surface CTE tailored boards containing composite material show that steady expansion rates of 2.5 ppm/°C - 4.0ppm/°C can be achieved. Figures 1 and 2 show test results of a Carbon composite/FR4 board with an expansion rate of approximately 2.5 ppm/°C. If this were a polyimide board, the CTE would be maintained until the glass transition temperature of the polyimide resin, approximately 235°C, is reached.

Aftermarket packaging and increased production reliability

The high expense of flip chip devices which have to use aftermarket packaging technologies such as solder columns to endure the CTE mismatch stress between a ceramic substrate and a typical organic board can be eliminated using a constrained printed circuit board. BGA packages which have the balls removed and columns attached outside the original IC production floor are common. This process can be eliminated in new board designs by matching the CTE of the board to that of ceramic, allowing designers to use the original CBGA package.

Furthermore, the high tensile modulus of Carbon composite laminate increases the stiffness of a printed circuit board or substrate. Common material such as FR4 has a stiffness of around 2.4 msi (millions of lbs per square inch), while the stiffness of Carbon composites range from 11 msi and 40 msi depending upon the material selected. This can eliminate the need for other stiffeners and mechanical reinforcements and increase shock and vibration reliability of the system. During the assembly process, the throughput of the pick and place machine can be increased as well as the reliability of the placement process, which often depends upon the rigidity of the board. In fact, when a thin board or substrate bows during placement, the risk of an unreliable connection at the bump or solder joint is higher. Placement machines must often be slowed down to eliminate this risk. In many cases boards must be put upon custom designed plates to keep them from bowing as the nozzle places the die or IC package onto the board. If a board has a very high tensile modulus, the placement process is more reliable and the chances of a disconnect at the bump or solder joint are less. When designing test and prototype boards, the tensile modulus can be of great concern, as fitting boards over fixtures over and over again requires a sturdy PCB.

Composite as a plane layer

The composite laminate must be used as a plane layer, preferably as a ground plane in the stack-up of a printed circuit board or substrate. It provides thermal conductivity throughout the plane, and acts like a heavy Copper layer without the higher CTE expansion rates and the weight premium of Copper. There are many benefits to using composite as a ground or a functional plane layer. It allows to reduce thermal resistance between the heat source (IC) and thermally conductive composite material by having all ground connections tied directly to the composite layer. Also, by using composite material as a plane layer allows to maintain a thinner PCB profile. To create a thermal path using composite laminate, the ground pins must be connected through Copper vias to the layer of composite laminate next to the surface dielectric layer (second functional layer from the surface in a PCB). Heat will travel from the pins to the composite layer and quickly move in the X and Y directions of the board. This in-plane thermal transfer mechanism minimises hot spots and enables to move heat from the sources to the edges, where heat can be most effectively dissipated or transferred through heat sinks, wedge locks or the chassis.

Thermal transfer rates of raw material

There are several types of composite materials, each with its own distinct properties for stiffness, thermal conductivity and weight. The thermal conductivity of the raw material is measured in Watts per meter-Kelvin. (W/mK)

The highest thermally conductive materials commonly used in boards today are metals like Copper, Aluminum, Copper invar Copper (CIC) and-Copper moly Copper (CMC). These range from 108 W/mK for CIC and 240 W/mK for Aluminum to 385W/mK for Copper. The thermal transfer rate of the raw fibres of a Carbon material can range from 10-620W/mK depending on the material selected. If a designer has a board which needs maximum thermal transfer rates

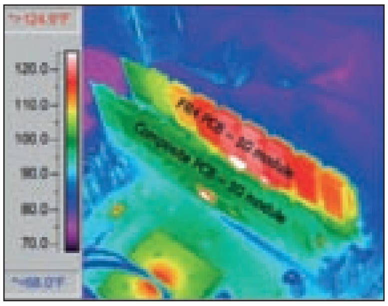


Figure 4 - The temperature difference (11°C) between a composite laminate and a standard module in an operating environment

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*	8 to 12	-0.41	30 to 35	1.7 to 1.8
High Modulus Carbon Fiber*	300-620	-1.5	100 to 130	2.1 to 2.2
Heavy Copper	385 to 400	17 to 19	12 to 16	8.90
Copper-Invar-Copper (CIC)	20 to 30	5 to 6	18 to 19	9.90
Copper-Molybdenum-Copper (CMC)	180 to 220	6 to 8	N/A	9.8 to 10
Non Woven Aramid composite	0.2 to 0.3	9 to 12	2 to 2.1	1.25 to 1.3
Copper C11000 full hard	385 to 400	17.00	6.40	8.90
Aluminum 5052	150	25	3.76	2.70
STABLCOR® Laminate	XY: 75 to 250	1 to 5	11 to 40	1.65 to 1.7

* [illegible]

Figure 5 - Properties chart comparing Carbon composite laminate to other common dielectrics and alloys

in the X and Y plane he may chose ST600 which has a raw material thermal conductivity of 620 W/mK and put one or more layers in the board stack-up to achieve the maximum thermal transfer rates possible. He can then possibly eliminate or shrink heat sinks on top of the components or board or eliminate fans and heat spreading material at the surface. The heat is spread quickly within the board towards the edges, and in the best thermal transfer applications is removed by attaching the board to a wedge lock, frame, or chassis.

The composite laminate must be symmetrical in relation to the thickness of the board because the Carbon composite has a very low CTE and very high tensile modulus that dominates the other materials such as FR4/polyimide. With a 10-layer PCB, for example, a composite laminate can be put in the centre of the stack-up, or two composite layers at layers 2 and 9. Depending on the tensile modulus or thermal conductivity needed, four layers could be used in a 10-20 layer board achieving four times the benefits of one Carbon composite layer.

Figure 4 shows two boards that have the same design, same chips, and the same stacking design and registers; the only difference is that one has the composite laminate inside.

The test was done at an Intel approved test lab by an independent test source, AMT. Two sets of identical memory modules were selected to compare the test results. One set uses standard FR4 PCB and other uses FR4 plus two composite layers. In this case the composite laminate is being used only as a heat spreader. Measurements were made using strategically attached thermocouples to the outside components and evaluating the heat as it was spread throughout the entire board. The thermocouple at the centre of the component registered the highest temperature. The modules were installed into an Intel Server motherboard and a CST RAM stress test was run for 50 minutes. The lab then did the identical test for a composite laminate module and compared the results.

It was considered that the difference could be far greater on the inside component of the memory stack because of the thermally conductive nature of the PCB, but thermocouples could not physically be attached there, so a thermal image of the two modules was taken while both were running for the same length of time in the RAM stress test environment. The inside component in the stack does not receive any kind of fanned air. The heat is trapped between a non-thermally conductive board and the outside component. The thermal camera showed an difference of 11°C between the two boards.

Placing die and sheet Silicon directly onto substrates or PCBs

As materials are perfected and continuous stress measurements are acquired through practical applications, the ability to place Silicon die and sheet Silicon directly on printed circuit boards (with little or no need for underfill and adhesion materials) will enable the speed and performance of electronic devices to increase. Carbon composite materials can enable such designs today, enabling designers to reach speeds that were not possible until now. These Carbon composite laminates have properties which change the physical parameters of a PCB or substrate. Figure 5 lists the properties of 3 types of Carbon composite vs. common alloys and dielectric materials. While Carbon works in conjunction with most of the materials in a normal PCB stack-up, replacing layers in a PCB with composite laminate will enhance the four most important properties of a PCB: surface CTE, stiffness, thermal conductivity and weight.

Tensile modulus, density and properties of raw materials

The tensile modulus of a Carbon composite laminate is orders of magnitudes stiffer than glass laminate. When Carbon composite is embedded in an FR4 or polyimide board, the stiffness increases up to 10 times depending on the volume of the Carbon composite vs. the volume of the dielectric material in the board. The weight of the composite is close to the weight of FR4 and polyimide, as shown in Figure 5. This is particularly important for space applications where weight is a premium cost to the project, and the replacement of CIC or heavy Copper an essential objective today.