The Thermal and Thermo-Mechanical Properties of Carbon Composite Laminate

Carol Burch, Kris Vasoya
ThermalWorks
Huntington Beach, CA 92646

Abstract
Carbon Composite raw material property comparison are summarized below:

-Thermal Conductivity – Watts per meter ● Kelvin.
The core material can spread up to 620.0 W/m●K.

-CTE – parts per million per □C.
Carbon Composite Laminate has a very low negative CTE, (-1.10 ppm/C) so it contracts very slightly as temperature rises. Traditional materials expand considerably as temperature rises. When in plane, the user can tailor the surface CTE of a standard Printed Circuit Board from 3ppm/C to 12 ppm/C, enabling direct die attach and WLP.

-Density – grams per cubic centimeter.
The material density (and therefore weight) is approximately equivalent to fiberglass. Standard FR4 is 1.85g/cm3 carbon composite is 1.76-2.20g/cm3. No weight premium.

-Tensile modulus of elasticity – MSI (1,000,000 PSI).
The carbon composite is much more rigid than traditional materials. It is 4 to 10 times the rigidity of standard Fr4. Tensile modulus is 34-130 MSI per layer depending on raw material selected.

-Dielectric constant – $\square_r$ (relative permittivity).
The relative permittivity of the new material is higher than traditional material, however, it is used only as a plane layer (preferably ground plane) and is isolated from the copper vias. This material can be drilled through easily so that signals pass through the carbon composite layer, are isolated, and still can be used throughout the entire board. This eliminates the concerns of the Dielectric constant of the core material and allows users to simply design the PCB as normal concerning vias.

Carbon composite laminate addresses CTE, Rigidity, thermal concerns, weight in a Printed Circuit Board.

Key Words: Carbon, Constrained CTE, Thermal Benefits, Rigid, Lightweight Printed Circuit Board or Substrate

Introduction

As the roadmap for silicon die mounted directly onto a printed circuit board advances, many technologies such as Die Attach Film, ACF/NCF, ACP/NCP, underfill and adhesion materials have moved quickly into mainstream use, gaining acceptance in products such as cellular phones, PDA's and disk drives. The die used in these applications is usually smaller in size, and solder interconnect failures are not as common with these lower shock and vibration applications. As the world moves to integrate large scale die onto the board with flip chip and direct die attach methods, dangerous Coefficient of Thermal Expansion (CTE) mismatches between the printed circuit board or substrate and the die must be addressed. Carbon has emerged as a new way to constrain the core of a printed circuit board or substrate, therefore allowing a silicon die that has an expansion rate of 2.5ppm/C to sit on organic material that has a similar 2-5ppm/C (parts per million per 1 degree Centigrade) expansion rate. 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. Until control of the stress that occurs at the flip chip die surface becomes possible, the risk of tomb stoning and cracks at bump level is eminent. Carbon composite laminate is available today which allows the designer to tailor the surface CTE of an organic substrate or printed circuit board down to the silicon die expansion rates and attach even large scale ASIC and Chip technologies directly to the PCB or substrate. The CTE of an organic PCB can also be tailored to the 6-8ppm /C expansion rate that enables to mount ceramic packages like CBGA reliably. In the following paper we will discuss the properties of a carbon core printed circuit board. The benefits of carbon go beyond surface CTE expansion control and include high tensile modulus (rigidity), low weight, and high thermal transfer rates. We will discuss these additional benefits in practical applications as well.

Flip chip technologies are gaining acceptance in mainstream design and solutions for reliable connection of bumps is critical to maintain the integrity of a design. Until now, the dielectric constant (13.36) of carbon in a PCB or Substrate was considered too high for use in electrical design. Methods to isolate carbon from signal carrying vias have been perfected and now allow designers to capitalize 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 causing the board manufacturer extreme added cost or capital equipment expenditures. Sequential lamination is possible and practical, while still adding carbon layers to the structure. Vibration and fatigue is a major reliability issue facing today's electronic packaging technologies [1]

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. Marrying these materials together without chip "packaging" has been a difficult task for designers because a die at 2.5ppm/C can not effectively sit on an organic substrate expanding at the much higher 17-19ppm/C rate without too much stress at the solder joint. Throughout the last few decades wire bonds were used between the die and the organic substrate to absorb the expansion mismatch, 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, Ball Grid Array (BGA), Chip Scale Package (CSP) and Multi Chip Packages (MCP) of today. In CSP small space applications the interconnection between signal bumps and the signal carrying board has been achieved to a large degree of efficiency, but in large scale direct die attach applications have been difficult. With high I/O count chips such as ASIC and Processing devices, and even memory chips, the ability to place the bare die on an organic Printed Circuit Board directly is hampered by shear stress caused by expansion mismatch at the tiny bump connections. The higher the connection counts on a chip and the smaller the connection pads, the harder it is to attach and adhere to a radically expanding substrate or board.

With carbon imbedded next to the surface layers of the printed circuit board, or in the center of a thin substrate, the surface expansion rate of the material can be controlled to match or come closer to the expansion rate of the silicon. Carbon composite laminate has low expansion rate generally 1.0 to 3.0 ppm/^{o}C depending on the type of carbon material used, and dominates or "controls" the expansion rate of the other organic materials in the Printed Wiring Board.

Expansion Control at the Surface

Strain Gage techniques described in the Vishay Measurements Group Guide to Strain Measurement Technology Tech Notes TN-513 [2] were used in a white paper study by Boeing and Auburn University to measure the expansion of a board constrained with carbon composite laminate carbon composite ST500 [3] and FR4 layers. This technique requires an application of a strain gage to both the test sample and a reference material having a known low expansion CTE such as Titanium Silicate. Strain gages utilized in this work were Measurements Group WK-00-125MG-350 having a gage factor of 2.01. The gages were mounted using M-Bond 43B adhesive. Omega 5TC-TT-T-36-36 thermocouples were also placed on both the test samples and the reference material. The instrumented samples were placed in a thermal chamber and the bridge output was nulled at 0^{0}C. The strains and temperatures were measured and recorded from –50^{0}C to +150^{0}C in 10^{0}C increments. Temperatures were allowed to stabilize for 45 minutes at each set point prior to taking the strain and temperature measurements. The data acquisition system consisted of National Instruments SCC-2345 carrier with SCC-SG02, 350 ohm, ¼ bridge strain conditioning modules and SCC-TC02 Thermocouple Input Modules. A National Instruments 6034E data acquisition board was utilized to perform the A/D conversion and interface to the PC running Labview v7.0 software for experiment control.

Results: —A third order polynomial curve fit was applied to the strain and temperature data output from each gage. The temperature dependent strain curves were subtracted per equation and added to the known reference expansion curve. This total curve was then differentiated with respect to temperature to calculate the temperature dependent CTE of the sample. Temperature dependent plots of the strain and CTE in each direction for both carbon composite ST500P/FR4 and a FR4 sample are shown in Figure 1 and Figure 2. The in-plane CTE for a typical FR4 board material is 16-20ppm/^{0}C. This study demonstrates that significant lower CTE can be achieved by use of carbon composite/FR4 hybrid PCB (~2.5ppm/^{0}C); thus reducing the in-plane CTE by approximately 80%.

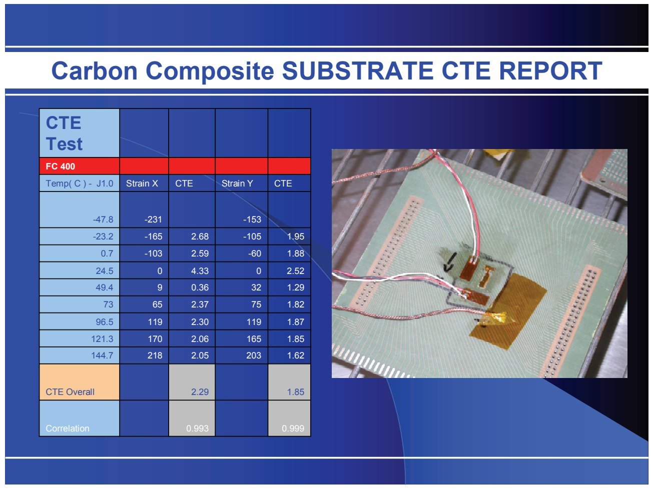

Figure 1 - CTE Report from Auburn University

The composite laminate material chosen and the layer of the board in which you put it determines the surface CTE rate of that board. If a designer chooses to have his board or substrate expand at anywhere between 3 and 12 ppm/C, he need only follow design guidelines for laminate type and stack-up placement to choose or "tailor" the surface CTE of the board. 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 temp. epoxy would have Tg 150^{o}C and the glass transition temperature of ultra high temp epoxy or material such a polyimide would have Tg 235^{o}C. Tests done on surface CTE tailored boards with composite material show that an expansion rate of 2.5 ppm/^{o}C - 4.0ppm/^{o}C can be achieved at a steady constant through temperature cycling. Below are test results of a Carbon Composite/FR4 board tailored to approximately 2.5 ppm/C expansion rate. If this were a polyimide board the CTE would be maintained until the glass transition temperature of the polyimide resin, approximately 235^{o}C.

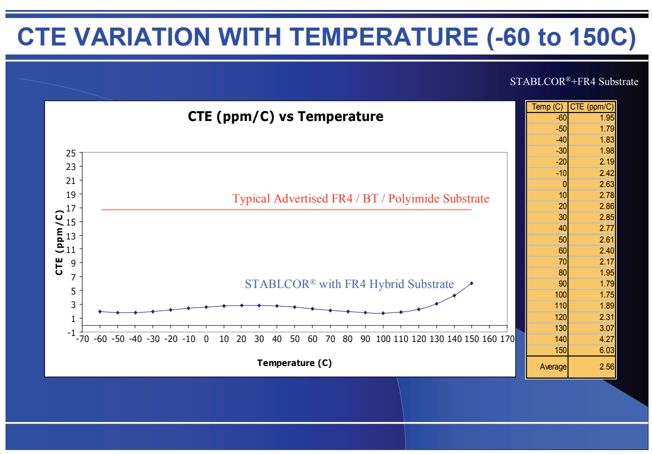

Figure 2 - Boeing/Auburn University CTE Test Results of the Composite Laminate Board vs. Standard FR4

Controlling CTE in Selected Areas of a Printed Circuit Board

There are many type of packaging technologies used in the electronics industries. Such as Plastic package, Ceramic packages, Flip Chip packages, Wafer level packages. All these various packages have different Co-efficient of thermal expansion values. When the application requires different type of packages mounted on the same printed circuit board, the one CTE value of printed circuit board favors reliability to the matching CTE packages, but has a negative effect on others. To solve this CTE matching with one type of packages and miss-match with other packages designer can use a method called "localized CTE". One section of the board can be constrained expansion at first surface CTE values, and other section can be constrained or controlled at second expansion rate. For example, First CTE values can be constrained to match with ceramic type packages and second CTE values can be matched to plastic type packages. A ceramic package tends to have CTE in a range of 6 to 9ppm/^{o}C and a Plastic package tends to have CTE values in a range of 14 – 17ppm/^{o}C. For example: a designer has a Ball Grid Array Chip Set with a high pin count on a Ceramic Substrate. This chip set is very sensitive to surface CTE on the board and could have reliability problems due to solder joint strain during thermal cycling, yet the rest of the integrated circuits on the board are wire bond, TSOP, Plastic package technology. If you control the expansion of the entire board at 6-8 ppm/C to match the Ceramic Packages you will increase reliability and reduce strain on that chipset, but at the same time you have increase strain with the opposite expansion rate of the plastic packages which expand at 14-17 ppm/C; creating a opposite and reverse mismatch. If the designer has the ability to section off the CBGA Chipset to one area of the board, then a board can be manufactured which expands at a similar rate to Ceramic in only that section, but not throughout the entire plane. This allows you to reliably place your plastic packaged components on the rest of the board without creating the "reverse mismatch" problem.

Aftermarket Packaging and Increased Production Reliability

The high expense of flip chips which have to use aftermarket packaging technologies such a solder columns to endure the CTE mismatch stress between ceramic substrates and typical organic board expanding at 17-19ppm/C can be eliminated using a constrained printed circuit board. BGA packages that 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 CTE of the board to ceramic and allowing designer to use the factory original CBGA package.

The high tensile modulus of carbon composite laminate [4] increases the stiffness of a printed circuit board or substrate. Common material such as FR4 is measured at 2.4 msi (million of lbs per square inch) and the carbon composites range from 20 msi to 78 msi average depending upon 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 and the reliability of the placement often depends upon the rigidity of the board. When a thin board or substrate bows during placement, the risk of an unreliable connection at the bump or solder joint is higher, and the placement machines must be slowed to compensate for the delicate material. In many cases boards must be put upon custom designed plates to keep the board from bowing as the nozzle places the die or IC package onto the board. If a board has extreme high tensile modulus, the placement process is more reliable, and the chances of a disconnect at the bump or solder joint is less. When designing test boards and prototype boards tensile modulus can be an extreme concern, fitting boards over fixtures time and time again requires strength in the PCB.

Composite as a Plane Layer

The composite laminate must be used as a plane layer, preferably ground plane in the stack-up of a printed circuit board or substrate. It has thermal conductivity throughout the entire plane, and acts like a heavy copper layer without the higher CTE expansion rates and the weight premium of copper. There are many benefits using composite as a ground or a functional plane layer. It allows you to reduce thermal resistance between heat source (IC) and thermally conductive composite material by having all ground connection tied directly to the composite layer. Also, by using composite material as a plane layer allows you to maintain thinner profile of the PCB. To create a thermal path using Composite laminate, you connect the ground pins through copper vias to the layer of composite laminate next to surface dielectric layer (second functional layer from the surface in a PCB). Heat will travel from pins to a composite layer and quickly move in the X and Y direction of the board. This allows you to minimize hot spots on the circuit board. Also this in-plane thermal transfer rate enables to move heat from the heat source to the edges, where heat can be most effectively dissipated or transferred when board is attached to a heat sink, wedge lock, or 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, and copper invar copper (CIC), copper moly copper (CMC). These range from 108 W/mK(CIC), 240 W/mK (aluminum) and 385W/mK (copper). The thermal transfer rate of the raw material 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 in the X and Y plane he may chose a material called ST600 [3] which has a raw material thermal conductivity of 620 W/mK and put one or more layers in the board stack-up to gain the maximum thermal transfer rates in the board. 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 by pulling the heat into the stack-up of the board. The heat is then spread quickly in the X and Y direction to the edges of the board, and in the best thermal transfer applications it is removed by attaching the board to a wedge lock, frame, or chassis.

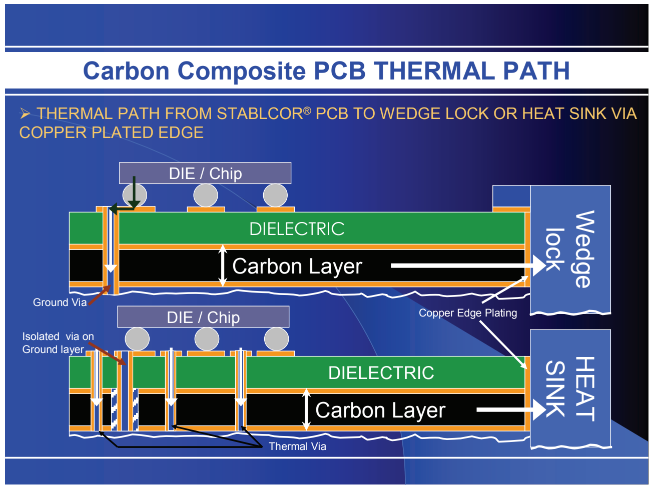

Figure 3 - Thermal Path to Wedge Lock or Heat Sink

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 which dominates the other materials such as FR4/polyimide. If you have a PCB with 10 layers for example: you could put single composite laminate in the center of the stack-up, or you could put 2 composites layers at layer 2 and layer 9. Depending on the tensile modulus you desire or thermal conductivity needed, you could effectively use 4 layers in a 10 -20 layer board and receive all property benefits of the carbon at 4 times the amount of using one composite layer.

CTE and Thermal Benefits in Memory Modules and Daughter Boards Placed in Sockets.
This is the least effective application for carbon composite laminate in relation to thermal dissipation because the modules and daughter boards are placed in a socket and the heat is only spread throughout the circuit board. Just like water evaporates faster when thrown on a sidewalk verses sitting in a bucket, the heat dissipates quicker when it is spread throughout the entire surface area of the board. The ability to direct die attach is another factor in performance. Cooling the memory module or daughter card allows for less stress at the solder bump joint, and therefore can increase reliability as well.

Summaries of test reports for a major leading semiconductor companies show substantial reduction in temperature between factory original memory modules and an identical memory module made with two layers of carbon composite laminate construction in the printed circuit board. The board is free standing in a memory module connector, and thermally not connected to any frame, chassis or heat sink. This example simply shows the composite laminate layer acting as internal heat spreader in the Memory Module printed circuit board, but essentially the heat is still trapped and has no conduction path from the PCB. Heat is essentially removed by natural and/or forced convection from the surface area of the PCB. The two boards shown below have the same design, same chips, 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+ two composite layer built in the PCB. In this case the composite laminate is being used only as a heat spreader, creating a larger thermal surface area. A summary of findings was calculated using strategically attached thermocouples to the outside components and evaluating the heat as it was spread throughout the entire board. The thermocouple in the center of the component registered the highest temperature. The modules were installed into a 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 differences.

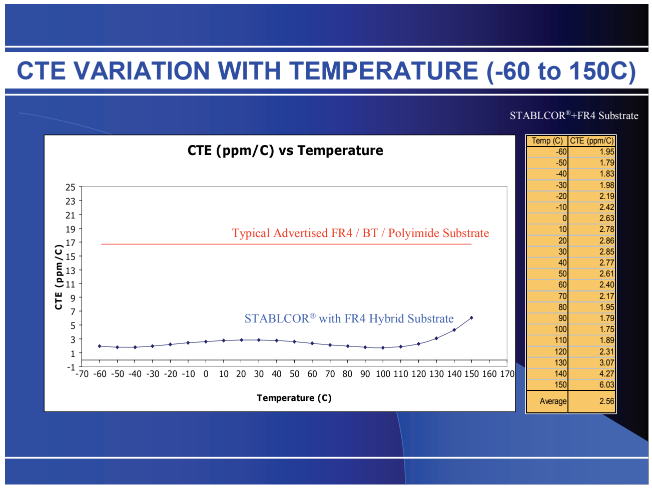

Figure 4 - The Composite Laminate Brought the Temperature of the Hottest Component Down by 6 Degrees Celsius

It was considered that the difference could be far greater on the inside component of the memory stack since 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 11 degree Celsius difference between the non composite board and the composite board.

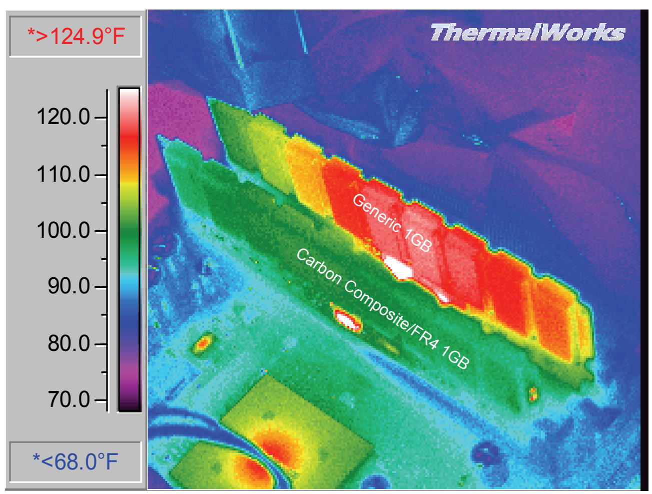

Figure 5 - The Composite Laminate Showed a Difference of 11 Degrees Celsius between Modules in an Operating Environment

Ability to Place Die and Sheet Silicon Directly onto Substrate or PCB

As materials are perfected and continuous stress measurements are acquired through practical applications from photovoltaic to space and satellite technologies, the ability to place silicon die and sheet silicon directly upon printed circuit boards [with little or no need for underfill and adhesion materials] will enable technologies to advance and speeds and performances to increase. Carbon composite materials can enable such designs today, and depending upon bump count, and total I/O count in a constrained core printed circuit board, extremely close CTE matching between chip and board or substrate can be accomplished. In many applications this enables designers to reach speeds that were not possible until now. Carbon Composite laminates have properties which change the physical parameters of a Printed Circuit Board or Substrate. Below is a chart listing 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 4 major properties of a PCB, Surface CTE, Stiffness, Thermal Conductivity, and weight or Heavy Copper is essential today.

RAW MATERIAL	THERMAL CONDUCTIVITY (W/m*K)	CTE (ppm/C)	DENSITY (g/cm3)	TENSILE MODULUS (msi)	DIELECTRIC CONSTANT (Dk)
ST600	620.0	-1.15	2.20	130.0	13.36
ST325	325.0	-1.15	2.17	114.0	13.36
ST10	8.0	-1.10	1.76	34.0	13.36
FR4	0.3	17.00	1.80	2.4	4.50
POLYIMIDE	0.3	17.00	1.70	3.0	4.20
COPPER	385.0	17.00	8.92	12.0	N/A
ALUMINUM	240.0	24.00	2.70	10.2	N/A
CIC	108.0	4.00	9.90	19.0	N/A

Stablcor® values represents data of raw fibers

Properties Chart Comparing Carbon Composite Laminate to Other Common Dielectrics and Alloys.

Tensile Modulus, Density and Properties of Raw Meterial

The tensile modulus of a carbon composite laminate is magnitudes stiffer than glass laminate. This can be shown on a properties chart. 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 composite is close to the weight of FR4 and Polyimide, as shown in properties chart above. In space applications where weight is a premium cost to the project, the replacement of CIC or Heavy Copper is essential today.

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References

[1] Lau, John H., "Solder Joint Reliability of BGA, CSP, Flip Chip, and Fine Pitch SMT Assemblies", p133, McGraw-Hill, 1997.

[2] Measurements Group Guide to Strain Measurement Technology Tech Notes TN-513

[3] Material Characteristics from Thermalworks data sheet ST500 /ST600

[4] D. Scott Copeland, "Material Characterization and Die Stress Measurement of Low Expansion PCB for Extreme Environments" Elastic Modulus