NON-WOVEN ARAMID REINFORCEMENTS; CONTROLLED THERMAL EXPANSION PREPREG AND LAMINATE FOR PRINTED WIRING BOARDS

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ABSTRACT:

Trends in electronics packaging toward higher clock speeds have brought PWB materials to higher I/O densities. Semiconductors with increased pin counts and bare chips wire bonded directly to substrates are utilized to increase device reliability and speed. This has pushed traditional woven glass reinforcement prepreg and laminates to their processing limits while electronics packaging continues to increase in density.

The move toward higher interconnection density with several new packaging trends, now in various modes of scale-up (BGA, TSOP, COB, DCA, LCCC, FPSMT, MCM-L) has focused attention on the mismatch in CTE's of traditional glass-based substrates with these new interconnection techniques. The CTE mismatch of glass-based substrates stands as a design limitation due to reduced solder joint reliability as these devices are thermally cycled in testing to simulate device operation. The faster clock speeds of chips today requires a greater attention to thermal management, since chips are evolving more heat and are spaced more closely together.

Non-woven aramid reinforced laminate systems have tunable in-plane CTE's that reduce the CTE mismatch between the semiconductors and the laminate substrate. This results in reduced strain on solder joints during thermal cycling, creating a higher reliability packaging system.

This paper covers a comparison of the non-woven aramid material properties to traditional materials, along with processing and design recommendations for commercial and military applications, utilizing high Tg epoxy and polyimide resin systems.

INTRODUCTION:

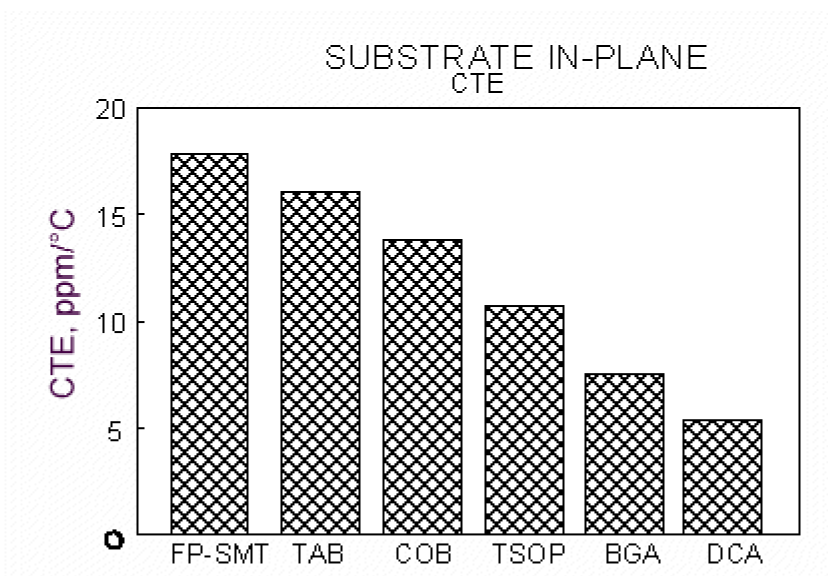
Electronics continues to push the limits of material performance in the various materials used to manufacture Printed Wiring Boards (PWB's). For PWB's and Multilayer Boards (MLB's) the traditional E-glass reinforcement in prepreg and laminate that has been with us the better part of 50 years, is starting to show some limitations when applied to the leading edge packaging and interconnection technologies of today (Table 1). As these E-glass based materials push the limits of performance and processability, the utilization of organic reinforcements has shown improvement in dielectric constant for faster signal propagation and reduced mismatch of Coefficient of Thermal Expansion (CTE's) for improved solder joint reliability (Fig 1.). This provides an alternate solution for such advanced surface mount techniques as Fine-Pitch Surface Mount (FPSMT), Direct Chip Attach (DCA) and Ball Grid Array (BGA) as traditional prepreg and laminate materials reach toward interconnections with smaller features and higher interconnection densities.

	Medium Density PWB	High Density PWB	MCM-L, Hybrids
# Layers	4-6	8+	8+
Line Width	3-6 mils	2-5 mils	1-3 mils
Dielectric Thickness	5-15 mils	3-10 mils	2-5 mils
Interconnect Density	> 150 in/in^2	250 in/in^2	> 400 in/in^2

TABLE 1: Comparison of Typical Design Attributes

A novel organic reinforcement called Thermount® shows promise as a material to help redefine the design limits of traditional prepreg and laminate materials when used in high interconnection density PWB's. Thermount® refers to an all-aramid reinforcement that is a registered tradename of the DuPont Company. This non-woven aramid reinforcement is processed into laminate and prepreg materials to meet the requirements of MIL-S-13949 slash sheets /22B /23B (High Tg Epoxy) and /31, /32 (Polyimide). All references to nonwoven aramid refer to the DuPont Thermount® product.

When considering MCM-L and other high interconnect density hybrid constructions, the goal is to minimize the CTE mismatch between the substrate and the component (comparison of Table 2 with Figure 1). As packaging techniques such as BGA, DCA and FP-SMT gain in popularity and increase in complexity, more emphasis is placed upon matching the laminate substrate CTE with the packaging components This becomes very important as chip clock speeds are faster (operate hotter) and components are placed closer together. Thermal management and reduced CTE mismatch are very important in reducing solder joint stress, so that as solder "work hardens" during the thermal cycling of powering electronic devices on and off, the solder joints are more reliable (not tending to pull apart in the "tug-of-war" induced upon solder joints by CTE mismatch between components and substrates).



DESIGN/CONSTRUCTION BENEFITS:

The lower permittivity of the non-woven aramid reinforcement (E r=3.9) vs. E-glass (E r=6.2), provides for faster signal propagation, allowing higher circuit density with less crosstalk. Combined with improved dimensional stability and surface smoothness, the non-woven aramid is suitable for smaller circuit traces and pads to provide speed advantages from both the contribution of the lower Er as well as the shorter signal path length (design miniaturization).

Another feature of the material is a smoother surface than conventional glass based laminates. This results in fewer shorts and opens after imaging processes, due to better conformance of dry film to the laminate surface in imaging fine lines and spaces.

As an all-polymer construction, non-woven aramid prepreg and laminate constructions show promise for the use of thinner dielectric layers. While the commercial market is reaching toward 2 mil dielectric spacings using glass reinforced material in low voltage devices such as PCMCIA cards , the bulk of the military market is 5 mil dielectrics or greater for higher voltage circuitry. The use of non-woven aramids shows more promise for higher reliability under HAST (Highly Accelerated Stress Testing), where product life cycles of 20 or 30 years are simulated under thermal, electrical and humidity testing. This high reliability shows promise for the use of laminate core thicknesses in the range of 2 to 3.5 mil dielectrics for size and weight reduction for higher signal power requirements.

Packaging Element	**In-Plane CTE (ppm/°C)**
Ceramic	5-7
Plastic	20-23
Silicon	3
Solder	23-25
E-Glass Reinforced Laminate	16-20
Non-woven aramid Laminate	7-10

Table 2:: CTE of Packaging Elements

Aramids are lower in density than E-glass. Laminates are approximately 25% lighter than equivalent E-glass dielectrics. This along with design miniaturization permitted by r advantages, provides further weight reduction and implied fuel savings for avionics, aerospace and other transportation applications. Considering that the non-woven aramids provide CTE constraint for packaging components, the use of CIC (Copper-Clad-Invar) CMC (Copper-Molybdenum-Copper) and other techniques is not required. This can push weight reduction well beyond the apparent 25% mark as new designs take advantage of this composite material in new PWB applications.

Since aramid fibers are noted for their negative coefficient of thermal expansion (negative CTE in the X, Y plane of the fiber), they are a natural selection for combination with such thermosetting resins as epoxy (isotropic CTE around 45 ppm/°C) or polyimide (isotropic CTE about 35 ppm/°C). The combination of aramid with the proper resin content provides X and Y planar CTE control for the packaging techniques that require substrate CTE control in the range of 7-10 ppm/°C (Table 4)

The CTE of the non-woven aramid can be described by the *Schapery Equation*, which takes into account, the CTE values of the individual components of the composite, the volume fraction and the modulus of each component. The problem with a direct solution is that the aramid fibers are randomly distributed, such that some components are out of plane, so the reinforcement has a lower effective modulus when it comes to the in-plane component. Figure 2a,b illustrate the reduction in X,Y CTE, and translation of some of the CTE to the Z-axis where there is less constraint in the composite.

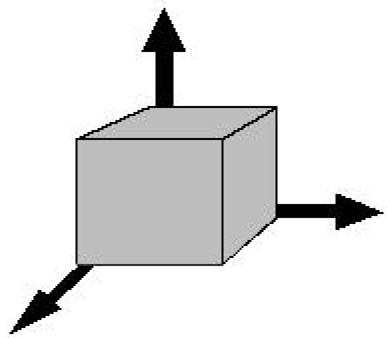


Figure 2a: Isotropic CTE of resin

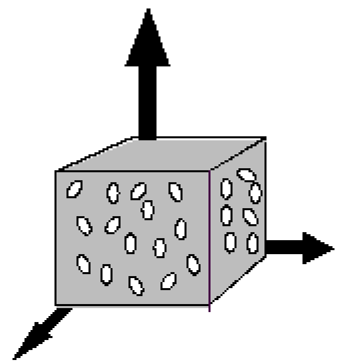


Figure 2b: Anisotropic CTE of reinforced resin

$$CTE_{composite} = \frac{CTE_r \ x \ Mod_r \ x \ Vol\%_r + CTE_f \ x \ Mod_f \ x \ Vol\%_f}{Mod_r \ x \ Vol\%_r + Mod_f \ x \ Vol\%_f}$$

where CTE_r = CTE of the resin (CTE_f for fiber reinforcement)

Mod_r = Modulus of the resin (Modf for fiber reinforcement)

The aramid construction also shows the following benefits when used in multilayer board applications:

Random pattern of fiber reinforcement results in less drill deflection and wander when drilling small diameter, high aspect ratio holes compared to glass fiber bundles that can deflect drills readily.

All polymer construction of the prepreg and laminate allows for elimination of glass-etch chemistry in wet processing operations. Drill desmear and etchback can be done with plasma and/or permanganate.

As an all polymer construction, ablative properties have shown promise for high speed formation of vias, eliminating the need for costly multiple relamination cycles.

Improved dimensional stability as a result of the random discontinuous fiber matrix vs. the variability of a continuous woven glass matrix shows promise for tighter annular ring/pad requirements to free up "real estate" for further design miniaturization.

The aramid construction is less abrasive to drills, resulting in more hits between drill sharpenings.

PREPREG AND LAMINATE

This non-woven aramid reinforcement has been prepregged with both epoxy and polyimide resins and laminated under conventional processing (Table 3.) The composites were coated to a nominal of 47% resin content by weight for optimal CTE control. The CTE vs. Resin Content and Copper foil content by weight response is illustrated in Figure 4.

MIL Classification Type: Generic Description: Product Designation:	GF FR-4/EGlass 42N	BF Epoxy/Aramid 55NT	GI Polyimide/EGlass 31N	BI Polyimide/Aramid 85NT
Density	1.6-1.8	1.3	1.5-1.7	1.25
Permittivity, (1MHz)	4.8	4.0	4.5	3.8
Dimensional Stability	± 0.05%	±0.03%	± 0.05%	±0.03%
Surface Smoothness, Angstroms	4200	2000	4200	2000

Table 3: Comparison of Bulk Properties

At 47% resin content, the matrix has the filling power approximately equivalent to a 60-65% resin content by weight E-glass prepreg (because of the lower density of aramid compared to E-glass, less resin is needed to fill the lower weight matrix), yet the non-woven aramid prepreg does not have an excessive coating of resin that would contribute rapidly to an increasing X,Y plane CTE, as shown occurring above 50% resin content by weight.

The non-woven aramid prepregs and laminates were combined with conventional resin system technology in standard prepregging and lamination processes to produce multilayer boards. Since the aramid is about half the density of traditional E-glass reinforcements, the non-woven aramid composites are approximately 25% lighter in weight. The weight reduction for avionics and aerospace can be even greater where CIC (Copper-Invar-Copper) is included in board designs for core constrainment of surface mount assemblies.

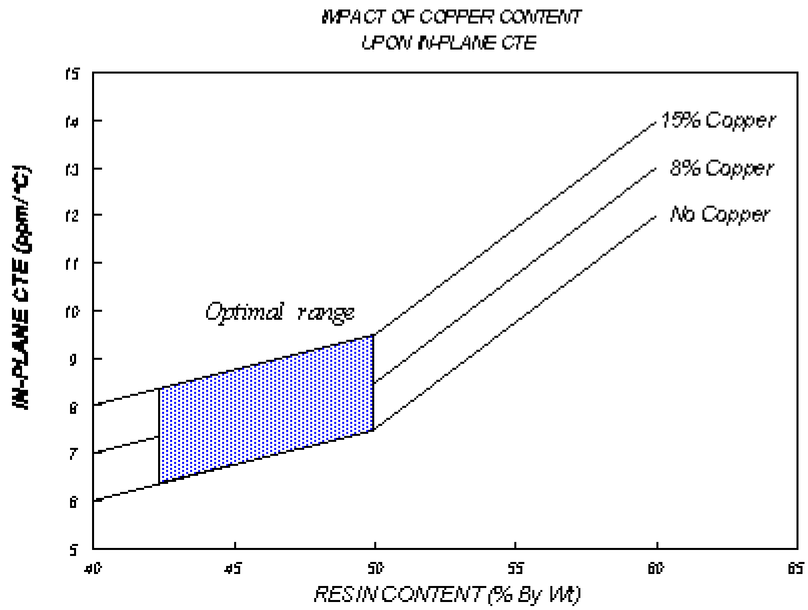


Figure 4: CTE Response as a Function of Composite Design

When considering the various materials used in constructing printed wiring boards, it was determined from the CTE's and moduli of various materials illustrated in Table 4., that the aramid reinforcement constructions was a natural selection to meet the objectives of lower in-plane CTE without the use of heavy constrainers such as CIC.

Materials	Modulus, (GPA)	Specific Gravity	CTE (ppm)
non-woven aramid	124	1.44	-5.0
Quartz	70	2.2	0.54
S-Glass	85	2.49	2.6
E-Glass	70	2.54	5.5
Epoxy Resin	6.5	1.35	45
Polyimide Resin	7.0	1.3	35
E.D. Copper Foil	117	8.92	17
Copper Clad Invar	140	8.33	3.6±1

Table 4: Comparison of CTE for Various PWB Components

MATERIAL PERFORMANCE COMPARISONS

The non-woven aramid laminate materials were compared to traditional E-Glass reinforced laminates for material characterization and subsequent printed wiring board processing.

Since the resin systems selected were traditional resin systems typically combined with E-glass, there weren't many surprises with the physical properties driven mainly by the resin portion of the composite (Table 5.) Glass transition temperatures were predictable, with 180°C for the multifunctional epoxy and 245-255°C for the polyimide. Electrical strengths were improved. Water absorption was anticipated to be higher due to the absorption of the aramid fiber vs. virtually none by the E-glass fibers. Subsequent evaluation through the multilayer board process has shown that moisture removal before critical process steps is adequate in preventing problems when boards are subjected to the rigors of soldering operations.

Peel strengths of copper foil were lower than anticipated. The failure mechanism was observed through the cohesive strength failure of the reinforcement, and not the separation of the copper from the resin. Though peels were roughly 25-25% lower than an e-glass construction, this did not present itself as a problem in the fabrication of printed wiring boards, or the thermal stressing of military coupons. The combination of the design of the reinforcement, use of class 3 foils and the design of the matrix resulted in boards that passed MIL-P-55110 testing. Careful control of plated copper elongations was one area noted for good hole wall integrity (nickel flash overstrike also studied to strengthen hole wall integrity). Constructions observed to pass MIL-P-55110 thermal shock (-65°C to 125°C), 100 cycles) were within the following thicknesses:

< 0.065" multifunctional epoxy (Z-axis CTE < 120 ppm)

< 0.070" polyimide (Z-axis CTE < 100 ppm)

Property	FR-4 (Tg 180)	55NT	GIN Poly	85NT
Construction	E-glass	nw Aramid	E-glass	nw Aramid
Peel Strength, (Lbs/in.)	8-9	4.5-5	7-8	4-4.5
Water Absorption, (%)	0.1	0.45	0.3	0.6
Dimensional Stability (%)	0.04%	0.02%	0.05%	0.02%
Thermal Conductivity (W/mk)	0.4	0.2	0.42	0.27
Density, (g/cc)	1.8	1.3	1.7	1.25
Electrical Strength, (V/mil)	1200	2000	1200	1500

Table 5: Performance Property Comparisons

High Tg Polyimide (250C) provided consistent performance in 55110 thermal stress and shock in constructions greater than 70 mils in thickness compared to multifunctional epoxy. This is most likely due to the impact of the total thermal expansion of multilayer boards. Table 6 compares typical CTE's from 50°C to 125°C vs. total substrate expansion from 50C to 250C. It is important to note that the effect of Z-axis expansion is a combination of the pre-Tg alpha, Tg of the material, and the post-Tg alpha, (where the resin expands at a four-fold or greater rate than below the Tg[1.)] For this reason, higher Tg materials tend to offset the impact of the increased out-of-plane CTE's when utilizing higher constrained X and Y in-plane designs. This results in decreased total Z-axis expansion, which is less destructive upon the copper in the Plated Through Hold (PTH), which needs to be ductile enough to withstand component soldering operations. By keeping the total expansion down (by material selection) and controlling the elongation of plated through hole copper, the PTH integrity has been shown to be robust through HAST (Highly Accelerated Stress Testing) and other simulation testing to validate assembly operations or testing these materials under accelerated product life simulation conditions [2].

Material Type	Pre-Tg alpha (ppm)	% Expansion, (50-250C)

FR-4, Tg 130C, E-glass	70-100	> 5%
FR-4, Tg 180C, E-glass	65-90	2.5-3%
FR-4, Tg 180C, Aramid	65-90	2.5-3%
Polyimide, 250C, E-glass	45-75	<1%
Polyimide, 250C, CIC constrained	55-90	<2.0 %
Polyimide, 220C, Aramid	95-110	3-4%
Polyimide, 250C, Aramid	75-100	<2.5%

Table 6. Comparison of Total Expansion of PWB Materials

PROCESSING AND DESIGN APPLICATIONS

As a material that is processable in most standard multilayer board shop equipment and processes, it is important to note some differences that the non-woven aramids provide. As with most high performance materials, moisture control is critical through lamination and assembly operations. Prepreg vacuum desiccation under standard conditions of 29 inches of vacuum for 12 to 16 hours was found suitable for most applications. Conventional copper cleaning was preferred to mechanical scrubbing to ensure the cores were not mechanically damaged or stretched to impact dimensional stability or CTE properties of the materials. Zero to +0.3 mils/inch artwork compensation, has been found acceptable for imaging, depending upon design and process. A comparison of E-glass to non-woven aramid shows the impact of dimensional stability upon registration in smaller features in illustrated Figure 5.

The aramid substrates were found to run through conventional alkaline and cupric chloride etch processes as well as most conventional aqueous resist strippers. Brown oxide was found better suited for the aramid constructions. Since the aramid fibers will absorb moisture, drying of core details as a minimum of one-hour at 270-300F was needed prior to lamination buildup.

Since the material is more compressible and porous than E-glass, the resin flow to lamination pressure relationship is different. In some instances, lamination pressure increases up to 25% have been observed to fill some design geometries. Melt rheology profiles were typical for the same resin configurations for E-glass, so kiss pressures and steps to high pressures were readily adaptable for the aramid substrates. For curing the resin matrices, the typical resin cure conditions were determined to be compared to the equivalent E-glass construction.

As was previously mentioned, the lower dielectric constant and reduced core thicknesses allow for thinner boards with smaller features To further push the limits of interconnect density, the use of blind vias has become important in leading edge pwb's. Traditionally, controlled depth or "peck" drilling and sequential lamination have been used at a substantial increase in fabrication time and manufacturing cost. As an all-polymer construction, laser drilling has shown promise for high speed, high throughput via formation.

Traditional thinking for designs will change with non-woven aramid constructions. 5 mil dielectrics will push to 2 to 3 mil dielectrics with a single-ply reinforcement. Since copper is the one component of the construction that contributes to planar expansion highly at 17 ppm, its use in power and ground planes will change from 2 ounce copper to 1 ounce copper (even as hatched grids) to minimize the impact on X, Y CTE. Signal layers will move to half-ounce or lighter for more complex multilayer designs. The aramid reinforcements are available in multiples and combinations of the following thicknesses in Table 7. and common core thicknesses in Table 8.

Non-Woven Aramid Style	E 210	E 220	E 230
Basis Wt. oz/yd	0.9	1.6	2.0
Thickness Yield per Ply	1.8 mils	3.0 mils	3.5 mils

Table 7. Non-woven Aramid Styles

Table 8. Common Thickness Constructions

Core Thickness, Mils	# plies E210	# plies E220	#plies E230
1.8	1	-	-
3.0	-	1	-
3.5	-	-	1
5	1	1	-
6	-	2	-
7	-	-	2
10	-	1	2

SUMMARY

The non-woven aramid constructions have been evaluated through prepreg coating and laminating operations as well as printed wiring board manufacturing operations with few changes from standard board processes. The material has also shown reliability through "torture testing" at several OEM's (to simulate assembly and accelerated product life testing.)

The non-woven aramid materials have shown promise as a reliable, cost-effective materials that will result in more imaginative board design as designers work toward higher interconnect density as processes such as laser via formation[3] become more main-stream.

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