A System of Producing High-Power RF Circuit Boards Employing a Low-CTE, Thermally Engineered Metalized Layer

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ABSTRACT

The paper will propose to present a technology for the fabrication of Printed Circuit Boards (PCBs), used primarily in high-power RF/millimeter wave applications, which involves the use of a thermally engineering metalized layer with superior thermal characteristics and a ceramic-matched co-efficient of thermal expansion (CTE). The resulting PCBs allow the user to direct die-attach high-power RF die, such as GaA and GaN devices through a cavity in the outer core layer(s), directly to the thermal layer below; and then wire bond to the surface conductive layer. The thermal characteristics of the engineered material quickly and efficiently evacuate the significant heat generated by the die while CTE "anchors" the resulting PCB substrate assuring the reliability of the die-attach wire bonds.

These PCBs are commonly constructed with other high technology materials such as polyimides, PTFEs and ceramic filled dielectrics and adhesive systems. Advanced process techniques are also employed in the fabrication of these PCBs: depth laser ablation and NC routing, blind and buried vias, via hole fill, edge plating, mixed finishes and multiple sequential lamination cycles. The presentation will explain the construction and provide general design guidelines.

This technology replaces the need for bulky, heavy heat sinking schemes around the high-power devices and ceramic hybrid packages. And since the item is essentially a Printed Circuit Board, made from otherwise typical Printed Circuit Board materials, the other electronic components in the design and on the board can be standard "plastic parts" attached in a standard process such as a vapor phase soldering. This results in an electronic board system that is smaller, lighter weight, and certainly much less costly than the ceramic hybrid, all-die alternative.

Thermal management of Printed Circuit Board (PCB) structures is a critical and ever-present issue, but perhaps never more than in the high power amplifier world of long-range communications devices. These designs operate on a constant delivery of localized high power feeding into precision RF (radio frequency) circuitry, usually on a PCB. The heat dissipated by these high power devices is significant and detrimental to the reliability of all of the components of the system.

There have been many methods developed and employed to measure, manage and mitigate this dissipated heat. Most involving thermally conductive materials such as aluminum, copper, graphite and composite combinations thereof. And while these approaches have been successful in addressing the heat dissipation factor in most of the applications, they all, however, lack a vital characteristic for the most sever of the environments: very high mechanical stability to protect against interconnect stress and component fatigue due to prolonged high thermal exposure.

In the most advanced high power designs the amplifiers are attached to the circuit substrate as bare die and wire bonded to the surface. The die-attach method is used both for device performance and miniaturization of the entire system. This has traditionally meant that the circuit substrate containing the RF circuitry is something on the order of a ceramic hybrid. Something made of materials with a dimensional stability – measured in CTE (coefficient of thermal expansion) – in the range of common ceramics, which is generally 5 to 20 ppm/°C. This is necessary for not only accurate die placement, but also subsequent reliability of the unit in operation. The "ribbons" commonly used for this wire bonding process are typically 0.001" (25.4 µ) in diameter and can be as small as 0.00025" (6.35 µ). Bonding these wires and then having them stay in place without breaking over the life of the system – many of which are designed to operate in an environment with dramatic temperature extremes and high shock and vibration – is of the utmost importance.

This results in a very costly and intricate electronic interconnect for three primary reasons:

1. Ceramic hybrids are significantly more expensive than PCBs (even very high technology PCBs). The materials are more costly, the process is more refined and the marketplace is much more limited.
2. All components mounted on to a ceramic circuit are required to be bare die – standard PCB SMT (surface mount technology) is not an option. This makes the component costs on these units very high as the user must source bare

die for even the common resistors and capacitors. This is assuming that they can get one of the manufactures to sell them these components in bare die. Often they will not due to the inefficiencies this causes in their manufacturing lines for what is eventually a very small sale. This leaves the user with the nearly ridiculous process of removing packaging material from “standard plastic” components to get them back to bare die form.

3. Interconnecting a ceramic circuit with the rest of the electronics in any given system may require extra “adaptive” items to account for the mismatch.

Over the last couple of years a relatively new, thermally engineered metalized layer (TEML) composite material is showing promise of fulfilling this critical gap. It is a copper-graphite composite that has excellent thermal conductivity properties (similar to copper) and at the same time a very low CTE, similar to ceramic (see Figure 1).

Feature	Unit	Copper Graphite	Epoxy	Graphite Epoxy	OFHC Copper	Aluminum
Thermal Conductivity						
x - y axis	W/mK	285 - 300	0.5	175	390	160
Z axis	W/mK	210	0.5	1	390	160
Heat Capacity (Cp)	J/g-K	0.433	0.6			
CTE (avg 20°C to 150°C)						
x - y axis	ppm/C	7	55	6.5	17	25
Z axis	ppm/C	16	55	55	17	25
Tensile Strength						
x - y axis	ksi	10			34 - 46	40.0
Z axis	ksi	5			34 - 46	40.0
Compressive Strength	ksi	28.5				88.0
Yield Strength (composite)	ksi	12.2			26 - 44	45.0
Elastic Modulus (Young's)	msi	11	3.5	11	17	1.0
Resistivity	μΩcm	4.36		2.85	1.71	0.04
Density	g/cc	6.07		1.65	9.10	2.70
Machinability (drill/rout)		excellent	excellent	fair	good	good
Plated Metal Adhesion		excellent	excellent	fair	excellent	good
Lamination Adhesives		standard	excellent	fair	excellent	good

FIGURE 1

The TEML is a copper-graphite composite that is cast into a block in a vacuum chamber at extremely high temperatures. The vacuum assures that all organics are purged during the process thereby relieving concerns of subsequent corrosion or galvanization. After the casting process the block is cooled and then undergoes a “slice and grind” operation to make sheets for use in PCB fabrication. The common sheet thicknesses are 10 mil, 20 mil and 40 mil (254 μ, 508 μ and 1016 μ). A very thin electro-less copper finish is added to encapsulate the composite and result in a sheet of TEML ready for use in a PCB.

Another increasingly critical attribute of advanced PCBs is the weight that they add to the systems that they anchor, specifically those employing traditional heat sinking technologies such as aluminum or copper. The TEML material can be advantageous in this regard also. It is 30% lighter than copper by mass and nearly the same weight as aluminum in comparable thermal conductivity volumes. And the most important feature for the PCB manufacturer is that the material combines well with standard PCB processes and materials - including materials designed for high frequency applications. And requires no special equipment to process.

In addition to the capability of direct die-attach, the PCB constructed with the TEML is more dimensionally stable than a standard PCB and so offers the user component mounting surfaces – Layers 1 and N – that can more effectively accept finer pitched devices. The PCB structure will more closely match advanced IC (integrated circuit) package CTEs. An SMT process can be employed – either vapor phase or standard - on the PCB with fiducial targets locating the placement of devices like BGAs (ball grid arrays) and other QFNs (quad flat no-lead). The TEML PCB will have the added benefit of allowing for lower reflow oven temperatures during processing. In the case of direct die-attach, on the surface or into a cavity, the TEML serves this dual purposes.

As mentioned the CTE serves to maintain the PCB at a stability level that will facilitate die placement and wire-bonding as well as assuring that the wire bonds survive over time. The TEML also works as a heat sink to evacuate the heat generated by the devices on the PCB – specifically high power amplifier die, such as GaNs (gallium nitride), GaAs (gallium arsenide) or other type of MMIC (monolithic microwave integrated circuit). Since the TEML is fundamentally conductive it is also often used as an electrical ground plane layer in PCB.

Fabricating a PCB with TEML is very much like making any other RF/microwave PCB with a few added steps (see Figure 2). For best utilization of the material's benefits the TEML should be located just inside the outer core of the PCB structure so that a cavity can be laser ablated through the outer core to expose the TEML. The die is subsequently placed in this cavity and wire-bonded to the surface circuitry. Thermal Vias can be located plentifully throughout the PCB for heat conductivity and electrical grounding purposes. These vias make electrical contact with the TEML layer and can be through, blind or buried (see Figure 3). Standard Signal Vias are made in much the same way they are in a standard PCB, but the TEML layer must first be pre-drilled with a larger diameter at every Signal Via location and then filled with a non-conductive, low CTE material (see Figure 4). This will assure that the resulting plated through hole will not make electrical contact with the TEML layer.

Depending on the overall layer count the fabricator may want to add an additional layer of TEML just inboard of the bottom outer core of the PCB to achieve a more balanced stack up and minimize warping. The outer layers of the PCB can be either a "foil lamination" or "core construction" technique. In either case the materials used must be engineered to result in a thickness that will – when the cavity is subsequently made – most closely match the thickness of the device to be attached. This will ensure the shortest distance between the pads on the device and the pads on the PCB surface where the wire bonds will make connections. It is critical to system reliability that these wires are as short as possible. The TEML has been used successfully with common PCB laminates and pre-pregs made of polyimide, polyimide-aramid, ceramic-filled and PTFE (polytetrafluoroethylene) materials. The materials are often selected for their electrical performance characteristics.

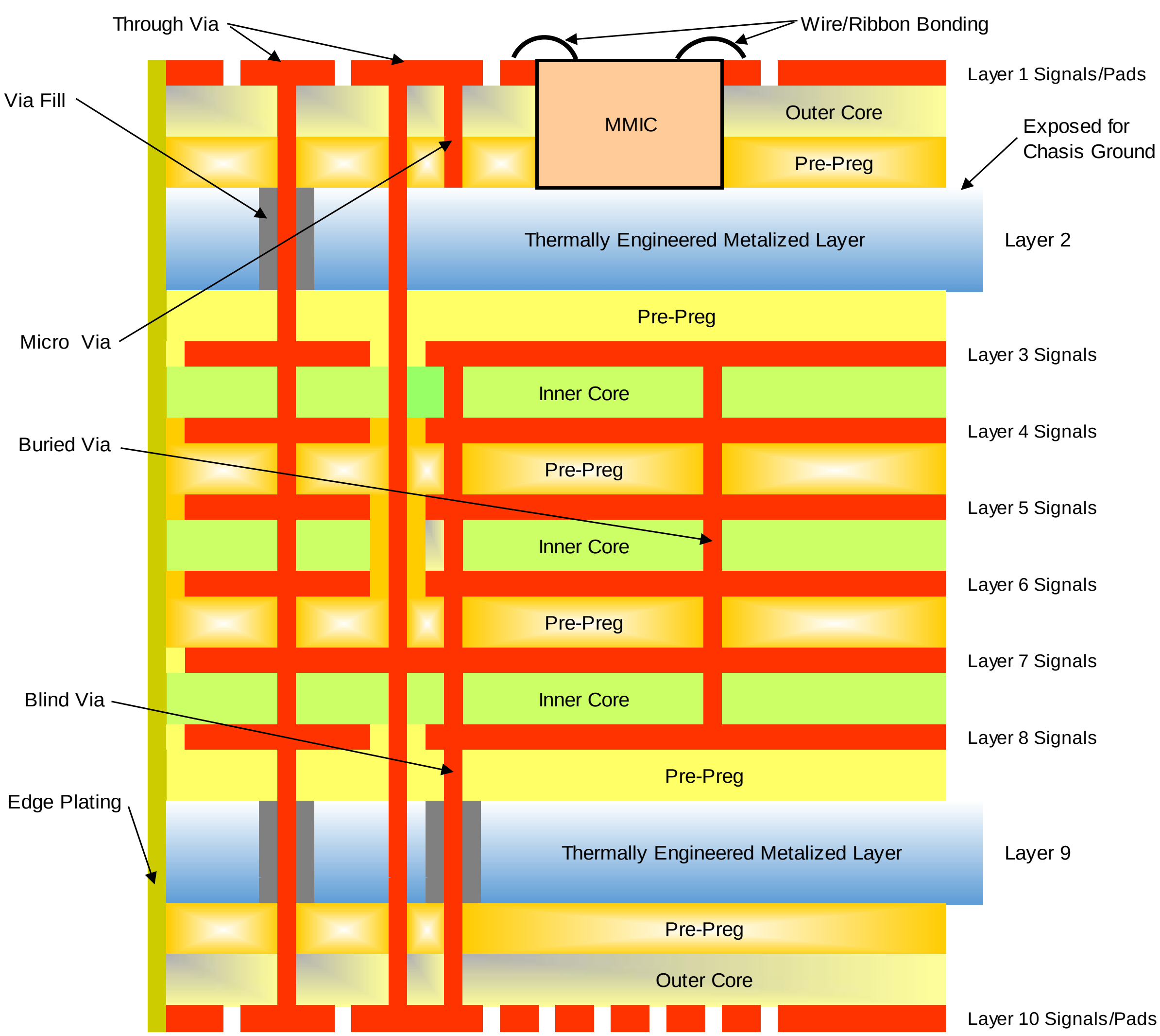

FIGURE 2

The wire-bonding process, often referred to as "chip & wire" occurs after all other components have been assembled to the PCB. These other components – those that do not require direct contact with the TEML for heat sinking – can be "standard plastic parts" that are often processed through a common SMT vapor phase operation. The die is then carefully placed in the cavity – usually over a thin layer of thermal epoxy (see Figure 5). The bottom of the cavity has been nickel-gold plated to provide an extra barrier and promote the heat sinking. The wire bonding process is very fragile. An ENEPIG (electroless nickel, electroless palladium, immersion gold) finish on the PCB outer circuitry is preferred by the wire bonders for best results – mitigation of embrittlement. Standard forms of wire bonding protection can be employed thereafter.

As previously mentioned the TEML will quickly and very efficiently conduct the heat generated on and inside the PCB. This heat still needs to be evacuated from the PCB for reliable operation. To complete the heat sinking system and further evacuate the heat from the PCB two popular options are available: "edge plating" or "wings". In the edge plating version the edges of the PCB are plated with copper and then a finish material – which contacts the TEML at its locations in the stack up.

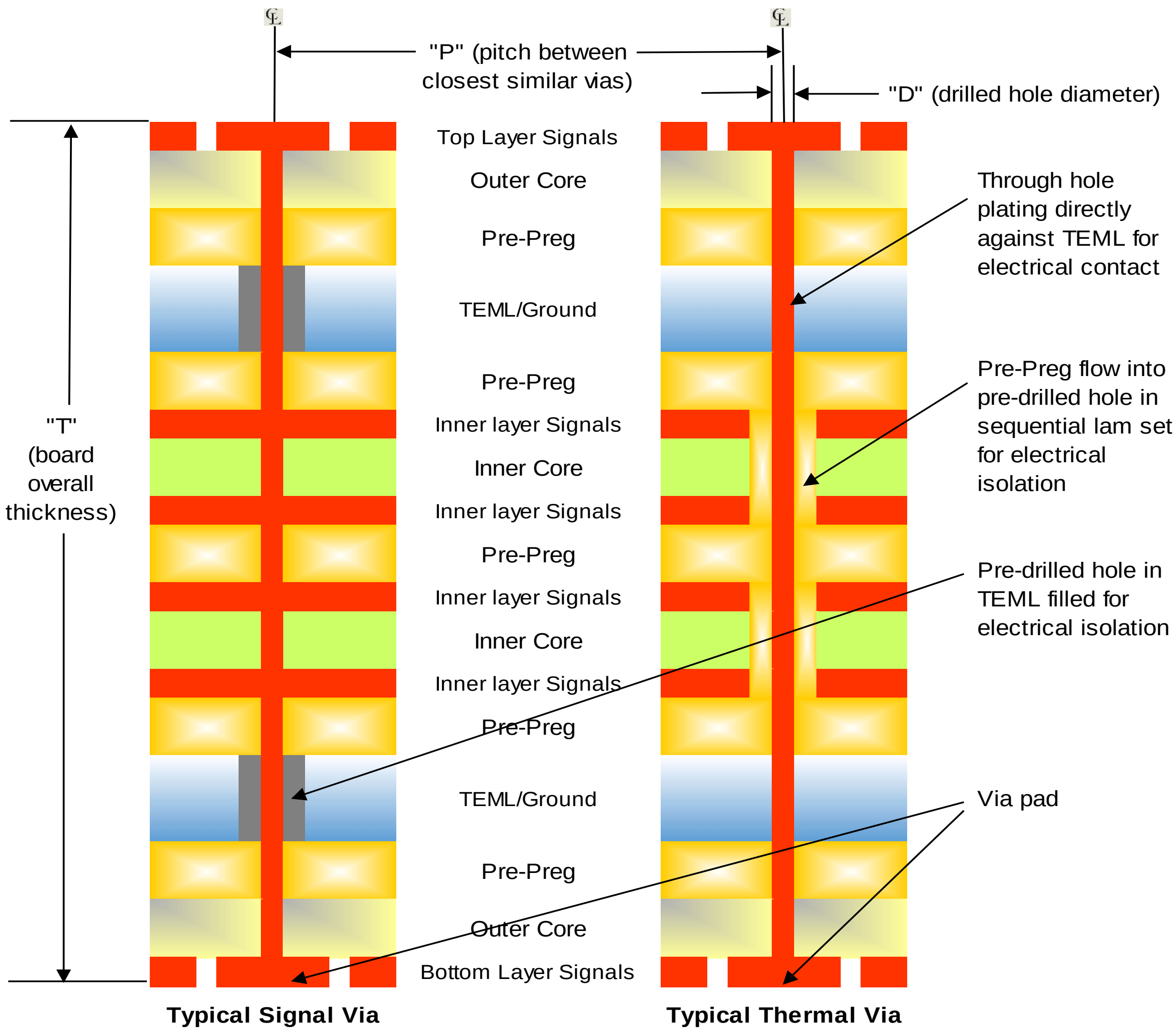

FIGURE 3

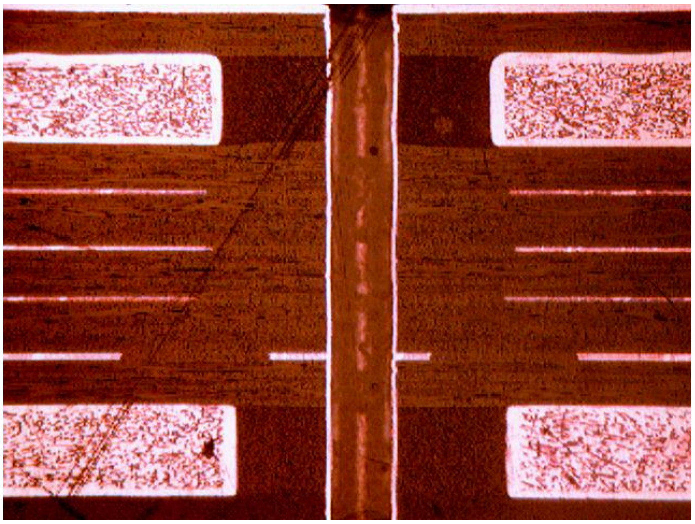

FIGURE 4

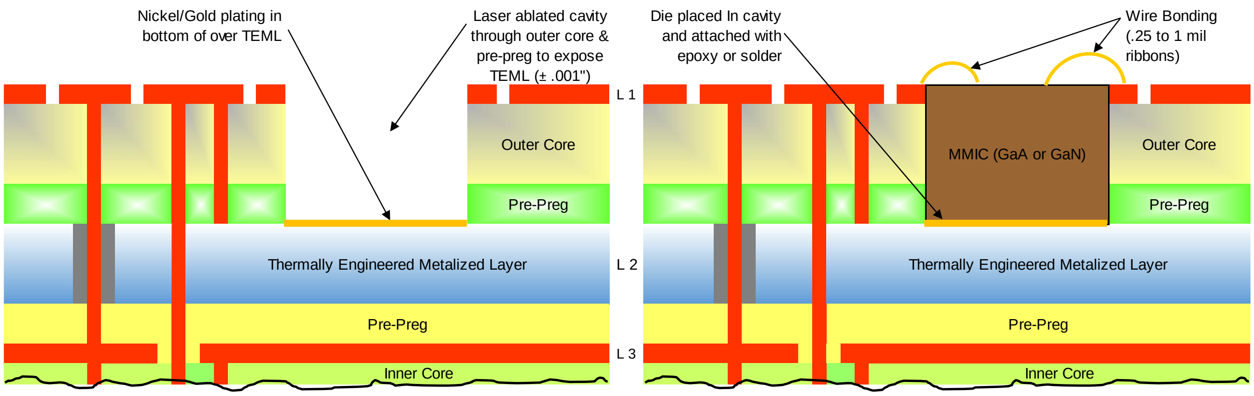

FIGURE 5

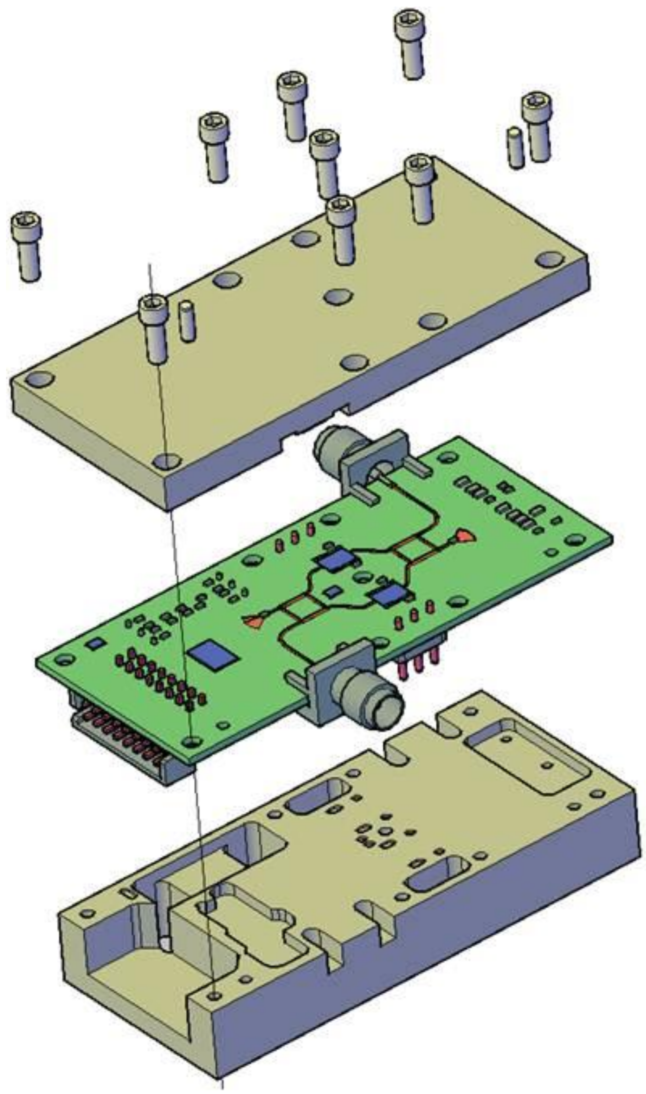

FIGURE 6

This edge-plated PCB can then be designed to contact the chassis of the system, usually made of aluminum, for further heat sinking (see Figure 6). In the wing option – or "Wedge Lock" as it is sometimes referred to - the TEML layers extend beyond the edges of the PCB and can then enjoy a three-point contact with the chassis. Either way the heat continues to move through the TEML and out of the PCB through the chassis and out the remainder of the heat sinking system.

TEML PCB designs are being considered and used in a number of applications. Originally the technology was developed to solve a significant challenge with a very high power, millimeter wave application. It was quickly adapted to other radar-like applications – like phased array - where RF/microwave PCBs commonly encounter heat issues generated from very small and sensitive integrated circuit components. More recently the technology has been adopted by the oil & gas industry for applications commonly known as "down hole" as well as by engineers involved in super-computing. Eventually the technology may find itself in common sensor and communications designs in commercial, automotive and even consumer applications.

In summary, a PCB constructed with TEML can solve the difficult challenges of efficient heat sinking with superior dimensional stability. The resulting system can be lighter, easier to manufacture, more reliable over time and less costly. The process to fabricate such PCBs is similar to ordinary techniques – with a few special steps – and does not require any special equipment.

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San Diego, CA

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- PCB thermal management a critical issue. Especially with high power amplifiers for long-range communication devices.
- Dissipated heat is significant and detrimental to system reliability.
- Many methods developed to address PCB thermal management: aluminum, copper and various composites used as heat sinks. Lacking superior mechanical stability.
- High power amplifier designs employ direct-die attach for performance and miniaturization. Bonding wires commonly 1 mil (25 µm) Ø and sometimes as small as .25 mil (6 µm) Ø.
- Substrate must be very stable – have a very low CTE (coefficient of thermal expansion). Ceramic substrates commonly used requiring all components to be bare die.
- Interconnecting ceramic hybrid to rest of system an be bulky.

- Recently developed, thermally engineered metalized composite layer for use in PCBs is able to provide superior thermal conductivity and very stable – ceramic-matched – stability.

- Material is copper/graphite composite cast into blocks in a vacuum chamber at extremely high temperatures. Organics are purged during casting mitigating subsequent corrosion or galvanization.

- Blocks are “sliced and ground” into 12” X 18” sheets for use in PCB stack ups. Common available thicknesses are

  - 10 mil (0.25 mm)
  - 20 mil (0.51 mm)
  - 40 mil (1.02 mm)

- Copper plating added to encapsulate composite.

- Material is very light weight vs. other heat sink material.

Feature	Unit	Copper Graphite	Epoxy	Graphite Epoxy	OFHC Copper	Aluminum
Thermal Conductivity						
x - y axis	W/mK	285 - 300	0.5	175	390	160
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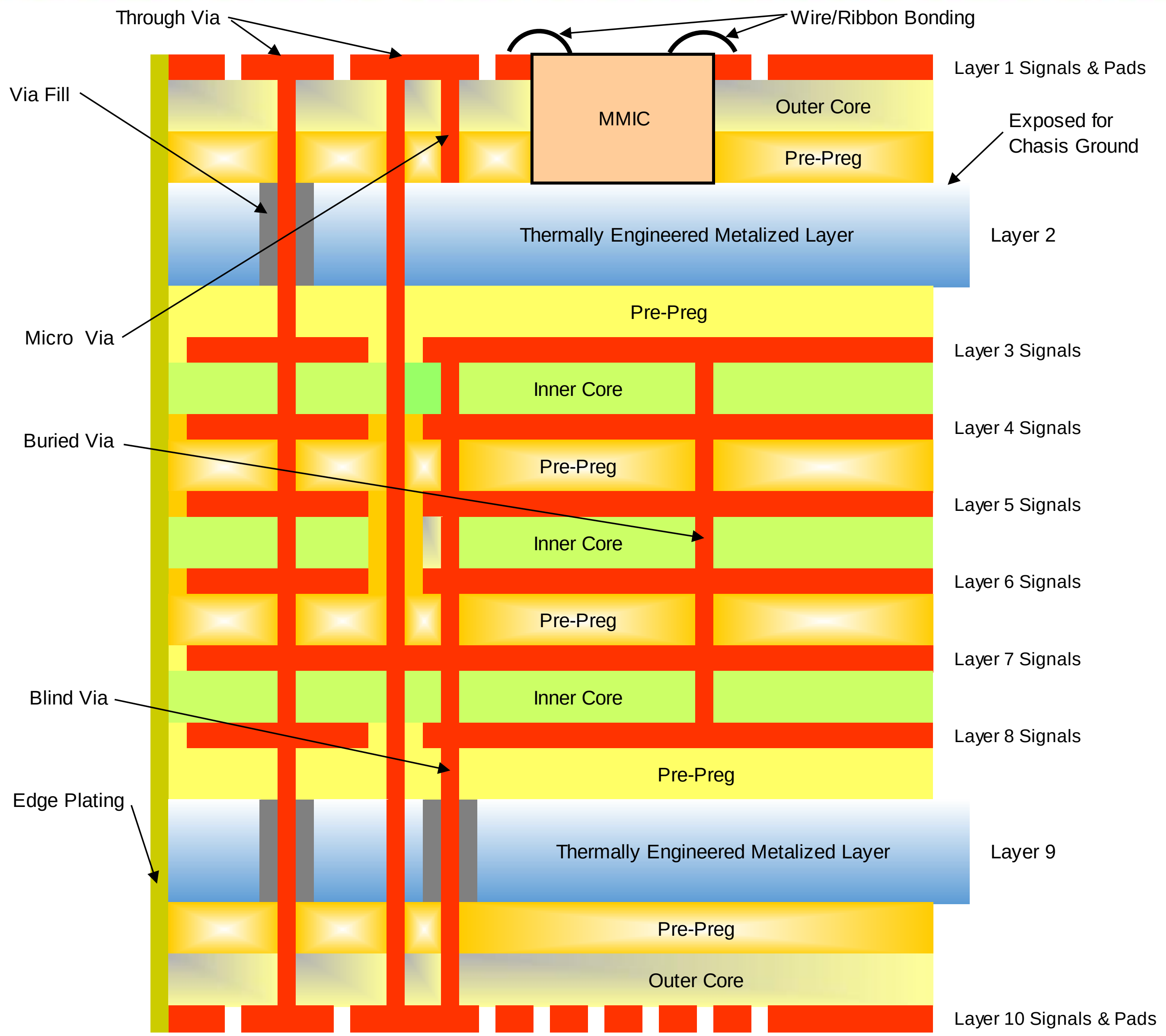
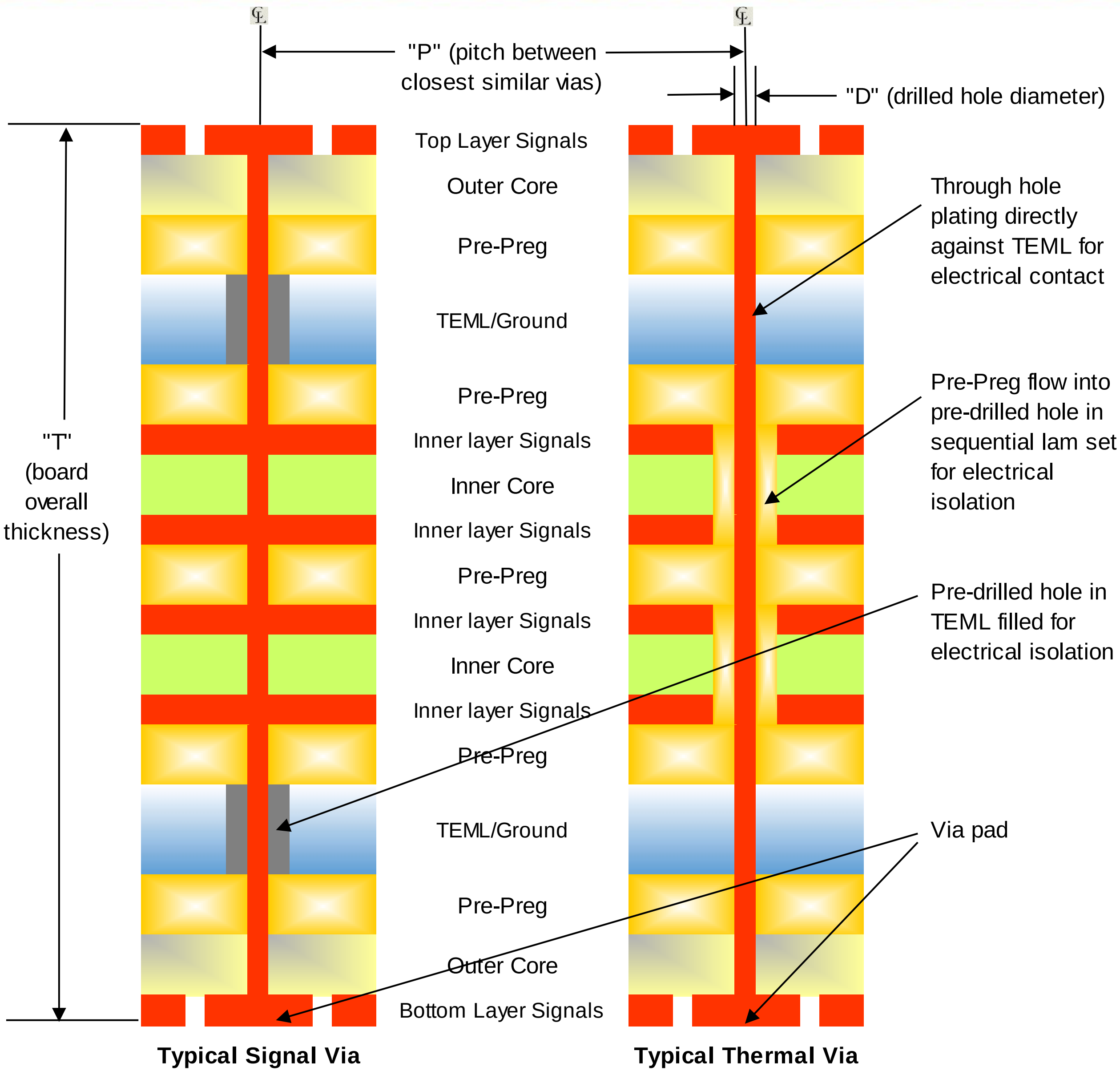
Machinability (drill/rout)		excellent	excellent	fair	good	good
Plated Metal Adhesion		excellent	excellent	fair	excellent	good
Lamination Adhesives		standard	excellent	fair	excellent	good

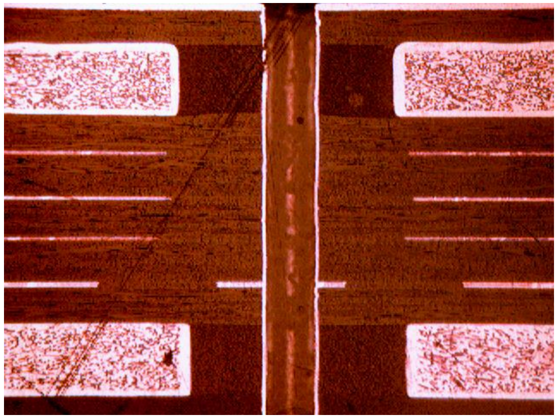
- TEML blends well with many commonly available PCB materials: polyimides, PTFEs, and ceramic-filled laminate. Processing is compatible with standard PCB methods and equipment.
- "Cap" or "Foil" construction/stack ups possible.
- TEML layer must be pre-drilled and backfilled at Signal Via locations with low CTE material.
- TEML material is conductive and commonly used as a ground plane. Edge plating or "wedge-locks" will continue the thermal conductivity out of the PCB.
- A balanced Stack Up in respect to the TEML will enhance bow & twist deterrence and result in a lower overall CTE for the structure.
- ENEPIG finish is best for wire bonding subsequent corrosion or galvanization.



Typical PCB Construction with 2 layers of TEML & bare die-attach wire-bonded on the Top Side

Typical Signal and Thermal Via structures





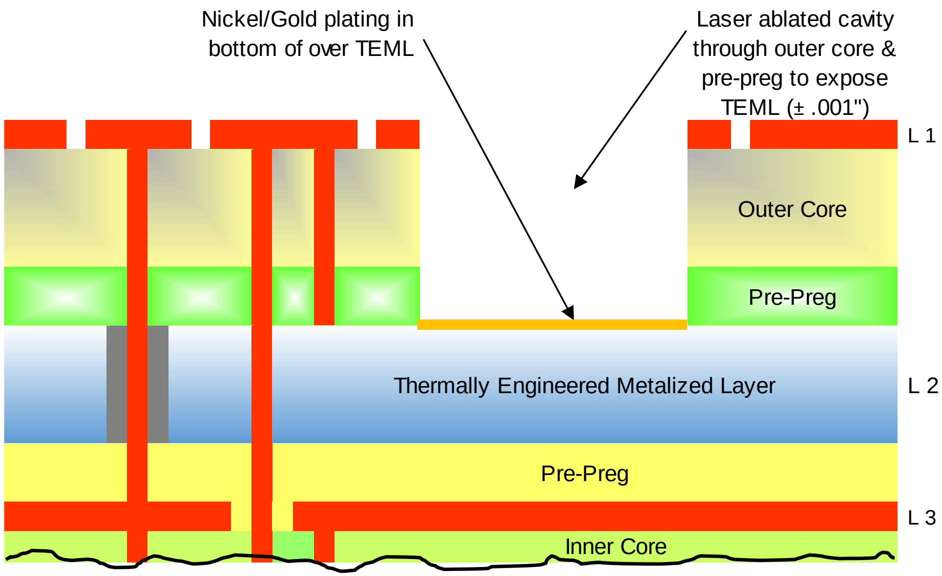
- PCB construction allows for use of standard “plastic” parts for all supporting components. A vapor phase process is common to assure proper component attachment.

- Mounting and wire bonding of the bare die - called “Chip & Wire” – occurs after all other components are assembled.

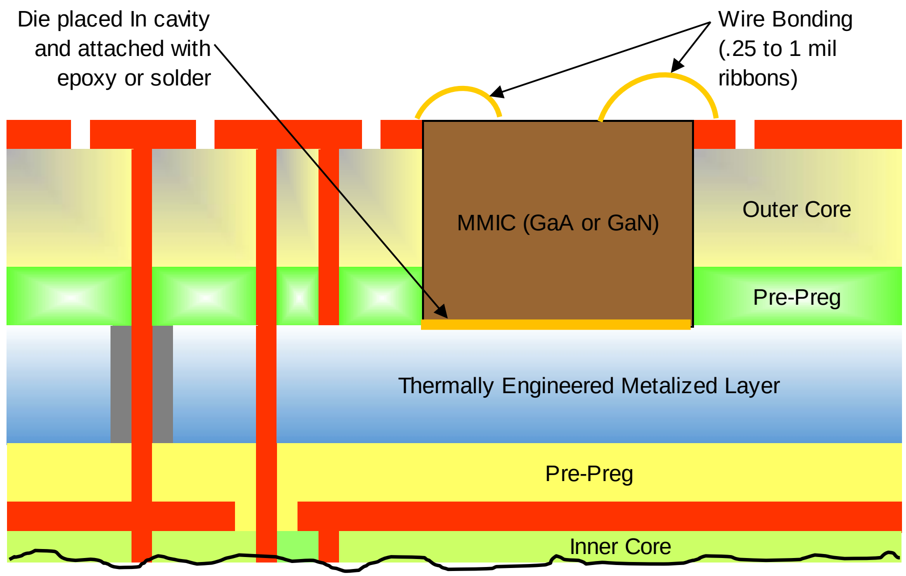
- Bare die – often GaA or GaN power devices – is placed into cavity through outer core and directly to composite layer with hi-temp solder (AuSn) or silver paste

- Au (gold) wires are common for RF applications - 1 mil (25 µm) down to .25 mil (6 µm) diameter.

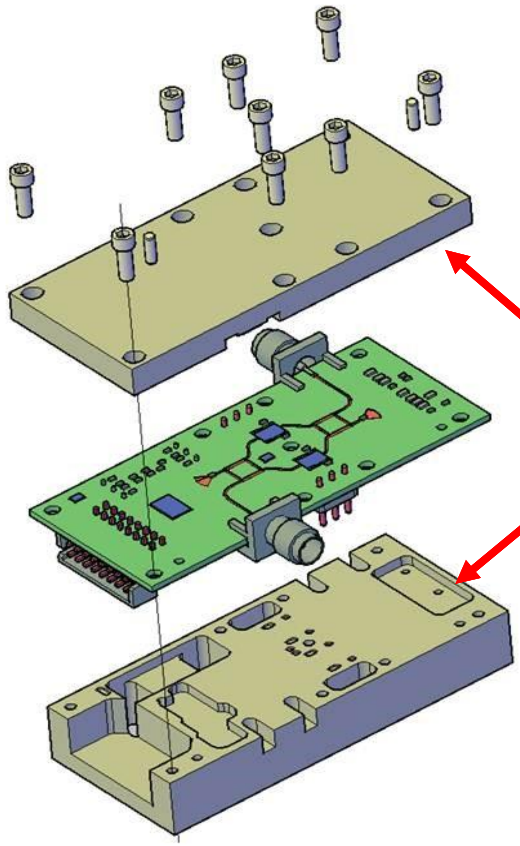
- Current technology is bulkier, less reliable and more expensive:
  - Ceramic hybrids are very costly to produce
  - All parts on Ceramic must be bare die
  - Standard PCB with glass feed-throughs is labor intensive and very large



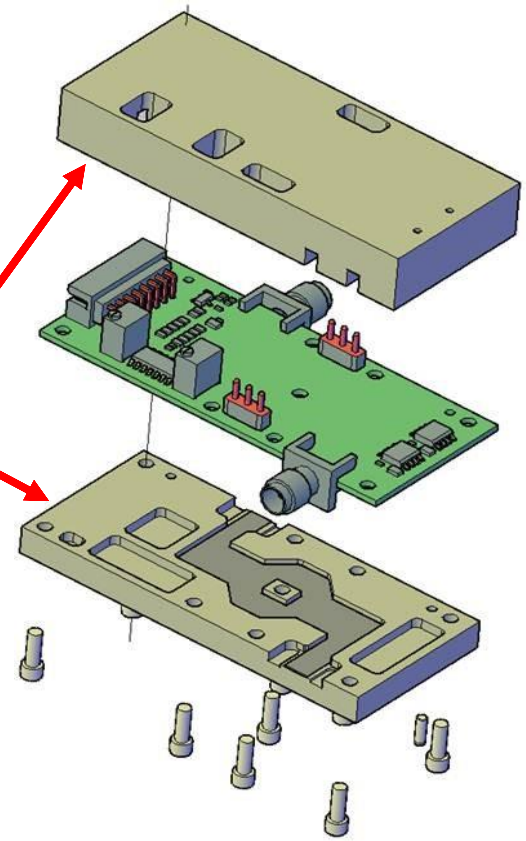
Cross-section of typical PCB with laser ablated cavity



Cross-section of typical PCB with bare die MMIC inserted and wire bonded



Aluminum milled chassis is electrical and thermal common ground



Exploded view of high power amplifier unit PCB – GaN bare die side up

Exploded view of high power amplifier unit with PCB – GaN bare die side down

SUMMARY

- Technology delivers superior thermal conductivity in a very stable package allowing for the selective application of fine-pitch and/or bare die along with standard parts on the same board.

- Achieves more interconnects in less space with less weight and at a lower cost than currently common alternatives.

- Will have wide application in many similar markets as the technology matures.

Thank You

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