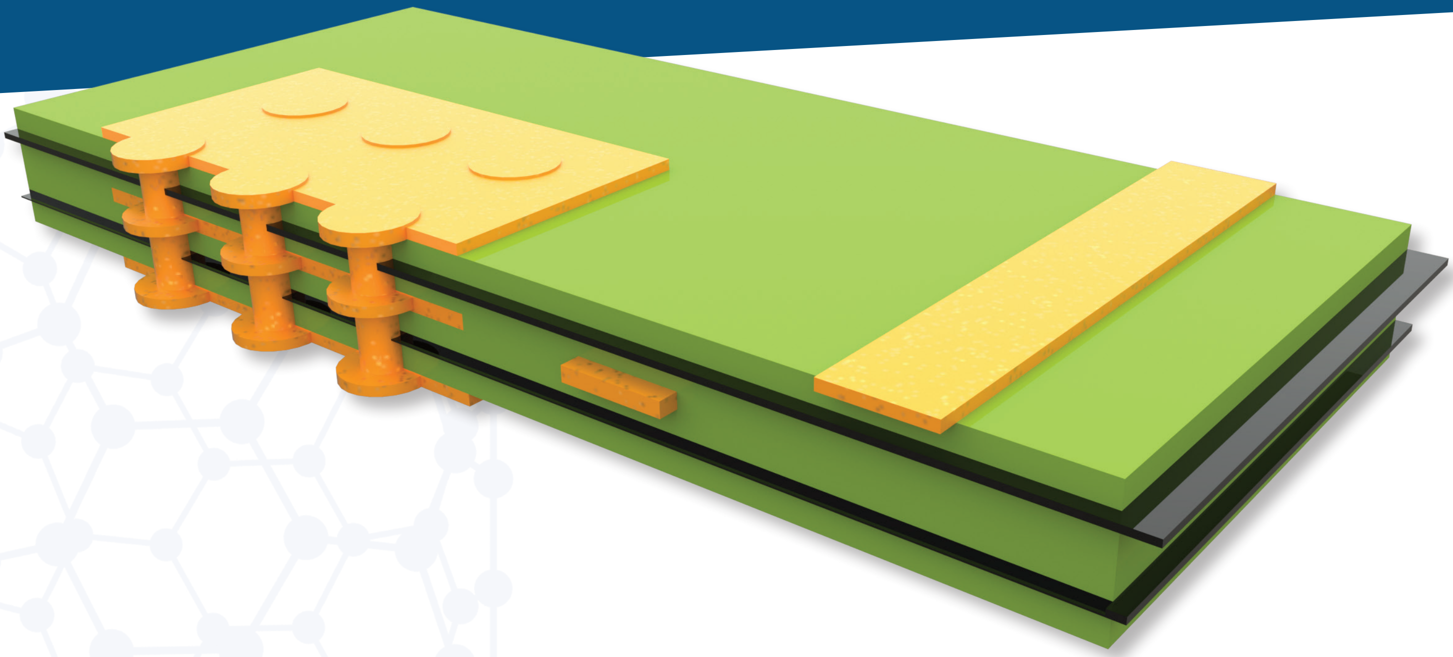
Use of Synthetic Graphite in High Performance RF and Microwave PCBs



John Priday,
Teledyne Labtech

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Introduction

The continued advances in miniaturization of electronic devices increases the challenges in managing waste heat. With active semiconductor devices becoming significant sources of heat, the printed circuit board (PCB) is asked to play multiple roles – to supply power to the device; to pass the increasingly high-speed signals between devices with as little loss as possible; and also, to play a significant part in passing heat energy away from such devices. In recent consumer electronics such as smartphones, the task of heat dissipation is not left solely to the PCB; areas of high heat concentration are also managed using pre-formed adhesive pads made from synthetic graphite, a good dissipator of heat. These are used to spread the heat energy over a wide area, reducing the temperature-induced stress on individual devices such as power amplifiers, improving life expectancy. Synthetic graphite has some appealing properties as we'll see later.

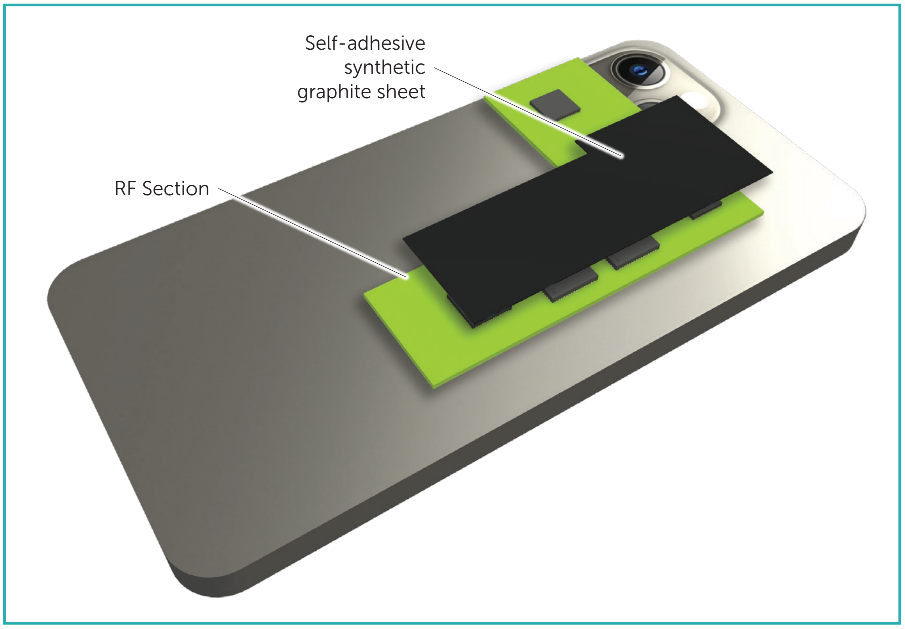

Figure 1: Typical smartphone RF section showing use of synthetic graphite pad to aid thermal management

Some of the most acute heat management challenges are seen in aerospace and defence applications. Usually these have an extreme focus on system size, weight, and power (SWaP), which makes heat management an even more critical topic. Such applications will typically sacrifice low cost to achieve the highest performance combination of thermal management, signal fidelity and size/weight. Examples include power amplifiers, phased array transmit/receive (Tx/Rx) modules and high speed digital processing cards. The most effective heat dissipation technique we've found for power devices is the use of copper coins which we've described elsewhere[1]. However, we wondered whether the benefits of synthetic graphite could be leveraged for SWaP-constrained medium power applications. Our concept was that PCBs use sheets of copper as ground planes. Could these be replaced with synthetic graphite instead?

1 Application Note - Thermal Management in High Performance RF and Microwave PCBs

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Why Care About Synthetic Graphite?

Synthetic graphite has an excellent in-plane thermal conductivity of between 1500 to 1600 W/mK (approximately 4 times that of copper) and densities between 2.0 to 2.1 g/cm^3 (approximately one quarter of copper). In other words, it's 4 times lighter than copper, and transfers heat 4 times better. It is available in thin sheets ranging from 10 µm to 40 µm in thickness and is typically supplied with a self-adhesive coating and on a carrier. What's not to like? The answer is two-fold: It is great at spreading heat across its width (x, y) but very poor at transmitting heat in its third dimension (z), for example down through the thickness of a PCB; a typical z-plane conductivity is 5 W/mK. More significantly it is very slippery – graphite is often used as a dry lubricant. This makes bonding it into a reliable PCB structure very difficult, akin to trying to glue a wet bar of soap. Given that many high-performance PCBs can use four to six copper planes or more, a reduction in mass of these would help the overall weight of a system.

Requirements for Using Graphite Planes in PCBs

High density active devices, often mounted in QFN style packages, can dissipate significant heat. One of many roles that the PCB must perform is to channel heat from the underside of the semiconductor devices through to the chosen heatsinking scheme as efficiently and effectively as possible.

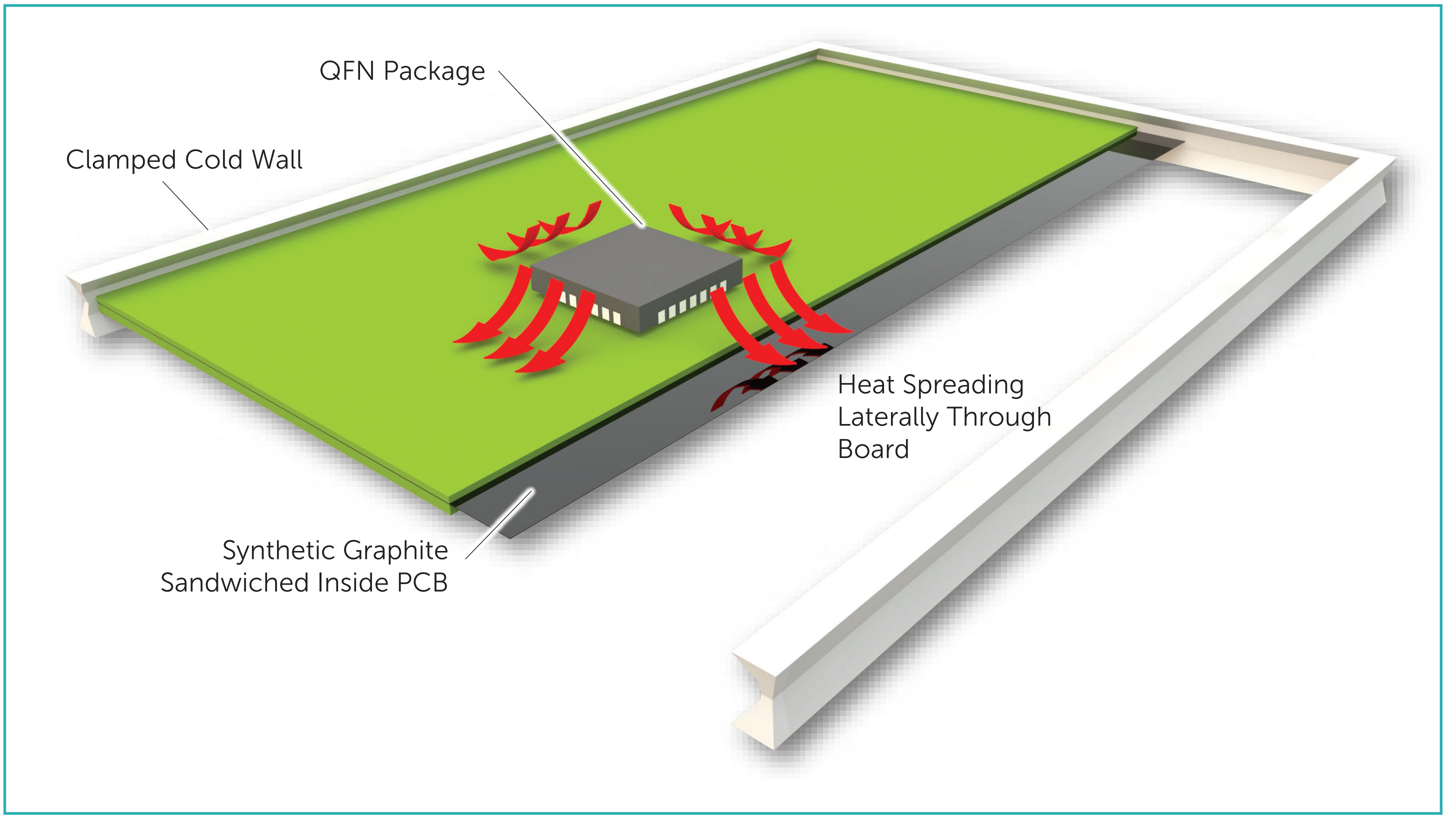

Figure 2: Aerospace card application with a QFN packaged high power device on a PCB. Thermal management is aided through use of cold walls and board clamps to allow heat to be moved into the enclosure. Use of thermal graphite would be beneficial if a suitable approach could be found to accomplish it.

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This is typically achieved through mounting devices on thermal/ground pads on the top layer of the PCB. These are then electrically and thermally connected to lower layers through plated through-hole (PTH) vias. Sometimes these are filled with solder, but more often with thermally conductive filler.

To replace copper planes in the PCB sandwich, graphite would have to perform well in several areas to be worth pursuing:

1. Have enough thermal advantage to be worth the effort.
2. Not add weight.
3. For the graphite planes to not significantly impact the passage of microwave signals in their role as ground planes.
4. To be mechanically robust and survive normal processing stresses during manufacture and use.
5. To be easy to process using normal PCB manufacturing techniques.

Development of Graphite-Layer PCBs

Of the needs listed above, the mechanical robustness requirement was by far the most difficult. We tried many different techniques to get the graphite layer to stick. Often thermal conductivity performance was good, but thermal stress tests would induce cracked vias and/or delamination. Patient development efforts eventually resulted in a successful approach, and it is the results of this that are described below. These use an evaluation PCB designed to allow each aspect of performance to be demonstrated.

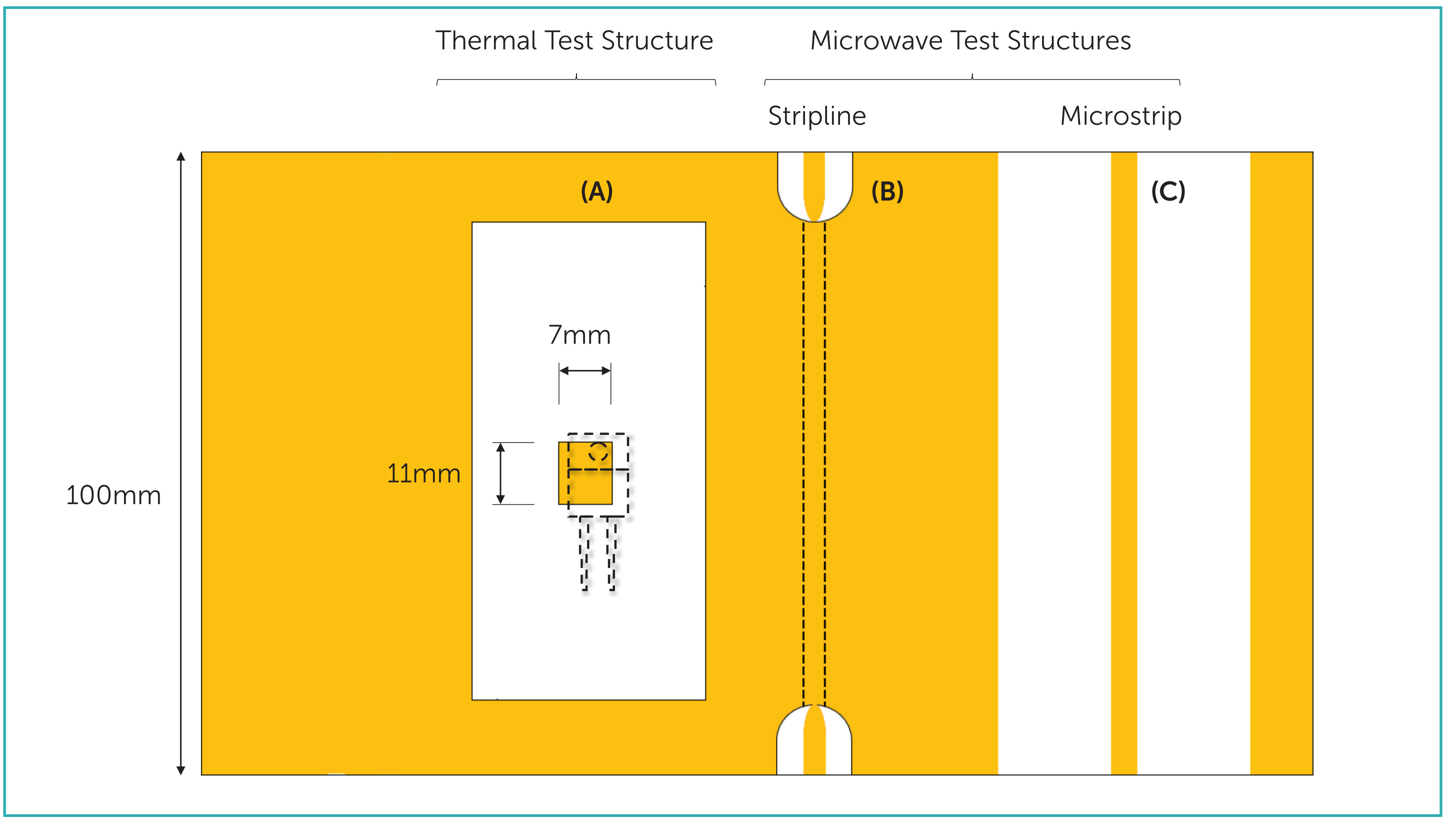

Figure 3: Test board designed to evaluate thermal conductivity performance (A), and microwave signal performance (B), (C).

Test PCB

An overview of the evaluation PCB is shown in Figure 3. The board was produced in two versions, one using two graphite planes, the other nearly identical but using copper planes. These are illustrated in Figure 4, with more detail given in the appendix.

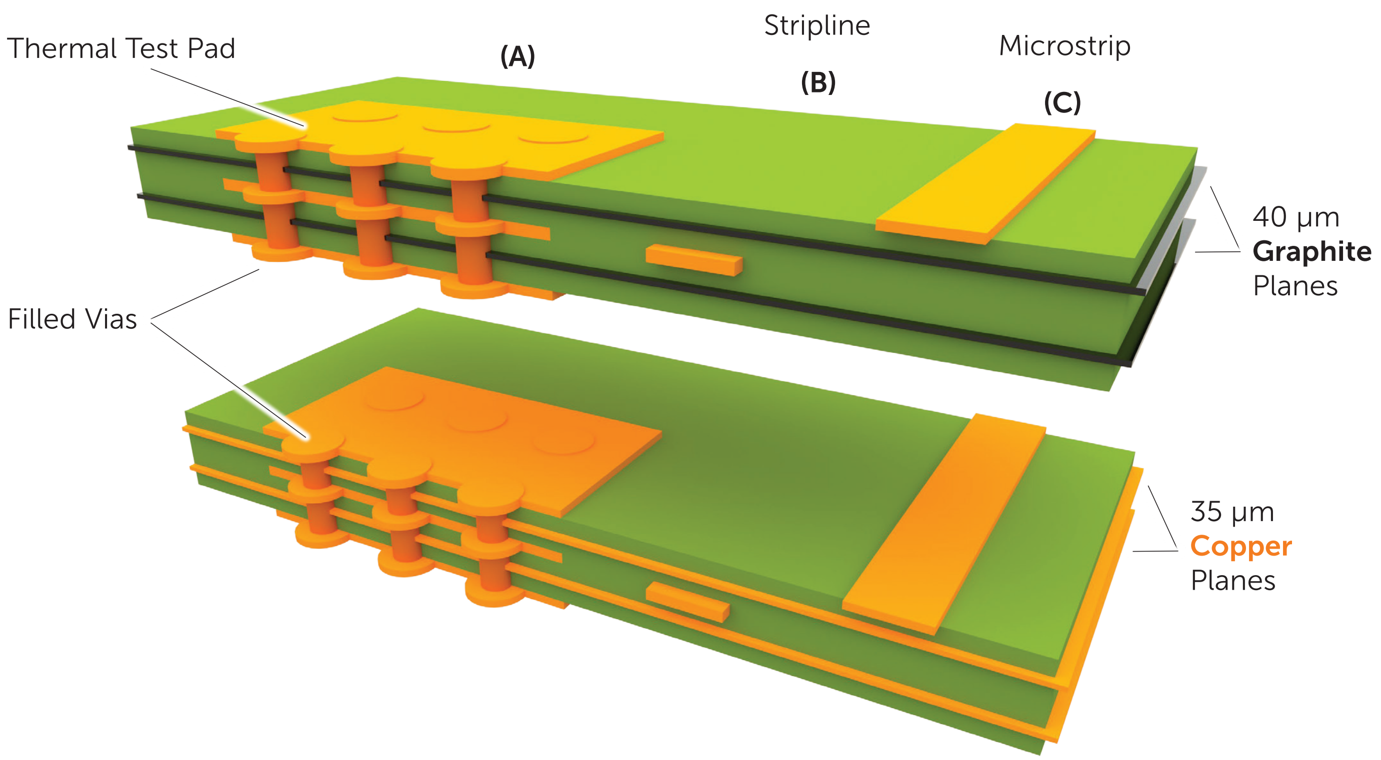

Figure 4: Illustration of the two nearly identical test boards, one using synthetic graphite planes, the other substituting copper planes.

Experiment 1: Is it Rugged?

The most extreme stress experienced by almost all PCBs is during processing. The thermal shocks of going through solder processing steps are extreme. Customers usually require PCBs to withstand two excursions from room temperature up to solder temperature for double-sided boards, then to allow for the possibility of three more re-work cycles in manufacture or repair. This is captured in IPC-650-TM-2.6.8 Condition A. Tests were performed with 1 cycle of 10 seconds solder float @ 288 °C and then 5 cycles, starting from ambient room temperature for each cycle. All tests passed. Figure 5 shows cross-sections taken post thermal stress. The only notable degradation seen was in the via filler that cracked after 5x thermal stresses (see figure 8), most likely a result of CTE (coefficient of thermal conductivity) mismatch. This was not deemed significant.

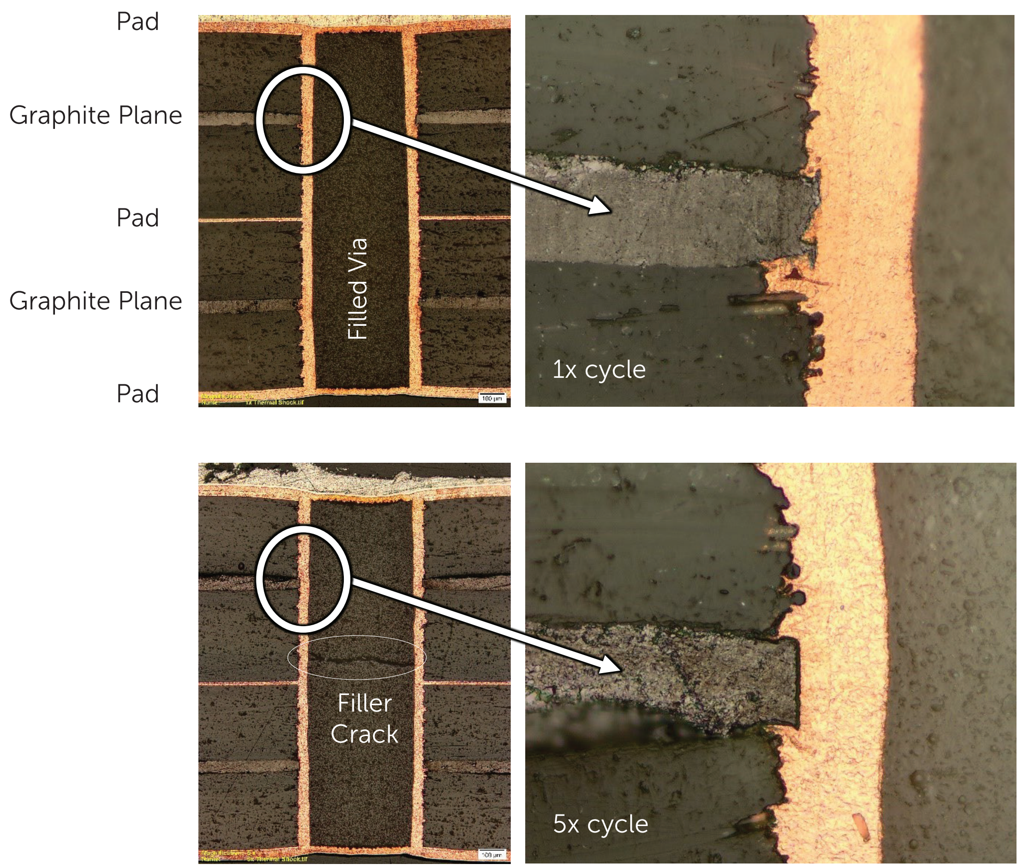

Figure 5: Cross-section of the graphite-plane PCB after thermal stress, after 1 cycle (above) and after 5 cycles (below).

Having survived the worst extremes of processing, boards will also withstand the rigors of real use.

Experiment 2: Can it Dissipate Heat?

Obviously, this is a wasted effort if the heat dissipation effectiveness is not significant. To explore this, a power resistor was mounted onto both PCBs using H20E conductive epoxy to act as a heat source. Thermal measurements were taken using a Teledyne FLIR infrared camera, as noted in Figure 6. In both cases the same power was applied (6.7 W) and allowed to stabilize for 5 minutes prior to taking any readings. The boards were suspended in free air with no additional heatsinking.

Copper Planes

Graphite Planes

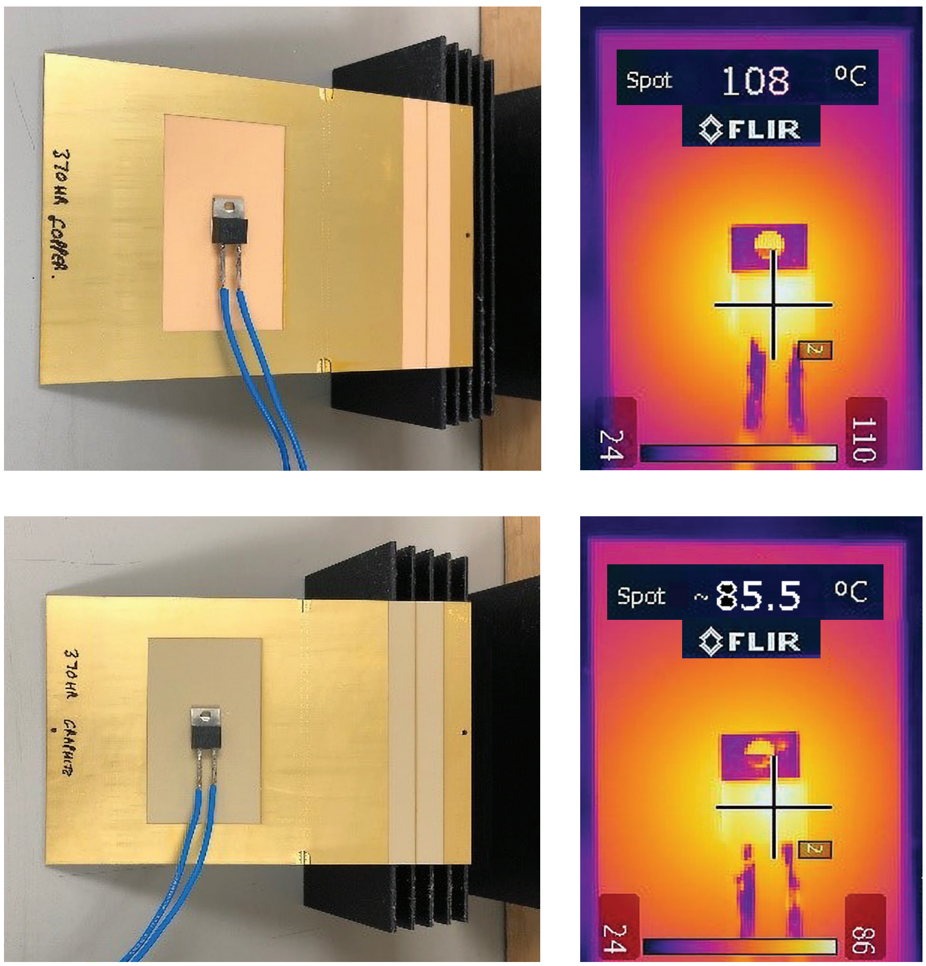

Figure 6: Thermal dissipation experiments. The test PCB with graphite planes (lower) showed significantly better dissipation.

As can be seen in Figure 6, the resistor was more than 20 °C cooler in the graphite-plane case compared to the equivalent using copper planes. This would significantly improve the Mean Time Between Failure (MTBF) reliability of a semiconductor device in normal use.

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Experiment 3: Does it Still Pass Microwave Signals?

Many high-performance PCBs also move wide bandwidth signals around, whether they are designed for use in signal chain applications, or, increasingly, high speed digital processing. It is therefore important for this new heat mitigation material to also not degrade signals significantly.

To evaluate microwave performance, our test structures had stripline (B) and microstrip (C) test paths. To make measurements, 10 mm aluminium plates were bonded onto the back of the two PCBs to allow mounting of SMA connector interfaces.

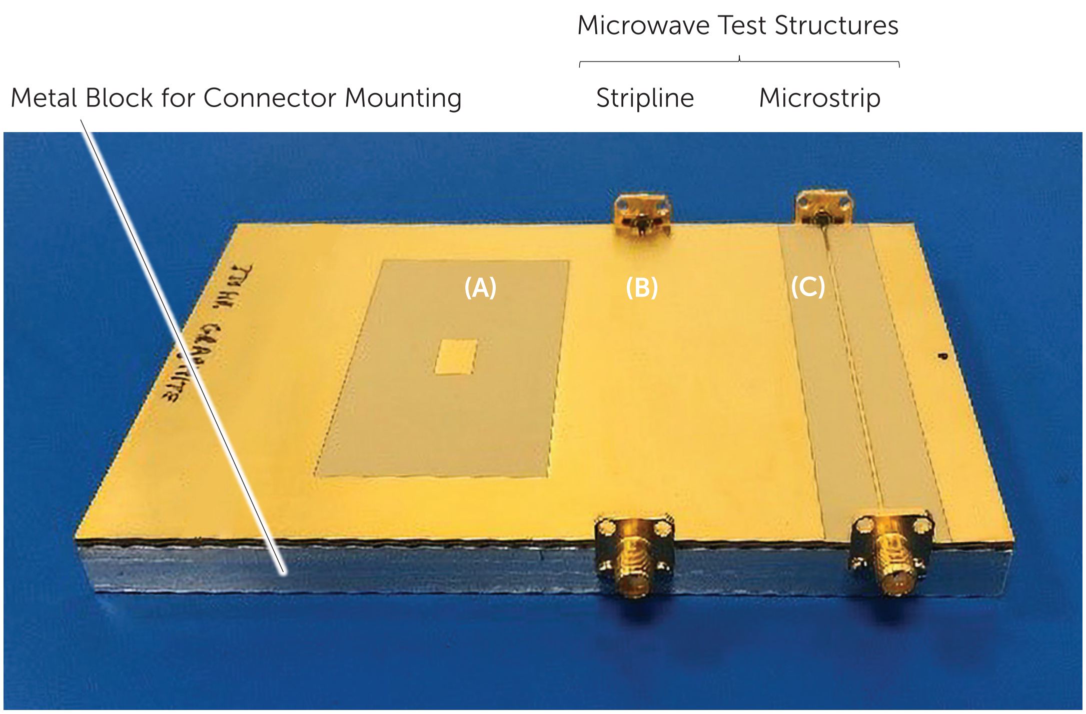

Figure 7: Graphite-plane PCB shown with test connectors and aluminum mounting block.

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A Vector Network analyser was used to conduct measurements over a frequency range of 5 to 20 GHz. The results are shown in Figure 8 for both stripline (B) and microstrip (C) test structures. The graphite planes caused a maximum degradation in insertion loss performance of, at most, 2 dB. Note that this was for a 100 mm trace length, which is two- to three-times a typical total length of signal path on most PCBs we see. For many applications, we believe this performance will be more than acceptable. (Results above 18 GHz for the stripline case were not optimal due to a mismatch at the connector interface.)

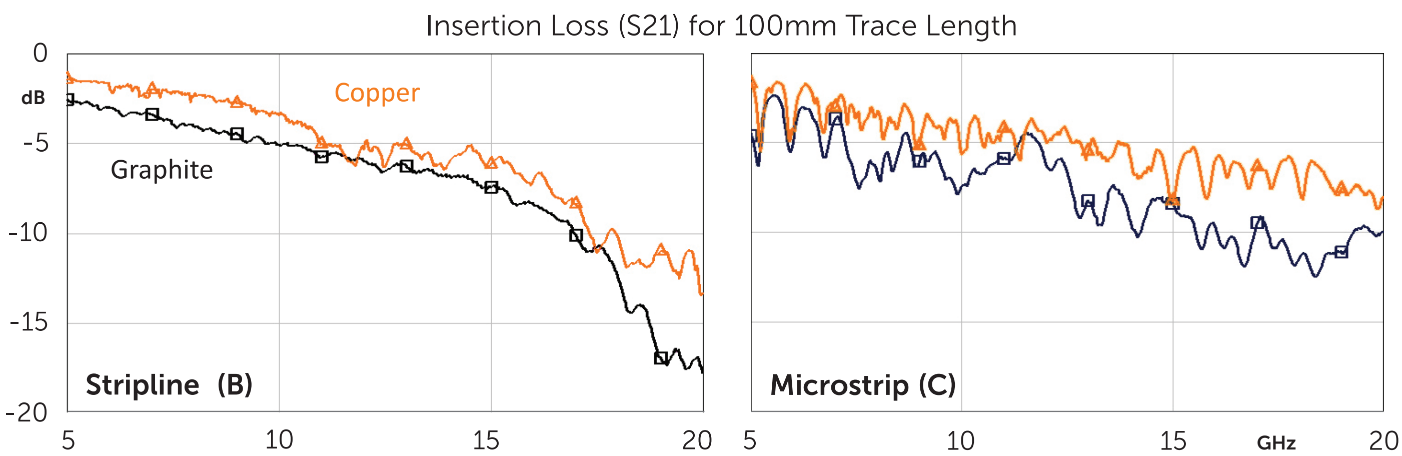

Figure 8: Measurements from 5 to 20 GHz of insertion loss (S21)

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Summary

We set out to investigate whether the replacement of copper planes in PCBs with synthetic graphite was both desirable, and practical. Using our list of criteria from earlier, we conclude the following:

1. Graphite-plane PCBs do have enough thermal advantage to be worth the effort, keeping a component more than 20 °C cooler in our example experiment.
2. Graphite-plane PCBs do not add weight, and actually weigh less, particularly when more ground plane layers are employed.
3. Such boards do not significantly impact the passage of microwave signals in their role as ground planes, showing less than 2 dB impact compared to copper for 100mm path lengths as both stripline and microstrip. As this is 2x to 3x normal total signal path lengths we encounter, we believe this will be acceptable in many applications.
4. These boards are mechanically robust and survive normal processing stresses during manufacture and use, proven through IPC-650-TM-2.6.8 thermal shock tests, even after 5 cycles from room temperature to 288 °C in 10 seconds each time with no cracked vias or layer delamination. They operate over the same temperature ranges as regular PCBs.
5. The new boards use normal PCB manufacturing techniques, with only a modest increase in time and cost.

Synthetic graphite offers a significant weight saving and offers benefits in terms of thermal management for PCBs that have medium power devices mounted on them. It's ability to carry and distribute heat efficiently in the X-Y plane, that can be taken out to the perimeter of the PCB and then extracted via clamps to a cold wall will be attractive for some applications. The additional benefit of allowing semiconductor devices to operate at substantially reduced stabilised temperatures will also enable improved MTBF predictions for PCBAs.

There are certain restrictions as a result of the necessity to maintain via integrity and we would strongly recommend early stage discussions with Teledyne Labtech to ensure all design for manufacture considerations are included.

Acknowledgements

KANEKA Corporation[1] for kindly supplying the synthetic graphite sheets Graphinity™ used.

John Priday, Chief Technical Officer of Teledyne Labtech, developed Labtech's microelectronic assembly (chip and wire) facility and oversees all microwave testing services. He started his career with Marconi Radar before moving the Marconi Research Centre in Great Baddow.

1 KANEKA | Electrical and electronic materials

Appendix – Test Board Construction

For our evaluation we selected 40 µm sheets of synthetic graphite that have a thermal conductivity of 1500 W/mK and a density of 2.0 g/cm³. Figure 9 shows the construction layers we used. For the copper equivalent board, the graphite planes were replaced with 35 µm copper planes.

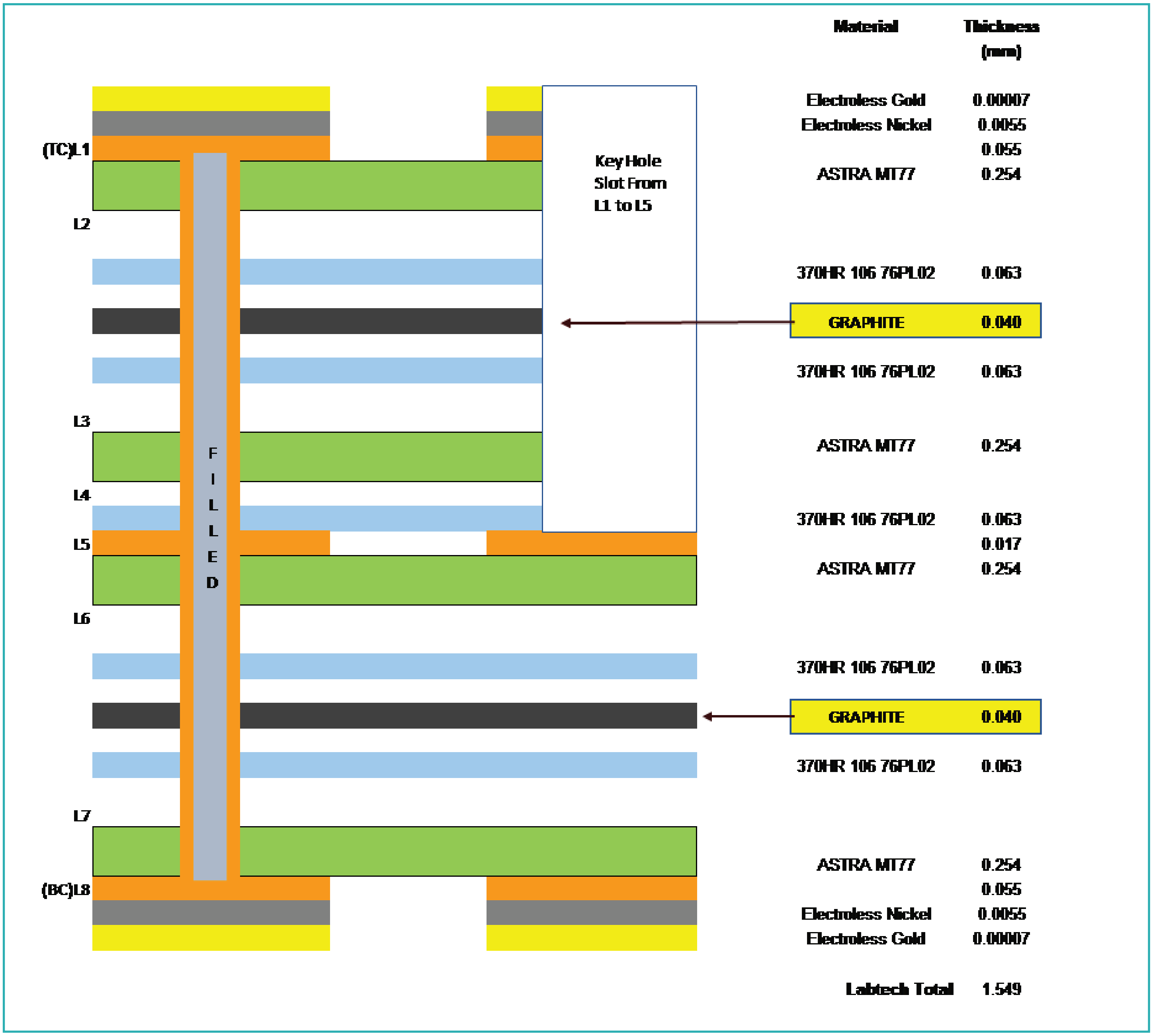

Figure 9: Construction of the synthetic graphite test board showing layer materials and thicknesses (mm)