

A Cost-effective Advanced Thermal Material for Metal-Core Printed Circuit Board (MCPCB)

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With the prevalence of power electronic products such as motor controllers and drivers, light emitting diode (LED) lighting modules, power supplies and amplifiers, etc, the industry has been forced to take into consideration thermal management while designing products. There are many thermal constraints associated with a power electronic system, for example, thermal impedance arises from the interfaces between components and PCB, heat sink and surround media, as well as the thermal interfaces at the chip packaging level. At PCB level, thermal constraint arises from the thermal conduction of the dielectric material.

One of the current approaches to enhance the efficiency of the thermal dissipation is the use of highly thermal conductive material such as those used in the Metal Core Printed Circuit Board (MCPCB). Nevertheless, the market of this thermal conductive material is dominated by the Japanese, American and Korean suppliers. In view of this, PCB Technology Centre of the Hong Kong Polytechnic University has launched a project to develop and formulate an appropriate synthesising technique for a MCPCB material with good thermal performance.

1. Details of the project

The scope of this project focused on enhancing the thermal conductivity of the insulation layer between the circuitry and the metal base plate for heat dissipation without compromising other major material properties. Instead of radically replacing typical PCB materials such as FR4 by other highly thermal conductivity material such as ceramics, we decided to modify existing PCB materials by adding filler to enhance its thermal conductivity. This not only minimises the material cost but also enables the new thermal conductive dielectric material to be compatible with existing PCB manufacturing processes. Among the factors that may influence the thermal conductivity of this dielectric, the types and the percentages of fillers are of paramount importance. Other factors such as the size effect of the filler and the amount of the coupling agent were also studied in this project. Details of the test matrix were shown in Table 1.

Table 1. Test matrix

Types of filler	Boron Nitride	Aluminium Nitride
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	(BN)		(AlN)
Weight percentages of the filler	10%	20%	30%
Sizes of the filler	53nm	0.15 μ m	4 μ m
Amount of the coupling agent (CA)	1%		2%

*The percentage of the coupling agent is in respect to the weight of boron nitride.
The coupling agent used in the study was 3-glycidoxypropyltriethoxysilane.*

Hexagonal boron nitride is a candidate to be used as filler as it possesses an intrinsic high thermal conductivity character. It also has lower dielectric constant. Aluminium nitride is used for comparison. Three different sizes of boron nitride were used, namely 53nm, 0.15 μ m and 4 μ m. The 4 μ m BN was sponsored by Momentive Performance Materials Quartz. Photos of these boron nitride powders are shown in Figure 1. The sub-micron sized boron nitrides are irregular in shape while the micron-sized one is in flake form. The resin used in the study is brominated epoxy resin solution.

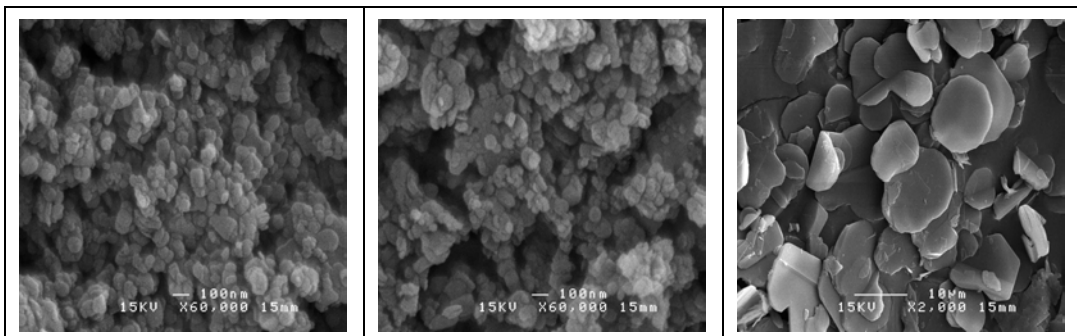


Figure 1. SEM images of the boron nitride powders, (left)53nm, (middle) 0.15 μ m, (right) 4 μ m

2. Preparation of the BN-filled thermal conductive dielectric

Figure 2 depicts the process flow for fabricating dielectrics with BN as filler (hereafter called BN-filled thermal conductive dielectric(s) or BN-filled dielectric(s)). The boron nitride powder was first surface treated with coupling agent. The surface treated boron nitride powder was then mixed thoroughly with epoxy resin and the resulting varnish was placed in a vacuum oven to remove the entrapped air and solvent. It was then thermal cured in a vacuum oven at 175°C for 2.5 hours. The process for preparing AlN-filled dielectric is the same as that of boron nitride.

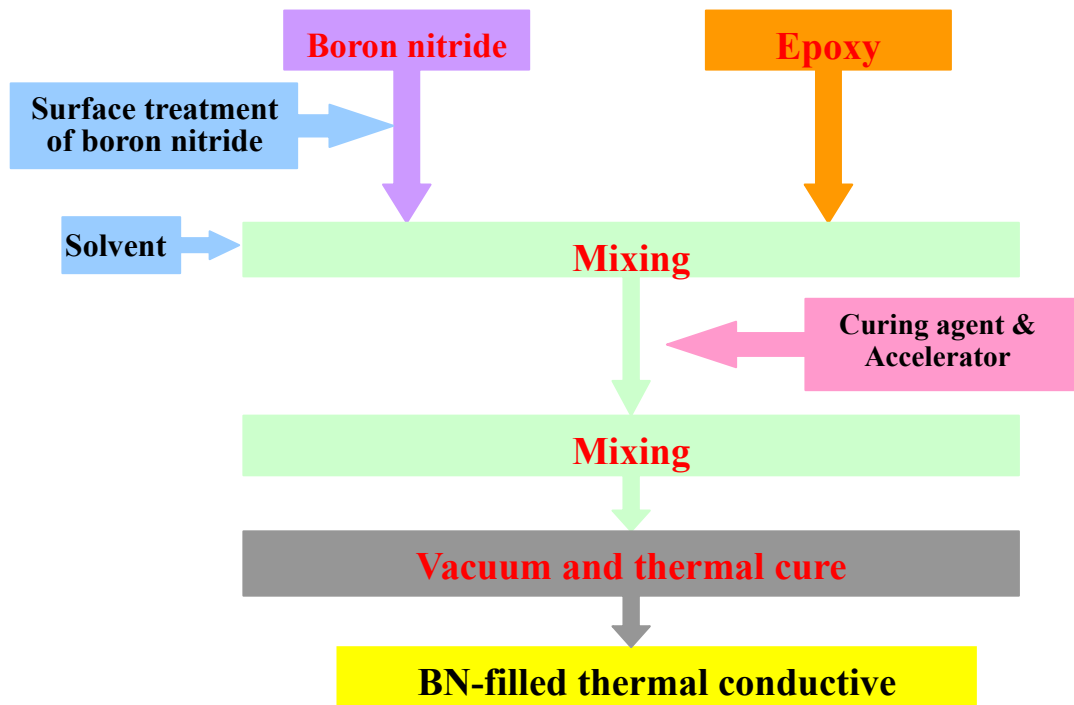


Figure 2. Process flow of preparing BN-filled thermal conductive dielectrics

3. Results and discussion

3.1 Thermal conductivity

- Size and percentage effects of the filler on the thermal conductivity
 Table 2 lists the results of the thermal conductivity of different filler-loaded thermal conductive dielectrics. It is observed that BN-filled dielectrics offer higher thermal conductivities than AlN-filled ones for any given filler loading, despite the pure filler powder having similar thermal conductivity. For the boron nitride filler, the maximum packing fraction is below 30 volume percentage which is much lower than that of aluminium nitride. In other words, boron nitride forms the thermally conductive networks at lower filler content than the AlN [1] and this attributes to the relatively high thermal conductivity of BN-filled dielectrics for a given filler percentage even though it has a slightly lower instinct for thermal conductivity than the aluminium nitride.

Table 2. Comparison of the thermal conductivity of different filler-loaded thermal conductive dielectrics

Percentage of filler	Boron Nitride (BN)	Aluminium Nitride (AlN)
10%	0.71	0.51

20%	0.71	0.54
Pure filler	70-120	140-180

The unit of the thermal conductivity is W/m.K

Figure 3 gives the results of the thermal conductivity of the BN-filled dielectric with varying sizes and percentages of boron nitride. It shows that for any given percentage of boron nitride, the larger the size of boron nitride, the higher the thermal conductivity will be. In addition, a higher percentage of boron nitride also gives higher thermal conductivity.

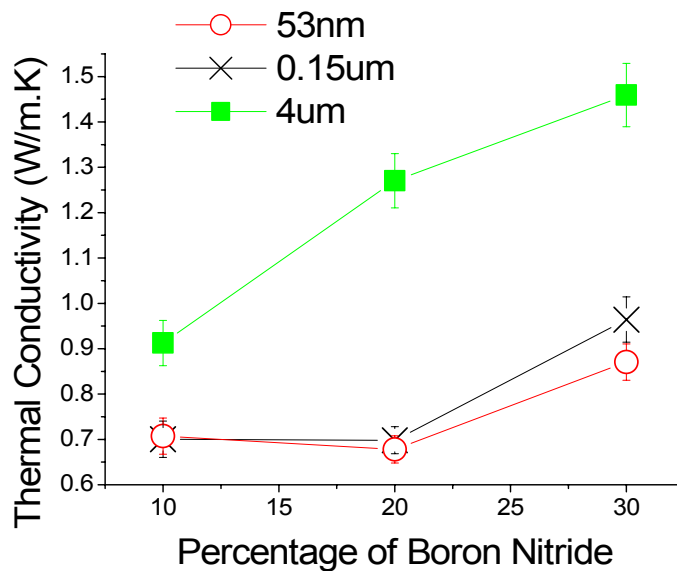


Figure 3. Thermal conductivity of dielectric with varying filler sizes and percentages of the boron nitride

It is easy to understand that more and larger boron nitride particles help to shorten the low thermal conductive path (i.e. epoxy matrix) and establish a high thermal conductive network (i.e. boron nitride) for heat conduction. In addition, larger size means lower surface to volume ratio, thereby, lower interfacial phonon scattering for a given weight of the filler [2]. Therefore, a higher percentage and larger size of boron nitride yields a higher thermal conductivity.

Figure 3 also illustrates that 20% of the sub-micron-sized boron nitride is the critical concentration at which boron nitrides start highly contacting with each other [1]. This helps to expedite the rising rate of the thermal conductivity with the boron nitride percentage.

The size and the percentage effects of boron nitride on the thermal conductivity can also be explained with the modified Bruggeman theory [3] for the thermal conductivity. When the dispersed filler is much more thermally conducting than the matrix, the model is represented as:

$$\frac{K_c}{K_m} = \frac{1}{(1-f)^{3(1-\alpha)/(1+2\alpha)}} \quad \text{Equation (1)}$$

where K_c is the thermal conductivity of the BN-filled dielectric
 K_m is the thermal conductivity of the epoxy resin
 f is the volume fraction of the BN
 α is a non-dimensional parameter which is inversely proportional to the radius of the dispersed BN

From Equation (1), it is obvious that the higher the volume fraction, f , of boron nitride, the higher the thermal conductivity of the BN-filled dielectric, K_c , will be.

- Coupling agent effect on the thermal conductivity

The coupling agent has two different reactive groups [4], i.e. hydrolysable and organofunctional groups. These different functional groups enable the coupling agent to function as intermediaries in bonding organic and inorganic materials, which do not tend to bond with each other. This improved bonding would lead to the increased thermal conductivity by minimising the heat scattering at the interface.

Figure 4 shows the effect of the amount of the coupling agent on the thermal conductivity of the BN-filled dielectric. It indicates that 1% of the coupling agent is sufficient enough to enhance the thermal conductivity. Further increase of the coupling agent causes the thermal conductivity to decrease as it becomes thermal barrier.

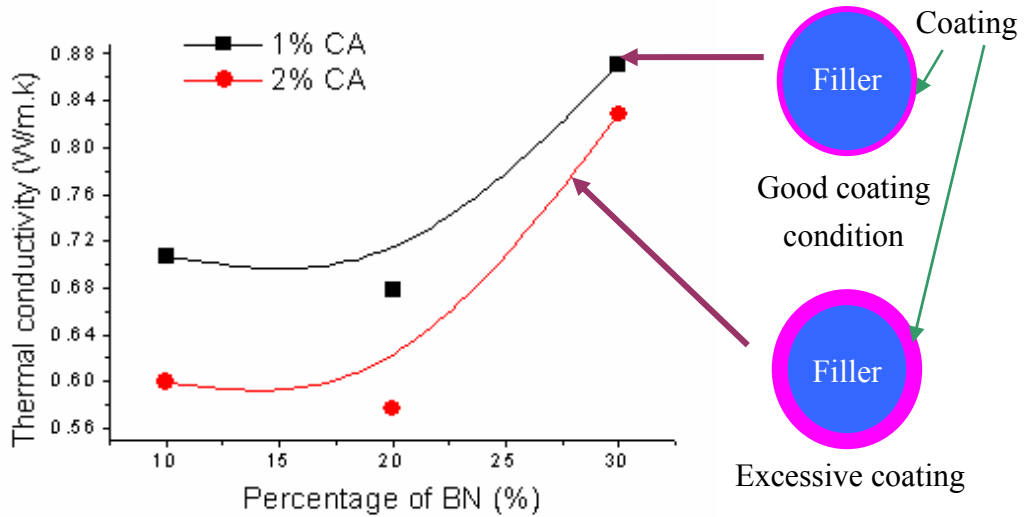


Figure 4. The effect of the coupling agent on the thermal conductivity

3.2 Cost impact

In general, the cost of micron-sized filler is lower than the sub-micron-sized, in addition, the amount of the micron-sized boron nitride required to produce a dielectric with the thermal conductivity over 1W/m.K is much less than that of sub-micron-sized. Therefore, the cost impact on manufacturing the conductive dielectric is minimised.

3.3 Characterisation tests

Various characterisation tests were conducted on this new material. The results were compared with pure epoxy and summarised in Table 3. It is observed that the sub-micron-sized boron nitrides behave similarly on many properties and are different from the micron-sized to a certain extent. The micro-sized boron nitride has a distinctive out-performance on improving the thermal conductivity, while the sub-micron-sized boron nitride is more effective on improving the electrical and thermal mechanical properties. Nevertheless, the primary target is to invent a new dielectric with high thermal conductivity without scarifying other major properties, so the micro-sized BN-filled dielectric is chosen. In fact, it also improves material properties to a certain degree.

Table 3. Summary of the characterisation tests on BN-filled dielectric

	53nm and 0.15µm	4µm
Thermal conductivity	Improved 129 – 154%	Improved 284%
Dk	Increased 3 - 4%	Increased 6%
Df	Improved 24 – 26%	Improved 16%

Tg	Improved 14 - 20%	Improved 9%
CTE (Pre-Tg)	Improved 23%	Improved 19%
CTE (Post-Tg)	Improved 24 - 27%	Improved 15%
Moisture absorption	Improved 50%	Improved 48%

The calculated data were based on 30% BN-filled dielectric.

4. Conclusions

The remarkably high thermal conductivity of the dielectrics fabricated in this project was accomplished by maximising the formation of conductive paths and minimising the thermal barrier. The former was done by using high thermal conductive filler, i.e. boron nitride, which was proven in our study to have a positive effect on enhancing the thermal conductivity of traditional PCB materials, in particular, the micron-sized boron nitride. The latter was achieved by using the coupling agent. 1% of the coupling agent in respect to the weight of boron nitride is optimised enough to coat the surface of boron nitride and enhance its interaction with the epoxy matrix. These BN-filled thermal conductive dielectrics outperform traditional PCB material in terms of material properties. Meanwhile, it is cost-effective. The only concern that arises from using this dielectric is that the drilling and routing parameters of this dielectric are different from that of the typical FR4 due to the presence of boron nitride. Nevertheless, MCPCB always comes with a base metal plate to act as a heat spreader, therefore, fine adjustment on the drilling, routing and punching processes, and the selection of proper types of drill bits are inevitable when using this kind of material.

References:

1. G.W. Lee, M. Park, J. Kim, J.I. Lee, H.G. Yoon, "Enhanced thermal conductivity of polymer composites filled with hybrid filler", *Composites: Part A* 37, 2006, pp727-734
2. H. Ishida, S. Rimdusit, "Very high thermal conductivity obtained by boron-filled polybenzoxazine", *Thermochimica Acta*, 320, 1998, pp177-186
3. A.G. Every, Y. Tzou, D.P.H. Hasselman, R. Raj, "The effect of particle size on the thermal conductivity of ZnS/diamond composites", *Acta Metallurgica et Materialia*, Vol. 40, No. 1, 1992, pp123-129
4. Martin W. Jawitz, *Printed Circuit Board Materials Handbook*, McGraw-Hill p2.15