

Advanced Diamond based Metal Matrix Composites for Thermal Management of RF Devices

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Abstract—GaN based RF devices are pushing the threshold on existing thermal management materials. High heat fluxes and the need for a heat spreader material with low CTE that is a close match to the device material (e.g. Silicon Carbide) is driving the need for higher thermal conductivity (>450W/mK) solutions. Aluminum diamond has been developed to meet this need with a CTE of 7.5ppm/K and thermal conductivity of 500W/mK.

Keywords- aluminum diamond, metal matrix composite, diamond MMC, high conductivity heat spreader, high TC and low CTE material

I. INTRODUCTION

Thermal management of RF amplifier devices is becoming more critical as GaN on Silicon Carbide (SiC) devices are being produced which have high power densities (4 to 11 W/mm of gate periphery [1]) that are substantially greater than previous Silicon based devices. The management of heat dissipation from GaN on SiC devices to the appropriate heat spreader material presents challenges that existing materials (Copper Tungsten, Copper Moly, Copper Moly Copper) fail to fully support and as a result these materials are limiting the performance benefits inherent to GaN. These bottlenecks include temperature de-rating of the device, power de-rating, impact on efficiency, and reliability reduction due to the inability of these materials to dissipate heat. Heat spreader materials present a unique challenge in that they need a CTE close to the semiconductor material (e.g. 4-8 ppm/K) and also have a high thermal conductivity [1]. Existing materials achieve low CTE at the trade-off of thermal conductivity. Development of metal matrix composite (MMC) materials with low CTE (4-8 ppm/K) and high thermal conductivity (>450W/mK), specifically those based on diamond particles, which have a high conductivity (between 1000-2000 W/mK) have existed since the early 1980's and have been watched with great interest over the years as a solution to existing thermal material limitations.

The commercial adoption of diamond based MMC's has been rather limited due to cost, ability of the manufacturing base to produce volume quantities, and the ability to meet all the technical requirements necessary for the material to be truly adopted by the customer base. This paper explains

NMIC's activities in addressing these issues and providing a high performance thermal management material that can be integrated into devices.

II. TECHNOLOGY AND MATERIAL SPECIFICATIONS

There are several key features NMIC has developed in order to produce an aluminum diamond based MMC heat spreader that will be able to meet customer technical requirements as summarized below:

1. High thermal conductivity (>450 W/mK)
2. Low CTE (4-8 ppm/K)
3. Low surface roughness (<1 μ m Ra)
4. Metallization that leads to successful die attach
5. Good dimensional tolerances and material stability

The key features (Fig. 1) developed by NMIC for aluminum diamond fabrication are in the areas of:

1. Conversion technology of diamond powder
2. Infiltration technology
3. Surface Control Technology
4. Cutting Technology

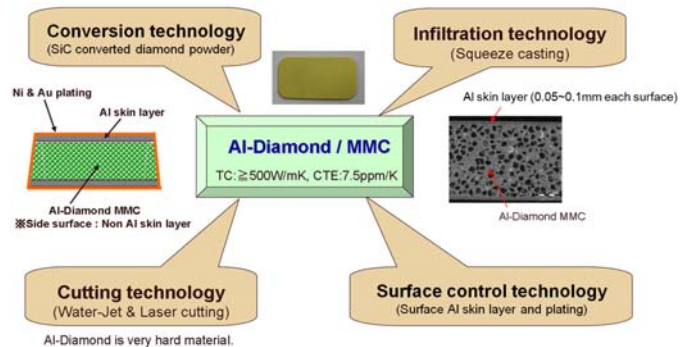


Figure 1. Key technological features of aluminum diamond material.

A. Conversion Technology (Silicon Carbide Surface Converted Diamond Powder)

Metal matrix composites used for thermal management applications are typically based on a primary metal (metal alloy such as aluminum, copper, or silicon) in combination with a secondary material such as diamond or silicon carbide. Aluminum diamond MMCs utilize an aluminum alloy composition infiltrated into a pre-form or packing of

diamond particles. These diamond particles are low cost industrial grade synthetic diamond. The size and ratio of diamond particles have been optimized to provide high thermal conductivity, low CTE, and good mechanical strength. Two diamond particle sizes (fine and coarse) are blended together to maximize loading which is typically 60 volume percent diamond powder. Evaluation has shown that the interface between the diamond particle and infiltrated aluminum alloy is critical in the overall thermal conductivity and thermal stability of the MMC [2]. The inability of aluminum to fully wet the diamond particles can cause formation of micro voids at this interface which can lead to the degradation in thermal conductivity (as this interface is critical in the phonon transfer between the metal and diamond). During temperature cycling these micro voids can cause the interface to fail leading to a decrease in thermal conductivity. For this reason, NMIC developed a process that produces a thin reaction formed and diffusion bonded functionally graded SiC surface layer on the diamond particles [3]. Unlike a SiC coating, which would provide an additional thermal interface between the SiC layer and diamond particle, the SiC surface conversion layer is part of the diamond particle and thus eliminates the significant thermal resistance to the diamond. In addition, the surface conversion on the diamond particle achieves minimal interface thermal resistance with the metal matrix which translates into good mechanical strength and stiffness, near theoretical thermal conductivity levels for the composite, complete wetting of the diamond particles by the aluminum due to the SiC surface layer, and the elimination of micro voids at the interface. Fig. 2 shows an SEM micrograph of non-converted and SiC surface converted diamond particles. Fig. 3 shows the significant color change of the diamond powder after SiC surface conversion.

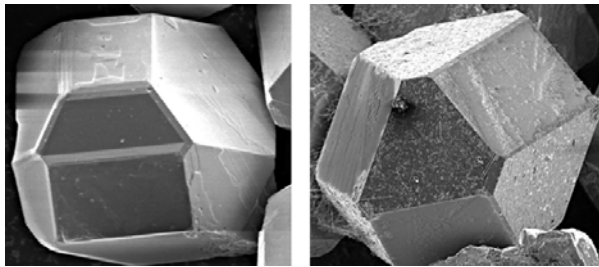


Figure 2. SEM micrograph of non-converted (left) and SiC converted (right) coarse diamond particle.



Figure 3. Non-converted (left) and SiC converted (right) diamond powder (coarse particle size shown).

Temperature cycling tests were performed on aluminum diamond samples, 12.7mm x 12.7mm x 1.5mm, fabricated using both SiC surface converted and non-converted diamond powder. The samples were exposed to 10 cycles at 500°C for 1 hour duration and thermal conductivity was measured via laser flash method after each cycle. Thermal conductivity of samples prepared with non-converted diamond powder quickly degraded while samples fabricated with SiC converted diamond powder maintained their thermal conductivity after each thermal cycle (Fig. 4). This test illustrates the importance of the metal to diamond interface and the role that SiC conversion plays in providing stable and consistent thermal performance.

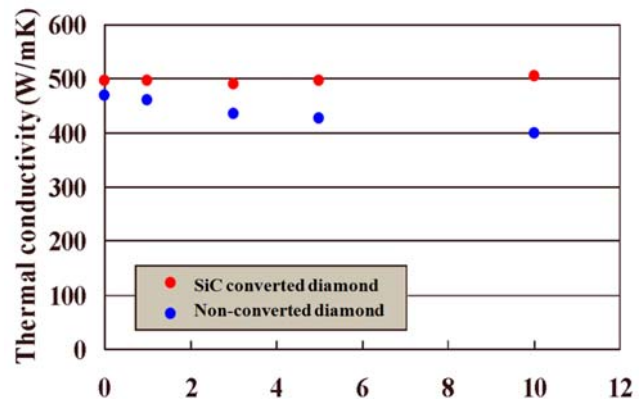


Figure 4. Thermal cycling results of aluminum diamond with SiC converted and non-converted diamond powder. TC vs number of cycles is shown.

B. Infiltration Technology (Squeeze Casting)

NMIC aluminum diamond is produced by a process referred to as squeeze casting. This process involves high pressure infiltration (50 to 150MPa) of molten aluminum or aluminum alloy into tooling that contains SiC converted diamond powder. The tooling is stacked to produce many plates that we refer to as the "mother plates" which vary in size and thickness based on the customers final part dimensions.

Squeeze casting achieves high pressure by mechanical compression of a molten metal into a sealed die containing the tooling. The squeeze cast pressure is higher than other processes, such as gas pressure assisted infiltration (GPI), and leads to generally higher thermal conductivity. In addition, the squeeze casting process consolidates the MMC much faster (seconds rather than minutes) than other processes, thus reducing the time aluminum or aluminum alloy is in a molten state. This reduces the reaction time available for the formation of aluminum carbide. Aluminum carbide formation is to be avoided as it leads to high thermal resistance at the diamond/aluminum interface and causes hygroscopic behavior [3] leading to a low thermal conductivity MMC and one prone to degradation during temperature or humidity cycling.

From a commercialization standpoint, squeeze casting is a proven high volume manufacturing process and is used

extensively in the production of other thermal management material such as aluminum silicon carbide.

C. Surface Control Technology (Aluminum Skin and Plating)

The roughness of the surface of the aluminum diamond heat spreader is a critical factor in achieving a void free interface to support successful die attach. Any voiding under the active area of the die significantly increases the possibility of high temperatures that can cause device failure. Typical surface roughness of less than 1µm Ra is required. For this reason, NMIC utilizes an in-situ produced aluminum alloy skin ranging in thickness from 0.05mm to 0.1mm on the top and bottom surfaces of the part (Fig. 5). This aluminum surface skin is not a coating but rather part of the microstructure of the MMC which provides a strong, homogenous, and smooth surface to apply subsequent metallization. A surface roughness of less than 0.6µm can be achieved.

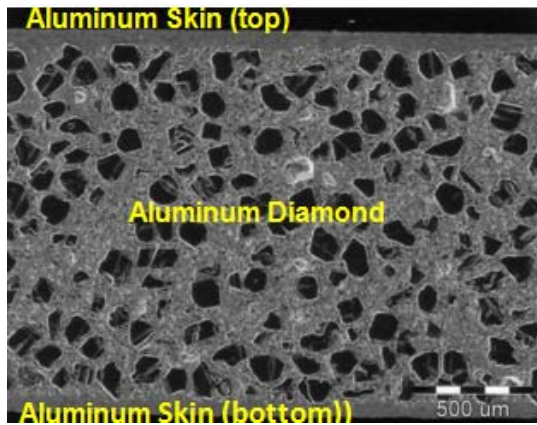


Figure 5. SEM micrograph of aluminum diamond cross section showing the aluminum skin layer.

Metallization is applied to the aluminum diamond MMC in a combination of nickel and gold. Surface pre-treatment of the MMC is an important step in achieving strong adhesion between the base nickel and aluminum diamond MMC. Electroless nickel followed by electric nickel plating with a combined thickness of 7.0µm is utilized as the initial metallization layer. This is followed by 2.0µm of gold plating. Both thicknesses can be adjusted to the customer’s preference within a range of 2 to 10µm for nickel and 1 to 5µm for gold plating. Testing has been performed in both basic and acidic solutions (simulating part cleaning processes at customer facilities) and by a bake test to determine plating adhesion characteristics via visual examination of the parts before and after testing and by measuring weight loss (Table 1 and Fig. 6).

TABLE I. WEIGHT LOSS AFTER CHEMICAL RESISTANCE TESTS

Sample	Plating		Weight loss (mg/cm ²)		
	Ni	Au	H ₂ SO ₄	HCl	KOH
STD. Type	7µm	2µm	0	0	0



Figure 6. Ni/Au plated aluminum diamond sample after bake test (no visual blisters observed)

The test procedure was performed on 12.7mm x 12.7mm x 1.5mm samples as follows:

- 1) Application of NMIC standard plating: Ni (7µm) + Au (2µm)
- 2) Test conditions (chemical resistance):
 - a. H₂SO₄/H₂O₂/H₂O = 5/1/1, 85°C for 2 minutes
 - b. HCl (18%), 25°C for 2 minutes
 - c. KOH (12N), 85°C for 2 minutes
- 3) Bake test: 450°C x 10 minutes

The tests show no weight loss and no visually observed blistering of the plating.

It can be argued that the best indicator of performance is performance itself, therefore the true indication of plating quality is to perform solder die attachment to the aluminum diamond MMC and subsequent product evaluation testing (die attach testing and yield, RF testing, thermal cycling, and RF thermal testing). This has been done successfully by NMIC customers utilizing Gold Tin (AuSn) solder between the aluminum diamond heat spreader and the die. Fig. 7 shows a SAM (Scanning Acoustic Microscopy) image of the part that illustrates no voiding under the die.



Figure 7. SAM image showing no voiding (Courtesy of Cree).

D. Cutting Technology (Waterjet and Laser Cutting)

Aluminum diamond is a very difficult material to cut due to the hardness of the diamond particles. NMIC utilizes both waterjet and laser cutting. From the mother plate produced by the infiltration process, NMIC cuts multiple parts. The size of the mother plate is optimized based on the part dimensions in order to reduce waste material that is the byproduct of cutting the part. Waterjet cutting is a faster

cutting method than laser but at the price of edge sharpness and dimensional tolerance. For the waterjet, the diamond particles are extremely hard and are basically cleaved whereas the laser sees the diamond as carbon and vaporizes it. Both methods leave some taper on the part between the top and bottom surface. Fig. 8 shows the edge appearance of waterjet and laser cut samples. Table 2 shows the design rules in terms of dimensions for aluminum diamond. The edge provided by a laser cut part has shown to provide better definition for optical pick and place equipment.

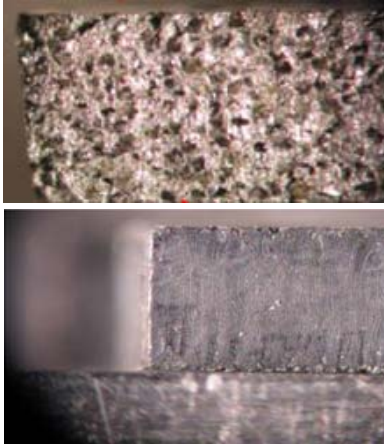


Figure 8. Side images of Waterjet (top image) and Laser cut (bottom image) aluminum diamond material.

TABLE II. DIMENSIONAL DESIGN RULES

Item	Standard	Special	Notes
Size Tolerance (mm)	±0.1*1	±0.05*2	*1 Waterjet *2 Laser cut
Thickness tolerance (mm)	±0.1	±0.05	
Max. thickness (mm)	3.0		
Thickness tolerance (mm)	±0.1	±0.05	
Side taper/thickness (µm/mm)	40*1 to 50*1	10*2	*1 Waterjet *2 Laser cut
Min. hole size (mm)	∅ 0.5*1	∅ 0.3*2	*1 Waterjet *2 Laser cut
Min. distance from side surface to hole	0.7*1	0.5*2	*1 Waterjet *2 Laser cut
Tolerance of Plating thickness (µm)	±1.0	±0.5	
Flatness (µm/inch)	≤ 50	≤ 40	
Surface roughness Ra (µm)	≤ 1.5	≤ 0.6	

E. Thermal and Mechanical Properties

The general properties of NMIC aluminum diamond are shown in Table 3.

TABLE III. PROPERTIES OF ALUMINUM DIAMOND

Item	Typical data
Diamond content (Vol%)	57
Density (g/cm ³)	3.17
Thermal conductivity (W/mK)	500
Specific heat (J/g-K)	0.62
Coefficient of thermal expansion (ppm/K)	7.5
Flexural Strength (MPa)	300
Young's modulus (GPa)	340
Electrical Resistivity (Ω-m)	3.7 x 10 ⁻⁷
Surface Roughness (µm Ra)	< 1.0
Melting Point (°C)	570

Aluminum diamond possesses thermal conductivity (500W/mK) that is 2.5 times higher than CuW (200W/mK). Thermal simulations show a 25% reduction [1] in junction die temperature. Testing performed showed that thermal models and IR scans correlate well with each other, thus validating the real world performance improvements possible by utilizing aluminum diamond heat spreader material.

Of additional importance is the CTE and thermal conductivity of the heat spreader materials as a function of temperature. Testing was performed from room temperature to above 400°C on aluminum diamond samples that were 12.7mm x 12.7mm x 1.5mm with skin thickness between 0.05mm and 0.1mm. These results are shown in Fig. 9 and Fig. 10. The CTE increases up to 400°C and then levels out. This is expected behavior as the temperature starts to approach the melting point of the aluminum alloy. The thermal conductivity decreases with increasing temperature as has been observed with other MMCs.

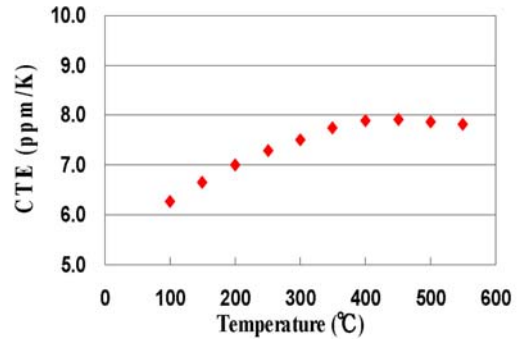


Figure 9. CTE versus Temperature

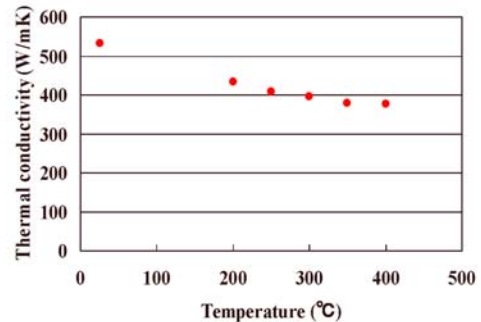


Figure 10. Thermal Conductivity versus Temperature

III. CONCLUSION

Aluminum diamond MMCs have better thermal conductivity than existing materials and have a CTE that is compatible with silicon carbide and other materials used in semiconductors. Simulation and testing have demonstrated the thermal performance advantage of this material and its readiness to be used in heat spreader applications for GaN devices. Extensive thermal testing has shown the ability of aluminum diamond to meet the challenging specifications required by customer applications and the unique technology

utilized in its production provides thermal stability that has proven to be difficult for other diamond based MMCs.

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