HOW NMIC ALUMINUM DIAMOND MMCs ARE FABRICATED

Semiconductor devices that deliver high power levels inherently generate large amounts of waste heat, which is the enemy of both device performance and longevity, as there is a direct relationship between increasing operating temperature and reduced operating life. As a result, removing heat quickly at the device level is important to manufacturers of these devices as well as all electronic components.

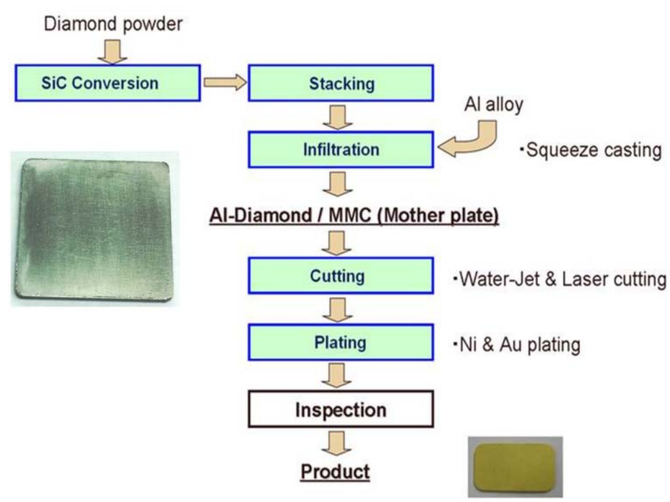
However, in the case of GaN RF power transistors, laser diodes, and package LEDs, the need is far more critical because they generate a disproportionately large amount of heat when compared with other types of semiconductor devices.

NMIC's goal was therefore to create a heat spreader material with superior performance to current materials, principally copper, copper-tungsten, copper-moly, and copper-moly-copper, used to make heat spreaders.

Diamond is fundamentally the best possible choice for such an application, as it has higher thermal conductivity than any other material known to man (and much higher than the aforementioned materials) but must be developed in such a form is to be usable in commercial applications.

METAL MATRIX COMPOSITES

The concept of using MMCs based on diamond for these applications was conceived more than 25 years ago and substantial research in academic, industry, and government, has been expended over the years.



1. The process flow employed in producing NMIC aluminum diamond MMCs.

The literature contains the results of these efforts using diamond and a variety of metals, but development at NMIC showed that aluminum appeared to be an excellent choice. MMCs in general combine a primary metal such as aluminum or copper in combination with diamond (silicon carbide has also been used).

NMIC's aluminum diamond MMC's employ an aluminum alloy composition that is infiltrated into a packing of industrial-grade diamond particles. Both the size and ratio of the diamond particles must be optimized to retain their high thermal conductivity as well as low coefficient of thermal expansion (CTE), and high mechanical strength. The process flow employed in producing NMIC aluminum diamond MMCs is shown in Figure 1.

HOW NMIC ALUMINUM DIAMOND MMCs ARE FABRICATED

Fine and coarse diamond particles are blended to produce a powder that is typically 60% diamond by volume. Research has shown that the interface between the diamond particle and aluminum alloy is a critical point in determining the overall thermal conductivity and thermal stability of the MMC.

If not fully wetted, the diamond particles can form micro voids at this interface with the result that under temperature cycling conditions the micro voids can cause the interface to fail, reducing thermal conductivity. Understanding this, NMIC creates a thin, reaction-formed and diffusion-bonded SiC surface layer on the diamond particles.

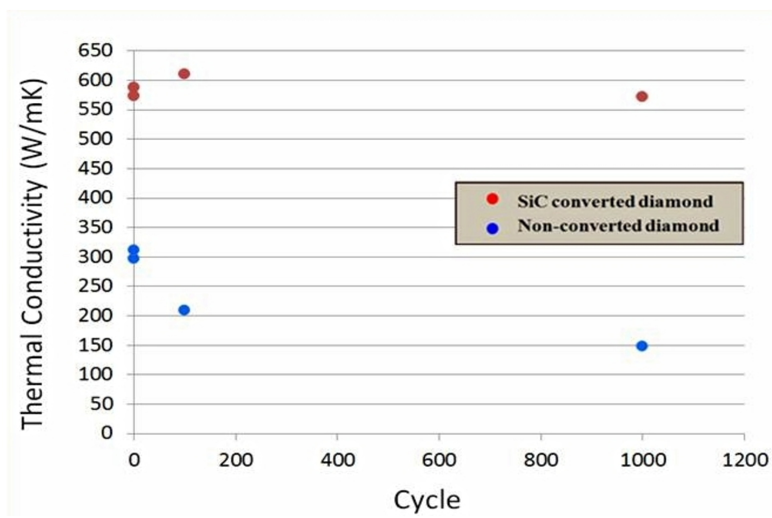
Unlike an SiC coating, which provides an additional thermal interface between it and the diamond particles, NMIC's SiC surface-conversion layer actually becomes part of the diamond particle, which eliminates thermal resistance to the diamond and produces minimal thermal resistance with the metal matrix.

The result is good mechanical strength and stiffness, near theoretical thermal conductivity the composite, complete wetting of the diamond particles by the aluminum as a result of the SiC surface layer, and elimination of micro voids at the interface.

Temperature cycling tests conducted by NMIC comparing aluminum diamond samples fabricated using both SiC surface-converted and non-surface-converted diamond powder were conducted exposing samples to 10 cycles at 500° C for 1 hr., with thermal conductivity measured via laser flash after each cycle. The non-converted powder quickly degraded while the SiC-converted powder maintained its thermal conductivity. The results are plotted in Figure 2.

PRODUCING ALUMINUM DIAMOND

While several methods have been employed to produce aluminum diamond, MMIC uses a process called squeeze casting, which is a proven high-volume process used to produce other thermal management materials such as aluminum silicon carbide (AlSiC). The squeeze casting process employs high-pressure infiltration of molten aluminum alloy into tooling that contains SiC-converted diamond powder.



2. Test results of SiC surface-converted and non-surface-converted diamond powder after 10 cycles at 500° C for 1 hr., Note degradation of non-converted powder.

1230 E Speedway Blvd, #211, Tucson, AZ 85721 • 520-300-9272 • fax: 520-300-7095 • info@nanomaterials-intl.com

HOW NMIC ALUMINUM DIAMOND MMCs ARE FABRICATED

The tooling is stacked to produce many "mother plates" at various size and thicknesses based on the required dimensions of the parts. Squeeze casting delivers higher pressure than other techniques, which in NMIC's experience results in higher thermal conductivity and consolidates the MMC in seconds rather than the minutes required by other processes.

The process inherently reduces the time that the aluminum or aluminum alloy are in a state that could allow aluminum carbide to form. Aluminum carbide leads to high thermal resistance at the diamond/aluminum interface and causes hygroscopic behavior that results in lower thermal conductivity and a finished product more likely to degrade during temperature or humidity cycling.

ALUMINUM SKIN AND PLATING

The surface of an aluminum diamond heat spreader must have a well-controlled level of roughness in order to produce a void-free interface. Voids are the enemy of achieving reliable, repeatable die attach, as they occur under the active area of the semiconductor die, dramatically increase the possibility of thermal "hot spots" that can cause device failure.

The surface roughness must be controlled to less than 1 µm Ra, and to achieve it NMIC employs an aluminum alloy skin that ranges in thickness from 0.05 mm to 0.1 mm on the top and bottom surfaces of the part. It is not a coating but is part of the microstructure of the MMC that provides a strong, homogenous, smooth surface on which subsequent metallization can be applied.

This technique repeatably produces surface roughness in NMIC parts of less than 0.6 µm. Nickel and gold metallization are applied to the aluminum diamond MMC after the surface is pretreated to ensure strong adhesion between the base nickel and aluminum diamond MMC.

Electroless nickel followed by electric nickel plating with a thickness of 7 µm is the initial metallization layer followed by 2 µm of gold plating. The thickness of both can be adjusted to customer specifications within a range of 2 to 10 µm for nickel and 1 to 5 µm for gold.

Squeeze casting consolidates an MMC in seconds rather than minutes required by other techniques

NMIC has extensively tested this process in both basic and acidic solutions that simulate the part cleaning process employed by device manufacturers. In no case has any weight loss or visually-observed blistering of the plating occurred.

To verify these results (that is, to validate plating quality), NMIC and one of its customers have performed solder die attachment to the MMC and evaluated the finished product with die attach testing in yield, RF, thermal cycling, and RF thermal testing using gold-tin solder between the heat spreader in the die. The results were excellent and well in agreement with predicted values.

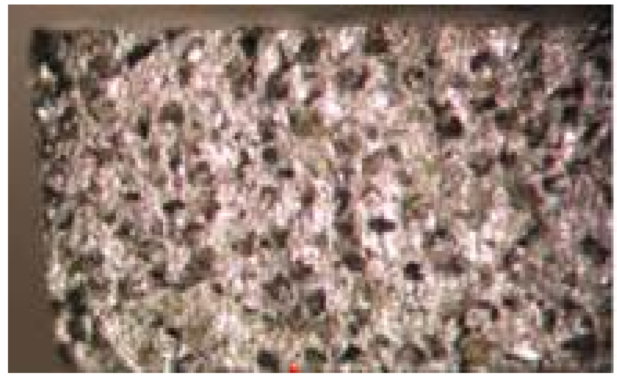
HOW NMIC ALUMINUM DIAMOND MMCs ARE FABRICATED

CHOOSING A CUTTING TECHNOLOGY

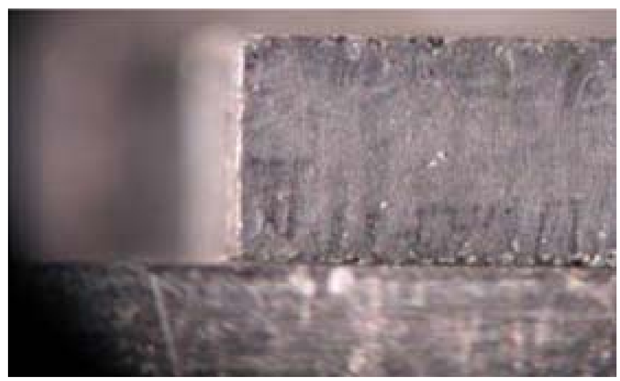
Diamond particles are extraordinarily hard and difficult to cut, which is true also of aluminum diamond, and water jet and laser cutting are employed for this purpose. NMIC cuts multiple parts from the mother plates produced by the infiltration process, with their size optimized to meet part dimensions to reduce the amount of waste material produced by the cutting process.

Waterjet cutting is faster than laser cutting but sacrifices edge sharpness and dimensional tolerance. The waterjet method produces diamond particles that are cleaved while the laser process treats the diamond as carbon and vaporizes it. Both methods leave some taper on the part between the top and bottom surface. The edge produced by the laser-cut parts provides better definition, which is desirable for use with optical pick and place automated manufacturing equipment. Micrographs illustrating the results are shown in Figures 3a and 3b.

Another measure of aluminum diamond MMC performance is the CTE and thermal conductivity of the finished heat spreader from room temperature to well above the junction temperatures produced by GaN RF power transistors. To validate this, NMIC conducted tests as high as 400° C on samples measuring 12.7 mm x 12.7 mm x 1.5 mm with skin thicknesses ranging from 0.05 mm to 0.1 mm. The results of these tests are shown in Figure 4 and 5. CTE increases up to about 400° C and then levels out or trends slightly downward, which is expected as the temperature starts to approach the melting point of the lead aluminum alloy.



a



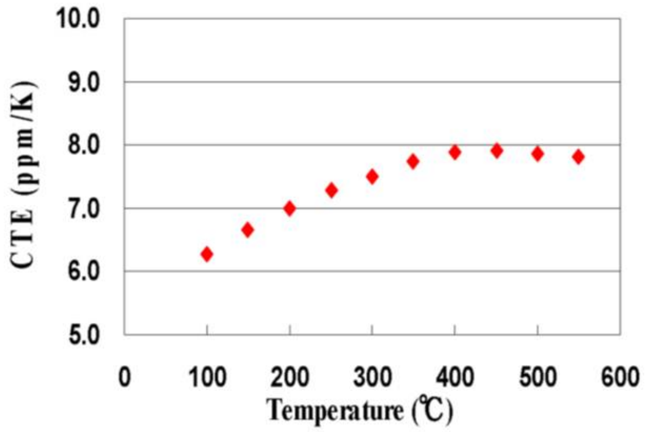
b

3. Comparison between waterjet-cut parts (a) and laser-cut parts (b).

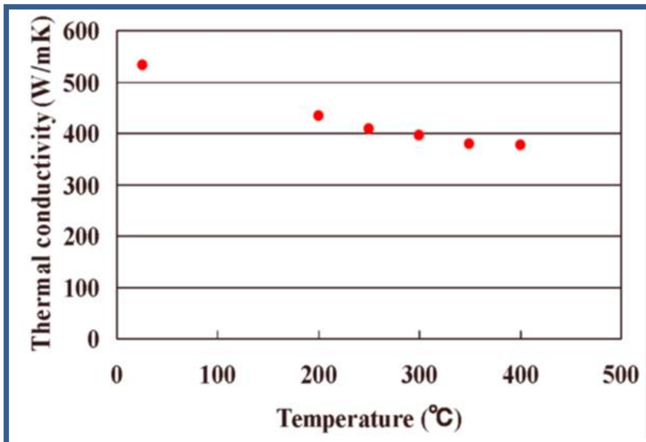
Thermal conductivity decreases with temperature as it does with all types of MMCs. However, it is important to remember that temperatures above about 250° C are the highest that GaN RF power transistors will experience, so an aluminum diamond heat spreader will perform optimally at any temperature experienced in service.

1230 E Speedway Blvd, #211, Tucson, AZ 85721 • 520-300-9272 • fax: 520-300-7095 • info@nanomaterials-intl.com

HOW NMIC ALUMINUM DIAMOND MMCs ARE FABRICATED



4. CTE remains in an acceptable region to very high temperatures.



5. Thermal conductivity remains at 400 W/mK or higher to about 250º C, in excess of GaN device junction temperatures.

SUMMARY

The development path that has resulted in NMIC's ability to produce commercially-viable, cost-effective aluminum diamond MMCs has been a long one and many techniques were explored before the final solution was achieved.

However, our final result provides benefits for manufacturers of GaN RF power transistors as well as the amplifiers in which they are employed and the systems they serve. There is currently no other solution that provides similar benefits. Continued development at NMIC will result in further performance advancements as well as reductions in cost.

1230 E Speedway Blvd, #211, Tucson, AZ 85721 • 520-300-9272 • fax: 520-300-7095 • info@nanomaterials-intl.com