Aluminum Diamond Meets Cost and Technical Challenges for Removing Heat from GaN Devices

Demonstrates a reduction in junction temperature of 25% in GaN HEMTs

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Gallium nitride (GaN) is today's compound semiconductor technology du jour thanks in no small part to its power density that when fabricated on a Silicon Carbide (SiC) substrate is currently as high as 11 W/mm of gate periphery at higher operating voltages -- about 10 times that of GaAs. However, GaN devices generate large amounts of waste heat that must be removed in order to ensure device and system longevity and optimum system performance. The unparalleled thermal conductivity and other properties of diamond based metal-matrix composites (MMCs) for heat spreaders have been "promising" for nearly 30 years. However, cost, inability to be produced in large quantities, and other factors have kept these MMCs from becoming commercially viable. Aluminum diamond MMC from Nano Materials International Corporation (NMIC) solves these problems for the first time. It can reduce device junction temperatures by up to 25%, has a coefficient of thermal expansion (CTE) close to that of SiC, and its metallization is well suited for die attach. It also has excellent dimensional tolerances and material stability and can be made economically in large quantities while adding a minimal cost to each GaN device.

NMIC's parent company has been developing aluminum diamond MMCs since the 1990s in order to overcome the major obstacles to its use for dissipating heat in RF power devices as well as laser diodes and other heat-intensive semiconductor applications. The company's work early on delivered thermal conductivity as high as 600 W/mK (thermal conductivity is a measure of the ability of a material to conduct heat measured in Watts per meter Kelvin). CTE, another critical parameter that must be as close as possible to that of the material to which is attaches, was also achieved quickly. The required tolerances, thickness control, skin layer, and surface roughness (all described later) took longer and required proprietary techniques to obtain. The most recent advances have been in reducing the cost of the process to make it fall within the increasingly-tight price constraints of GaN device manufacturers.

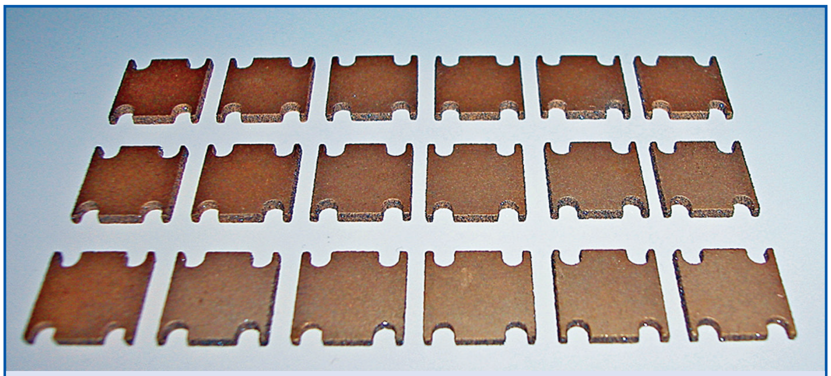

Figure 1a: Nickel-and gold-pated aluminum diamond heat spreaders

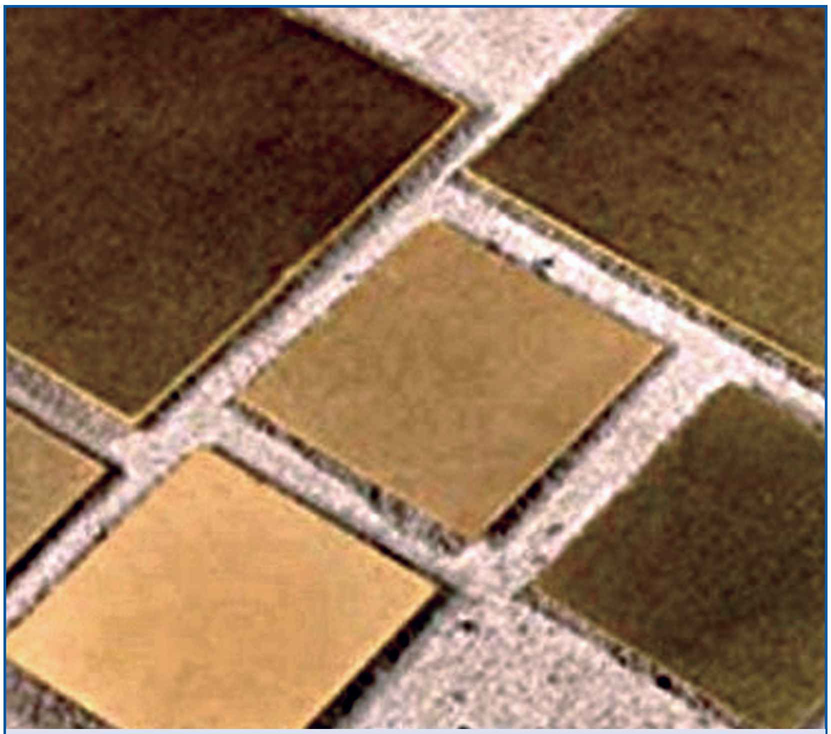

Figure 1b: Heat spreaders cut to a specific customer requirement

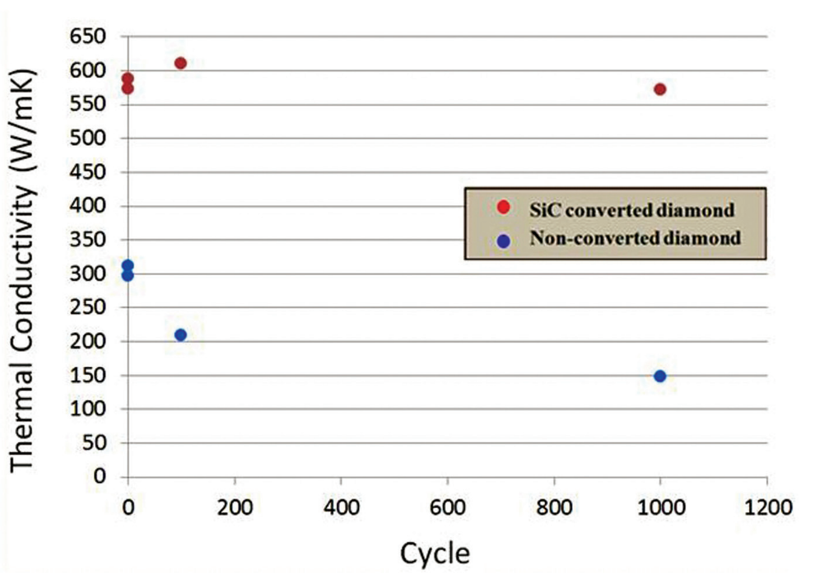

Figure 2: Key technological features of aluminum diamond

With all of the challenges that had to be overcome to achieve this breakthrough, it's reasonable to ask whether this long road to commercial availability was worth the effort. The performance of NMIC's aluminum diamond answers this question. Polycrystalline diamond, whether natural or synthetic, has the highest thermal conductivity of any material on Earth, ranging from 1200 to 2000 W/mk. When used in an aluminum diamond MMC, the effective conductivity remains over 500 W/mK, which is far higher than common heat spreader materials such as copper tungsten (200 W/mK), copper molybdenum (250 W/mK), and copper-molybdenum-copper (350 W/mK). The latter three materials simply cannot dissipate as much heat from a GaN device as aluminum diamond, so compromises must be made with these materials that keep optimum performance of GaN devices from being achieved.

The results of this work have resulted an MMC with nickel-gold electrolytic or electroless plating in the thicknesses required for use as a heat spreader and in virtually any shape and size typical of GaN HEMT or MMIC devices (Figures 1a and b). It is available as MMC material alone or incorporated within a package, allowing it to accommodate the specific needs of device manufacturers and package suppliers.

MMCs and Aluminum Diamond

MMCs consist of a metal such as aluminum, copper, or silicon, in combination with diamond or silicon carbide. Aluminum diamond MMCs are composed of aluminum alloy in combination with low-cost, industrial-grade synthetic diamond particles (Figure 2). To deliver the required thermal conductivity, CTE, and mechanical strength, both fine and coarse diamond particles are blended to allow the most diamond (60 volume percent) to be incorporated in the mix. Optimum thermal conductivity and thermal stability can only be achieved when the interface between the diamond particles and aluminum alloy is free of "micro voids" that cause the interface to fail during temperature cycling and reduce thermal conductivity. Without the ability to handle wide temperature swings, an MMC is essentially worthless for use as a heat spreader.

To eliminate this problem, NMIC developed a process that produces a precise SiC surface layer on the diamond particles. While a conventional SiC coating provides an additional thermal interface between the SiC layer and diamond particle, NMIC's SiC surface-conversion layer actually becomes part of the diamond particle. The surface conversion on the diamond particle results in minimal thermal resistance of the metal matrix, achieving high mechanical strength and stiffness, thermal conductivity of the composite near the theoretical limit, and complete wetting of the diamond particles by the aluminum that eliminates voids at the interface. Temperature cycling tests on NMIC's aluminum diamond performed by NMIC consistently show that the thermal conductivity of samples prepared with non-converted diamond powder quickly degrade while aluminum diamond samples fabricated with SiC-converted diamond powder maintain their thermal conductivity during temperature cycling.

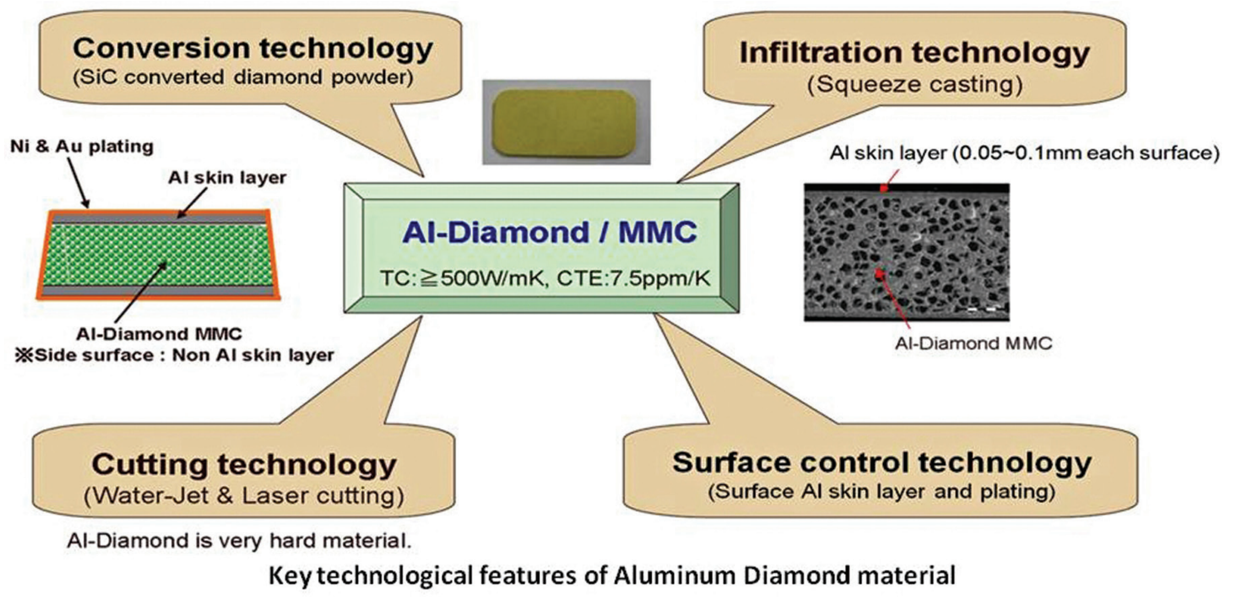

Figure 3: Results from a test of CTE versus temperature show that CTE remains within an acceptable range

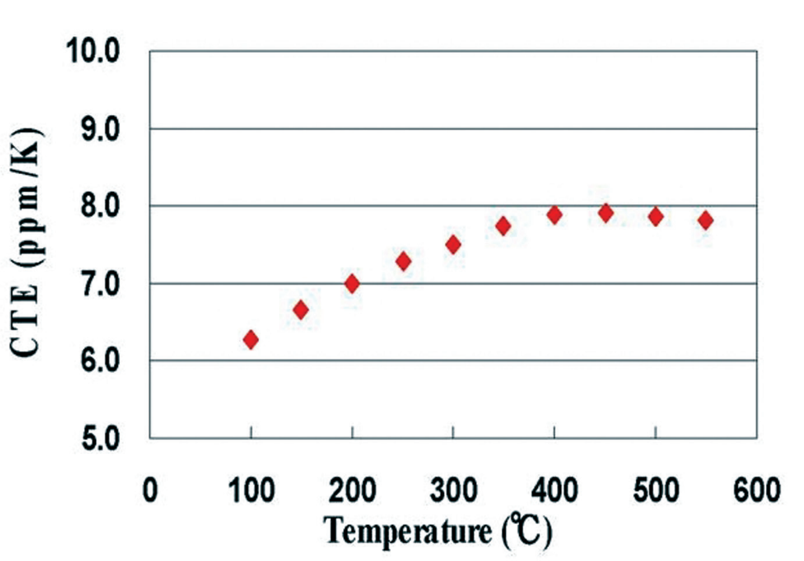

Figure 4: Thermal conductivity rolls off with temperature but remains well above 400 W/mK through 200° C

NMIC produces aluminum diamond by "squeeze casting", which is a proven high-volume manufacturing process and is used extensively in the production of other thermal management materials such as aluminum silicon carbide (AlSiC). It employs high-pressure infiltration of molten aluminum or aluminum alloy into a preform that contains SiC-converted diamond powder. The pressure achieved by squeeze casting is higher than processes such as gas pressure-assisted infiltration and results in higher thermal conductivity. It also consolidates the matrix in seconds rather than minutes required by other processes, reducing the time aluminum or aluminum alloy is in a molten state. This is important because there is little reaction time available to allow aluminum carbide to form. Aluminum carbide increases thermal resistance at the diamond/aluminum interface, reduces thermal conductivity, and degrades performance during temperature or humidity cycling.

The surface roughness of an aluminum diamond heat spreader is also a critical factor in achieving the void-free interface required to support successful die attach. Voids under the active area of the die significantly increase the possibility that hot spots will be created that lead to device failure. NMIC utilizes an aluminum alloy "skin" ranging in thickness from 0.05 to 0.1 mm on the top and bottom surfaces of the part. This skin becomes part of the matrix microstructure ensuring a strong, homogenous, smooth surface on which to apply metallization.

This nickel and gold metallization is then applied to the aluminum diamond matrix. Electroless nickel followed by electric nickel plating (typically 7 µm in total thickness) is the initial metallization layer followed by 2 µm of gold plating. The key elements of aluminum diamond are shown in Figure 3. Extensive testing has been performed in both basic and acidic solutions that simulate cleaning processes performed during device fabrication along with bake tests to determine plating adhesion characteristics. Performance in both cases was evaluated by visual examination before and after testing and by measuring weight loss.

No weight loss or blistering of the plating occurs and excellent test results in solder die attach, yield, and RF and thermal testing have also been obtained by NMIC customers using gold tin (AuSn) solder between the aluminum diamond heat spreader and the die. Tests of CTE and thermal conductivity of NMIC's aluminum diamond from room temperature to higher than 400° C show that CTE increases up to 400° C and then slowly declines at temperatures much higher than what is required of a GaN heat spreader (Figure 4). In addition, thermal conductivity decreases with increasing temperature but remains more than 400 W/mK well past the operating temperature of GaN devices (**Figure 5**).

Summary

It's safe to say that GaN has enormous potential in both defense and commercial applications for several important reasons. It has the highest power density of any compound semiconductor material employed for generating RF power, can operate reliably at high operating voltages, can produce devices with very broad bandwidths well into the millimeter-wave region, has low drain-source capacitance making it easy to match, among others. As a result it will complement existing semiconductor-based RF power technologies in some applications and replace them in others. However, its Achilles heal is the large amount of heat that such high-density devices produce when operating at high voltages. NMICs aluminum diamond provides GaN device manufacturers with a way to improve GaN device performance at minimum increase in cost, and in the high volumes their popularity will require. For more information, visit www.nanomaterials-intl.com.

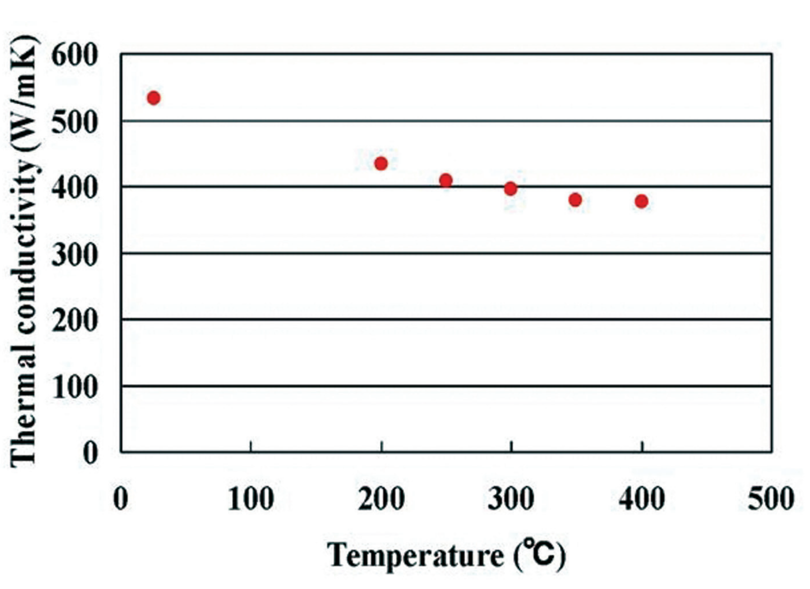

Figure 5