Aluminum Diamond Heat Spreader Demonstrates 25% Reduction in GaN Die Temperature

by Kevin Loutfy, Nano Materials International Corp.

One of the greatest challenges in fully exploiting the advantages of GaN RF power transistors and MMICs has been dissipating the heat they generate, thanks to GaN's inherently high power density. Ridding GaN-based amplifiers and their host systems of heat begins at the device and its package and extends outward to the subsystem and system levels. At the device level, the goal is to move as much heat away from the die as quickly as possible through its carrier to the amplifier body where it can be "heat-sinked" away and dissipated with air or liquid cooling.

Aluminum diamond metal matrix composites (MMCs) shown in Figure 1A and B used as heat spreaders between the active device and its mounting surface are proving to be the most effective way to remove heat from discrete RF power transistors and MMICs. Results from several organizations show good agreement of thermal models with IR scans and show a marked reduction in transistor junction temperature of about 25% when compared to a copper/tungsten heat spreader. The results were repeatable and substantial enough that one GaN device vendor has been able to eliminate the temperature derating curve on some of its GaN-device data sheets. Thermal conductivity degrades slowly to about 400 W/mk through 200º C (Figure 2).

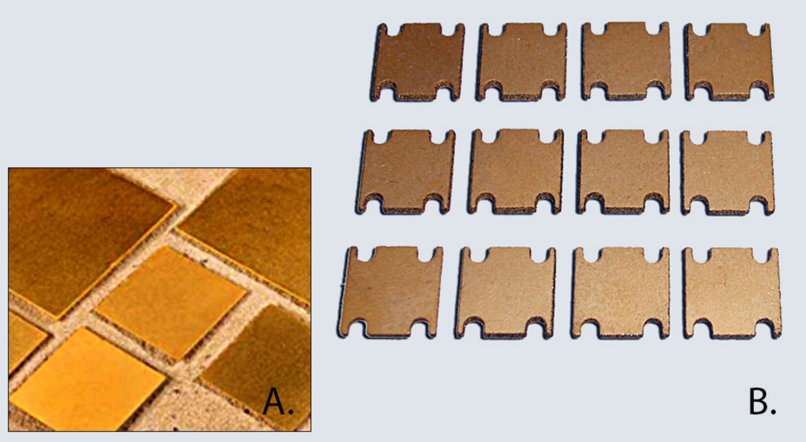

Figure 1: Blanks of NMIC's nickel-and gold-pated aluminum diamond MMC heat spreaders before (a) and finished thermal spreaders (b) fabricated to customer-specified shapes.

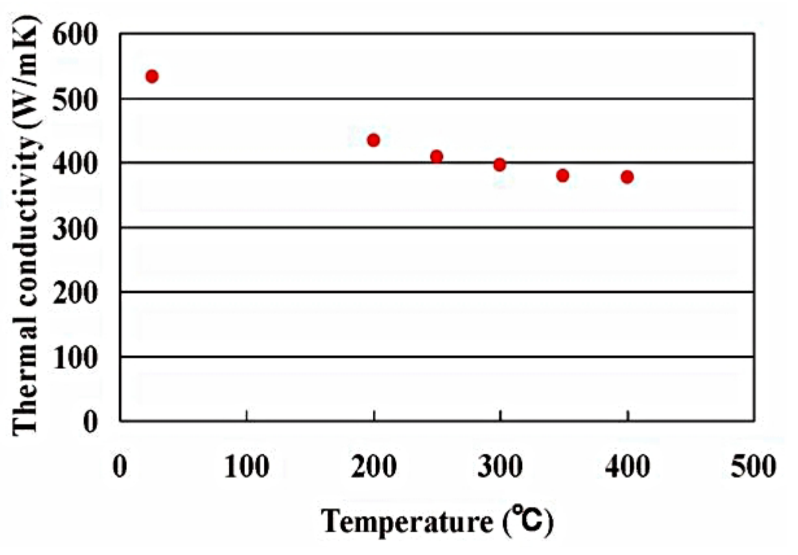

Figure 2: The slow reduction in thermal conductivity of aluminum diamond MMCs over temperature is more gradual and consistent than other materials or material combinations. It remains above 400 W/mK through 200º C, a temperature that is at or above that exhibited by GaN devices.

Aluminum diamond MMCs are also inherently lighter than any other material or material combination used for GaN thermal spreaders. The density of aluminum diamond is 3.17 g/cm^3, versus 10 g/cm^3 for 85% molybdenum/15% copper, and 17 g/cm^3 for 85% tungsten/15% copper. For a device that occupies 1 cm^3, aluminum diamond would weigh 3.2 g, molybdenum/copper would weigh 10 g, and copper/tungsten would weigh 17 g. Aluminum diamond's much lower weight has obvious beneficial implications in applications such as airborne Active Electronically-Steered Array (AESA) radars, in which hundreds or thousands of GaN MMICs are used and pounds could be shed from the overall system. As a result, aluminum diamond MMCs are an increasingly important element of prototype RF power generation subsystems for upcoming radar, electronic warfare (EW), and communications systems.

Moving the Heat Out

Heat dissipation has always been a major concern for systems that generate RF power, but GaN is taking this issue to a much higher level. GaN die can produce more than 11 W per millimeter of gate periphery — 10 times that of GaAs, but as removing the heat from GaN RF power transistors and MMICs has often not been possible when running at saturated power, designers back off their RF power output to lower-than-desired levels, somewhat negating GaN's primary strength. This approach has been commonplace since GaN devices were first used in RF amplifiers but is becoming less and less tolerable as the technology is being used in larger numbers and in more diverse applications.

Consider that GaN is the device of choice for use in coming generations of AESA-based radar and EW systems, and will be used in many cases instead of GaAs, which is a staple of current MMIC T/R modules in phased-array radars. The result is a lot more heat to dissipate, and in order to conform to DoD's Size Weight and Power (SWaP) mandate, the less cooling overhead the better.

The Search for New Solutions

Heat spreaders are typically made from a combination of copper for high thermal conductivity and either tungsten or molybdenum to reduce coefficient of thermal expansion. Of the common combinations, copper/molybdenum/copper has the greatest thermal conductivity, reaching 310 W/mK. In contrast, diamond has the highest thermal conductivity of any material on Earth, ranging from 1200 to 2000 W/mk, so it is not surprising that this appealing characteristic has led researchers to overcome obstacles blocking its commercialization as a substrate material or heat spreader.

Diamond materials development accelerated in lockstep with GaN's rapid advancement from research device to service in the field, the latter being the result of government/industry partnerships spearheaded by the Defense Research Projects

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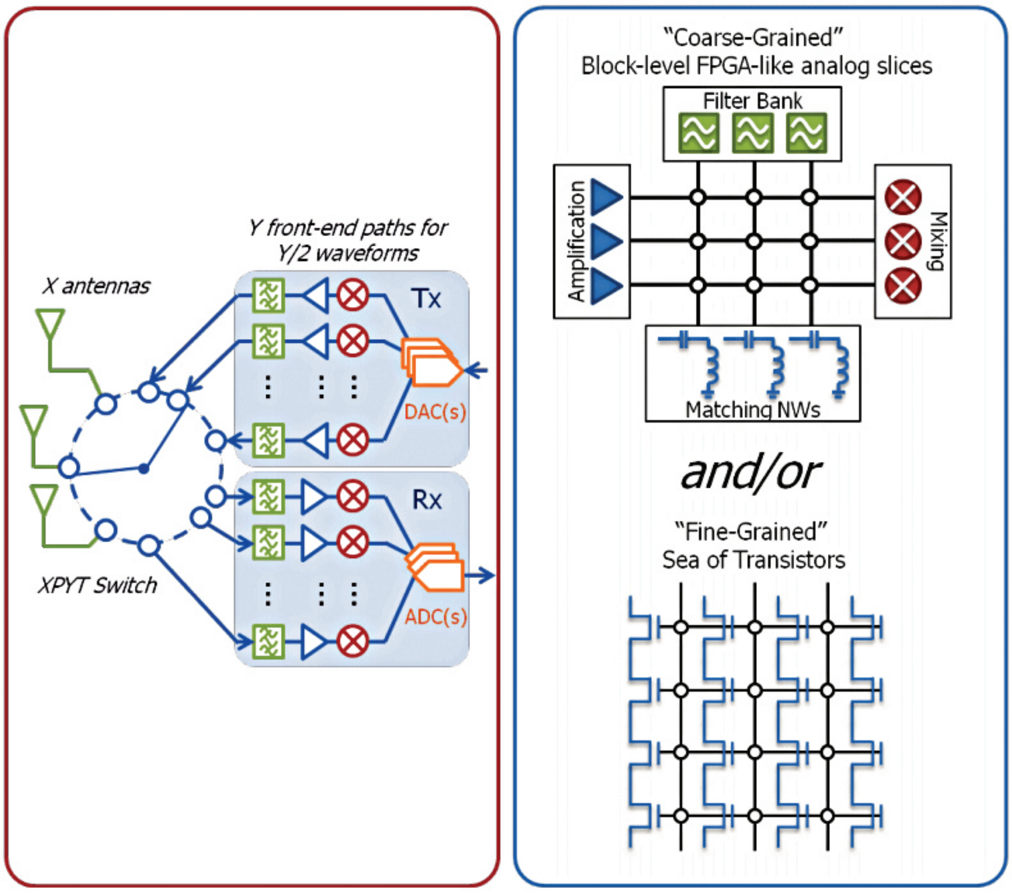

Figure 3: The "RF-FPGA" concept is another example of a DoD program dedicated to higher functional integration in the RF domain, and in which GaN is a likely component. In (a) current RF design is shown and in (b) the desired goal.

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Agency (DARPA) and the U.S. Navy, and championed "on high" by the U.S. Department of Defense. When GaN RF power transistors were rushed into service in Iraq and Afghanistan in the mid-2000s as the RF power source for the jammer amplifiers in the Joint Counter Radio Controlled Improvised Explosive Device - Electronic Warfare (JCREW) program, the "era of GaN" had begun. This program today is well into its third phase, a testament to how, when the need is indisputable, government and industry working together can achieve remarkable feats.

The Road to Ubiquity

GaN will not replace GaAs and LDMOS technologies for RF power generation but will be found anywhere its particular strengths are called for, such as generating substantial amounts of RF power at frequencies beyond the reach of its counterparts. Even a cursory inspection of next-generation DoD programs in development or nearing limited production makes it obvious that GaN is the future RF power generation technology of choice.

To see why this is true, it is important to remember that DoD is intent on minimizing the number of one-off designs in its radar and EW inventories and appears to be confident that radar, EW, communications, and probably Identification Friend or Foe (IFF) can be handled by a single system. These two goals: "open-architecture" designs and multifunctionality, are formidable technological challenges, but the potential benefits are immense. They are achievable at the highest level through the use of the AESA architecture, not just to replace passive or active legacy radars but also to enable EW's future "selective jamming" as well. Funnel down further into the architecture and broadband, high-power, high-voltage, high-power-density GaN MMICs are one of the key enablers of the entire scheme.

At the program level, the most visible beneficiary will be the Next-Generation Jammer (NGJ), one of the most highly-regarded and thus hopefully less "trimmable" programs for which GaN is the "recommended" device technology. This program and others will change the radar

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and EW paradigm from its current state to a flexible, fast-reacting, multi-function environment for many decades to come.

Another program in which GaN offers big benefits is the Navy's Integrated Topside (InTop) program, whose goal is to solve two major problems, the first of which is having too many purpose-built, single-function, incompatible systems in the inventory, and the second is the typical forest of antennas adorning the topside of most Navy ships, creating inevitable interference problems and potentially making the ship more vulnerable.

InTop aims to create a scalable portfolio of EW, radar, and communication systems that can support multiple classes of ships and other Navy platforms via an open architecture and the use of the same antennas by EW, radar, and communications systems. That GaN will play a role in various aspects of this program appears a virtual certainty. These two examples are just the tip of the GaN iceberg, which makes finding a way to get the most from GaN not only desirable from a technical perspective but essential, as it is being demanded by DoD.

At the research level, within its Microsystems Technology Office's Adaptive RF Technology (ART) program, DARPA is calling on industry to develop what it calls Radio Frequency Field Programmable Gate Arrays (RF-FPGAs). The goal is to enable a common hardware architecture that makes it possible to use the same set of RF front-end components in multiple platforms through programmability of the transceiver (**Figure 3**). Thus any such RF-FPGA employing GaN devices, for example, would be used in multiple platforms and would span communications, EW, and signals intelligence. These are just three of many radar and EW upgrade programs in which GaN devices will (or are already) being used. GaN is not the technology panacea for every radar, EW, or communications system, but its effects will nevertheless be profound.

Aluminum Diamond Rises to the Top

Of the various diamond-based alternatives, aluminum diamond MMCs developed by Nano Materials International Corp. (NMIC) have created significant interest because they not only provide high thermal conductivity of more than 500 W/mK (twice that of their nearest competitor) but solve other problems that have bedeviled diamond for so long. Aluminum diamond MMCs have a coefficient of thermal expansion (CTE) of 4 to 8 ppm/K, which is close to that of SiC (the substrate material of choice for most high-performance GaN devices).

In addition, its nickel-gold plating ensures successful die attach using gold-tin or gold-germanium solder, and dimensional tolerances and material stability with temperature are excellent. NMIC's aluminum

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Making the Matrix

It has taken more than a decade to overcome the hurdles on the way to achieving aluminum diamond metal matrix composites that can be reliably produced in large quantities at low cost. However, considering the benefits they can deliver to GaN device, amplifier, and subsystem manufacturers, the effort was well worth it.

To create an MMC, a metal such as aluminum, copper, or silicon is combined with diamond or silicon carbide. In the case of NMIC's MMCs, an aluminum alloy and low-cost, industrial-grade synthetic diamond particles are employed. Besides having unparalleled thermal conductivity, diamond is also extremely hard. So while the end product must have high thermal conductivity and a CTE close to that of SiC, it must also retain mechanical strength. To achieve this, fine and coarse diamond particles are blended to allow the most diamond (60% by volume) to be incorporated in the mix.

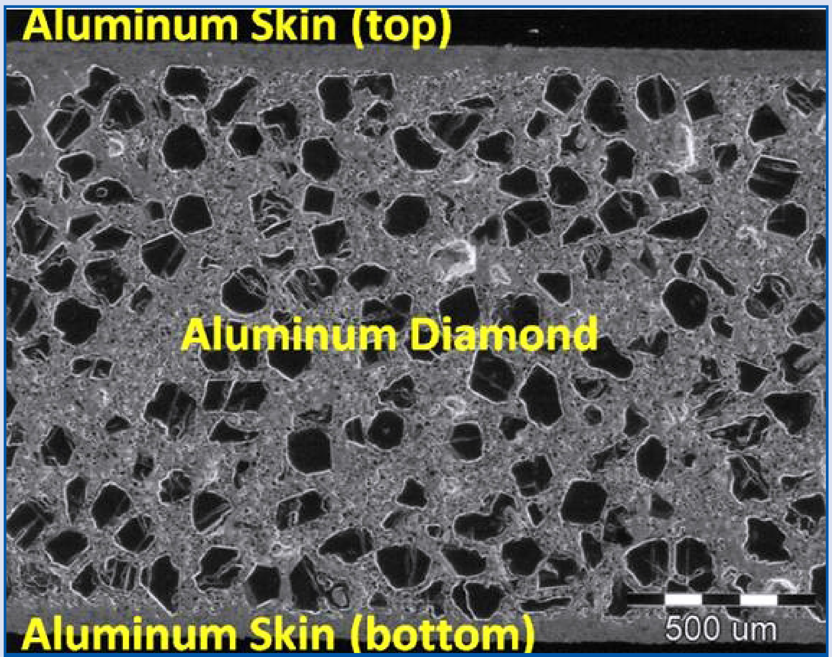

Figure 4: An aluminum diamond MMC showing top and bottom layers of aluminum "skin" and the primary material between them.

Voids under the active area of a die are the bane of all RF power device manufacturers because they make it possible for hot spots to arise that lead to premature device failure. To meet manufacturer requirements, NMIC's product has been refined to reduce even extremely small voids between the diamond particles and aluminum alloy to maintain optimum thermal conductivity and thermal stability. It employs an aluminum alloy skin from 0.05 to 0.1 mm thick on the top and bottom surfaces of the part and the skin becomes part of the matrix microstructure (**Figure 4**). This ensures that a strong, homogenous, smooth surface with surface roughness of less than 1.0 µm Ra is created onto which metallization can be applied (**Figure 5**).

For use as a heat spreader, an MMC must be able to survive wide swings in temperature encountered in operation, which NMIC solved by creating a process that produces a precise SiC surface layer on the diamond particles. While a conventional SiC coating acts as an additional thermal interface between the SiC layer and diamond particles, NMIC's SiC surface-conversion layer actually becomes part of the diamond particles themselves, which results in negligible thermal resistance in the metal matrix, high

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diamond MMCs can be made in any thickness required by a heat spreader and in any shape and size typical of GaN HEMT or MMIC devices. They are available as MMC material alone or incorporated within a package in order to meet the specific needs of device manufacturers and package suppliers.

Cost No Longer a Deterrent

One of the initial problems faced by NMIC and others working with diamond was achieving the ability to manufacture parts economically in large quantities. This is obviously critical in highly cost-sensitive commercial applications. However, it is equally important in radar and EW systems as hundreds or thousands of MMIC-based T/R modules, each using multiple GaN MMICs, are employed. However, continuing improvements in process technology and other factors have allowed NMIC to reduce the cost to a minimal amount per device.

The timing of this cost reduction is good, as the cost of GaN RF power devices is also dropping, so that when GaN's power density is taken into consideration, it is now possible to manufacture GaN MMICs that deliver more power at less cost per generated watt than GaAs, which has had more than 25 yr. to mature. GaN-based radars and EW systems will require fewer MMICs to generate a specific RF power than can GaAs, which inherently improves reliability and reduces cost. In addition, as GaN has much higher power density per millimeter of gate periphery, a GaN MMIC can be one-quarter to one-third the size of a GaAs MMIC that delivers the same power.

From a direct cost perspective, while SiC is much more expensive than GaAs, less of it is needed to generate a specific RF output power. So if the total cost of a finished GaN wafer is twice as much as a GaAs wafer but the die is one-quarter to one-third the size of its GaAs counterpart, the GaN device actually costs about 30% less per watt than GaAs.

In the future, aluminum diamond MMCs are likely to further reduce overall GaN cost, although more subtly, as they lower device operating temperature, which increases device operating life, reduces cooling overhead, and allows the device to deliver its rated power. All of these benefits will be delivered at a minimum cost per device. The aluminum diamond MMC manufacturing process itself has been enhanced to deliver high volumes of thermal spreaders with high yield and short delivery times, as several thousand parts can be fabricated at the same time.

Summary

The U.S. Department of Defense as well as defense agencies worldwide are in the process of upgrading their radar, EW, ECM, and communications systems to address new threats, funding constraints, and changes in their host platforms. GaN technology will have a major role in determining the ultimate performance of these systems, and enhancements such as aluminum diamond MMCs will in turn increase the capability of the GaN devices themselves. Aluminum diamond technology has not yet reached its limit in achievable thermal conductivity, so advances are likely to further allow GaN RF power transistors and MMICs to meet even more stringent demands in the future. More information about NMIC's aluminum diamond MMCs is available at www.nanomaterials-intl.com or by calling (520) 574-1980.

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strength and stiffness, and allows thermal conductivity to extend to near the theoretical limit.

NMIC produces the aluminum diamond itself by a process called "squeeze casting," a manufacturing-proven process widely used 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, as aluminum carbide increases thermal resistance at the diamond/aluminum interface, reduces thermal conductivity, and degrades performance during temperature or humidity cycling.

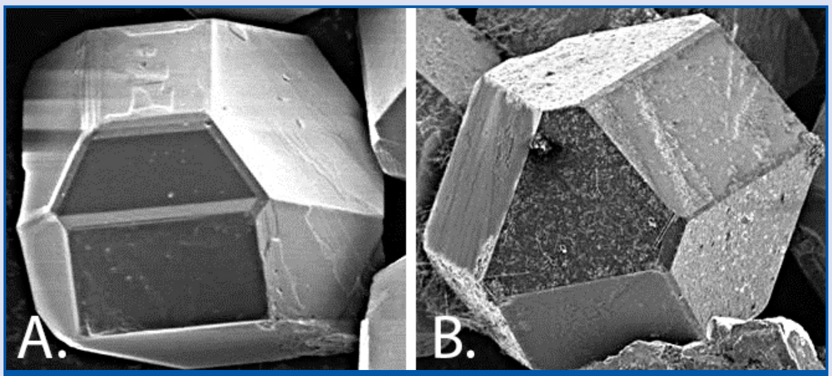

Figure 5: The diamond before (a) and after (b) the SiC conversion process.

Nickel-gold plating is applied to the MMC to support die attach. Nickel plating and then gold plating are applied as the initial plating, followed by 2 μm of gold, after which chemical resistance and bake tests to determine plating adhesion are conducted to validate the plating process. Customers have also performed these tests to simulate the cleaning that occurs during device fabrication, and no weight loss or blistering of the plating occurred.

Solder die attach, yield, and RF and thermal testing are now routinely obtained by the company's customers using gold tin solder between the aluminum diamond heat spreader and the die. CTE and thermal conductivity 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. In addition, thermal conductivity decreases with increasing temperature but remains more than 400 W/mK well past the operating temperature of GaN devices.

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