# Aluminum Diamond Application Profile:

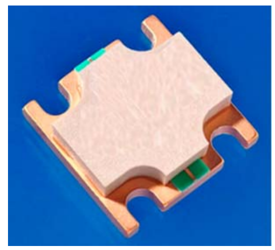
## *GaN RF Power Transistors*

The emergence of Gallium Nitride (GaN) is arguably the most impressive compound semiconductor development in many years. When employed for generating RF power in the form of transistors or Monolithic Microwave Integrated Circuits (MMICs), it offers significant benefits that silicon and gallium arsenide (GaAs) cannot match.

GaN achieves these benefits through its higher power density, which is currently up to 11 W/mm of gate periphery (total gate periphery being defined as the total number of gates multiplied by their width), and its ability to operate at high voltages over broad bandwidths, while potentially delivering high RF power output at frequencies well into the millimeter-wave region.

However, it's high power density translates into significant amounts of waste heat that must be dissipated if the device is to achieve its optimum performance and operating life. If the problem can be mitigated, the potential for GaN RF power transistors in defense programs such as the Next Generation Jammer (NGJ) as well as in a broad range of commercial applications cannot be overstated.

This characteristic is perhaps the greatest impediment to GaN's ability to achieve its potential, and solutions are actively being found at the device through system levels. It is at the device level where NMIC's aluminum diamond MMCs offer a unique solution.



**TAKING OUT THE HEAT**

Tackling GaN's heat dissipation challenge will take place in three areas: at the system level, at the amplifier, and at the device itself. At the system level, it is likely that active cooling such as liquid cooling will be the solution, particularly when amplifiers are delivering high RF power levels.

At the amplifier level, the traditional method of heat dissipation is through the use of heat sinks and perhaps materials such as thermally annealed graphite. At the device level, heat spreaders placed between the active device and its mounting surface are the first line of defense in removing heat. This is currently being accomplished by copper-tungsten, copper-moly, and copper-molly-copper solutions that have been used extensively for many years.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However, GaN presents challenges in heat dissipation that have not been encountered before and the inherent properties of these materials makes them unsuitable for the task if optimum device performance and operating life are to be achieved.

**THE CHALLENGE AND PROMISE OF DIAMOND**

Diamond has been studied for more than 25 years for use as a heat spreader material for high-density RF power devices. The continued pursuit of diamond for this application, especially considering the significant technical challenges required to make it viable for commercial use, is based on the material's extraordinarily potential.

Diamond, both natural or synthetic, has the highest thermal conductivity of any material on Earth. Polycrystalline diamond has thermal conductivity between 1200 and 1500 W/mK, which is much higher than silicon carbide's (SiC's) 400 W/mK as well as silicon and sapphire, whose thermal conductivities are 150 W/mK and 35 W/mK respectively.

Diamond's thermal conductivity ranges from 2 to 6 times that of oxygen-free, high-conductivity copper (OHFC), and at least twice that of any other material combination used for heat spreaders and substrate material as shown in the table.

Diamond also has electrical resistivity between $10^{13}$ and $10^{16}$ ohms/cm, which is significantly better than SiC and about the same as sapphire.

| Material | Thermal Conductivity (W/mK) | CTE (ppm/K) |
|---|---|---|
| Diamond | 1500 | 1.4 |
| NMIC aluminum diamond | 500 | 7.5 |
| Cu | 393 | 17 |
| Silicon | 136 | 4.1 |
| SiC | 430 | 4 |
| AlSiC | >175 | 7.9 |
| W90Cu | 185 | 6.5 |
| W75Cu | 225 | 9 |
| Mo70Cu | 185 | 9.1 |
| Mo50Cu | 250 | 11.5 |
| CuMoCu | 220 | 6 |
| CuMoCu | 310 | 8.8 |
| Cu/Mo70Cu/Cu | 340 | 8 |

However, while diamond has been researched for its potential use as a substrate material, development efforts at NMIC have shown that it is best suited as a heat spreader rather than a substrate. A heat spreader, as its name suggests, essentially takes heat from the device and spreads (dissipates) it so that it can be removed rapidly from the device to some other larger surface such as a heat sink.

The challenge arises from creating a material that has a coefficient of thermal expansion (CTE) as close as possible to that of the device substrate material, which in the case of GaN is SiC. It must achieve this without reducing its primary benefit, thermal conductivity, to a point at which overall each printer performance is compromised.



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This is accomplished by forming a metal matrix composite (MMC), which consists of a primary metal such as aluminum or copper with a secondary material such as diamond or SiC. NMIC's MMCs employ an aluminum alloy composition that is infiltrated into a packing of diamond particles.

The size and ratio of diamond particles to aluminum must be optimized to provide three key characteristics: high thermal conductivity, low CTE, and good mechanical strength, and other characteristics must be optimized as well. Finally, all of this must be accomplished in such a way that the end result is a product that not only meets customer technical requirements but does not add substantially to the cost of the host product.

**THE CHOICE FOR GaN**

NMIC's aluminum diamond MMC material accomplishes all of the aforementioned goals to produce the first such material that meets the challenges dictated by GaN RF power devices:

• **High thermal conductivity**: While less than pure diamond itself, NMICs MMC material achieves thermal conductivity of at least 450 W/mK, which is still at least twice that of its nearest competitor.

• **Well-matched CTE**: With values of 4 to 8 ppm/K, the material is close to that of SiC (as well as silicon, GaN, and GaAs), an essential requirement for device compatibility.

• **Low surface roughness**: An essential requirement to eliminate the possibility of voids between the device and heat spreader, which would result in thermal hotspots.

• **Compatible metallization:** ensures successful, avoid-free die attach.

• **Excellent dimensional tolerances** and material stability.

• **Manufacturability:** In large quantities and in sizes and shapes compatible with GaN devices.

As a result, NMIC's meet all of the technical requirements that are required for use as a heat spreader. Significant development efforts have also resulted in NMICs ability to manufacture its aluminum diamond MMCs at costs acceptable to device manufacturers.

It is the first such MMC material to do so.

**Questions?**

NMIC can answer any questions and provide quick turnaround of samples and prototypes. For more information please contact us:

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