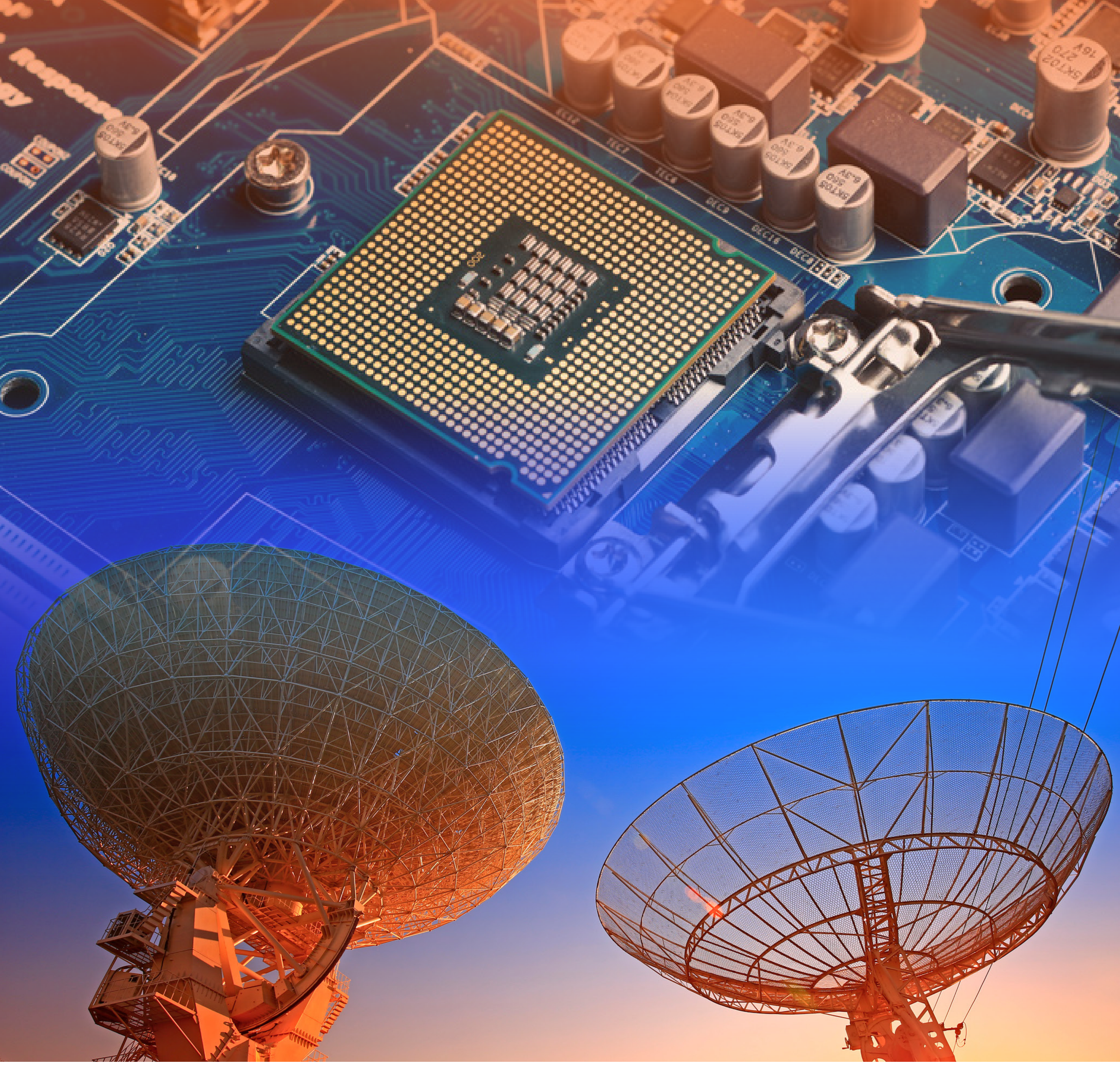
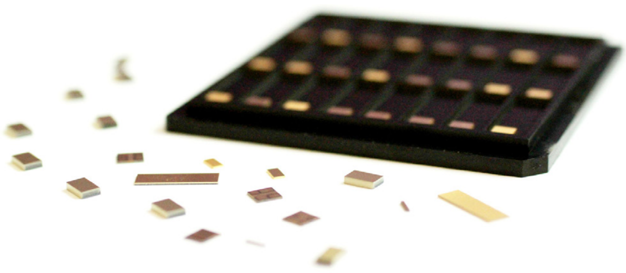


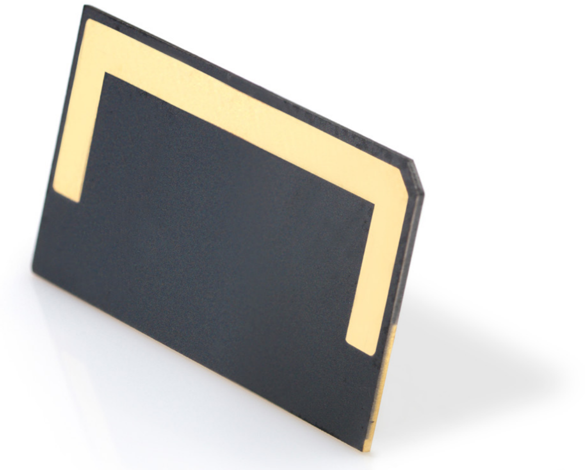
Diamond heat spreaders enhance the performance of GaN-on-SiC RF power amplifiers

elementsix™
DE BEERS GROUP

Diamond's unequalled thermal conductivity makes it the ultimate heat spreader for high-power semiconductor chips. Diamond's ability to cool GaN-on-SiC radio frequency (RF) amplifier MMICs paves the way for higher power and more reliable radar, wireless communications, and electronic warfare technologies.



Element Six (E6) metallized diamond heat spreaders



E6 Diafilm™ Series

The opportunity
Enhancing RF power amplifiers in defense, satellite and mobile communications

GaN RF power amplifiers (PAs) offer significant advantages compared to silicon-based devices, where high powers at high RF frequencies in a reduced footprint are required. GaN RF PAs are revolutionizing performance in a range of RF end markets, from satellite and mobile communications, to radar and electronic warfare [1].

The challenge
GaN power amplifiers are performance-limited due to thermal management bottlenecks

Despite the inherent advantages of GaN PAs, the limited power added efficiency (PAE) of these devices leads to heat dissipation within a very small volume. This can produce heat fluxes measuring several times those at the surface of the sun (multiple kW cm^{-2}), resulting in excessive device temperatures. For reliable operation, the transistor junction temperature should remain well below a maximum value, limiting the RF power density of the device. Achieving next level performance requires new solutions to address this thermal management challenge.

The solution
CVD diamond heat spreaders

Synthetic diamond's outstanding thermal conductivity provides a consistent heat spreading capability, unmatched by any other material, leading to reduced junction temperatures, uniform heat fluxes, and a significant improvement in thermal performance. E6's Diafilm™ heat spreaders, grown by chemical vapor deposition (CVD), are available in metallized and unmetallized formats. Our world-leading range of thermal grades delivers thermal conductivities that far exceed those of traditional heat spreader materials, such as copper and aluminium (Figure 1).

When used with appropriate die attach methods, Diafilm heat spreaders provide reliable solutions for improved thermal performance of semiconductor chips. In collaboration with teams from the Chip Integration Technology Centre (CITC) and TNO Defence, Safety & Security, we investigated the impact of CVD diamond heat spreaders on the performance of high power GaN-on-SiC PAs.

Thermal conductivity

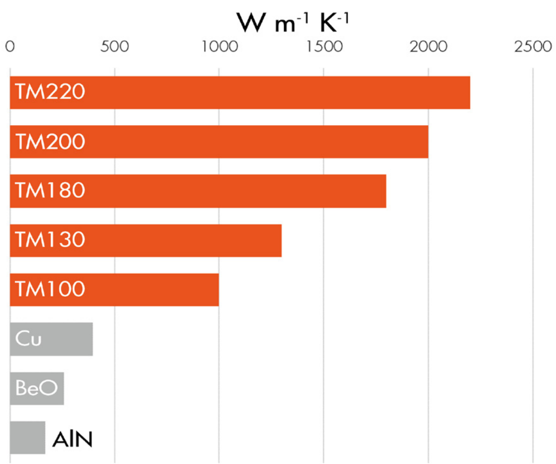


Figure 1 Room temperature thermal conductivity of different thermal grades of synthetic diamond manufactured by E6, in comparison to standard thermal management materials.

The results

Enhanced RF and thermal performance of GaN-on-SiC amplifier MMICs

For this case study an existing S-band (2.9 – 3.4 GHz) GaN-on-SiC amplifier monolithic microwave integrated circuit (MMIC), 100 µm thick, designed for pulsed radar applications was used [2]. This features a peak output power of 400 W at 55% PAE for 55 V drain bias and operation under a short pulse width of 2 µs at 1 % duty cycle. For such a PA the peak power dissipation is mainly located beneath the output stage transistors and the dissipation density can be as high as 5 kW cm^{-2}, based on 189 W dissipation in an area of 5.4 mm × 0.7 mm. For reliable operation, **the junction temperature of the transistors should remain well below 250 °C** and, due to the high power dissipation, this is only possible when operating with a small duty cycle and short pulses.

CVD diamond heat spreaders of thickness 0.5 mm and with room temperature thermal conductivity of 1000 (TM100) and 2200 W m^{-1} K^{-1} (TM220) were metallized with Ti/Pt/Au layers for facilitating die attach and for providing an RF ground for the PA. A nano-silver sinter paste was dispensed on each metallized diamond heat spreader and the gold metallized MMIC dies were wet mounted to the diamond using a die-bonder. Post wet-mounting, the die-diamond stack was sintered by a pressure-less sintering process under nitrogen atmosphere in multiple stages. The drying stage is performed at 90 °C, in which the solvent evaporates, leaving behind the nano-Ag particles. The sintering stage is at 250 °C, whereby the particles agglomerate into a dense silver film. This process was repeated to bond the die-diamond stack to a CuMo cooling block. The resulting sintered interface thicknesses were approximately 35 µm. An image of a die-diamond-CuMo stack is shown in Figure 2.

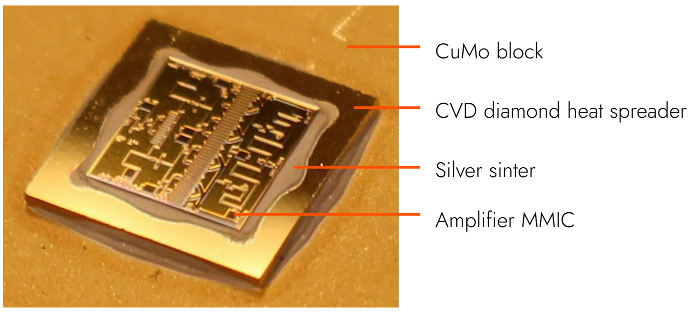


Figure 2 Example of an assembled die-diamond-CuMo stack

The MMICs mounted on diamond heat spreaders were compared to an identical reference MMIC directly silver-mounted to a CuMo block. Based on the measured PAE for various pulse widths and duty cycles, an estimate was made of the MMIC temperature. **Devices with diamond heat spreaders showed a significant decrease in MMIC temperature. For example, for a 1 ms pulse width, 10 % duty cycle RF pulse, the MMIC backside temperature was reduced by 25 °C or more** as illustrated in Figure 3.

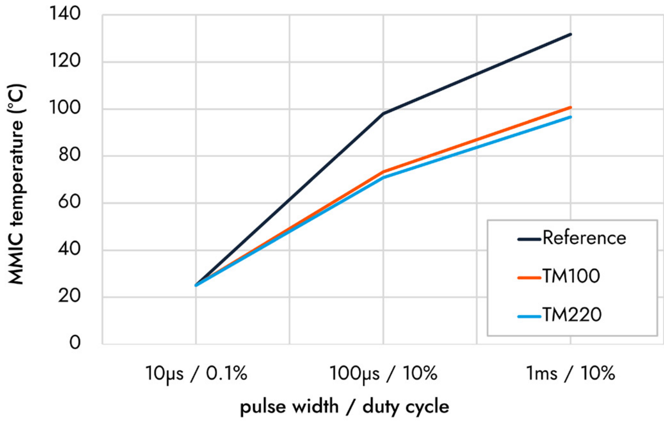


Figure 3 MMIC temperature for increasing pulse width and duty cycle

Based on thermocouple measurements of the CuMo carrier below the MMIC, it was estimated that the thermal resistance of the MMIC package was reduced by 30%, demonstrating the effectiveness of the diamond heat spreaders. Thermal simulations estimated that the amplifiers with **diamond heat spreaders can be operated at up to 10× to 100× longer pulse widths** than the reference sample, while maintaining a junction temperature of 250 °C (Figure 4).

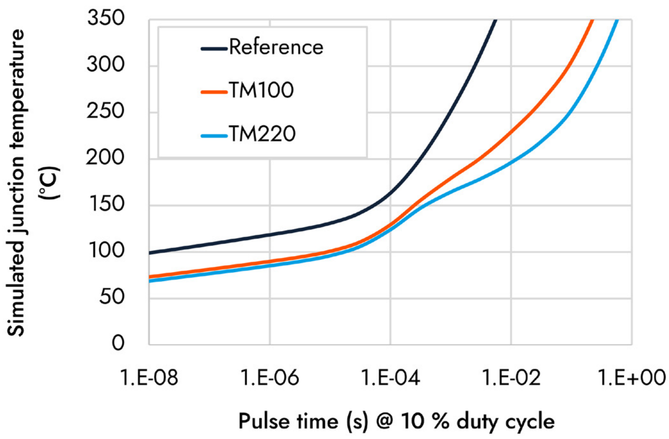


Figure 4 Simulated junction temperature of the PA, vs pulse width, for a 10 % duty cycle

These results conclusively demonstrate the effectiveness of CVD diamond heat spreaders in significantly improving the thermal and RF performance of GaN-on-SiC power amplifiers.

Further reading

1. Andrew Moore and Jose Jimenez, GaN RF Technology for Dummies. John Wiley & Sons, Inc, 2015.
2. A. P. de Hek, G. van der Bent, and F. E. van Vliet, "400-Watt S-band Power Amplifier MMIC," presented at the 16th European Microwave Integrated Circuits Conference (EuMIC), London, UK, 2022, pp. 160–163.

Element Six is a global leader in the development and production of synthetic diamond and tungsten carbide solutions. For over 70 years, our innovation expertise has enabled a wide range of industries, from aerospace and mining, to semiconductors and sensing. Part of the De Beers Group, our primary manufacturing sites are located in the US, UK, Ireland, Germany and South Africa. Our sites in Ireland and Germany are ISO 50001 certified.

Through the Anglo American and De Beers Groups, Element Six is a member of the UN Global Compact (UNGC). The UNGC drives business awareness and action towards the UN Sustainable Development Goals (SDGs), focussing on 10 principles around human rights, labour, environment and anti-corruption. Element Six works within the De Beers Group Building Forever commitment and Science Based Target Initiative (STBi), which is also based on the UNGC principles.

We incorporate and take responsibility for these principles through the Element Six Code of Conduct, Our Values, Responsibilities and Policies.

At Element Six, we have active communities working towards sustainability from a variety of angles, such as environmental impact, inclusion, diversity and community outreach, both internally and externally.

Contact us

Europe
Customer Services
T +44 1344 638 200
E technologies@e6.com

Americas*
T +1 408 986 2400
E ustechnologies@e6.com

*Registered with the Department of State for handling ITAR sensitive and controlled defense projects.

e6.com | e6cvd.com