GaN HEMT Near Junction Heat Removal

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GaN HEMT technology is transforming applications in communications, radar, and electronic warfare by offering more than 5x higher RF transmit power over the existing GaAs-based technologies. The high breakdown voltage and current handling capability of GaN HEMTs enables for the same device size, a 10x increase in RF power using GaN-based devices in place of conventional GaAs-based devices. However the ultimate power and performance of GaN technology cannot be exploited in real applications due to thermal limitations on performance and reliability. The high power density in GaN HEMTs translates to mega-watts/cm^2 heat dissipation at the device gate region. Increasing the heat conductance near the GaN device junction is critical to reduce device junction temperature for reliable operation and performance.

Advanced diamond seeding and growth methods to directly deposit high thermal conductivity diamond with a low interface resistance is a promising near junction heat removal approach for GaN HEMT MMICs. Thermal conductivity of >1500 W/mK with a low boundary resistance of <10 m^{2}K/GW within a micron from the GaN HEMT device channel is key to increase the power handling of GaN HEMT devices by more than 3x with no change to operating junction temperature. We are developing and optimizing nanocrystalline diamond (NCD) seeding approaches to grow uniform and dense diamond films with high quality interfaces with engineered grain structures to achieve thermal conductivities greater than 1300 W/mK in the first few microns of growth.

To fully characterize the thermal characteristics of our diamond growth process, diamond windows deposited on Si were characterized by picosecond time-domain thermoreflectance (TDTR). Nanocrystalline diamond, grown from a seed layer on Si wafers, was fabricated into free-standing windows as shown in Fig. 1.

Three diamond films of different thickness, 0.5µm, 1µm and 5.6 µm, were measured using this approach to better resolve the thermal characteristics of the films. TDTR of the thinnest, 0.5 µm, film was sensitive primarily to diamond heat capacity. The value measured was 1.98 MJ/m^{3}K.

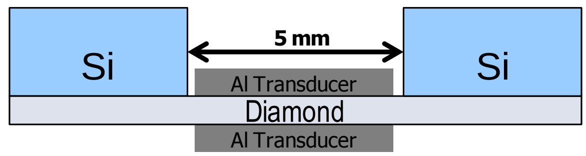

Fig. 1. Diamond on Si wafer sample geometry used for the NCD thermal characterization measurement.

Measurements of the thickest, 5.6 µm, film are shown in Fig. 2. A two layer model was fit to the measured results to extract characteristics of the low thermal conductivity film coalescence region and the high thermal conductivity bulk region. The best-fit model indicates a film coalescence region thickness of 760 nm with a thermal conductivity of 80 W/mK, leading to a total equivalent interface thermal resistance of 9.5 m^{2}K/GW. The bulk diamond region was found to have a thermal conductivity of 1340 W/mK through-plane and 965 W/mK in-plane.

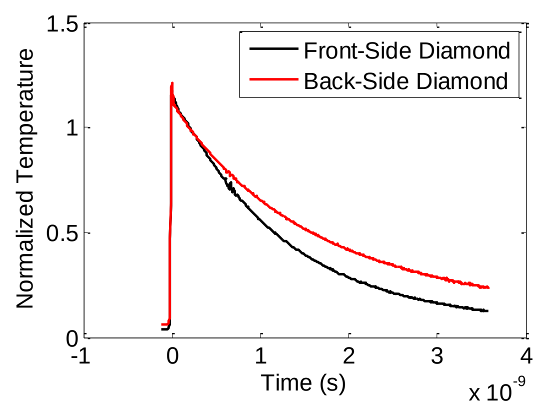

Fig. 2. Thermal decay curve of Al on the frontside and backside the free-standing diamond window.

We are optimizing diamond film nucleation and growth methods to improve thermal conductivity near the interface. We have measured film conductivities > 1300 W/mK in the diamond film coalescence region on Si wafers. The optimized diamond nucleation and growth methods will be integrated with GaN HEMT devices to evaluate advanced device scale heat removal approaches integrating diamond materials less than a micron away from the device channel.