

GaN MMIC Impingement Jet Cooled Embedded Diamond

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Abstract

GaN HPA MMIC technology will benefit significantly from higher power handling capability, reduced die size and lower peak channel temperature, enabling increased power output and efficiency, additional system functionality, and reduced size, weight, power and cost (SWAP-C). High-thermal conductivity diamond substrates [1] and diamond via technology [2] are promising recently proposed solutions which can reduce the temperature drop between the device channel and the system heatsink. However thermal management at the heatsink subsequently becomes the next bottleneck and an increased challenge due to the compact die size and concentrated heat flux. The direct integration of microfluidic impingement jets under each HEMT device can help overcome this significantly increased thermal load.

INTRODUCTION

Despite the relatively high thermal conductivity of SiC substrates, high-power GaN HEMT electronics on SiC substrates are ultimately limited in performance by thermal constraints. Die size, gate pitch, gate periphery and unit cell spacing have to be carefully designed to avoid exceeding the maximum device channel temperature which is determined by reliability lifetime predictions. In this paper we report on a design approach and provide initial results of the integration of a microfluidic impingement jet with an embedded diamond-lined microchannel using our production GaN-on-SiC HEMT epitaxial wafers and standard frontside processing. The combination of diamond coating with high-performance microfluidic cooling enables dramatically improved RF power density, die size compaction and reduced channel temperature; all while leveraging a highly manufacturable GaN-on-SiC front- and backside fabrication process technology.

IMPINGEMENT JET MICROFLUIDIC DESIGN

A simplified cross-section drawing of an individual jet impingement cooled embedded diamond device is shown in Figure 1. Coolant is supplied from a fixture baseplate into a silicon micromachined manifold inlet (not shown). The liquid supply is distributed in parallel to impingement jet nozzles under each device in the MMIC PA. The individual HEMT unit cell device is shown in the figure. Micromachined nozzles direct high velocity fluid against the diamond lining in the impingement jet cavity.

The impacting fluid jet minimizes the boundary layer thermal resistance, enhancing local conjugate heat transfer under the HEMT devices. Heat is first spread from the channel hot spot in the diamond layer before being transferred into the impinging liquid. The heated coolant is then directed away from the die and exits out through two adjacent return passages in the manifold below.

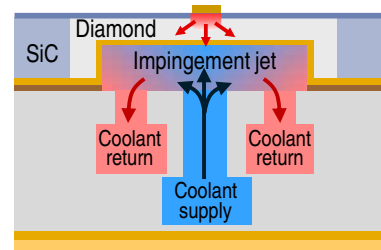


Figure 1. Impingement jet cooled embedded diamond GaN HEMT unit cell cross-section.

MODEL RESULTS

Conjugate heat transfer computational fluid dynamics (CFD) simulation was used to model the effectiveness of the impingement jet at thinning the thermal boundary layer. Coolant flow velocity results are shown in Figure 2 with a 6.7W GaN HEMT unit cell device using a propylene glycol and water mixture with a flow rate of 0.23 cm³/s and an inlet temperature of 27°C. The high velocity at the back of the hotspot eliminates the associated thermal resistance otherwise impeding heat transfer in the critical region directly beneath the GaN HEMT device.

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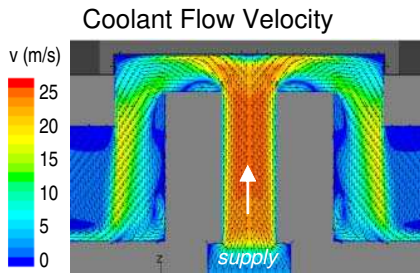


Figure 2. Conjugate heat transfer analysis of submerged microfluidic impingement jets under a 6.7 W GaN HEMT active device.

In each circuit twelve device unit cells are combined in a two-stage power amplifier configuration. Electro-thermal model results of dissipated power, RF output power and channel temperature are shown in Figure 3. The computational results demonstrate substantial improvement in output power and power handling at a reduced channel temperature.

The CFD simulation conditions assume adiabatic boundary conditions in which all of the energy is transferred into the traversing coolant. Approximately 50% of the heat transfer was predicted to occur within the impingement jet in the SiC/diamond wafer, while the remaining 50% of the heat is transferred to the liquid in the silicon manifold portion. In practice, while the fluid-cooled die could be attached to a heat sink or air-cooled for even further improvements, a fully “remote-cooling” paradigm, in which the waste heat is rejected far from the electronics, greatly increases the SWAP-C savings for the overall system.

EXPERIMENTAL RESULTS

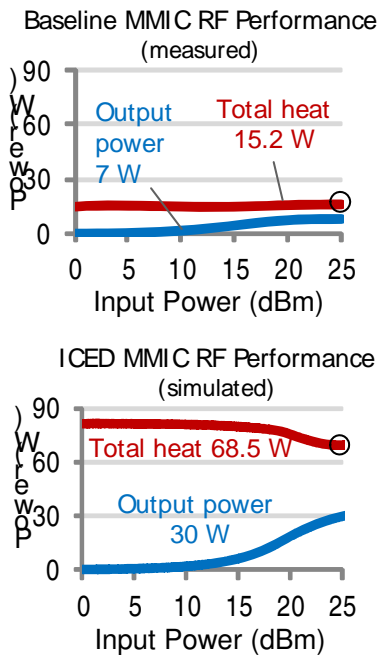


Figure 3. Improvements of the impingement cooled embedded diamond structure over a typical GaN on SiC HEMT MMIC. Channel temperature simulations for the baseline MMIC resulted in a peak temperature of 186°C (top) while the impingement jet MMIC was 165°C (bottom).

To validate the CFD model results and demonstrate the thermal improvements, a thin-film resistor-based thermal demonstration circuit was fabricated and tested. A GaN-on-SiC epitaxial wafer was thinned and the SiC substrate backside patterned with microchannels openings. A standard AlGaIn/ GaN HEMT epitaxial layer profile was used to most closely match the thermal properties of an active GaN HEMT device. Polycrystalline CVD diamond was then deposited in the microchannels to form a conformal lining in the opening. Diamond was depositing using a high-power microwave CVD process with a nanocrystalline diamond particle seed layer. A planarization process was used to remove the diamond from the back of the SiC substrate outside the channels to minimize wafer stress and warp, and improve the flatness of the manifold to die bonding surface.

Frontside thin film resistors (TFRs) were used to approximate the heat load of the active RF HEMT devices with the same footprint and total DC power dissipation. The die was then eutectic attached to a silicon microfluidic manifold which contained internal distribution and impingement jet passages. The design of the distribution manifold was optimized for reduced flow resistance and balanced flow performance to each of the diamond microchannels. The vertical impingement jet nozzles were designed to maximize conjugate heat transfer with the diamond surface while minimizing pressure drop. The integrated manifold and die was then eutectic bonded to a metal test fixture containing a DC wire bonding substrate and threaded fluid fittings.

Photograph and microscope images of the assembled TFR die and silicon manifold are shown in Figure 4. Two stages of resistors were fabricated approximating the layout of a MMIC PA. Two of the predicted hottest stage-2 resistors and two of the coldest stage-1 resistors were connected in 4-wire configuration in order to simultaneously dissipate power and measure the

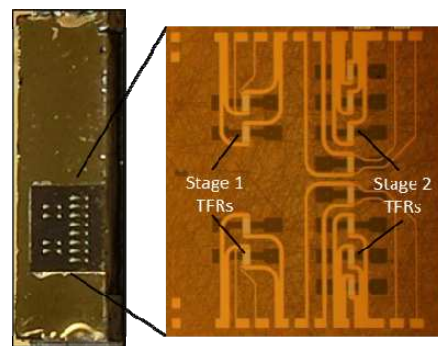


Figure 4. Assembled thermal demonstration die and manifold (left) and die frontside (right) showing 12 TFR heaters with 4-wire integrated temperature sensors.

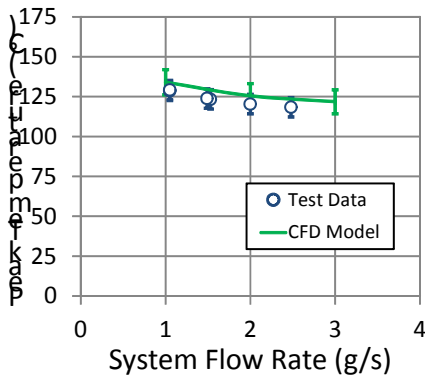


Figure 5. Measured thin film resistors results compared to CFD model calculations. The test and model temperature data were taken at the hottest resistor in stage 2.

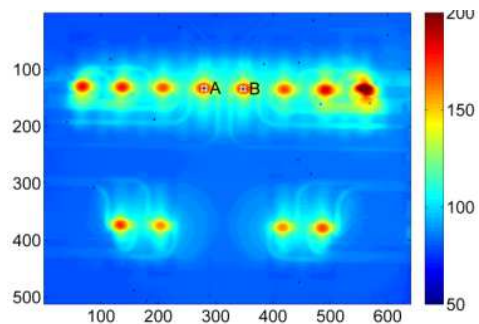
temperature as a resistive temperature detector.

The assembled embedded diamond jet impingement structure was tested using a propylene glycol and water mixture with an inlet pressure of 1 MPa and a fluid inlet temperature of 70°C. All twelve thin film resistors were biased to a total of 30W and characterized using high-resolution IR thermography. The measured hot spot temperature and comparison to the CFD model are shown in Figure 5. The dependence of peak resistor temperature with total circuit fluid flow rate is plotted and a close match to the data was found. Measurement and modeled

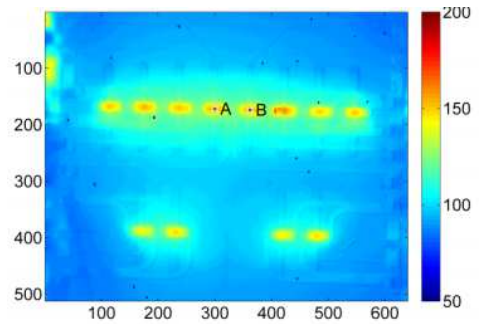
estimated error are included in the plot as error bars. The resistor IR temperature measurement was calibrated using emissivity values calculated by a temperature controlled baseplate calibration process. It is noted that the predicted error is relatively small compared to the typical error of IR temperature measurements taken on GaN HEMT devices. This is due to larger uniform area of the thin-film resistors and the opacity of the metal resistor layer.

Two different circuit layouts were evaluated having two die sizes. The die with the smaller footprint, designated TDV12, had rectangular microchannels etched into the die. The die with the larger footprint, designated TDV12XL, had an H-shaped microchannel etched into the die. To ensure the test reflected the best thermal performance, the experiments used the maximum coolant flow rate that could be sustained at a 1 MPa pressure drop. The die power dissipation was limited to 45W to maintain the integrity of the resistors that provided the equivalent HEMT heat sources and minimize the risk of damage during thermal excursions.

Two IR thermal images of the top surface of the thermal demonstration circuit die operating at 45W total heat dissipation is shown in Figure 6. The die-level heat flux at this thermal load is 680 W/cm² for the TDV12 and 526 W/cm² for the TDV12XL. The temperature contours matched those predicted by the CFD calculations. The heated region is well confined to the heat load locations with minimal thermal interactions between neighbors. This trend is especially prominent in the plot for the TDV12XL die for which the larger spacing between heat sources further reduces mutual heating effects on the die.



(a) TDV12XL – H-Channel – Flow = 4.1 g/s



(b) TDV12 -- Straight Channel – Flow = 2.3 g/s

Figure 6. Thermally calibrated IR temperature maps of thermal demonstration circuit TDV12XL (a) and TDV12 (b) biased at 45 W power dissipation.

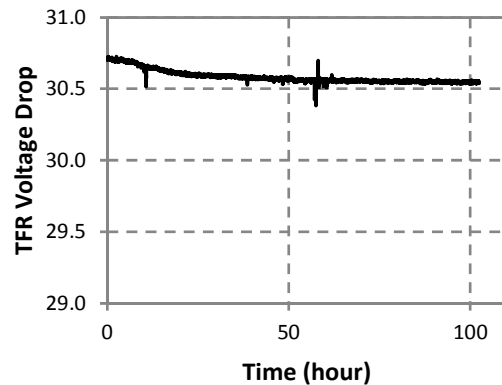


Figure 7. Extended testing of the microfluidic-cooled thermal demonstration circuit.

As an early stability evaluation, extended testing of the demonstration circuit TDV12XL was performed for 100 hours. The flow rate was held at 4.4 g/s with a pressure drop of 972 kPa and an inlet temperature of 70°C. The voltage drop of the hottest resistor is plotted in Figure 7. The relative stability of the voltage drop suggests stable temperature and constant thermal resistance of the diamond and the impingement jet microfluidic assembly. Small changes in the resistance were observed after the test due to

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degradation of the contacts under the high current load required to reach the target power dissipation for the equivalent resistor circuit.

CONCLUSIONS

The embedded diamond and jet impingement approach presented in this paper has been shown to mitigate self-heating thermal limitations and afford extremely aggressive design compaction not possible with existing state of the art GaN-on-SiC HEMT RF electronics. We have developed a highly manufacturable thermal management approach enabling a dramatically improved power handling capability for GaN HPA technology.

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ACRONYMS

GaN: Gallium Nitride
MMIC: Monolithic Microwave Integrated Circuit
HEMT: High Electron Mobility Transistor
RF: Radio Frequency
CFD: Computation Fluid Dynamics
PA: Power Amplifier
HPA: High Power Amplifier
CVD: Chemical Vapor Deposition
IR: Infrared
TFR: Thin Film Resistor