Thermal and Mechanical Sensors for Advancement of GaN RF MMIC Technologies

B. Wagner*, H.M. Harris*, M. King*, H. Chan*, N. Minor* and L. B. Burns[1]
*Georgia Tech Research Institute, Electro-Optical Systems Laboratory Atlanta, GA 30332
brent.wagner@gtri.gatech.edu; (404) 407-6468
[1]PEO Integrated Warfare Systems, Naval Sea Systems Command, Washington, D.C. 20376

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Abstract

A series of diagnostic structures particularly suited to the advancement of GaN-based semiconductor devices on silicon carbide substrates were developed and fabricated directly on the GaN epitaxial layers/SiC substrates. These structures include heat source die that replicate GaN on SiC high power amplifiers from a geometric power dissipation density perspective, temperature sensors, and strain gauges. These devices can be used as test and evaluation tools to reduce packaging and thermal management system development cycles as well as process control monitors and in-situ diagnostic devices to improve the operation and maintenance of RF systems.

INTRODUCTION

Continuing developments in GaN on SiC high power RF amplifier technology have led to an ever increasing ability/demand to produce higher power levels in smaller packages. However, this increase in performance has created the concomitant need to manage higher levels and densities of dissipated power. This is important due to the detrimental effects of temperature and temperature cycling on device efficiency, gain, power output, mechanical stability and ultimately, device lifetime. In a typical radar application, heat removal at the MMIC level occurs through a conductive heat path rather than direct radiative or convective cooling. Thus, the design of and materials used in the packaging and thermal management system must be carefully considered, and their effect on device performance evaluated typically through both FEA thermal simulations and physical validation through a series of measurements that can include IR thermal microscopy and micro Raman measurements. This requires assembly of the thermal stack and die attach of a MMIC, use of an RF test and measurement system co-located with the IR or Raman systems, and devolving of dissipated power from input and measured data to accurately assess the thermal management design. The purpose of this work is to develop heat source die to emulate MMICs thermally, while reducing the packaging and thermal management system development cycle time by eliminating the need to use expensive and sensitive RF die and greatly simplifying the test setup requirement. Also, integration of thermal and strain sensors on-chip provides a built-in means of assessing die temperature and strain with the prospect of integration with RF MMICS for real time monitoring and life prediction during device operation.

HEAT SOURCE DIE

GTRI has developed a process for building NiCr thin film resistor-based heat source die. These die are fabricated on GaN/SiC substrates and are designed and fabricated to replicate the gate periphery and gate to gate spacing of actual MMICs. These devices serve both as thermal die to evaluate the complete thermal management system (e.g., coolant temperature rise, thermal interface material (TIM) effects, etc.), as well as providing a validation of thermal models without the complexities and cost of using full RF devices. Dissipated power levels can be emulated using DC and pulsed DC drive without the need for gate control and at reduced risk of device damage.

Initial thermal validation devices were produced with various numbers of "gate fingers" at varying spacing on the same die while further devices were designed to match MMIC geometries of interest. These resistor elements were fabricated by depositing a 1700Å layer of NiCr (80/20 wt%) on GaN epitaxial transistor structures grown on SiC substrates. Contact pads were formed by selectively electroplating gold through a photoresist mask. Figure 1 shows a photograph of an exemplary 3.8mm x 6mm MMIC type heat source die with NiCr fingers located between the gold plated bus bars.

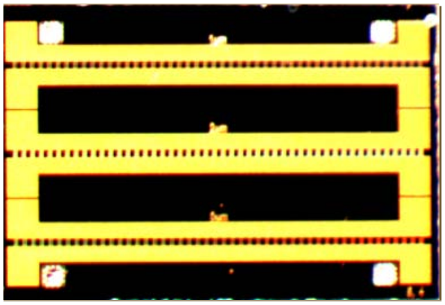

Figure 1. NiCr-resistor based heat source die for evaluating thermal management systems.

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Figure 2 shows an image of a finite element thermal model of a heat source die with an associated IR thermal image (inset) of a custom four-finger heat source element. Figure 3 shows the associated plot of measured channel temperature and model temperature as a function of dissipated power density.

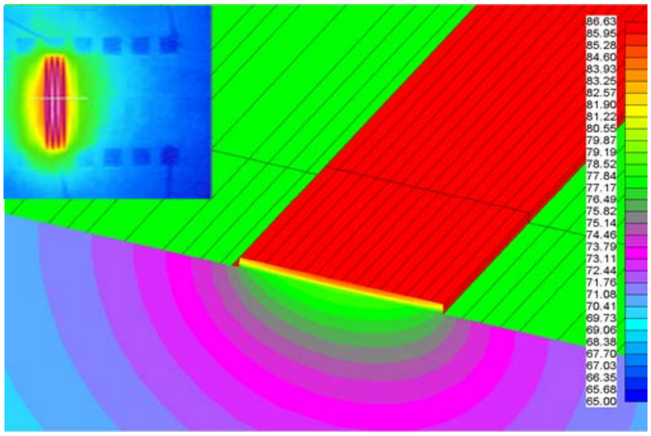

Figure 2. Thermal model of NiCr heat source resistor with associated measured thermal image of a four finger device (inset).

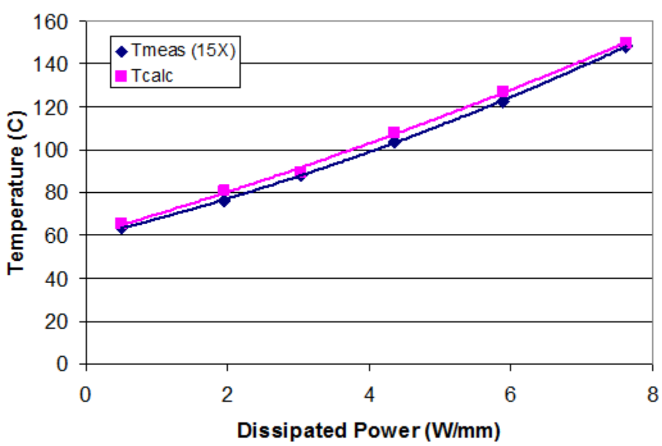

Figure 3. Comparison of measured and simulated peak temperature as a function of dissipated power density for a device as shown in Figure 2.

TEMPERATURE SENSORS

As described above, the performance of RF MMICs is critically dependent upon temperature. The addition of temperature sensors to MMICs provides a means of assessing RF and thermal performance on the chip itself. Three types of sensors are under consideration. These include thermocouples, resistance temperature devices (RTDs) and semiconductor devices (e.g., Schottky diodes, MIS devices, etc.). Preliminary results obtained for Ni based RTDs are described below.

Thin film resistor structures were fabricated from 100nm thick electron-beam deposited Ni layers and initial measurements of resistance as a function of temperature carried out on the temperature controlled wafer chuck of a Cascade probe station. Figure 4 shows measured resistance in response to a series of programmed step changes in wafer chuck temperature. It is apparent that the sensor resistance follows the input temperature. Taking data from the stabilized resistance/temperature regions, a calibration curve was developed as shown in Figure 5.

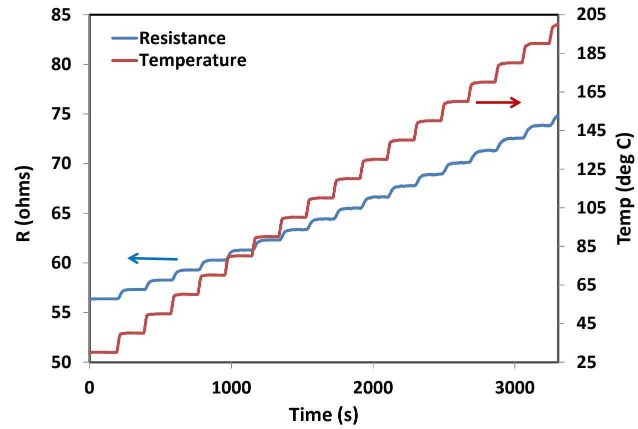

Figure 4. Ni temperature sensor resistance as a function of wafer probe station chuck temperature.

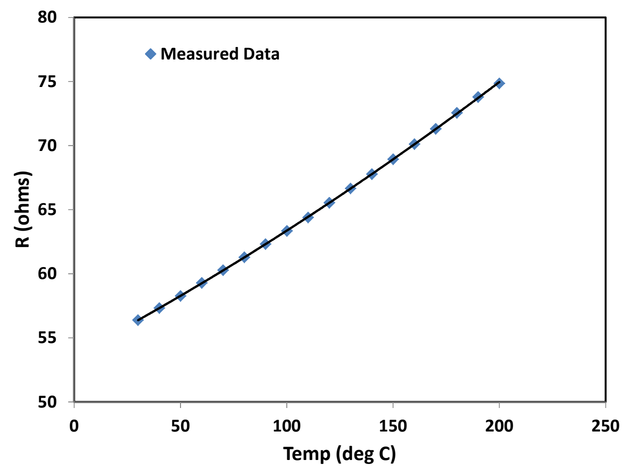

Figure 5. Ni temperature sensor calibration curve.

The resistance of RTDs can be characterized by the equation[1] $R_T = R_0 [1 + aT + bT^2]$, where R_0 is the RTD resistance at 0°C, and the coefficients a and b characterize the RTD. Fits to the data yields values of 53.7 ohms, 1.63×10^{-3} °C^{-1} and 1.76×10^{-6} °C^{-2} for R_0, a and b, respectively.

STRAIN GAUGES

Similar to the RTDs, strain gauges are based upon resistive elements except that, in this case, changes in resistance are due to strain causing bowing of the thin film resistors leading to an increase or decrease in resistance.

The monitoring of strain during the processing and operation of MMICs will enable assessment of thermal expansion mismatch, process monitoring and perhaps life monitoring.

In addition to the heat source die application described above, NiCr (80/20 wt.%) films were chosen for strain gauge applications because of their high resistivity, low temperature coefficient of resistance (TCR), and low temperature dependence of gauge factor. The gauge factor (GF) of a strain gauge is the ratio of relative change in electrical resistance to the mechanical strain which is the relative change in length. Kazi, Wild, Moore and Sayer reported the variation of the gauge factor of sputtered nichrome films with film thickness and found the GF to be nominally 2.5 for thicknesses from 0.1 to 0.5 microns. This implies that nichrome should result in a reproducible strain gauge.[2] Figure 6 below shows a micrograph of orthogonal strains gauges under development. Characterization is currently underway.

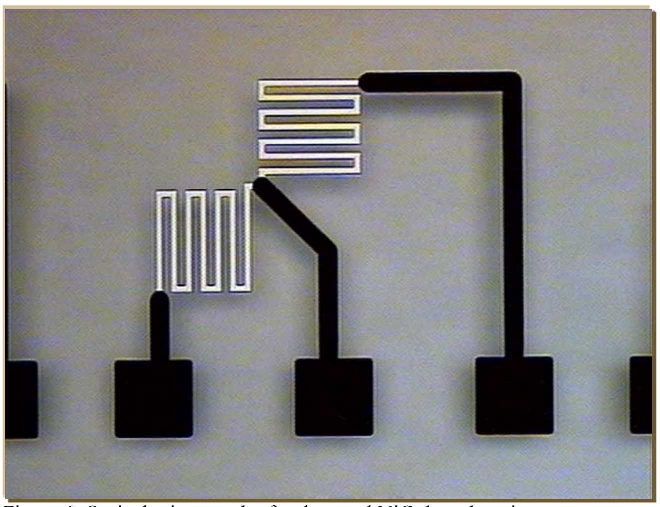

Figure 6. Optical micrograph of orthogonal NiCr based strain gauges.

CONCLUSIONS

We report on a group of thin film devices that can be used as test and evaluation tools, process control monitors and in-situ diagnostic devices. These devices include heat source die, temperature sensors, and strain gauges fabricated directly on GaN epitaxial layers on SiC. Dissipated power of over 70W has been demonstrated in a 22.8 mm^2 GaN on SiC die having 96 parallel fingers. This power level is equivalent to a MMIC HPA operating at a dissipation density of 7.3W/mm. Development continues on the temperature sensors and strain gauges and combinations of these structures are under consideration for inclusion in MMIC design. MMIC packaging development cycle time and especially simulation and testing resource commitment can be greatly reduced when using these structures concurrently with MMIC design and fabrication.

ACKNOWLEDGEMENTS

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REFERENCES

[1] *Measuring Temperature with RTDs – A Tutorial,* National Instruments Application Note 046, 1996.

[2] Imam H. Kazi , P.M. Wild, T.N. Moore , M. Sayer, *Characterization of sputtered nichrome (Ni–Cr 80/20 wt.%) films for strain gauge applications,* Thin Solid Films 515, 2602 (2006).

ACRONYMS

AlGaN: Aluminum Gallium Nitride
DC: Direct Current
FEA: Finite Element Analysis
GaN: Gallium Nitride
IR: Infrared
MIS: Metal Insulator Semiconductor
MMIC: Monolithic Microwave Integrated Circuit
Ni: Nickel
NiCr: Nichrome
RF: Radio Frequency
RTD: Resistance Temperature Device
SiC: Silicon Carbide
TCR: Temperature Coefficient of Resistance
TIM: Thermal interface Material

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