Demonstration of X-band T/R MMIC Using AFRL AlGaN/GaN MMIC Process

J.K. Gillespie[1*], K.D. Chabak[1], A. Crespo[1], R.C Fitch[1], D.W. Ferwalt[3], D.E. Frey[3], J.D. Gassmann[3], R.D. Gilbert[1], A.J. Green[2], K.D. Leedy[1], R.K. Mongia[3], B.S. Poling[1], K.A. Sutherlin[1], S.E. Tetlak[1], J.P. Theimer[1], G.D. Via[1], D.E. Walker Jr[1], M. Walker[3], G.H. Jessen[1]

[1]Air Force Research Laboratory, Sensors Directorate, Wright-Patterson Air Force Base, OH 45433
[2]Wyle Laboratories, Dayton, OH 45431
[3]Cobham Advanced Electronic Systems, San Jose, CA 95138
*e-mail: james.gillespie.5@us.af.mil *Phone: (937) 522-3252

Keywords: Gallium Nitride, Power Amplifier, Low Noise Amplifier, T/R MMIC, X-band

Abstract

In this paper, we report on the development of a Monolithic Microwave Integrated Circuit (MMIC) process based on an existing non field plate mm-wave AlGaN/GaN device process. This process was optimized for high efficiency wide-band operation and has been used to demonstrate X-band power and low noise circuits for scanned array applications. A Transmit and Receive (T/R) circuit was designed using this process and fabricated as a direct drop-in replacement for a three-chip X-band GaAs T/R function. This chip consisted of a power amplifier (PA), a low noise amplifier (LNA), multiple limiters and a high power T/R switch. First pass T/R MMICs achieved 30-dB small signal gain in transmit mode, 35.5-dBm output power, and 25% power added efficiency (PAE) at X-band. In receive mode, small signal receive gain measured >20 dB, and LNA noise figure measured 2.2 dB.

INTRODUCTION

The Air Force Research Laboratory (AFRL) has been developing Gallium Nitride (GaN) device technology for mm-wave frequency applications since 2003.[1] The early AFRL 0.14µm non field plate GaN HEMT process was refined into a Monolithic Microwave Integrated Circuit (MMIC) capability based on feedback from REMEC Defense and Space. In 2011, REMEC/Cobham presented results from an AlGaN/GaN broadband LNA designed by Cobham and fabricated using the AFRL GaN MMIC process.[2] Since then, a number of improvements have been implemented including: the addition of a dielectric process for metal-insulator-metal (MIM) capacitors, development of a robust uniform resistor process, and development of a backside via process. In order to maintain backside capability during the development process, a parallel outsourced backside process was maintained.

Along with AFRL funding and in collaboration with Cobham Advanced Electronic Systems, an integrated X-band AlGaN/GaN T/R MMIC was designed and demonstrated. This T/R MMIC was designed for broadband, high-efficiency functions consisting of an integrated power amplifier (PA), low noise amplifier (LNA), limiter, and a high power T/R switch as a replacement for three separate GaAs MMICs. The motivation was to demonstrate the integration of multiple functions in order to reduce cost and improve performance.

In this work, we demonstrate an X-band AlGaN/GaN T/R MMIC using a high-efficiency, mm-wave GaN technology for power and low noise transceivers at X-band.

DISCUSSION

AFRL/RY (Sensors Directorate) has been developing AlGaN/GaN devices for over 15 years. As early as 2004 work was done to improve device Si_3N_4 passivation to reduce dispersion and increase breakdown voltage while maintaining high frequency operation. This work was presented at the Electro Chemical Society (ECS) Meeting in 2004.[3] These results demonstrated that by making the dielectric more silicon rich, the breakdown could be maximized while at the same time reducing dispersion. Soon after these results were published, collaboration was started with REMEC who later became part of Cobham Advanced Electronic Systems. The device process was examined closely to see if a streamlined MMIC process was possible. The goal was to demonstrate MMIC circuits using the device process with as few modifications as possible. The first process iteration included thickening the first interconnect metal to 0.5µm, adding a TaN resistor process and increasing the plated Au top interconnect metal thickness to 6µm for high power applications.

To reduce process modifications, device passivation was used as the capacitor dielectric. With these modest process modifications, REMEC designed their first set of MMIC components (diodes, limiters, switches and mixers). Results from this mask design were reported at the 2009 Government Microcircuit Applications & Critical Technology Conference (GOMAC).[4] Measurements from this first component mask were used to design the first AFRL AlGaN MMICs. Results from these designs were used to flush out process capability, design rules and evaluate circuit test structures and models. The mask consisted of broadband power and low noise distributed amplifiers. Figure 1 shows measured results for the LNA over three temperatures.

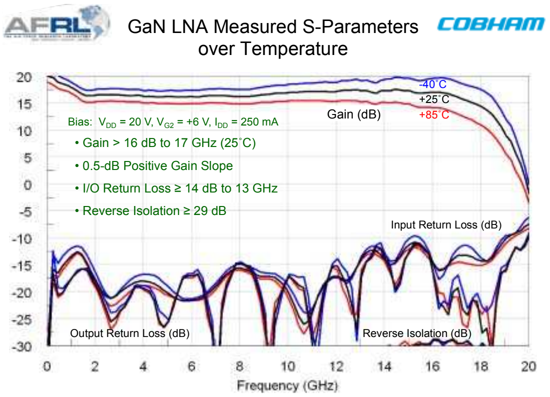

Figure 1. LNA measured results over temperature

The power amplifier had poor yield due to leaky capacitors and poor resistor contacts. The poor capacitor yield was the result of using the device passivation for the capacitor dielectric. As it turned out, the best passivation for eliminating device dispersion resulted in leaky capacitors. The resistor contacts were failing due to step coverage issues between the first interconnect metal and the thin film resistors. Also, the TaN resistor deposition was not uniform across the wafer. As a result of the original circuit run, a second dielectric step for capacitors was developed, TaN resistors were replaced with W_5Si_3 and plated interconnect metal was added to all resistor contacts and gate tabs. Ultimately a 14-mask layer process was finalized which included two dielectric layers, one six-micron interconnect layer and a 13 ohm/square W_5Si_3 resistor. Figure 2 shows the improvement in resistor uniformity. Figure 3 shows completed components using the latest process. Figure 4 shows an SEM cross section of a typical 0.14µm T-gate.

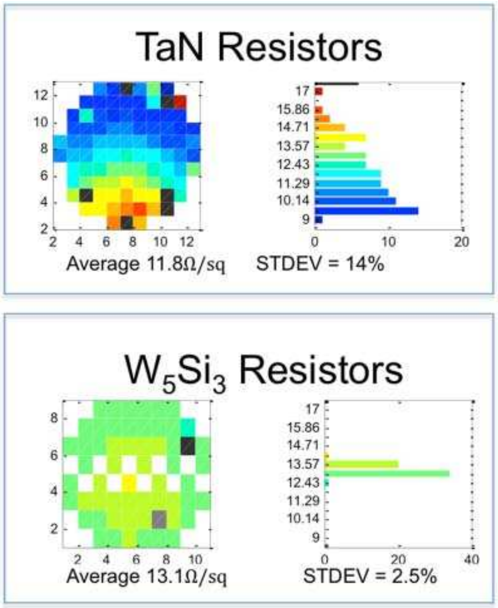

Figure 2. TaN vs W_5Si_3 comparison

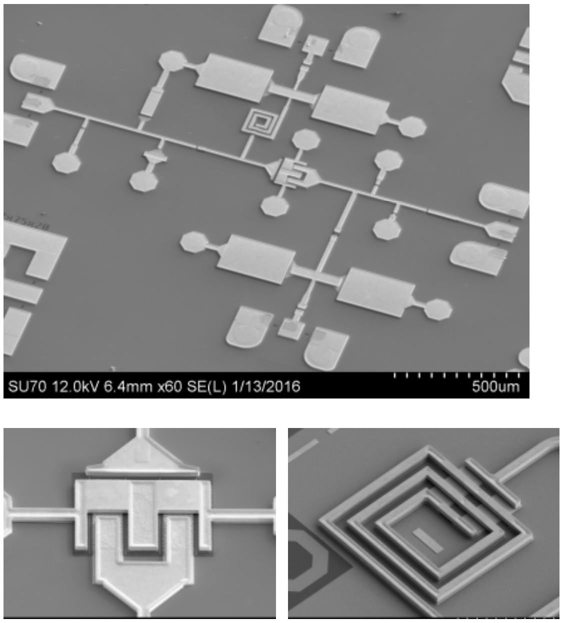

Figure 3. Sample circuit components including a standard evaluation circuit (single-stage amplifier), device and inductor

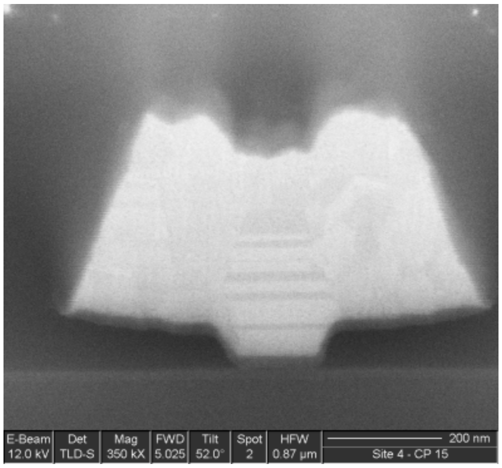

Figure 4. AFRL Standard 0.14µm T-gate

RESULTS

Leveraging the AFRL partnership with Cobham, a 0.14µm GaN T/R MMIC has been successfully demonstrated. This single T/R MMIC is designed to replace three GaAs MMICs in an existing array. The first pass T/R MMIC achieved 60% on-wafer RF MMIC functional yield with 30-dB small signal gain in transmit mode, 35.5-dBm output power, and 25% PAE at X-band.(Fig. 5) In receive mode, small signal receive gain measured >20 dB (Fig. 6), and LNA noise figure measured 2.2 dB (Fig. 7) before the T/R switch. New device models are under development for use in the second design iteration. The first-pass measured results show great promise for future improvements in efficiency, power, size and extended frequency range for array applications.

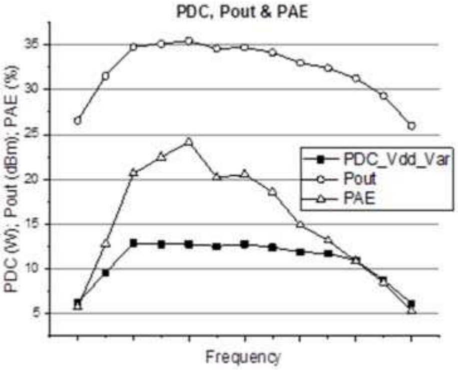

Figure 5. T/R MMIC power performance

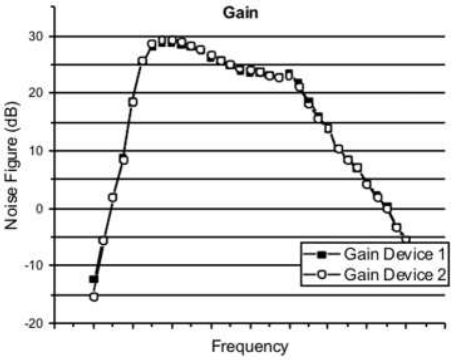

Figure 6. T/R MMIC LNA gain response for multiple devices

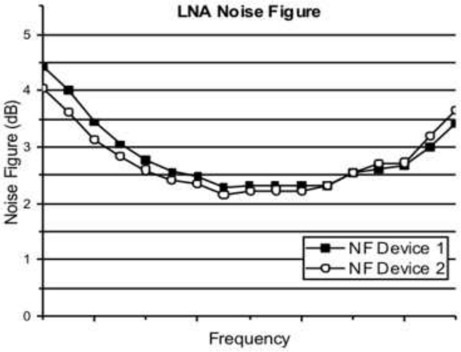

Figure 7. T/R MMIC LNA Noise Figure results for multiple devices

FUTURE WORK

Two areas of development are being planned. 1. Scaling the MMIC devices for higher frequency by scaling the epitaxial stack, shrinking the gate length and reducing source drain spacing. 2. Mature the dual band process that was reported in 2015.[5] This process modification will add a source connected field plate to increase breakdown voltage on select devices. The resulting process will add no additional process steps. Power measurements from two devices, one a standard non field plate device and one a field plate device, both having gone through the same modified process are shown in Figure 7 below.

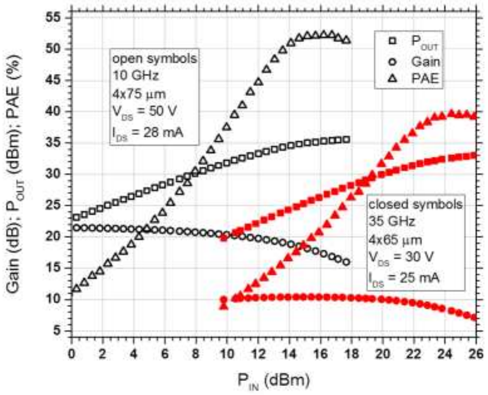

Figure 8. Sample X and Ka-band power performance for 4x75 µm and 4x65µm FP and T-gate devices using same process

ACKNOWLEDGMENTS

Authors would like to acknowledge Andrew Browning and Jason Hickey for Plasma processing and metal deposition services

REFERENCES

[1] G. Jessen, R. Fitch, J. Gillespie, G. D. Via, N. Moser, M. Yannuzzi, A. Crespo, J. Sewell, R. Dettmer, T. Jenkins, R. Davis, J. Yang, M. Asif Khan, and S. Binari, “High Performance 0.14 µm Gate-Length AlGaN/GaN Power HEMTs on SiC”, IEEE ELECTRON DEVICE LETTERS, VOL 24, NO. 11, NOVEMBER 2003

[2] R. Benelbar, R. Mongia, J. Dishong, B. Preskenis, S. Nelson, J. Gillespie, T. Quach, L. Orlando, A. Mattamana, K. Groves, K. Chabak, A. Crespo, R. Fitch, M. Trejo, and T. Dalrymple, “A 1 to 20 GHz GaN HEMT Low Noise Amplifier”, GOMAC 2011

[3] R. Fitch, J. Gillespie, G.D. Via, D. Agresta, T. Jenkins, G. Jessen, N. Moser, A. Crespo, A. Dabiran, A. Osinsky, “Effect of Silicon Nitride PECVD Growth on AlGaN/GaN HEMT Dispersion and Breakdown Characteristics “, ECS Fall, 2004

[4] S. Nelson, J. Dishong, G. Clark, B. Preskenis, J. Gillespie, T. Quach, L. Orlando, K. Groves, A. Mattamana, G.D. Via, A. Crespo, G. Jessen, C. Bryant, T. James, E. Darvin, J. Merenda, “GaN HEMTs for Wideband Transceivers”, GOMAC 2009

[5] R. C. Fitch, Jr., D. E. Walker, Jr., A. J. Green, Stephen Tetlak, J. K. Gillespie, R. D. Gilbert, K. A. Sutherlin, W. D. Gouty, J. P. Theimer, G. D. Via, K. D. Chabak, G. H. “Implementation of High Power Density X-Band AlGaN/GaN HEMTs in a 0.14 µm Millimeter-Wave GaN MMIC Process”, IEEE ELECTRON DEVICE LETTERS, VOL. 36, NO. 10, OCTOBER 2015

ACRONYMS

AlGaN:	Aluminum Gallium Nitride
dB:	Decibel
dBm:	Decibel (referenced to milliwatts)
GaAs:	Gallium Arsenide
GaN:	Gallium Nitride
LNA:	Low Noise Amplifier
MMIC:	Monolithic Microwave Integrated Circuit
PA:	Power Amplifier
PAE:	Power added Efficiency
Si_3N_4:	Silicon Nitride
TaN:	Tantalum Nitride
T/R:	Transmit/Receive
W_5Si_3:	Tungsten Silicide