Radiation-tested, High-Efficiency, GaN-on-Diamond Power Amplifiers and Satellite Radios

Daniel Francis[*], Brian Loran, Marty Yarborough, Larry Witkowski,
Paul Saunier, Kris Kong, Ty Mitchell, and Felix Ejeckam

Akash Systems inc.
[*]Daniel.Francis@AkashSystems.com

Abstract

In this work, we use 4-inch GaN-on-diamond wafers to fabricate, package and test RF power amplifier devices; we thermally test the devices, compare them to equivalent GaN/SiC devices; we radiation-test the devices for the first ever publication of such results. We also build space ready radios using the power amplifiers. Here, we show how improved thermal extraction associated with the diamond substrate leads to improved thermal performance in the device and improved overall radio performance. We show device level Noise Power Ratios exceeding those typical for equivalent GaN on SiC devices, thermal performance at packaged level and finally improved size, weight, and power performance (SWAP) for space ready radios.

Introduction

The idea of integrating diamond with semiconductors as a way of cooling the active devices dates back at least to the 1960's [1,2]. However, these early attempts were always devices soldered onto the diamond heat spreader which limited the thermal impact of the diamond.

The authors pioneered the first ever demonstrations of GaN-on-Diamond wafers, transistors, and power amplifier devices in 2003-2006 [3,4,5]. By 2013 multiple groups used GaN-on-diamond to demonstrate 3X increase in the power density achievable compared to GaN on silicon carbide [6,7] and using this same process RFHIC and GCS demonstrated record level power densities of up to 22W/mm RF on reliable devices [8]. Akash has demonstrated excellent performance at 20GHz devices with up to 60% PAE. However, the demonstration of improvements over GaN/SiC in fully packaged, field ready devices has been hard to come by. Here we show results of GaN devices at high frequencies, performing with high noise power ratios with thermal performance exceeding that of GaN/SiC devices, radiation tested and finally in a full space ready radio system. Figure 1 Shows a 4" GaN-on-diamond HEMT wafer with an inset device cross-section.

Experimental Details

GaN-on-diamond wafers are prepared by the direct diamond formation (DDF) process [3]. The diamond is typically between 100 and 200 microns thick. In its final form, the wafer consists of a 750nm GaN epitaxial layer on a free-standing CVD diamond substrate. The CVD diamond has thermal conductivity of greater than 1,600 W/mK.

The diamond wafer is polished to reduce back-side roughness and TTV both of which are necessary for processing of the HEMTs.

The HEMT fabrication uses Ti/Al/Ni/Au Ohmics, a trunk etch in SiN for the gate formation, and a Tcap metallization. The devices are a result of multiple process runs. The gate length and source-drain spacing vary according to the target device performance, from a minimum gate length of 150nm to a maximum of 500nm. S-D spacing similarly vary from 2 to 6 microns.

The Akash PA Module is built based on this GaN-on-Diamond substrate. The proximity of the GaN to the diamond enables a rapid/efficient heat extraction during RF operation. The ensuing reduction in the gate's thermal rise (i.e., the difference between the gate and the baseplate temperatures) of a GaN-on-Diamond device leads directly to extended lifetimes, greater RF output power, improved linearity at high saturated power, and it enables CW operation where pulsed-mode is otherwise needed to prevent self-heating. In a space operating environment characterized by vacuum, limited power supply, size and weight constraints, GaN-on-Diamond enables increased design flexibility for boosting overall performance.

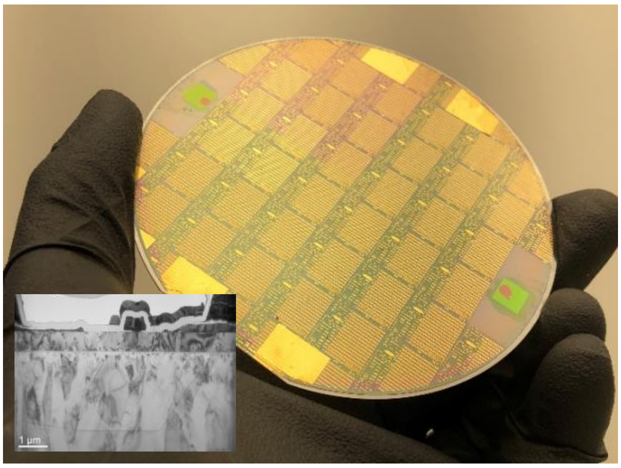


Figure 1 Processed 4" GaN-on-diamond wafer with multi-finger HEMTs. Inset a TEM cross section of a HEMT device.

Results and discussion

We compare the thermal properties of GaN-on-diamond with a GaN/SiC multi-finger FET. Both devices have 10 fingers and 40 um gate to gate spacing. GaN-on-diamond thermal measurements and thermal extracted models can be seen in figure 2. GaN-on-Diamond shows a ~65- 70^0C lower channel temperature.

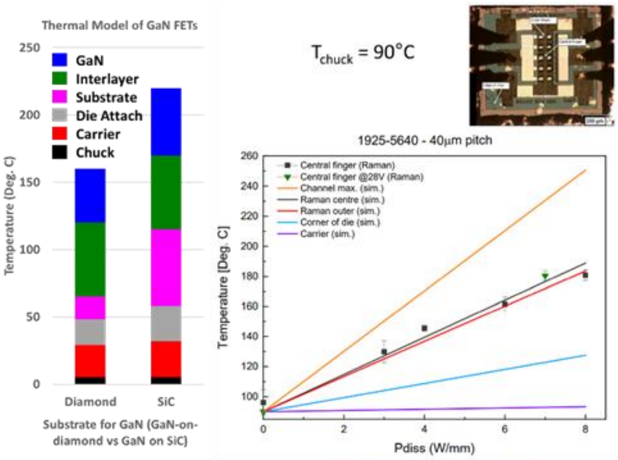


Figure 2 Thermal comparison of GaN-on-diamond with commercial GaN/SiC devices. Right shows the Raman thermal measurements of the GaN-on-diamond devices (Measured device picture inset). Left shows the modelled thermal breakdown for each structure.

The proximity of the GaN to the diamond allows for efficient heat extraction and consequently CW operation. However, the heat extraction has other benefits. The thermal load on GaN HEMTs not on diamond can lead to signal crosstalk between channels. The cross talk between channels is characterized by the noise power ratio (NPR). By efficiently extracting the heat, we observe improved NPR for GaN-on-diamond devices. Here we measure the NPR for a 5W HEMT PA , tested at 10GHz with a channel spacing of 100MHz tested near saturation and backing off power for various data communication protocols. See Figure 3.

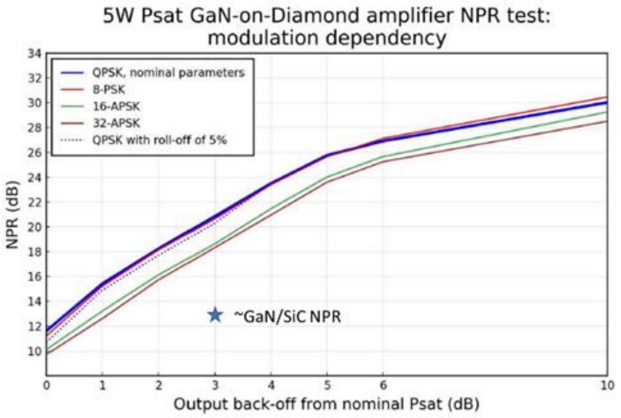


Figure 3 NPR measurements of a 5W GaN-on-diamond amplifier

In addition to testing the cingulated device we have built full radios where the final amplification stage uses GaN-on-diamond HEMT amplifiers. The space ready radio operates as an X-band radio transmitter, with the ability to transmit DVB-S2/S2X modulated signals directly to an antenna.

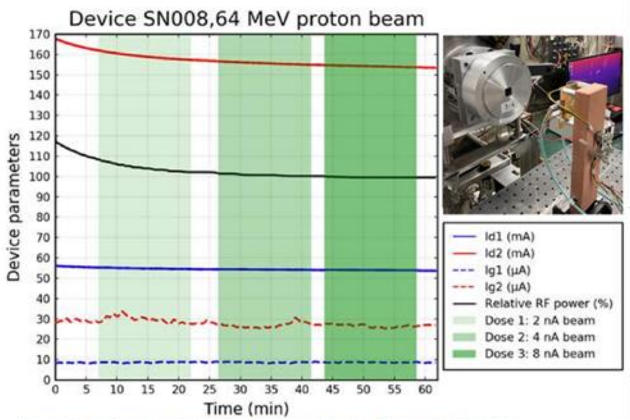
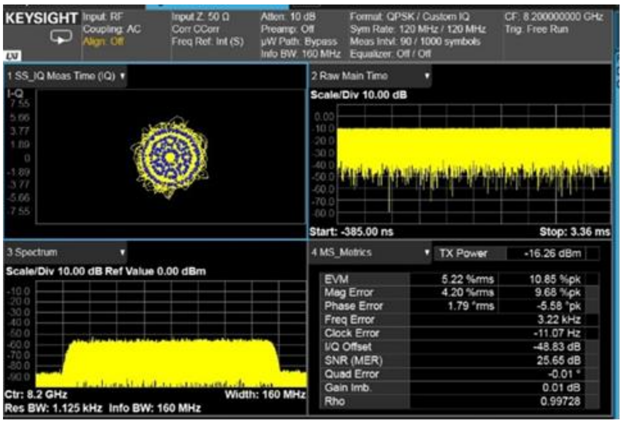


Figure 4 Radiation tests on GaN-on-diamond FETs

We tested the radio both for transmission capabilities as well as the radiation resilience. The radiation tests were in accordance with the ASTM International standards for proton beam radiation testing of electronics and can be found in figure 4. The changes visible in the plot are associated with the temperature stabilization of the test apparatus. Results show no changes with doses equivalent to up more than 100 years in LEO orbit.



```
KEYSIGHT  Input: RF       Input Z: 50 Ω        Atten: 10 dB        Format: QPSK / Custom IQ           CF: 8.200000000 GHz
          Coupling: AC    Corr CCorr           Preamp: Off         Sym Rate: 120 MHz / 120 MHz        Trig: Free Run
          Align: Off      Freq Ref: Int (S)    µW Path: Bypass     Meas Intvl: 90 / 1000 symbols
                                               Info BW: 160 MHz    Equalizer: Off / Off

4 MS_Metrics    TX Power      -16.26 dBm

EVM             5.22 %rms     10.85 %pk
Mag Error       4.20 %rms      9.68 %pk
Phase Error     1.79 °rms     -5.58 °pk
Freq Error                     3.22 kHz
Clock Error                  -11.07 Hz
I/Q Offset                   -48.83 dB
SNR (MER)                     25.65 dB
Quad Error                    -0.01 °
Gain Imb.                      0.01 dB
Rho                            0.99728
```

Figure 5 Spectrum and constellation measurement of the radio output (8.2 GHz) at 120 Msymbols/s, 128-APSK (643 Mbit/s)

The DVB-S2/S2X modulator is based on an FPGA implementation and follows the ETSI DVB-S2/S2X standards. The FPGA generates a baseband signal which is sent to the digital upconverter for quadrature modulation on to an IF carrier in the L-band.

The L-band IF signal is then upconverted to X-band, in the range of 8025 to 8400 MHz (i.e. an EESS Space-to-Earth band). After filtering to suppress undesired mixer components (e.g. image frequency, LO feedthrough), the signal is boosted to the final output power level by several amplification stages.

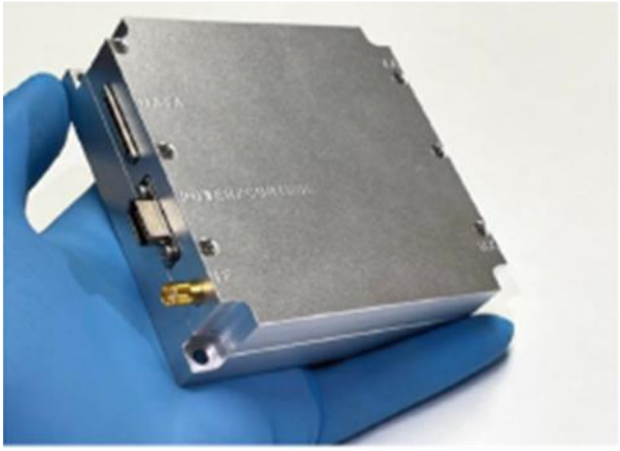


Figure 6 Image of the full radio.

The final amplifier stage is a GaN-on-Diamond RF power amplifier module. The Akash PA Module provides significantly lower channel temperatures and higher Power Added Efficiency (PAE) compared to GaN-on-SiC, GaN-on-Silicon, Si or GaAs PAs. Depending on the device type and design, up to a 50% reduction in the thermal rise enables CW operation where pulsed operation is sometimes needed and providing approximately a 10-20% boost to PAE. This radio including the transmitter and receiver is 100x100x25mm, weighs 0.5Kg, and outputs 5W at 8.4 GHz, transmitting up to 643 Mbits/second in a 100MHz bandwidth. Spectrum and constellation measurements can be found in figure 5 and the fully assembled radio in figure 6.

Conclusions

We have demonstrated GaN-on-diamond amplifiers Noise Power Ratios of 20dB at a 3dB back off from Psat, and a space ready radio capable of transmitting 650 Mbits/second at X-band, all operating in CW mode without active cooling. Crucially, this paper represents the first report of the radiation resilience of GaN-on-Diamond power amplifiers. These results demonstrate how GaN-on-diamond RF power amplifiers can assist in building the most capable space ready radio systems.

As we send components into space, critical parameters are the items size, weight, and power (SWAP). The diamond substrate in GaN-on-diamond gives the radio a high level of flexibility in designing the component's SWAP. Comparing the GaN-on-diamond radio to competing radios, competitors are typically three times the size and weight or a fraction of the power and data rate of GaN-on-Diamond radios. The differentiator is the efficient heat extraction of diamond.

References

1. Swan, C. B. et al., Proc. of the IEEE, 55(9), 1617-1618, 1967.
2. Dyment, J.C. et al., Applied Physics Letters, 11(9), 292-294, 1967.
3. "First GaN-on-Diamond transistor announced by Group4 Labs, Emcore, and AFRL" in Semiconductor Today, Aug 2, 2006
4. D. I. Babic et. al., MIPRO, 2010 Proc. of the 33rd Int'l Conv, Opatija, Croatia, 24-29 May 2010, pp. 60-66
5. D.I. Babic et. al., in MIPRO 2013, May 20-24, 2013 Opatija, Croatia.
6. Dumka, D.C., et al., IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS) 1-4, 2013.
7. M. Tyhach, et al., IEEE Lester Eastman Conference on High Performance Devices (LEC), 1-4, 2014.
8. Hou, D., et al., Proc. CS MANTECH Conf. May 2019.

ATTENTION: File must be submitted in PDF format and the size limit is 5Mb. The submission deadline is 11 February 2022.

---

1 Swan, C. B. et al., *Proceedings of the IEEE*, 55(9), 1617-1618, 1967.

2 Dyment, J.C. et al., Applied Physics Letters, 11(9), 292-294, 1967.

[3] Francis, D.; Faili, F.; Babić, D.; Ejeckam, F.; Nurmikko, A.; Maris, H. “Formation and characterization of 4-in. GaN-on-diamond substrates.” Diamond Relat. Mater. 2010, 19 (2), 229−233.