Comparison of GaN on Diamond with GaN on SiC HEMT and MMIC Performance

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Keywords: GaN on Diamond, Diamond, GaN, MMIC

Abstract

This paper discusses the result of work by Raytheon and Group4 Labs to compare performance between GaN HEMTs and a GaN MMIC when fabricated on silicon carbide and diamond substrates. Wafers were fabricated and the performance of the epi, process coupons, and individual FETs are compared. We also report on the design, fabrication, and performance of a GaN on Diamond MMIC power amplifier, the first of its kind to the knowledge of the authors.

INTRODUCTION

As GaN device technology matures into production it has become clear that thermal impediments are limiting GaN from achieving its full potential. One heat management strategy is to replace the silicon carbide (SiC) substrate (~350 W/m-°K) with a much higher thermal conductivity diamond substrate (~1200 W/m-°K). In this paper we describe the results of an effort to fabricate nearly identical GaN HEMTs on both SiC and diamond substrates to enable RF measurements for direct performance comparisons. In addition, we have designed, fabricated, and tested a MMIC on a diamond substrate, which to our knowledge is the first time this has been demonstrated and published.

MATERIAL

GaN on Diamond and GaN on SiC wafers were prepared by Group4 Labs, an industry leader in GaN on Diamond wafer development.[1] Careful consideration was given to make epitaxial layers as similar as possible to minimize near-junction differences that may influence thermal performance (Figure 1).

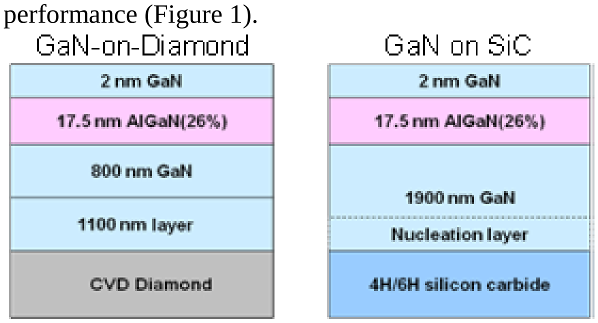

Figure 1: GaN epitaxial layers for Diamond and SiC substrates were selected to be as close to each other as possible

For GaN on Diamond, the GaN epi was grown on Silicon and transferred to diamond using Group4 Labs' patented transfer process. The GaN on SiC active device region was grown with similar structure to the GaN on Silicon. Upon receipt, both types of epi material were characterized using standard procedures. The results are summarized in Table 1.

Property	Units	GaN on SiC	GaN on Diamond
Sheet Resistivity	Ohm/sq	404	440
Wafer Diameter	mm	100	48
Threshold Voltage	V	-3.5	-1.6
Wafer Thickness	um	500	553

Table 1: Epi parameters for GaN on SiC and GaN on Diamond wafers

This data shows the GaN epi on diamond has a higher sheet resistivity, which typically results in a device with lower current and power. The GaN epi on diamond also has a higher turn on voltage, indicating a lower charge, resulting in lower Idss and potentially lower power.

FABRICATION

The GaN on SiC wafers were processed in the 100mm GaN production line at Raytheon's foundry in Andover, MA. The 48mm GaN on Diamond wafer was mounted on a thermal expansion-matched thick carrier plate for robust wafer handling and reduction of wafer bow and was then processed in Raytheon's development foundry, also located in Andover, MA. Both wafers were processed using stepper photolithography with HEMT gates formed using e-beam lithography. Each wafer was patterned with near identical masks that included test structures, multi-fingered HEMTs, and separate MMICs, each optimized for performance on its corresponding SiC or diamond substrate. HEMTs were fabricated on both substrates with reduced gate to gate spacings to test the limits of photolithography capability. Process coupon monitors were fabricated in conjunction with the HEMTs and measured in-process to indicate the quality of the device fabrication. The data from these coupon monitors on both the GaN on SiC and GaN on Diamond wafers is summarized in Table 2.

Property	Units	GaN on SiC	GaN on Diamond
Substrate Leakage	uA	0.14	0.53
Contact Resistance	Ohms	0.62	0.92
Sheet Resistivity	Ohms/sq	381	484
Contact Resistance	Ohms	0.29	0.49
Drain Pinchoff Leakage	uA/mm	24	99
Gate Pinchoff Leakage	uA/mm	25	27
Imax	mA/mm	1054	699
Idss	mA/mm	766	416
Gm	mS/mm	345	261
Pinchoff	V	-2.95	-2.12

Table 2: Process coupon monitor data for GaN on SiC and GaN on Diamond wafers

Comparing the properties in Table 2 shows that the GaN on diamond wafer exhibits higher substrate leakage, contact resistance, and sheet resistivity. A small coupon transistor with 2 gate fingers also exhibits higher device pinchoff and leakage on GaN on Diamond, as well as lower Imax and Gain. The trend of these parameters agrees well with the measured epi parameters and indicates that HEMTs on this initial GaN on Diamond wafer will have lower Imax, Gain, RF Power, and PAE. We are currently working to improve the GaN on Diamond epi material and expect that GaN on Diamond will achieve similar material properties to standard GaN material but with greatly improved thermal performance.

RESULTS

DC and RF performance were measured on identical devices on both diamond and SiC substrates. DC I-V curves examine the quality of the epi by analysis of key device parameters such as gm and Imax. DC I-V data representing typical performance of similar devices on SiC and Diamond is shown in Figure 2. This plot shows how drain current and transconductance change as gate voltage is swept from complete pinchoff to forward bias.

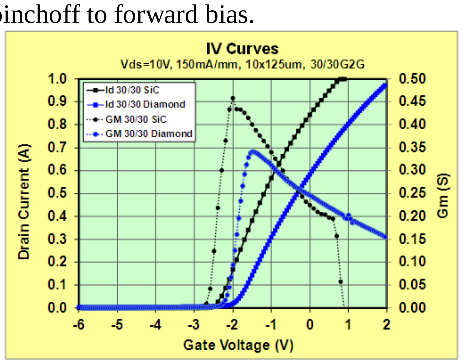

Figure 2: Curves for a 1.25mm FET comparing performance on GaN on SiC and GaN on Diamond

As expected from the in-process coupon data, a 10 finger, 1.25mm FET on diamond has less gain than its counterpart on SiC, likely due to differences in epi properties, and not intrinsic to the substrate material. The difference in turn on voltage observed in initial characterization is also evident. Different turn on voltages makes comparing Imax a bit more difficult, with maximum drain current measurement also limited to 1A. By comparing the difference in turn on voltage for Diamond and SiC with the difference in gate voltage when drain current exceeds 1A, there is a shallower slope for Diamond. Had measurement capability exceeded 1A, it is likely that the SiC device would show a higher Imax than diamond.

After DC I-V, small-signal transistor performance was characterized, comparing performance of parameters such as gain and f_{max}. Figure 3 shows the maximum gain derived from measured S-Parameters for both GaN on Diamond (black) and GaN on SiC (red) substrates. The devices shown have gates spaced 10um apart, condensed in size from a typical value of 30um. Small-Signal gain is compared at the location of k-break, where gain transitions from maximum available gain to maximum stable gain. This occurs at approximately 12 GHz. As expected from coupon measurements and IV data, the diamond devices have slightly lower gain than their counterparts on SiC. Despite different epi quality, this data shows that high performance condensed gate to gate spacing devices can be fabricated on both SiC and Diamond substrates.

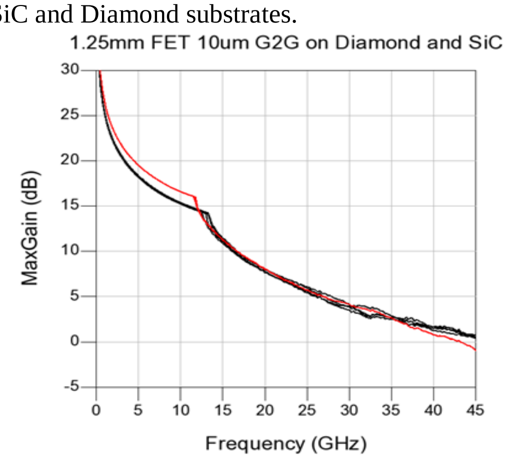

Figure 3: Small-Signal MaxGain curves on 1.25mm FETs with 10um gate to gate spacing on GaN on Diamond (black) and GaN on SiC (red)

Large-signal measurements on these same devices were then collected using a Maury loadpull system, where individual HEMTs are optimized for PAE under identical bias and temperature conditions. This data was collected at 10GHz and 28V VDS and is summarized in Table 3. The devices on SiC exhibited typical performance, averaging 5.5W/mm and 61% PAE. The GaN on Diamond devices averaged lower at 4.5W/mm and 47% PAE. As discussed previously, this difference in performance is related to the quality of the epi material on this initial GaN on Diamond wafer. Based on the learning from this effort, work is ongoing to improve the epi material.

	Pout (W/mm)	PAE (%)
GaN on SiC	5.5	61
GaN on Diamond	4.5	47

Table 3: Summary of Loadpull Performance for 1.25mm FET with 10um gate to gate spacing

In addition to HEMTs, an X-Band PA MMIC was designed and fabricated on each substrate. Performance of the MMIC on SiC and diamond was measured using on-wafer RF probe. The performance of the MMIC on SiC was in agreement with past MMIC data and FET loadpull data. The output power of the GaN on Diamond MMIC is what was expected based on FET loadpull results discussed above. PAE is slightly lower than loadpull results likely due to non-optimal passive matching in the input matching network and output matching network of the MMIC. To our knowledge this is the first demonstration of a GaN on Diamond MMIC Power Amplifier. The design was based on several assumptions regarding passive matching on diamond substrates. These assumptions will be refined based on these measurements for future GaN on Diamond MMIC designs.

CONCLUSION

This work, a collaborative effort between Raytheon and Group4 Labs, demonstrated the ability to fabricate multi-finger transistors with condensed gate to gate spacings on GaN on SiC and GaN on Diamond substrates. It also demonstrated to our knowledge the first MMIC Power Amplifier on GaN on Diamond.

ACKNOWLEDGEMENTS

This work is sponsored in part under AFRL contract FA8650-09-C-5404 monitored by John Blevins, AFRL.

REFERENCES

[1] Babic, Dubrakvo *et al.* “GaN on diamond Field Effect Transistors: From Wafers to Amplifier Modules,” MIPRO/MEET International Conference, May 2010

ACRONYMS

GaN: Gallium Nitride
SiC: Silicon Carbide
PAE: Power Added Efficiency
Pout: Output Power
MMIC: Monolithic Microwave Integrated Circuit