GaN Technology Overview: Accomplishments and Challenges

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Abstract - **This paper reports the (published) status of the AlGaN/GaN technology in the United States. Activities can be divided between AlGaN/GaN on SiC substrates for military applications, sponsored by DoD and AlGaN/GaN on Si for Base Stations. No doubt that early emphasis for US DoD has been "performances" (the W/mm race!) and progress has been fast, probably culminating with UCSB and Cree demonstrating 32W/mm at 4 GHz. These excellent performances have been made possible by the introduction and refinement of the "Field-Plate". Understandably, the emphasis is now reliability, and all the challenges have not been conquered. In the commercial world, Nitronex has been pionneering AlGaN/GaN on Si, manufacturing large gate width devices using MOCVD grown 4" Si substrates; 20W at –39dBc is achieved with 11.5dB gain and 25% pae (28V bias) over 1.8-2.2GHz. Excellent reliability is extracted with over 20 years MTTF. TriQuint has demonstrated the potential of GaN on Si for higher frequencies with 7W/mm with 38% pae and 9dB gain at 10GHz.**

I. INTRODUCTION

The advantages of GaN are well known: the wide bandgap allows high breakdown voltage (typically >100V), the higher charges (than with GaAs) give higher current (1- to 1.4A/mm). As a result, reported power density are is 5- to 20X that of GaAs based devices. Very importantly, the high power density achieved with high voltage allows smaller devices, higher impedance and therefore larger bandwidth and easier matching. Also very important is the thermal management and SiC substrates with their excellent thermal conductivity are critical in the success of high power GaN devices. The GaN MMICs will be smaller, the output easier to match with smaller matching loss, therefore allowing higher efficiency. Very important also is GaN e-saturated velocity which higher than that of GaAs, particularly at large voltages. Excellent performances are therefore possible at higher frequencies. TriQuint and Rockwell have already demonstrated good performances at Ka and above. The challenge for GaN is now improved performance (efficiency) and particularly reliability. Not many data have been published on reliability, all with reduced operating voltages. GaN on Si very important for cost, good thermal properties and excellent demonstrated reliability by Nitronex at 2.14GHz. TriQuint has extended the operating frequency of GaN on Si to 10GHz while maintaining good reliability.

II. X-BAND PERFORMANCES

At X-band, TriQuint was the first to release a state-of-the-art 11W/mm with 9.7dB gain and 50.6% power-added efficiency at 10GHz (press release May 2003). These results truly showed for the first time the potential of GaN since excellent power density was achived without sacrifying power added efficiency nor gain. Cornell's has published [1] a very good study comparing the attributes of the field-plate to that of the standard gate.

Field-plate gates have become the standard to achieve state-of-the-art performances at X-band and below. By spreading the electric field near the drain edge of the gate, a field plate allows an increase in the breakdown voltage and a reduction in the surface high field trappng effects, enhancing current-voltage swings at high frequencies. Consequently, devices with a well design field plate gate have much higher output power density (up to 2- to 3 times) than that of a conventional gate while improving the power added efficiency at higher drain voltage.

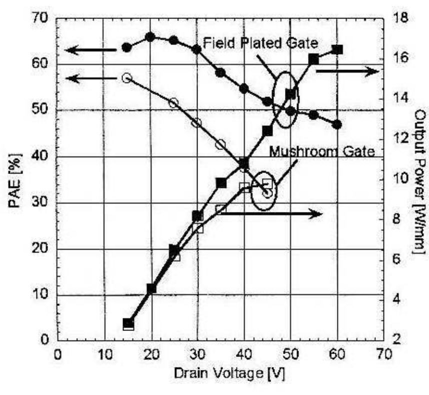

Fig. 1. Output power and PAE as function of increasing drain bias for devices with and without field plate.

Typical of a well designed field-plate is Cornell's plot comparing the output power density and efficiency at 10GHz for a conventional and field plate gate 150µm device for drain bias of 15- to 60V. Figure 1 shows the output power and pae as function of increasing drain bias for a device with a field plate and another with a conventional gate.
It can be seen that the conventional gate device output power has a saturation behaviour at 45V bias with 9.8W/mm, whereas the field plate device has its output power increasing linearly with drain bias up to 60V (already reaching 12.2W/mm at 45V bias), reaching an impressive 16.5W/mm. Most importantly is the efficiency behaviour. Whereas the efficiency of the device with a conventional gate decreases from 57% at 15V bias down to 32% at 45V bias, the efficiency of the field-plate device stays always higher, reaching an impressive maximum of 65% at 25V and stays above 50% up to 50V bias (with associated 14.2W/mm). Even at 60V bias, the efficency is 47%. The associated gain given in this publication is also an excellent 10dB whereas the small signal gain is 16dB.

Cree has achieved what could be called the "ultimate performance" by optimizing all aspect of the device. Their work in reported in [2]. In contrast to more conventional AlGaN/GaN HEMT, these devices included a thin AlN barrier adjacent to the GaN channel. It has been found that this barrier allows higher sheet charge and mobility. Additionally, Fe doping of the GaN buffer was used, allowing much improved breakdown voltage and reduced buffer leakage. The field plate topology Cree uses is shown in Figure 2

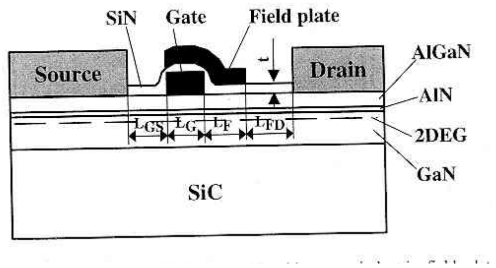

Fig. 2. Schematic of Cree field plate topology

There are a few important dimensions in this structure. The gate length Lg determines the transit time under the gate. The SiNx thickness t controls the onset for additional channel depletion under the field plate while the field plate Lf dictates the size of the field-reshaping region. For this paper, t was chosen as 2000A and Lf varied form 0 to 1.1µm. The maximum current exceeded 1.2A/mm and the dc breakdown voltage was greater than 170V for devices where the field plate "width" Lf was 1.1µm. These devices optimized for high voltage operation could be biased up to 120V. A 246µm device with a 1.1µm long field plate and a 3µm field plate to drain separation achieved a CW power density of 32.2W/mm at 4GHz with associated gain of 14dB and PAE of 54.8%. Figure 3 shows the corresponding power sweep.

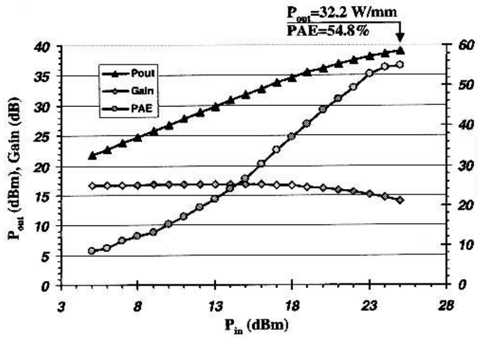

Fig. 3. Power sweep at 4GHz of a Cree device biased at 120V and capable of 32.2W/mm

III. PERFORMANCES AT KA-BAND AND ABOVE

Electron velocity in GaN is 1.8- to $2x10^7$ cm/s; contrary to GaAs, it seems that this saturated velocity does not decrease significantly with drain bias. Although AlGaN/GaN devices have not reached their full potential, excellent performances have been achieved.

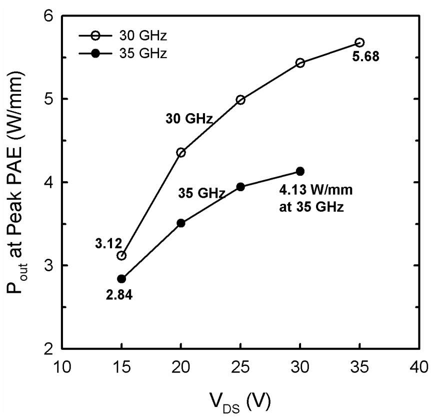

Fig. 4. TriQuint 200µm AlGaN/GaN 30- and 35GHz output power density at peak pae as a function of drain bias.

At 30- and 35GHz TriQuint achieved 5.68W/mm (at 35V bias) and 4.13W/mm (at 30V bias) respectively with a 200µm X 0.35µm conventional gate devices. Figure 4 shows the output power density at peak PAE as a function of drain bias of the conventional gate devices. The corresponding power added efficiencies are good, with a maximum of 44.2% at 30GHz and 15V bias (3.12W/mm power density) and 31.9% at 35GHz (2.84W/mm power density). Figure 5 shows the maximum PAE as a function of drain bias at 30- and 35GHz for the 200mm device.

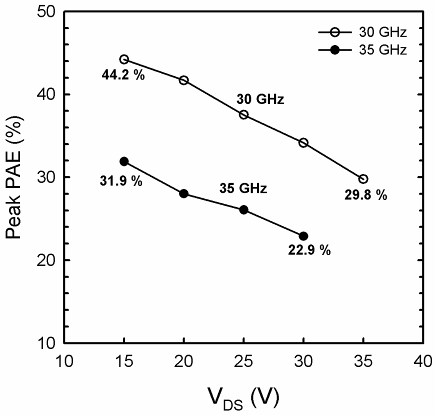

Fig. 5. TriQuint 200µm AlGaN/GaN 30- and 35GHz Maximum PAE as a function of drain bias.

Rockwell Scientific Company pushed the technology further with a 100µm X 0.18µm demonstrating 2.82W/mm and 5.8dB small-gain at 40GHz. Figure 6 show the corresponding plot.

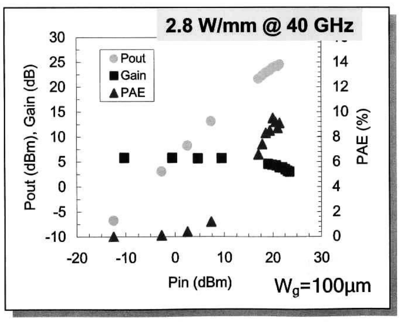

Fig. 6. Rockwell 100µm X 0.18µm performance at 40GHz

IV. AlGaN/GaN CHALLENGES

Although excellent performances have been demonstrated (as shown above) the AlGaN/GaN HEMT devices are still immature. Their performances are limited by current collapse (gate lag) and knee voltage walk-out. Current collapse (well known phenomena also with GaAs based pHEMT) happens when all the DC current is not available for RF swing, therefore reducing the available power density (and efficiency) of the device; it can be visualized by gate lag experiments. Quality of the buffer layer, active layer and most importantly passivation of the surface (gate-drain area) control the amount of current collapse. The field plate gate, by controlling/reducing the electric field in the gate-drain area drastically reduces the current collapse.

Another phenomena which limits the performances of AlGaN/GaN devices is the knee voltage walk-out. Bruce Green presents in [5] a dynamic load line analysis illustrating the corresponding mechanism of premature gain compression. Figure 6 shows the evolution of the dynamic loadlines during 2dB steps and compares them to measured dc I-V characteristics of the device.

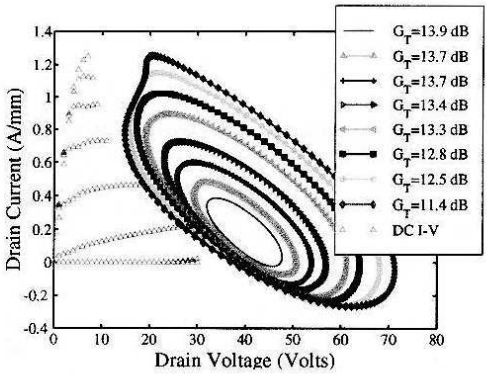

Fig. 6. Computed dynamic loadline for a device under pulsed RF measurement conditions at 8GHz and 40V bias [5]

From these data, it can be seen that at compression, the loadline is significantly distorted.

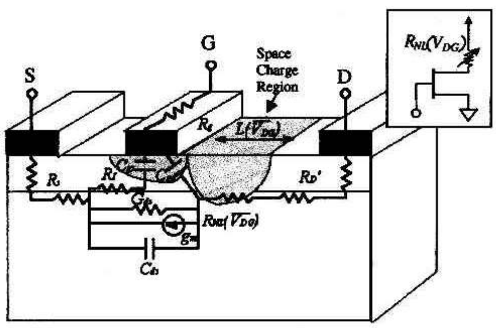

Fig. 7. Schematic illustration of bias dependent drain-resistance model used to explain the knee voltage walk-out

From the graph, it can be seen that the RF knee voltage is approximately 12V, considerably larger than the 4V observed for DC. Bruce Green shows that the Ron of the device increases with drain bias voltage (therefore the knee voltage increases), negating the advantage of larger drain voltage for efficiency improvement. This walk-out of the knee voltage arises from the lengthening of the gate-drain space-charge region that is controlled by the bias point. This increase in Ron can be thought of an additional bias-dependent drain resistance R_{NL}
As shown in the schematic cross section of Figure 7.

Most important for the new AlGaN/GaN technology is its reliability. As pointed out in the introduction, it seems that, in the US, emphasis was first given to performance improvement. Consequently, although the reliability issues are well known (short term power drift) and discussed in panel sessions, no comprehensive paper have been published.

V- GAN ON SILICON SUBSTRATE

Excellent results have been achieved with the GaN on Silicon technology. Silicon substrates offer the potential for low-cost and high volume while the thermal properties are quite compatible with high power densities. Nitronex is leading the field and has reported (in Compound Semiconductor) 156W output power with 15.9dB gain and 60% pae (28V bias) at 2.14GHz with two 36mm devices in a package. Excellent reliability results have also been reported by Nitronex with extrapolated MTTF of 20 years at 200C junction temperature at 28V bias.
TriQuint has reported [6] record performances of GaN on Si devices at 10GHz with 200μm devices. Maximum power is 7W/mm with 9.1dB gain and 38% pae at 40V drain bias. When tuned for maximun efficiency, power is 3.9W/mm with 52% and 9dB gain at 20V bias.

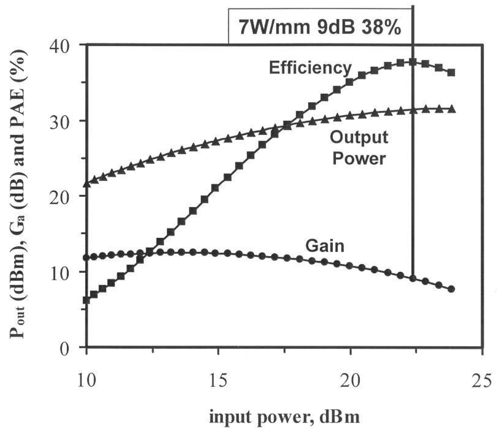

Fig. 8. TriQuint GaN on Si 200μm at 10GHz

VI. CONCLUSIONS

In this paper, we have overviewed briefly the state of AlGaN/GaN on SiC devices in the US, given the best performances achieved at X-band, Ka-Band and above, reviewed their limitations and given a brief summary of possibilities introduced by GaN on Si substrates.

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