Quest for Vacuum Tubes' Replacement: 150 V UHF GaN Radar Transistors

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Abstract— **This paper analyzes the requirements for solid-state devices to replace vacuum tubes in radar systems and introduces a 700 W GaN transistor operating at 150 V at UHF frequencies with 80% drain efficiency. The signal during the RF tests employed 52 μs and 100 μs pulse width with a duty cycle ranging from 2% to 5% and 10% at a frequency of 430 MHz. Although the prototype transistor presented in this paper consists of only two chips inside a small package with 30 mm total gate periphery, it can easily be scaled up to larger periphery and a larger package for power in the 2 kW – 3 kW range. This is believed to be the first demonstration of RF solid-state devices operating at 150 V ever reported for UHF radar systems.**

Keywords—amplifier, GaN transistor, radar, RF, solid-state, UHF, vacuum tubes.

I. INTRODUCTION

Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) unique and desirable attributes for radar and telecom radio frequency (RF) and microwave applications are well documented in the technical literature of the last 10 to 15 years. GaN technology is already mature and nowadays innovation is measured in incremental improvements in performance, or in its superior performance compared to mainstream silicon or gallium arsenide (GaAs) technology, or on the effort to reduce its high cost structure for adoption in more commercial applications such as microwave heating, particle accelerators and medical equipment. However, there is still a need for investigating and advancing system level functionality that the GaN material and the mature processing can afford and that is not achievable, or plainly much harder to achieve, with alternative technology. This paper addresses the operation of RF GaN HEMT devices biased at 150 V in the UHF band where there is no silicon equivalent, and it is demonstrated how this technology can displace obsolete vacuum tubes for very high power RF applications. In order to produce a very high power RF transistor e.g. > 1 kW requires either a very high current or a very high voltage. A large current implies a large gate periphery, and hence chip size, which equates to high cost and low load impedance which restricts the achievable operational bandwidth. High voltage, on the other hand, has no adverse impact on die size or cost, and maintains high load impedance for broad bandwidth operation, but it increases the dissipated heat density. This latter issue is severe for CW operation but entirely manageable in pulsed operation used in radar systems. GaN transistor technology operating at 28 V and 50 V is mature and readily available from several manufacturers. High breakdown voltage in AlGaN/GaN HEMT transistors is a desirable feature that enables high voltage blocking capability in power management applications and high voltage operation in RF power amplifiers. Although there is an ongoing research effort to achieve ever-higher breakdown voltage for high voltage switching in power conversion applications, much less attention is devoted to high power RF amplifiers in GaN technology operated at 100 V bias or higher. GaN devices for power switching applications exist from several manufacturers with breakdown voltages from 200 V to 600 V to 1200 V and higher. These devices are optimized to minimize on-resistance and operate at kilohertz frequencies or 1 MHz at most for high efficiency dc-dc converters. As such, they are un-suitable or very ineffective for operation at UHF and potentially at L-band. In reference [1] a recent study is presented where 600 V GaN HEMT's and GaN diodes are utilized in power conversion applications.

A first report of GaN devices operating at 125 V with very promising results was published in reference [2]. Such a technology could be used in high power RF amplifiers for applications in UHF weather radar, long-range tracking radar, particle accelerators, microwave sintering and other ISM applications, or as vacuum tubes replacement in general. Extensive RF burn-in tests at 125 V to address the reliability of this technology is reported in [3]. The target application for this earlier work was spaceborne SAR, but the devices were operated in practice at 75 V or 100 V for added reliability.

Although there are silicon devices such as the bipolar junction transistor and vertical or lateral diffused MOS field effect transistors which can operate at 100 V bias at VHF frequencies or lower, the only > 100 V UHF transistor that is available is the silicon carbide (SiC) static induction transistor (SIT). Unfortunately, the SIT has lower than 10 dB gain and barely 50% efficiency at 450 MHz which is lower than vacuum tubes can achieve [4]. SiC SITs are at a considerable disadvantage compared to GaN HEMTs for this application for two main reasons. Firstly, in GaN HEMTs the current flows in an un-doped region of GaN in the form of a 2D electron gas. Because this region is un-doped it has very high mobility whereas in SiC the electrons flow in a region of doped SiC which results in degraded mobility due to scattering with the doping atoms. The low mobility of SiC results in higher on-resistance and hence lower efficiency than is obtained with a comparable GaN HEMT. A second consequence of electron transport in GaN HEMTs occurring in an un-doped region of GaN is that the saturated drift velocity is higher than in a SiC SIT, again because of reduced scattering. The g_m and hence the RF gain of the transistor is proportional to the saturated drift velocity, and hence GaN HEMTs have higher gain than SiC SITs. These two advantages provide the motivation for the development of the 150 V GaN HEMT's reported in this paper.

The demonstration device we present in this article uses 2x 15 mm GaN HEMT dice in a small RF ceramic package, and it achieves greater than 700 W output power in pulse operation with 25 dB gain and 80% drain efficiency corresponding to a power density of almost 25 W/mm. Although 700 W output power is modest, what is impressive is that it is achieved with only two 15 mm chips. Moreover, this device reaches 700 W with an output impedance of 16 Ω so there is plenty of scope to achieve 2.5 kW output power and still result in optimum load impedance of 4.5 Ω which is easy to match to 50 Ω. One possible way to realize a 2.5 kW GaN transistor is to use a single 150 V RF GaN die of 30 mm and incorporating 4 of these chips into a larger package. Given the relatively high load impedance for this device, production yield in a manufacturing line is also expected to be good. It is anticipated that this 150 V RF GaN technology could displace vacuum tubes as it can easily achieve the same output power, has higher efficiency, better reliability typical of solid-state technology, no need of kV power supplies, and benign failure where one failing device does not shut down the entire system.

II. VACUUM TUBES VERSUS 150V RF GAN

RF radar systems need a short pulse length in order to detect objects close to the radar (e.g. 6 µs for an object 1 km away), and a low pulse repetition frequency with very high peak power for unambiguous detection of objects far away (e.g. 1.6 kHz pulse repetition rate, equivalent to 1% duty cycle, for an object 100 km distant). These requirements are ideally suited to the characteristics of vacuum tubes such as Magnetrons, Klystrons and Travelling Wave Tubes. These devices use kilo-volt power supply voltages and are capable of supplying mega-Watt output power levels at microwave frequencies. Thus a form, fit and function solid-state replacement for a tube-based transmitter needs a transistor with at least 1 kW to 2 kW output power or higher in order to make it economically and technically feasible in terms of the number of transistors needed, overall size etc. However, RF power transistors in the 28-150 V range severely limit the peak power that is possible, but they can operate at very long pulse lengths and high duty cycles – even up to CW conditions. This means that by using relatively few transistors with 1 kW power output it is possible to achieve high average power on a par with that from tube radars so that the overall sensitivity and long range detection performance of the radar is not degraded. However, it is necessary to use pulse-compression technology [5] in order to achieve the same resolution and minimum radar detection range. Thus radar systems designed from the outset to use transistors typically employ pulse lengths in the 100's of µs, up to 20 ms even, with duty cycles ≥ 10% and pulse compression ratios of 100 or more. To illustrate the equivalence, a 10 kW peak power solid-state radar that used 50 µs pulse length, 10% duty cycle and 10:1 pulse compression would have the same radar performance in terms of resolution and maximum range as a 100 kW tube radar that used 5 µs pulse length and 1% duty cycle since the mean transmitted power is identical in both cases. It is relatively easy to combine ten 1 kW amplifier modules using a 10-way radial combiner [6]. Therefore, the approach we propose with 150 V RF GaN power amplifiers is well justified.

III. 150V GAN RF CHARACTERIZATION

This paper introduces a GaN HEMT transistor operating at 150 V with 700 W output power, 80% drain efficiency and 25 dB power gain in pulse mode at 430 MHz. In order to operate at 150 V it has a breakdown voltage of 600 V. The drift region extension is the most sensitive parameter for achieving higher breakdown voltage; it increases from 210 V with 4.15 µm drift extension to 390 V with 6.65 µm and to 610 V with the longer drift region of 9.15 µm [2]. With a breakdown voltage of 610 V, the transistor topology featuring the 9.15 µm gate-drain extension is definitely suitable for operation up to 150 V in a class E amplifier where the ratio between bias and maximum drain voltage can be as high as 3.6x the supply voltage [7]. For class B, F or inverse F amplifiers this technology could operate at 200 V. Nominal saturation current density is ~0.5 A/mm and the specific on-resistance is ~6 ohm-mm. At 100 V bias, C_{DS} is 1 pF/mm, C_{GD} = 0.2 pF/mm and C_{GS} = 6 pF/mm. Therefore, the 15 mm die is rated at 7.5 A maximum current and 0.4 Ω on-resistance with input, feedback and output capacitances of 90 pF, 3.2 pF and 15 pF respectively. For comparison, a typical power management 600 V transistor would have 20 A current rating with 0.15 Ω as reported in Table 1 from reference [1], which is similar to ~3x our 15mm device. However, the input and output capacitances for the 20 A power switching device is 815 pF and 95 pF at 100 V bias, respectively. In contrast, our 15 mm die has equivalent input and output capacitances of only 270 pF and 45 pF when scaled to match the 20 A current rating, which are much smaller than in the typical power switching transistor and explain why GaN transistors designed for power switching applications are not ideal for applications in UHF power amplifiers which are the focus of our work. The differences are attributed to gate length and details of the field plate design, which are typically different in RF devices compared to switching transistors. Figure 1 in the next page shows the 2-chip device. It has no output match but it uses a T-network at the input side that includes series resistance to reduce the gain and ensure good stability.

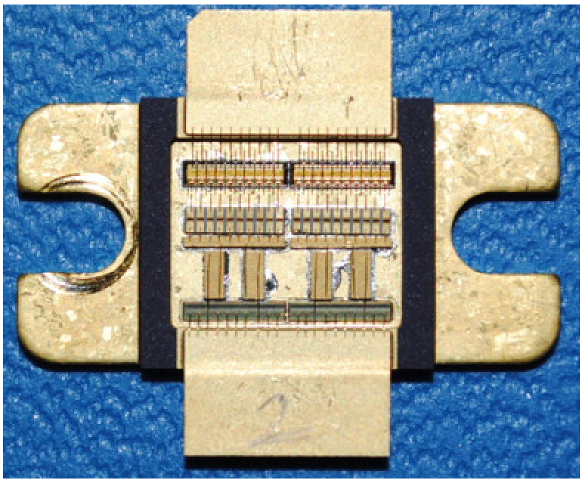

Figure 1. Assembled 150 V 700 W device with two GaN chips positioned next to the output package lead (top side in the figure).

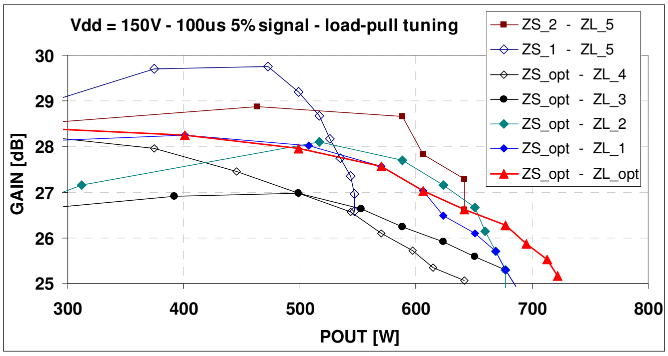

Fig.2. Measured load-pull data of gain vs. output power drive-up at 430 MHz and 150 V bias. Pulse length is 100 µs and duty factor is 5%. In red triangles are data for optimum load impedance and maximum output power of 720 W.

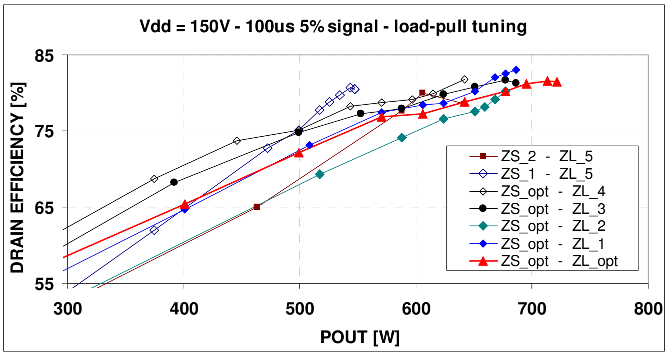

Fig.3. Measured load-pull data of drain efficiency vs. output power drive-up at 430MHz and 150 V bias. Pulse length is 100 µs and duty factor is 5%. In red triangles are the data for optimum load impedance and maximum output power of 720 W with peak drain efficiency > 80%.

Results from our load pull analysis are shown in Figures 2 and 3, where gain and drain efficiency versus output power are plotted for different source and load impedances. The different source and load impedances are synthesized by positioning several slug tuners along an external 50 Ω waveguide, but no measurement was made to determine their values. The signal used has 100 µs width and 5% duty cycle, which is short for typical solid-state technology but still significantly longer than the signals used in actual vacuum tube radars. Quiescent current of the 30 mm device is set at 60 mA. Since the device would typically be used in radar operation with gate modulation, the reported efficiency values assume zero quiescent current when the RF pulse is off. The load pull measurements were obtained by varying the load impedance at the fundamental frequency of 430 MHz, but the test fixture used has some level of 2nd and 3rd harmonic tuning implemented, hence the relatively high drain efficiency reported in our measurements. The load pull results identify the optimum impedance where the device achieves 720 W output power with 25 dB gain and 81% drain efficiency with a 100 µs signal pulse width and 5% duty cycle.

Next, with the load impedance set at this optimum value, the response of the device to different signals is analyzed. The following combinations were used: 52 µs and 100 µs pulse width; duty cycle varied from 10% to 5% to 2%. Results from our measurements are shown in Figures 4 and 5 where gain and drain efficiency versus output power are illustrated. The measured data indicate that there is a small increase of saturated output power to 730 W with the shorter duty cycle of 2% regardless of the pulse width being 52 µs or 100 µs. However, the particular die design used in the demonstration device easily handles duty cycles of 10%, albeit with a reduced saturated power of 675 W, as proven by the measured data in Figure 4.

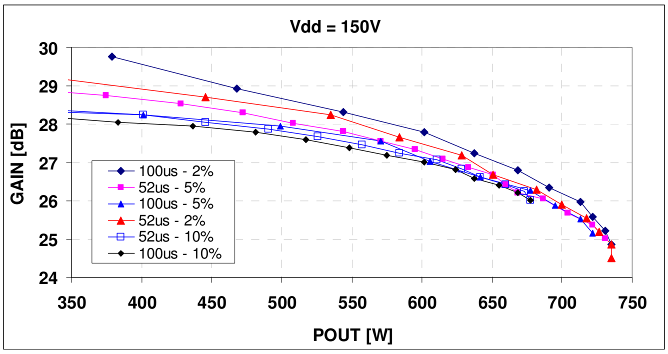

Fig. 4. Gain vs. output power drive-up at 430 MHz and 150 V bias. Pulse width is 52 µs and 100 µs; duty factor is varied from 10% to 5% and 2%.

On the other hand, in Figure 5, in the next page, results show that drain efficiency improves with the shorter duty cycle and ranges from 77% at 10% duty cycle to 81% with 5% duty cycle, and to almost 85% with 2% duty cycle.

These relatively high values of peak efficiency close to saturated power arise from two different features. First of all, as briefly mentioned earlier the test fixture does include tuning of the 2nd and 3rd harmonics. It was designed for a different experiment reported in reference [8] where harmonic tuning had been optimized at 100 V operation for a 250 W device. This suggests that proper harmonic tuning at 150 V might yield yet higher efficiency in the 90% level. In comparison, the best efficiency that vacuum tube devices can achieve is 65%. Secondly, it is worth recalling that the optimum load impedance of this 700 W device is around 16 Ω requiring only a ~3x impedance transformation to match it to a standard 50 Ω load. This feature is often overlooked but it is worth mentioning for comparison that a 700 W device operating at standard 50 V bias would have an optimum load impedance of 1.8 Ω and requires a 28x impedance transformation to match it to 50 Ω. The higher the impedance transformation ratio, the more loss is incurred in the matching network, further decreasing the efficiency.

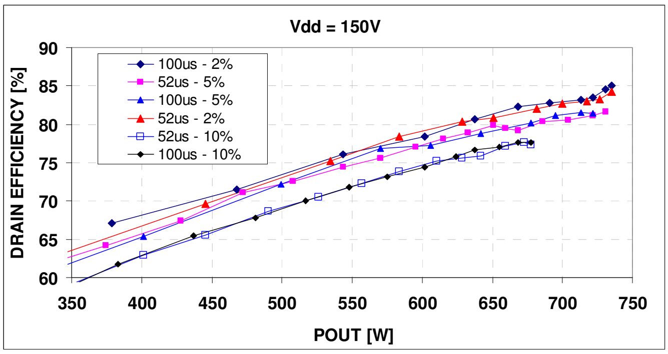

Fig. 5. Drain efficiency vs. output power drive-up at 430MHz and 150V bias condition. Pulse width is 52µs and 100µs; duty factor is varied from 10% to 5% and 2%.

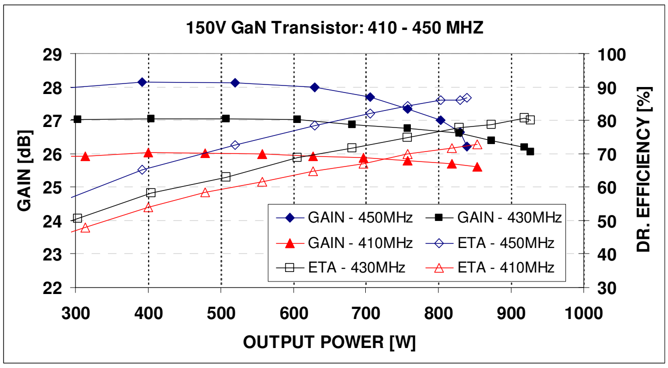

Fig. 6. Power gain and drain efficiency vs. output power at 410 MHz, 430 MHz and 450 MHz at 150 V bias. Pulse width is 100 µs; duty factor is 5%.

Finally, UHF radar systems operate over a frequency range of 420-450 MHz while all the data presented above is at the spot frequency of 430 MHz. Next we have characterized the device from 410 MHz to 450 MHz with a fixed output load impedance to understand the broadband RF performance. Data for power gain and drain efficiency are shown in Figure 6. A signal of 100 µs pulse width and 5% duty cycle was used. The load impedance was optimized at 450 MHz. The device achieves over 800 W across the band, but we see 2 dB gain variation and it is compressing at 450 MHz with just over 800 W output power and efficiency of almost 90%, whereas it has not even reached P1dB at 410 MHz. At 430 MHz we obtained P1dB of 900 W with 80% drain efficiency.

With further optimization of the load impedance across the band it is possible to improve gain flatness to 1dB with Pout > 800W and drain efficiency ~80%. Nonetheless the data demonstrate the broadband capabilities of the 150 V GaN radar transistors. With greater than 800 W from just 30 mm die periphery and 75% drain efficiency, this 150 V GaN technology is a serious contender for displacing vacuum tube devices in radar applications.

IV. CONCLUSIONS

A UHF GaN radar transistor designed to operate at 150 V has been introduced and characterized at 430 MHz. Over 80% drain efficiency at an output power of 700 W has been demonstrated. The signal during the RF tests employed 52 µs and 100µs pulse width and a duty cycle ranging from 2% to 5% and 10%. The 150V RF GaN technology pushes the boundaries of existing high power solid-state radar technology and with further development it is an ideal candidate to replace vacuum tubes in UHF radar systems.

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