The Application of GaN HEMTs to Pulsed PAs and Radar Transmitters

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Abstract—**Gallium Nitride (GaN) solid-state devices are emerging as a replacement for vacuum electron devices (VED) in radar systems. These solid-state devices have significant thermal and trapping effects that, although not ruling out their use, do complicate it. This paper evaluates several commercial GaN devices, using pulse testing, under conditions typical of modern, high-frequency radar systems. It is found that the I-V characteristics of these GaN devices vary with the pulse repetition frequency (PRF). Hence, the design methodologies employed must take this into account, especially when multiple- or staggered-PRF strategies are employed in the radar system.**

Keywords- radar systems, solid-state devices, gallium nitride, charge trapping, pulse repetition frequency, staggered PRF

I. Introduction

The realm of high microwave-power generation, once ruled exclusively by Vacuum Electron Devices (VED), is being revolutionised by the introduction of new, wide-bandgap, solid-state High Electron Mobility Transistors (HEMT) fabricated on novel III-V group alloys. Gallium Nitride (GaN) in particular has become a popular choice with designers when high power [1] and high linearity are required at high frequency.

Transistors fabricated on this material overcome most of the major limitations of existing high-frequency solid-state devices such as Gallium Arsenide (GaAs) HEMTs. GaN HEMTs are characterised by high electron mobility, crucial for high-frequency operation, high charge density and electron saturation velocity, which allows high currents to be generated, and a higher breakdown voltage, which permits a much higher drain voltage and, together with high current, is the key to achieving high microwave power. In fact, improvements of a factor of ten in output power may be achieved with GaN HEMTs when compared to their GaAs counterparts. The ability of GaN devices to operate at high temperatures is another major advantage of this material and, along with the abovementioned benefits, makes GaN an excellent candidate for the replacement of VEDs currently utilised in some radar systems [2].

GaN technology, however, is not as well understood as other, more established, technologies and hence the appropriate and thorough characterisation of GaN devices is crucial to the achievement of the required performance. The current-voltage (I-V) characteristics, in particular, are an extremely-important tool and play a key role in the design of power amplifiers. They determine the voltage and current boundaries at which the transistor may be operated and, coupled with a load line, allow an appropriate choice of bias point for the class of operation desired. In addition, trapping effects which may affect a particular device, may also be detected by means of the appropriate pulsed I-V measurements [3].

A major difference between GaAs and GaN HEMTs is the existence of long time-constant traps in the latter (typically hundreds of seconds) which may considerably affect the operation of the transistor [4]. Although suited to the characterisation of many commercial devices, readily-available semiconductor parameter analysers, such as the Agilent 4145, do not easily detect traps in GaAs and GaN devices, having time constants longer or shorter than the hundreds of *ms* of the measurement times of these instruments. In order to assess the effects that these traps may have on the I-V characteristics of a transistor, more complex and powerful characterisation systems need to be used. To this end the Arbitrary Pulsed Semiconductor Parameter Analyser (APSPA) system, designed by Macquarie and Sydney Universities [5], was utilised to carry out a pulsed I-V characterisation of Cree and Nitronex GaN samples (CGH40010 and NBT25 respectively). In Section II, the APSPA is described in more detail along with the test methodology utilised to detect long time-constant trapping.

With the APSPA system, an I-V characteristic is measured by sitting at a specific gate and drain bias voltage for a long time and then jumping to each v_{GS} and v_{DS} point for a comparatively short time to measure the drain current. This is usually done to avoid self-heating and trapping effects in the measured data. However, in this paper the authors take a different approach to measuring the pulsed I-V characteristics and explore it at Pulse Repetition Frequencies (PRFs) and duty cycles which are typical of high-frequency radar systems. This is done in an attempt to identify the effect of operational parameters of radar amplifiers on the device and to identify the characterisation and design methodology which may be necessary when utilising GaN devices for the pulsed applications of radar.

GaN HEMTs are shown to have different I-V characteristics depending on the PRF and duty cycle. This has implications for the design of power amplifiers utilised in radar transmitters and, in particular, for those used in staggered-PRF systems, which utilise more than one PRF to improve the performance of the system.

The usefulness of such a technique may be explained as follows: with pulse delay ranging, range is determined by measuring the time between the transmission of a pulse and the reception of an echo (Fig. 1). The range for which the round-trip transit time equals the inter-pulse period is called the maximum unambiguous range R_u (Fig. 2). An echo generated by a target at a range greater than R_u will be received after a second pulse has been transmitted and hence may appear closer than it actually is (Fig. 3). Its true range in this case would therefore be the sum of its apparent range plus some multiple of R_u (Fig. 3, Fig. 4). As long as there is a possibility of detecting any targets at ranges greater than R_u, all observed ranges are ambiguous. To resolve the ambiguities one may switch between two or more PRFs and measure the changes, if any, in the apparent ranges (Fig. 4) [6].

If staggered PRF is used, designers therefore need to take changes in the I-V characteristics due to PRF into account in order to carry out an amplifier design which maximises the performance of the GaN amplifiers.

Although relevant for GaN amplifier design, breakdown voltage, another important parameter which greatly affects the amplifier performance, and any dependency on PRF, will not be discussed in this paper.

II. Test Methodology

A pulse measurement of a transistor is performed by maintaining, for most of the time, a constant quiescent bias on the device under test. Periodically, a rapid pulse is applied to the device's terminals and during the brief interval of the pulse, the terminal voltage and current are measured.

APSPA allows the user to vary the parameters of the sweep across a much-wider range than most commercially-available instruments and it also allows the use of scripts which may excite the transistor in specific, user-defined, non-repetitive patterns.

If inadequate quiescent times are used, *i.e.*, if the transistor is not left to settle for long enough between measurements at different points, inaccurate curves may be obtained. APSPA overcomes this problem and allows the identification of traps with time constant of hundreds, even thousands of seconds.

Fig. 5 shows the characteristics for the Nitronex NBT025 transistor, measured over a range of times and regimes. Quiescent times of *1* and *10 seconds* are not suitable to identify an appropriate dc characteristic for this transistor. This is because of insufficient charging of the trap state. This is detected by exploring the various bias points on the characteristic both in a *step and sweep* and in a random order (shuffle) and clear differences appearing on the I-V plot.

For the Nitronex device it was found that when each point was analysed after the transistor had been kept at the relevant bias point for *100s*, no changes occurred in the characteristic when two different random orders were utilised to explore each point. Hence, *100s* is long enough for trap states to be established. The *100s* curve in Fig. 5 may be seen as an asymptotic curve which is reached and maintained after the appropriate quiescent time is reached. Similar results were observed for the Cree device which confirmed the presence of long time-constant traps in both transistors.

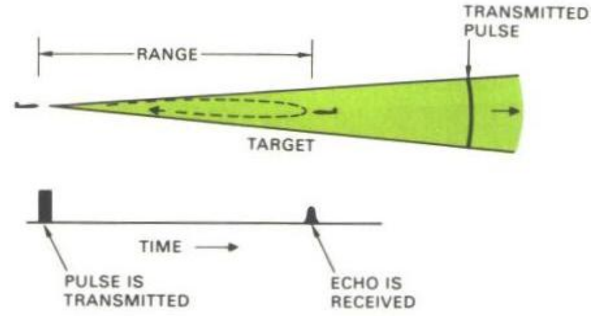

Figure 1. Pulse Delay Ranging [6].

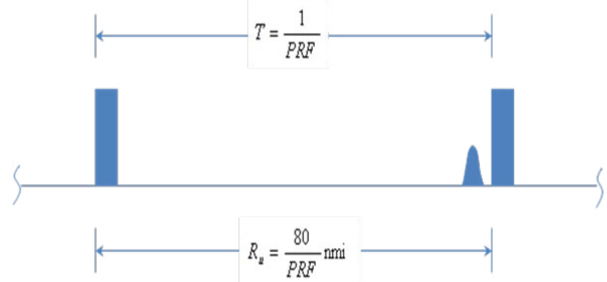

Figure 2. Longest range for which unambiguous return may be received [6].

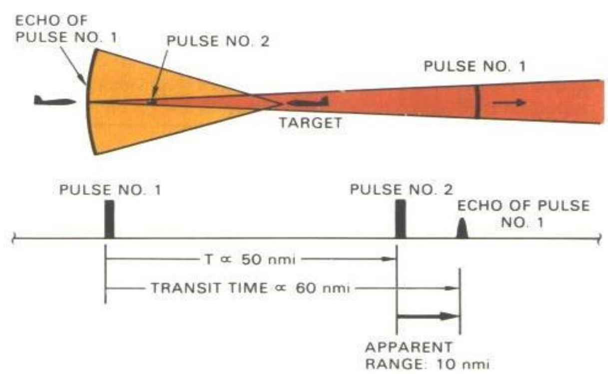

Figure 3. Apparent Range [6].

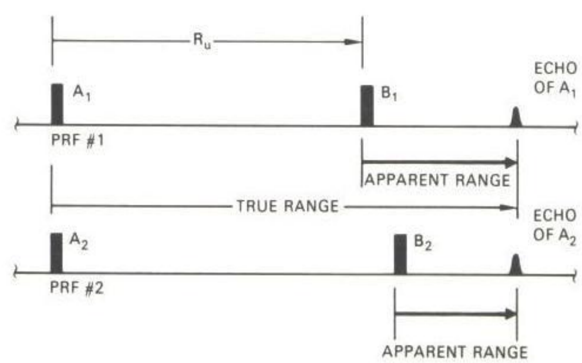

Figure 4. A change in PRF may identify range as ambiguous [6].

Note also that considerable difficulty with oscillations is experienced with these measurements.

The authors' main aim with this paper was not just to verify the presence of traps which are characteristic of commercial GaN devices but to assess their effect at device level when the transistor is operated in a pulsed fashion, at typical radar PRFs and duty cycles. In this paper PRFs of *100* and *400 kHz* are examined and a fixed *20%* duty cycle is used.

For each PRF, the transistor is pulsed continually for *100s*, *i.e.*, the voltages at its drain and gate terminals are pulsed to the various points of the characteristic at the pulse repetition frequency and duty cycle chosen. One set of measurements is then taken at the start of this *100s* excitation and one at the end. It should be stressed that during the *100s* which separate the two data acquisitions, the transistor is being continually pulsed from the quiescent point to every point in the characteristic. It was found that there were no significant differences hence no distinction will be made between the two measurements in subsequent sections.

III. Results

For both Cree and Nitronex transistors a knee-voltage increase (of approximately *2V*) may be observed at a higher PRF, as shown in Fig. 6 and Fig. 7.

Fig. 6 also shows that, for the Cree transistor, a higher drain current is available at lower PRFs for voltages greater than *8V*. In the case of the Nitronex (Fig. 7), this was only observed at the lower v_{GS} (bottom 3 curves) whereas at the highest v_{GS} biases (top 2 curves) an opposite effect was observed.

In addition, Fig. 6 highlights the fact that $r_{DS\text{-}on}$ for the Cree device is consistently higher when the transistor is pulsed at *400 kHz* than when it is pulsed at *100 kHz*. In the case of the Nitronex (Fig. 7), the opposite effect is observed and a higher $r_{DS\text{-}on}$ is observed at lower PRFs for gate bias voltages greater than *–1.2 V*. For v_{GS} lower than *–1.2 V*, the data collected may be affected by oscillations which are suggested by the considerable current swings present at the higher end of the v_{DS} range.

Tests were repeated after *100s* and there were no differences in the measurements, again suggesting that these changes in the I-V curves are not due to thermal effects.

IV. Discussion

The experiments highlight a significant degree of knee-walkout when the pulse repetition frequency at which the I-V characterisation was conducted was increased form *100* to *400 kHz*. This significant change in the characteristics would cause considerable changes in the amplifier load line, particularly at the lower end of the v_{DS} range, where hard-clipping effects may be more extensive than would be predicted from the I-V curves measured at lower PRFs. This may introduce a greater degree of non-linearity as well as a decrease in the efficiency of the amplifier. A putative explanation for this effect is the interaction between the trap time constants and the comparable periods and duty cycle of the driving waveforms and that the trap characteristics are different for the Cree and Nitronex devices.

The measured data also highlights another way in which the efficiency may be affected by the PRF. As show in Fig. 6, at the higher end of the v_{DS} range, the Cree device is able to supply a higher i_D at *100 kHz* PRF, which would increase the amplifier efficiency. For the Nitronex transistor (Fig. 7) the opposite applies and a higher current-availability is observed at *400 kHz*.

V. Conclusions

The pulsed I-V characteristics measured at different PRFs showed significant differences. This highlights the need for an appropriate device characterisation as a first step in the pulsed-amplifier design process, which takes into account operational parameters such as PRF and duty cycle.

It would also mean that, if staggered PRF is used, different pulse powers would be produced by the transmitter amplifier. This could cause the following inconsistencies in the performance of the amplifier. Firstly, the interpreted cross-sectional area of the target may vary, which would increase the emphasis on the need for some output-power sensing arrangement. Secondly, inconsistencies in the radar's maximum-achievable range across the PRF-range utilised may be present. Conversely, the variation of transistor performance with PRF may yield a specification test for acceptance of these devices.

Another important parameter which would need to be investigated and which may affect the design of the pulsed power amplifier is the breakdown voltage V_{BD}, which may also be affected by PRF. In order to determine its influence on the amplifier performance, a considerable extension of the v_{DS} range would need to be explored.

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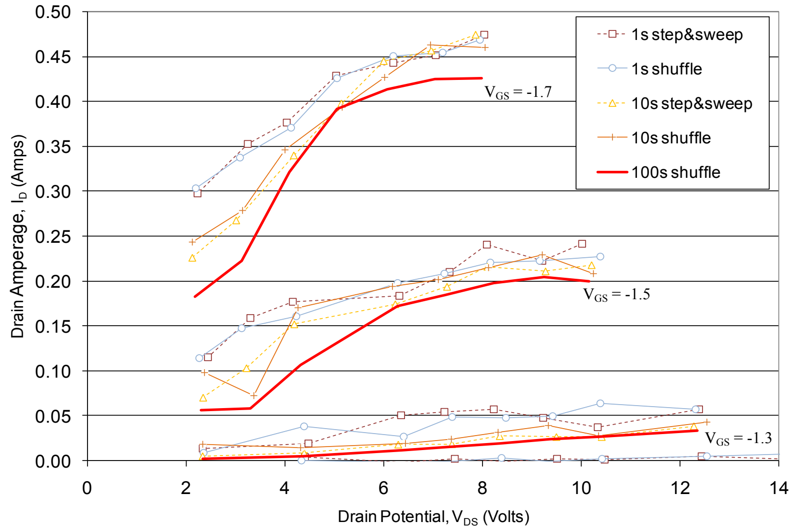

Figure 5. Pulsed I-V Characteristics for the NBT025 and a range of quiescent times.

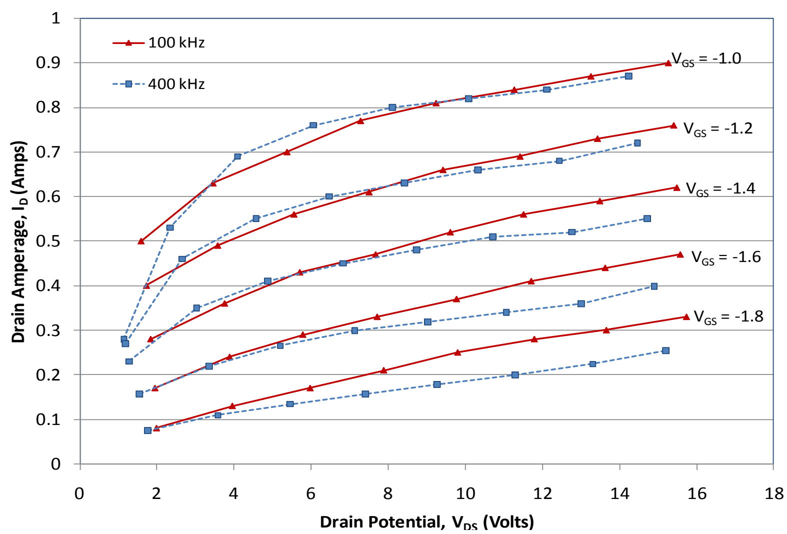

Figure 6. Cree CGH40010 pulsed I-V plots at *100* and *400 kHz* PRF and *20%* duty cycle.

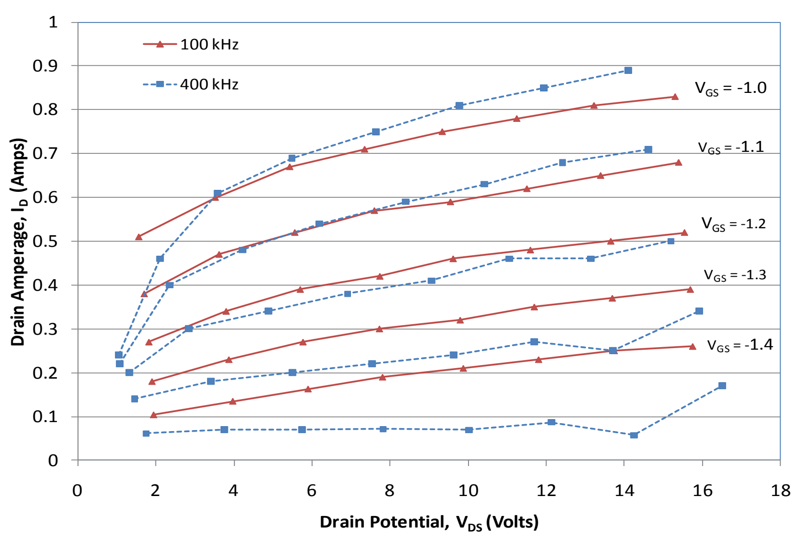

Figure 7. Nitronex NBT025 pulsed I-V plots at *100* and *400 kHz* PRF and *20%* duty cycle.