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An experimental study of switching GaN FETs in a coaxial transmission line

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Keywords

«Component for Measurements», «Gallium Nitride(GaN)», «Device application», «Device Characterization», «Power semiconductor device», «Emerging Technology», «Measurement».

Abstract

The switching characteristics of GaN FETs have not yet been measured accurately because of their small electromagnetic size in relation to the circuit and the electromagnetic environment the measurements are exposed to. Switching GaN FETs in a transmission line will allow for measurements to be taken in an electromagnetically defined environment. The transmission line is adapted to take optimum measurements. This is proven by the waveforms presented.

1. Electromagnetic perspective of GaN switches and circuits

GaN HEMT transistors hold the promise of more than an order of magnitude decrease in switching times in comparison to the presently available silicon FETs [1-2]. The extremely small dimensions of the GaN FETs that have become commercially available, coupled to the miniature surface mount packages they are supplied in, results in the electromagnetic “footprint” of the mounted device being almost negligible in comparison to that of the rest of the converter circuit. The largest electromagnetic effect of the device itself is probably the relatively high output capacitance, of which its effects are shown in this paper. The package inductance is negligible. Consequently, the switching characteristics obtained in practice are bound to be dictated by the circuit and not by the packaged device.

Furthermore, the electromagnetic environment of a converter on PCB can at best be considered to be ill-defined, since all types of stray electric and magnetic fields exist in, above and below the board, changing for every different lay-out. Thus, improving the switching characteristics has been achieved by improving lay-out three-dimensionally [3-4], with great effort, thus reducing the stray electromagnetic “footprint” of the converter circuit. However, it still is not clear what the actual device switching behavior is. Any attempt at measurement inside the converter circuit to determine the characteristics of the switching disturbs the electromagnetic footprint of the carefully laid out converter and the device by adding stray electromagnetic volume evidenced by oscillations [4-5].

Especially current measurement becomes extremely problematic, even when using miniature coaxial shunts for frequency accuracy.

In an effort to characterize the switching behavior of the device, these measurements should:

- be done in an exactly defined electromagnetic environment;
- be done where the electromagnetic environment does not influence the switching;
- be done by switching the device into a perfect resistive load, so that the device and not the circuit determines the switching behavior.

However, since the electromagnetic footprint of the packaged device is so small, the switching device can be placed inside the coaxial shunt. This has led us, after considering this possibility, to place the device inside a short lossless coaxial transmission line, terminated in its characteristic impedance by an appropriate resistive disc, consequently presenting pure resistive impedance. In this set-up, the dimensions of the transmission line become unimportant. Furthermore, at the nanosecond level of transition times, this setup is the only way of experimentally constructing a pure resistive load. This can also be coupled to the idea of a thin radial current shunt [6] serving as the termination of the transmission line. When the thickness of this resistive layer is negligible in comparison to the skin depth at the highest frequency in the waveform, the voltage across this resistive layer presents an accurate view of the current. It is to be expected that the practical execution of these ideas will bring its own difficulties. It is the purpose of this paper to explore these experimental difficulties and report on the exciting results.

2. Experimental construction

In order to switch a GaN FET inside a transmission line, the switch can be positioned in four possible configurations. These are shown in Fig 1 and can be subdivided into two types of configurations, namely, an un-charged transmission line, Fig 1(a) and (b) (where the switch is located on the source side of the transmission line) and a pre-charged transmission line, Fig 1(c) and (d) (where the switch is located on the load side of the transmission line).

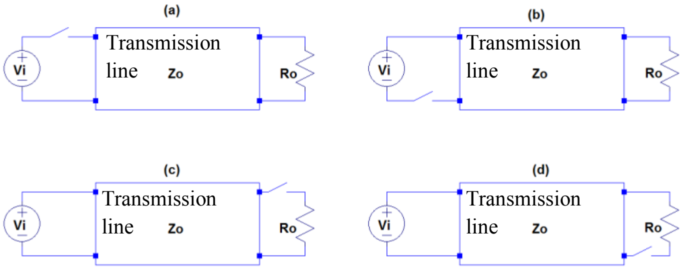

Fig 1: Switch and load configurations using a transmission line

The two configurations which are investigated through experimentation, and discussed in this paper, are Fig 1(b) and Fig 1(c). Configuration Fig 1(b) was selected as the un-charged transmission line setup and Fig 1(c) for the pre-charged transmission line setup. The transmission line must be short enough so as to not affect the switching transients through dispersion, but it must be long enough to establish a plane electromagnetic wave-front in the coaxial structure. Since $\varepsilon_r = \mu_r = 1$ for an air core coaxial line, the velocity of the electromagnetic wave-front will approximate the speed of light. GaN transistors are capable of switching within a few nanoseconds and even sub-nanosecond speeds [7]. Thus the chosen propagation delay through the transmission line was chosen to be 500ps resulting in a length of 0.15m. The cross sectional dimensions of the transmission line were chosen to give a designed characteristic impedance of 50Ω. Further work is being done on determining the best dimensions for such an experimental setup. The reason for choosing 50Ω in this paper is because of the 50Ω measurement standard in measurement equipment. The 50Ω characteristic impedance will allow high bandwidth measurements of the voltage across the terminating load resistance. A tapered coaxial structure was made to maintain a characteristic impedance of 50Ω for the different diameter coaxial structures. The tapered structure will be shown later in Fig 3 and Fig 4. The tapered coaxial structure is essentially a coaxial 1 to 1 impedance transformer with a low loss connection.

The original idea was to maintain maximum bandwidth accuracy of measurement instruments by terminating and matching all impedances into 50Ω. However, the 50Ω measurement termination will in fact load the measurement. Therefore high impedance measurement passive probes were used. The tapered structure was still needed for the radial terminating resistors to be measured simultaneously. The cone structure further eliminates external flux from coupling onto the measurement.

The 50Ω transmission line and switch was initially terminated by a resistance equal to the characteristic impedance. This is to eliminate any reflections that will affect the measurement, since reflections superimposed on the waveform, may appear to be voltage overshoot due to circuit effects. Further terminating load resistances can be looked at in simulation and will be discussed. A thin film resistive load disc is necessary to eliminate skin effect at the short switching times. This disc was made from discrete surface mount resistors as shown in Fig 2. This is not ideal since the discrete resistors will have inductance, but this construction has proven to be sufficiently near an ideal disc for the purpose of these preliminary investigations. However, a solid resistive disc would be best. The position and placement of the resistor disc is critical. The transient electromagnetic wave must reach the resistive load and dissipate in the thin film. A thick resistive material will experience time dependent skin effect which will result in a voltage overshoot in the measurement.

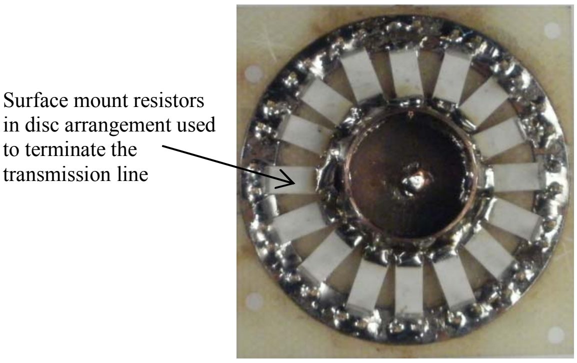
Surface mount resistors in disc arrangement used to terminate the transmission line

Fig 2: Terminating disc constructed from radially arranged SMD film resistors

The cross section of the pre-charged configuration of Fig 1(c) is shown in Fig 3(a) and the equivalent circuit schematic is shown in Fig 3(b). Since the GaN FET switch is inside the transmission line, the measurement probe must also be inserted inside the transmission line to measure the voltage across the switch. This is best done by taking advantage of the field-free region of coaxial transmission lines. The hollow area inside the inner conductor is field-free [8]. Therefore no external varying flux can couple onto the measurement leads if placed in this field free region.

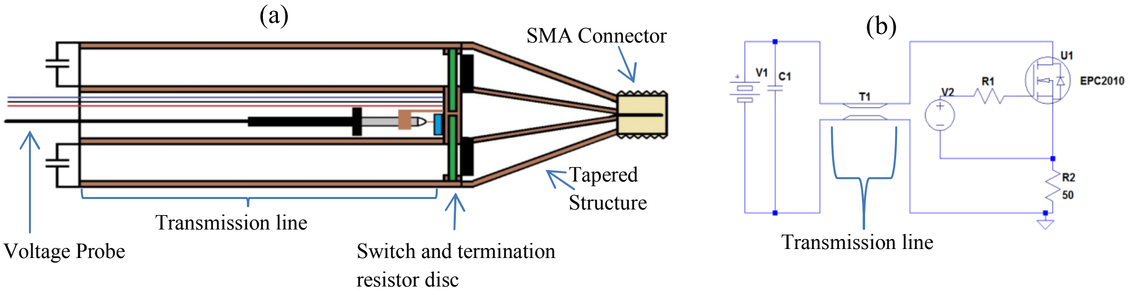

Fig 3: Cross sectional image of the pre-charged transmission line structure according to Fig 1(c)

The voltage across the switch and the voltage across the resistor cannot be measured simultaneously unless isolated probes are used. The physical construction with the outer conductor of the coaxial transmission line, being the ground potential, fixes the ground measurement reference. If care is not taken in the measurement, the probe can place low impedance in parallel to the terminating resistor, which could destroy the switch. The driver signal to the switch must be isolated in order to be able to measure the voltage across the resistive load.

The un-charged transmission line cross section and equivalent circuit schematic is shown in Fig 4 (a) and (b). Unlike the pre-charged structure, the voltage measurement probe is no longer situated inside the field free region, since the GaN FET to be measured is no longer situated inside the transmission line. Shielded, low inductance probe tip connectors were constructed to minimize external flux from coupling onto the measurement leads as explained in detail in [8]. However this may only be a concern for low voltage measurements. The voltages to be measured will be over 100 volts and therefore the magnitude of the induced voltage due to flux coupling is expected to be negligible.

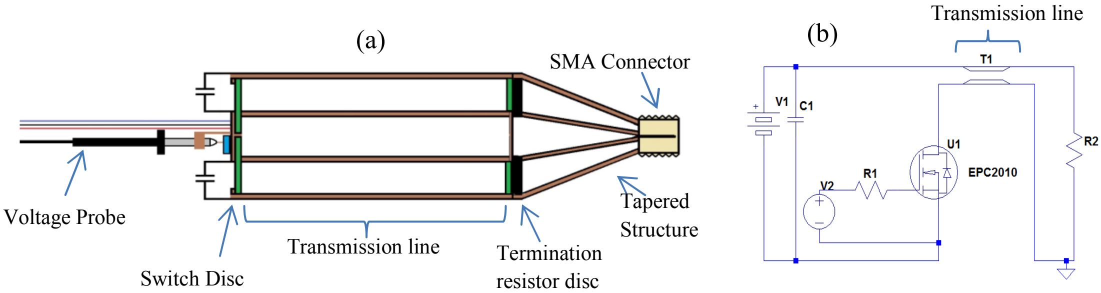

Fig 4: Cross sectional image of the un-charged transmission line structure according to Fig 1 (b) and circuit diagram

The fully assembled structures of both the pre-charged and the un-charged transmission lines including the tapered cone structure, switch and load boards are shown in Fig 5. The voltage source at the input is simulated by a total of 200µF of capacitors. Different technology types of capacitors were used in parallel for optimum time response.

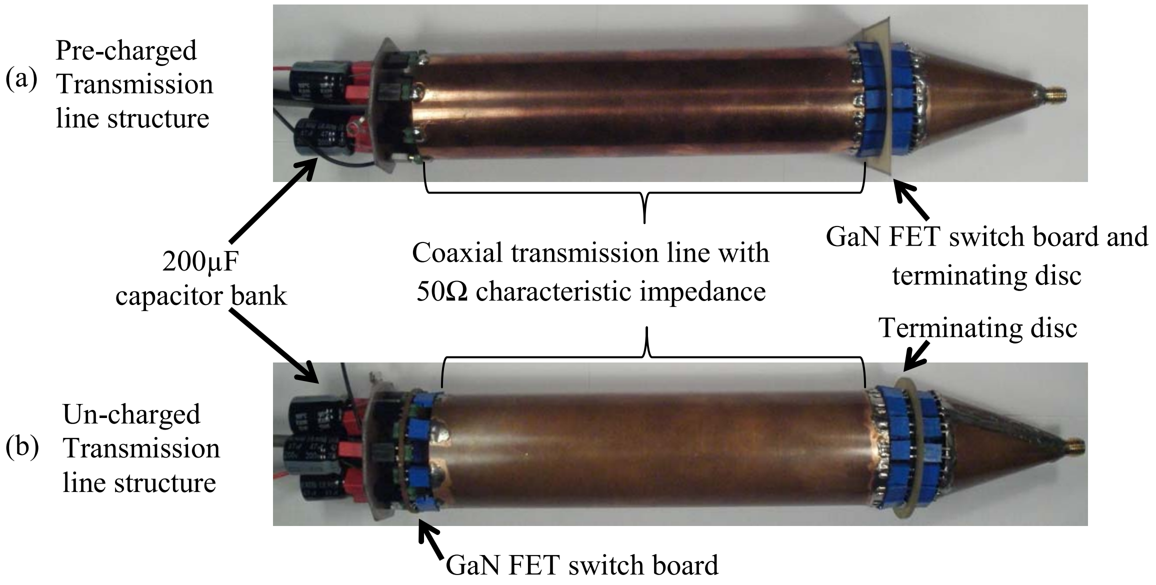

Fig 5: Fully assembled coaxial transmission line structures

It should also be noted that the driver pull down path had to be dampened because the inductance in the pull down path, and the gate capacitance of the GaN FET, caused ringing of the driver signal, with an overshoot large enough to switch the gate back on. The switch boards, on which the GaN FET is mounted, resemble a disc with two parallel plates. There is a possibility that the board could add a considerable capacitance to the circuit. The capacitance of the board was measured using a capacitance bridge and the parasitic capacitance of the board was 44pF. That is much smaller than the output capacitance of the GaN transistor which ranges between 270pF and 900pF [7]. Hence the PCB capacitance is negligible. Details on the experimental procedure and the results are discussed next.

3. Results

A voltage pulse with 1 microsecond width was applied to the gate of the GaN FET device in the transmission line structures. The GaN FET switch chosen for the experimental setup is a 200V, 12A, GaN device from EPC, with part number EPC2010 [7]. The switch-on and switch-off transients of both the drain-source voltage and the drain current were then measured. The experimental measurements shown were captured using a Tektronix DPO7254, 2.5GHz oscilloscope (bandwidth limited to 500MHz due to the passive probe used), a Tektronix P5050 passive voltage probe (with a 500MHz bandwidth), and special PCB probe tip attachments for low inductance measurements. The bandwidth specifications can be equated into a relative rise time using equation (1) as found in [9]

$$t_r = \frac{1}{\pi f_{3dB}} \tag{1}$$

The fastest rise time which can be measured using the equipment bandwidth specification is 637ps. The high insertion impedance of the passive probes allows for the required voltages, of up to 200V, to be measured if needed. Alternatively, any voltage measurements below 5V peak can be measured using a SMA to SMA cable with a much higher bandwidth specification. Active probe technologies allow for measurements at a much higher bandwidth, but are limited in peak voltage capabilities, at much lower than 200V. Therefore the measurement instruments used might distort the 1ns transmission line reflections in the measurement. For this reason the results are verified with LT Spice IV simulations. The GaN FET spice model used was obtained from EPC [10]. The physical limitations of the measurement setup as well as real inductances in the experimental setup can limit the switching transients. Simulating the setup will reveal the switching transients of an ideal measurement.

The terminating resistor is changed in simulation and the effects are observed and compared. The simulation results can also be verified mathematically with transient transmission line theory as found in [11]. Simulation allows for both the voltage and current measurement to be made simultaneously, which cannot be done with the pre-charged transmission line setup, because of physical grounding issues as discussed earlier.

3.1 Transmission line measurements on the pre-charged transmission line

In the following, three curves are shown each time, i.e. simulation with an ideal switch, simulation with the device model provided by EPC [10], and the experimental measurement.

The pre-charged transmission line switch-on transient is expected to show a reflection, even under matched load conditions. This initial reflection is due to the direction of the current flow once the switched is closed, and is equivalent to twice the flight-time of the transmission line. The source impedance is also not matched to the characteristic impedance of the transmission line, and a reflection occurs at the source which then propagates to the terminating resistor, where the energy in the reflection will completely dissipate, only if the terminating resistor and the characteristic impedance are matched. This is shown in the ideal switch simulation in Fig 6(a) and can also be modeled mathematically [11]. The effect is not visible in the experimental measurement or the simulated eGaN FET measurements in Fig 6(a), because of the non-ideal switch characteristics which will be discussed later.

The setup was initially terminated with a 50Ω resistive disc as shown in Fig 2. Due to the tolerances of the SMD resistors used, the load disc resistance was measured as 52Ω. The output capacitance of the GaN FET reduces with an increase in the drain voltage [7]. The setup was therefore tested at 175V input voltage and the transmission line was terminated into the 52 Ω terminating resistor. These pre-charged transmission line measurements are shown in Fig 6, where an EPC2010 eGaN FET device from EPC was used [7].

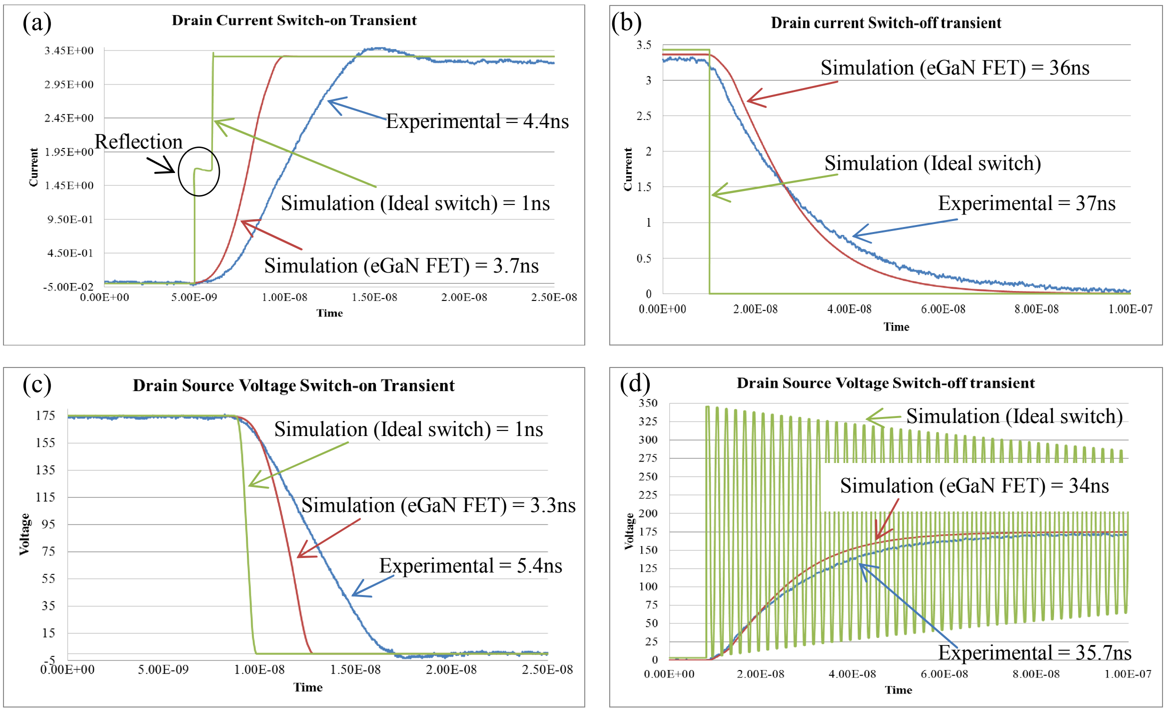

Fig 6: Pre-charged transmission line switching measurements at 175V into a 52Ω terminating resistor

It is shown in Fig 6 that under these resistive conditions, the current through the GaN FET, in the experimental measurement, reaches the maximum value of 3.4A in just 4.4ns. The gate drive voltage was measured separately and was measured to rise in 7ns. This is slower than the rise time of the drain. This is not a concern since the EPC2010 device has a threshold voltage of 1.4V [7]. A voltage overshoot can be seen in the experimental switch-on transient of Fig 6(a). The overshoot is in fact a reflection, because the terminating resistance is slightly larger than the characteristic impedance. The bandwidth limitations of the equipment used distort the waveform. High output capacitance effects are clearly visible in the eGaN FET simulation and experimental results shown in Fig 6(b), causing the transients to appear to occur in 37ns. The reason for this is that the non-linear output capacitance is charged through the 52Ω terminating resistor in the switch-off transient, which causes a long time constant. In Fig 6(c), it can be seen that the 5.4ns experimental fall time of the drain-source voltage is increasingly longer that the 4.4ns rise time of the source drain current. We believe this to be due to the internal discharge of the parasitic output capacitance of the device.

The reflections shown in the ideal switch voltage of Fig 6(d) are due to the sudden removal of the terminating resistor from the transmission line when the switch is turned off. Without the terminating resistor, the transmission line is effectively terminated into large impedance, which is not matched to the characteristic impedance of the transmission line, hence the reflections occur. The reason for the continuous reflections is because the source impedance is also not matched to the transmission line impedance, causing reflections there as well. The reflections traverse back and forth in the transmission line and dissipate the energy slightly with each reflection until there is no more electromagnetic energy left. This cannot be seen in the experimental and simulated waveforms due to the parasitic output capacitance of the device.

3.2 Transmission line measurements on the un-charged transmission line

The un-charged 50Ω transmission line structure was terminated into 52Ω resistor. The experimental and simulated waveforms are indicated in Fig 7 for the EPC2010 GaN device from EPC [7]. In this case, the ideal switch was also simulated in place of the GaN FET device, but with the 52Ω terminating resistor to indicate any reflections due to the mismatch to the transmission line.

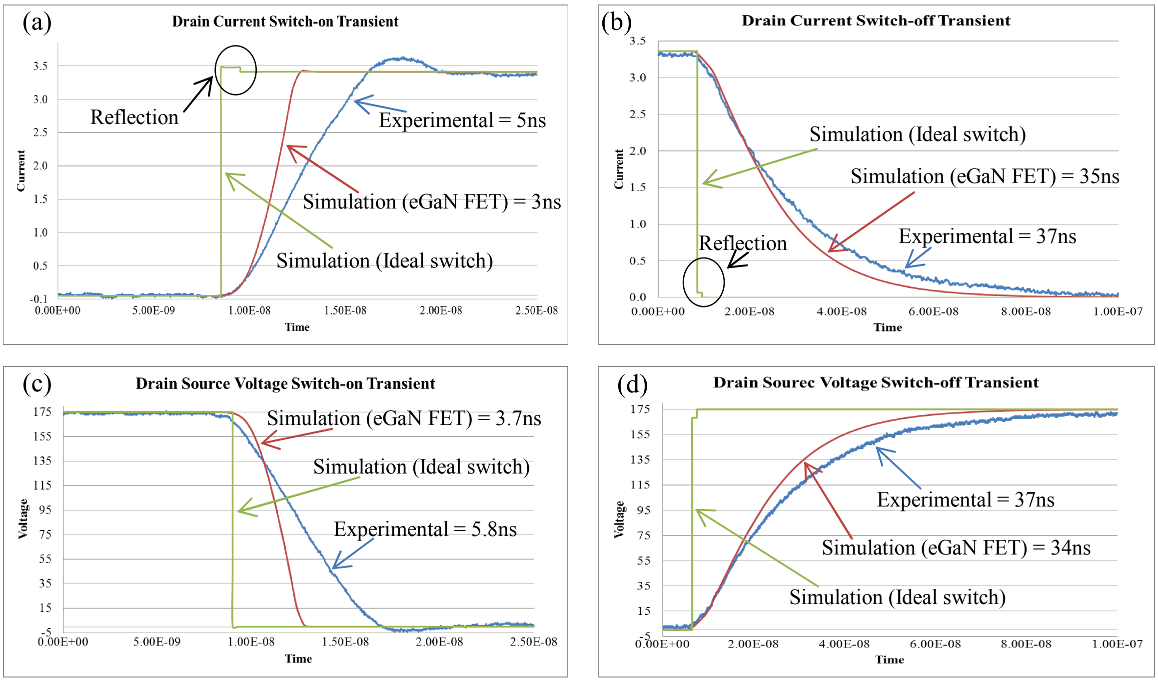

Fig 7: Un-charged transmission line switching measurements at 175V into a 52Ω terminating resistor

When terminated into the 52Ω, the reflection overshoot in Fig 7(a) is due to the not perfectly matched terminating resistor and characteristic impedance, as was seen before in Fig 6(a). Due to the mismatch, the ideal switch simulation also displays a reflection shown in Fig7 (b). The effects of the large output capacitance can again be seen in Fig 7 (b) and (d) with very similar time constants to what was measured in Fig 6 (b) and (d). Again the device switching characteristics matches approximately the turn-on characteristics of Fig 6.

From the results in the previous experiment, it is clear that if any observations on turn-off of the source drain current are to be made, the load that the transmission line is presenting must enable charging of the parasitic output capacitance in a time much shorter than the drain current turn-off. For a 50Ω line, this would mean a terminating resistor much less than 50Ω, leading to enhanced transmission line effects. Terminating resistors of 12Ω and 0.1Ω were chosen, constructed in the same way as previously.

The EPC2010 device used is rated at a continuous drain current of 12A if the temperature is maintained at 25 degrees Celsius [7]. Since no cooling is implemented, the terminating resistance was chosen as 12Ω, to not allow more than 12A to pass through the GaN FET at 140V. The terminating resistance of the 50Ω transmission line was then changed to 12Ω and the same measurements were recorded, and are shown in Fig 8.

The low termination resistance compared to the characteristic impedance cause reflections as shown in Fig8 (a) and (b). The reflections are clearly visible in the ideal switch simulation results, and their effect on the switching transitions of the switching transition measurements of the simulated GaN FET and experimental measurements. The switch-off transient is measured to be 10.5ns in Fig 8(b) compared to the previously measured 37ns in Fig 7(b). This is evidence that the output capacitance is now charging faster through the lower terminating resistance.

A slower rise time is measured due to the reflections as shown for the ideal switch in Fig 8(a). The experimental current rise time was measured as 6.2ns. The experimental current fall time, shown in Fig 8(b), was measured as 10.4ns.

As was observed in Fig 7(d), when the GaN FET is effectively disconnects the terminator resistor, the energy in the transmission line reflects. This is again observed in the ideal switch simulation, and is more pronounced, in Fig 8(d).

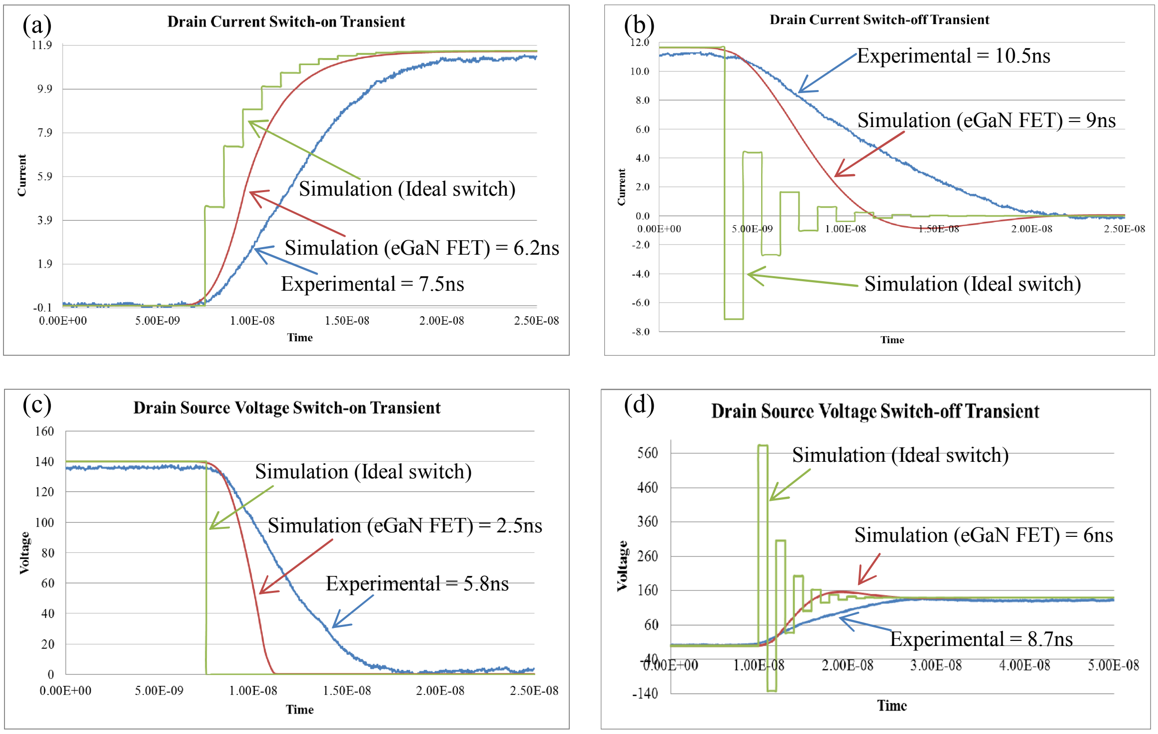

Fig 8: Un-charged transmission line switching measurements at 140V into a 12Ω terminating resistor

In order to properly characterize the switch-off transient, the un-charged TX line needs to be terminated into a very low shunt resistance. The low termination resistance will ensure that the large output capacitance time constant does not mask the switch-off transient of the GaN FET. The terminating shunt resistor of 0.1Ω was used and a source voltage of 1.5V. The source capacitance was increased to 2800µF to stabilize the voltage source. The results are shown in Fig 9.

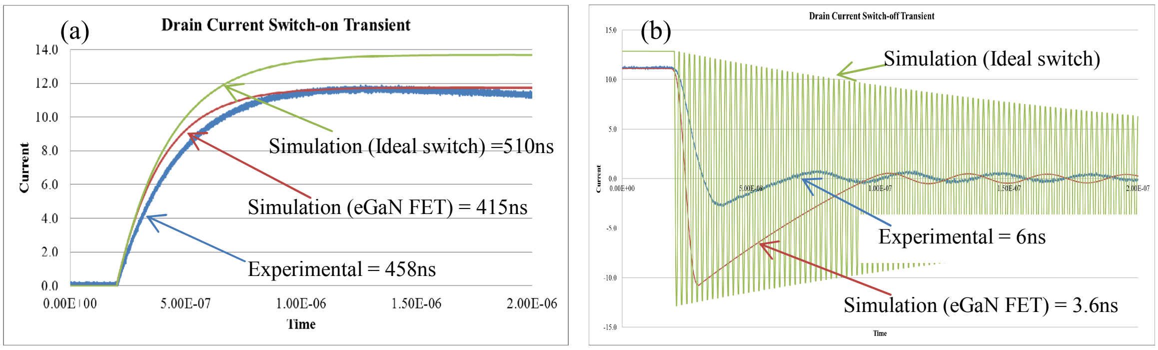

Fig 9: Un-charged transmission line switching measurements at 1.5V into a 0.1Ω terminating resistor

The slow rise time shown in the switch-on transient of Fig 9(a) is caused by the multiple reflections in the transmission line. Similar to Fig 8(a), except since the termination resistance is orders lower in resistance, the reflections are orders of multiples larger in number. The terminator resistor is only 0.1Ω compared to the 50Ω characteristic impedance. The focus of this experiment though is the switch-off transient. The experimental measurement shows that the current falls from 12A to 0A in 6ns, which is the fastest current fall time measured thus far.

The experimental and simulated eGaN FET drain current, in the switch-off transient of Fig 9(b), shows a similar effect to reverse recovery. The simulation measurement with the eGaN FET shows the same results, but with less damping. This effect was investigated further by also showing the simulated result for an ideal switch. Again, as was seen previously, there are reflections in the switch off transient.

5. Discussion

The measurements and findings thus far indicate that switching inside a transmission line yields clean and low noise measurements. This enables the determination of the current rise time of the EPC2010 eGaN FET as 4.4ns, and the current fall time as 6ns, as is measured in the electromagnetically defined environment with an almost perfect resistive load. The close similarities between the experimental and the simulated eGaN FET are remarkable. The output capacitance must charge through the termination resistance, but the transient caused by the output capacitance masks the actual switch-off transient of the drain-source conduction. In order to see the switch-off transient, the termination resistance and output capacitance time constant must be negligible in comparison to the drain source transition current. To properly investigate the switching characteristics of GaN devices, the transmission line must be matched with the terminating resistance. The switch-on transients can be accurately measured with the matched system, but the switch-off transients require closer attention.

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