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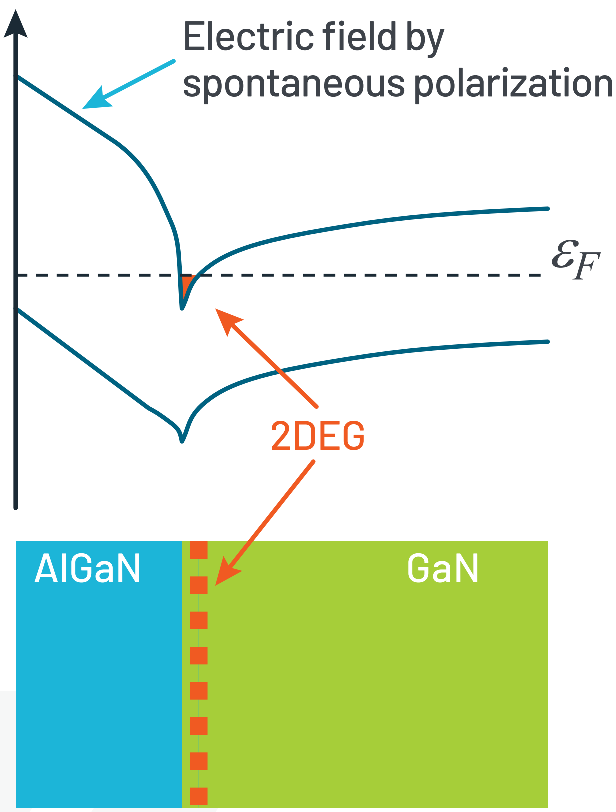
Challenges in GaN HEMT Power Device DC Characterization

APPLICATION NOTE



KEITHLEY
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Introduction

Power electronics technologies have been rapidly changing to meet new requirements. CO_2 reduction, higher efficiency with low power consumption, and system downsizing have been main drivers of new technologies in power electronics applications. Wide bandgap (WBG) semiconductors are widely adapted to convert power in the power electronics. Specifically, Gallium Nitride (GaN) devices have been prevalently leveraged in high-speed applications inclusive of consumer products to high power use cases due to the GaN devices operating very fast and with high efficiency while also housed within a small structure. Still, there are some remaining challenges in DC I-V characterization. This application note will provide details regarding oscillation of GaN HEMT devices during DC characterization and propose better ways to mitigate said oscillation.

Keithley provides a variety of High Power SourceMeter® source measure units (SMUs) to characterize components such as the power MOSFET. The 2657A High Power System SourceMeter Instrument is capable of sourcing 3 kV, and the 2651A — another high-power system SourceMeter instrument — is 50 A capable in pulse mode operation. The 8010 Test Fixture can be used with either SourceMeter SMU to hold and shield your power device. The ACS and KickStart software packages offer a means to establish automated setups and perform execution of I-V characterization tests for power MOSFET devices.

GaN HEMT Structure

GaN HEMT devices have a mainly lateral structure as shown in **Figure 1**. This device utilizes the benefit of a hetero junction characteristic at the interface of the GaN and the AlGaN materials where a deep valley of 2DEG (Dimension Electron Gas) conduction energy level is formed, allowing a large quantity of electrons to enter it. These particular electrons can have higher mobility than in other regular states, and this high mobility aids in increasing the current from drain to source. This type of device structure is called a high electron mobility transistor or HEMT. An inconvenience of this device is that it is normally turned on, which is not desired in most applications. This normally on-state GaN HEMT device is called a depletion mode GaN (or D-mode GaN for short). To turn the GaN HEMT device off, some level of negative gate bias is required to deactivate the 2DEG. For readers interested in the normally on-state GaN HEMT device characterization, an application note entitled "Power Sequence for GaN HEMT Characterization" can be found on tek.com.

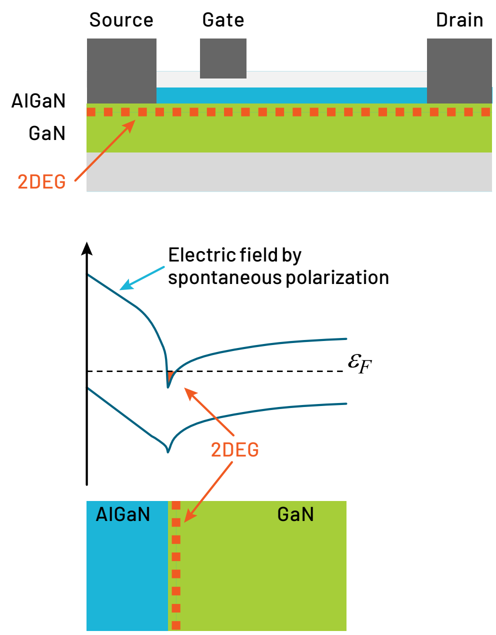

Figure 1. Typical GaN HEMT device.

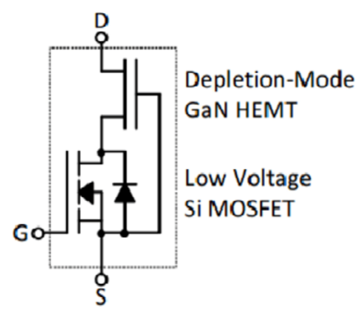

Figure 2. Cascode of GaN HEMT device.

Enhancement mode GaN HEMTs (E-Mode GaNs for short) have been introduced to enable a normally off device state by adding a p-type doped GaN layer between the AlGaN and the gate metal. This p-type doped GaN layer acts as a normal positive bias to prevent the 2DEG from being formed. When the gate bias is present, the majority carriers move away from the AlGaN interface so the 2DEG can be formed at the gate bias. The Cascode structure in **Figure 2** is another technology that has been introduced to ensure the normally off device state. In the Cascode, a regular Si MOSFET is added to a HEMT to invert the on state of the device to the off state. The presence of a gate bias at the Si MOSFET can switch the device state on.

High Speed of GaN HEMT Device

The GaN HEMT is well known as a device that supports high frequency switching. With respect to use as a high power device, the electrons driven by a voltage bias will cause the drift current, resulting in some collisions and scattering as the electrons move through the semiconductor materials. This scattering can disrupt and limit drift current. However, this carrier scattering is minimized in the 2DEG of the HEMT such that electron mobility is multiple times higher than the mobility of other technologies.

With all MOSFET devices, input capacitance (Ciss) — inclusive of the capacitance between gate and source (Cgs) and the capacitance between gate and drain (Cgd) — will affect the switching speed at the gate, slowing it down and reducing its efficiency. To reduce its impact and promote maximum output power at the drain, the input capacitance should be charged up quickly by first applying a bias to the gate. The GaN device is less impacted by capacitance of the gate. In comparison to other high power MOSFET devices, the GaN HEMT input capacitance is usually about ten times lower allowing the device to have faster state switching and resulting in less power loss.

Most high power vertical device MOSFETs have a body diode for third quadrant operation shown in **Figure 3**. Many power conversion applications utilize the third quadrant operation. When the device is off state, the body diode can still make current flow for opposite current in the third quadrant. When the device is switched off completely with the body diode, the drain voltage ramps up and the drain falls down to zero. The problem is that the body diode needs some time to recover (the reverse recovery time or T_{rr}) and that negatively impacts the switching speed, because some charges accumulated during third quadrant operation make reverse current. This is illustrated in **Figure 4**. The device needs the Trr to recover from the effects of charging (or Q_{rr} — reverse recovery charge). In contrast, the GaN HEMT device has no inherent body diode in its structure, and the T_{rr} and Q_{rr} are minimized or eliminated altogether thus accelerating its switching speed. Note, though, that there is still body diode in the cascode type of GaN device because of the regular Si MOSFET.

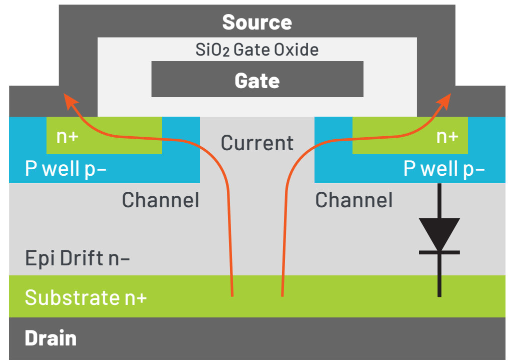

Figure 3. Typical high power MOSFET with body diode.

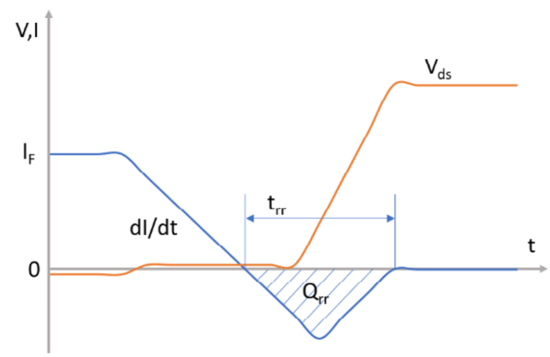

Figure 4. Reverse recovery timing example.

Oscillation in GaN HEMT DC Characterization

The lateral structure limits current delivery but promotes a speed advantage. Additionally, high-speed GaN devices may introduce another challenge in DC characterization causing frustration for test engineers and circuit designers alike: oscillation. The remainder of this application note focuses just on oscillation in DC characterization. When the devices are in the off state and only leakage level current is flowing, there is almost zero oscillation. It is the on state where several complicated oscillation issues might occur. One such case can arise when your test instruments use a feedback control loop technology to generate an output voltage and current with some amount of bandwidth. The oscillation can occur if the instrument band couldn't over the load band in the high capacitive load or inductive load.

If the capacitance of a device gate is high enough, then this could also promote oscillation. A remedy to suppress this might be to include some amount of series resistance at the gate; this series resistance may be effective but not work out perfectly. The capacitance of a GaN HEMT device is usually ten times lower than other types of power MOSFET devices. The oscillation can also originate in the drain terminal of the GaN HEMT device at very high frequencies, transferring over or coupling to the gate terminal via the capacitance between them.

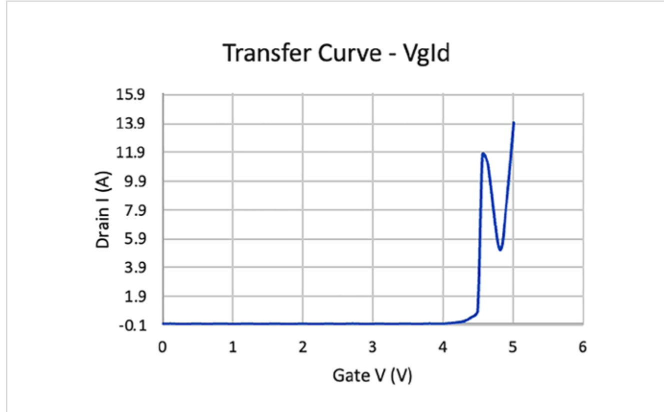

Figure 5. Transfer curve (VgId) with oscillation.

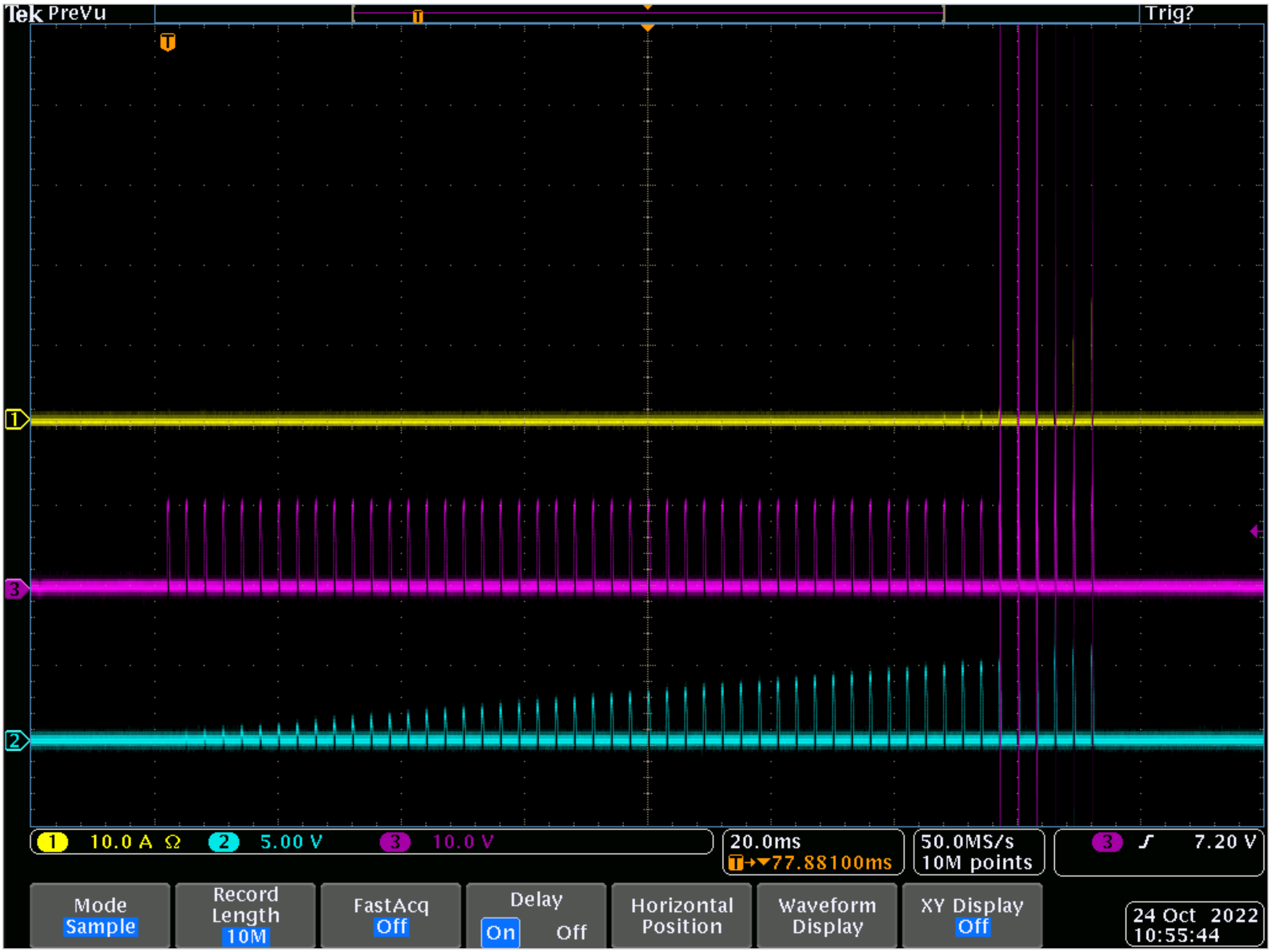

Figure 6. Oscilloscope waveforms of the Vg-Id test (yellow – drain I, magenta – drain V, blue – gate V).

Figure 5 shows an oscillation in the Vg-Id characterization. Oscillations are present in the threshold voltage region in this case, but this can occur any time the device is in the on-state. The example is of the cascode type, which has a higher threshold voltage than the pure HEMT type due to the integrated Si MOSFET (as noted earlier), and pure HEMT devices have a lower threshold voltage than other device structures. **Figure 6** shows the oscilloscope waveform of the I-V characterization where oscillations are observed in the signals of drain current, drain voltage, and gate voltage each. **Figure 7** shows the single waveform of the sweep measurement, while **Figure 8** magnifies the oscillation with a frequency higher than 3 MHz for this GaN HEMT device, well beyond DC instrument band.

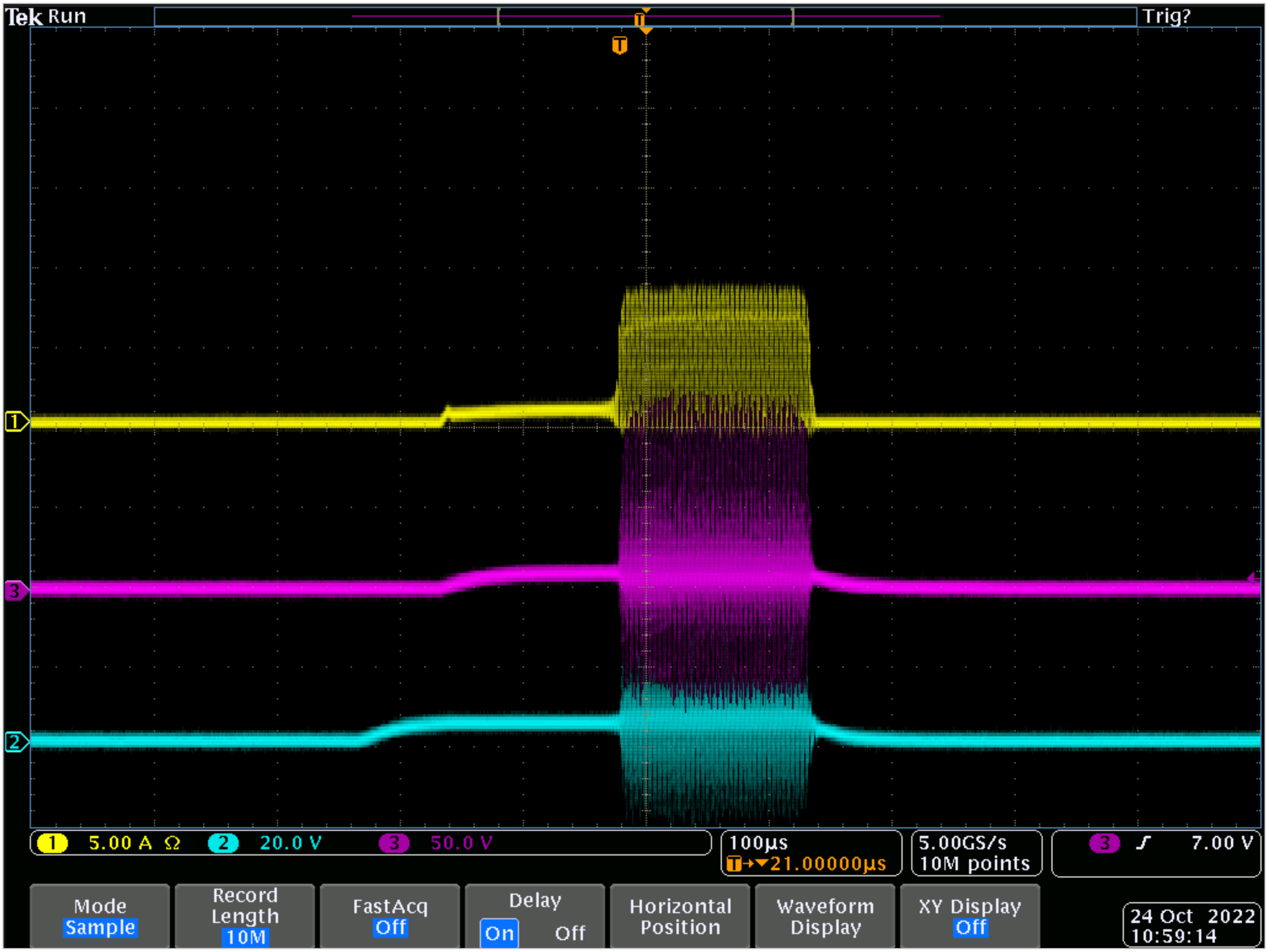

Figure 7. Single waveform capture of the sweep measurement (yellow – drain I, magenta – drain V, blue – gate V).

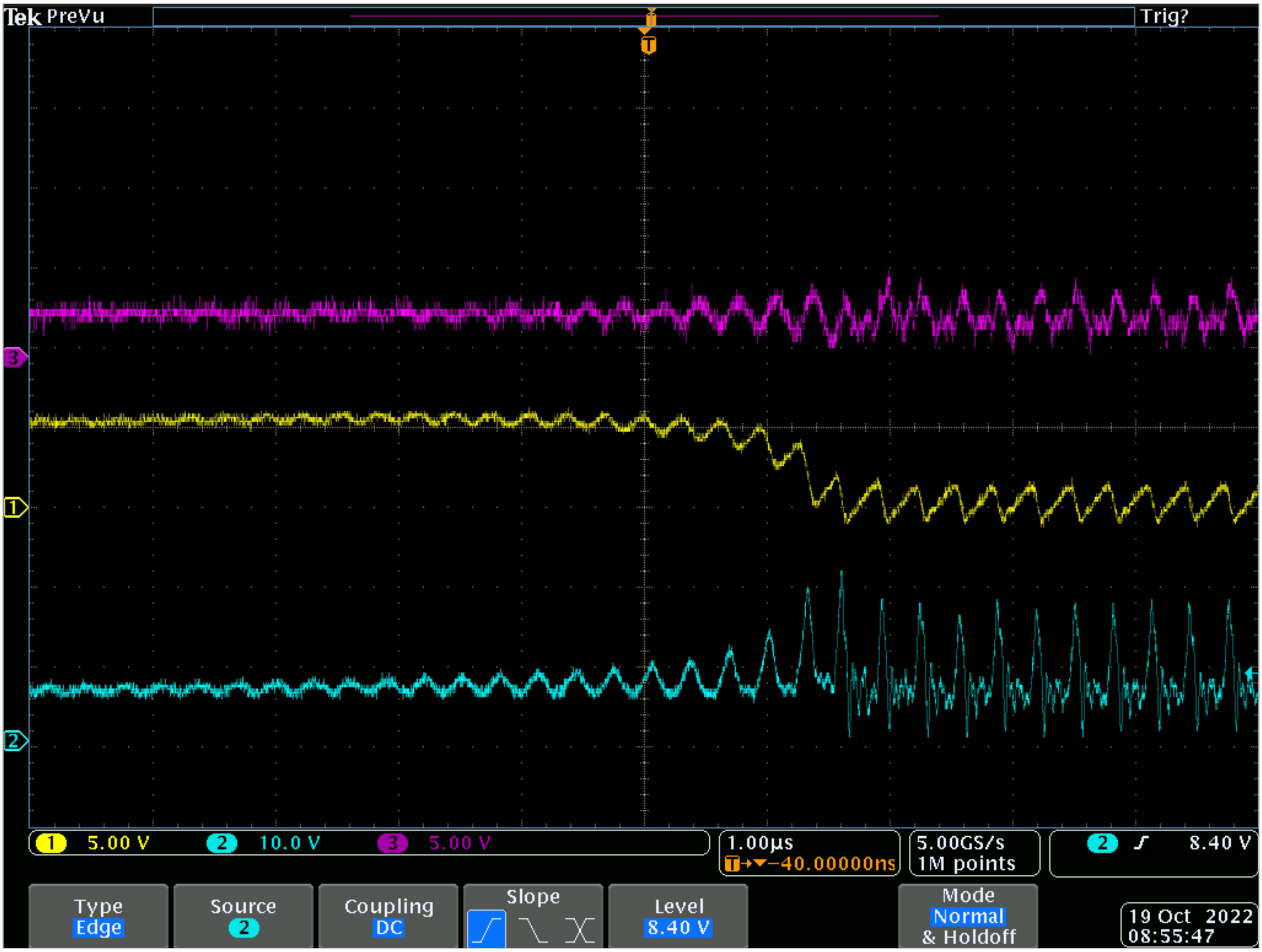

Figure 8. Zoom-in on the high frequency oscillation (yellow – drain I, magenta – gate V, blue – drain V).

Inductance in the Connection Setup

Addressing cable inductance is critical to avoid the oscillation when performing DC characterization of a high speed GaN HEMT device. Keithley offers a low inductance cable (2651A-KIT in **Figure 9**) designed to be used with the 2651A High Current SourceMeter SMU. The one-meter-long cable has a mere 195 nH inductance at 100 kHz, far less than that of a regular BNC cable. Triaxial cables typically have about double the inductance of standard coaxial cable and are not recommended for high frequency device testing.

Figure 9. 2651A-KIT cable for use with the 2651A.

Additionally, Keithley provides the 8010 High Power Device Test Fixture in **Figure 10,** which is excellent for GaN device test and includes a built-in safety interlock. Note, too, that even when using a triaxial cable to connect a 2636B

SourceMeter SMU to the gate (via the triaxial terminal interface), the fixture uses the inner shield of triaxial cable in the low side, which aids in reducing the cable inductance.

Figure 10. 8010 High Power Device Test Fixture rear view.

Figure 11 offers the transfer curve test comparison using the 8010 High Power Test Fixture (with the triaxial cable in the gate connection) and shows that the oscillation (from **Figure 5**) is no longer evident. If oscillation persists when using the triaxial cable with the 8010 fixture, lower inductance can be achieved using coaxial cable. The coaxial cables can be connected directly to the devices through the rear access port of the 8010 fixture. Keithley offers a blue, lower inductance coaxial cable (SC-182) that has better inductance performance than a standard coaxial cable. A 2601B-PULSE-CA3 is the blue lower inductance coax cable terminated by BNC. These lower inductance cables are great when interfacing with a probe station for low power GaN HEMT device test.

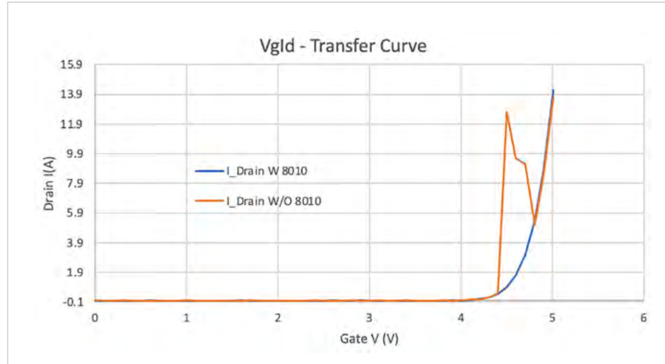

Figure 11. Vgld curve (transfer curve) with the 8010 fixture.

Ferrite Bead on Drain

In most cases, oscillation can be solved in proper cabling to the test fixture. However, the oscillation may persist in cases where long cables are used in connection to a probe station, among other reasons. The basic characteristics of ferrite beads are similar to inductors, though their high frequency impedance characteristics are different from those of inductors. In comparison to inductors, ferrite beads have a high resistance (R) component and low quality factor (Q), pushing them to act more like resistors at high frequency and eliminating energy storage - characteristics commonly utilized for suppressing high frequency oscillation and noise. **Figure 12** shows the ferrite beads at work (added on the drain terminal and as close to the device as possible) effectively eliminating the oscillation presented in the earlier example shared in **Figure 7**. Placing the bead on drain is much more effective than on gate terminal.

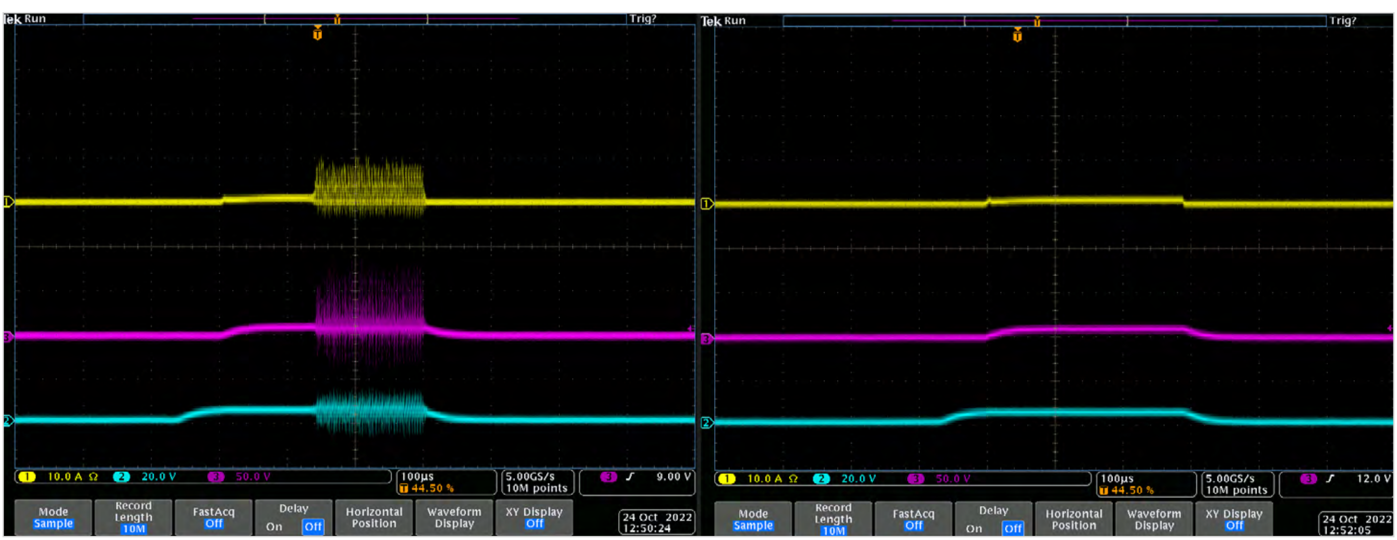

Figure 12. Ferrite bead effectiveness on drain (left - without ferrite bead, right – with ferrite bead) (yellow – drain I, magenta – gate V, blue – drain V).

Capacitor on Drain

Most GaN HEMT devices have very low output capacitance (Coss), typically lower than 1 nF. Adding a capacitor between the drain and source can absorb the high frequency oscillation and noise. At the DUT circuit board design level where GaN HEMPT devices are employed, an RC snubber circuit is commonly used to suppress oscillation. Capacitors alone or capacitors with resistors are an effective means to minimize the oscillation. **Figure 13** is the waveform capture for when 10 nF capacitor is placed at the drain terminal of the device as close as possible. It is effective to put it as close as possible to the device.

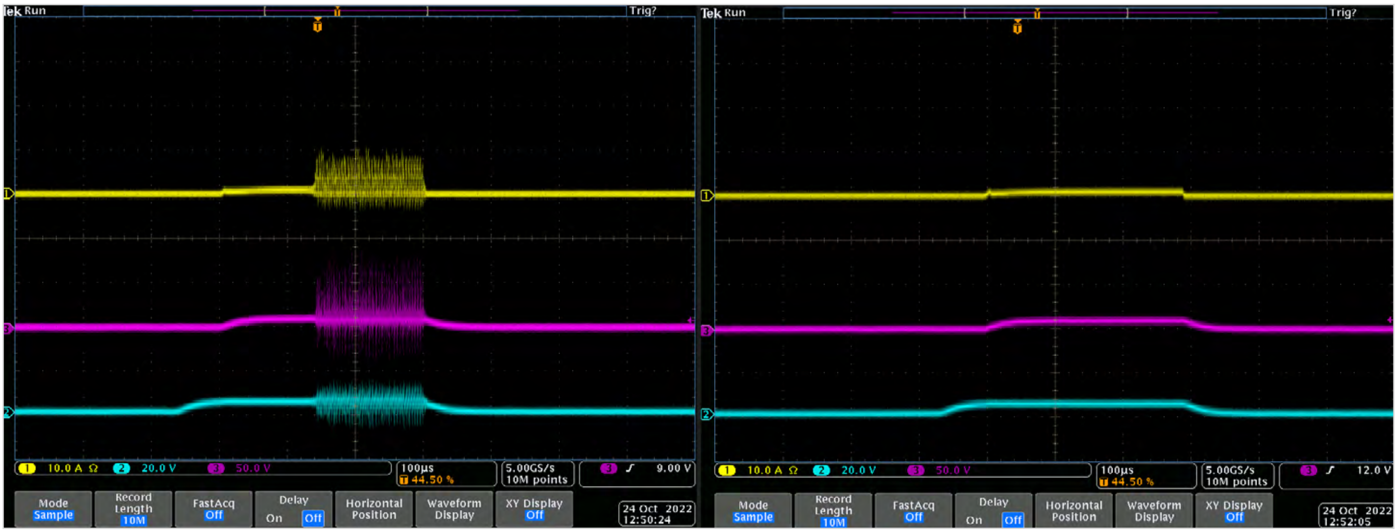

Figure 13. Capacitor effectiveness on drain (left – without capacitor, right – with capacitor).

Conclusion

GaN HEMT devices are very fast and efficient and have a unique structure and performance, but oscillation is one of the primary challenges with high frequency devices during the DC characterization. This application note discussed the oscillation challenges and offered best practices (optimized cabling and connection, adding ferrites or capacitance, and other) to best address the need to minimize or eliminate the different oscillation contributors. Keithley high power SourceMeter SMU options (both the 2651A and 2657A) and the 8010 High Power Device Test Fixture are a great combination for GaN HEMT device test. Additionally, Keithley software options such as ACS Basic and KickStart both support GaN HEMT DC characterization.

For more information on high power device testing or the instruments and software mentioned above, visit tek.com.

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