AN5770

Application note

Probing considerations for PowerGaN transistors

Introduction

Nowadays, ever increasing demand for power and high efficiency is the most crucial challenge in the power electronics environment. Power density and system cost are two additional requirements, which are gaining importance; so, device technology and electronic components must be properly selected to target all the above-mentioned specifications.

Wide-bandgap technology represents a breakthrough in modern power electronics: in fact, silicon carbide (SiC) is the key technology in high-power and high-voltage applications (i.e. traction inverter for EV), while gallium nitride (GaN) is increasing its importance and diffusion in medium power and high frequency applications (i.e. power conversion) [1].

GaN power devices have better figure-of-merit (FOM, $R_{DS(on)} \cdot Q_g$) than silicon ones, thanks to lower specific R_{DSon} and very low-intrinsic capacitances [2]. This leads to better efficiency, higher power density and increased maximum frequency in power converters. Very low gate charge values mean high switching speed for GaN technology, which can switch from off-state to on-state (and vice versa) in few nanoseconds. High slew-rate (even bigger than 100 V/ns) across the power devices are quite common with GaN technology. Fast-switching nodes and signals need very thorough measurement techniques to catch all the most important details of high-speed waveforms.

The main goal of this note is to provide complete user-focused guidelines to accurately measure the main electrical signals across a power GaN transistor.

In the first and second chapters, the voltage measurement technique, both for ground-referenced and floating signals, will be analyzed, highlighting the most common errors using incorrect probing systems. Third chapter will analyze the most common techniques for device current measurement, clarifying their respective advantages and drawbacks.

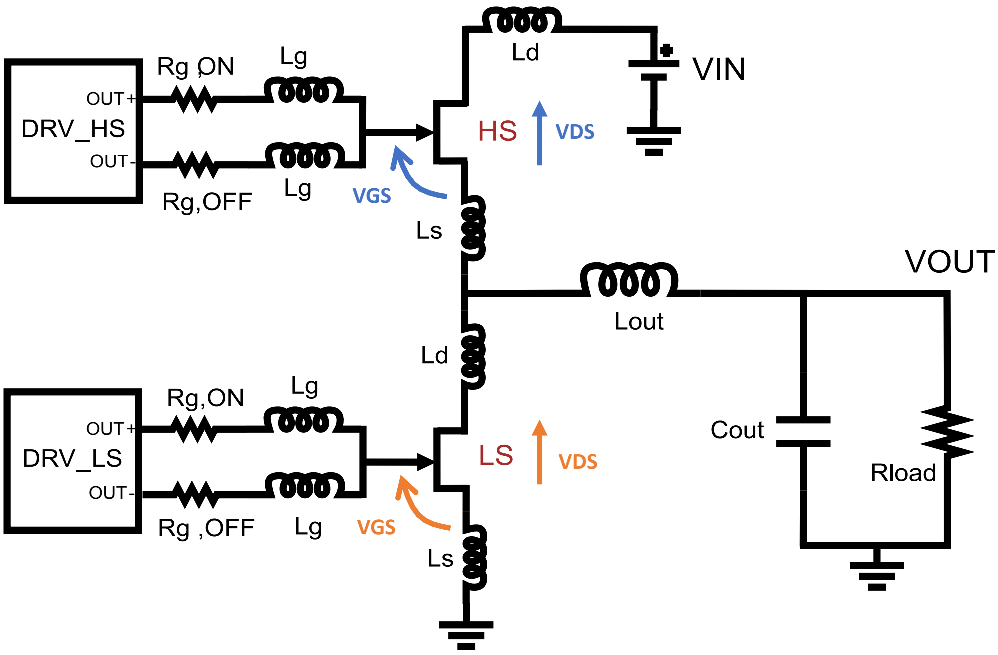
1 Ground-referenced measurements

In power converters, two different voltage measurements are present:

- Ground-referenced
- Floating

A voltage drop between a certain circuit node and ground level is "ground-referenced", while a floating signal is referred to a node, which can assume different values during normal operation. The following figure shows a simplified schematic of a step-down DC-DC converter: High Side signals (gate-source V_{GS} and drain-source V_{DS}, in blue) are floating voltages, while Low Side gate-source (V_{GS}) and drain-source (V_{DS}), highlighted in red, are ground-referenced.

Figure 1. Step-down DC-DC converter



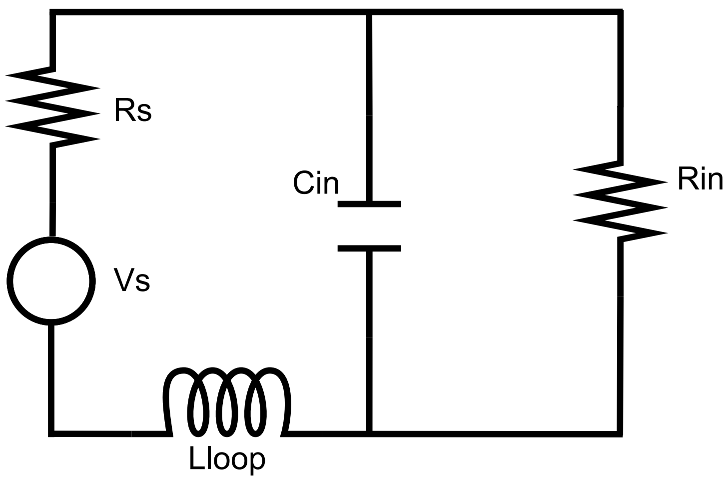
Let us considering a ground-referenced voltage. Typically, it can be measured with good accuracy by using a passive voltage probe. These probes can detect signals with maximum amplitude from hundreds of volts up to few kilovolts, offering a high input impedance (tens of MΩ) (see next figure).

Figure 2. **Passive voltage probe**

The ground connection is realized by long ground wire (the so-called “alligator clip”): this is the standard connection, widely used, for example, for the traditional silicon technologies. This type of probe grounding allows the connection of all the probe ground clips in the same point, easing the measurement process. With high-speed technologies and fast switching devices (like Gallium Nitride), the standard ground lead can dramatically reduce the measurement accuracy.

The following figure shows the basic equivalent circuit model of a voltage passive probe [3].

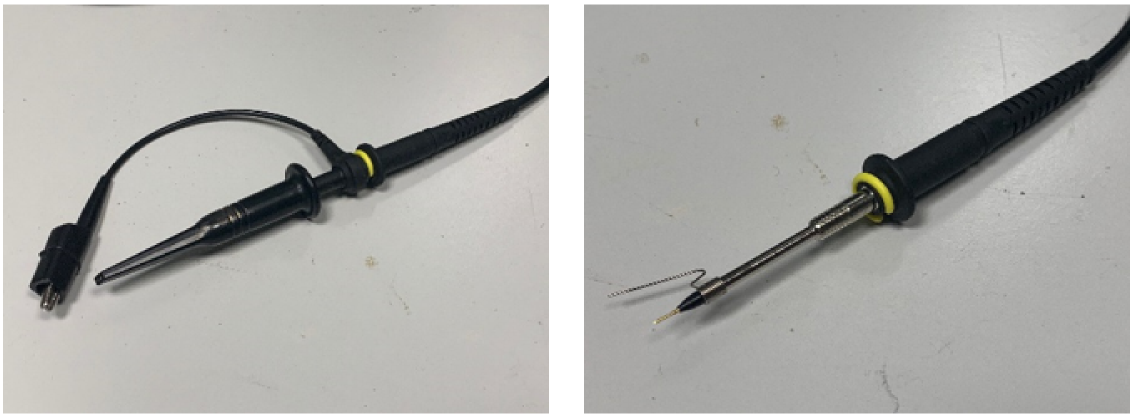
Figure 3. **Passive voltage probe–equivalent circuit model**



Here, Rin is the input impedance of the probe, Cin the input capacitance, while Rs and Vs are the series resistance and the signal to be detected. Typically, input impedance and capacitance are in the range of 10 MΩ and 10 pF for a 500 MHz 10:1 passive probe. The value of loop inductance (Lloop) is strictly related to the technique of grounding the scope probe. The longer is the ground wire the bigger is the distributed inductance, which can couple with the probe input capacitance creating an unavoidable high-frequency ringing.

The following figure reports two different grounding ways: the standard ground lead (or alligator clip) and an optimized connection (ground spring).

Figure 4. Standard ground lead (left) and ground spring (right)



With the help of a pSpice simulator and using the circuit of Figure 3. Passive voltage probe–equivalent circuit model in the DC-DC converter (Figure 1. Step-down DC-DC converter), it is possible to evaluate the impact of the ground loop inductance on the measured voltage. Three different and increasing loop inductances are considered ($L_{loop3} > L_{loop2} > L_{loop1}$).

Next figure shows the rising and falling edges of Low Side gate-source voltage.

Figure 5. Simulated low side V_{GS} with different ground loop inductances (turn-on)

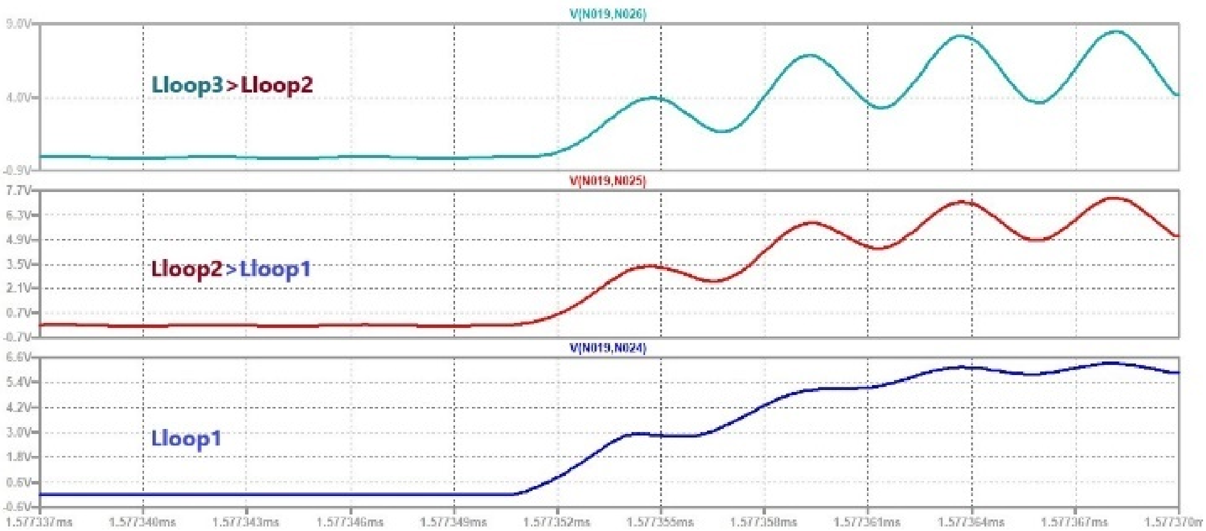
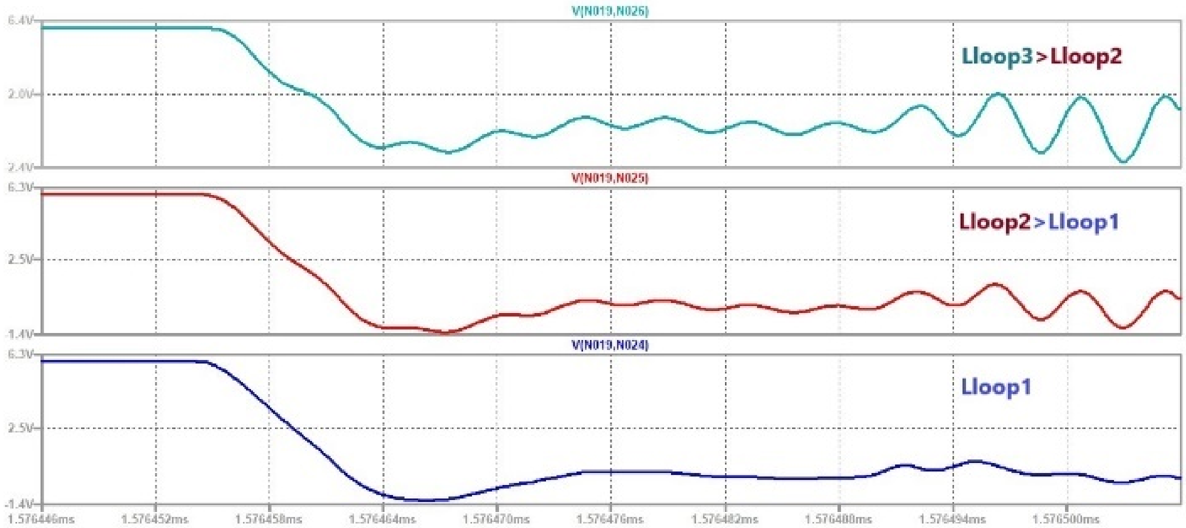


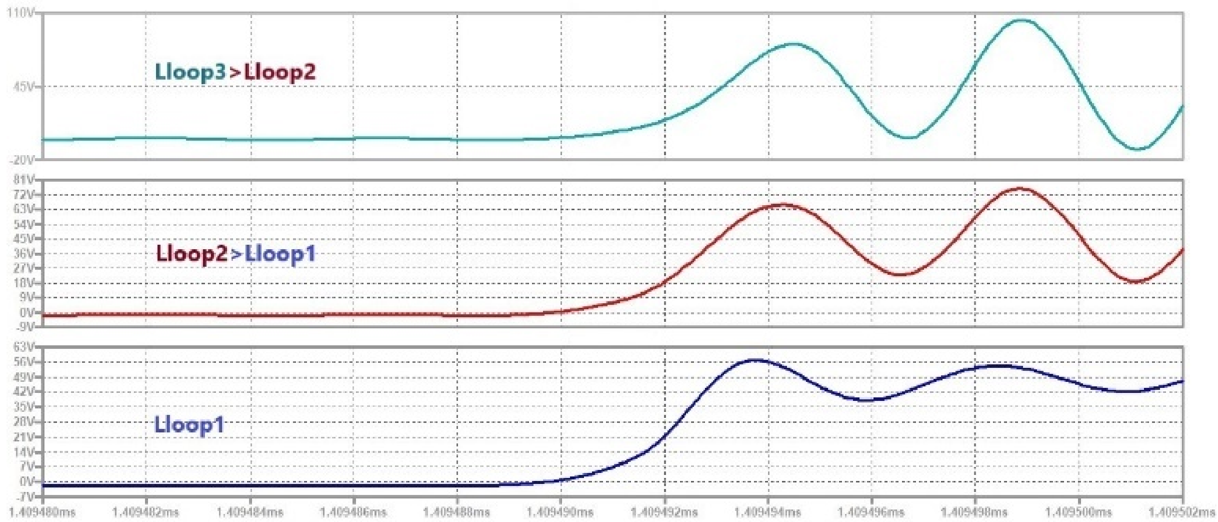
Figure 6. **Simulated low side V_{GS} with different ground loop inductances (turn-off)**



Both at turn-on and turn-off, bigger loop inductance creates higher ringing, which drastically worsens the measurement accuracy.

Similar considerations are still valid for Low side drain-source voltage, as shown in the following figure: here, too high ground loop inductance generates a huge drain-source overshoot, which is higher than device breakdown voltage.

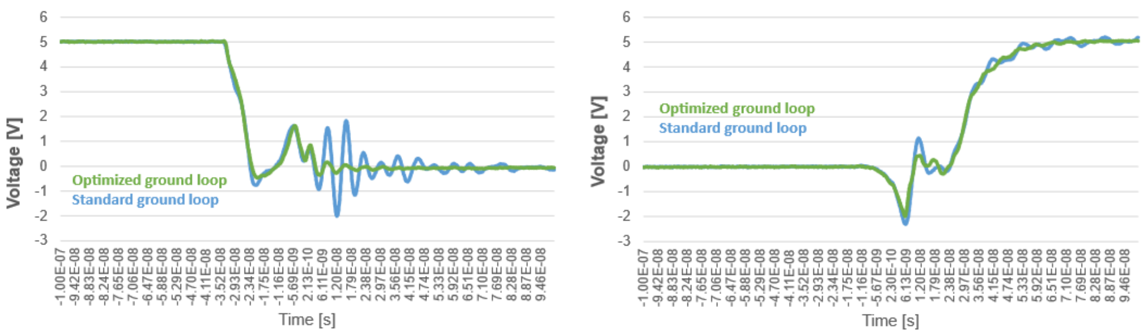
Figure 7. **Simulated Low side V_{DS} (turn-off zoom) with different ground loop inductances**



Real captures during experimental tests can confirm the simulation findings: a real DC-DC converter with GaN transistors as High side and Low side devices is considered as reference test platform.

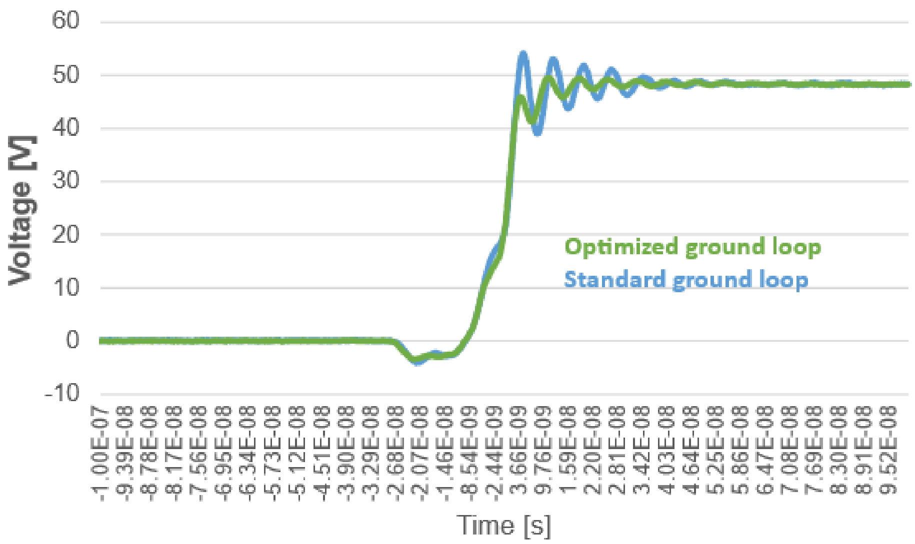
Next figure shows Low side gate-source voltage during turn-on and turn-off transients. Optimized ground loop (ground spring as shown in Figure 4. Standard ground lead (left) and ground spring (right)) improves the measurement accuracy, with lower spurious bouncing and ringing in both switching edges.

Figure 8. Low side V_{GS} measurements with standard and optimized ground loop



Similar results are still valid for drain-source voltage, as reported in the following figure.

Figure 9. Low side V_{DS} measurements with standard and optimized ground loop



Summarizing what analyzed in this paragraph, here following some basic recommendations for accurate ground-referenced voltage measurement.

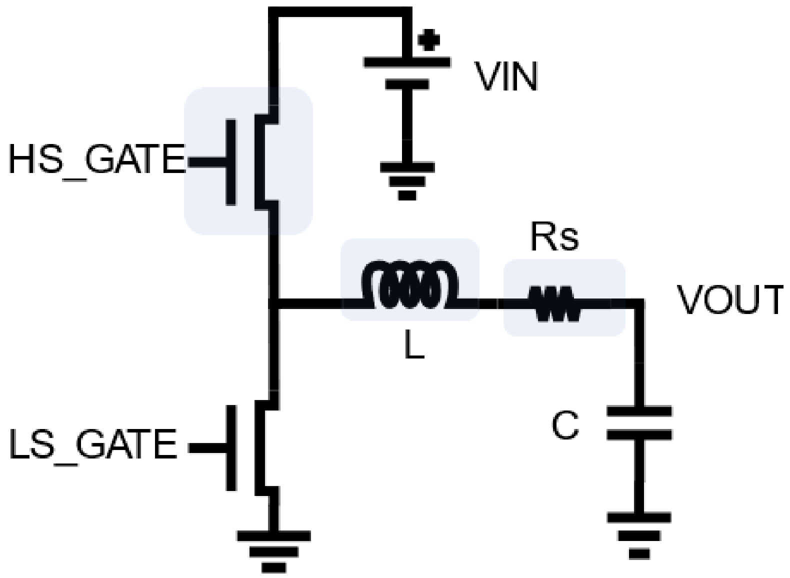
Table 1. Recommendations for ground-referenced measurements

Group reference	Value
Type of probe	Passive
Ground loop	As short as possible (ground spring)
Bandwidth	500 MHz
Measurement points	Closest to power device

2 Floating voltage measurement

A floating measurement reads the voltage between two points in a circuit, neither of which is at ground level. Non-referenced ground measurements are very common in power converters, especially in bridge topologies, when the power transistors work as high side switch or when there are electronic components used in ungrounded position (free-wheeling diodes, inductor, transformer, ungrounded resistors). Here below, highlighted in blue, ungrounded components in a synchronous buck converter.

Figure 10. Ungrounded components in a synchronous buck converter



Traditionally, the most common methods to measure floating voltages are:

1. Using two single-ended voltage probes and making the mathematical difference by the oscilloscope;
2. Using high-performing differential probe.

The first method is a pseudo-differential measurement strategy and consists in two different single-ended measurements by two ground-referenced passive voltage probes, which are connected at the two test points of interest. Their ground clips are referred to the same point. Then, using the oscilloscope, it is possible to create a mathematical difference between the measured signals. Referring to the Figure 1. Step-down DC-DC converter, high side gate-source voltage will be given by:

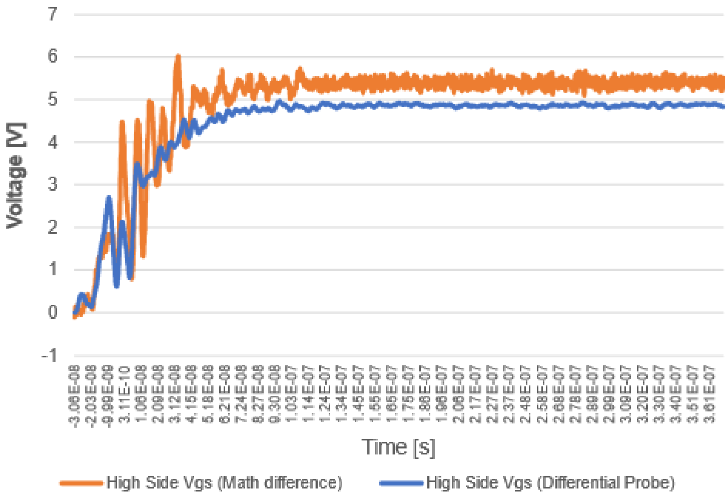
$V_{gs,high\text{-}side} = V_{g,GND} – V_{s,GND}$

Where $V_{g,GND}$ and $V_{s,GND}$ are referenced-ground gate voltage and source voltage measurements respectively. If, for example, Ch1 is $V_{g,GND}$ and Ch2 is $V_{s,GND}$, the oscilloscope returns as Ch1-Ch2 the desired measurement. This approach is sometimes used when proper differential test equipment is not available; moreover, it can be adequate for some low frequency signals. However, there are several constraints with this technique. First, both probes and oscilloscope must be well matched (gain, offset, delay and frequency response): in fact, any mismatch can be seriously affect the measurement reducing its accuracy. Then, a common mode rejection ratio is very poor when the switching frequency increases. Finally, if the two signals are not properly scaled, the oscilloscope may be overdriven getting wrong measurements.

The next method for measuring differential voltages uses differential probes. This approach returns best measurement accuracy, even if the right probe must be well matched with application features and measurement tasks. A differential probe is an active device, with a differential amplifier in the probe tips measuring only the voltage across the two testing points. Differential probes offer low capacitance inputs, so any point in the circuit under test can be measured with minimum loading.

Next figure shows high side gate-source voltage captured with math difference of passive probes and with differential probe. Differential approach gives back more accurate measurement.

Figure 11. **High side gate-source voltage waveform**



As told before, the right probe must have adequate specifications for an accurate measurement; these features must be strictly related to application requirements. For differential probing, three technical features are fundamental for a good probe selection:

1. **Bandwidth**: the fastest transient in the application fixes bandwidth needs. In fact, spikes, glitches and other noise that must be investigated will require higher bandwidth. Fast rise times ("ns" range), typically measured with GaN devices, need probes with large bandwidth (hundreds of MHz) and very short rise time (< 5 ns).
2. **Input impedance**: The key parameters are input resistance and capacitance, that determine the circuit loading in the whole frequency range. A high input resistance (MΩ range) and a low input capacitance (few pF) will minimize circuit loading improving measurement accuracy.
3. **Common mode rejection ratio (CMRR)**: This parameter identifies the probe's ability to reject any common-mode signal. High CMRR means reduced impact of a common-mode signal on the differential measurement.

Typically, high-voltage differential probes can offer bandwidth in (100–500 MHz) range, with low input impedance. Their CMRR is good (even higher than 80 dB) at DC and low frequency, while it falls at high frequencies. Considering new applications and the development of wide-bandgap semiconductors, the measurement requirements become more and more challenging. Gallium nitride (GaN) technology may offer smaller die size with an extremely low figure-of-merit (FOM, $R_{DS(on)} \cdot Q_g$): for this reason, it is the best choice in high frequency systems and it is increasing its importance and diffusion in power conversion applications. At the same time, these advanced performances require adequate equipment and probing system. In high voltage and high frequency systems, extremely good CMRR at high frequency is mandatory, especially for floating voltage measurements. In these cases, isolated measurement solutions are available in the market today: they provide high CMRR for accurate signal representation together with galvanic isolation between the probe tip and the oscilloscope for better safety against dangerous high-voltage levels. The main technical specification of high-voltage differential probes and isolated measurement systems are summarized in the following table.

Table 2. **HV differential probe vs. isolated measurement solutions**

Parameter	High-voltage differential probe	Isolated solutions
Bandwidth	From 100 MHz to 500 MHz	Up to 1 GHz
Isolation	No	Galvanic/Optical
CMRR (Low Freq.)	≈ 85 dB	≈ 150 dB
CMRR (high Freq.)	From 30 dB to 50 dB	≈ 100 dB
Rise time	< 2 ns	< 1 ns

3 PowerGaN current measurement

Switching current is a fundamental parameter for a complete electrical characterization of the Power GaN. Gallium nitride devices are suitable for high efficiency and high-power density applications, showing extremely fast switching transients due to low intrinsic capacitances and low parasitic inductances. Very short rise and fall times (few ns), that are typical for GaN devices, entail large bandwidth for test equipment, as reported below:

$$BW = \frac{0.35}{t_{rise/fall}}$$

Moreover, GaN transistors are very sensitive to parasitic inductance due to their switching speed; consequently, device current waveform is particularly difficult to measure without introducing spurious noise on the circuit under test. Normally, for traditional silicon technologies, device current is measured by adding an external loop and inserting current measurement equipment (i.e., current probe) into the circuit [4]. This technique increases the parasitic inductance, and it cannot be used for faster Power GaN devices; hence, for these transistors, current measurement become more and more challenging.

There are three common methods to measure the transistor current: coaxial current shunt, Rogowski coil and active current transformer. Here following, all these methods are reviewed highlighting their advantages and limitations.

3.1 Coaxial current shunt

Coaxial current shunts (or current viewing resistors, see next figure) are suitable for high frequency measurements, thanks to the minimization of skin effect [5]. They are designed to sustain large current and power peak generated in the circuit under test. The most of coaxial current shunts are suitable for surge currents but it is possible to use them for steady-state measurements: in this case, the average wattage rating has not to be exceeded [6]. Moreover, they have high performance also in accuracy and rise time, while the bandwidth can reach even GHz range.

Figure 12. **Coaxial current shunt**

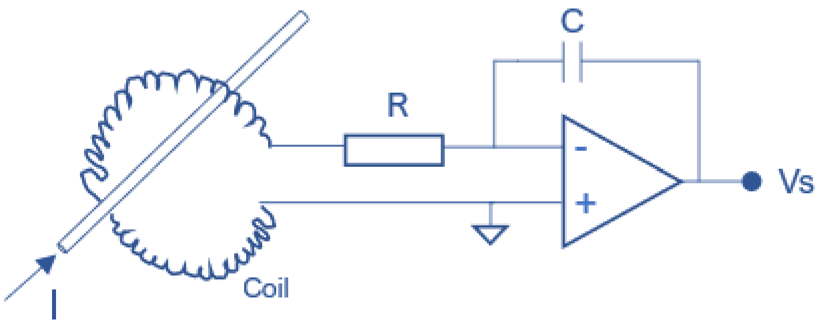
The two main drawbacks are large size and the additional parasitic inductance introduced in the circuit (several nH).

3.2 Rogowski coil

A Rogowski coil is an electrical transducer for measuring AC currents, such as pulsed or sinusoidal currents. It is formed by an air-cored coil and an integrator (see next figure).

The coil is placed around the current-carrying conductor: the induced voltage is proportional to the rate of change of the current flowing in the conductor. Then, the integrator provides an output voltage that is proportional to the input current.

Figure 13. **Schematic diagram of a Rogowski coil**



Rogowski coils can measure large currents (from mA to kA) without saturation effects due to non-magnetic air core. It is also a flexible solution, because of it can be inserted between the pins of through-hole packages without adding external loops. Compared with other equipment, Rogowski coil has lower cost.

The major limitation is that Rogowski coil can measured only AC currents, so it is not suitable for DC measurements. Moreover, this kind of equipment will lead to large coil inductance limiting its bandwidth.

3.3 Current transformer

Current transformers (next figure) are widely used in power converters for detection, protection and current sensing. They can measure very large (kA range) currents, by selecting the right shape and size of this device [7].

Figure 14. **Current transformers**

The bigger advantage is the isolated output; furthermore, through SMA output connector, they can be connected to oscilloscopes and other measuring instruments. Recently, very compact surface-mount current transformers are available in the market, but they have limited current capability.

Large size (for high current transformer) and reduced bandwidth are the main drawbacks of this solution, together with the additional parasitic inductance introduced in the circuit under test.

Here below, there is a brief summary of this section.

Table 3. Comparison of common methods to measure PowerGaN transistor current

Type of equipment	Advantages	Limitations	Suitable for
Coaxial current shunts	• Accuracy • Rise time • Bandwidth	• Size • Steady-state behavior • Parasitic inductance	• Surge currents • Switching losses
Rogowski coil	• Flexibility • Large current range • Cost	• Bandwidth • AC only	• High current measurements
Current transformer	• Isolation	• Size (for high currents) • Bandwidth • Parasitic inductance	• Low bandwidth applications

4 References

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[5] “A study on shunt resistor based current measurements for fast switching GaN devices”, T. Wickramansinghe, B. Allard, C. Buttay, C. Joubert, C. Martin, J. Moignoitte, H. Morel, P. Bevilacqua, T. Le, S. Azzopardi, IEEE 2019

[6] T&M Research Products, Inc. Web Site (http://www.tandmresearch.com/#)

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Revision history

Table 4. **Document revision history**

Date	Revision	Changes
11-Feb-2022	1	First release.

Contents

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