How to measure the world's fastest GaN power switches

Gallium Nitride (GaN) FETS are poised to replace silicon power devices in voltage regulators and DC-DC power supplies. Their switching speeds are significantly faster and their RDS(on) is lower than silicon MOSFETS. That can lead to higher power efficiency power sources, which is good for all of us. If you're designing power circuits with GaN devices, you need a grasp of the device's switching speed. To measure that, you're oscilloscope, probes, and interconnects must be fast enough to minimize their effect on the measurements.

One of the most frequent questions I receive on the subject of device performance is "how fast are they, really?" My general response is that they are blazingly fast but that we just don't know quantitatively how fast. To find out, I made some measurements using a 33-GHz real-time oscilloscope and a high-speed transmission-line probe. I'll discuss the design limitations that mask the device's speed, and what's in store for the future. With these measurements, I believe we'll be designing power supplies switching at 250 MHz before long.

Figure 1 shows two evaluation boards used to perform the measurements. Both boards include a gate-voltage regulator, driver, pulse conditioner, and two eGaN switches. The board on the right is a complete DC-DC converter, which includes a Gen4 monolithic half-bridge (both switched on one die) and includes an L-C output filter. The board on the left uses individual Gen3 eGaN devices in a half-bridge configuration, lacking the L-C output filter. In both cases, an external pulse generator provides a PWM (pulse-width modulated) signal through a BNC connector soldered to the test board's PWM input. The switch rise time is measured on each board at input voltages of 5 V and 12 V.

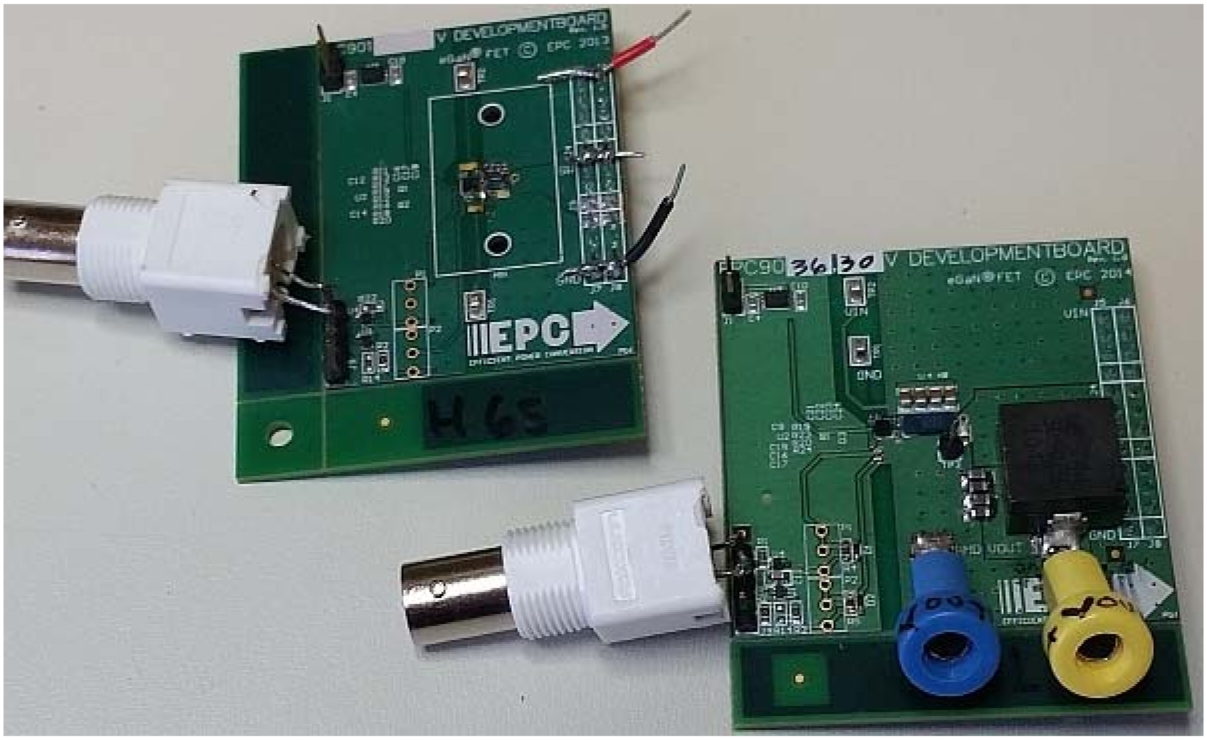


Figure 1. The test boards are shown with the half bridge configuration only on the left and the complete DC/DC converter on the right. The banana sockets allow connection of the board to an electronic load. BNC connectors provide access to an external pulse generator.

Instrument and probe requirements

To ensure that the instrument and probe don't significantly impact the measurement, we can assume that the rise times of the probe, oscilloscope, and the half-bridge can be added using root sum squares. This isn’t always true, but for our initial estimates we'll assume this relationship holds.
The measured rise time of the half-bridge including the rise time of the oscilloscope and the rise time of the probe is:

$$t_{measured} = \sqrt{t_{scope}^2 + t_{probe}^2 + t_{half-bridge}^2}$$

The actual rise time of the half-bridge is determined as follows:

$$t_{half-bridge} = \sqrt{t_{scope}^2 + t_{probe}^2 - t_{measured}^2}$$

To restrict the measurement error to some percentage, K, the rise time of the instrumentation can be related to the actual rise time:

$$\sqrt{t_{scope}^2 + t_{probe}^2 + t_{half-bridge}^2} = (1 + K) \cdot t_{half-bridge}$$

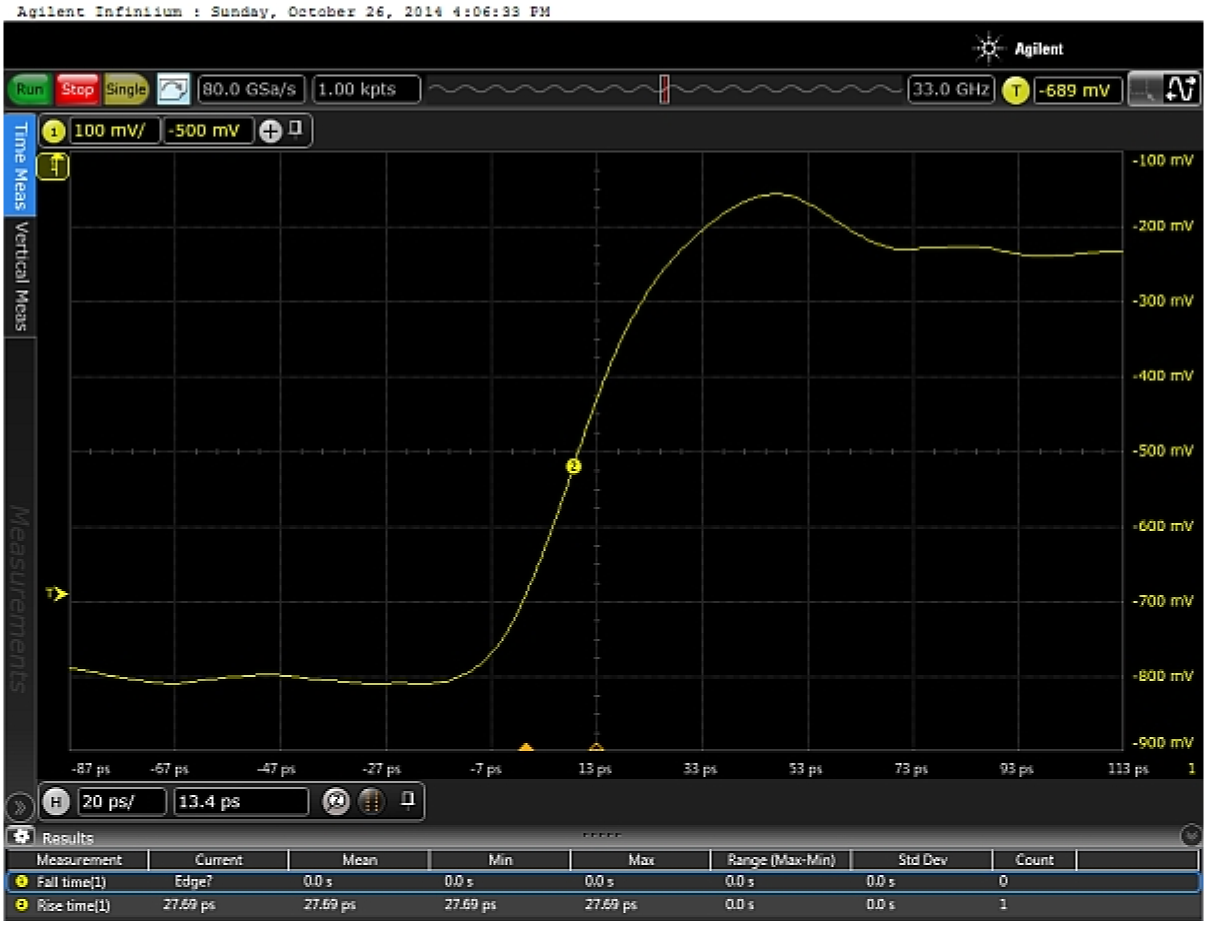
Solving for K, the ratio of the instrument rise time to the actual half-bridge rise time is:

$$Ratio(K) = \sqrt{K} \bullet \sqrt{K+2}$$

So for the two examples, if we wish the measured result to be less than 5% or less than 10%, then the rise time of the oscilloscope and the probe needs to be less than 32% or 46% of the FET rise time, respectively. Stating it differently, the instrumentation should be 3.1 or 2.2 times faster than the FET rise time, respectively.

Measuring Switching Performance

The oscilloscope used here is a Keysight 90000-X Series 33 GHz oscilloscope with a Teledyne LeCroy PP066 transmission line probe. The connection between the oscilloscope and the probe is made through a 50 GHz Huber+Suhner Sucoflex-100 cable. The rise time of this setup is recorded using a 20 ps fast edge pulse and the result is shown in Figure 2. The oscilloscope and probe used for these measurements represent "overkill" because they're much faster than the minimums noted above in order to assure that the measurement is valid.



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Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
Fall time(1)	Edge?	0.0 s	0.0 s	0.0 s	0.0 s	0.0 s	0
Rise time(1)	27.69 ps	27.69 ps	27.69 ps	27.69 ps	0.0 s	0.0 s	1

Figure 2. An edge pulse rise time of approximately 20 ps is measured using a 33 GHz Keysight Infiniium 90000-X oscilloscope with a Huber Suhner Sucoflex 100 50 GHz cable and a Teledyne

Lecroy PP066 transmission line probe. The measured result shows that the test setup has a rise time that is faster than 27.69 ps, which includes the 20ps pulse rise time.

The resulting 27.69 ps includes the 20 ps pulse rise time, which can be subtracted using root-sum squares to determine the rise time of the oscilloscope, probe head, and cable. Without subtracting out the pulse edge, we can be 100% certain that the instrumentation rise time is faster than 27.69 ps, so we'll use that to be conservative.

In accordance with the previous calculations and using the conservative 27.69 ps instrumentation rise time, we can measure a half-bridge rise time within K%.

$$t_{half-bridge} = \frac{27.69\ ps}{\sqrt{K}\sqrt{K+2}}$$

The measurement setup can measure 276 ps with 0.5% accuracy and 619 ps with 0.1% accuracy. The complete instrument setup is shown in Figure 3.

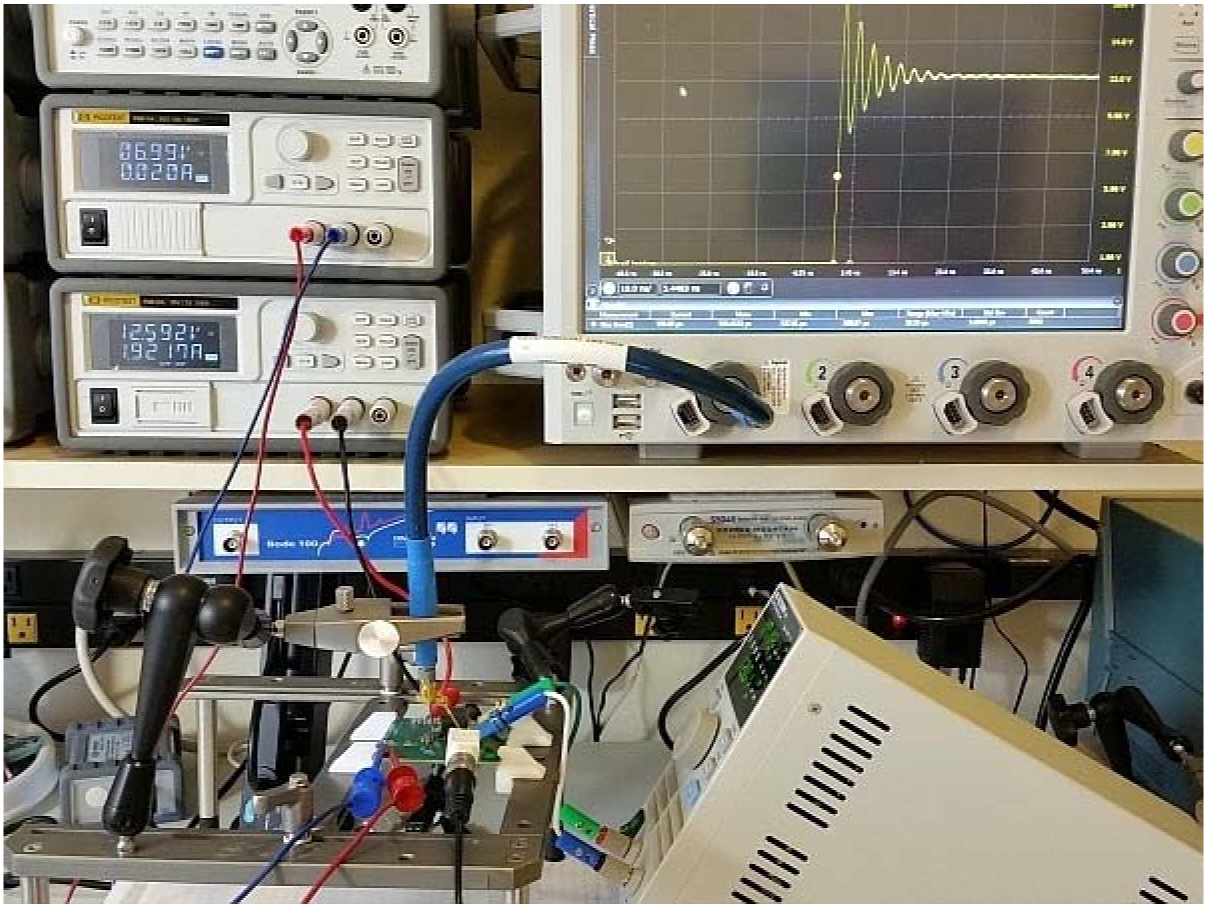

Figure 3. The complete instrument setup is shown for the DC/DC converter. The input voltage is regulated at 12V at the test board input and 7V is provided to the gate drive regulator. The load is

seen on the lower right and the Keysight 90000-X oscilloscope, Teledyne Lecroy PP066 transmission line probe and Huber Suhner Sucoflex 100 cable can all be seen in this image.

Measured performance

The rise time results in Figure 4 are for the DC/DC converter operating at approximately 1 V output and a 20.0 A load current. The measurements are performed at both 5 V and 12 V input at the test board.

Figure 4. The rise time measurements for both 12 V input and 5 V input, at the test board, are 682.33 ps and 561.13 ps, respectively. The DC/DC converter is operating at 20.0 A load.

The rise time results are shown in Figure 5. For the half bridge alone, also with 5 V and 12 V input at the test board.

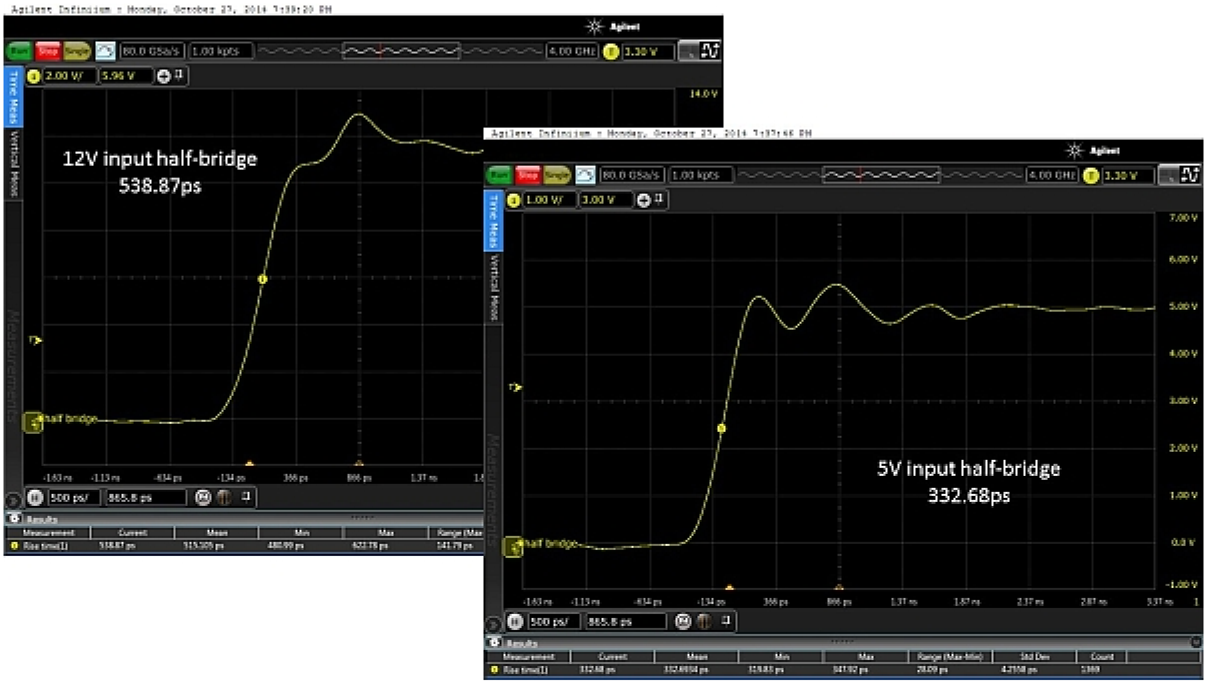

Figure 5 The rise time measurements for both 12 V input and 5 V input, at the test board, are 538.87 ps and 332.68 ps respectively. This is just the half bridge so there is no loading.

All four measurements are within the 0.5% accuracy range as calculated previously, based on the 27.69 ps rise time of the probe and oscilloscope and the fastest rise time measurement of 332.68ps. The results are summarized in Table 1.

	DC/DC Converter	Half-Bridge Only
5V input	561.13ps	332.68ps
12V input	682.33ps	538.87ps

Table 1. Summary of test results.

These measured rise times are roughly three times faster than an equivalent silicon MOSFET and with roughly one third the RDS(on). The end result is typically 3% higher efficiency and reduced thermal load.

Design Limitations

With these measurements in hand, you can see that these devices are blazing fast, but we still don't know how fast they can be and may never know. How can that be, given that we just measured these speeds?

There are several key limitations that we can't assess, at least not right now. One is that the ringing, evident in all of the rise-time measurements, is due to a resonance between the power-loop inductance and the lower GaN transistor capacitance. The capacitance is fixed, while the inductance is at least partly, if not significantly, due to the ESL (equivalent series inductance) of the input capacitors and the interconnecting PCB planes.

The driver has connections through PCB traces and the driver itself has an edge speed of approximately 1 ns, significantly slower than the GaN FET switching speed. As the GaN technology progresses towards its material limit (still orders of magnitude away), and better drivers, reduced parasitics, and increased integration become a reality, the speed/performance will continue to improve. At the same time, the GaN FET output capacitance will continue to reduce, further increasing the potential switching speed.

What this all means

Allowing the switching speed to be 1%-2% of the switching period for hard switch applications, you can see that switching speeds can approach 50 MHz. Currently, the limitation is the parasitic elements of the gate driver, which cannot operate at these speeds. Using resonant switching topologies, my crystal ball says we will conceivably have DC/DC converters switching at 250 MHz or more. Silicon devices will also continue to improve, though the fundamental material limits will not be able to match the performance of GaN devices.