Whitepaper

Power GaN technology: the need for efficient power conversion

Dr Dilder Chowdhury - Device Architect GaN

One of the key challenges for industry is to reduce power losses. Facing growing pressure from society and increasing government legislation for reduced CO2 emissions, many industries are investing in more efficient power conversion and increased electrification. These include automotive electrification, telecom infrastructure, server storage, and industrial automation, where there is significant growth in the use of power electronics. That in turn is leading to increased demand for efficient, innovative, high-power FETs based on GaN technology.

Within the semiconductor industry, the biggest motivation and driver for power device innovation is improved efficiency in power conversion. Amongst the various technologies, gallium nitride (GaN) technology shows the greatest performance benefits, when compared to silicon (Si) and silicon carbide (SiC) solutions. Specifically, GaN field-effect transistors (FETs) deliver the best efficiency with low system costs while making systems lighter, smaller, and cooler.

Since power GaN transistors and specifically GaN-on-Si devices were introduced to the market, significant improvements in performance, reliability, cost, and availability have taken place. More capable GaN power transistors are becoming available to drive higher power. Compatible with electric vehicle (EV) requirements they are also well positioned for applications in data centers, telecom infrastructures, and industrial applications.

Automotive electrification leads the drive on efficiency

Electrification in the automotive sector is likely to be the biggest beneficiary of the new power GaN FET technology. To make all-electric vehicles (xEVs) efficient power conversion is key as any power loss in xEVs can impact range, one of the primary concerns surrounding electric vehicles. Those losses also mean cooling systems are needed to dissipate the heat generated, adding to a vehicle's system complexity and crucially weight.

While the automotive industry is working to address many issues including battery weight and power density, there is a drive for significant improvement in the following areas:

- Improved and more efficient power conversion
  - AC/DC onboard charging
  - DC/DC power conversion
  - DC/AC inverters to drive the traction motors
  - improved power density
  - simpler drivers and control scheme
- Improved traction motors
  - improved efficiency
  - better torque and power
  - lower losses
  - higher dv/dt handling capability
- Improved batteries, storage, and battery-management system

More efficient power conversion can help significantly in many ways. For example, improving the efficiency of a 200 kW inverter from 95% efficiency to 99% efficiency reduces power loss in a full load from 10 kW to 2 kW, or about one-fifth. Not only is the loss 8 kW lower (which can be effective for useful traction power), but the reduced need for cooling can also help by reducing the cooling energy consumption and on the size and weight of the cooling system. This in turn, can lead to a longer operating range or the same range with a smaller battery.

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EFFICIENCY WINS.

The above demonstrates the importance of achieving extremely high efficiencies. Power GaN FETs based on GaN-on-Si epitaxy (epi) help significantly in this area by offering higher efficiency, but also by offering the scalability to support xEV growth ambitions. The simple Si fabrication (fab) process steps also allow the best cost roadmap for commercial viability. Power GaN technology currently supports 400 V battery systems with 650 V devices and can serve battery systems up to 800 V with 1200 V power GaN devices. The power range for both can be up to 300 kW.

High voltage silicon transistors reaching their limits

High-voltage (HV) power semiconductor switches are the fundamental building blocks of any power conversion. In the absence of better alternatives, Si-based insulated-gate bipolar transistors (IGBTs) currently dominate the traction inverter market, even with significant technology maturity. Incrementally higher efficiencies have been achieved through improvements to Si IGBTs, and by combining them with SiC diodes, but the possibility for further improvement is limited. Si IGBTs are also fundamentally limited in operating frequency, speed, and have poor high-temperature performance and low-current characteristics.

At higher frequencies, Si super junction (SJ) technology dominates the market for AC/DC power factor corrector (PFC) and DC/DC power conversion. But inherent material limitations, including switching crossover, conduction, and reverse recovery losses, limit the ability to achieve higher efficiencies for high-frequency operation.

Power GaN steps up as replacement

In contrast, wide bandgap (WBG) materials, like GaN and SiC, are free from reverse recovery loss and can offer very low switching cross-over losses (due to very fast turn on and off characteristics) and lower conduction losses. WBG materials with a higher critical electric field and higher mobility together give the lowest source drain on-state resistance $RDS_{(on)}$ for higher voltages and a significantly better switching figure of merit. The WBG devices beginning to enter the market show significant promise and remove many of the limitations naturally imposed by Si IGBT and Si SJ devices.

Some of the difficult switched-application topologies where Si SJ FETs cannot be used due to diode reverse recovery can easily use power GaN FETs and take full advantage of the reduced component counts and higher efficiency with simpler control schemes. The faster switching speeds and higher frequencies of operation enabled by GaN power transistors help improve signal control, higher cut-off frequencies for passive filter designs, and lower ripple currents, allowing for smaller inductors, capacitors, and transformers. Consequently, the compact and smaller system solution offers cost savings.

Figure 1 shows the cross-section for a GaN high electron mobility transistor (HEMT), which works with the formation of the 2D electron gas (2DEG) due to the spontaneous and piezoelectric polarization combined at the interface of GaN and aluminium gallium nitride (AlGaN) layers. Epi is formed on the Si substrate via the seed layer. Then a graded layer of GaN and AlGaN layers are added before the pure GaN layer grows. Finally, a thin layer of AlGaN forms the 2DEG. Electron mobility in this layer is very high, hence the name.

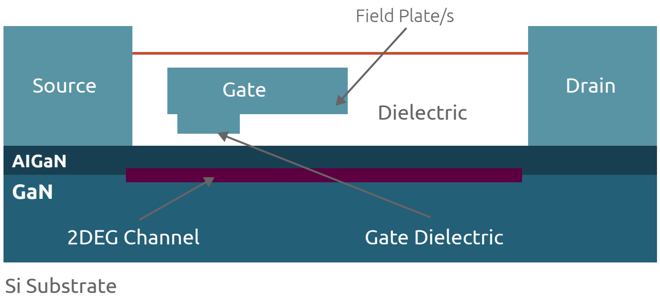

Figure 1 GaN HEMT structure

Cascode simplicity and robustness

There are two main options for current power GaN FETs: enhancement mode (E-mode) or single-die normally off devices and depletion mode (D-mode) or two-die normally off devices. While there are concerns on the stability and leakage currents of the E-mode gates, driving the two-die normally off or cascode configuration D-mode devices currently is simple and robust. Therefore, for operations up to 1 MHz switching frequency, cascode GaN FETs are best suited.

The GaN-on-Si two-die normally off configuration allows significant design flexibility. Nexperia GaN FETs offer a ± 20 V gate rating with an oxide / insulator gate, 4 V gate threshold voltage with 0 V real turn off, and low gate charge. Hence, simple Si drivers are suitable for use with these devices and for 0–8, 10, or 12 V, any gate drive can be used. In contrast, SiC technology generally requires at least 15 V, and a very-high-current driver with a negative gate drive capability to turn off the device adds costs for the driver as well as increased driver and switching losses. Nexperia GaN devices also feature an exceptionally good, built-in, antiparallel diode that helps with the robust freewheeling conduction path. The cascode version offers significant freedom to make the gate structure design and have the same robustness expected by automotive customers.

Figure 2 shows how combining a low-voltage (30 V) robust Si MOSFET with the cascode configuration D-mode GaN FET can eliminate all of the major concerns regarding the poor gate structures of the E-mode devices and make the entire usage very simple. Low-voltage Si-based gate structures are a very mature technology which engineers are accustomed to using.

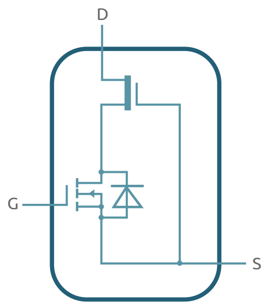

Figure 2 Cascode schematic

The reverse recover charge (Q_{rr}) for low-voltage Si is very low (see *Figure* 3) and allows the full potential of the power GaN technology. In addition, driving a cascode device is simple. Cascode device operation is shown for different bias situations in *Figure* 4. Power GaN FETs can be used in a bidirectional form to allow simpler bidirectional power conversion.

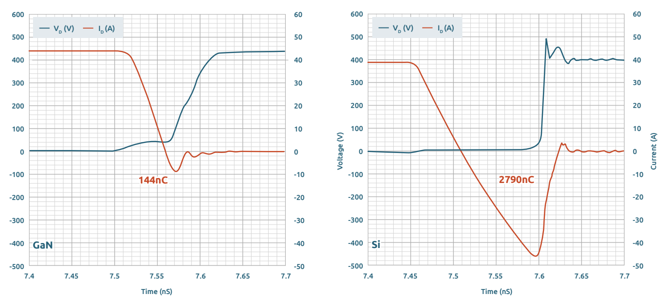

Figure 3 Qrr, Reverse recovery charges for GaN FET vs Si FET

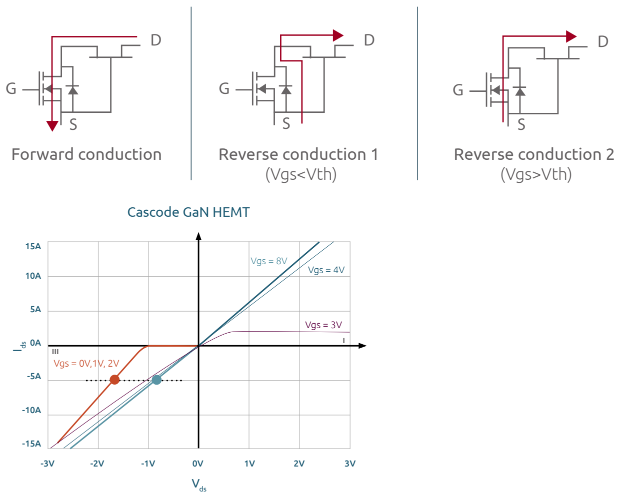

Figure 4 GaN FET operation

Application and performance

Whether it is the AC/DC PFC stage, a DC/DC converter (*Figure* 5), or traction inverter (*Figure* 6), the basic building block for most topologies is a half-bridge (*Figure* 7).
So when GaN FETs are compared against Si FETs in a simple boost converter, the GaN FET shows its superior performance.

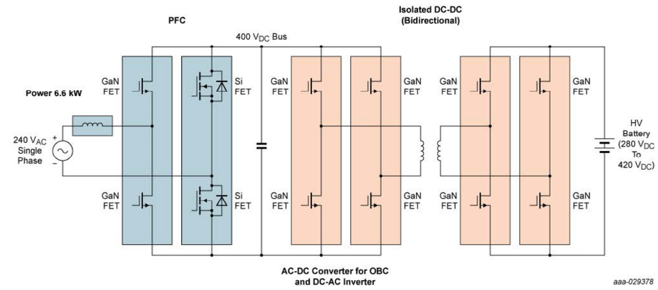

Figure 5 AC-DC PFC stage and isolated DC-DC configuration

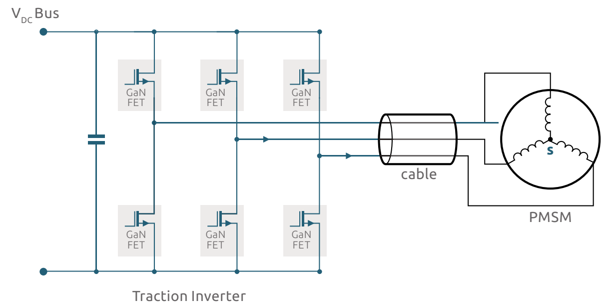

Figure 6 Traction Inverter

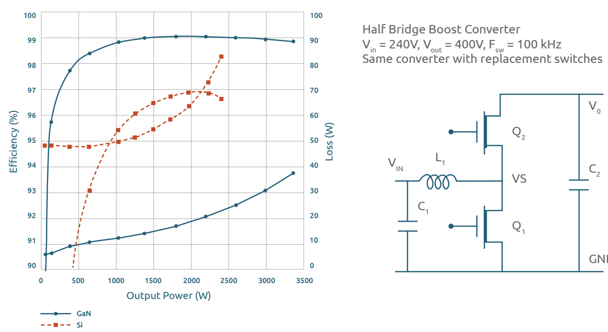

Figure 7 Half bridge boost converter (GaN switch vs Si CoolMOS

GaN FET losses are significantly lower due to the absence of reverse recovery losses and switching crossover losses. It is possible to achieve nearly ideal turn on and off losses with dV/dt of approximately 200 V/ns. GaN switches are extremely fast and routinely used in the radio-frequency amplifiers at gigahertz frequencies. While at those frequencies they operate at much lower voltages, it does show their ability as both use the GaN HEMT structure.

Since the GaN devices are very fast and can be used in applications with high dV/dt and high dI/dt, care must be taken to optimize the PCB layouts. To minimize parasitic inductances, layout optimization is pretty much fundamental to power GaN use.

To maximize the performance of surface-mount packages and low inductance, high-current, high-performance modules are essential.

Currently, using GaN devices in a traction inverter means slowing it down significantly to save the motor windings. They are nearly limited to a dV/dt of 10 V/ns, which holds significant potential to improve the motors and take the frequency up to 40 kHz to improve the power density significantly.

Quality and reliability

Power GaN FET technology currently shows good quality and reliability as multiple vendors have demonstrated Joint Electron Device Engineering Council (JEDEC) and Automotive Electronics Council (AEC) Q101 quality standards. These are the minimum standards that must be fulfilled to demonstrate the reliability of power GaN technology.

However, for GaN devices, existing quality standards are not sufficient as the material is new and operates differently. For example, dynamic $RDS_{(on)}$ or current collapse phenomena is well known for power GaN FETs. Material quality, trapping, and appropriate detrapping that is responsible for the dynamic Rds(on) can be measured and given high-level confidence for its usage as the values are getting better and are now around 10%.

Going even further beyond AEC Q101, qualifications for validating the reliability of GaN FETs under actual operating conditions, several identical half-bridge circuits (with continuous current conduction mode) were prepared using one high-side and one low-side GAN063-650WSA. These were operated continuously for 1,000 hours as synchronous-boost converters with the following conditions: Vin = 200 V, Vout = 48 V, Pout = 80 W, Tj = 175 °C, and frequency = 300 KHz. There was no indication of any degradation in the performance of any circuits for all samples for the entire 1,000 hr duration of the test. Following high temperature switching tests, all devices were tested for shifts in dynamic Rds(on), leakage current and threshold voltage. All parameters were found to be stable, with any parametric shifts below the allowed levels.

The device specification has 800 V transient voltage capability guaranteed by test to eliminate any concerns for over voltage spikes. Similarly, other overstresses like voltage and temperatures were used and different acceleration factors defined for the end-of-life and Failure in Time (FIT) rates estimated for the application situations. As the volume of products shipped increases, real field failure rates will be determined.

Ready for market

Power GaN technology is ready to take its place in the market for efficient power conversion. We are already beginning to see its adoption in non-automotive segments, and it will soon be used in automotive applications which can take advantage of lower losses and higher power densities. While Si technology is well established in the market, it is reaching its limits. As its benefits become clear and the volume of installed devices grows, Power GaN technology will become the norm for high efficiency power conversion.

To find out more visit www.nexperia.com/gan-fets

About Nexperia

Nexperia is a leading expert in the high-volume production of essential semiconductors that are required by every electronic design in the world. The company's portfolio includes diodes, bipolar transistors, ESD protection devices, MOSFETs, GaN FETs and analog & logic ICs. Headquartered in Nijmegen, the Netherlands, Nexperia annually ships more than 90 billion products, meeting automotive standards. These products are recognized as benchmarks in efficiency – in process, size, power and performance — with industry-leading small packages that save valuable energy and space. Nexperia has over 12,000 employees across Asia, Europe and the US.

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