GaN Transistors for Efficient Power Conversion

For over three decades, power management efficiency and cost showed steady improvement as innovations in power MOSFET structures, technology, and circuit topologies paced the growing need for electrical power in our daily lives. In the new millennium, however, the rate of improvement slowed as the silicon power MOSFET asymptotically approached its theoretical bounds.

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Power MOSFETs first started appearing in 1976 as alternatives to bipolar transistors. These majority carrier devices were faster, more rugged, and had higher current gain than their minority-carrier counterparts. As a result, switching power conversion became a commercial reality. AC/DC switching power supplies for early desktop computers were among the earliest volume consumers of power MOSFETs, followed by variable speed motor drives, fluorescent lights, DC/DC converters, and thousands of other applications that populate our daily lives.

Many generations of power MOSFETs have been developed by several manufacturers over the years. Benchmarks were set, and fell, every year or so for 30 plus years. There are still improvements to be made. For example, Superjunction devices and IGBTs have achieved conductivity improvements beyond the theoretical limits of a simple vertical majority carrier MOSFET. These innovations may still continue for quite some time and will certainly be able to leverage the low cost structure of the power MOSFET and the well-educated base of designers who, after many years, have learned to squeeze every ounce of performance out of their power conversions circuits and systems.

The GaN journey begins

HEMT (High Electron Mobility Transistor) Gallium Nitride (GaN) transistors on Silicon Carbide (SiC) substrates first started appearing in about 2004 with depletion-mode RF transistors made by Eudyna Corporation in Japan. GaN RF transistors have continued to make inroads in such applications as several other companies have entered in the market. Acceptance outside this market, however, has been limited by device cost as well as the inconvenience of depletion mode operation.

Properties*	GaN	Si	SiC
E_G (eV)	3.4	1.12	3.2
E_{BR} (MV/cm)	3.3	0.3	3.5
V_S (x 10^7 cm/s)	2.5	1.0	2.0
μ (cm^2/Vs)	990 - 2000	1500	650

Table 1: Material properties of GaN, SiC, and Silicon at 300 K

In June 2009 Efficient Power Conversion Corporation (EPC) introduced the first enhancement-mode GaN on silicon (eGaN®) FETs designed specifically as power MOSFET replacements to be produced on standard Silicon manufacturing technology and facilities.

Table 1 shows four key electrical properties of three semiconductor materials (GaN, Si, SiC) contending for the power management market. One way of translating these basic crystal parameters into a comparison of device performance in a power transistor is to calculate the best theoretical performance that could be achieved in each of the three candidates.

For power devices there are many characteristics that matter in the variety of power conversion systems available today. Five of the most important are conduction efficiency, breakdown voltage, switching efficiency, size and cost.

Using the data from table 1 (and adjusting for the enhanced mobility of the GaN 2D Electron Gas), we can calculate the theoretical minimum device on-resistance (the inverse of conductivity) as a function of breakdown voltage and as a function of material.

As shown in Figure 1, SiC and GaN both

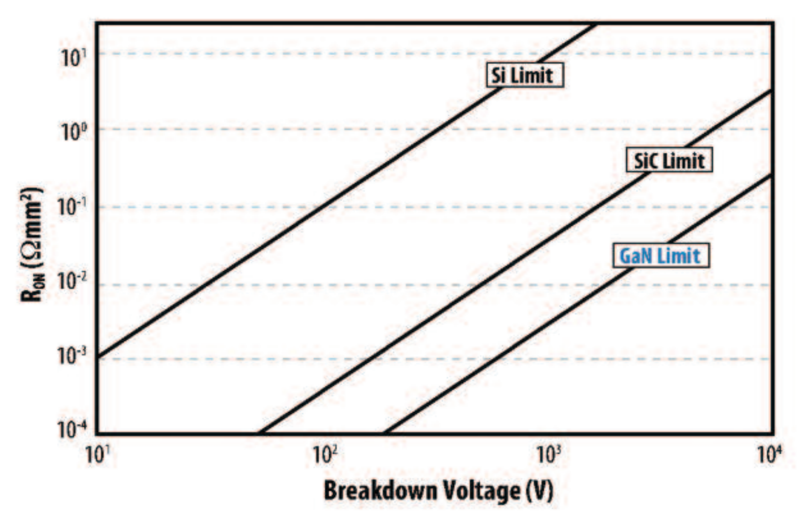

Figure 1: Theoretical on-resistance vs blocking voltage capability for Silicon, Silicon Carbide, and Gallium Nitride

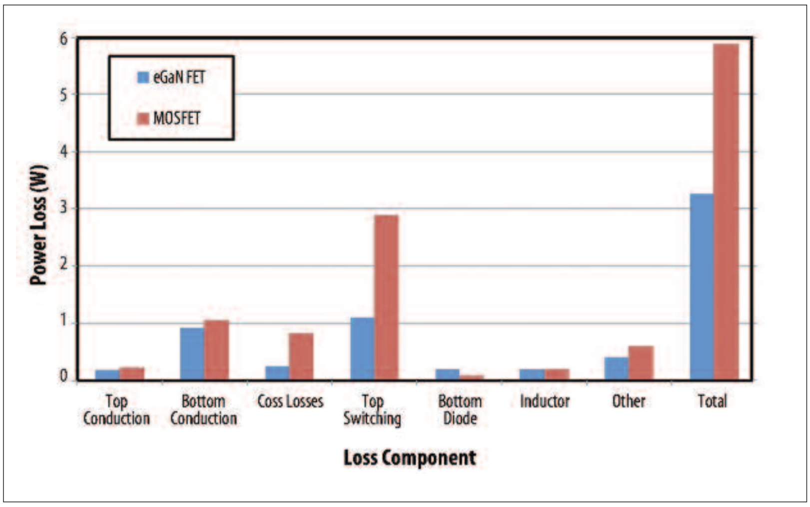

Figure 2: Comparison of switching losses of eGaN FETs vs Silicon MOSFETs in a 12 V/1.2 V Buck Converter operating at 1 MHz. For each socket both devices have similar on-resistance

have a superior relationship between on-resistance and breakdown voltage due to their higher critical electric field strength. This allows devices to be smaller and the electrical terminals closer together for a given breakdown voltage requirement. GaN has an extra advantage compared with SiC as a result of the enhanced mobility of electrons in the 2DEG. This translates into a GaN device with a smaller size for a given on-resistance and breakdown voltage.

In Figure 2 is a comparison between Silicon MOSFET and eGaN FET power losses for a common Buck Converter circuit. The on-resistances of the transistors are equal, so the difference in total power losses can be attributed to the superior switching capability of the eGaN FETs. The eGaN device's lateral structure also lends itself to flip-chip packaging, which is a very high performance packaging solution due to the minimal increase in on-resistance and terminal inductance. Add to this a distinct die area advantage over Silicon and the resultant solution is a superior power device in a high performance package that is significantly smaller than anything available today.

EPC's normally-off eGaN FETs (Figure 3) stem from a relatively new technology and, as such, remain somewhat more expensive to produce than their Silicon counterparts. This, however, is a temporary situation. There are no insurmountable barriers to achieving an even lower cost for an equivalent performance eGaN FET compared with a power MOSFET or IGBT.

Enhancement mode FET structure

EPC's enhancement mode process begins with Silicon wafers. A thin layer of Aluminum Nitride (AlN) is grown on the Silicon to provide a seed layer for the subsequent growth of a Gallium Nitride heterostructure. A heterostructure of Aluminum Gallium Nitride (AlGaN) and then GaN is grown on the AlN. This layer provides a foundation on which to build the eGaN FET. A very thin AlGaN layer is then grown on top of the highly resistive GaN. It is this thin layer that creates

a strained interface between the GaN and AlGaN crystals layers. This interface, combined with the intrinsic piezoelectric nature of GaN, creates a two dimensional electron gas (2DEG) which is filled with highly mobile and abundant electrons.

Further processing of a gate electrode forms a depletion region under the gate. To enhance the FET, a positive voltage is applied to the gate in the same manner as turning on an n-channel, enhancement mode power MOSFET. A cross section of this structure is depicted in Figure 3. Additional layers of metal are added to route the electrons to gate, drain, and source terminals. This structure is repeated many times to form a power device as shown in Figure 4. Conveniently, eGaN FETs behave similarly to Silicon MOSFETs with some exceptions that will be explained below.

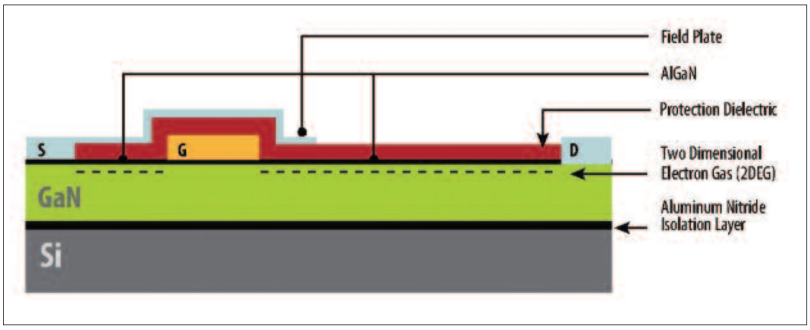

Figure 3: eGaN® FET structure

$R_{DS(ON)}$ versus V_{GS} curves are similar to MOSFETs. EPC first generation GaN transistors are designed to operate with 4 - 5 V gate drive. The temperature coefficient of $R_{DS(ON)}$ of the eGaN FET is also similar to the Silicon MOSFET as it is positive, but the magnitude is sligthly less. The 125°C point is 1.6 times the 25°C point for the EPC1001 compared to 1.7 for Silicon.

The threshold of Gallium Nitride transistors is lower than that of Silicon MOSFETs. This is made possible by the almost flat relationship between threshold and temperature along with the very low C_{GD}. Since the device starts to conduct significant current at 1.6 V, care must be taken to ensure a low impedance path from gate to source when the device needs to be held off during dv/dt in a rectifier function.

In addition to the low $R_{DS(ON)}$, the lateral structure of the eGaN FET makes it a very low charge device as well. It has the capability of switching hundreds of volts in nanoseconds, giving it multiple megahertz capability. This capability will lead to smaller power converters, and higher fidelity class D audio amplifiers. Most important in switching is C_{GD}. With the lateral structure, C_{GD} comes only from a small corner of the gate. An extremely low C_{GD} leads to the very rapid voltage switching capability of GaN transistors.

C_{GS} consists of the junction from the gate to the channel, and the capacitance of the dielectric between the gate and the field plate. C_{GS} is large when compared with C_{GD}, giving eGaN FETs good dv/dt immunity, but still small when compared with Silicon MOSFETs giving them very short delay times, and good controllability in low duty cycle applications. A 48 V to 1 V buck regulator has been demonstrated at 1 MHz using 100 V eGaN FETs from EPC. C_{DS} is also small, being limited to the capacitance across the dielectric from the field plate to the drain. Capacitance versus voltage curves for eGaN FETs are similar to those for Silicon except that, for a similar resistance, its capacitance is significantly lower.

The last part of the performance picture is that of the so-called"body diode". EPC's GaN transistor structure is a purely lateral device, absent of the parasitic bipolar

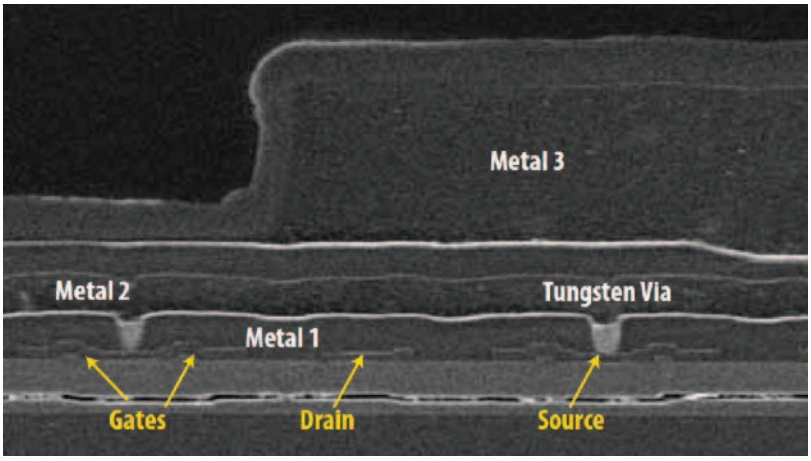

Figure 4: SEM micrograph of an eGaN FET

junction common to Silicon-based MOSFETs. As such, reverse bias or "diode" operation has a different mechanism but similar function. With zero bias gate to source, there is an absence of electrons under the gate region. As the drain voltage is decreased, a positive bias on the gate is created relative to the drift region, injecting electrons under the gate. Once the gate threshold is reached, there will be sufficient electrons under the gate to form a conductive channel. The benefit to this mechanism is that there are no minority carriers involved in conduction, and therefore no reverse recovery losses. While Q_{RR} is zero, output capacitance (C_{OSS}) has to be charged and discharged with every switching cycle. For devices of similar $R_{DS(ON)}$, eGaN FETs have significantly lower C_{OSS} than Silicon MOSFETs. As it takes threshold voltage to turn on the eGaN FET in the reverse direction, the forward voltage of the "diode" is higher than Silicon transistors. As with Silicon MOSFETs, care should be taken to minimize diode conduction.

Conclusion

Enhancement mode transistors using Gallium Nitride grown on top of Silicon have characteristics very similar to the power MOSFET, but with improved high speed switching, lower on-resistance, and a smaller size than their Silicon predecessors. eGaN FETs provide superior performance when compared to MOSFETs. For 200 V devices, the lead is about 10x. As the specific $R_{DS(ON)}$ for eGaN decreases, its lead in RxQ figure of merit will increase. As voltage increases with planned new releases up to 600 V, the comparisons will become even more favor able towards eGaN FETs. Due to their increased switching frequency, they can increase the performance of applications currently using standard MOSFETs and enable applications beyond the range of Silicon and open applications that were not achievable with Silicon-based FET technology.

Literature

White Paper "Gallium Nitride (GaN) Technology Overview", EPC 2012

Product Brief "eGaN® FETs: Ultra High Efficiency Power Switch", EPC 2013

APEC 2013, Professional Education Seminar 7, "GaN Transistors for Efficient Power Conversion"