AN-009: EPC Space Discrete HEMTs and Third Quadrant Operation.

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Introduction

Design engineers will notice that for all EPC Space discrete eGaN HEMT products in the portfolio that "third quadrant" operation is possible, even though they are lateral devices without the parasitic "body" diode that results from their construction. This application note will explain the third quadrant behavior of the eGaN HEMT, why it is more "lossy" as compared to a silicon MOSFET, and what the designer can do to ameliorate the effects of that difference.

Third Quadrant Operation Definition

The third quadrant operation of a power semiconductor is as shown pictorially in Figure 1:

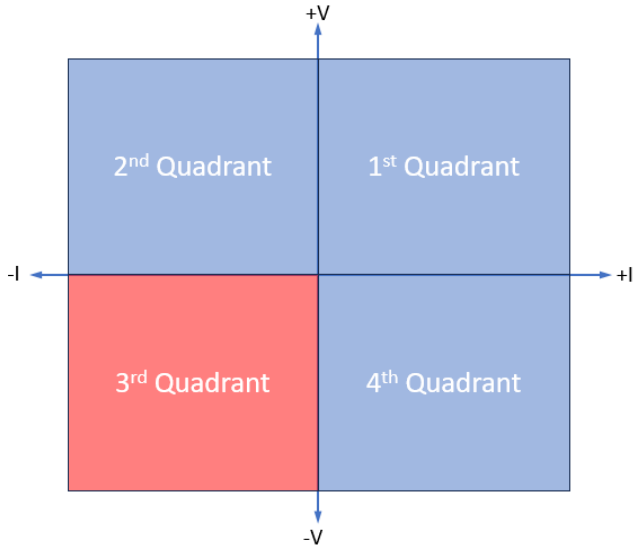


Figure 1. *The Four Quadrants of Semiconductor Device Operation.*

The operating situation under consideration is the case where the device is burdened with negative voltage and negative current. In the case of the discrete power HEMT, the device would be biased such that the source is at a higher potential than the drain and current is leaving the drain (sourced) by the device.

The MOSFET Body Diode, A Review

Every conventional vertically-constructed MOSFET has a parasitic diode structure fabricated into it as a vestige of the device's construction, as shown in Figure 2:

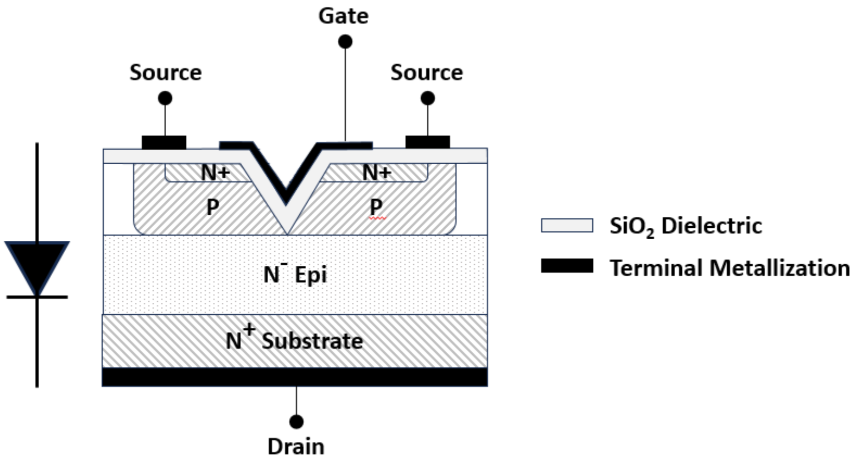


Figure 2. *Conventional Silicon MOSFET Construction and the S-D Body Diode.*

The diode that is formed not only has a forward voltage associated with it but it also has a charge associated with the junction. This charge results in a reverse recovery time. Manufacturers have recognized these two parasitic parameters and have optimized each to reduce their effects on the efficiency provided by the device. Still, these MOSFETs have S-D forward voltages in the range of 0.9-1.8V and reverse recovery charge in the range of 1-20nC.

The "Body Diode" in eGaN HEMTs

In contrast to the silicon MOSFET, due to its lateral construction, the eGaN HEMT has no integral diode structure similar to a conventional silicon MOSFET to act as the diode shown in Figure 2. This lateral structure is shown in Figure 3:

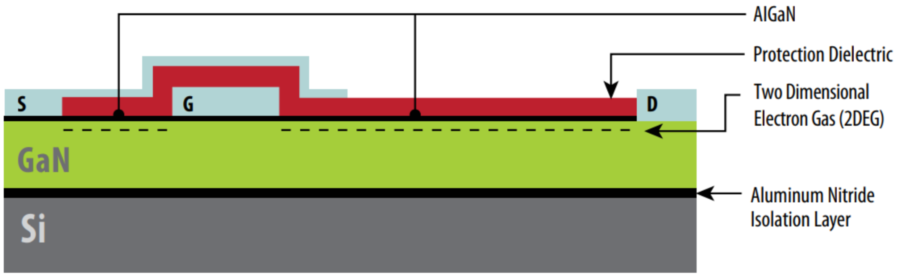


Figure 3. *Cross-Section of eGaN HEMT Structure Showing Lateral Channel Construction.*

Two Modes of Third Quadrant Operation in both Silicon MOSFETs and eGaN HEMTs

Just like a conventional silicon power MOSFET, an eGaN power HEMT has two modes of third quadrant operation. The first mode is identical for both technologies – the current flow from source to drain is controlled by the gate being raised above Vgs(th). In this mode the S-D voltage is minimized and conforms to I_D * Rds(ON). This voltage is illustrated by the green line in Figure 4.

The second mode is where a divergence in the mechanism for conduction in the third quadrant exists. For the silicon MOSFET, the parasitic body diode conducts and the S-D voltage is its forward voltage, Vf. This voltage is illustrated by the red curve in Figure 4.

The conduction in the third quadrant for the eGaN HEMT is slightly more complicated. In the third quadrant the when the HEMT is OFF -- the gate-source voltage is set to below Vgs(th). The source-drain channel now has a non-linear, diode-like response to the drain current carried by the device, as shown by the orange curve in Fig. 4. The previous curves are shown in comparison to the forward voltage, Vf, of a typical power Schottky diode, shown by the blue curve in Fig. 4.

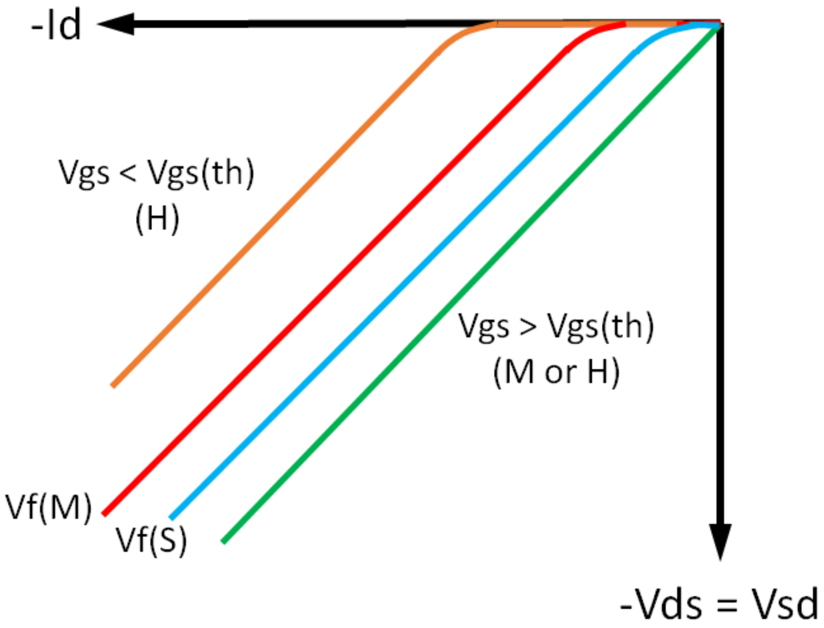


Figure 4. *Third Quadrant Behavior of an eGaN HEMT (Compared to a Power Schottky Diode).*

Now, the reason that the HEMT channel conducts current when Vgs < Vgs(th) and the drain current flows from the source to the drain is because the voltage gradient source-to-drain causes the depletion region under the gate to acquire a negative potential. As soon as the gate voltage exceeds the gate-drain threshold potential, the device turns ON and the two-dimensional electron gas (2DEG) channel becomes quasi-saturated and resistive, with the same Rds(ON) as encountered in the first quadrant. The resultant ON-state voltage at higher currents in the third quadrant is Vgs(gd,th) + (Id * Rds(ON)). Since the third quadrant threshold voltage is in the typical range of 1.5 to 3.5V, the resultant voltage at a given negative drain current is significantly higher than would be for an antiparallel Schottky diode connected from drain-to-source. This is where the higher third quadrant losses arise in the average eGaN HEMT!

Upon review of the EPC Space discrete HEMT products data sheets it is obvious that operation in the third quadrant brings with it higher losses than with a MOSFET or utilizing an eGaN HEMT and adjunct Schottky diode. However, unlike the MOSFET, but much like the Schottky, the eGaN HEMT has NO stored charge, and thus no reverse recovery time. So, the key to minimizing losses in the HEMT during 3rd quadrant operation is to keep the dead time as short as possible. If this is not possible due to the circuitry driving the HEMT, then it is recommended that an adjunct Schottky diode be connected/employed anti-parallel with the HEMT's drain and source, as physically close to the HEMT's package as possible, to minimize the inductance from package-to-package.

Encountering Third Quadrant Operation

Figure 5 shows a simplified half-bridge power stage as one might find in a typical step-down DC-DC converter.

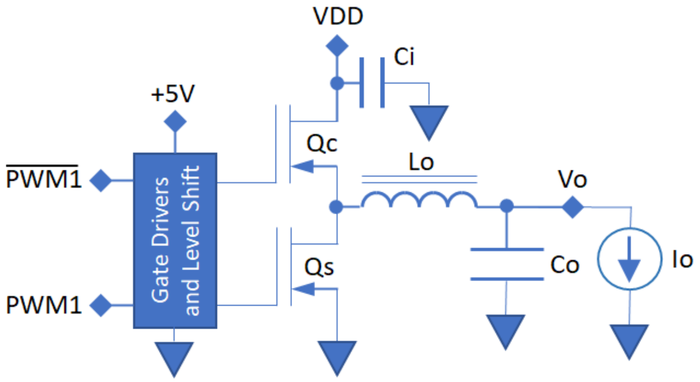


Figure 5. *Half-Bridge Step-Down Power Stage.*

Over a single PWM switching cycle (Ts), transistor Qc is turned on for duration D * Ts (where D is the duty cycle and Vo = D * Vdd). After the period D * Ts has expired, transistor Qc is turned OFF. A delay time period, also known as the "dead time" (t_{dead}) is then allowed to elapse before transistor Qs is turned ON. This dead time ensures that due to timing disparities between the Qc and Qs gate drivers that power switches Qc and Qs never conduct simultaneously, a situation known as cross-conduction or shoot-through (because extremely high, uncontrolled current 'shoots through' from Vdd to ground when low ON-resistance switched Qc and Qs are on simultaneously). The Qc-to-Qs switching event is shown pictorially in Figure 6.

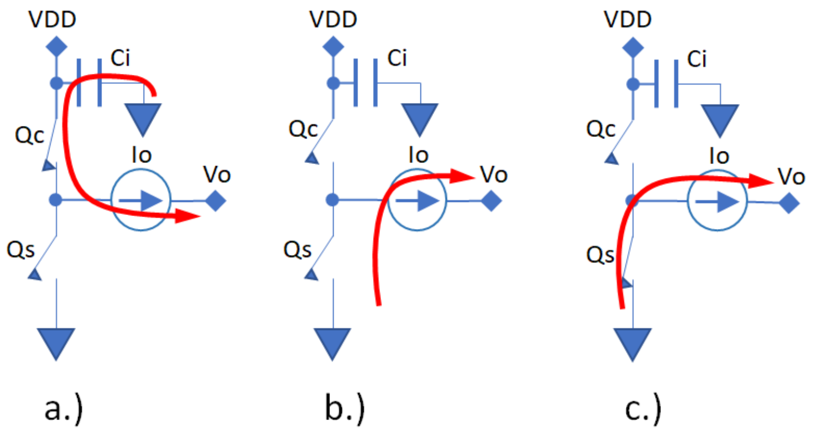


Figure 6. *Half-Bridge Qc-to-Qs Switching Event.*

Figure 6b.) illustrates the dead time interval. In this interval a “phantom” diode, representing a body/Schottky/HEMT diode, conducts current Io. The current Io is representative of the output inductor, whose current is considered essentially constant during the very brief switching intervals under consideration. In the case of the HEMT, when Qc is turned OFF (the gate-source voltage is ~0V), the current flowing as Io is “caught” by transistor Qs, with a voltage Vgs(gd,th) + (Id * Rds(ON)).

At the end of the time period (1 – D) * Ts, transistor Qs is once again turned OFF creating the same situation as illustrated in Fig. 6b.). This condition persists for the time duration t_{dead} and then transistor Qc is turned ON and the switching cycle repeats.

Reducing Third Quadrant Power Loss in eGaN HEMTs

The power loss associated with the eGaN HEMT with Vgs < Vgs(th) operating in the third quadrant (3Q) is defined as:

$$\mathbf{Pd(3Q) = 2 * (Vsd * Id) * t_{dead} * fs}$$

Where Vsd = Vgs(gd,th) + (Id * Rds(ON)), and the factor of 2 is required because there are two dead time periods (t_{dead}) per switching cycle (Ts = 1 / fs).

As previously mentioned, there are two ways to reduce the third quadrant losses in the eGaN HEMT to an acceptable level in a given operating situation. The first and most optimal technique is to limit the dead time to as short an interval as possible. This remedy is possible in most terrestrial applications where a great number of high-speed, low (and matched) throughput delay gate driver or controller ICs are available. However, in the space venue, for which EPC Space discrete HEMTs are designed and specified, and where rad-hard performance is paramount and mandatory, the choices of drivers and controllers are more limited, and their performance is less optimized than strictly non-rad hard terrestrial controllers. As a result, it may not be possible for the dead time to be reduced to a satisfactory level to achieve the packaged HEMT's power dissipation and maximum junction temperature goals over its entire ambient operating temperature range.

This is where the second technique becomes useful. An adjunct anti-parallel Schottky diode, Ds, is incorporated in the circuit along with power switch Qs as shown in Figure 7:

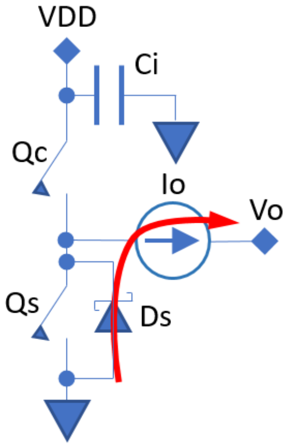
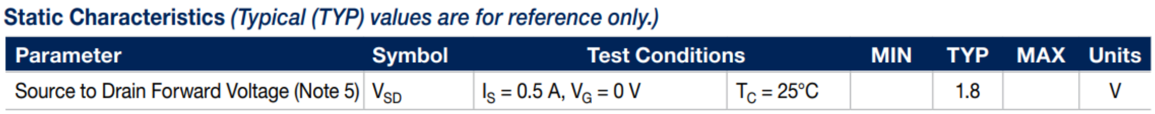


Figure 7. *Circuit of Figure 3b.) With Diode Ds Included.*

When power switch Qs is turned OFF during the dead time, diode Ds will now conduct and commutate the switched current Io. The forward voltage (Vf) of Ds may be chosen such that it is less than the Vsd of Qs, as typical high-peak-current-rated Schottky diodes have maximum forward voltages less than 1.2V. Thus, the third quadrant losses are "off-loaded" onto Ds, which will bear far less power loss during this time than the power HEMT, Qs.

The Problem With Specifying Third Quadrant Operation

In fact, EPC Space specifies the Vsd of any discrete power HEMT in our discrete product portfolio as a typical value at -0.5A of drain current, as illustrated in Figure 8 for the EPC7018G (a 90A device in the "G" package):



Static Characteristics *(Typical (TYP) values are for reference only.)*

Parameter	Symbol	Test Conditions		MIN	TYP	MAX	Units
Source to Drain Forward Voltage (Note 5)	V_{SD}	I_S = 0.5 A, V_G = 0 V	T_C = 25°C		1.8		V

Figure 8. *EPC7018G Typical Vsd Specification.*

Accordingly, the Vsd will vary according to the Vgs(gd,th) of the particular device in question along with the series voltage drop determined by Id * Rds(ON). Thus, the Vsd can range from 0.8V at best-case Vgs(gd,th) and at light loads to a value of (2.5 + (80 * 0.006)) = 2.98V at full load and maximum Rds(ON). This Vsd value as compared to a typical Schottky diode at this value of load current is as much as three times higher. And, accordingly, the losses per unit time at the same operating current are up to three times greater!

It should also be reminded that the Vgs(gd,th) has a negative temperature coefficient (decreases with increasing temperature) and the Rds(ON) has a positive temperature coefficient, as shown in Figure 9 (from the EPC7018G data sheet):

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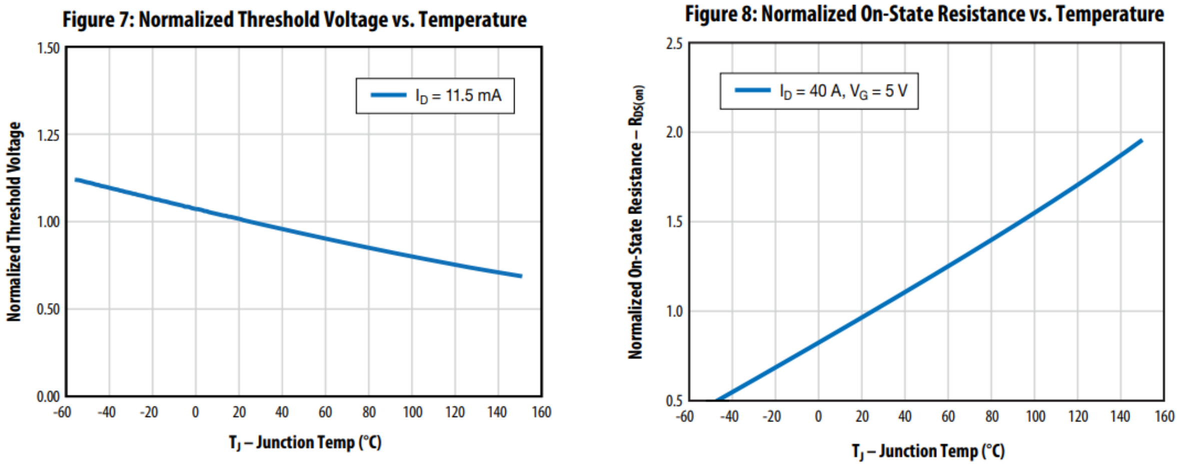

Figure 7: Normalized Threshold Voltage vs. Temperature

Figure 8: Normalized On-State Resistance vs. Temperature

Figure 9. *EPC7018G Typical Vsd(gd,th) and Rds(ON) Temperature Dependence.*

The result of these behaviors is that the Vsd of the HEMT experiences different die temperature-related deviations at different operating currents and different die power dissipations (from DC, switching and AC losses). This temperature dependency makes it that much more difficult to predict the resultant Vsd of the HEMT at a particular operating point. In effect, the actual Vsd of the HEMT will always be slightly higher than the estimated value.

Vsd Considered an "Uncontrolled" Parameter

Because the Vsd is dependent upon the values of three parameters – Vgs(gd,th), Id and Rds(ON), as well as the die temperature, EPC Space considers Vsd an "uncontrolled" parameter. So, we discourage third quadrant operation not because it is deleterious to the operation of the HEMT, or destructive. It is because the losses are not quantifiable on a data sheet because the value of Vsd, and the dead time losses associated, are dependent upon so many parameters and operating variables. And for our customers in the space community, designers and end-users who are more concerned with reliability and operation in a harsh environment than most other disciplines, accurately quantifying the various parameters and characteristics of a device is of primary importance.

Help Is On The Way!

Recognizing that the present situation with 3rd quadrant losses may not be acceptable with all end-users and customers, EPC Space (and EPC Corp) is/are actively involved with the research and development of GaN-based Schottky diodes. These diodes will constitute a family of devices whose current carrying capabilities range to 20A and whose reverse voltages extend from 20V to 300V. The forward voltages of these devices range from 0.9 to 1.8V. These diodes are planned to be housed in low-inductance, ceramic and hermetic packaging similar to the EPC Space discrete HEMT products.

This new product line of GaN diodes will serve to ameliorate the losses in the 3rd quadrant for the present discrete HEMT product portfolio all the way up to 300V, without the necessity to de-rate the diodes as is necessary for conventional silicon Schottky devices. The reason being that the GaN diodes will be every bit as radiation-hardened/tolerant as the eGaN HEMTs are! And best of all, in addition to the other advantages of these diodes, they will incur ZERO stored charge. So, the benefits of the silicon MOSFET's body diode are now similarly afforded to any eGaN power HEMT.

Another very exciting development in progress at EPC Space (and EPC) is/are the creation of what may be termed a "HEMTkey" device, which incorporates Schottky diodes in the same physical semiconductor structure as the eGaN HEMT power switch. Thus switch-diode functionality will be all "in-house" on a single die, thus yielding the ultimate in performance and efficiency for this function. As such, any and all inter-package inductance will be eliminated and the resultant 3rd quadrant losses will be as small as possible.

For news regarding these two developments please visit the EPC Space website frequently for the status of these new products and their anticipated product releases.

Conclusion and Summary

The third quadrant conduction behavior of eGaN HEMTs vs conventional silicon MOSFETs is discussed, relating to the power dissipations of the devices. Although EPC Space discourages third quadrant operation of its discrete HEMT devices, if an end-user does use a HEMT in the third quadrant, this operation will not harm or cause the HEMT to be destroyed. Rather, EPC Space considers the Vsd of a HEMT an "uncontrolled" parameter that is dependent upon more than two other variables (current, voltage, temperature, etc.), and operation in the third quadrant should be carefully considered and analyzed by the designer, considering all the variables involved. Our recommendation to carefully design for or to avoid third quadrant operation is based solely on recognizing our space customers demanding requirements and design/de-rating criteria.

Alternative methods to reduce third quadrant power dissipation are presented: reduction of dead time and the utilization of an adjunct, anti-parallel Schottky diode. The satisfactory reduction of the dead time periods may not always be possible due to the limited availability of space-grade, rad-hard gate drivers and controller ICs, so the adjunct Schottky may be the go-to method to reduce or eliminate the third quadrant losses in the eGaN HEMT.

Future developments with regards to GaN Schottkies and eGaN "HEMTkeys" are mentioned and the reader is instructed to visit the EPC Space website for future details and information about specifications and anticipated product releases.

References

Lidow, Alex, editor, "*GaN Power Devices and Applications*", First Edition, Power Conversion Publications. ISBN 978-0-9966492-2-3

EPC Space Discrete HEMT Products Data Sheets

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