RF GaN HEMT Primer

Abstract

The high performance of the GaN HEMT creates exciting opportunities, especially in RF applications. A high-level explanation of how the GaN HEMT achieves its performance is the subject of this application note. A generalized explanation of the GaN HEMT structure reveals how a two-dimensional electron gas (2DEG) is generated and controlled. Ideal output characteristics, including reverse conduction, are explained, as well as the exceptionally low capacitances. Fundamental limitations warrant precautions, including wide voltage margin to mitigate charge trapping, and careful thermal management. Nonlinear models for accurate simulation accelerate and derisk the design process.

1. Introduction

The gallium nitride high electron mobility transistor (GaN HEMT) has significant advantages over competing technologies, particularly high frequency and high temperature operation, which is critical for radio frequency (RF) operation. It also has low on-resistance for a given voltage rating and very fast switching.

Following an abbreviated description of the GaN HEMT construction, this application note explains the operation and unique features of a GaN HEMT in general, with emphasis on RF applications. The intent is to help better understand at a circuit level how a GaN HEMT works, what its strengths and limitations are, and how to successfully use it.

2. GaN HEMT Structure

GaN is a compound semiconductor that combines gallium and nitrogen from the periodic table of elements columns III and V respectively. Unlike silicon (Si) and silicon-carbide (SiC) from column IV that are fabricated from grown crystal ingots, commercially available GaN devices are fabricated onto a substrate of another material, commonly silicon, silicon-carbide, or sapphire (aluminum oxide). Silicon is the lowest cost substrate material, but RF GaN transistors usually use SiC as a substrate because of its lower thermal resistance, better lattice and thermal expansion match with GaN, and its ability to withstand high temperature.

Fig. 2-1 shows a cartoon drawing of a GaN HEMT cell cross-section along with a partial electron energy band diagram. Cells are replicated many times in parallel on a power transistor chip. A simplified description of the layers in a GaN RF transistor is as follows. Aluminum nitride (AlN) is commonly grown on the substrate first as an isolation layer, also called a seed or nucleation layer. Next is a transition layer to accommodate dissimilar crystal structures and to minimize leakage current to the substrate. The transition layer could be multiple layers and different materials or doping. The transistor itself is formed by a layer of AlGaN, called a barrier layer, over a layer of GaN, called a buffer layer. The abrupt AlGaN/GaN heterojunction forms spontaneous and piezoelectric polarization because AlGaN has a wider bandgap than GaN, and the heterojunction creates stress, mostly in the AlGaN layer.

We recall that bandgap refers to the energy difference between the top of the valence band E_V and the bottom of the conduction band E_C, which are shown in Fig. 2-1, and there are no electron states within the bandgap. An electric field across the AlGaN layer induces electrons from the AlGaN layer to accumulate at the GaN side of the AlGaN/GaN interface. This migration of electrons bends the energy bands until the Femi level E_F is constant. On the GaN side of the heterojunction, the conduction band E_C exceeds the Fermi level E_F, which creates a two-dimensional electron gas (2DEG). These electrons are free to move laterally between source and drain contacts, as opposed to being loosely bound to atoms in the crystal structure as in Si or SiC. The exceptionally fast movement of electrons prompted the name High Electron Mobility Transistor (HEMT).

Although omitted from the cross-section drawings in this application note, a gate cap layer or a dielectric layer can be added between the AlGaN layer and the gate. Passivation over the AlGaN layer mitigates charge trapping and other damage. This is usually silicon nitride (SiN). A source field plate shapes the intense electric fields and shields the gate. Real designs may differ significantly from this simplified description, but this basic structure is sufficient to explain the operation of the GaN HEMT.

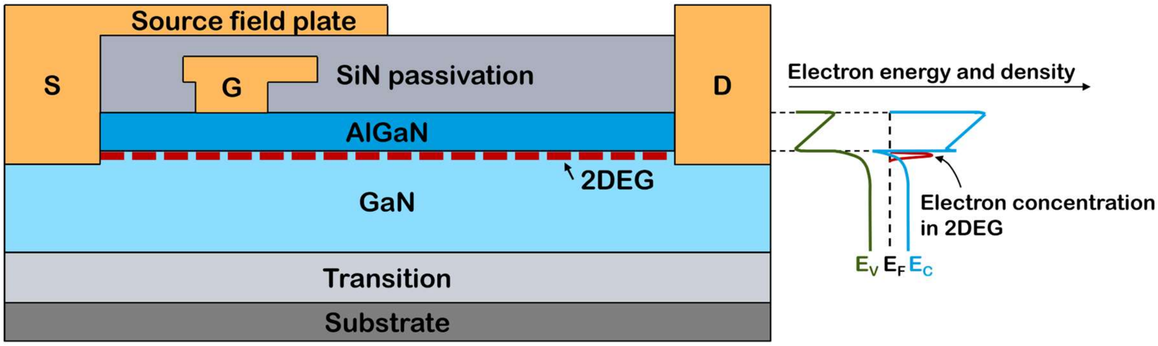


Fig. 2-1 GaN HEMT cell cross-section and electron energy band diagram

To block current from flowing, electrons are depleted from under the AlGaN/GaN interface. This is done by a metal gate. (Gate oxide is generally not used as in a MOSFET.) With no bias on the gate, electrons move freely and the HEMT is normally on. Applying a negative gate-source bias compensates electron donor sites in the AlGaN and hence depletes (repels) electrons from the 2DEG near the gate where the energy bands increase. When the bias is sufficiently negative, current flow is blocked even with high V_{DS} by the highly resistive AlGaN and GaN between the drain and source terminals.

There is no PN junction in a HEMT, which is quite different from a MOSFET or a JFET. No PN junction means there cannot be a body diode. Reverse current can flow, as will be explained. There is no reverse recovery charge, which significantly reduces hard-switching power loss. Another advantage is better radiation hardness compared to a silicon MOSFET.

So far, the transistor described is normally on, which is usually the type used in RF applications. Power electronic designers prefer a normally off transistor. Adding a layer of p-type GaN under the metal gate shifts the electron energy bands up and prevents the formation of 2DEG under the gate, even with no bias on the gate. In other words, electrons are depleted under the p-GaN gate, and the HEMT is normally off. Applying a sufficiently positive gate bias creates a conductive channel under the gate as in a MOSFET, again allowing bidirectional current flow. The remainder of this application note is about the depletion-mode, normally on GaN HEMT. The fundamental characteristics are the same for both except of course for the threshold voltage.

3. Ideal Output Characteristic

A negative voltage at the gate with respect to either the source or the drain hinders the migration of electrons to the 2DEG. Imagine that the drain to source voltage V_{DS} is low compared to the voltage rating, but high enough so that current freely flows when the HEMT is on, such as when the gate-source voltage V_{GS} is zero. Decreasing V_{GS} reduces the electrons available from the AlGaN layer to form the 2DEG near the gate, and the HEMT becomes increasingly resistive between drain and source. With sufficiently negative V_{GS}, the 2DEG electrons are depleted near the gate, and current "pinches off". This is indicated graphically in Fig. 3-1. The threshold voltage $V_{GS(th)}$ is characterized at low drain-source voltage V_{DS}, usually 5 to 10 V, and a specified, a small drain current, usually in the milliamp range. To ensure that the HEMT remains off during operation, V_{GS} should be below the minimum threshold voltage. It is therefore useful to think of the threshold voltage more as an indicator of when a part begins to switch on rather than off.

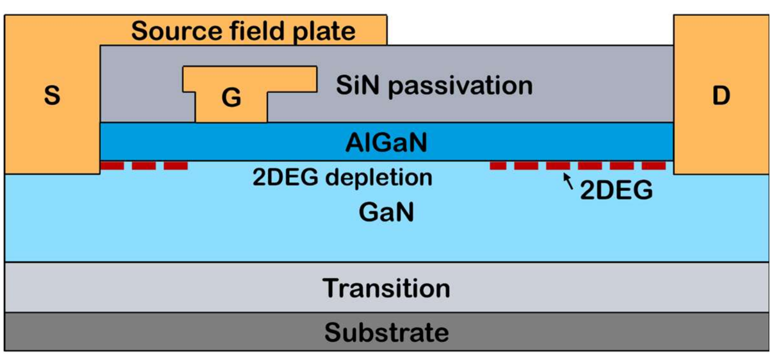


Fig. 3-1 GaN HEMT blocking drain-source current under high drain-source voltage

A thought experiment helps to understand the operation of the HEMT. Suppose that V_{GS} is fixed, slightly above $V_{GS(th)}$, and V_{DS} steadily increases from zero. At first, current flows freely, limited by V_{DS} and the on-resistance of the HEMT, and drain-source current I_D increases along with V_{DS}. At some point as V_{DS} increases further, there are too few remaining electrons in the 2DEG to sustain a corresponding increase in I_D, and the I_D versus V_{DS} curve “bends” and the slope becomes flatter. This is seen in quadrant 1 of the output characteristic curves of Fig. 3-2. The knee voltage for each V_{GS} curve can be estimated as $V_{GS,knee} = V_{GS(th)} + V_{DS}$. Past this knee in the I_D versus V_{DS} curve, I_D is mostly determined by V_{GS} and less by V_{DS}. Therefore, in this saturation mode, the transistor is gate controlled. This is where an RF amplifier operates. Remembering that we are still describing a depletion mode HEMT, increasing V_{GS} above zero further increases I_D, but a safe limit is typically only +1 V. Excessive V_{GS} can permanently damage the gate structure. (The gate injection transistor (GIT) eliminates this weakness, but this is beyond the scope of this application note.) Likewise, increasing V_{DS} beyond a safe limit causes permanent damage, similar to overvoltage of a multilayer ceramic capacitor.

Referring again to Fig. 3-2, a GaN HEMT can block tens to hundreds of Volts in quadrant 1, but very limited voltage in quadrant 3. The reverse blocking voltage depends on the gate-drain and gate-source voltages, and little on temperature due to the weak temperature coefficient of the threshold voltage. Negative V_{DS} tends to increase conductivity and overcomes the tendency of negative V_{GS} to reduce it when, approximately, $V_{DS} \leq V_{GS} - V_{GS(th)}$. This relationship can be verified by examining a GaN HEMT device datasheet. An easy way to remember this relationship is that the V_{DS} reverse knee voltage is approximately the amount that V_{GS} is driven more negatively than $V_{GS(th)}$. Another easy way to remember it is by rearranging and combining $V_{DS} \leq V_{GS} - V_{GS(th)}$, showing that reverse current begins flowing when $V_{GD} \geq V_{GS(th)}$, almost as if the drain and source terminals swapped functions.

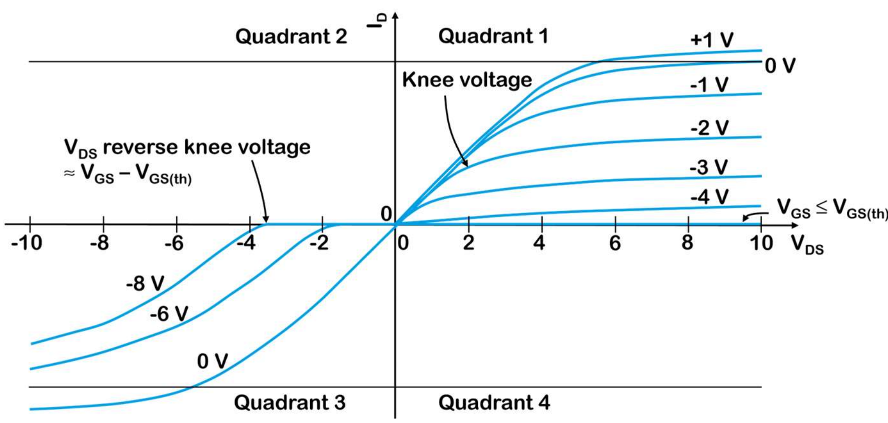


Fig. 3-2 Output characteristic curves of a generic GaN HEMT with various V_{GS} and $V_{GS(th)}$ = -5 V

Notice how the reverse conduction curves flatten out as with the forward conduction curves, but at a higher current magnitude, as evident by the two horizontal lines at equal current magnitude, one positive and one negative, in Fig. 3-2. This is because decreasing V_{DS} with a fixed V_{GS} increases V_{GD}, which increases conductivity. As with forward current, this happens until the number of electrons in the 2DEG cannot support a linear increase in reverse current. The GaN HEMT has a positive temperature coefficient of on-resistance, which causes the slope of the curves in Fig. 3-2 to reduce with increasing temperature.

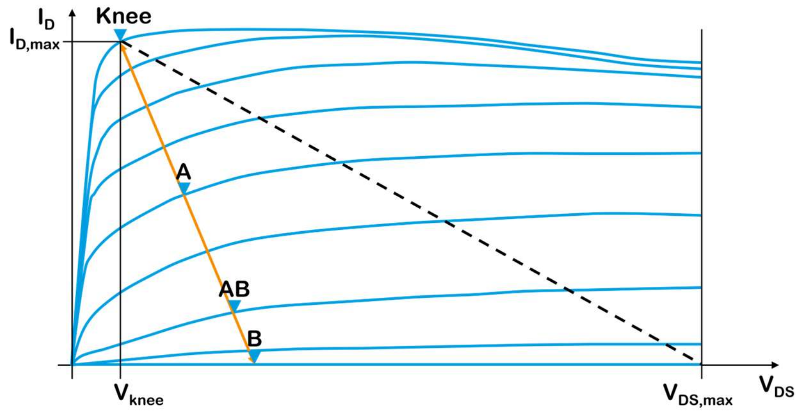


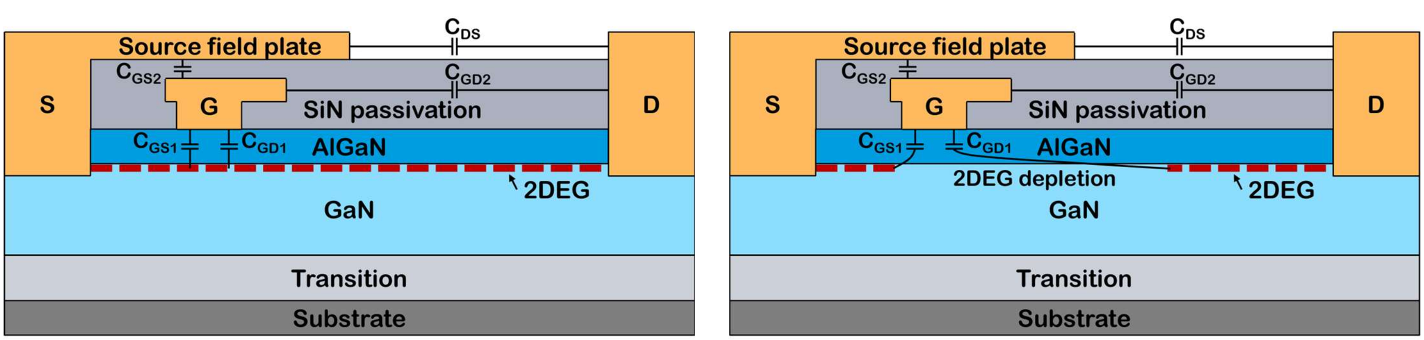
Fig. 3-3 GaN HEMT output characteristic with load lines for an RF amplifier

Fig. 3-3 shows generic output characteristics for a GaN HEMT. RF amplifiers are generally common source with the load attached to the drain. Therefore, the drain voltage changes with drain-source current. Fig. 3-3 shows output characteristic curves with two of countless possible AC load lines. The black dashed line represents a theoretical maximum voltage and current swing, but operation along that line would be erratic, resulting in a load loop instead of a load line, explained by charge trapping. The orange line represents a typical load line with a class B bias point at significantly less than half the maximum voltage. Bias point markers are for class A, class AB, and class B operation. The load lines intersect the knee of the top curve, which is the maximum V_{GS} curve. To maximize current and voltage peaks before clipping and thereby optimize power output, the load resistance should be the reciprocal of the load line slope [2].

Most GaN HEMT designs have a non-negative, or at least weakly negative temperature coefficient of $V_{GS(th)}$. This is a major factor preventing the formation of thermally unstable hot spots due to current crowding on the HEMT chip while operating in the saturation region [1]. This is where RF amplifiers operate, so this flat $V_{GS(th)}$ temperature coefficient is yet another significant advantage of the GaN HEMT over silicon-based MOSFETs, which always have a negative threshold voltage temperature coefficient because of the inversion layer in the channel.

4. Capacitances

The lack of a PN junction in the HEMT results in unique capacitance characteristics. Another look at the GaN HEMT construction helps to explain this.



(a) (b)

Fig. 4-1 GaN HEMT structure showing capacitances (a) biased on, and (b) biased off with high V_{DS}

Fig. 4-1 shows the cross section of a GaN HEMT cell, this time with capacitances added. In (a) the HEMT is on and V_{DS} is very low, and in (b) the HEMT is off and blocking high voltage. In both cases, C_{RSS}, which is the gate-drain capacitance, has two parts, C_{GD1} and C_{GD2}, as indicated in Fig. 4-1. Similarly, the input capacitance C_{ISS} has two parts, C_{GS1} and C_{GS2}, in parallel with C_{RSS}. The output capacitance C_{OSS} is the sum of C_{RSS} and C_{DS}. C_{GD1} and C_{GS1} decrease with increasing V_{DS} because of the longer distance between the gate and the 2DEG.

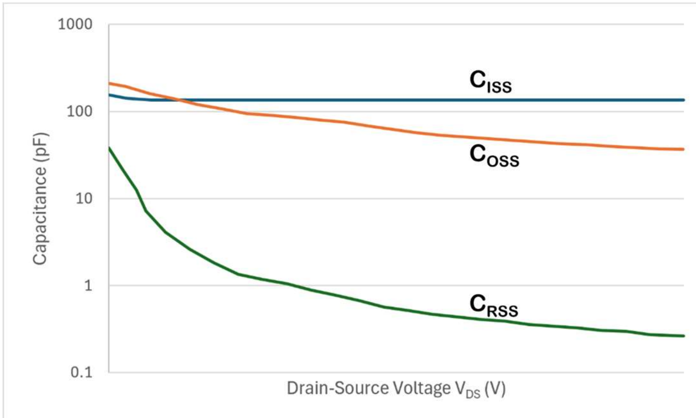


Fig. 4-2 Capacitance versus V_{DS} curves

Fig. 4-2 shows capacitance versus V_{DS} for a generic GaN HEMT. V_{DS} is swept from zero nearly to the rated voltage. As mentioned, the increase in V_{DS} reduces C_{GS} and C_{GD}, which causes a corresponding decrease in all three capacitances C_{ISS}, C_{OSS}, and C_{RSS}. There are two important characteristics to notice here. First, the GaN HEMT is renowned for low capacitance in general, but especially C_{ISS}, which is significantly lower than the closest competing technology. Second, the GaN HEMT has lower C_{RSS} especially at low V_{DS}, and the decrease in C_{RSS} versus V_{DS} is monotonical and has a more gradual slope than competing technologies with the same voltage rating and similar on-resistance. These are considerable advantages for the GaN HEMT for both switch-mode and RF applications. The well-behaved C_{RSS} simplifies control, and the low C_{ISS} makes the GaN HEMT responsive (low phase noise) and easy to drive (low gate drive power, high gain), especially at RF frequencies. These are main reasons a GaN HEMT based RF amplifier can operate at tens of gigahertz, and another is of course the exceptionally high saturated electron velocity.

5. Electron Mobility and Saturated Velocity

Electron drift velocity v_d is the average velocity of electrons moving through a piece of material with an electric field E applied across it. The electron mobility μ_e is defined as $\mu_e = v_d/E$. With the drift velocity v_d directly proportional to the electric field E, the low-field electron mobility is constant. In very large electric fields, electron mobility depends on the electric field, and electron velocity no longer increases linearly with the electric field, and eventually not at all as electrons reach saturation velocity.

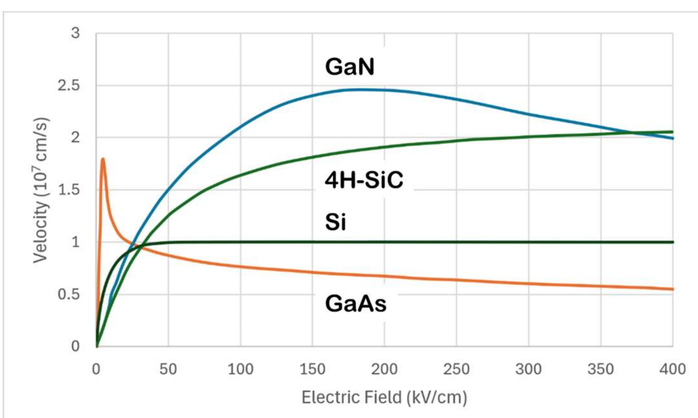


Fig. 5-1 Electron velocities versus electric field in various semiconductors

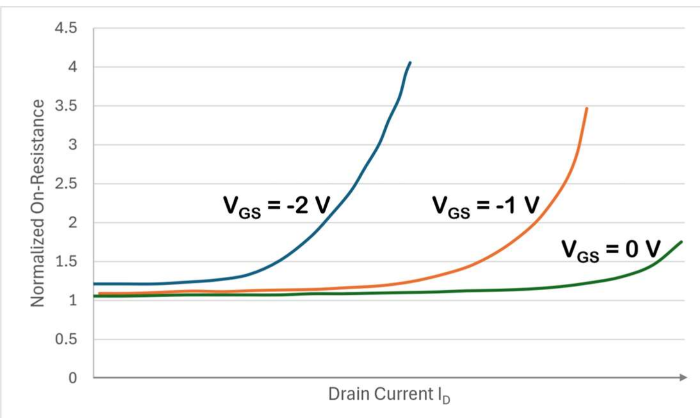
Fig. 5-1 shows electron velocities versus electric field for gallium-arsenide, silicon, silicon-carbide, and gallium-nitride. The slope of each curve is electron mobility. Here we see that GaAs has by far the highest mobility, but only at a low electric field. At higher electric fields it has the lowest carrier mobility of the group, including silicon. GaN has the highest saturated velocity of the group, in the range of electric field where an RF device operates. The highest saturated velocity combined with low capacitances make GaN a top performer in RF power amplifiers and switches, especially in radar applications.

6. GaN HEMT Limitations

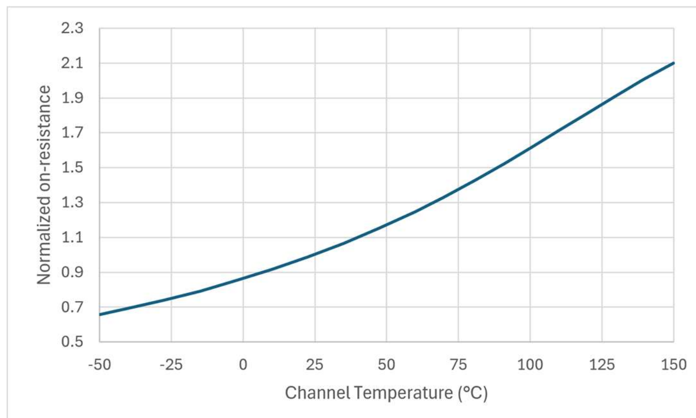
The GaN HEMT has outstanding performance in both switch-mode and RF applications. Both applications benefit from the high conductivity, fast switching, and low gate drive power. However, the GaN HEMT struggles to compete with a SiC MOSFET when operating with DC link voltage above 400 V. Where the GaN HEMT really shines is in RF applications, with about 10x higher voltage ratings than GaAs or silicon-based laterally-diffused metal-oxide semiconductor (LDMOS), delivering higher output power at high frequency. To utilize it successfully, it is important to understand its limitations.

6.1. Thermal Runaway from Overloading

Something to be aware of rather than a defect, especially for an RF switch, the GaN HEMT has a rather sharp increase in on-resistance above a certain current, as seen in Fig. 6-1(a). This effect strongly depends on V_{GS} and temperature. As mentioned before, the GaN HEMT has a positive temperature coefficient of on-resistance as seen in (b) where normalized on-resistance is plotted versus channel temperature. This increase in on-resistance versus temperature is typical of modern majority-carrier transistors and is mostly due to the intrinsic material characteristics in the GaN HEMT.



(a)



(b)

Fig. 6-1 Normalized on-resistance of a generic GaN HEMT (a) versus I_D at various V_{GS}, and (b) versus channel temperature

The GaN HEMT has very high efficiency, which allows a small chip size for the same output power compared with competing technologies. This makes thermal management a primary concern, despite the low thermal resistance per chip area of the GaN HEMT with a SiC substrate. Safe operation dictates adequate current and thermal margin to avoid the risk of thermal runaway. A key to successful implementation is accurate nonlinear device modeling to account for the interaction of various parameters, such as the change in conductivity versus current [2], [3]. Models for accurate simulation and evaluation boards for testing greatly reduce risk and speed development time.

6.2. Charge Trapping

Charge trapping is when electrons become stuck in the AlGaN and GaN surfaces or within the GaN buffer while the device is operating, especially with high V_{DS}. This reduces the number of electrons available in the 2DEG, resulting in “current collapse”, or “knee walkout”.

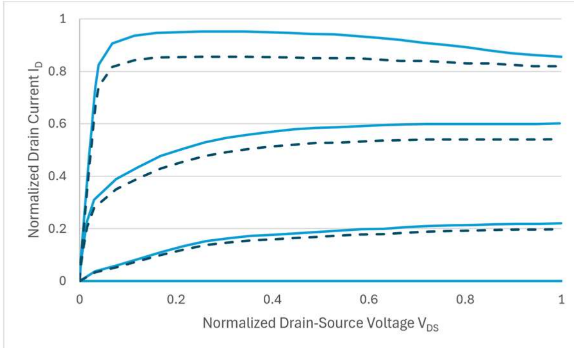


Fig. 6-2 Dashed curves showing current collapse with I_D and V_{DS} normalized to maximum values

Fig. 6-2 shows the effect of charge trapping on the output characteristics of our generic GaN HEMT. The dashed curves show how charge trapping reduces (collapses) the current and moves the knee voltage down and to the right, compared with the solid curves representing performance without charge trapping.

Charge trapping is strongly affected by V_{DS}. It is mitigated both by design and by applying sufficient margin from maximum voltage, current, and temperature ratings. We saw this in Fig. 3-3 with the typical load line well away from the maximum drain-source voltage. This is important for long-term, reliable operation of GaN HEMTs.

7. Summary

The GaN HEMT structure centers around the AlGaN/GaN interface with its spontaneous and piezoelectric generation of highly conductive two-dimensional electron gas (2DEG) that gives the GaN HEMT its exceptional performance characteristics. Ideal output characteristics look similar to a JFET except the reverse current flattens out (at a somewhat higher current magnitude than with forward current). Capacitances in the GaN HEMT are lower than competing technologies, especially the input capacitance. High electron mobility, low capacitances, and low thermal resistance per chip area make the GaN HEMT ideally suited for RF applications. Adequate voltage, current, and thermal margin are necessary for a long-lasting, reliable amplifier. Nonlinear models for accurate simulation reduce risk and accelerate the design process.

References

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Revision History

Revision	Author	Date	Description
A	Jonathan Dodge, P.E.	30 July 2026	Initial draft

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Important Notices