Gate-Drain Breakdown Effects Upon the Large Signal Performance of GaAs MESFETs

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ABSTRACT

GaAs MESFETs often demonstrate a negative breakdown slope characteristic. This slope can be critical in determining the RF performance of MESFET amplifiers. It is demonstrated that as the breakdown slope decreases, RF power performance is degraded. Tuning is also important because this adjusts the load line to allow maximum voltage and current swings on the drain. Reverse breakdown followed by foward gate conduction are confirmed to be the main saturation mechanisms for GaAs MESFETs.

INTRODUCTION

The use of GaAs MESFETs in an expanding array of microwave and millimeter wave circuits, components, and systems, places increasingly rigorous requirements on improved device reliability and reduced fabrication costs. A problem often encountered is that devices from different wafers with virtually identical measured DC characteristics often demonstrate substantially different RF performance. The inconsistant ability of DC characteristics to predict RF performance forces wafers to be fully processed and the devices RF characterized before good wafers can be identified. This adds significant time and costs to the fabrication procedure. The use of microwave CAD is also hindered since almost all commercially available software packages make use of empirical *fits* to the DC I-V characteristics to define the device nonlinearities.

In this work, an advanced, physically based GaAs MESFET model is used to investigate the large signal RF performance of GaAs MESFETs as a function of the gate-drain breakdown characteristics. The model allows the negative or backward slope of the MESFET breakdown characteristic. That is, MESFETs demonstrate increasing breakdown voltage as the gate bias is increased[1,2]. The model used in this work is the only model presented to date that correctly accounts for this phenomena. It is known that saturation in MESFETs under normal operating conditions occurs due to breakdown[3,4]. In this work it is demonstrated that the breakdown slope is critical in determining the RF performance of the device.

DEVICE MODEL

The model used in this work is a physics based MESFET model[5] that solves the semiconductor equations in closed form with appropriate approximations and incorporates a number of important phenomena such as domain charge formation, velocity vector rotation, and a depletion transition region. This model is nested in a flexible circuit configuration thus allowing simulation of different microwave components such as amplifiers, mixers, or oscillators. The harmonic balance technique is used to interface the linear circuit to the nonlinear part of the model. The model uses measured or theoretical material and physical data as its input, and it outputs DC and RF performance, impedance, and spectrum information. The addition of the variable negative breakdown slope to the MESFET model permits the investigation of gate-drain breakdown and its affect on MESFET performance.

The planar MESFET used in this work has a gate length of 0.42μm and a gate width of 1000μm. The pinch-off breakdown voltage is Vds=12.5V and the locus of drain-source voltage versus gate bias measured at a gate current of 1mA/mm is used to define the breakdown slope. The reverse breakdown current is limited by a small resistance between the gate and drain. The MESFET is an ion implanted device with peak doping of $2.1 \times 10^{17} cm^{-3}$ and a straggle of 0.093μm. The pinch-off voltage is Vgs= -5.5V

DISCUSSION

As GaAs MESFETs are being used more in monolithic circuits and systems, the need for fast and accurate modelling for analysis and design has become very important. Nonlinear effects such as forward conduction of the Schottky gate contact and reverse bias gate-drain breakdown are difficult to model correctly and accurately. Typically, these effects are modelled by simple diodes or nonlinear switches added to device models. The use of equivalent cir-

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cuits to characterize the nonlinearities of a MESFET has the disadvantage that there can be many solutions to fitting empirical expressions to measured data. Physically based models solve the semiconductor equations and Poisson's equation to provide a more accurate simulation of device performance, but generally also represent gate conduction characteristics with equivalent diodes. With physically based models, material and physical parameters are used to match and predict measured MESFET RF and DC performance. This is in contrast to equivalent circuit models that need measured device performance data before the equivalent circuit components can be determined.

In this work, a Class A amplifier, using the MESFET described above, is simulated at 10 GHz, the pinch-off breakdown voltage is Vds=12.5V. The MESFET, in general, has a breakdown characteristic that demonstrates increasing breakdown voltage as the gate bias is increased[1,2]. This backward or negative slope affects the RF performance by acting as a saturating mechanism for the MESFET. The dynamic I-V characteristic at the drain contact can be superimposed on the DC I-V characteristics of the device to give visual confirmation that the gate-drain breakdown slope affects the voltage and current flowing through the device, therefore affecting RF performance. The GaAs MESFET investigated was operated under Class A conditions in both 50Ω and impedance matched RF circuits. Tuning affects RF performance in a fundamental manner. More precisely, as will be seen in the Results section, tuning adjusts the load such that a maximum voltage and current swing is available across the I-V plane, for a given DC bias condition. This means that maximum RF device output power comes from a load line that extends from the pinch-off breakdown voltage to the knee of the Idss curve. When the device is mismatched to any degree, the load line deviates from the slope that allows the maximum voltage and current swings and thus the RF power performance is degraded. Normally a Class A device is biased near $\frac{1}{2}$Idss and $\frac{1}{2}$Vgdbd to try to maximize the voltage swing on the drain, under matched conditions. If the device output impedance is matched to the load, the Q factor is increased meaning there could be a significant amount of reactance seen by the drain. This causes the load line waveform superimposed on the I-V curves to open and be more ellipsoidal. When the device is loaded with 50Ω, the only reactance is due to the drain source capacitance of the device, which is normally small. Under these conditions, the dynamic load line is essentially real.

When the device is impedance matched, the dynamic load line becomes ellipsoidal. A negative breakdown slope can cause early saturation or waveform clipping, because the open ellipsoid can overlap the breakdown boundary depending on the severity of the breakdown slope and the size of the ellipsoid. This can be critical for matched or highly reactive loads. For the 50Ω case, the load line only covers a small area on the I-V plane, but the 50Ω mismatch can cause the load line, due to its slope, to overlap into the breakdown region at the peak voltage of the drain, and thus clipping occurs.

RESULTS

Different breakdown slopes were simulated and their effects on RF performance noted. Breakdown slopes varying from infinity (constant drain-source breakdown) to -0.05A/V were investigated. The pinch-off breakdown voltage was held constant. Breakdown is often measured at pinch-off with a gate current of 1mA/mm and the measured BVgd can be identical for a variety of breakdown slopes. As the breakdown slope decreases, it takes less drain voltage for a given gate bias to cause breakdown and the resulting RF saturation. At 10 GHz the RF power performance of the amplifer under matched and 50Ω conditions can be seen for the three different breakdown slopes in Figure 1 and Figure 2, respectively. As the breakdown region encroaches upon the operating load line, which varies from verticle to a slope of -0.1A/V, increasingly greater power and efficiency degradation occurs. For the 50Ω system, the PAE is degraded by nearly 10% by varying the breakdown slope from vertical to -0.1A/V.

The impedance matched system RF performance does not demonstrate extreme performance degradation. The reason for this can be seen in Figure 3 and Figure 4. Figure 3 shows the dynamic load line at 0dB, 1dB, and 5dB gain compression for the matched amplifier with a reverse breakdown slope of -0.05A/V. Figure 4 shows the amplifier under 50Ω conditions at 0dB, 7dB, and 9dB gain compression for a breakdown slope of -0.1A/V. From these two figures, it is observed that the process of matching for maximum output power adjusts the load line such that it allows maximum voltage and current swing on the drain, extending between the pinch-off breakdown voltage and the knee of the Idss curve. This is in contrast to the 50Ω system results in Figure 4 which show that early saturation occurs due to reverse breakdown, followed by foward gate conduction. Saturation in the matched system is caused less by the reverse breakdown slope boundary in the I-V plane than by the pinch-off breakdown voltage and the foward gate conduction at the knee of the Idss curve. Rectification effects due to forward gate conduction and reverse breakdown produce changes in the DC channel current and, therefore, shifts in the device operating or Q point.

The effects of varying breakdown slopes upon RF performance can be seen in Figures 5 and Figure 6. Figure 5 shows the RF drain voltage waveform at 1dB gain compression under 50Ω conditions for reverse breakdown slopes of vertical, -0.1A/V, and -0.05A/V. Figure 6 shows the same waveform under matched conditions at 1dB gain compression for the same reverse breakdown slopes. It is observed that the 50Ω condition causes greater waveform degradation with decreasing breakdown slope, and thus decreased RF power performance. The matched amplifier is not significantly affected by the change in breakdown slope. This is due to the load line avoiding the breakdown region as can be seen in Figure 3.

CONCLUSIONS

The negative breakdown slope is fundamentally important to the large signal operation of MESFETs. Gate-drain breakdown is the dominant saturation mechanism in GaAs MESFETs, and generally occurs before foward gate conduction. A greater breakdown slope allows more I-V plane operating area for drain current and voltage waveforms, and thus will allow improved RF performance by minimizing saturation. Tuning is also important since an increase in circuit reactance produces an ellipsoidal dynamic I-V characteristic. The ellipsoidal characteristic permits the increased opportunity for the dynamic drain voltage to enter the breakdown region. Mismatched devices often saturate before matched devices because the drain waveforms are more likely to be clipped due to breakdown.

REFERENCES

[1] R. Yamamoto, A. Higashisaka, and F. Hasegawa, "Light Emission and Burnout Characteristics of GaAs Power MESFETs," IEEE Trans. Electron Dev., vol. ED-25, pp. 567-573, June 1978.

[2] M. Fukuta, K. Suyama, H. Suzuki, Y. Nakayama, and H. Ishikawa, "Power GaAs MESFET with a High Drain-Source Breakdown Voltage," IEEE Trans. Microwave Theory Tech., vol. MTT-24, pp. 312-317, June 1976.

[3] H.Q. Tserng, W.R. Frensley, and P. Saunier, "Light Emission of GaAs MESFETs Under RF Drive,"IEEE Electron Dev. Let., vol. EDL-1, pp. 20-21, Feb. 1980.

[4] W.R. Frensley, "Power Limiting Breakdown Effects in GaAs MESFETs," IEEE Trans. Electron Dev., vol. ED-28, pp. 962-970, Aug. 1981.

[5] M.A. Khatibzadeh and R.J. Trew, "A Large-Signal, Analytic Model for the GaAs MESFET", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, pp. 231-238, Feb. 1988.

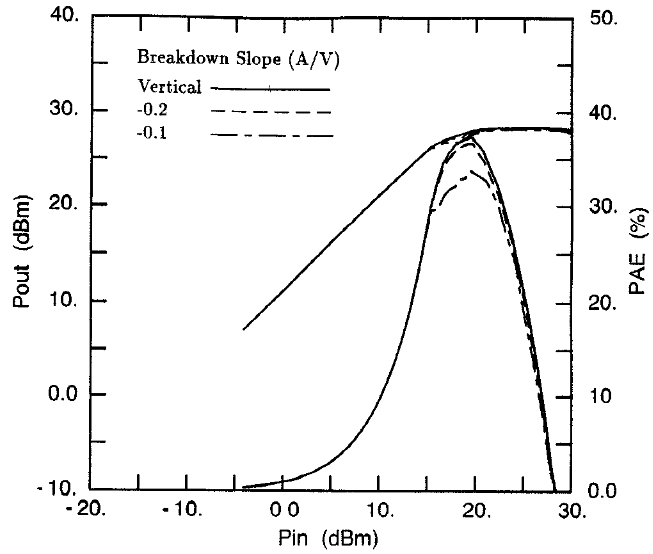

Figure 1: RF Output Power and Power Added Efficiency of the Matched Amplifier for Three Different Breakdown Slopes.

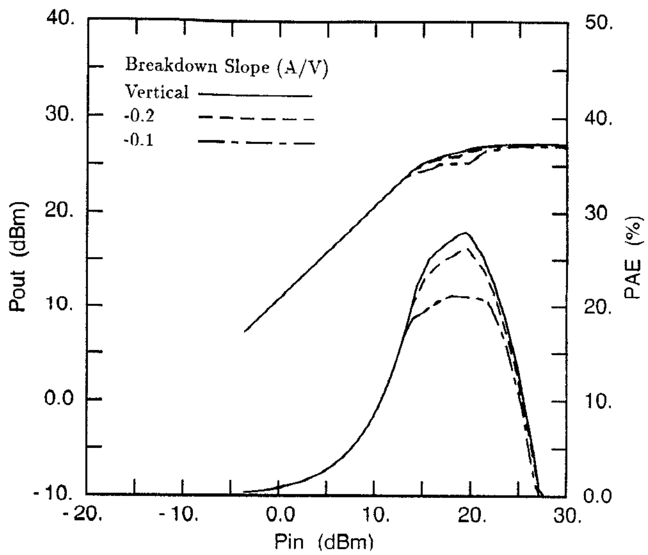

Figure 2: RF Output Power and Power Added Efficiency of the Amplifier Under 50Ω Conditions for Three Different Breakdown Slopes.

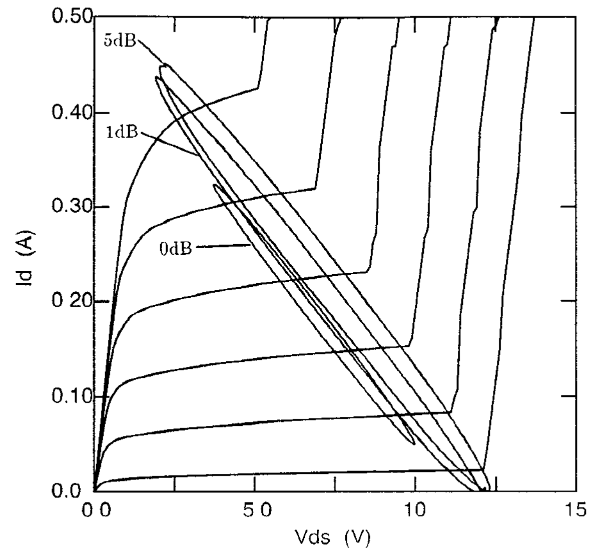

Figure 3: I-V Characteristics for the Matched Amplifier With a Breakdown Slope of -0.05A/V With Pinch-Off Breakdown Voltage of 12.5V for 0dB, 1dB, and 5dB Gain Compression.

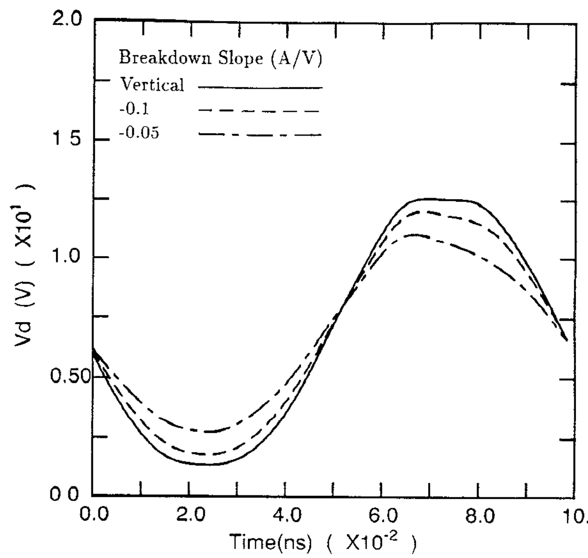

Figure 5: RF Drain Voltage of the Amplifier Under 50Ω Conditions at 1dB gain Compression for Three Different Breakdown Slopes.

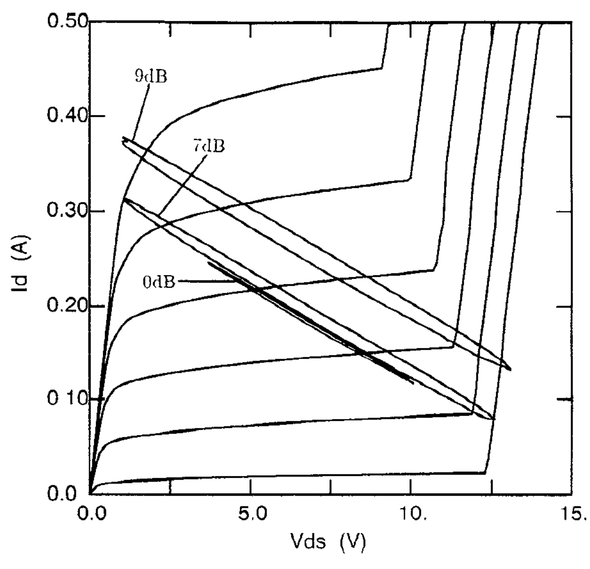

Figure 4: I-V Characteristics for the Amplifier Under 50Ω With a Breakdown Slope of -0.1A/V With Pinch-Off Breakdown Voltage of 12.5V for 0dB, 7dB, and 9dB Gain Compression.

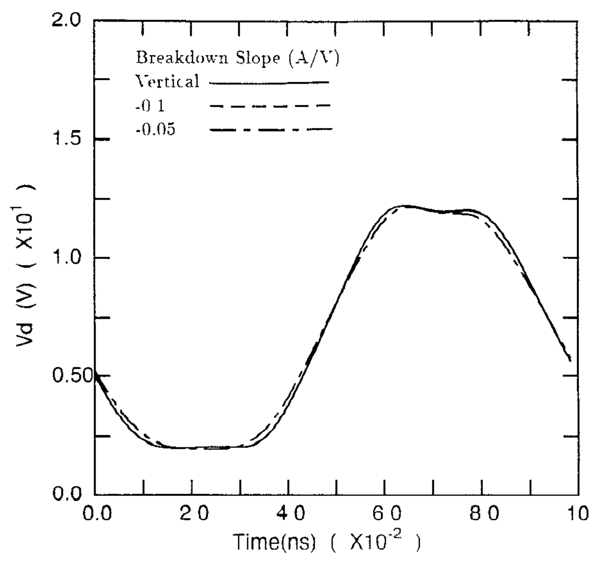

Figure 6: RF Drain Voltage of the Amplifier Under Matched Conditions at 1dB gain Compression for Three Different Breakdown Slopes.