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AlGaN/GaN HFET Amplifier Performance and Limitations*

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***Abstract* — Wide bandgap semicondctor field-effect transistors based upon the AlGaN/GaN heterostructure often demonstrate premature saturation and degradation of the RF output power, power-added efficiency, and gain as the device is driven into saturation. The effect is generally accompanied by 'current slump', where the dc current decreases with increasing RF drive. It is demonstrated that charge non-confinement in the 2DEG under large-signal conditions can produce source resistance modulation that degrades RF performance consistent with experimental data.**

I. INTRODUCTION

Field-Effect Transistors based upon the AlGaN/GaN heterostructure are potentially attractive for applications requiring high RF output power and the ability to operate at high ambient temperature. These devices are predicted from theoretical models to be capable of producing RF output power on the order of 10-12 W/mm of gate periphery [1] with power-added efficiency approaching theoretical limits. Spot experimental results indicate performance in agreement with the theoretical predictions, with slightly over 10 W/mm RF power [2,3] obtained in C-band and X-band. Power-added efficiency, with good gain, also approaches the theoretical expectations, at least through C-band. However, the RF performance of these devices often experience limitations due to physical effects associated with nonlinear charge phenomena in the two-dimensional gas that forms at the hetero-interface between the AlGaN and GaN. These effects result in an increase in channel resistance that varies with RF drive. The performance limitations are investigated and it is demonstrated that charge non-confinement produces a source resistance modulation at high current conditions that can limit the dynamic RF voltage and current, thereby limiting RF output power and efficiency. The effect is simulated in a large-signal RF model and produces results in agreement with experimental data.

II. PREMATURE SATURATION

AlGaN/GaN HFET's designed for maximum RF output power often demonstrate premature saturation of the RF output power, reduced power-added efficiency, and gain compression at RF drive levels lower than would normally be expected. In addition, the dc drain current is observed to decrease as a function of increasing RF drive, in opposition to the normal operation of field-effect transistors. Generally, when FETs are driven into saturation the dc drain current will increase as a function of RF drive due to clipping of the RF current waveform when the gate diode is driven into forward and reverse conduction under large-signal conditions. The dc channel current is the average value of the drain-source current waveform, and this waveform is distorted so that more current flows under forward conduction of the gate electrode. The results is an increase in dc current with RF drive.

This behavior can be altered under certain conditions in AlGaN/GaN HFETs, and it is sometimes observed that the dc drain current decreases with RF input drive, as shown in Fig. 1, creating a premature saturation effect. This produces degradation in RF output power and power-added efficiency with increasing RF drive and highly non-linear performance results.

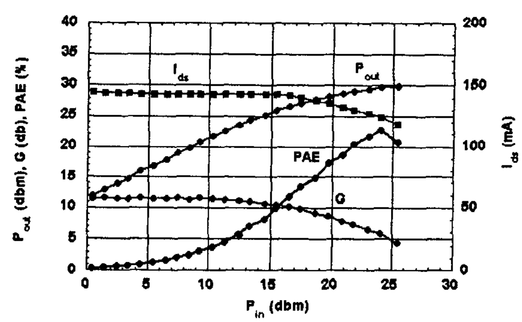

Fig. 1 Performance of an 18 GHz AlGaN/GaN HFET Amplifier Demonstrating Current Slump and Premature Saturation

This effect is sometimes referred to as 'current slump', and has been observed in a variety of AlGaN/GaN HFET's, and if not corrected, will limit or preclude the application of these devices as power amplifiers in many communications and radar applications where high linearity is required.

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There are several locations within the HFET, as shown in Fig. 2, where nonlinear charge behavior could produce premature saturation. Of the possible sources of nonlinear behavior, the AlGaN surface has been shown to have significant effects upon device performance. It has been shown that performance degradation can be caused by a high density of surface charging states that deplete the conducting channel, thereby producing a reduction in current as the states become increasingly charged [4-6]. Rectification of the gate current causes a dc current to flow into the surface states, thereby permitting the surface to become negatively charged.

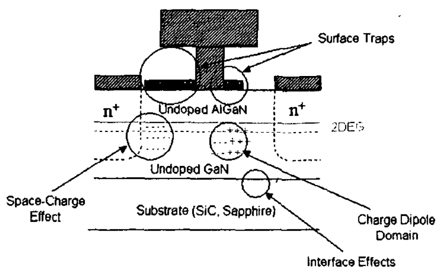

Fig. 2 HFET Structure Indicating Locations of Physical Effects Limiting RF erformance

This mechanism produces a premature saturation effect that varies with the condition of the AlGaN surface, with the greatest RF performance degradation obtained from devices with unpassivated surfaces. However, surface passivation is found to reduce premature saturation, but not eliminate it, and premature saturation is often observed with passivated devices. It is found that surface state arguments alone cannot explain the experimental data.

III. CHARGE NON-CONFINEMENT UNDER LARGE-SIGNAL CONDITIONS

Theoretical modeling has shown that nonlinear charge effects due to non-confinement of the electrons in the 2DEG that forms at the AlGaN/GaN heterointerface can be a cause of premature saturation. The band diagram for the heterointerface is shown in the sketch in Fig. 3. Under high current injection conditions the channel current density can achieve very high values, on the order of $J_{ds}>10^6$ A/cm^2. Under these conditions the space-charge from the high density of injected channel electrons can produce two nonlinear phenomena: (1) space-charge suppression of the electric field, primarily in the gate-source region, and (2) scattering of electrons from the 2DEG into the bulk AlGaN and GaN layers. The result is that electrons can be forced out of the 2DEG when the RF channel current is at peak magnitude during the positive portion of the current swing. The most significant effects occur in the region of the channel between the gate and source contacts.

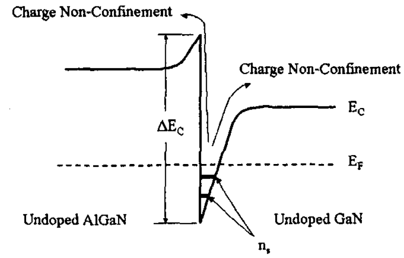

Fig. 3 Energy Band Diagram for an AlGaN/GaN Heterojunction Showing Electron Non-Confinement

Scattering of the 2DEG electrons into the GaN layer is much more likely due to the lower energy barrier between the 2DEG and the surrounding bulk layers. However, once the electrons are transferred from the 2DEG a parallel conducting path is formed. Due to low mobility of electrons in the bulk GaN or AlGaN, layers a parasitic resistance is generated that acts in parallel with the channel resistance, but is modulated in magnitude in-phase with the RF channel current.

IV. SOURCE RESESTANCE MODULATION

The source resistance modulation is demonstrated in Fig. 4, which shows a simulation of the source region of an AlGaN/GaN HFET under high current injection conditions.

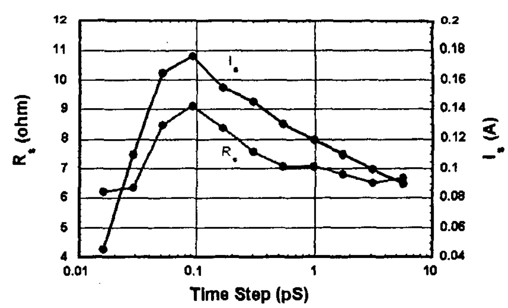

Fig. 4 HFET Source Resistance Modulation Due to High Current Density

To obtain these results the gate was ramped with a time dependent voltage sufficient to vary the channel current from pinch-off to a forward bias on the gate of about +1 v. The forward bias is sufficient to cause the onset of nonlinear charge effects, but less than the forward bias obtained in experimental devices.

As shown in Fig. 4, the source resistance increases at high current and directly follows the high current amplitude. Under reduced channel current near pinch-off, the source resistance maintains a low and constant magnitude. The source resistance is modulated, therefore, in response to the current density and is characterized with a highly nonlinear current dependent characteristic. This modulation results from a combination of space-charge and electron non-confinement effects under high current conditions, and is present independent of surface passivation. The modulation increases rapidly once the threshold for space-charge limited current flow and electron non-confinement are achieved. The source resistance increase can become significant and modulation of R_s by an order of magnitude for a doubling of channel current can easily be observed.

The source resistance modulation can produce the current slump and premature saturation observed in experimental data. This is demonstrated in Fig. 5, which shows the dynamic load line superimposed upon the i-v characteristics for an AlGaN/GaN HFET.

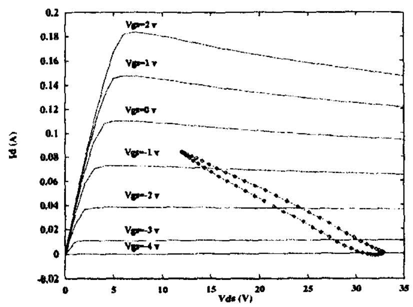

Fig. 5 Dynamic Load Line at 10 GHz Showing Effects of Source Region Resistance Modulation Under Large-Signal Operation for an AlGaN/GaN HFET Class A Amplifier (Vds=25 v, Class A/B)

The transistor was biased with a drain bias of V_{ds}=25 v and tuned for maximum power-added efficiency under class A/B conditions at 10 GHz. The results were obtained using a large-signal simulator that includes a physical model for the device embedded into an RF circuit environment. The physical model permits the effects of source resistance modulation to be investigated.

As shown in Fig. 5, the increased source resistance under high channel current limits the dynamic response of the RF i-v characteristic and reduces the magnitude of the current-voltage swings that can be achieved. The source resistance is modulated so that it increases during the high current, low voltage portion of the dynamic characteristic. The increased resistance prevents the dynamic i-v characteristic from achieving the full swing available from the dc I-V characteristic. In fact, for the simulation shown in Fig. 5, the RF voltage does not fall below about 12 v. This result is consistent with measured dynamic RF i-v characteristics [3]. The effect becomes more significant as the device is driven into saturation, and is most pronounced when the device is biased class A and driven with a large-signal gate voltage. Under these conditions a large forward bias RF current can flow through the gate electrode. Large-signal simulations show that the gate current can be on the same order of magnitude as the channel current. Under these conditions space-charge and charge non-confinement effects in the source region occur, resulting in source resistance modulation.

V. RF PERFORMANCE DEGRADATION

The increased source resistance during the high current portion of the RF cycle prevents the RF current from obtaining the full swing available in the absence of space-charge effects, thereby degrading the dc and RF performance of the device. The result is degradation in the dc and RF performance of the device, as shown in Fig. 6.

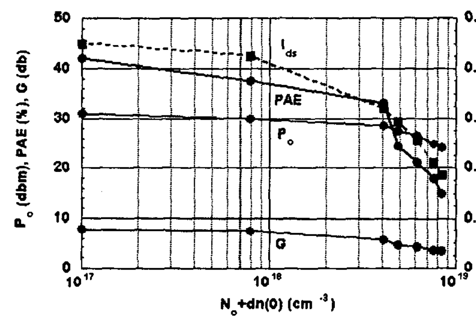

Fig. 6 RF Performance as a Function of Injected Charge for an AlGaN/GaN HFET Showing Premature Saturation

These results were obtained from the simulation of an AlGaN/GaN HFET amplifier operating under class A/B conditions, and include source resistance modulation. As shown in Fig. 6, the dc channel current demonstrates current slump and decreases with increasing RF drive, in agreement with the experimental data shown in Fig. 1. The decreased channel current, in turn, produces a decrease in RF output power, power-added efficiency, and gain, consistent with the observed premature saturation phenomenon. The large-signal simulation results shown in Fig. 6 are for the operation of an AlGaN/GaN HFET amplifier at 10 GHz and are in excellent agreement with experimental data.

It is observed that a relatively small variation in source resistance can have a significant effect upon the large-signal performance of the device. The source resistance will be modulated in response to the current, and will, therefore, vary throughout the RF cycle. The result is a nonlinear source resistance, as shown in Fig. 7, that will degrade device linearity, as well as degrade RF output power, power-added efficiency, and gain.

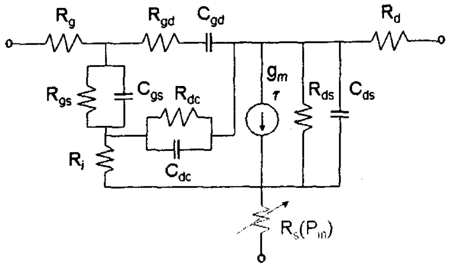

Fig. 7 HFET Equivalent Circuit Showing a High Current Nonlinear Source Resistance Modulation

AlGaN/GaN HFETs, in fact, do not currently demonstrate good linearity, as indicated in third order intercept measurements, which are typically in the range of 22-25 dbm as shown in Fig. 8.

The modulated source resistance also degrades the frequency response of the HFET. As source resistance increases the external device transconductance, g_m, will decrease. This, of course, produces a reduction in the device f_T, thereby limiting the upper frequency at which the device can operate. The reduction is a function of the RF drive, so that frequency performance is decreased as the device is driven to increased levels of RF power.

VI. CONCLUSION

Field-Effect Transistors based upon the AlGaN/GaN system can produce RF output power on the order of 10-12 W/mm. However, these devices often demonstrate current slump and premature saturation of the gain, accompanied by degradation of the RF output power and power-added efficiency. It is shown that source resistance modulation under high current injection conditions can produce premature saturation effects consistent with experimental data. Elimination of the effect will require design modifications that increase the threshold for space-charge effects to become significant.

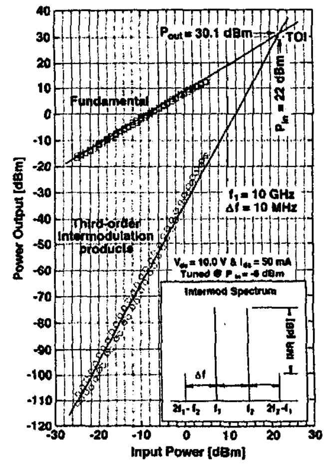

Fig. 8 3rd Order Intercept Measurements for an AlGaN/GaN HFET Amplifier

REFERENCES

1. R.J. Trew, "Wide Bandgap Semiconductor Transistors for Microwave Power Amplifiers," IEEE Microwave Magazine, vol. 1, pp. 46-54, March 2000.
2. Y.F. Wu, D. Kapolnek, J.P. Ibbetson, P. Parikh, B. Keller, and U.K. Mishra, "Very-High Power Density AlGaN/GaN HEMT's," IEEE Trans. Electron Dev., vol. 48, pp. 586-590, Mar. 2001.
3. V. Tilak, B. Green, V. Kaper, H. Kim. T. Prunty. J. Smart, J. Shealy, and L. Eastman, "Influence of Barrier Thickness of the High-Power Performance of AlGaN/GaN HEMT's," IEEE Electron Dev. Lett., vol. 22, pp. 504-506, Nov. 2001.
4. B.M. Green, et. al., "The Effects of Surface Passivation on the Microwave Characteristics of Undoped AlGaN/GaN HEMT's," IEEE Electron Dev. Lett., vol. 21, pp. , June 2000.
5. X.A. Dan, E.T. Yu, E.J. Piner, and B.T. McDermott, "Influence of Surface Processing and Passivation on Carrier Concentrations and Transport Properties in AlGaN/GaN Heterostructures," J. App. Phy., vol. 90, pp. 1357-1361, Aug. 2001.
6. R. Vetury, N.Q. Zhang, and U.K. Mishra, "The Impact of Surface States on the DC and RF Characteristics of AlGaN/GaN HFET's," IEEE Trans. Electron Dev., vol. 48, pp. 560-565, Mar. 2001.