Nonlinear GaAs MESFET Modeling Using Pulsed Gate Measurements

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***Abstract* —The effects of traps in GaAs MESFET's are studied using a pulsed gate measurement system. The devices are pulsed into the active region for a short period (typically 1 μs) and are held in the cutoff region for the rest of a 1 ms period. While the devices are on, the drain current is sampled and a series of "pulsed gate" $I-V$ curves are obtained. The drain current obtained under the pulsed gate conditions for a given V_{gs} and V_{ds} gives a better representation of the instantaneous current for a corresponding V_{gs} and V_{ds} in the microwave cycle because of the effects of traps. The static and pulsed gate curves were used in a nonlinear time-domain model to predict harmonic current. The results showed that analysis using pulsed gate curves yielded better predictions of harmonic distortion than analysis based on conventional static $I-V$ curves under large-signal conditions.**

I. Introduction

MOST PRESENT nonlinear modeling techniques for GaAs MESFET's use dc $I-V$ characteristics to represent the nonlinear drain current. Usually the drain current (I_{ds}) is plotted as a function of the drain-to-source voltage (V_{ds}) for various gate biases (V_{gs}). Yet there is some evidence that these dc curves may not accurately characterize the device at microwave frequencies. For example, the value of output resistance taken directly from the dc curves using

$$\frac{1}{R_o}=\left(\frac{\partial I_{ds}}{\partial V_{ds}}\right)_{V_{gs}} \qquad (1)$$

often does not agree with the value taken from the small-signal model at RF frequencies. Camacho-Penalosa and Aitchison reported that the output resistance of a MESFET varies as a function of frequency from dc to about 100 kHz, and they attributed this variation to the presence of traps at the epilayer–substrate interface [1]. More recently, Ladbrooke and Blight attempted to tie together several anomalous effects including the low-frequency dispersion of the transconductance and the rate and sweep dependence of the drain current characteristics by analyzing the role of surface states in the operation of the MESFET. They emphasize that although the characteristic frequencies of these states are typically in the kHz range they nonetheless affect the microwave frequency operation of the device by modifying the shape of the depletion region for a given V_{gs} and V_{ds} [2]. Smith *et al.* developed a technique for measuring the nonlinear characteristics based on RF measurements and reported good results in predicting harmonic content. However, their setup was elaborate and difficult to implement [3].

The purpose of our work was to explore a means of detecting whether traps play a role in MESFET operation and to determine if models based on transfer characteristics obtained under "pulsed" conditions are more accurate than models based on standard dc curves. In our work we developed a simple means of representing the nonlinear drain current at microwave frequencies based on pulsed gate measurements of I_{ds} versus V_{ds}. The devices are biased in cutoff for most of the time and are pulsed on for a short period of time. The drain current is sampled while the device is on and the value is held using a sample and hold type circuit. Hence a series of pulsed gate curves are obtained and compared to conventional static transfer curves.

To test the accuracy of the pulsed gate curves, measurements are taken to determine the output resistance of the device as a function of frequency from dc to 1 MHz. These results are compared to values obtained graphically from the transfer curves and also from fitting the microwave frequency S-parameter values to an equivalent small-signal model. Both sets of curves are then used in a nonlinear time-domain analysis model to predict harmonic content, and the results are compared to measured values.

II. Experimental Setup

The overall block diagram of the circuit used to obtain our pulsed gate measurements is shown in Fig. 1. The function of the sample and hold circuit is to determine the magnitude of a signal at a given instant and to hold that value for future processing without providing a load to the signal source. In our setup we used the commercially available Harris HA-5320 S/H amplifier, which met the experimental criteria for acquisition time (time required for the output voltage to match the input voltage to within a certain percentage during the sample phase) and droop rate (voltage drop during hold phase).

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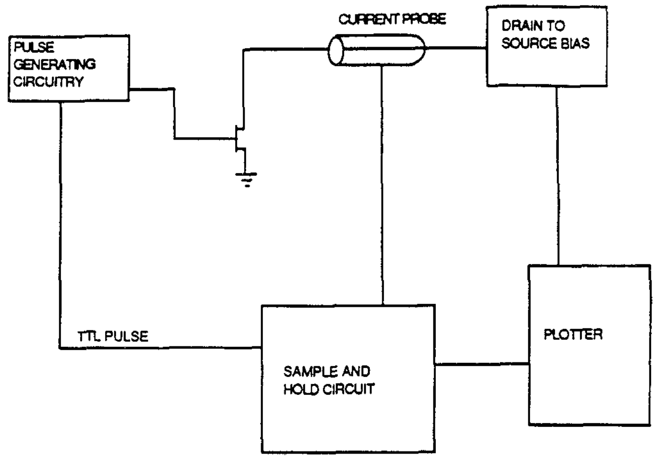

Fig. 1. Schematic diagram of pulsed $I-V$ measurement setup.

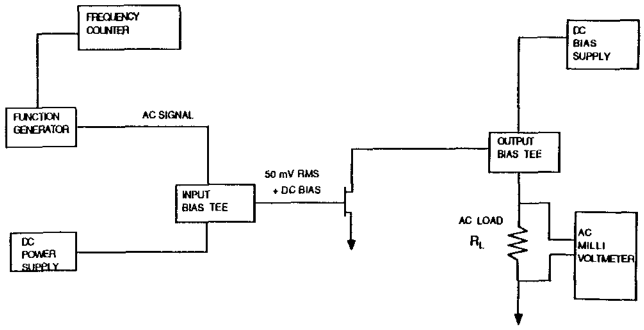

Fig. 2. Schematic diagram of low-frequency g_m and R_o measurement setup.

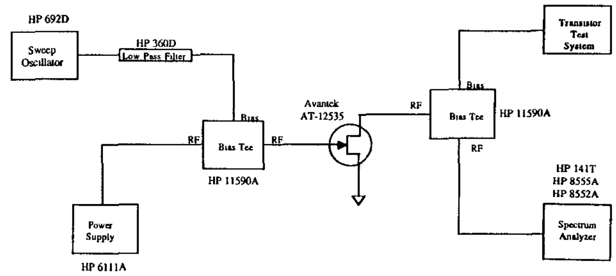

Fig. 3. Schematic diagram of microwave distortion measurement setup.

The timing sequence starts when a positive gate pulse from the pulse generator biases the device into the active region for a 1 μs period. The pulse amplitude determines the value of V_{gs}. This gate pulse also goes to trigger a second pulse generator which, after a very slight delay, provides a signal to drive the S/H amplifier into the sample mode. The delay is provided to ensure that the device is fully on and to allow for any response time of the current probe. The output of the current probe (proportional to I_{ds}) is the signal input of the S/H amplifier and is sampled during this period. The device is then biased into the cutoff region for a relatively long period (typically 1 ms), and the value of I_{ds} is held by the S/H amplifier. The cycle repeats all the while ramping V_{ds}. Since the ramping speed is slow compared to 1 ms, a set of smooth I_{ds} versus V_{ds} pulsed gate curves is produced for various V_{gs}.

The output resistance of the device as a function of frequency was found by connecting the MESFET in the common-source small-signal amplifier configuration shown in Fig. 2 following the method of Borrego *et al.* [4]. At low frequencies the capacitances of the MESFET equivalent circuit appear as open circuits. The transconductance g_m and the output resistance R_o can be determined by solving for the transfer function of the equivalent circuit, which gives the equation

$$\frac{1}{R_o}[R_S + R_D + R_L] = g_m\left[\frac{V_{\text{in}}}{V_{\text{out}}}R_L - R_S\right] - 1. \quad (2)$$

The series resistances R_S and R_D are obtained using standard techniques. The transconductance and output resistance are obtained by measuring the voltage gain for various load resistances R_L and using these data in a linear plot of the above equation. The procedure was repeated at various frequencies from 100 Hz to 1 MHz.

III. Microwave Harmonic Distortion Measurement Setup

We obtained distortion measurements at microwave frequencies using the setup shown in Fig. 3. In order to eliminate any harmonics generated by the sweep oscillator, we inserted a filter before the transistor. We loaded both the input and the output of the MESFET with 50 Ω in order to avoid the complications of designing a wide-bandwidth (3–9 GHz) matching network. The fact that we measured harmonic distortion at the higher input power levels ensured that we were in the nonlinear mode, even with the impedance mismatch. In order to cover both the linear and saturated regions, we used a range of input power levels from -10 dBm to $+10$ dBm.

We tested a packaged version of an Avantek AT-12535 GaAs MESFET suitable for low-noise applications from 2 to 12 GHz and biased it with a drain-to-source voltage of 2.0 V and a drain current of 20 mA. This MESFET has a 0.5 μm gate length by 500 μm gate width structure with air bridge interconnects between drain pads. We mounted the MESFET on a 30 mil alumina carrier with APC-7 launchers, and contact between the carrier and the MESFET was maintained by pressure.

Our first step in measuring distortion was to connect the sweep oscillator via the low-pass filter to the spectrum analyzer to determine the absolute power available from the source. Next, we connected the signal generator via the low-pass filter to the transistor and connected the spectrum analyzer to the output of the transistor to measure the absolute power levels delivered to the load of the fundamental, second-, and third-harmonic signals. To prevent harmonic distortion due to the spectrum analyzer's mixer, we sufficiently attenuated the signal using its built-in attenuator.

IV. Results

How traps might cause a difference between dc transfer curves and 1 MHz transfer curves would depend on the number and location of the traps, the capture and emission

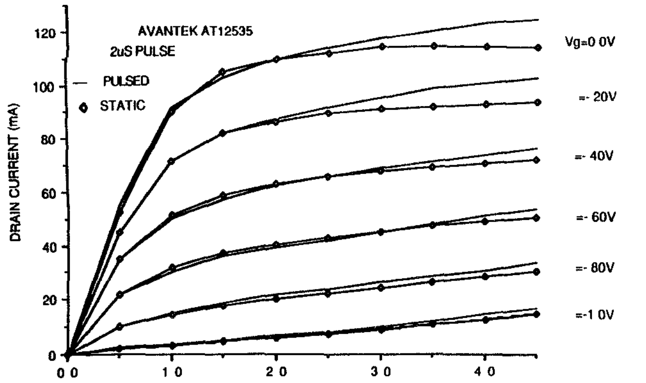

Fig. 4. Comparison of static and pulsed drain characteristics for Avantek device.

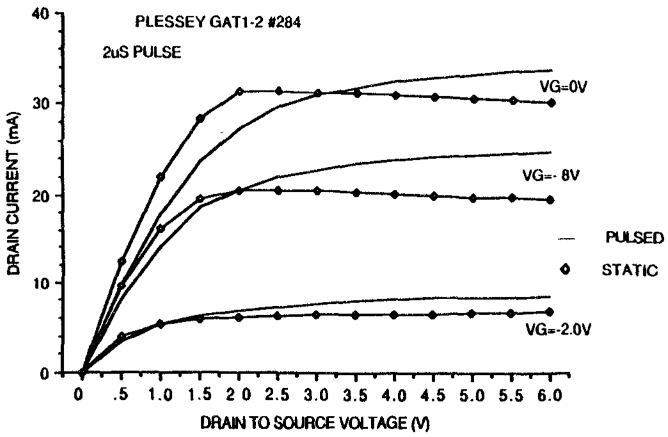

Fig. 5. Comparison of static and pulsed drain characteristics for Plessey device.

rates of the traps, and whether they were hole or electron traps. These factors in turn would depend on the processing techniques used to fabricate the devices and could be expected to vary greatly. Hence a qualitative description of how pulsed gate and dc transfer curves differ may vary greatly from one device to another. We used our pulsed gate measurement system on several different types of discrete devices and found that in each case the pulsed gate curves differed from the static curves. Figs. 4 and 5 show the results for a 0.5 μm gate Avantek AT 12535 device and an older 4 μm gate Plessey GAT-1 device. Similar results were obtained for other devices.

An examination of the pulsed gate curves yields several interesting observations. First we note that the pulsed gate curves yield a finite value for the output resistance in the saturation region. For the Plessey device the conventional $I-V$ curves have a negative slope in the saturation region which would give a negative value for R_o. Also we see that the value of output resistance obtained under pulsed conditions is smaller (larger slope in the $I-V$ curves) than the value from the static curves. This would confirm the Camacho-Penalosa results that the output resistance decreases from dc to RF frequencies. The current from the static measurements was greater than the current from the pulsed rate curves for a given bias condition in the linear region. This effect was much more pronounced in the older, longer channel length Plessey device than in the

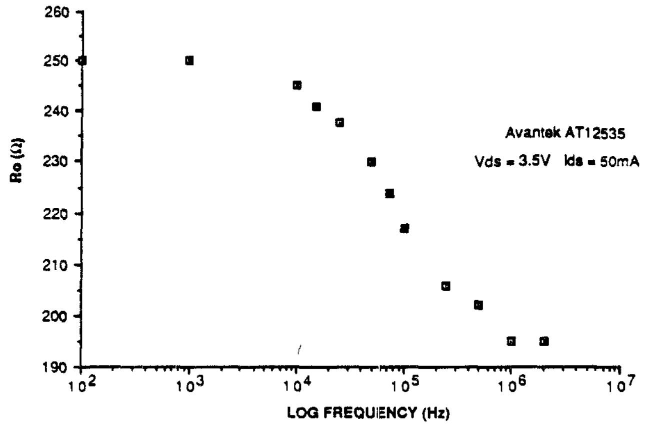

Fig. 6. Frequency dependence of small-signal output resistance R_o.

TABLE I

COMPARISON OF MEASURED VALUES OF R_o, AND VALUES OBTAINED GRAPHICALLY FROM THE $I-V$ PLOTS

Bias point:	$V_{ds} = 3.5$ V, $V_{gs} = -0.4$ V	$V_{ds} = 3.5$ V, $V_{gs} = -0.6$ V	$V_{ds} = 3.5$ V, $V_{gs} = -0.8$ V
R_o (100 Hz)	279 Ω	256 Ω	267 Ω
R_o (Static $I-V$)	290 Ω	255 Ω	263 Ω
R_o (1 MHz)	190 Ω	192 Ω	208 Ω
R_o (Pulsed $I-V$)	192 Ω	189 Ω	212 Ω

Avantek device, and was observed in all devices tested. In the saturation region the current obtained under pulsed conditions was greater than the current obtained under dc conditions for a given bias point for the two devices shown. This effect was not observed in all devices tested; for some devices the pulsed gate curves showed less drain current for a given bias in both the linear and the saturation region. Possible explanations for these observations will be given shortly.

To check the accuracy of our system we measured the output resistance as a function of frequency for the Avantek device, and the results are shown in Fig. 6. The results were similar to those reported by Camacho-Penalosa except for the fact that the frequency dependence extended to a slightly higher frequency. We then computed the output resistance graphically from the static and pulsed $I-V$ curves. Table I lists the results of our analysis.

We see that there is excellent agreement between the measured values of R_o at low frequency and the value obtained graphically from the static curves and between the measured value of R_o obtained at 1 MHz and the value obtained graphically from the pulsed gate curves. To get a *rough* comparison of how the values of R_o compared to values obtained from microwave frequency measurements, we fitted the small-signal equivalent circuit (Fig. 7) to S-parameter data. The result yielded $R_o = 202$ Ω at $V_{gs} = -0.8$V, $V_{ds} = 3.54$, which is close to both our measured 1 MHz value and the value obtained from the pulsed gate measurements. We conclude that the pulsed gate measurements yield graphic results for R_o that are much closer to actual microwave values than results taken from static $I-V$ curves.

In our work, we used the nonlinear time-domain model of Curtice and Ettenberg [5], [6], which we felt accounted

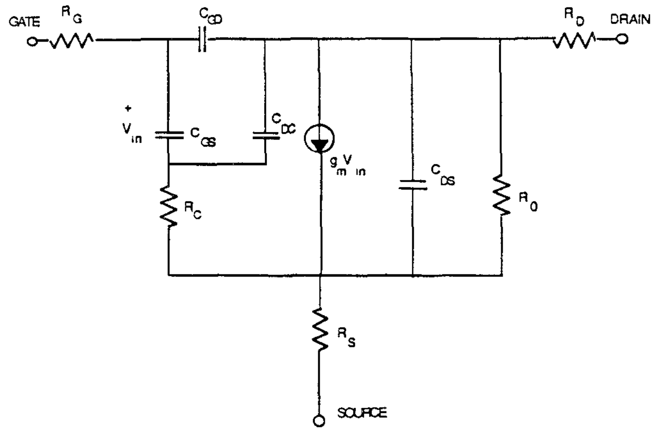

Fig. 7. MESFET small-signal equivalent circuit.

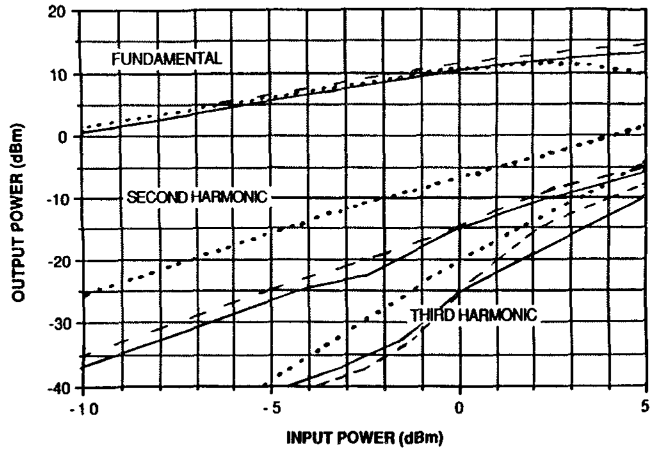

Fig. 8. Comparison of fundamental power and harmonic distortion measurements. ——— Microwave measurements. ---- Predicted using pulsed $I-V$ characteristics. ···· Predicted using static $I-V$ characteristics.

for most of the factors that contribute to harmonic products. A cubic fit, hyperbolic tangent function is used to represent the drain current:

$$I_{ds} = \left(A_0 + A_1V_1 + A_2V_1^2 + A_SV_1^3 \tanh\left(\gamma V_{\text{out}}\right)\right.$$
$$V_1 = V_{\text{in}}\left[1 + \beta\left(V_{\text{BIAS}} - V_{\text{out}}\right)\right] \tag{3}$$

where A_0, etc., are the fitting coefficients, γ is a hyperbolic tangent fitting parameter, β is the coefficient for pinch-off change, and V_{BIAS} is the dc bias point at which the parameters were evaluated.

Two sets of SPICE analyses were conducted to predict harmonic content, one using static $I-V$ curves and one using pulsed gate $I-V$ curves. The results were compared to measured values and are given in Fig. 8. The parameters used in the two analyses were identical except for the fitting parameters for representing the nonlinear drain current. The results indicate that the analysis based on static $I-V$ curves gave adequate predictions in the linear region for the fundamental output power. However, analysis based on the pulsed gate measurements gave much better results in predicting the 1 dB compression point and in predicting the second- and third-harmonic output power levels.

V. Discussion

The conclusion reached from the above results is that for large-signal and/or nonlinear analysis, pulsed gate $I-V$ curves give a better representation of the nonlinear drain current than static $I-V$ curves due to the presence of traps. Because the emission rate of traps is slow compared to the microwave signal, the number of traps at a given instantaneous voltage in the microwave cycle will be different from the number of filled traps at the corresponding dc condition.

As Ladbrooke and Blight [2] argue, the number of filled traps depends on the bias condition and affects the shape of the depletion region and, hence, the operation of the device for a given V_{gs} and V_{ds}. Further, as we stated, the time constants of these traps are such that the occupancy will be unable to follow the microwave signal and hence the number of filled traps will be fixed or frozen. For deep levels the capture rate is much faster than the emission rate, so we feel that the number of occupied states for the microwave signal will correspond to the largest number of occupied states that the dc + ac signal "sees."

For small-signal conditions the dc + ac signal is obviously close to the dc bias so that the number of occupied states that the microwave signal is fixed at is very close to the corresponding dc level. In this case we would expect that the drain current obtained from conventional static $I-V$ curves would give good results in predicting output power and harmonic content. Our results confirmed this expectation.

Under large-signal conditions the number of traps that are occupied could differ significantly from the number at the dc bias point. Hence the actual instantaneous drain current for a given V_{gs} and V_{ds} could differ significantly from the corresponding drain current obtained from static $I-V$ curves.

In our test setup we held the devices well into cutoff (large negative V_{gs}) for most of the period. Using the argument of Ladbrooke that thermonic field emission from the drain edge of the gate is the source of electrons that occupy surface states, we would expect that the largest number of surface states would be occupied under the large negative gate bias condition. When we pulse our gate on for a short period the surface state occupancy does not have a chance to change. Hence in our pulsed gate system we are measuring the drain current with a constant "worst case" number of filled surface states. This argument is borne out by our earlier observation that for all devices tested the current obtained from our pulsed gate measurement system in the linear region was less (i.e., a larger series resistance was present) than the current obtained from static $I-V$ measurements. Further this effect was more pronounced in the large-dimension, larger-series-resistance Plessey device, as we would expect. To summarize this argument, in the linear region we measured less current in the pulsed gate condition because more surface states were occupied and hence the series resistance was higher.

We cannot explain the observation of larger drain current in the saturation region for the pulsed gate $I-V$ curves for some of the devices in terms of the occupancy of surface states. As was pointed out earlier the difference between the pulsed gate and static $I-V$ curves depends directly on the number, location, and characteristics of the traps, which can be expected to vary greatly from device to device. It is possible that the increased current in the saturation region for the pulsed gate curves can be attributed to the occupancy of traps at the epilayer–substrate interface.

VI. Conclusions

Although the characteristic frequency of traps in GaAs MESFET's is typically in the kHz range, the traps nonetheless affect the performance of a device at microwave frequencies because they affect the general shape of the depletion layer. The number of occupied states cannot vary with the microwave signal. Hence under large-signal conditions, the instantaneous drain current obtained using static $I-V$ curves for a given V_{gs} and V_{ds} is not accurate. In this work we present a simple means of generating a set of pulsed gate $I-V$ curves. For nonlinear or large-signal analysis these curves give a better representation of the nonlinear drain current than static $I-V$ curves. The advantages of our measuring system are that it is convenient to set up (commercially available sample and hold amplifiers are available as IC's), it gives a set of curves which can readily be compared to static $I-V$ curves, and an accurate value of the output resistance can be obtained.

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