Novel Technique for Determining Bias, Temperature and Frequency Dependence of FET Characteristics

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Abstract—**A novel measurement of the dynamics of HEMT and MESFET behavior permits classification of dispersion effects and identifies operating regions that they affect. This reveals a simple structure to the otherwise complicated dynamic behavior that has concerned circuit designers. With this insight, it is possible to predict biases, temperatures and frequencies that dispersion will or will not affect. It is interesting to note that, for some devices, dispersion effects can be seen to exist at microwave frequencies and may therefore contribute to intermodulation distortion.**

I. Introduction

The variation of HEMT and MESFET characteristics with operating condition (bias, temperature and frequency) is a significant effect for many applications. Effective designs require descriptions of the device that predict the extent of these variations and the conditions where they occur. Ideally, the operating-condition dependency should be measured, quantified, and incorporated in FET models used to simulate circuits.

Self-heating [1] and charge trapping related to impact ionization [2][3] and leakage currents [4] are known to contribute to the variation of FET characteristics. Each contribution is thought to have an effect at a specific range of operating conditions.

A novel technique involving dc, large-signal pulse and small-signal RF measurements is proposed to identify the dynamics of thermal and trapping dispersions in FETs. This is discussed in Section II. The results of this are presented in Section III and the implications discussed in Section IV. Finally, some conclusions are drawn in Section V.

II. Measurement of FET Dynamics

Time-evolution measurements [4] give, for an initial bias, a set of I/V characteristics as a function of time. Analysis of these measurements provides a comprehensive understanding of the bias, temperature and frequency dependence of the FET characteristics. In particular, the journey from a starting bias point to any new bias point is observable.

The large-signal time-evolution data is easily measured with pulse techniques for time periods greater than the fastest pulse measurement. Large-signal characteristics over shorter time periods are not resolvable. However, small-signal parameters can be measured with RF techniques. Transconductance and drain conductance determined numerically from pulse data, together with RF measurements, can therefore be employed to obtain small-signal parameters from dc to microwave frequencies. The results can be usefully presented by intrinsic gain (transconductance divided by drain conductance) as a function of operating condition. Although this measurement is limited to small-signal parameters and necessarily considers many biases rather than a single bias, it provides a comprehensive measurement of dispersion dynamics in FETs.

The intrinsic gain over the 10 decades of frequency from 1 Hz to 10 GHz, or in pulse terms from 160 ms down to 16 ps, is shown in the contour map of Fig. 1. For each bias point, the small-signal parameters were derived from pulse data measured with an enhanced arbitrary pulsed semiconductor parameter analyzer[1] [5] for frequencies below 1 MHz, and from Y-parameters measured with a network analyzer for frequencies above 1 MHz.

III. Intrinsic Gain

The results presented here summarize a study of large-signal pulse and small-signal RF measure-

[1] Arbitrary Pulse Semiconductor Parameter Analyzer, 2001 [Online]. http://www.elec.mq.edu.au/cnerf/

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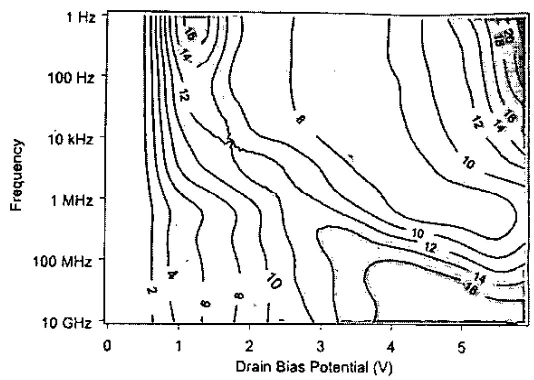

Fig. 1. Intrinsic gain versus drain bias for the HEMT operating at 25° C with $V_{GS} = -0.4$ V.

ments that encompass an extremely wide range of frequencies from dc to microwave and a wide range of bias and temperature. Measurements were made for both a MESFET and a HEMT at temperatures ranging from 10° C to 70° C, and for a range of V_{GS} biases. These measurements were on standard geometry devices at PCM sites on wafers recently manufactured in commercial processes.

The intrinsic gain for the MESFET in Fig. 2 is shown as frequency slices of a contour map. Comparison with pulsed-I/V data in Fig. 3 shows that the drain conductance as a function of time or frequency is seen to correlate with Fig. 2 at the 2V drain bias. For example, the intrinsic gain at 1 Hz is very large because the drain conductance is near zero.

Variation with V_{GS} and temperature is not dramatic. There is an increase in low-frequency intrinsic gain with either V_{GS} or temperature. High-frequency gain increases with V_{GS} but decreases with temperature. Of note is that above 1 MHz for the MESFET, there exists a region of isodynamic characteristics, in that there is no change in gain.

The intrinsic gain for the HEMT is shown in Fig. 1 and Fig. 4, for temperatures of 25° C and 70° C, and as frequency slices of the contour maps in Fig. 5 and Fig. 6. The latter is comparable to pulsed-I/V data in Fig. 7, where the drain conductance is seen to be the same at all frequencies, which correlates with the intrinsic gain of Fig. 6 for the 2.5V bias. The pulsed-I/V at 25° C, not shown here, shows a decrease in drain conductance at 1 MHz corresponding to the increase in gain at the 2.5 V bias point in Fig. 5.

Variation with V_{GS} and temperature is more complicated than for the MESFET because the dispersion mechanisms are more complex. Low-frequency gain deceases with V_{GS} while high-frequency gain is largely unaffected. Low-frequency gain also increases with temperature while high-frequency gain decreases. Referring to Fig. 1 and Fig. 4, it is seen that the contours change in a complicated manner. Higher temperature and changes in gate bias potentials affect the knee region, especially at low frequencies. There is little change at high drain bias.

Of note is that above 1 MHz there exists a region of isodynamic characteristics for low drain potentials, in that the gain remains constant. Also of note is that at high drain potentials, there is dispersion of gain at microwave frequencies.

IV. Dispersion Mechanisms

The dispersion effects can be modelled to a good approximation by considering three principal causes: a change in drain current due to a self-heating thermal effect; a change in effective gate potential due to a potential at electron traps; and a change in effective gate potential due to a potential at hole traps [6].

The thermal effect, evident in both the MESFET and HEMT at high power levels, stems from heating due to power dissipation. At high frequencies, the temperature of the device is set by the bias and the gain is that of the FET for the corresponding temperature. At low frequencies (< 10 kHz), the average power dissipation, and hence temperature, varies with the signal. The variation of temperature over the course of a signal swing reduces the output conductance, which increases the gain. For sufficiently high power levels, not shown here, the output conductance, and hence gain, becomes negative.

Consider the effect on the intrinsic gain of electron traps alone. At high frequencies the gain is not significantly affected because the trap potential remains constant relative to the signal. At low frequencies, the trap potentials change with the signal. The potential of the electron traps can be linked to a gate-drain leakage electron current from which they are filled [6]. As the gate-drain potential V_{GD} increases, so does the gate-drain current and hence the negative trap potential. Thus an increase in drain potential gives a more negative trap potential that reduces the drain current, so the drain conductance is reduced, which increases gain. This effect is the principal cause of *drain overshoot* and the converse is the cause of *gate lag*. The frequency at which gain increases varies with drain bias. This is because the trap occupancy rate increases as the gate-drain current increases. For the MESFET in Fig. 3, the characteristics do not change if V_{GD} is not changed, because there is no change in its electron trap potential.

Consider the effect on the intrinsic gain of hole traps alone. It is assumed that the trapped holes stem from impact ionization, only evident in the HEMT. The potential of the traps have a significant influence on the drain current through the transconductance of the device, whereas the impact ionization current in itself is an insignificant contribution.

As is the case with the other dispersion effects, the gain is not significantly affected at high frequencies because the trap potential remains constant. At low frequencies, the trap potential does change with the signal and there is a significant reduction in intrinsic gain. The reduction is most pronounced in the region of the *kink* in the drain characteristic, which is exactly what would be expected from the corresponding large increase in drain conductance. The frequency at which this occurs is linked to the magnitude of the impact ionization current and hence to the drain bias. The impact ionization current at high drain bias, as observed in measured gate current, is orders of magnitude larger than the gate-drain leakage current. Hence the occupancy rate of the hole traps is orders of magnitude faster than that of electron traps, so the dispersion effect extends to microwave frequencies.

An increase in temperature has a similar effect to a decrease in gate bias potential. Either will increase the gate-drain leakage current and impact ionization current, if present. These changes increase the occupancy rate of traps and has the effect of simply shifting the trap-related dispersion of FET characteristics to higher frequencies.

This model of the dispersion effects gives an understanding of the effect of bias, temperature and frequency on the characteristics of a FET. This is invaluable for assessing the dispersion of circuit design parameters. For example, the shift in gain of a FET with temperature can be determined from the position of the operating condition in relation to the intrinsic gain contour map.

There is also an implied effect on distortion and intermodulation that should be investigated. Dispersion of characteristics at signal frequencies may have a significant distorting effect. Also, differences due to dispersion between the characteristics at various frequencies of a multi-tone signal may affect the level of intermodulation.

V. Conclusion

An investigation of the various effects that influence the behavior of typical HEMTs and MESFETs has been presented. A technique for measuring intrinsic gain over a wide range of bias, temperature and frequencies has been proposed to give a comprehensive view of dispersion of FET characteristics. It was shown that there are dispersion effects that can be significant at microwave frequencies. Intrinsic gain is an excellent figure of merit for device assessment and study of bias, temperature and frequency dependence of dispersion and related distortion mechanisms.

Acknowledgements

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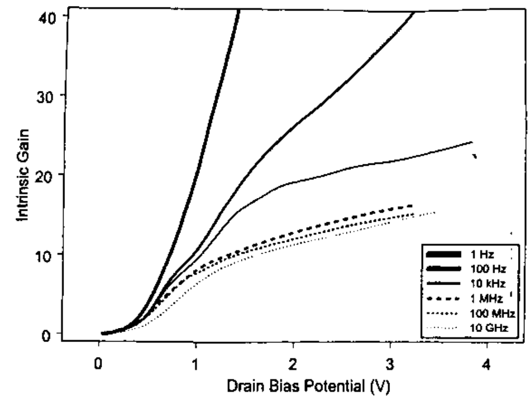

Fig. 2. Intrinsic gain versus drain bias for the MESFET operating at 25° C with $V_{GS} = -0.4$ V.

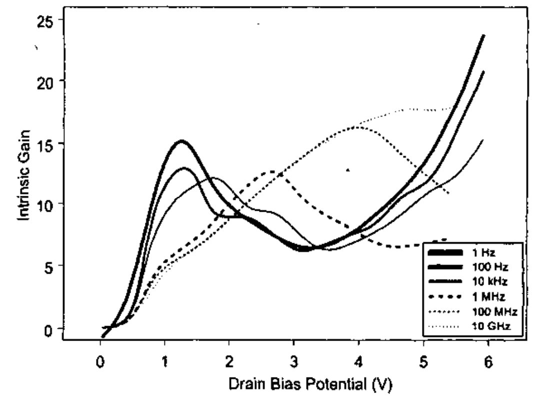

Fig. 5. Intrinsic gain versus drain bias for the HEMT operating at 25° C with $V_{GS} = -0.4$ V.

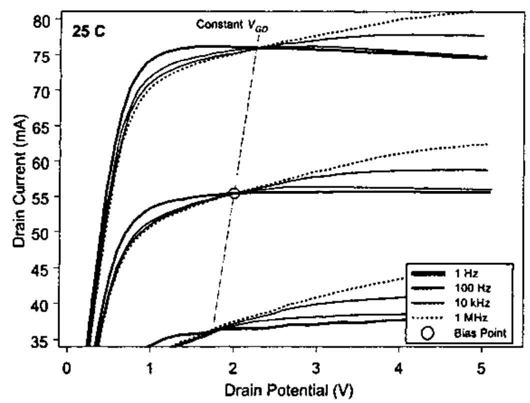

Fig. 3. Pulsed-I/V characteristics for the MESFET operating at 25° C with V_{GS} at –0.6, –0.4 and –0.2 V as the parameter.

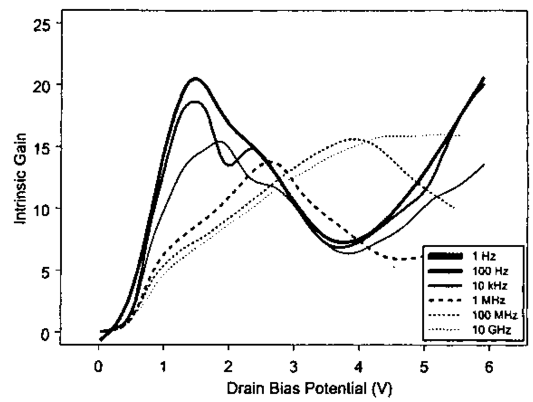

Fig. 6. Intrinsic gain versus drain bias for the HEMT operating at 70° C with $V_{GS} = -0.4$ V.

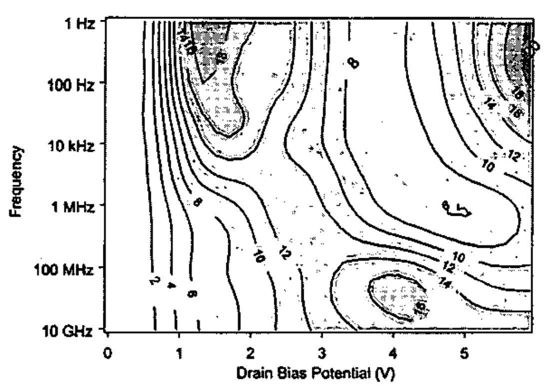

Fig. 4. Intrinsic gain versus drain bias for the HEMT operating at 70° C with $V_{GS} = -0.4$ V.

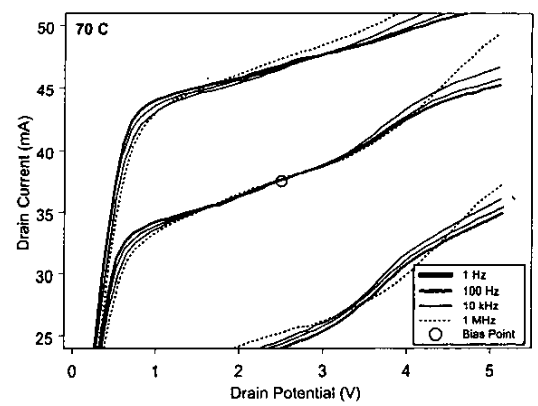

Fig. 7. Pulsed-I/V characteristics for the HEMT operating at 70° C with V_{GS} at –0.6, –0.4 and –0.2 V as the parameter.