THE TROUBLE WITH MICROWAVE TRANSISTORS AND HOW TO AVOID IT

Anthony E. Parker
Department of Electronics,
Macquarie University, Sydney AUSTRALIA 2109, mailto:tonyp@ieee.org
James G. Rathmell
School of Electrical and Information Engineering,
The University of Sydney, AUSTRALIA 2006, mailto:jimr@ee.usyd.edu.au

Abstract:– Microwave transistors, both HEMT and MESFET in either GaAs or InP, have characteristics that vary with both operating condition and frequency. A simple structure to this otherwise complicated dynamic behaviour of the FETs is revealed by large-signal pulse and small-signal RF measurements. These variations can be explained in terms of thermal effects and trap-related effects. The intrinsic gain, over frequency and bias, is proposed as an indicator of the impact on signals and distortion generation. An understanding of this is necessary in using these devices.

I. Introduction

The variation of HEMT and MESFET characteristics with operating condition and frequency, known as *dispersion*, is a significant effect for many applications and hinders design optimization. Understanding these affects, so that they can be accommodated or avoided, would improve the circuit design process. This requires device descriptions that predict dispersion or that can identify conditions where dispersion occurs.

The dynamic behaviour of dispersion in FETs can be linked to charge trapping and heating. The former is related to impact ionization and leakage currents, some of which contribute to gate current.

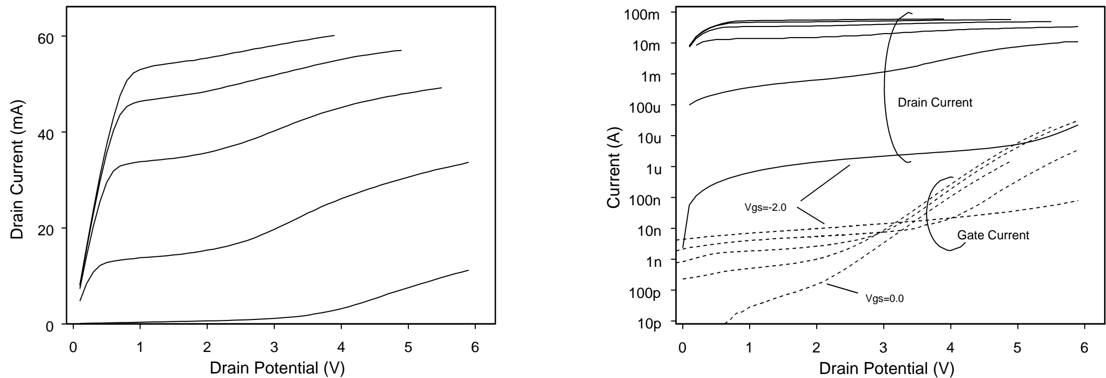
Trap-related dispersion occurs because the potential of trap sites around the channel contribute to the overall controlling *gate* potential of the FET [1][2]. Changes in the occupancy of the trap sites produce variations in the characteristics of the FET. The time constants of these variations are determined by the probability of trap occupancy, so are proportional to the currents that provide the charges to the trap sites. If these currents also contribute to the gate current, then the time constants for trap-related dispersion effects will be linked to the gate current.

To study dispersion, a pHEMT with dc characteristics shown in Fig. 1 was analyzed. These measurements were performed on standard geometry devices at PCM sites on wafers recently manufactured in commercial processes.

The characteristics of the HEMT in Fig. 1(a) are dominated by the *kink* effect that is accompanied by a significant rise in gate current in Fig. 1(b) caused by impact ionization. If the time constant for this dispersion can be inferred from the gate current, then it would be expected that the dispersion at large drain potentials would occur at very high frequencies because the gate current is high. At low drain potentials, the dispersion would be at lower frequencies corresponding to the lower gate current.

Devices that do not exhibit a kink, such as typical MESFETs, have a simpler gate current characteristic. In these devices the trap-related dispersion is expected to be at a frequency that increases moderately with drain potential as the gate current increases.

To explore the nature of the dynamic behaviour of FETs, a transient measurement of the time-evolution of drain characteristics can be used to identify thermal and trap-related dispersions and the frequencies at which they occur. This is discussed in Section II. To extend this further in the range of frequencies covered, RF measurements were performed. These are discussed



(a) Drain current with V_{GS} from -1.5 to 0.5 V.

(b) Drain current(—) and gate current (- -) with V_{GS} from -2.0 to 0.5 V.

Fig. 1. Steady-state drain (—) and gate (- -) currents of the HEMT with V_{GS} in 0.5V steps as the parameter.

in Section III. In the light of the results of these, dispersion effects are further discussed in Section IV. Finally, some conclusions are drawn in Section V.

II. Time-evolution Characteristics

Time-evolution measurements [1] give, for an initial operating condition, a set of I/V characteristics as a function of time. This can be displayed as a set of surfaces, each for a constant gate potential, of drain current versus time and drain potential as is shown in Fig 2.

An enhanced arbitrary pulse semiconductor parameter analyzer[1] was used to measure the time-evolution of the HEMT [2][3]. The enhancements provided the stability and accuracy required for time-domain measurements over many decades of time, from less than 80 ns to well over 1 s. For each point in the characteristic, several points in its vicinity were measured and the current determined by software interpolation. This was repeated for each point in the final characteristics and at each time point.

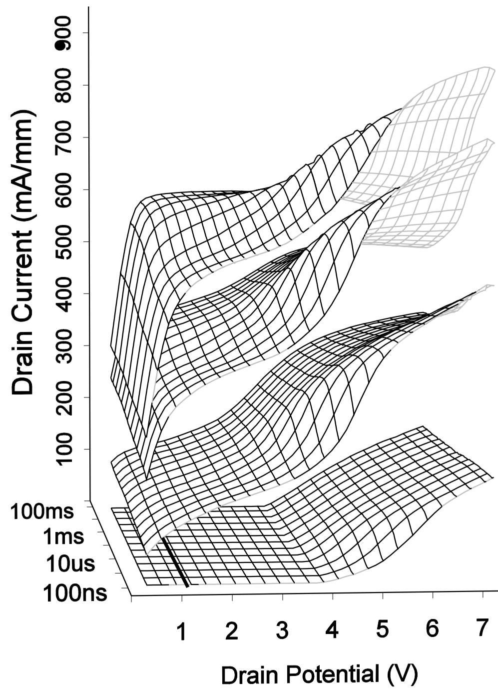
The journey to a new dc operating condition encounters various effects that are observed in the shape of the surfaces of the time-evolution characteristics, because they give a comprehensive view of the change in drain current after a step change from a specific bias point. The effects of the extent and direction of the change are clearly seen.

The time-evolution characteristics of the HEMT in Fig. 2 are dominated by the *kink* effect that can be related to the significant rise in gate current in Fig. 1(b) caused by impact ionization. The time-evolution characteristics of a MESFET, also analysed in this study, did not exhibit a kink, but rather had dispersion at rates dependent on drain potential, consistent with a simpler gate current characteristic.

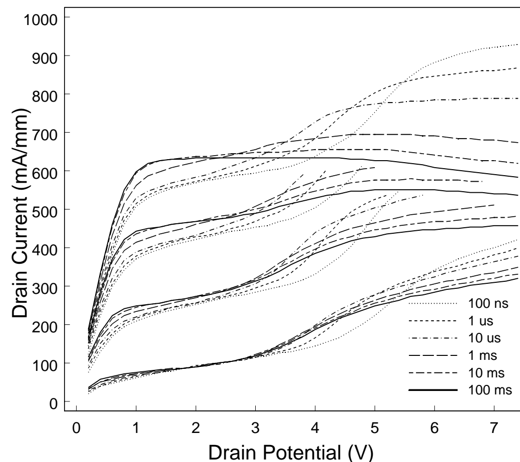
A. Observed Dynamic Behaviour

The kink effect in the HEMT time-evolution characteristics of Fig. 2 arises from an increase in current after a time related to drain potential. This is often referred to as *gate lag* and can be related to positive traps being formed at a rate proportional to an impact ionization current [4][5]. At potentials near or above that of the kink effect in the dc characteristics, there

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



(a) Time-evolution characteristics.



(b) Time slices of the time-evolution characteristics. The 100ns curves, from the front edge of Fig. 2(a), are the characteristic normally measured by a good pulsed-I/V system. The 100ms curves, from the rear edge of Fig. 2(a), approximate the dc characteristic.

Fig. 2. Measured characteristics of the HEMT in Fig. 1 from the initial condition $V_{GS} = -2.0$ V, $V_{DS} = 1.2$ V, with v_{GS} at –1.2, –0.8, –0.4, and 0.0 V as the parameter.

is a rapid, faster than 10 μs, increase in trap potential consistent with the presence of moderate impact ionization.

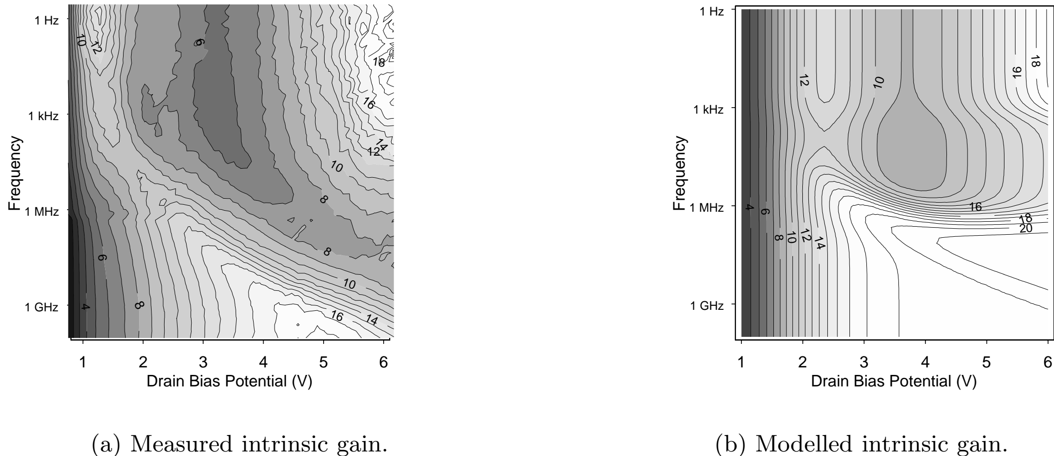
At potentials below that of the kink there is a significant dispersion with time constants from 100 μs to over 10 ms. The long time constants are due to the slow occupancy rate of the trap sites, which is to be expected because the contributing currents are low at these potentials.

At high potentials, the effect of heating due to power dissipation causes a reduction in drain current, possibly after an initial fall due to the formation of negative traps before or near the first 100ns measurement. The initial high drain current is often referred to as *drain overshoot*. At high power levels, it is possible to model the reduction in current due to heating and extract the isothermal characteristics [1]. The high-frequency trapping effects, not completely observable in the pulse data, are investigated below with RF measurements.

The time-evolution characteristics of the MESFET exhibited a simple *drain overshoot* followed by a fall in current when stepping to a potential higher than the initial bias. This can be explained by a minor contribution from heating due to power dissipation and a major contribution due to occupancy of negative charge traps.

B. Regions of Isodynamic Behaviour

The measurements of the HEMT at drain potentials below 3 V and at times less than 1 μs give isodynamic characteristics because they are not affected by the observed dispersion effects. At higher drain potentials, it would require much shorter pulses to obtain isodynamic characteristics. Alternatively, it may be possible to extrapolate the isodynamic measurements provided the dispersion mechanisms are understood. The existence of fast dispersion effects can be checked with RF measurements.



(a) Measured intrinsic gain.

(b) Modelled intrinsic gain.

Fig. 3. Measured and modelled intrinsic gain of the HEMT in Fig. 1 at $V_{GS} = -0.5$ V.

III. Small-signal RF Measurements

The data presented in the time-evolution characteristics are for the single bias point, or initial condition, of the measurement. Points and surfaces that are not near the bias point give a picture of the large-signal transient behaviour of the device. However, the period from the instant of change to the time of the first measurement at 100 ns is not resolvable by the pulse equipment. To fill in this gap, RF measurements can be employed, but are limited to small-signals.

In the region near the bias point, the transconductance and drain conductance parameters can be determined from the slopes of the characteristic. The small-signal intrinsic gain (ratio of transconductance to drain conductance) is a figure of merit that can thus be determined as a function of bias and time or frequency. This figure of merit ignores the large-signal aspects of the dynamic behaviour, but is a parameter that can be determined at microwave frequencies from measured Y-parameters. The intrinsic gain over many decades of frequency can be determined from pulse measurements for low frequencies, and RF measurements for high frequencies.

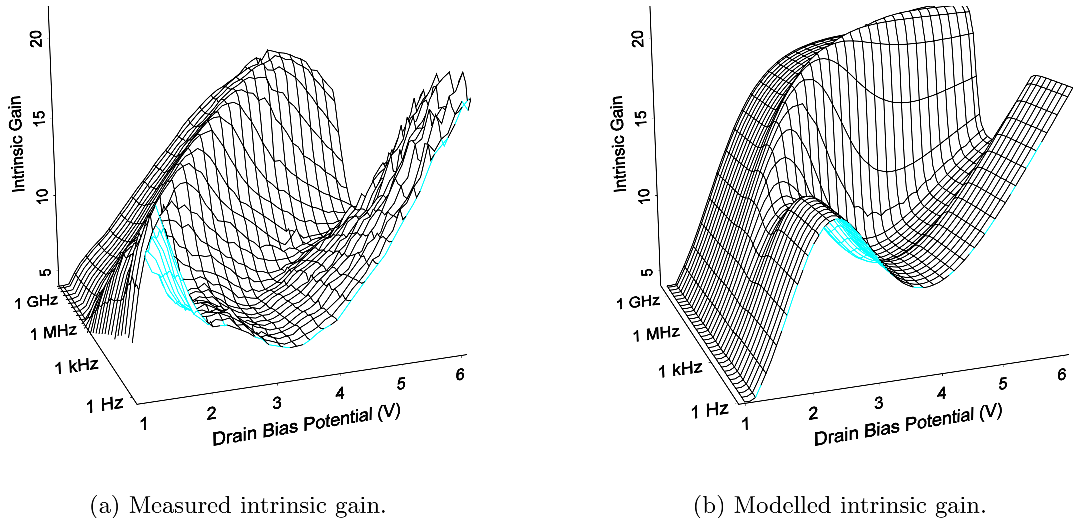
The intrinsic gain over more than 10 decades of frequency shown in Fig. 3(a) was extracted from pulse data for frequencies below 1 MHz, and measured with a network analyzer for frequencies above 1 MHz. This shows contours of small-signal intrinsic gain at a fixed gate bias as a function of drain bias and frequency. Looking along the 10GHz line, this figure shows a gain that increases from zero to about 17 as the drain bias varies from zero to 6 volts. This behaviour would essentially be the same at all frequencies except that dispersion effects occur and alter the intrinsic gain. To illustrate the mechanisms that contribute to the frequency dependence, a simple model is presented in Fig. 3(b) [6].

IV. Dispersion Effects

The dispersion effects evident in Fig. 3(a) can be modelled to a good approximation by three principal causes; a thermal effect and two trap-related effects.

The thermal effect is caused by heating due to power dissipation alone. At high frequencies, the temperature of the device is set by the bias and the gain is that of the basic FET. This increases with drain bias until saturation occurs. At low frequencies (< 1.5 kHz), the average power dissipation varies with the signal and the gain rises because the output conductance reduces. For sufficiently high power levels, not shown here, the output conductance would become negative.

Traps having an effect on the controlling potential are either electron traps or hole traps.



(a) Measured intrinsic gain.

(b) Modelled intrinsic gain.

Fig. 4. Comparison of measured intrinsic gain and the illustrative intrinsic gain model of Fig. 3.

Considering the effect on the intrinsic gain of electron traps alone, at high frequencies, the trap potential remains constant, so the gain is not significantly affected. Although in the high-frequency region there is a change in bias current due to the trap potential, this has little effect on the intrinsic gain. At low frequencies, the trap potentials change with the signal. As the drain-gate potential increases, so does the drain-gate 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.

The frequency at which gain increases varies with drain bias. This is because the trap occupancy rate increases as the gate-drain current increases.

Considering the effect on the intrinsic gain of hole traps alone, it is assumed that the trapped holes stem from impact ionization. This potential has 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 relative to the signal. 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.

An increase in hole trap occupancy has the effect of increasing drain conductance and this occurs in the vicinity of the kink. The frequency at which this occurs is linked to the magnitude of the impact ionization current and hence to the drain bias.

Despite the simplistic explanation of the effects of these three dispersions on intrinsic gain, it largely explains the overall behaviour. The contour plot of Fig. 3 is shown in Fig. 4 as a surface. It clearly shows a reduction in gain at low frequencies near a drain potential of 4 V, a saddle in the gain at a drain potential of about 2 V, and a ridge in the surface at about 2 kHz. The existence of a region of isodynamic behaviour above 1 MHz and at drain potentials less than 3 V is also predicted.

The differences between the real device of Fig. 4(a) and the model of Fig. 4(b) arise from simplifications in the explanation.

In the real device of Fig. 4(a), the heating effect is through a distributed conduction path to ambient, so the rise in gain at the high-potential low-frequency corner would occur over a wider range of frequencies than is shown in Fig. 4(b). However, the range of frequencies remains independent of drain bias.

The linking of electron traps to a simple description of gate-drain current is not accurate at low drain potentials, and does not consider any other drain-source leakage currents that may be present. These are likely to contribute to a significant dispersion in the saturation knee region of the characteristics that is observed in a real device. The drain current saturation knee at low frequencies is often sharper than and at a lower potential than that of the knee at high frequencies (compare Fig. 1 and Fig. 2). The sharpening of the knee at low frequencies may be able to be explained in terms of electron trap occupancy from drain-source leakage and a more accurate gate-drain current description. The fact that these are not included in the simple model is apparent in the differences between the isodynamic regions of Fig. 4.

The model uses a simple description of impact ionization, which does not appear to predict the shift of the kink to higher frequencies at higher drain potentials that is observed in the real device.

The model does, however, provide the insight necessary to interpret the measured intrinsic gain surface. The important result to note here is that the trapping effects are significant at microwave frequencies when operating at higher drain potentials. Also, there exists an isodynamic region of operation at low drain potentials and sufficiently high frequencies.

V. Conclusion

An investigation of the various frequency-dependent effects that influence the behaviour of typical HEMTs and MESFETs has been presented. A simple model of these effects was shown to approximate the behaviour, with the differences offering suggestions for model improvement. It is shown that there are dispersion effects that are significant at microwave frequencies. It also shows the dispersion, and hence distortion, that a signal will produce, depending on the chosen bias and frequency components. This work also reveals the region of time and potential at which an isodynamic pulse measurement of drain characteristics can be made.

Acknowledgements

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