RELATING DYNAMICS OF FET BEHAVIOR TO OPERATING REGIONS

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Abstract:– Dispersion effects and the operating regions they effect are identified in a HEMT and a MESFET. Large-signal pulse and small-signal RF measurements reveal a simple structure to the otherwise complicated dynamic behavior of the FETs. A simple model demonstrates how heating, impact ionization, and leakage currents can contribute to this behavior and that each has an effect in specific regions of bias and operating frequency. It is possible to identify operating conditions that will or will not be affected by dispersion with measurements over a wide range of frequencies from dc to microwave and a range of terminal potentials.

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 effects, so that they can be accommodated or avoided, would improve the circuit design process. This requires device descriptions that predict dispersion or identification of conditions were dispersion occurs.

The dynamic behavior 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.

The potential of trap sites around the channel contribute to the overall controlling gate potential of the FET. 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 charges to the trap sites. If these currents also contribute to the gate current, then the time constants for trap-related dispersion can be inferred from the gate current.

For this study a pHEMT with dc characteristics shown in Fig. 1 and a MESFET with dc characteristics shown in Fig. 2 were analyzed. These are 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 occurs 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.

The characteristics of the MESFET in Fig. 2(a) show a simpler gate current characteristic, Fig. 2(b), and do not exhibit a kink. 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 dynamic behavior of dispersion in 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.
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 drain current versus time and drain potential surfaces, each for a constant gate potential, as in the example shown in Fig 3.

An enhanced arbitrary pulse semiconductor parameter analyzer\(^1\) was used to measure the time-evolution characteristics of the FETs [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. Transconductance and drain conductance were also determined numerically from the several samples in the vicinity of each point.

Fig. 3. Measured characteristics of the HEMT in Fig. 1 from the initial condition $V_G = -2.0 \text{ V}$, $V_D = 1.2 \text{ V}$, with $V_G$ at $-1.2$, $-0.8$, $-0.4$, and $0.0 \text{ V}$ as the parameter.

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

The time-evolution characteristics of the HEMT in Fig. 3 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 the MESFET in Fig. 4 do not exhibit a kink, but rather have a dispersion at rates dependent on drain potential. This is consistent with the simpler gate current characteristic in Fig. 2.

A. Observed Dynamic Behavior

The kink effect in the HEMT time-evolution characteristics of Fig. 3 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 \cite{4,5}. At potentials near or above that of the kink effect in the dc characteristics, there is a rapid, faster than $10 \mu\text{s}$, 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 $100 \mu\text{s}$ 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 MESFET time-evolution characteristics of Fig. 4 exhibit 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. The time at which the drain current starts to fall is dependent on the drain potential stepped to. For 6 V the current starts to fall within 1 µs; at 4 V the current does not fall within the first 5 µs; and at 3 V there is no fall until after 1 ms. The fast time at higher drain potential is explained by a fast trap occupancy rate, which can be linked to the higher gate currents, as shown in Fig 2(b).

There is a delayed rise in current (gate lag) when stepping the MESFET to a lower potential. The time at which these occur is of the order of 10 ms in all cases shown in Fig. 4. The change in trap potentials is at the recombination rate (rather than the occupancy rate) of the traps, which is relatively constant.

B. Regions of Isodynamic Behavior

For the HEMT, measurements 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.

The measurements of the MESFET at drain potentials below 4 V and at times less than 1 µs give isodynamic characteristics.

III. SMALL-SIGNAL RF MEASUREMENTS

The data presented in the time-evolution characteristics is 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 behavior 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. This figure of merit ignores the large-signal aspects of the dynamic behavior, 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. 5 was extracted from pulse data for frequencies below 1 MHz, and measured with a network analyzer for frequencies above 1 MHz. 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 behavior would be essentially the same at all frequencies except that dispersion effects alter the intrinsic gain. To illustrate the mechanisms that contribute to the bias and frequency dependence, the following simple model is presented.

IV. ILLUSTRATIVE MODEL

The following model has been created to illustrate the thermal and trapping mechanisms involved in the dynamic behavior of FETs. This model has been greatly simplified for clarity of the illustration, so it is not
Fig. 4. Time-evolution characteristics of the MESFET in Fig. 2 after steps from four initial bias points to drain potentials at one of the three gate potentials. Current was measured at times after the step of 750 ns, 8 $\mu$s, 35 $\mu$s, 2 ms, and 63 ms, which, with the annotated gate potentials, is the parameter.
a detailed description of the device. It is, however, adequate for explaining the dynamics involved and their influence on measured terminal characteristics.

A. Simple Model

At moderate gate potential, the transconductance and drain saturation characteristic are described by a power of gate potential with a hyperbolic tangent of drain potential as follows:

\[ i_{DS} = \beta v_{GST}^{-2} (1 - \delta \bar{P}) \tanh(\alpha v_{DS}), \]
\[ v_{GST} = v_{GS} + \gamma v_{DS} - \gamma_E v_{E} + \gamma_H v_{H} - V_{TO}. \]

The basic parameters in this simple description are the transconductance parameter \( \beta \) [AV\(^{-2}\)], saturation potential \( \alpha \) [V\(^{-1}\)], pinch-off potential \( V_{TO} \) [V], and intrinsic gain parameter \( \gamma \).

B. Power Dissipation and Trap Potentials

The remaining parameters deal with the influence of power dissipation and the additional controlling potentials from traps.

The \textit{thermal resistance–temperature coefficient} parameter \( \delta \) [W\(^{-1}\)] sets the reduction in drain current with average power dissipation \( \bar{P} \).

The negative-trap gain parameter \( \gamma_E \) sets the decrease in current that is caused by the electron trap potential \( v_E \) and the positive-trap gain parameter \( \gamma_H \) sets the increase in drain current due to the potential of hole traps \( v_H \).

C. Dynamics

Average power dissipation and trap potentials are determined dynamically from heating rate and trapping rates, respectively. For this simple model, it is sufficient to assume that the dynamics are determined by mechanisms with a single time constant that can be described by first-order differential equations.
The average power is determined from instantaneous power over time-constant $\tau_0$ [s] as follows:

$$i_{DS} v_{DS} = \overline{P} + \tau_0 \frac{d}{dt}\overline{P}. \quad (3)$$

This time constant is determined by the physical structure of the thermal path from the device. It is therefore constant with respect to electrical conditions.

The hole and electron trap potentials are respectively assumed, for this illustration, to be linked to impact ionization current $i_{II}$ and drain-gate leakage current $i_{GD}$. These currents are approximately given by the following expressions:

$$i_{II} = A \exp \left( \frac{-B}{v_{DS} - V_S + \sqrt{(v_{DS} - V_S)^2 + 2}} \right), \quad (4)$$

$$i_{GD} = I_{BD} \left( \exp \left( \frac{v_{DS} - v_{GS}}{V_{BD}} \right) - 1 \right), \quad (5)$$

where $V_S$ [V] is the critical drain potential for onset of impact ionization, and $A$ [A], $B$ [V], $I_{BD}$ [A], and $V_{BD}$ [V] are fitting constants.

The following differential equations relate each trap potential to their related current:

$$\ln \left( \frac{i_{II}}{A} + 1 \right) = v_H + \tau_H \frac{A}{i_{II}} \frac{d}{dt}v_H, \quad (6)$$

$$\ln \left( \frac{i_{GD}}{I_{BD}} + 1 \right) = v_E + \tau_E \frac{I_{BD}}{i_{GD}} \frac{d}{dt}v_E. \quad (7)$$

The rate of trap potential change is a function of the number of charges available to fill the traps. Thus the time constants in these relationships are assumed to be a function of the current that provides the charge. It is assumed that there is a logarithmic relationship between trap potentials and their respective currents. Note that this simple implementation does not differentiate between trap occupancy and recombination rates.

**D. Simulation**

The illustrative model was implemented in Mathcad\textsuperscript{2} and used to calculate the intrinsic gain over a surface of drain potential and frequency. The parameters were chosen to approximate the measured results of Fig. 5. The results of this are shown in Fig. 6. This shows contours of small-signal intrinsic gain at a fixed gate bias as a function of drain bias and frequency. The four graphs show the effect of thermal and trapping dispersions individually and together.

**D.1 Thermal Effect**

Fig. 6(a) shows the effect on intrinsic gain of 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.

The model shows a single time-constant transition at a frequency set by $\tau_0$.

\textsuperscript{2}Registered trademark of MathSoft Inc., Cambridge, MA, http://www.mathsoft.com/
Fig. 6. Illustrative simulation of the influence of thermal and trapping effects on the intrinsic gain of a FET as a function of drain bias and frequency at a gate bias potential of −0.5 V. The darker areas correspond to regions of lower gain. The model of Eqs (1) to (7) were used with parameters: $\alpha = 1.05 \text{ V}^{-1}$, $B = 1.25 \text{ V}$, $\beta = 400 \text{ mA V}^{-2}$, $\gamma = 0.04$, $V_{BD} = 700 \text{ mV}$, $V_S = 3.5 \text{ V}$, and $V_{TO} = -1.5 \text{ V}$, and time constants $\tau_\delta = 100 \mu\text{s}$, $\tau_E = 2 \mu\text{s}$ and $\tau_H = 50 \text{ ns}$.

D.2 Electron Traps

Fig. 6(b) shows 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. This gives an increase in intrinsic gain that is observed in Fig. 6(b).

The model shows that the frequency at which gain increases varies with drain bias. This is because the trap occupancy rate increases as the gate-drain current increases.
D.3 Hole Traps

Fig. 6(c) shows the effect on the intrinsic gain of hole traps alone. The model assumes that the trapped holes stem from impact ionization. The potential of the traps has a significant influence on the drain current through the transconductance of the device, whereas the impact ionization current alone is an insignificant contribution. The latter has therefore been ignored.

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 the model shows 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.

D.4 Composite Simulation

Despite the simplifications made in the model, the simulation of intrinsic gain affected by all three dispersion effects, shown in Fig. 6(d), has the characteristics of the real device shown in Fig. 5. These are compared in Fig. 7. There is a reduction in gain at low frequencies near a drain potential of 4 V; there is a saddle in the gain at a drain potential of about 2 V; and there is a ridge in the surface at about 2 kHz. The existence of a region of isodynamic behavior above 1 MHz and at drain potentials less than 4 V is predicted.

The differences arise from simplifications in the model.

In a real device, 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. 6(a). However, the range of frequencies remains independent of drain bias.
The model links electron traps to a simple description of gate-drain current, which 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. 3). The sharpening of the knee at low frequencies can be explained in terms of electron trap occupancy from the 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. 7, where the increase in measured gain is a more linear function of drain potential.

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

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 behavior of typical HEMTs and MESFETs has been presented. A simple model of these effects was shown to approximate the behavior, with the difference offering suggestions for model improvement. It is shown that there are dispersion effects that are significant at microwave frequencies. This work also reveals the region of time and potential at which an isodynamic pulse measurement of drain characteristics can be made.

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