Over-Temperature Noise Modeling of Submicron Devices Brought the Question: Is the Diffusion Coefficient Temperature Dependent?

Author: Ali Boudiaf, Solid State Tuner Manager, Maury Microwave Corporation

Abstract: *A new procedure is presented for modeling the variations with temperature of the noise source coefficients related to the gate and the drain of a field effect transistor (FET). The experimental results obtained for a temperature range over 60°C to 140°C are compared to two recent similar studies, using a Pseudomorphic HEMT. It is demonstrated that good agreement can be obtained for some of the temperature coefficients for both the small signal model and the internal noise sources. Further in the analysis of the drain noise source, which comes from fluctuations in the electron velocity, which in turn is related to the electron diffusion constant D, we were able to quantify the temperature dependence of this coefficient.*

Introduction

Very low noise figures with high associated gain performance requirements are now being met by the sub-micrometer PHEMT transistors, which are replacing MESFETs because of their lower noise performance for the same gate length. To support the design of communication systems, such as satellite systems, operating in varied environments, accurate noise models are required which can predict all the noise parameters of the transistor over a wide frequency range[1], but also over a wide temperature variations.

Although there are several "Noise Temperature" models in the literature[2, 3] these models are not predictive in the sense that they can be used to compute noise parameters over different operating temperatures. Gate temperatures are approximately equal to the operating temperature, but very large drain temperatures are observed, which leaves us with the unanswered question: *How does the drain temperature change with the operating temperature?* There is not much data in the scientific literature that allows us to answer this question[4].

In this paper, we present a procedure for modeling the temperature dependence of both the small signal model and the noise coefficients that characterize the equivalent gate and drain noise sources. Experimental results are reported for 0.5µm gate length PHEMTs, the extracted temperature dependent noise model is compared to two previous works[2, 3] in the same area using the same kind of device.

Modeling Versus Temperature

The procedure is based on Pucel *et al.* model[5], shown in **Figure 1**. The intrinsic noise sources are represented by a drain current source: $\langle i_d^2 \rangle$, in parallel with the output conductance G_{ds}, and by a gate current source: $\langle i_g^2 \rangle$ in parallel with C_{gs} and R_i. These two equivalent noise sources are correlated and can be expressed with the dimensionless constants P, R and C, defined by:

$$\begin{aligned} P &= \frac{\langle i_d^2 \rangle}{4kT\Delta f\, g_m} \\ R &= \frac{g_m \langle i_g^2 \rangle}{4kT\Delta f\, C_{gs}^2 \omega^2} \\ jC &= \frac{\langle i_g^* i_d \rangle}{\sqrt{\langle i_g^2 \rangle \langle i_d^2 \rangle}} \end{aligned} \quad (1)$$

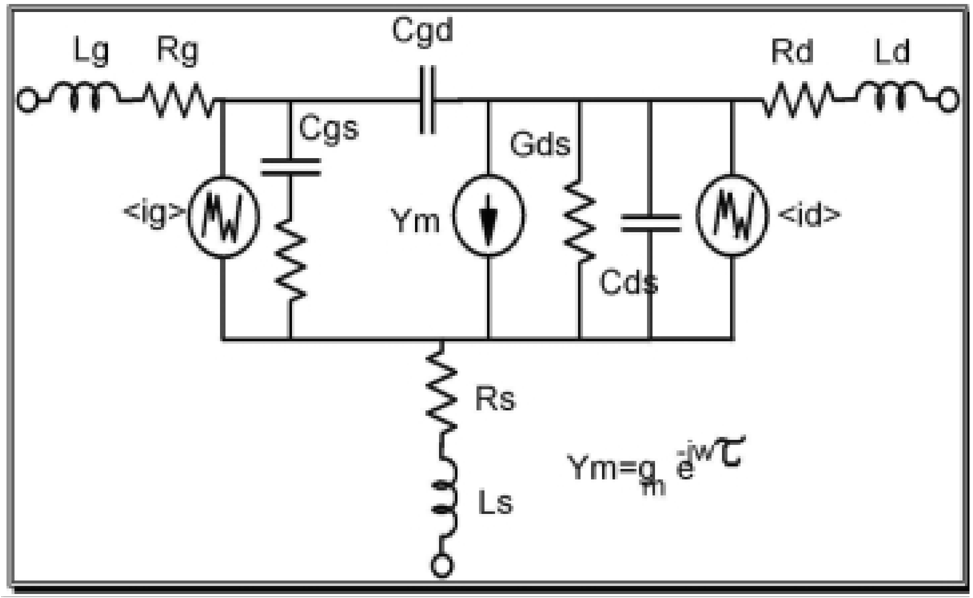

Figure 1. Small Signal and Noise Equivalent Circuit Parameter Model.

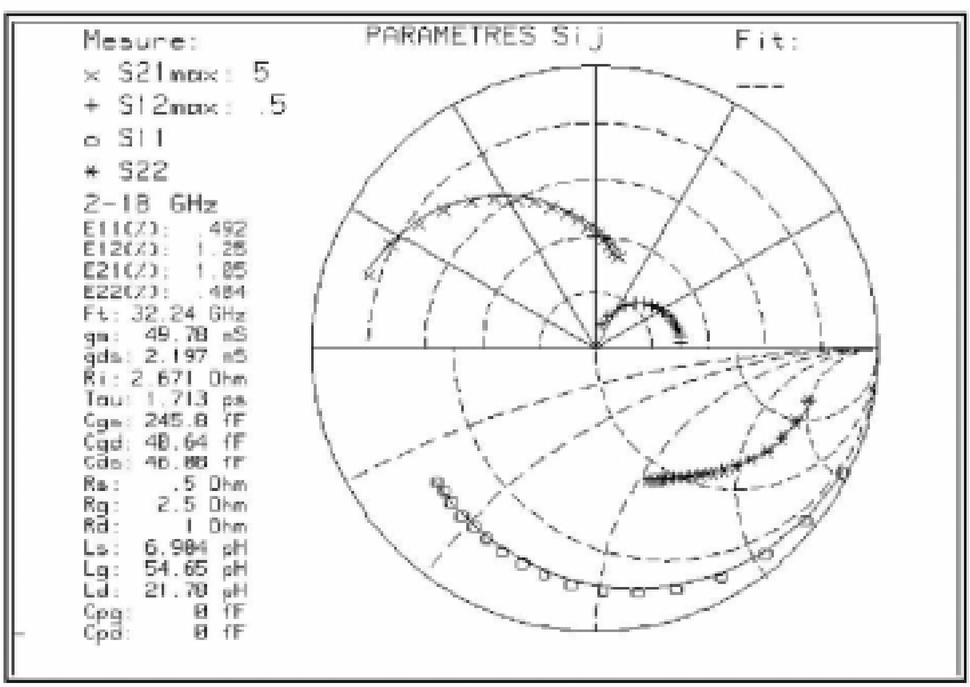

Figure 2. Measured and Simulated S-parameters 0.5x200µm PHEMT.

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This noise modeling procedure requires the measurement of the s-parameters and the noise parameters, to extract the small signal equivalent circuit parameters and the noise coefficients, defined by P, R and C, together versus the temperature variation. The relation of noise model parameters versus temperature is supposed to be quasi-linear and can be approximated by the following relation[1]:

$$Pr(T) = Pr(T_0) \cdot [1 + B(T - T_0)] \quad (2)$$

where $Pr(T)$ is the parameter value at the temperature of interest, $Pr(T_0)$ is the reference temperature parameter value $(T_0 = 296K)$, and B is the linear fitting coefficient to be determined.

Pospieszalski[6] developed an intrinsic noise model in terms of two temperature, called T_g and T_d. These can be related to Pucel's PRC factors using:

$$P = \frac{T_d}{T_0\, g_m\, R_{ds}} \quad (3)$$

$$R = g_m \frac{R_i\, T_g}{T_0} \quad (4)$$

The origin of the drain noise source comes from fluctuations in the electron velocit, which in turn is related to the electron diffusion constant D and the electron mobility through the Einstein relationship:

$$D = \frac{kT\mu_n}{q} \quad (5)$$

So whether P and R scale as T/T_0 depends on D/μ being equal to kT/q. The objective of this study is to try to confirm or deny this statement.

$$v_{sat} = L_g \frac{g_m}{C_{gs} + C_{gd}} \quad (6)$$

$$B_{ft} = \frac{1}{f_T(T_0)} \frac{\partial f_T}{\partial T} = \frac{1}{v_{sat}(T_0)} \frac{\partial v_{sat}}{\partial T} \quad (7)$$

$$B_{ft} = -1.44 \qquad [-1.0 \qquad -2.5] \cdot 10^{-3}/K \quad (8)$$

The electron velocity v_{sat} can be estimated from **Equation (6)**, then the thermal coefficient B_{ft} can be calculated with **Equation (7)**. The obtained result in **Equation (8)** is within the range of the published values obtained by other means.

$$\frac{1}{S_{id}(T_0)} \frac{\partial S_{id}}{\partial T} \approx \frac{1}{g_m(T_0)} \frac{\partial g_m}{\partial T} + \frac{1}{P(T_0)} \frac{\partial P}{\partial T} \quad (9)$$

$$\approx \frac{1}{D_{||}(T_0)} \frac{\partial D_{||}}{\partial T} - \frac{1}{v_{sat}(T_0)} \frac{\partial v_{sat}}{\partial T} \quad (10)$$

$$B_{D||} = 0.77 \cdot 10^{-3}/K \quad (11)$$

Equations (9) and **(10)** report the relationships between the parallel diffusion constant, electron velocity, the transductance and P extracted noise coefficient. The result obtained in **Equation (11)** suggests that the main origin of noise variation with temperature is due to the diffusion coefficient, it is proporational to temperature variation.

Experimental Results

To demonstrate the noise modeling procedure, s-parameter and noise paramater measurements were made on a 0.5x200µm PHEMT (A1GaAs/InGaAs/GaAs). The measurements were made using an on-wafer probe station with Cascade Microtech HF probes, over a temperature range from -60°C to 140°C performed by the Thermo-Jet system (SAGEM). The s-parameter measurements were made from 100 MHz to 26.5 GHz using the HP8510 network analyzer, and the noise parameters measurements were performed between 2 and 12 GHz using ATN NP5 system. The calibrations were performed each time at the measurement temperature after chuck temperature stabilization.

Results of this noise modeling procedure are reported in **Table 1**, at $I_{ds} = I_{dss}$, with results from two other references. We have observed that the minimum

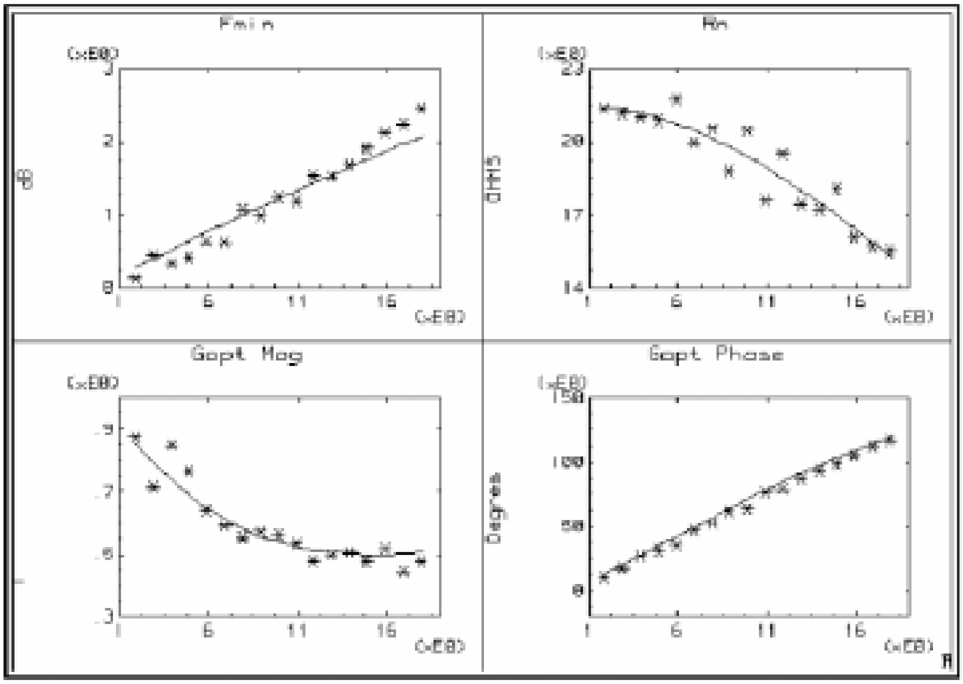

Figure 3. Measured and Simulated Noise Parameters of 0.5x200µm PHEMT.

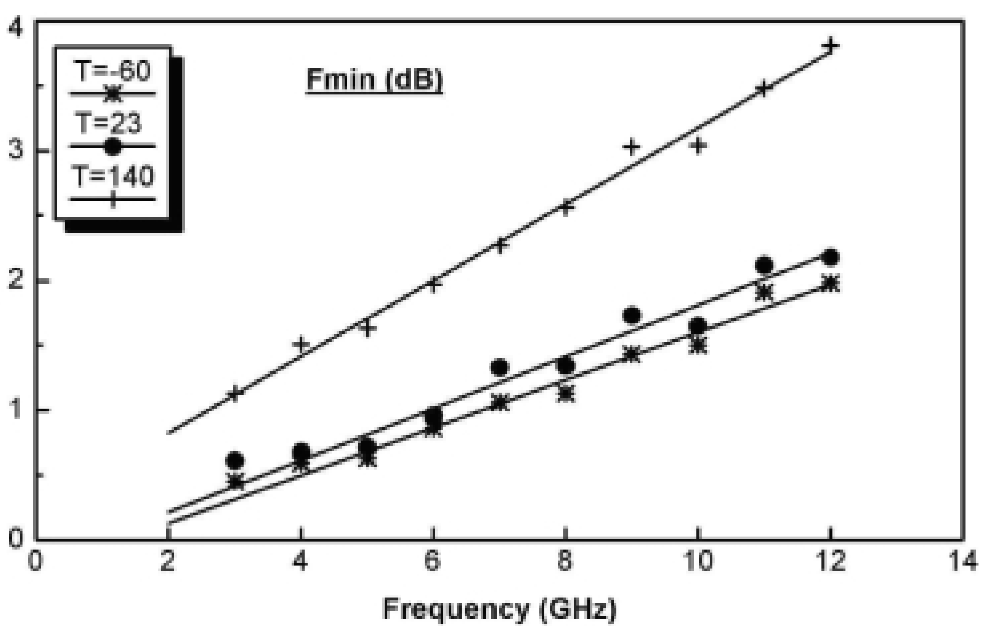

Figure 4. Measured Temperature Dependent Variation of F_{min} at $I_d = I_{dss}$.

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resistance (R_n) **Figure 5**, exhibit a larger relative increase with increasing temperature than the optimum reflection coefficient (Γ_{opt}) **Figure 6**. The same effect is observed at I_d = 50%I_{dss}.

Parameter	T1	T2	T3
f_T [GHz]	36.1 (-1.44)	—	68 (-1.43)
g_m [mS]	75 (-0.97)	171 (-1)	150 (-1.03)
C_{gs} [fF]	330 (0.43)	397 (-0.13)	276 (0.31)
C_{gd} [fF]	46 (-0.38)	65 (-0.36)	40 (0.10)
C_{ds} [fF]	41 (-1.08)	64 (-0.78)	48 (0.10)
R_{ds} [Ω]	324 (0.31)	93 (0.41)	154 (0.46)
R_i [Ω]	2 (-2.81)	1.9 (2.85)	—
τ [ps]	1.5 (4.81)	0.36 (-0.18)	0.48 (-0.64)
P	1.34 (3.18)	0.69 (3.5)	—
R	0.29 (6.31)	0.13 (38.6)	—
C	0.24 (-1.41)	0.82 (-8.5)	—

T1: PHEMT (PML) 0.5 × 200 μm $V_{gs} = 0$ V, $V_{ds} = 3$ V.
T2: PHEMT [3] 0.25 × 300 μm.
T3: PHEMT [2] 0.25 × 200 μm $V_{gs} = 0$ V, $V_{ds} = 2$ V.

Table 1. Reference Temperature Parameter Value $P(T_0)$ (Linear Fitting Coefficient $B[10^{-3}/°C]$).

The extracted values of the temperature coefficients B[10^{-3} /°C], **Table 1** and **Figures 7** thru **10**, show that for the parameters f_T, g_m, C_{gs}, R_{ds} and P, they are of the same order of magnitude compared to the results in [2,3]. It demonstrates that for these parameters, the extracted temperature coefficients are less sensitive to the modeling method and to the measurement errors than for the rest of the parameters. The temperature coefficients for R and C were expected to be different since the noise model is different between reference[2] and our work.

Conclusion

A new noise modeling procedure has been introduced for FET's that is useful for the temperature dependent modeling of PHEMT noise parameters. A comparison with two previous works shown that the extraction of the temperature coefficients is less sensitive to the used method for some of the model parameters, but still critical for some others.

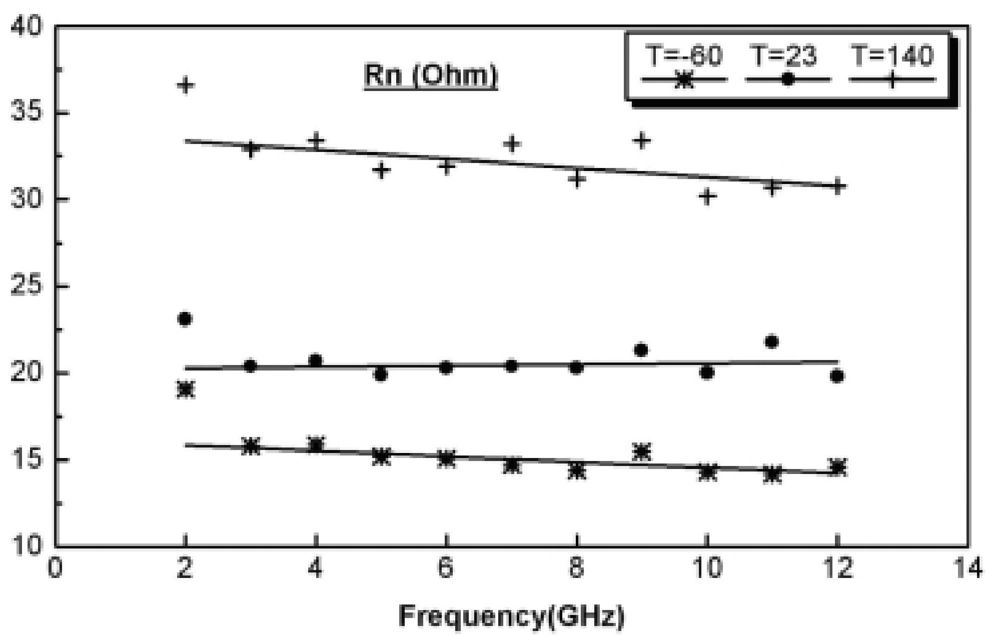

Figure 5. Measured Temperature Dependent Variation of R_n at I_d = I_{dss}.

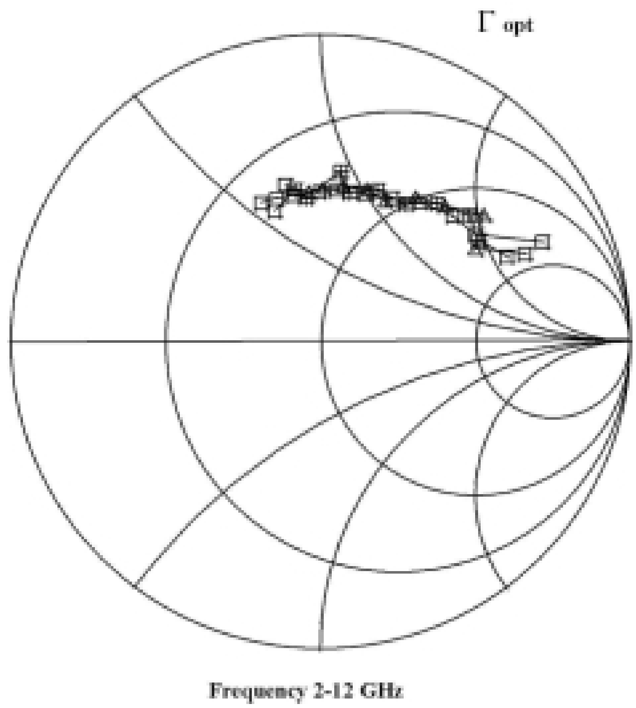

Figure 6. Measured Temperature Dependent Variation of Γ_{opt} at $I_d = I_{dss}$.

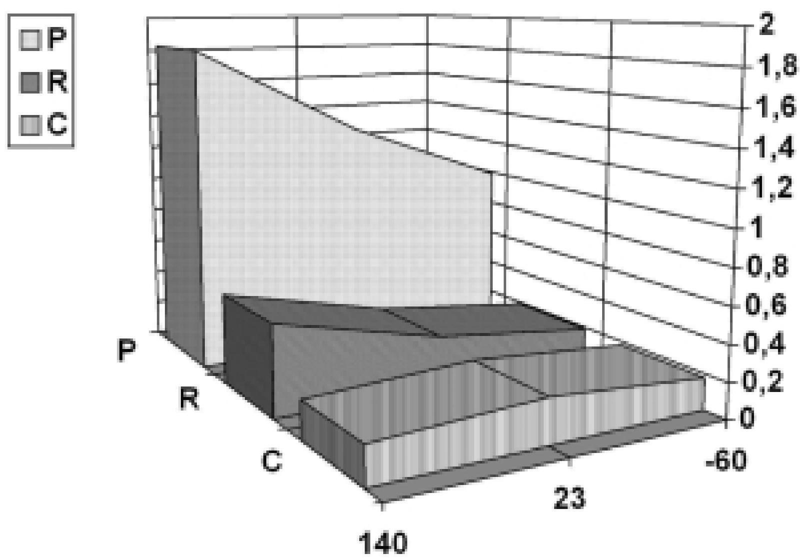

Figure 7. Extracted Noise Coefficients P, R and C Versus Temperature at $I_{ds} = I_{dss}$.

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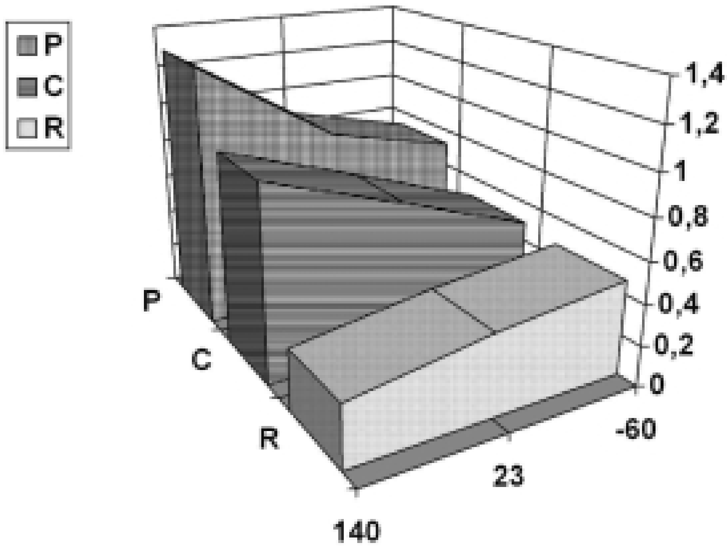

Figure 8. Extracted Noise Coefficients P, R **and** C **Versus Temperature at** $I_{ds} = 50\% I_{dss}$.

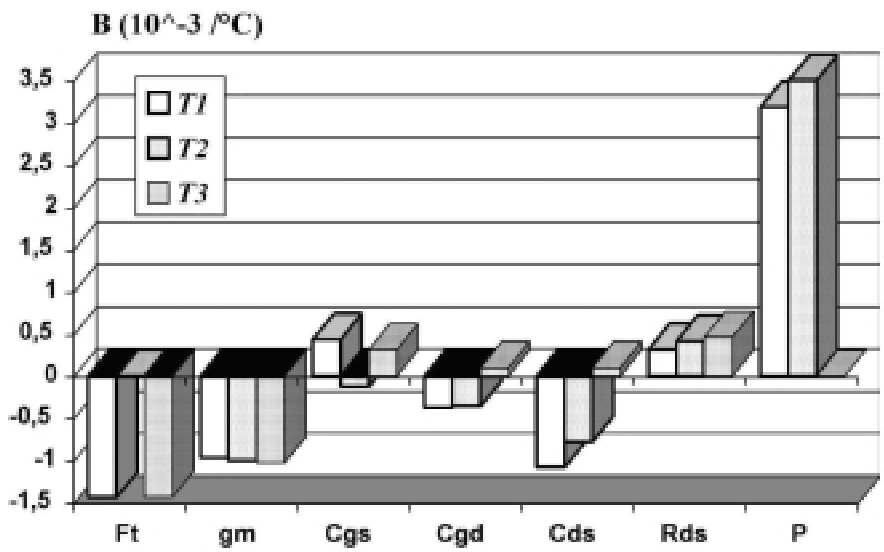

Figure 9. Thermal Coefficient Comparison.

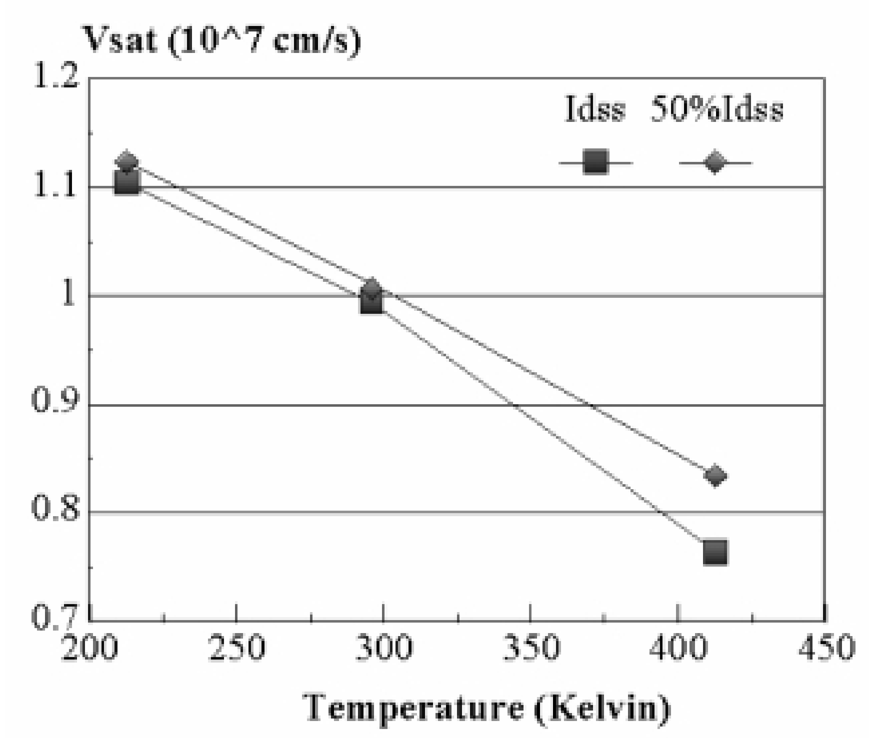

Figure 10. Thermal Coefficient Comparison.

References

1 R.E. Anholt *et al.*, *Experimental Investigation of the Temperature Dependence of GaAs FET Equivalent Circuits*, IEEE Trans. Electron Dev., Vol. 39 No. 9, September 1992, pps. 2029-2035.

2 J. Pence *et al.*, *High Frequency Over-Temperature, Measurements and Modeling*, application note Cascade Microtech, 1994.

3 S. Lardizabal *et al.*, *Experimental Investigation of the Temperature Dependence of PHMET Noise Parameters*, IEEE MTT-S Intl. Microwave Symp. Dig., 1994, pps. 845-848.

4 A. Boudiaf *et al.*, *An Accurate and Repeatable Technique for Noise Parameter Measurements*, IEEE Trans. on I & M, Vol. 42 No. 2, April 1993, pps. 532-537.

5 R.A. Pucel, H.A. Haus, and H. Statz, *Signal and Noise Properties of Gallium Arsenide Microwave Field-Effect Transistors*, Advances in Electronics and Electron Physics, Vol. 38, New York: Academic Press, 1975, pps. 195-265.

6 M.W. Pospieszalski, *Modeling of Noise Parameters of MESFETs and MODFETs and Their Frequency and Temperature Dependence*, IEEE Trans. Microwave Theory Tech., Vol. 37, 1989, pps. 1340-1350.

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