ANALYSIS OF WAVE PROPAGATION EFFECTS ON MICROWAVE FIELD-EFFECT TRANSISTORS

Mohammed S. Hakim* and Samir M. El-Ghazaly

Department of Electrical Engineering, Arizona State University, Tempe, AZ 85287-5706, USA

Abstract:

As the operating frequency increases, electromagnetic wave propagation effects on FET electrodes cannot be ignored. In this paper, these effects are investigated by analyzing two devices; the conventional MESFET and the INGFET, which is properly designed to exploit the wave propagation effects. The wave effects are analyzed using a CAD model which accounts for the semiconductor characteristics and the nonstationary electron dynamics, the electromagnetic characteristics and the parasitic elements of the device. The importance of including the wave propagation effects in the device analysis is strongly manifested in the results. It is shown that the amplification factor of the gainful mode of the INGFET is larger than that of the MESFET for higher frequencies and wider devices. Also, the INGFET exhibits higher gain when operated in the TWT mode and when terminated with 50-Ω loads as well.

1. Introduction:

In the mm-wave range, the FET width becomes comparable to the wavelength. Therefore, the transistor cannot be treated as a point, or a lumped element any more [1]. The high frequency aspects, including distributed effects, propagation delays, electron transit-time, parasitic elements, and discontinuity effects, become important and have to be thoroughly investigated [1-3]. In addition, coupling the energy from the device to the circuit, (i.e. the matching problem), becomes an involved issue, and approaching it using a simple circuit concept that neglects the distributed effects of the feeding and output lines can be a very limited approach. This process is more complicated when the characteristic impedance of some transmission-lines utilized becomes either undefined or not uniquely defined, when not operated in a pure TEM mode.

In this paper the wave propagation effects on high frequency transistors are assessed by comparing the characteristics of two transistors; one of them is optimized to exploit the wave propagation effects [1], and the other structure is the conventional GaAs MESFET. The wave propagation effects are incorporated in the analysis using a complete CAD technique.

MM

2. CAD Approach for Incoirporating Wave Propagation Effects:

The approach to study devices, mainly FETs, that involves electromagnetic-wave propagation effects, including distributed effects, must be based on both guidedwave theory and semiconductor device theory. The method used in this paper can be divided into three fundamental steps. Step 1; a small-signal equivalent circuit model for the semiconductor device is developed. This is done using a two dimensional energy balance model that accounts for the nonstationary effects. The transmission line model representing the waveguiding structure around the semiconductor device is also developed in the form of resistance-capacitance-inductance model. This is a quasi-TEM model. Both the conductor losses and the losses inside the semiconductor material are included. Step 2; the two models are blended together to form a system of linear equations, which is solved for the propagation characteristics over this active transmission-line [1,2,4]. Step 3; the excitation problem is solved by the terminating the device with a set of load impedances, and solving for the device gain and the appropriate signal excitations. Every one of these steps involve many intermediate steps. The intermediate steps are detailed in [1,5].

* Now with Intel Corporation.

3. The compared structures:

To properly assess the wave propagation effects on the transistor performance, the above mentioned approach is utlized to obtain and compare Characteristics of two FET structures; the Inverted gate Field Effect Transistor (INGFET) and the conventional MESFET. The two structures have similar semiconductor characteristics as shown in Fig. 1. However, their electromagnetic characteristics are different. The waveguiding structure of the INGFET is optimized to allow phase velocity matching between the input wave (i.e., the signal to be amplified) and the output wave (i.e., the amplified signal) [1]. This is achieved by having the gate on the side of the ground plane and operating the device in a common-gate configuration. The conventional MESFET is not optimized for wave propagation effects, and thus may not be suitable for high frequency operation.

The device parameters used in this comparative study are shown in Table I and Fig. 1. The active parameters are obtained from the semiconductor model and the passive parameters are obtained from the electromagnetic model. The physical dimensions are selected to be the same for the two devices. Differences in the electric parameters are attributed to the differences between the structures themselves.

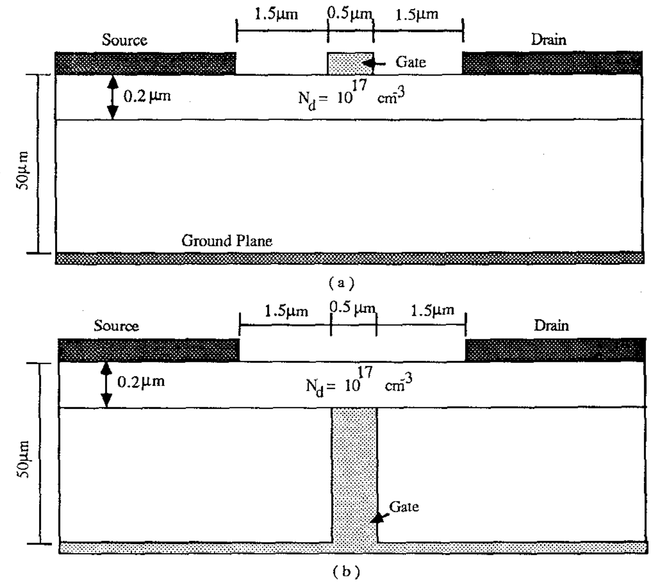

Fig. 1. (a) The conventional MESFET and (b) the INGFET (not to scale).

Table I

	Parameter	Description	MESFET	INGFET	Units
ACTIVE	R_i	Channel resistance	2.04	2.04	Ω mm
	C_i	Depletion capacitance	0.9×10^{-12}	0.8×10^{-12}	F/mm
	R_{dg}	Drain-gate bulk resistance	0.938	0.938	Ω mm
	R_{sg}	Source-gate bulk resistance	0.938	0.938	Ω mm
	r_d	Drain (output) resistance	120	150	Ω mm
	g_m	Transconductance	0.14	0.3	S/mm
	C_{dg}	Intrinsic gate-drain capacitance	0.33×10^{-13}	0.33×10^{-13}	F/mm
	C_{ds}	Intrinsic source-drain capacitance	0.5×10^{-12}	0.5×10^{-12}	F/mm
PASSIVE	R_d	Drain resistance	0.5	0.5	Ω /mm
	R_g	Gate resistance	4.0	1.149	Ω /mm
	R_s	Source resistance	0.5	0.5	Ω /mm
	C_{dg}	Gate-drain capacitance	0.042×10^{-12}	0.14×10^{-12}	F/mm
	C_{sg}	Source-gate capacitance	0.042×10^{-12}	0.14×10^{-12}	F/mm
	C_{ds}	Source-drain capacitance	0.052×10^{-12}	0.29×10^{-14}	F/mm
	L_d	Drain inductance	0.82×10^{-6}	1.25×10^{-6}	H/mm
	L_s	Source inductance	0.82×10^{-6}	1.25×10^{-6}	H/mm
	L_g	Gate inductance	3.7×10^{-6}	3.7×10^{-6}	H/mm
	L_{dg}	Drain-gate (mutual) inductance	1.046×10^{-9}	1.869×10^{-9}	H/mm

Table I. The active and passive parameters of the two devices.

4. Results and Discussions:

The propagation constants and the characteristic impedances of the two structures are calculated and shown in Fig. 2. It is interesting to notice that these results physically represent the propagation characteristics on infinitely long active transmission lines, which have both active and passive coupling. These results demonstrate that two possible modes can exist on the transistor electrodes; a *lossy mode* and a *gainful mode*. These results are consistent with those reported in [1]. From Fig. 2(a), it is obvious that the gain factor (α_G) of the INFET is considerably larger than that of the conventional MESFET although they

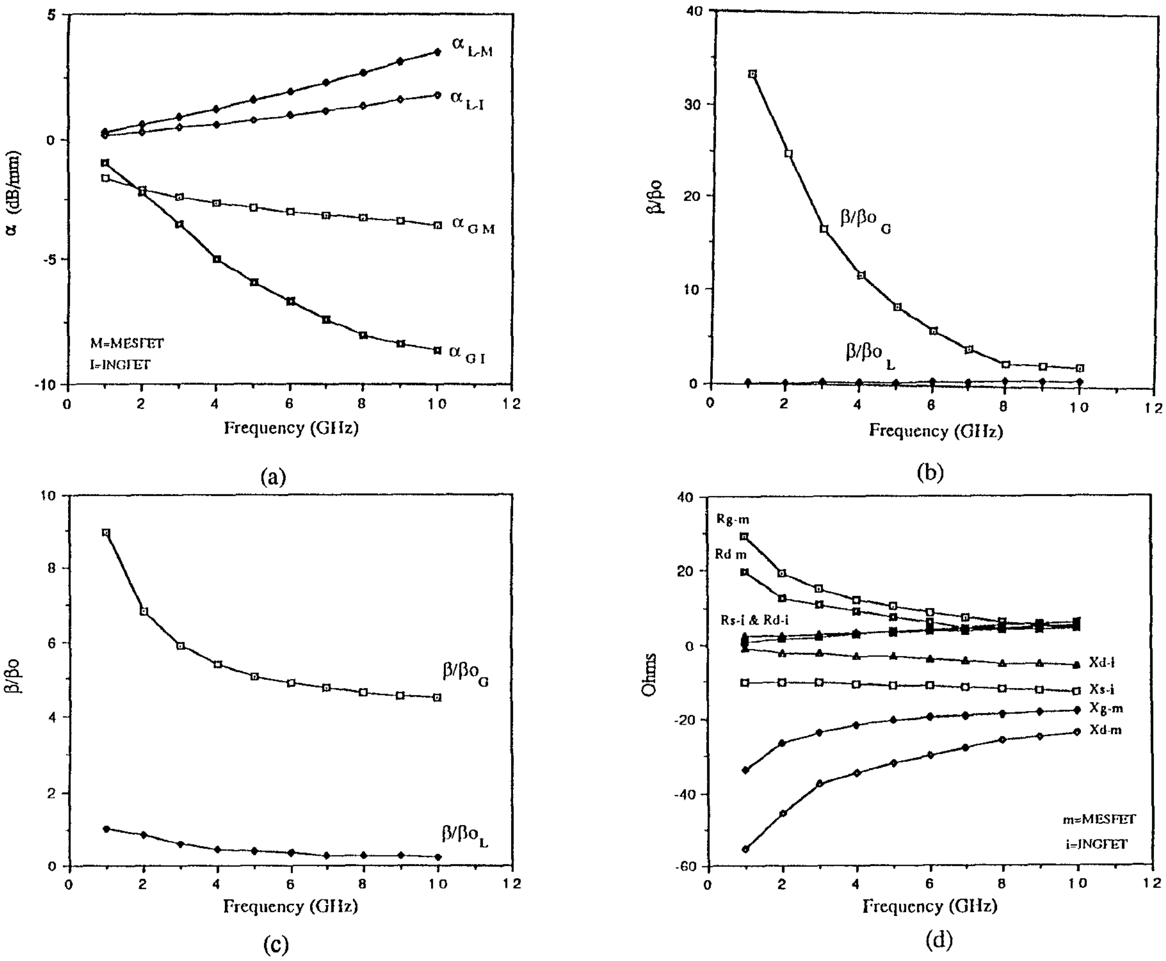

Fig. 2. (a) The amplitude factor of the two devices. (b) The dispersion characteristics of the INGFET. (c) The dispersion characteristics of the MESFET. (d) The impedances of the different modes, (R_s+j X_s) source line impedance, (R_g+j X_g) gate line impedance, and (R_d+j X_d) drain line impedance.

have the same semiconductor dimensions, for frequencies above 2 GHz. The obvious reason is that the INGFET is designed to exploit the wave propagation effects, while the conventional MESFET is not. For frequency lower than 2 GHz, the conventional MESFET Produces higher gain factor. This can be explained by noticing that below 2 GHz, the wave propagation effects are negligible; thus the optimization of the INGFET produces an insignificant effect.

The wave propagation effect on the device operation and gain is also investigated. Several cases are studied. When the device is terminated by the characteristic impedance of the *gainful mode*, the device operates in the pure traveling-wave transistor mode. The gain characteristics from the two devices when operated in this mode are shown in Fig. 3. The INGFET produces higher gain than the MESFET for frequencies above 4 GHz. For frequencies lower than 4 GHz, the MESFET provides better performance for two reasons; 1) it has a larger α_G, and 2) it is operated in the common-source configuration versus the common-gate configuration suitable for the INGFET. The gain characteristics when the two devices are terminated in 50-Ω loads are shown in Fig. 4. It is shown that as the frequency increases, the gain of the MESFET decreases much faster than that of the INGFET. To visualize the wave propagation effects in wide transistors, two cases for each transistor are shown in Fig. 5. This case is of a special importance for power transistor operation. This figure shows that the INGFET produces higher gain than the conventional MESFET when devices are long or at higher frequencies. It should be noted that the wave propagation effects are more pronounced in the two cases.

5. Conclusions:

Wave propagation effects on Field Effect Transistors are analyzed using a CAD model that accounts for both the semiconductor and the electromagnetic aspects of the device. This technique is applied to two FET structures. The results show that the device performance is considerably affected by the wave effects. Significant improvement can be obtained when the device structure is optimized to exploit the wave effects and use it to enhance the transistor performance.

Acknowledgment:

This work was supported, in part, by National Science Foundation, grant ECS 9108933.

References:

[1] S. El-Ghazaly and T. Itoh, "Traveling-Wave Inverted-Gate Field-Effect Transistors: Concept, Analysis and Potential;" *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1027-1032, 1989.

[2] A. Holden , D. Daniel , I. Davis, C. Oxley and H. Rees, "Galliun: Arsenide Traveling-Wave Field Effect Transistors;" *IEEE Trans. Electron Devices*, vol. 32, no. 1, pp. 61-66, 1985.

[3] K. Fricke and H. Hartnagel, "GaAs MESFET Optimization and New Device Applications Based on Wave Property Studies;" *IEEE MTT-s Symp. Digest*, 1985, pp. 192-195.

[4] K.-H. Kretschmer, P. Grambow, and T. Sigulla, "Coupled-Mode Analysis of Traveling-Wave MESFETs;" *Int. J. Electron.*, vol. 58, pp. 639-648, 1985.

[5] M.S. Hakim, Effect of Wave Propagation on Microwave Field Effect Transistor Structures, *M.S. Thesis*, Arizona State University, Tempe, Arizona, 1992.

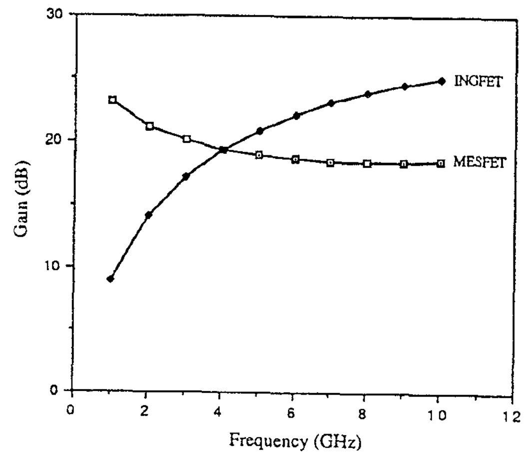

Fig. 3. The gain for the traveling-wave transistor mode. (Device width = 1 mm).

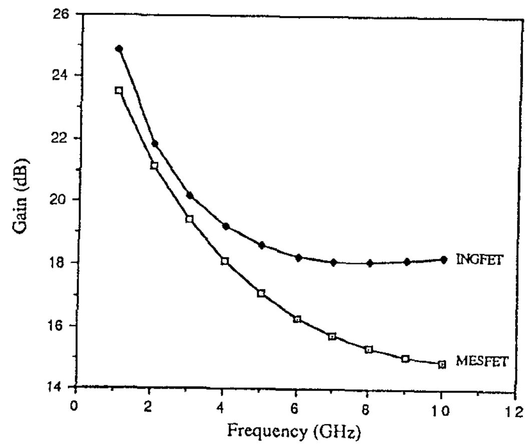

Fig.4. The gain when the devices are terminated with 50–Ω loads. (Device width = 1 mm).

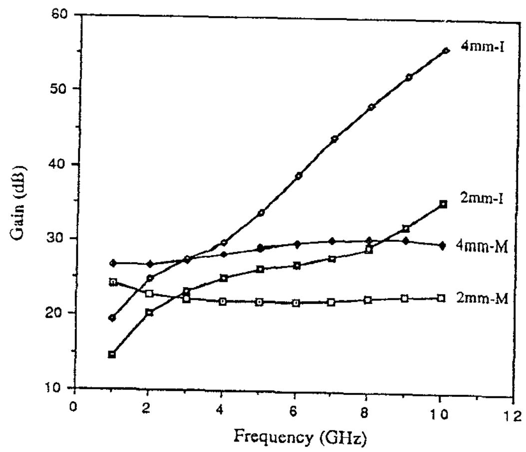

Fig. 5. Gain characteristics of the traveling-wave transistor mode for different transistor widths.