A Non-Quasi-Static Small-Signal MOSFET Model for Radio and Microwave Frequencies Including Spreading Gate Resistances and Capacitances

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Abstract – A new physically consistent, fully analytical non-quasi-static (NQS) small-signal MOSFET model for analysis and simulation of radio and microwave frequency circuits is proposed. Some results of a 3D analysis of spreading gate resistances and capacitances, main features and experimental verification of the new NQS four-terminal model are presented in this report. The validity of this model is experimentally proved up to 27GHz.

I. INTRODUCTION

To successfully design radio frequency integrated circuits (RFICs), an adequate NQS small-signal MOSFET model is needed. Such a model should take into account (i) the velocity saturation effect of carriers in the channel of the transistor, (ii) electrical coupling between the channel and the transistor structure (the gate and body), (iii) 3-dimensional nature of parasitic spreading resistances and capacitances of a system consisting of the resistive gate, semiconductor substrate, and the drain and source metallization, and (iv) various parasitic resistors and capacitors connected in series between the body of the intrinsic transistor and metal paths on the chip.

Known MOSFET models used in designing integrated circuits in radio frequency (RF) range can be split into two groups, namely quasi-static (QS) and non-quasi-static (NQS) models. QS approaches do not aptly describe operation of the MOSFET at high frequencies or under fast transients. This stems from the fact that the QS approximations assume the movable carriers in the channel of the transistor to respond instantaneously to the perturbations induced by a time-varying external bias, thereby neglecting the delay, dynamic properties of the channel, and the coupling between the electron beam and the structure (the gate and body). As a result, serious inconsistencies arise when the QS approach is used to RF MOST modeling. For instance, according to models presented in [1,2] magnitudes of transadmittances of voltage-controlled current sources tend to infinity as frequency increases, which is an obvious inconsistency. It is worth mentioning that any charge-based model, such as BSIM3v3, MOS Model 9 or EKV is inherently composed of such current sources as those in [1,2].

To overcome the limitations, various NQS models have been proposed [2-5]. For instance, in works [3] and [4], the NQS effect is included in the models by multiplying the transconductance g_m by $\exp(-j\omega\tau)$, resulting in no decreasing in the magnitude of the transadmittances as ω goes to infinity. Widely used NQS BSIM3v3 model [5] is a charge-based model developed on the channel charge relaxation time approach under constant mobility assumption. Moreover, the channel of the MOSFET is modeled in work [5] as an RC distributed transmission line, which is not an adequate model of the intrinsic part of the transistor because any line of this type is not unilateral (i.e, $y_{12}\neq 0$). The intrinsic MOSFET without parasitics has to be unilateral ($y_{12}=0$) for the reason that charge carriers (electrons or holes) are only injected through the source-channel barrier potential.

To overcome the above-mentioned weak points of existing models an attempt has been made in work [8] to derive a set of partial differential equations for coherent physics-based small-signal NQS model of the intrinsic MOSFET operating under any external small-signal excitation.

The intrinsic NQS four-terminal MOSFET model and parasitic components of the transistor have been presented and verified experimentally up to 27GHz in [9]. Even though we have assumed in that verification that the body of the intrinsic transistor is ideally shorted to its source and values of parasitic resistances R_{gd} and R_{gs} are of the order of tens of ohms, we have attained close accuracy (closer than for other models) in fitting theoretical to experimental characteristics. However, to improve the accuracy of the theoretical

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description, especially for the short-circuit output admittance y_{22}, we had to abandon the simplifying assumption that the body of the intrinsic transistor was perfectly shorted to the source, and to carry out some theoretical research on the way in which a three-dimensional (3D) set composed of four elements, namely the resistive gate and semiconductor substrate and the conducting drain and source can be represented. In other words, we have conducted this basic research with the aim of defining an equivalent-circuit for parasitic elements relating to the gate and predicting ranges of variations of these elements.

The purpose of this report is to propose a new non-quasi-static small-signal MOSFET model taking into account parasitic spreading resistances and capacitances of the transistor gate. In section II, a close set of basic equations and main features of the new NQS small-signal model of the intrinsic transistor are described. In section III, a theoretical basis and some results of our simulations required to determine the values of parasitic spreading resistances and capacitances relating to the gate are presented. The new complete (intrinsic and extrinsic) NQS MOSFET model and its experimental verification are given in section IV.

II. THE INTRINSIC TRANSISTOR – AN NQS MODEL [8]

A novel, fully analytical NQS small-signal four-terminal model of the intrinsic MOSFET has been proposed in [8]. The frequency-domain equations for the NQS model has been presented in [9]. To develop the model, which is consistent with physics, it was necessary to consider the intrinsic part of the transistor as a two-dimensional object into which a continuous compressible charge medium is injected, [6], [7], to include the carrier velocity saturation effect, and to involve an electrical coupling produced by the transverse electric field between the perturbated carriers in the channel and both the gate and body; the gate and body are assumed to be conductors.

An equivalent circuit for the NQS small-signal four-terminal model of the intrinsic MOSFET is comprised of six elements depicted in the area enveloped with dashed line in Fig.3. They can be expressed as follows:

$$g_{ds} = g_{ds}\,|_{quasi-static} \quad (1)$$

$$C_{gb} = \frac{g_m \eta L}{(1+\eta)\mu(E_0)E_0}, \left(\eta = \frac{g_{mb}}{g_m}\right), \quad (2)$$

$$y_{mg} = g_m \exp(\gamma L), \ \ y_{mb} = g_{mb} \exp(\gamma L), \quad (3)$$

$$y_{gs} = j\omega \frac{C_{gb} D_C[\exp(\gamma L) - 1]}{\eta \gamma L(1 - \gamma V_T / E_0)}, \quad (4)$$

$$y_{bs} = j\omega\eta C_{gb} \frac{D_C[\exp(\gamma L) - 1]}{\gamma L(1 - \gamma V_T / E_0)}, \quad (5)$$

where:

$$\gamma = \frac{E_0}{2V_T} - \frac{1}{2}\sqrt{\frac{\sqrt{a^2+b^2}+a}{2}} - j\frac{1}{2}\sqrt{\frac{\sqrt{a^2+b^2}-a}{2}}, \quad (6)$$

$$a = (E_0 / V_T)^2, \ b = \frac{4\omega(1+D_C)}{V_T \mu(E_0)}, \ V_T = \frac{kT}{q}, \quad (7)$$

$$\mu(E_0) = \frac{\mu_0}{[1+(E_0/E_C)^\beta]^{1/\beta}}, \ E_0 = \frac{|V_{DS}|}{L}, \quad (8)$$

in which g_{ds}, g_m and g_{mb} are respectively small-signal quasi-static (low-frequency) drain-source conductance, transconductance of the gate and transconductance of the body at the Q-point of the transistor. μ_0, E_C and E_0 are respectively, the low-field carrier mobility, the characteristic field and the static longitudinal electric field at the Q-point. D_C is a dynamic coupling factor – proportional to the rate of variations in the excess carrier concentration, $0<D_C<1$. V_{DS} is biasing drain-source voltage and L – the channel length.

One can see from (3) and (7) that the real part of the quantity γ, termed a propagation coefficient, is a decreasing function of frequency ω, which implies that the magnitudes of the transadmittances y_{mg} and y_{mb} tend to zero as ω goes to infinity. One can also see that the phases of y_{mg} and y_{mb} are not linear functions of ω; in commonly used models based on transit-time approximation, the phase is a linear function of ω. It was demonstrated in Fig.2 in work [9] that the short-circuit input admittance y_{11} of an intrinsic MOS transistor in common-source configuration can take on inductive character for certain interval of frequencies. *According to this model, frequency characteristics of* the intrinsic transistor are V_{DS}-dependent functions. This model does not make use of non-reciprocal capacitances. The model can be applied to both long- and short-channel devices and to both above-threshold and subthreshold range of operation of the transistor. The proposed model is valid from zero Hz up to microwave frequencies.

III. PARASITIC GATE RESISTANCES AND CAPACITANCES

In deriving the NQS small-signal model of the intrinsic transistor, it was assumed the gate, substrate, drain and source regions are ideal conductors. To be more realistic, we had to take into account a finite conductivity of these regions. Due to the principle of superposition, it is possible to do it in a separate analysis. Our analysis was aimed at defining an equivalent circuit for spreading gate resistances and capacitances, determining ranges of variations of the equivalent circuit elements and answering the question whether values of the parasitic elements are frequency-dependent or not.

From the electromagnetic field theory point of view, the stated problem is a quasi-static one because physical sizes of typical MOS transistors are much less than the wavelengths corresponding the signal frequencies under consideration. Thus, we need to solve numerically the complete set of Maxwell's equations in 3D space in the frequency domain for finding quasi-static solution.

In general, the transistor structure which should be analyzed is asymmetric, however, for our purposes it is sufficient to consider a symmetric structure presented in Fig.1(a). As seen in the Fig., the gate, source and drain form coupled strips placed on a SiO_2 layer grown upon the resistive semiconductor substrate (the body). Geometrical and electrophysical parameters of the structure are similar to those of the transistor examined in the next section, namely: $L_G=L_{GS}=L_{GD}=0.4\mu m$, $L_D=L_S=2\mu m$, $T_G=0.4\mu m$, $T_D=T_S=0.6\mu m$, $T_{0X}=0.1\mu m$, $W=10\mu m$, $\sigma_g[Sm^{-1}] \in [2\cdot 10^4, 10^6]$ (poly-Si gate), $\sigma_b \approx$ hundreds of Sm^{-1}. From the physical propagation mechanism, it appears reasonable to assume the equivalent circuit shown in Fig.1(b). The system illustrated in Fig.1 seems simple and perhaps the most useful model for studying the high-frequency properties of the parasitic gate resistances and capacitances.

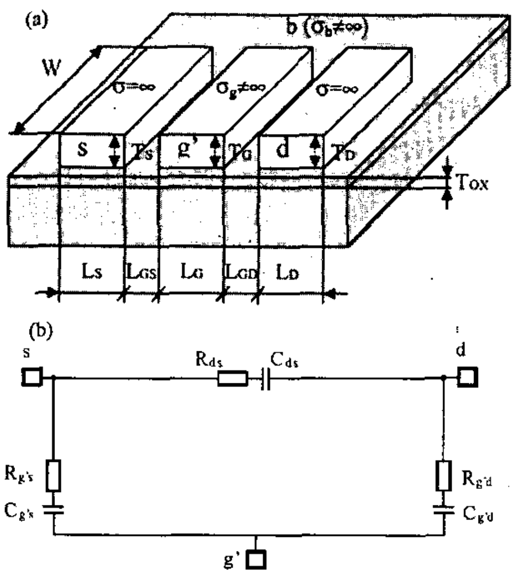

Fig.1. (a) An isometric view of symmetric coupled strips representing the gate, drain, and source of the MOS transistor, (b) an equivalent circuit.

First, in our study, an equivalence between calculated scattering parameters for the structure and two-port admittance parameters was found; the S-parameters were calculated using a commercially available high frequency simulator based on finite elements method on the assumption that the TEM odd- and even-modes can propagate in the structure. The odd-mode can be excited by applying the same in magnitude but opposite in phase signals to external strip conductors (the drain and source) and even-mode by applying signals of the same magnitudes and phases. The inner strip (the gate) in both cases is grounded. Then, values of the equivalent circuit elements were extracted from the admittance parameters.

For the sake of brevity, we cannot present detailed results and discussion of our analysis. We can only state that the equivalent circuit from Fig.1(b) can be used to represent the spreading gate resistances and capacitances over the investigated frequency range of 1 – 30 GHz, however, for some proportions of σ_g to σ_b this equivalent circuit can become inadequate – dispersive behaviors of the circuit elements are observed. Obviously, in a real transistor $C_{g's} \neq C_{g'd}$ and $R_{g's} \neq R_{g'd}$ due to lack of symmetry. To conclusion, depending on values of geometrical and electrophysical parameters of the structure, the parasitic gate resistances can vary from hundreds of Ω to a few tens of $k\Omega$, and $C_{ds} \neq C_{g'd}$ in general. Results of this 3D analysis were used as input data for global extraction of the model parameters.

IV. COMPLETE NQS MODEL AND ITS VERIFICATION

Adding parasitic elements to the NQS model of the intrinsic transistor results in a complete NQS MOSFET model. The parasitics are included in Fig.2. and the complete developed model is presented in Fig.3.

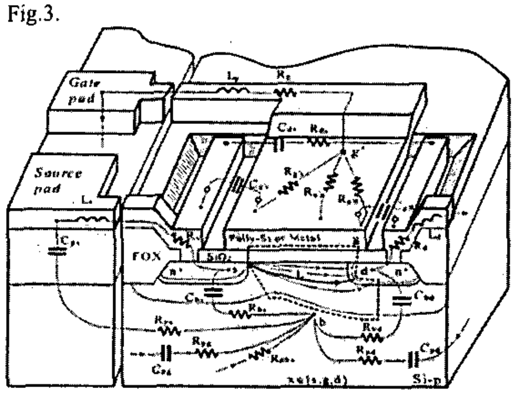

Fig.2. An isometric view of n-channel MOSFET, showing the intrinsic transistor and parasitic components.

Results of the modeling have been verified experimentally up to 27GHz on the basis of measured characteristics of 0.4-μm MOSFET in common source configuration presented in work [4].

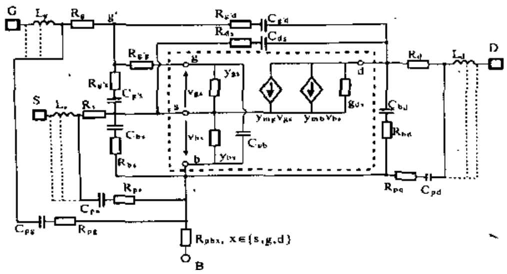

Fig.3. A complete non-quasi-static small-signal four terminal model of the MOSFET for radio and microwave frequencies, with subcircuit enveloped in broken line being the intrinsic transistor.

The proposed NQS model fits Y-parameters of the transistor very well as shown in Fig.4, especially as compared to those predicted by BSIM3 model, cf. [4]. Comparing results of experimental verification presented in [9] to those depicted in Fig.4, we can state that applying a knowledge of the ranges of variations of parasitic gate resistances and capacitances predicted by our 3D analysis greatly improved a degree of accuracy (cf. y_{22}-parameter).

V. CONCLUSIONS

In this report, we propose a novel complete non-quasi-static four-terminal small-signal MOSFET model for RF and microwave frequency IC design. No non-reciprocal capacitance is implemented in this model. The magnitude of the transadmittance y_{21} is a decreasing function of frequency. Very good agreement between calculated and measured characteristics is also a valid evidence that supports the proposed model. Unlike the known models, there are no physical inconsistencies in this model.

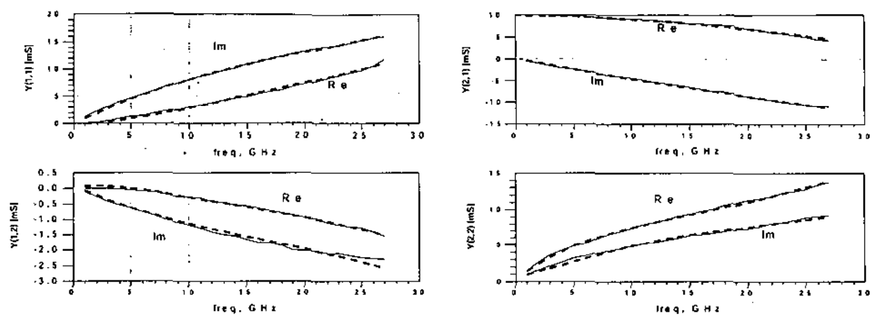

Fig.4. Experimental verification of the proposed model. Comparison between measured and calculated Y-parameters for a transistor in common-source configuration (solid lines - experimental characteristics after [4], broken lines – theoretical results).

REFERENCES

[1] C.C. Enz, Y. Cheng, "MOS Transistor Modelling for RF IC Design", *IEEE Trans. on Solid-State Circuits,* Vol.35, No.2, 2000, pp. 186-201.

[2] J.M. Sallese, A.-S. Porret, "A Novel Approach to Charge-Based Non-Quasi-Static Model of the MOS Transistor Valid in all Modes of Operation", *Solid-State Electronics,* Vol.44 (2000) pp. 887-894.

[3] T. Manku, "Microwave CMOS-Device Physics and Design", *IEEE J. of Solid-State Circuits,* Vol.34, No.3, 1999, pp. 277-285

[4] Sung R. et. al. , "Extraction of High-Frequency Equivalent Circuit Parameters of Submicron Gate-Length MOSFET's", *IEEE Trans. on Electron Devices,* Vol.45, No.8, 1998, pp. 1769-1775.

[5] Chan M. et. al. , "A Robust and Physical BSIM3 Non-Quasi-Static Transient and AC Small-Signal Model for Circuit Simulation", *IEEE Trans. on Electron Devices,* Vol.45, No.4, 1998, pp. 834-841.

[6] S. Selberherr, "Analysis and Simulation of Semiconductor Devices", Wien: Spinger-Verlag, 1984.

[7] K. Yamaguchi, "Field-Dependent Mobility Model for Two-Dimensional Numerical Analysis of MOSFET's", *IEEE Trans. on Electron Devices,* Vol.ED-26, No.7,1979.

[8] W. Kordalski, "An Injection Non-Quasi-Static Small-Signal MOSFET Model", *International Conference on Signals and Electronic Systems, 17-20 October 2000,* 2000, Ustroń, Poland.

[9] W. Kordalski, T. Stefański "A Non-Quasi-Static Small-Signal Model of the Four-Terminal MOSFET for Radio and Microwave Frequencies", *1st IEEE International Conference on Circuits and Systems for Communications,* 26-28 June 2002, 2002, St.Petersburg, Russia.