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TIME- AND FREQUENCY-DOMAIN QUASI-2D SMALL-SIGNAL MOSFET MODELS

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CONTENTS

SELECTED LIST OF SYMBOLS AND ACRONYMS

Symbols

Certain symbols which are used only locally within a section, or whose meaning is clear from the context, are not included in this list.

C_{bd} – body-drain capacitance
C_{bs} – body-source capacitance
C_{bc} – quasi-static body-to-channel capacitance, Sec. 3.7.3
C_{ds} – drain-source capacitance
C_{gb} – gate-body capacitance
C_{gc} – quasi-static gate-to-channel capacitance, Sec. 3.7.2
C_{gd} – gate-drain capacitance
C_{gs} – gate-source capacitance
D_C – dynamic coupling factor of the channel, Sec. 3.3.1
D_p – diffusivity of holes
D_V – dynamic channel-to-current coupling factor, Sec. 3.3.1
D_S – dynamic channel deformation factor, Sec. 3.3.1
d_l – longitudinal dynamic carrier-to-channel coupling factor
$\mathbf{E}$ – electric field vector
E – total longitudinal electric field in the channel
E_0 – steady-state longitudinal electric field in the channel
E_1 – small-signal longitudinal electric field component in the channel
E_{CB} – total transverse electric field on the bottom channel surface, see Fig. 3.3
E_{CB0} – steady-state transverse electric field on the bottom channel surface, see Fig. 3.3
E_{cb} – small-signal transverse electric field component on the bottom channel surface, see Fig. 3.3
E_{CG} – total transverse electric field on the top channel surface, see Fig. 3.3
E_{CG0} – steady-state transverse electric field on the top channel surface, see Fig. 3.3
E_{cg} – small-signal transverse electric field component on the top channel surface, see Fig. 3.3
g_{ds} – quasi-static small-signal drain-source conductance
g_{dsD} – DIBL part of g_{ds}
g_{dso} – ohmic part of g_{ds}
g_m – quasi-static gate small-signal transconductance
g_{mb} – quasi-static body small-signal transconductance

I_{ch} – channel current
i_b – small-signal body-terminal current
i_d – small-signal drain-terminal current
i_g – small-signal gate-terminal current
i_s – small-signal source-terminal current
$\mathbf{J}$ – current density vector field
J – total conduction current density, see (3.60)
J_0 – steady-state conduction current density
J_1 – small-signal conduction current density
J_t – total current density, see (3.59)
J_{t1} – total small-signal current density, see (3.67)
J_{dis} – displacement current density
J_{dis1} – small-signal displacement current density = displacement current density J_{dis}
L – channel length
L_G – gate length
k_D – dimensionless factor, $k_D = g_{dsD} / g_{ds}$
N_d – concentration of ionized donors
p – total concentration of holes at Q-point, see (3.4)
p_0 – steady-state concentration of holes at Q-point
p_1 – small-signal concentration of holes at Q-point
Q_B – total body charge per unit area at Q-point, see (3.13)
Q_{B0} – steady-state body charge per unit area at Q-point
Q_b – small-signal body charge per unit area at Q-point
Q_G – total gate charge per unit area at Q-point, see (3.12)
Q_{G0} – steady-state gate charge per unit area at Q-point
Q_g – small-signal gate charge per unit area at Q-point
q – magnitude of the elementary charge
q_b – overall excess depletion region charge, see (3.143)
q_g – overall excess gate charge, see (3.142)
S – dimensionless parameter, see (4.2)
t_{ox} – oxide thickness
V_{BC} – dc body-channel voltage, see Fig. 3.5
V_{BS} – dc body-source voltage
V_{CS} – dc voltage drop across the channel, see Fig. 3.5
V_{DS} – dc drain-source voltage
V_{GC} – dc gate-channel voltage, see Fig. 3.5
V_{GS} – dc gate-source voltage
V_T – threshold voltage
v_{bs} – small-signal body-source voltage
v_{ds} – small-signal drain-source voltage
v_{gs} – small-signal gate-source voltage
X – total thickness of the channel at Q-point, see (3.6)
X_0 – steady-state thickness of the channel at Q-point

X_1 – small-signal thickness of the channel at Q-point
X_{ch} – average channel thickness, see (4.16)
X_D – channel thickness at the drain
X_d – total thickness of the depletion region at Q-point, see (3.11)
X_{d0} – steady-state thickness of the depletion region at Q-point
X_{d1} – small-signal thickness of the depletion region at Q-point
X_S – channel thickness at the source
y_{bs} – small-signal body-source admittance, see (4.107)
y_{Db} – small-signal body-to-source transadmittance, determined by DIBL see (4.123)
y_{Dg} – small-signal gate-to-source transadmittance determined by DIBL, see (4.122)
y_{ds} – small-signal drain-source admittance, see (4.121)
y_{gs} – small-signal gate-source admittance, see (4.95)
y_m – gate small-signal transadmittance, see (4.94)
y_{mb} – body small-signal transadmittance, see (4.106)
W – width of transistor
ε_0 – permittivity of free space
ε_s – relative permittivity of solicon
η – dimensionless factor, $\eta = g_{mb} / g_m$
ξ – distance (from the source) along the channel
$\mu(\xi, t)$ – total bias-dependent mobility of holes at Q-point, see (3.5)
$\mu_1(\xi, t)$ – differential of μ_q at Q-point, see (3.70) and (4.8)
μ_d – differential mobility at Q-point, see (4.10)
$\mu_q, \mu_q(\xi)$ – mobility of holes at Q-point
τ – relaxation time
τ_{tr} – transit time of carriers across the channel
υ – velocity of carriers
ω – angular frequency

Acronyms

2D – Two-Dimensional
AC, ac – Alternating Current
ACP – Air Coplanar Probe
BSIM – Berkeley Short-channel IGFET Model
CLE – Channel-Lengthening Effect
CSE – Channel-Shortening Effect
CTME – Channel Thickness Modulation Effect
DC, dc – Direct Current
DCTME – Dynamic Channel Thickness Modulation Effect
DIBL – Drain-Induced Barrier Lowering
GCA – Gradual Channel Approximation
GCDE – Gradual Channel Detachment Effect
HSDMAGFET – Horizontally-Split-Drain Magnetic Field-Effect Transistor

MOS – Metal Oxide Semiconductor
MOSFET – Metal Oxide Semiconductor Field-Effect Transistor
NQS – Non-Quasi-Static
NQSCCPR – Non-Quasi-Static Channel Charge Partition Rule
Q-point – Quiescent Point
QS – Quasi-Static
QSCCPR – Quasi-Static Channel Charge Partition Rule
RF – Radio Frequency
VNA – Vector Network Analyzer

Chapter 1

INTRODUCTION

Wiesław Kordalski

This monagraph deals with modeling the small-signal operation of the MOS transistor, and presents original, not yet fully published, results of our research on time- and frequency-domain physics-based small-signal MOSFET models.

To design reliably circuits for communications in the range of radio or microwave frequencies, an adequate non-quasi-static (NQS) MOSFET model is indispensable. Quasi-static (QS) approaches do not accurately describe the 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 perturbed carrier beam and the transistor structure (the gate and the body).

Passing over the narrow-channel effects, the MOS transistor is inherently a two-dimensional (2D) device. Thus, to derive an NQS four-terminal small-signal MOSFET model valid in time and frequency domains, one should solve a closed set of partial differential equations, namely: continuity, transport and Poisson's equations. The set of equations cannot be exactly solved in the analytical form in 2D space, which implies the necessity for researchers to decompose the 2D problem into simplified ones.

An adequate model of the channel, especially its shape, is one of the most important issues in the derivation of a small-signal model of the transistor.

In models whose derivation is based, either explicitly or implicitly, on the gradual channel approximation (GCA), presented in e.g. [1–8], the shape of the channel is unrealistic, because its thickness decreases as the distance from the source of the transistor increases, see, e.g. [2–5]. The GCA is one of the assumptions which are most commonly put forward in analytical and semi-analytical approaches to the calculation of the value of the charge induced in the channel. The GCA amounts to the assumption that the surface density of the total uncompensated semiconductor charge, and thus of the channel, is determined only by the transversal electric field acting on the semiconductor surface. For this reason, apparent physical contradictions can appear if the approximation is used, which was pointed out, for instance, in [9–12]. It is the GCA that leads in consequence to such non-realistic phenomena as the channel pinch-off or the channel-shortening effect (CSE). Therefore, a more comprehensive analysis on the channel shape is an obvious need.

In so-called charge-based or surface-potential-based models, e.g. [13–16], the channel is assumed to be a charge sheet of negligible thickness; however it is difficult to find physical reasons justifying this shape of the channel.

Some attempts were undertaken in order to overcome limitations imposed by the GCA. For example, the question of how changes of the longitudinal electric field component in the drain-to-source region affect the channel charge were considered in several works, e.g. [9–12], however, in each of them there were made some restrictive assumptions dealing with the shape of the depletion region. Namely, in all the works the depletion region and the channel were assumed to be rectangular, which is an unrealistic assumption.

In derivation of quasi-2D dc MOSFET models, which are briefly presented in [17–21], the MOSFET is considered as a 2D object in which the channel has also a 2D nature. The GCA is abandoned in this approach (non-GCA models). In description of these models, there are no such unrealistic terms as pinch-off and channel-shortening effect. According to these models, the channel has the shape of a curvilinear tetragon, and its thickness increases as the distance from the source of the transistor increases. This shape of the channel results from the qualitative and quantitative analysis carried out in detail in the next chapter. {It is worth mentioning that the key features of these quasi-2D dc MOSFET models are the main assumptions of the concept of a new horizontally-split-drain magnetic field-effect transistor (HSDMAGFET) described in works [22–26]}

Other few problems emerge when the exact knowledge of the small-signal behavior of the MOSFET and an adequate small-signal model of the device for radio and microwave frequencies are needed [27]. In addition to an appropriate channel model of the transistor, an adequate small-signal MOSFET model should take into account: the velocity saturation effect of carriers in the channel of the transistor; the field-dependent mobility; the electrical coupling between the perturbed charge in the channel and the gate and the body; local variations in the channel thickness; and the drain-induced barrier lowering (DIBL) effect.

Known small-signal MOSFET models used in designing integrated circuits in the radio frequency (RF) range can be split into two groups: quasi-static (QS) and non-quasi-static (NQS) models. The 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 voltage, thereby neglecting the delay, dynamic properties of the channel, and the coupling between the perturbed carrier beam and the structure (the gate and the body). As a result, serious inconsistencies arise when the QS approach is used to modeling an RF MOS transistor. For instance, according to the model presented in [28], magnitudes of transadmittances of voltage-controlled current sources tend to infinity as frequency increases, which is an apparent contradiction.

To overcome the limitations, various models have been proposed in [29–36]. However, there are also weak points in those models. For instance, one can infer from the results presented in [32–35] that the magnitude of the gate transadmittance (y_m) does not decrease as the angular frequency ω tends to infinity. The widely used NQS BSIM3 model [36] is a charge-based model developed on the channel charge relaxation time approach. Moreover, the channel of the MOSFET is modeled in work [36] as an RC distributed transmission line, which is not an adequate model of the transistor because any line of this type is not unilateral (i.e., the two-port admittance parameter $y_{12} \neq 0$). The intrinsic MOSFET (without parasitic elements) has to be unilateral ($y_{12} = 0$) for the reason that the charge carriers (electrons or holes) are injected only through the source-channel barrier potential. Besides, the transport equation for current carriers injected into the channel differs substantially from that for the current in the resistive layer of an RCline (ohmic transport mechanism). This is the fundamental reason for which any RC-line-based small-signal model of the intrinsic MOSFET is not adequate.

A phenomenon that is not included in known small-signal models is the dynamic channel thickness modulation effect (DCTME), see, e.g. [29–31].

The DIBL effect is also not included in the vast majority of known small-signal models, see, e.g. [28–36], and if it is considered, the applicability of these models is limited to a low-frequency range. For example, this phenomenon is included in the model presented in [37], but the model is quasi-static and its validity is restricted to a quasi-static frequency range.

To surmount the above-mentioned weak points of existing models, an attempt has been made to derive from first principles a new DIBL-included physics-based quasi-2D NQS frequency-domain small-signal model of the four-terminal MOSFET operating at an arbitrarily located quiescent point (Q-point). The model is briefly reported in [27, 38–42]. The new model is valid from zero Hz to well above the cut-off frequency f_T and takes into account: the velocity saturation effect of carriers in the channel; the dependence of the mobility on electric field; the electrical coupling between the perturbed charge in the channel and the gate and the body; local variations in the channel thickness; and the DIBL effect. According to the author's knowledge, there is no small-signal model in the literature that takes into account all these effects together. Moreover, there are no non-reciprocal capacitances in the new model, and the GCA is abandoned.

The purpose of this monograph is to present a detailed derivation and results of experimental verification of the new time- and frequency-domain quasi-2D NQS four-terminal small-signal MOSFET models which take into account the DIBL effect.

The monograph is arranged as follows.

The purpose of Chapter 2 is to give a physical background to the new time- and frequency-domain small-signal models. Theoretical discussion and results of numerical analysis in 2D space are given in order to introduce the following three phenomena: gradual channel detachment effect (GCDE), channel thickness modulation effect (CTME), and channel-lengthening effect (CLE). Based on these phenomena, a quasi-2D dc channel representation and a quasi-2D dc representation of the MOSFET are defined.

In Chapter 3, a novel quasi-2D NQS four-terminal time-domain small-signal MOSFET model is presented. A set of partial differential equations for the new physics-based small-signal model is derived. The set consists of a quasi-2D small-signal continuity equation, a quasi-2D small-signal Poisson's equation, and a quasi-2D small-signal transport equation. All the equations give a mathematical description of the behavior of the carriers in the channel and charges in the gate and the body. A set of supplementary equations for coupling and non-capacitive displacement currents in the MOSFET under dynamic operation is also derived. Based on the quasi-2D dc MOSFET representation, a useful formula for the gate-to-body capacitance C_{gb} is derived, and some rules dealing with channel-to-gate and channel-to-body coupling currents are established. Reciprocal capacitances occurring in this model are defined. The model we propose in this chapter provides the background to a novel frequency-domain small-signal MOSFET model.

In Chapter 4, a novel DIBL-included quasi-2D NQS four-terminal frequency-domain small-signal MOSFET model is proposed. The model takes into account: the velocity saturation effect of carriers in the channel; the dependence of the mobility on electric field; the electrical coupling between the perturbed charge in the channel and the gate and the body; local variations in the channel thickness; and the DIBL effect. Unlike other models, this one is composed only of reciprocal capacitances. A closed set of partial differential equations defining the model in the time domain is formulated and solved in the frequency domain. The solution indicates that two types of waves can propagate from the source to the drain, viz., a longitudinal wave of a disturbance in the carrier density and a transverse wave of a disturbance in the channel thickness. A closed set of equations for frequency-domain non-capacitive terminal currents in the MOSFET under dynamic operation is also derived.

In Chapter 5, the results of experimental verification of the new DIBL-included quasi-2D NQS four-terminal frequency-domain small-signal MOSFET model are presented. For the purpose of the verification, test transistors and dummy structures were designed and fabricated in 0.35-µm technology. The de-embedding procedure is based on the open-short method, optimized for RF measurement up to 30 GHz of scattering parameters of the transistors in the common source configuration with the use of air coplanar probes (ACPs).

The last part includes a summary.

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