A Simplified Methodology for the Extraction of the ACM MOST Model Parameters

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Abstract

The ACM model is a powerful tool for the simulation of MOS transistors. Unlike most of the available models, it presents simple and precise equations, allied to a small number but meaningful Physical parameters. This article presents a simplified methodology for extracting the parameters of the ACM model. Unlike usual methods for device characterization, which require the availability of expensive equipment, this methodology is based on simulation. Simple and low cost, it can be reproduced easily by those who plan to use the ACM model but do not know its parameters for a given process. In this work, the ACM parameters were extracted from the BSIM 3 parameters available for a 0.8μm technology.

1. Introduction

Many compact models of the MOS transistor appeared with the development of CMOS technology. The first ones were very simple, based on physics, but used different equations for each operating region of the transistor. At the end of a long evolutionary process the family of BSIM models appeared. Unfortunately, these models are made up by an extremely complex set of equations and often use more than one hundred parameters.

Furthermore, the evolution of electronic circuits imposes stringent requirements on the simulation model. The model must be precise in all regions, preserve the drain-source symmetry of the MOSFET and be charge conserving. In order to fulfill these requirements, the Laboratório de Circuitos Integrados (LCI) has developed a model for simulation of MOS transistors: the *Advanced Compact MOSFET* (ACM) *Model* [4]. Based on physical principles, the ACM model is very simple and uses a small set of parameters.

With the implementation of the ACM model in a commercial circuit simulator [5], the development of appropriate techniques to extract the model parameters is a must. The objective of this work is to present a simplified methodology for the extraction of the ACM parameters from those available for the BSIM 3V3 model.

2. Description of the ACM model

ACM is a physics-based MOSFET model described by a small set of parameters. The use of the substrate voltage as the reference voltage allows for a symmetric role of source and drain. Therefore, ACM is appropriate to simulate low-voltage circuits and those that are sensitive to charge variations.

The equations for the ACM model are presented in references [1-3]. The eleven parameters of the intrinsic MOS transistor described in Table I, together with W (channel width) and L (channel length), allow us to simulate the transistor behavior for any set of applied voltages. All parameters except for the last three in Table I are conventional parameters of MOS transistor models available in SPICE-like simulators.

Table I: Parameters of the ACM model

Parameter	Description	Units
VTO	Zero-bias threshold voltage	V
GAMMA	Body-effect parameter	$V^{1/2}$
PHI	Surface potential	V
TOX	Gate oxide thickness	m
LD	Lateral diffusion	m
XJ	Junction depth	m
UO	Low-field mobility	cm^2/Vs
VMAX	Saturation velocity	m/s
THETA	Mobility reduction parameter	V^{-1}
SIGMA	Drain-induced barrier lowering parameter	m^2
PCLM	Channel length modulation parameter	-

The small number of parameters in the ACM model not only simplifies the description of the device but also reduces the complexity of parameter extraction. We have employed three methods for the extraction of the ACM parameters:

1. The mapping of BSIM parameters onto ACM parameters;
2. Determination of ACM parameters from simulation;
3. Experimental determination of the ACM parameters.

The first two methods are described in this paper.

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3. Extraction via mapping of BSIM parameters onto ACM parameters

Here we describe the procedure to determine the ACM parameters of a 0.8μm MOS technology from the BSIM 3V3 [8] model, whose parameter values are supplied by AMS (*Austria Mikro Systeme International*) [10]. In this method, some BSIM parameters are directly converted to ACM parameters, e.g., VTO and TOX. The others are expressed as functions of BSIM parameters, as shown below. The results are given in Table II.

$$\mathrm{GAMMA}=\frac{(2\cdot\varepsilon_{Si}\cdot q\cdot \mathrm{NCH})^{1/2}}{C_{ox}} \tag{1}$$

$$\mathrm{PHI}=2\cdot\phi_t\cdot\ln\left(\frac{\mathrm{NCH}}{n_i}\right) \tag{2}$$

$$\mathrm{THETA}=\frac{\mathrm{UA}}{\mathrm{TOX}}+\frac{\mathrm{UB}}{\mathrm{TOX}^2}\cdot\left[\frac{(\mathrm{VDD}-2\cdot V_{T0})}{(V_{DD}+V_{T0})^2-(3\cdot V_{T0})^2}\right] \tag{3}$$

$$\mathrm{SIGMA}=\theta_{DIBL}\cdot\mathrm{ETA0}\cdot(L_{eff})^2 \tag{4}$$

where $L_{eff} = L_{drawn} - 2\cdot\mathrm{DLC}$ and θ_{DIBL} is defined in [7] and [8].

Table II: Results of mapping BSIM parameters onto ACM parameters

ACM Parameter	BSIM Parameter	Result	Units
VT0	VTH0	0.836	V
GAMMA	—	0.71	$V^{1/2}$
PHI	—	0.81	V
TOX	TOX	$15.8\cdot10^{-9}$	m
LD	DLC	$209\cdot10^{-9}$	m
XJ	XJ	$300\cdot10^{-9}$	m
U0	U0	487	$cm^2/V\cdot s$
VMAX	VSAT	$9.08\cdot10^{4}$	m/s
THETA	—	0.12	V^{-1}
SIGMA	—	$4.4\cdot10^{-20}$	m^2
PCLM	PCLM	1.01	—

4. Extraction by Simulation

A set of very simple circuits was developed to determine the ACM parameters. These circuits can be used for parameter extraction, either by experiment or by simulation.

For the extraction by simulation, an MOS transistor with W=35μm and L=5μm and BSIM3V3.2.2 [8] were used. The following sections present the strategies for the extraction of the ACM parameters.

4.1 Extraction of I_S

The specific current (I_S) is the normalization current of an MOS transistor defined in [3] by

$$I_S=\mu\cdot C'_{OX}\cdot n\cdot\frac{\phi_t^{\,2}}{2}\cdot\frac{W}{L} \tag{5}$$

Even though I_S is not an ACM parameter, it is widely used for design purposes and parameter extraction [2,3]. A proper definition of I_S is given in Fig. 2; $3\cdot I_S$ is the current in a saturated transistor for which $V_G=V_{T0}$ and $V_S=0$.

The normalized current (i_f) indicates the inversion level of the MOS transistor. It is defined by

$$i_f = I_F/I_S \tag{6}$$

where I_F is the drain current in saturation.

For the circuit in Fig. 1, it can be demonstrated that, in strong inversion ($i_f>100$), the current I_S can be determined from

$$I_S \cong I\cdot\left(\frac{\Delta I/I}{2\cdot\Delta V_S/\phi_t}\right)^2,\qquad \Delta I<<I \tag{7}$$

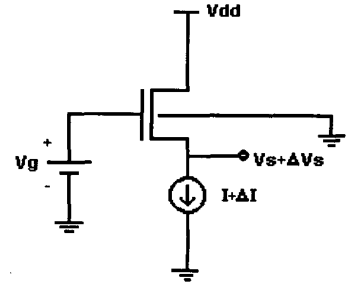

Fig. 1: Circuit for the Extraction of I_S.

Using V_{DD}=5V, V_G=5V, I=40μA e ΔI=4μA, we obtain $I_S = 310nA$

4.2 Extraction of V_{T0}

V_{T0} is the zero-bias threshold voltage.

A bias current equal to three times the specific current (I_S) is applied to a saturated MOSFET, as shown in Fig. 2. For this bias condition, the gate voltage (V_G) is equal to the threshold voltage (V_{T0}), as can be demonstrated from the ACM equations. Thus, V_{T0} is determined by measuring V_G in the circuit shown in Fig. 2.

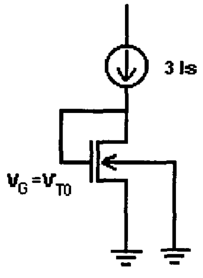

Fig. 2: Circuit for the Extraction of V_{T0}.

In our example we have measured $V_{T0}=0.845V$, which is slightly different from its normal value $(V_{T0} = 0.836V)$.

4.3 Extraction of GAMMA (γ)

GAMMA is the *body effect* coefficient, whose value can be calculated from the expression of n [5]:

$$\gamma = (n-1) \cdot 2 \cdot \sqrt{2 \cdot \phi_F + V_P} \tag{8}$$

where V_P is the *pinch-off* voltage of the MOS transistor [5] and $n = \left(\frac{dV_P}{dV_G}\right)^{-1}$. For the determination of γ we need to know both V_P and n.

4.4 Extraction of V_P

If the drain current is set to $3I_S$, as shown in the circuit of Fig. 3, then $V_P = V_S$. So, the *"pinch-off"* voltage (V_P) is obtained from the simulated DC transfer curve. The V_P versus V_G curve is presented in Fig. 4.

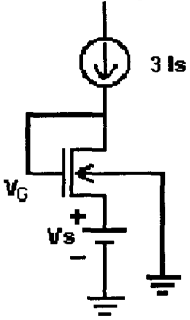

Fig. 3: Circuit of extraction of VP and n.

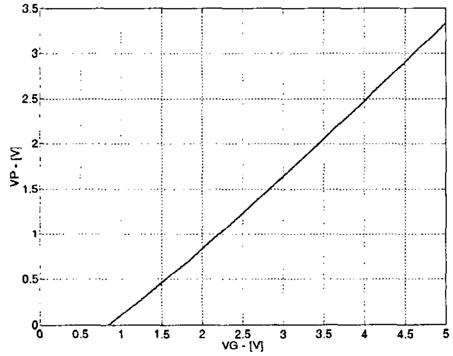

Fig. 4: V_P versus V_G

4.5 Extraction of n

The plot of n versus V_G (Fig. 5) is obtained by calculating the derivative of the $V_P(V_G)$ characteristic.

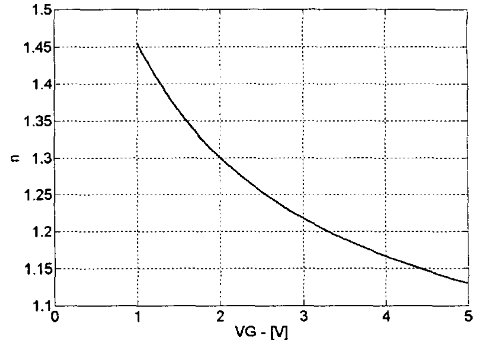

Fig. 5: n versus V_G.

4.6 Calculation of γ

The approximate value of $2\phi_F$ is 0.7. For $V_{GB} = 2.5V$, n=1.25 (Fig. 5) and $V_P = 1.23$ (Fig. 4). From equation (8): $\gamma = 0.69\ V^{1/2}$

4.7 Extraction of μ_0 and θ (THETA)

μ_0 is the carrier mobility for low values of the electric field. θ is the ACM fitting parameter which accounts for the mobility variation with the transverse field. The expression for the mobility [4] is:

$$\frac{1}{\mu} = \frac{1}{\mu_0} \cdot \left[1 + \frac{\theta}{C_{ox}} \cdot \left(Q_B + \frac{Q_I}{2}\right)\right] \tag{9}$$

In the DC simulation of the circuit in Fig. 6, I_D is obtained as a function of V_{GS} with the transistor biased in the linear region ($V_{DS} \approx 100mV$) and in strong inversion. V_{GS} varies from $2 \cdot V_{T0}$ to V_{DD}.

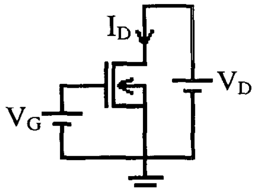

Fig. 6: Circuit for the Extraction of μ_0 and θ (THETA).

Using the equation

$$\left[\mu \cdot C'_{OX} \cdot \left(W/L\right)\right]^{-1} \cong (V_{GS} - V_{TO}) \cdot \frac{V_{DS}}{I_D} \tag{10}$$

the $1/\mu \cdot C'_{ox} \cdot (W/L)$ versus V_{GS}-V_{T0} curve is obtained by means of a DC transfer simulation, as shown in Fig. 7. In the ACM model, this curve can be expressed by the equation below:

$$\frac{1}{\mu \cdot C'_{OX} \cdot \left(W/L\right)} = \frac{\theta \cdot (V_{GB} - V_{T0})}{2 \cdot \mu_0 \cdot C'_{OX} \cdot \left(W/L\right)} + \frac{\left(1 + \theta \cdot \gamma \cdot \sqrt{2 \cdot \phi_F}\right)}{\mu_0 \cdot C'_{OX} \cdot \left(W/L\right)} \tag{11}$$

For the ACM model, the relationship (1/μ) vs V_{GS} is linear. However, BSIM3 [8] models the mobility with both linear and quadratic dependence on V_{GS}. Therefore, a straight line, as illustrated in Fig. 7, approximates the plot of the curve $1/\mu$ for the purpose of extracting both μ_0 and θ.

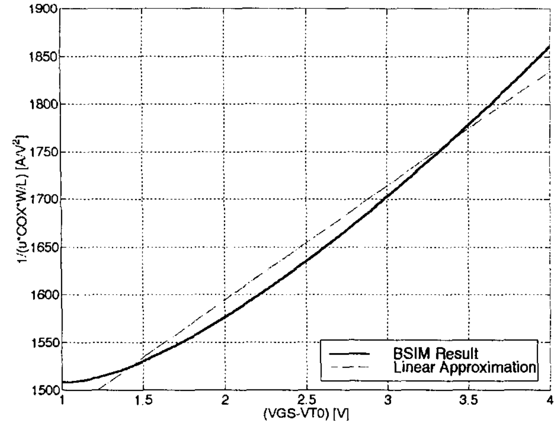

Fig. 7: Curve for the extraction of μ_0 and θ.

Using equation (11) and from the coefficients (A and B) of the straight line in Fig. 7, it is possible to extract the values of μ_0 and θ:

$$\mu_0 = \frac{1}{C'_{OX}\cdot(W/L)\cdot\left(B-2\cdot A\cdot\gamma\cdot\sqrt{2\cdot\phi_F}\right)} = 514\,\mathrm{cm}^2/V\cdot s$$

$$\theta = 2\cdot\mu 0\cdot C'OX\cdot(W/L)\cdot A = 0.20\,V^{-1}$$

4.8 Extraction of SIGMA

DIBL (Drain-Induced Barrier Lowering) is a phenomenon characterized by the progress of the depletion layers associated with the drain and source under the gate, due to the increase of the drain (V_D) and source (V_S) voltages. This effect is more important in weak inversion than in strong inversion due to the larger influence of the depletion charge in weak inversion. This effect is modeled by SIGMA, defined [5] as:

$$\mathrm{SIGMA} = \sigma\cdot(L_{eff})^2 \tag{12}$$

where σ represents the variation of the threshold voltage with both V_D and V_S:

$$V_T = V_{T0} - \sigma\cdot(V_D + V_S)/2 \tag{13}$$

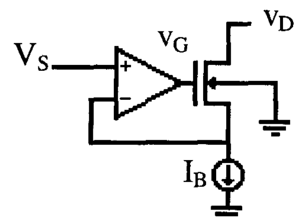

Fig. 8: Circuit for the extraction of Sigma.

Since the DIBL is more important for short-channel transistors, the channel length was set to the minimum for this technology (0.8µm). In order to avoid the influence of other effects, such as SCBE (substrate current induced body effect) and CLM (channel length modulation), in the determination of SIGMA, the BSIM parameters corresponding to SCBE and PCLM were set to very low values. In this case, the voltage gain $\Delta v_D/\Delta v_G$ gives the value of σ according to

$$\sigma = -\frac{1}{\mathrm{Gain}} = -\frac{gm_d}{gm_g} \tag{14}$$

Using $I_B = 0.1\cdot I_S$ (weak inversion) and varying V_D from 200mV to 500mV, we obtained the plots in Figures 9 and 10:

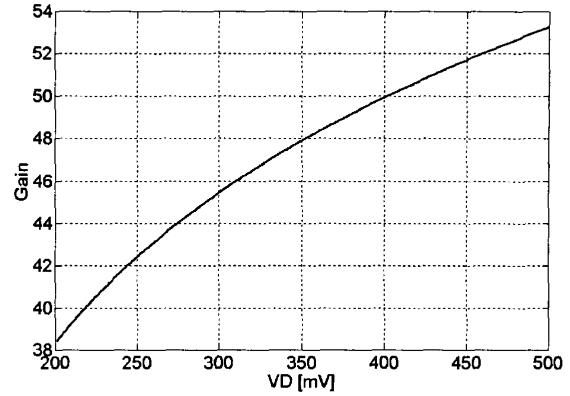

Fig. 9: Gain (vd/vg) versus V_D

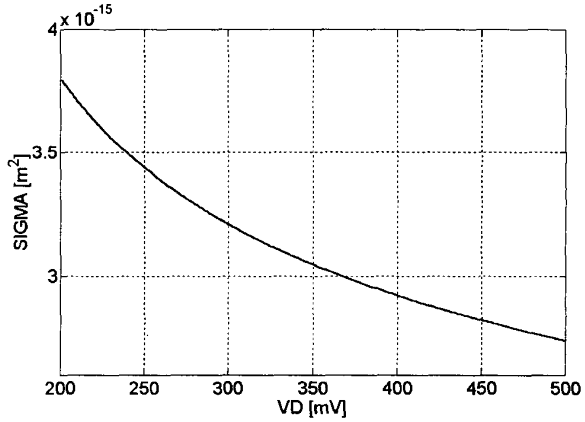

Fig. 10: SIGMA versus V_D.

As shown in Fig. 10, SIGMA depends on V_D. The value of SIGMA adopted in this work was measured at V_D = 350 mV, resulting in SIGMA=$3.2\times10^{-15}\mathrm{m}^2$

4.9 Extraction of PCLM

PCLM stands for the CLM parameter [5]. It represents the reduction of the effective length of the inversion channel due to an increase in the drain voltage V_D. The equivalent length (Leq) becomes Leq = Leff - ΔL, where ΔL is the "pinched-off" part of the channel that corresponds to the CLM, calculated [5] as

$$\Delta L = P_{CLM}\cdot L_C\cdot\ln\left[1+\frac{(V_{DS}-V_{DSAT})}{L_C\cdot \mathrm{UCRIT}}\right] \tag{15}$$

The PCLM parameter can be obtained by plotting the Early Voltage (V_A) as function of V_{DS}-V_{DSSAT} obtained using the circuit of the Fig. 11. V_A is defined as $V_A = I_D \cdot \frac{dV_D}{dI_D}$

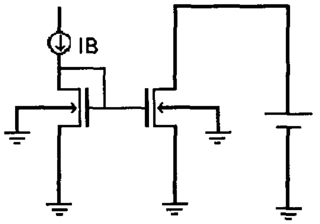

Fig. 11: Circuit for the Extraction of PCLM

The plot of V_A vs. V_{DS} using the BSIM model in SMASH is shown in Fig. 12. The value of I_B is such that the inversion level i_f = 200. In this case we used a transistor with W = 350μm and L = 50μm, which has the same aspect ratio as the one used before.

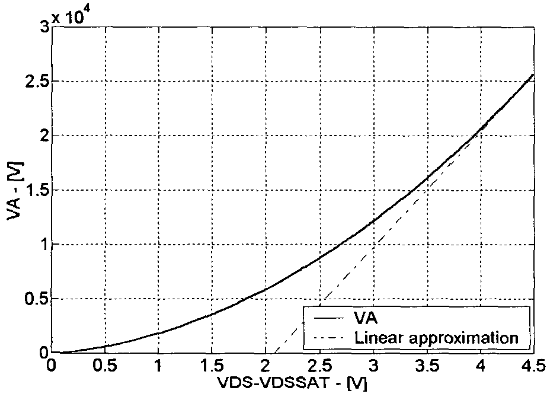

Fig. 12: VA as a function of (V_D - V_{DSSAT})

To extract the PCLM, we have calculated the Early voltage (V_A) from the ACM model. The result given in (16) has been derived assuming that CLM is the dominant short channel effect. The PCLM is determined from the slope of the straight line shown in Fig. 12.

$$V_A = \frac{L_{eff} \cdot UCRIT}{P_{CLM}} \cdot \left(\varepsilon \cdot \sqrt{1+i_f} + 1\right) \cdot \left(1 + \frac{(V_{DS} - V_{DSAT})}{L_C \cdot UCRIT}\right) \quad (16)$$

where: $\varepsilon \cong \frac{\phi_t}{L_{eff} \cdot U_{CRIT}}$, $L_C = \sqrt{\varepsilon_{Si} \cdot \frac{X_j}{Cox}}$,

$$V_{DSSAT} = \phi_t \cdot \left[\ln\left(1 + \frac{\sqrt{1+i_f} - 1}{0.5 \cdot \varepsilon \cdot i_f}\right) + \sqrt{1+i_f} - 1\right]$$

5. Results

Table III presents the parameters extracted for the ACM model from simulation with the BSIM model. There are the extracted (or converted) parameters and also some technology dependent. Parameters TOX, LD, XJ and VMAX have been mapped directly to ACM while the remaining parameters but PHI have been extracted by simulation. The value of PHI, which is very close to the BSIM corresponding value, has been taken arbitrarily.

Meaningless results for the value of SIGMA can be obtained when using a non-minimum channel transistor.

Table III: ACM Simulation Parameters.

Parameter	BSIM3	Extracted Value	Units
VT0	0.836	0.845	V
GAMMA	0.71	0.69	$V^{1/2}$
PHI	0.81	0.7	V
TOX	$15.8 \cdot 10^{-9}$	$15.8 \cdot 10^{-9}$	m
LD	$209 \cdot 10^{-9}$	$209 \cdot 10^{-9}$	m
XJ	$300 \cdot 10^{-9}$	$300 \cdot 10^{-9}$	m
U0	487	514	$cm^2/V \cdot s$
VMAX	$9.08 \cdot 10^4$	$9.08 \cdot 10^4$	m/s
THETA	0.12	0.20	V^{-1}
SIGMA	$4.55 \cdot 10^{-16}$	$3.2 \cdot 10^{-15}$	m^2
PCLM	1.01	1.23	—

The version of the ACM model currently available in SMASH [6] has some differences in comparison with the version of ACM previously shown. Table IV presents a list of the ACM parameters for use in the current version of SMASH.

Table IV: ACM Simulation Parameters (version currently available in SMASH).

Parameter	BSIM3	Extracted Value	Units
VT0 (1)	0.786	0.795	V
GAMMA	0.71	0.69	$V^{1/2}$
PHI	0.81	0.7	V
TOX	$15.8 \cdot 10^{-9}$	$15.8 \cdot 10^{-9}$	m
DL (2)	$-418 \cdot 10^{-9}$	$-418 \cdot 10^{-9}$	m
XJ	$300 \cdot 10^{-9}$	$300 \cdot 10^{-9}$	m
U0	487	514	$cm^2/V \cdot s$
UCRIT (3)	$1.86 \cdot 10^6$	$2.06 \cdot 10^6$	V/m
THETA	0.12	0.20	V^{-1}
SIGMA	$4.55 \cdot 10^{-16}$	$3.2 \cdot 10^{-15}$	m^2
LAMBDA (4)	1.01	1.23	—

(1) The current version of ACM, in [6], has an error of $2\phi_t$ in the evaluation of V_T.

(2) $DL = -2 \cdot LD$

(3) $UCRIT = VMAX/U0$

(4) LAMBDA = PCLM

Fig. 13 shows the log(I_D) versus V_G curves obtained for an MOS transistor of W=35μm and L=5μm, using the BSIM 3V3.2.2 and ACM models. AMS supplies the BSIM 3 parameters while the ACM parameters are shown in Table IV.

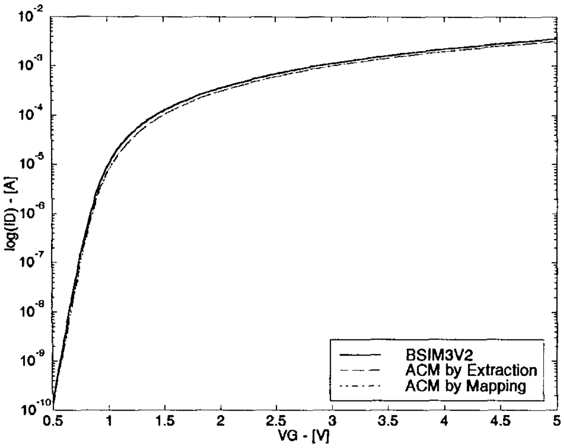

Fig. 13: log(I_D) versus V_G curve.

Fig. 14 shows the I_D versus V_D curve for the same transistor.

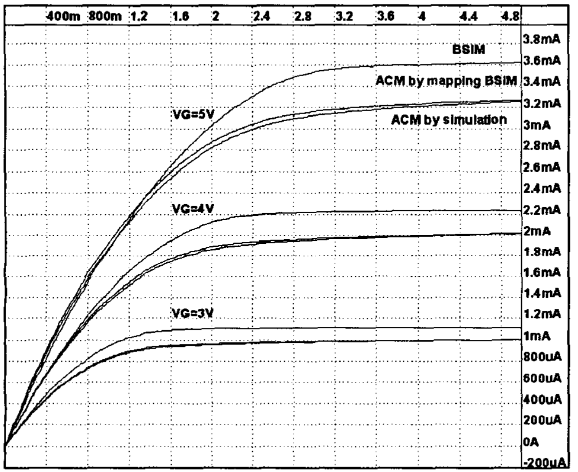

Fig. 14: I_D versus V_D curve.

6. Conclusion

The purpose of this work was to present a simplified methodology for the extraction of the parameters of the ACM model. Considering that the main goal of this work is simplicity rather than accuracy, the methodology shows good results, as the curves presented in Figures 13 and 14 demonstrate.

The option of extracting the model parameters starting from a set of parameters from another model has the disadvantage of being strongly dependent of the model used as a reference. Therefore, some parameters might not be satisfactorily extracted, and have to be approximated.

An alternative to avoid the problem of a poor reference model should be the parameter extraction laboratory measurements with real transistors. The price to be paid, however, would be the need for the test devices.

Acknowledgments

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