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THE ACM MODEL FOR CIRCUIT SIMULATION AND EQUATIONS FOR SMASH

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Abstract - **This document presents a physically based model for the MOS transistor, suitable for analysis and design of integrated circuits. The static and dynamic characteristics of the MOSFET are accurately described by single-piece functions of the inversion charge densities at source and drain. A new compact physical approach for saturation is presented. Short-geometry effects are included by adapting results previously reported in the technical literature to our model.**

1. INTRODUCTION

MOSFET models included in circuit simulators can be classified into the following three categories [9]: analytical models, table lookup models and empirical models. Practically all the models in current use are analytical.

MOSFET analytical models are based on either the regional approach or surface potential formulations, or semi-empirical equations [1]. Models based on the regional approach use different set of equations to describe the device behavior in different regions. In the regional approach, the weak and strong inversion regions are generally bridged by using a non-physical curve fitting. Models based on surface potential formulation are inherently continuous; however, they demand the solution of an implicit equation for the surface potential. Semi-empirical models take the risk of becoming neither scalable nor suited for statistical analysis.

ACM model is a charge-based physical model [1-3]. All the large signal characteristics (currents and charges) and the small signal parameters ((trans)conductances and (trans)capacitances) are given by single-piece expressions with infinite order of continuity ($C\infty$ functions) for all regions of operation. ACM model preserves the structural source-drain symmetry of the transistor and uses a reduced number of physical parameters. It is also charge-conserving and has explicit equations for the MOSFET 16 (trans)capacitances.

The model features can be summarized as follows:

- single-piece expressions with infinite order of continuity for all regions of operation;
- source-drain symmetry of the transistor;
- charge-conserving equations;
- physically based equations for the vertical field dependence of carrier mobility, carrier velocity saturation and saturation voltage;
- geometric dependence of electrical parameters;
- independence of technology;
- easily measurable parameters.

Some advantages of the model over the BSIM [10] model are the use of simple expressions to describe all regions of operation as well as the symmetry of the MOSFET and a smaller number of device parameters. Moreover, all the parameters have a strong physical basis.

To our knowledge, the EKV model [6] is the most appropriate model current available in simulators. It preserves the device symmetry, is described by physical parameters and uses single-piece expressions. However, it uses a non-physical interpolating curve to bridge the gap between weak and strong inversion. As a result, the small-signal parameters, specially the capacitances, are quite difficult to model.

This document describes the parameters and the equations of the ACM model implemented in SMASH.

The ACM model is useful not only to simulate high current density circuits but also low voltage operated circuits because it represents accurately the moderate and weak inversion regions.

2. VARIABLES AND PARAMETERS

The device input variables and the model parameters are listed in the tables below.

2.1 Device input variables

NAME	DESCRIPTION	UNITS	DEFAULT
L	channel length	m	1E-4
W	channel width	m	1E-4
AD	drain diffusion area	m^2	0
AS	source diffusion area	m^2	0
PD	drain diffusion perimeter	m	0
PS	source diffusion perimeter	m	0
NRD	number of squares for calculation of drain resistance	squares	0
NRS	number of squares for calculation of source resistance	squares	0

2.2 Model parameters (.MODEL)

2.2.1 Parameters common to all model levels

NAME	DESCRIPTION	UNITS	DEFAULT
CREC	gate-source/drain overlap capacitance/m of channel width	F/m	0.0
CGSO	gate-source overlap capacitance / m of channel width	F/m	0.0
CGDO	gate-drain overlap capacitance/ m of channel width	F/m	0.0
PB	junction contact potential	V	0.8
CGBO	gate-bulk overlap capacitance / m of channel length	F/m	0.0
CJ	zero bias bottom junction capacitance / area	F/m^2	0.0
CJSW	zero bias side-wall junction capacitance/m	F/m	0.0
MJ	exponent for bottom capacitance formula	-	0.5
MJSW	exponent for side-wall capacitance formula	-	0.33
IS	junction saturation current	A	0.0
JS	junction saturation current density	A/m^2	0.0
LDIFF	lateral diffusion width	m	0.0
FC	coefficient for reverse formula in junction capacitance	-	0.5
RD	drain ohmic resistance	ohm	0.0
RS	source ohmic resistance	ohm	0.0
RDC	drain contact resistance	ohm	0.0
RSC	source contact resistance	ohm	0.0
RSH	diffusion sheet resistance	ohm/sq	0.0

2.2.2 FLOMOS model parameters

NAME	DESCRIPTION	UNITS	DEFAULT
UO	mobility	$cm^2/V.s$	550
TOX	oxide thickness	m	1.5E-8
VTO	threshold voltage (V_{DB}=V_{SB}= 0V)	V	0.77
GAMMA	body effect coefficient	sqrt(V)	0.77
PHI	surface potential	V	0.61
LAMBDA	CLM coefficient	-	0.25
WETA	narrow channel effect coefficient	-	0.26
LETA	short channel effect coefficient	-	0.44
DW	channel narrowing width	m	-0.1E-6
DL	channel shortening length	m	-0.4E-6
UCRIT	longitudinal critical field for mobility degradation	V/m	2.6E6
THETA	mobility reduction coefficient due to transversal field	1/V	0.08
XJ	junction depth	m	0.25E-6
SIGMA	DIBL coefficient	m^2	3E-15

2.2.3 Available internal variables

NAME	DESCRIPTION	UNITS
GMD	drain transconductance (dI/dVD)	A/V
GMS	source transconductance (-dI/dVS)	A/V
GMG	gate transconductance (dI/dVG)	A/V
LOG(GMD)	log(GMD)	
LOG(GMS)	log(GMS)	
LOG(GMG)	log(GMG)	
VP	pinch-off voltage	V
N	slope factor	-
VDSAT	drain-to source saturation voltage	V
IBD	bulk-drain diode current	A
IBS	bulk-source diode current	A
GBD	dIBD/dVDB	A/V
GBS	dIBS/dVBS	A/V
QID	inversion charge density at drain	C/m^2
QIS	inversion charge density at source	C/m^2
QI	total inversion charge	C
QG	gate charge	C
QB	bulk charge	C
QD	drain charge	C
QS	source charge	C
CGG	dQG/dVG	F
CGD	-dQG/dVD	F
CGS	-dQG/dVS	F
CGB	-dQG/dVB	F
CBG	-dQB/dVG	F
CBD	-dQB/dVD	F
CBS	-dQB/dVS	F
CBB	dQB/dVB	F
CDG	-dQD/dVG	F
CDD	dQD/dVD	F
CDS	-dQD/dVS	F
CDB	-dQD/dVB	F
CSG	-dQS/dVG	F
CSD	-dQS/dVD	F
CSS	dQS/dVS	F
CSB	-dQS/dVB	F
COX	weff.leff.eps_ox/tox	F

3. Model equations for SMASH

3.1 Inversion charge densities

The fundamental approximation in FLOMOS is the linear dependence of the inversion charge density on the surface potential [1]:

$$dQ'_I = nC'_{OX}\, d\phi_S \tag{1}$$

where n, the slope factor, is the partial derivative of Q'_I/C'_{OX} with respect to ϕ_S, calculated at $\phi_S = 2\phi_F + V_P$.

Equation (1) has allowed the model in [1] to be fully formulated in terms of the inversion charge densities at the source (Q'_{IS}) and drain (Q'_{ID}) channel ends.

According to [3, 11] the relationship between the inversion charge density and the terminal voltages is

$$V_P - V_C = \phi_t\left[\frac{Q'_{IP} - Q'_I}{nC'_{OX}\,\phi_t} + \ln\left(\frac{Q'_I}{Q'_{IP}}\right)\right] \tag{2}$$

where V_C is the channel voltage, V_P is the pinch-off voltage, Q'_{IP} is the inversion charge density at pinch-off ($Q'_{IP} = -\, nC'_{OX}\phi_t$) and ϕ_t is the thermal voltage.

Equation (2) cannot be solved analytically for Q'_I but it can be approximated [3] by

$$q = \ln\left[1 + \frac{e^{u-1}}{1 + k(u)\ln(1 + e^{u-1})}\right] \tag{3}$$

where

$$u = \frac{V_P - V_C}{\phi_t} \tag{4}$$

$$q = -\frac{Q'_I}{nC'_{OX}\,\phi_t} \tag{5}$$

$$k(u) = 1 - \frac{84.4839}{u^2 + 150.8640} \tag{6}$$

The relative and absolute errors in the inversion charge density due to this approximation are less than 1% and less than 0.1 $nC'_{OX}\phi_t$, respectively. The absolute error in the voltage is less than $0.1\phi_t$.

3.2 Pinch-off voltage

The drain current of a MOS transistor, if velocity saturation is not considered, can be written as

$$I_D = f(V_P, V_S) - f(V_P, V_D) \tag{7}$$

where all potentials are refered to the bulk [1, 6].

For a long and wide transistor the pinch-off voltage is a function only of V_G, but for short and narrow channel devices V_P becomes a function of V_G, V_S and V_D. To maintain the symmetry of equation (7) V_P is modeled as

$$V_P = V_{PO} + \frac{\sigma}{n}(V_S + V_D) \tag{8}$$

V_{PO} is the pinch-off voltage at equilibrium (V_S=V_D=0).

$$V_{PO} = \left(\sqrt{V'_G + \left(\frac{\gamma'}{2}\right)^2} - \frac{\gamma'}{2} \right)^2 - PHI \tag{9}$$

where
$$V'_G = V_G - V_{TO} + PHI + GAMMA.\sqrt{PHI} \tag{10}$$

To avoid the possibility of a denominator equal to zero in (13) and to extend the validity of (37) to the accumulation region the smoothing function (A1) is applied to V'_G with $x = V'_G$, and $\delta = \phi_t$.

PHI is a fitting parameter and its value is usually about $2\phi_F$ (twice the Fermi potential). γ' is the body effect parameter at equilibrium including the short and narrow channel effects due to charge sharing [5].

$$\gamma' = GAMMA - \frac{\varepsilon_o \varepsilon_{Si}}{C'_{OX}} \left[\frac{2.LETA}{L_{eff}} - \frac{3.NP.WETA}{W_{eff}} \right] \sqrt{PHI} \tag{11}$$

The second term in equation (8) accounts for the drain induced barrier lowering (DIBL) [11,12] where

$$\sigma = \frac{SIGMA}{L_{eff}^2} \tag{12}$$

3.3 Slope factor

The slope factor is given by [1]

$$n = 1 + \frac{\gamma'}{2.\sqrt{\mathrm{PHI} + V_{PO}}} \tag{13}$$

3.4 Mobility reduction

The mobility reduction due to the vertical field is modeled by [3]

$$\mu = \frac{\mu_o}{1 + \mathrm{THETA}.\gamma'\sqrt{V_{PO} + \mathrm{PHI}}} \tag{14}$$

3.5 Velocity saturation

The effect of velocity saturation in our model is based on the expression [7] below:

$$\mu_S = \frac{\mu}{1 + \frac{\mu}{v_{lim}} \frac{d\phi_S}{dx}} \tag{15}$$

The substitution of both the approximation in (1) and (15) into the differential equation of the drain current leads, after integration along the channel, to

$$I_D = \frac{\mu W_{eff}}{C'_{OX} L_{eq}} \frac{1}{1 + \frac{\left|Q'_F - Q'_R\right|}{Q'_A}} \left(\frac{Q'^2_F - Q'^2_R}{2.n} \right) \tag{16}$$

where

$$Q'_{F(R)} = Q'_{IS(ID)} - n.C'_{OX}\phi_t \tag{17}$$

$$Q'_A = nC'_{OX}\, L_{eq} \mathrm{UCRIT} \tag{18}$$

$$\mathrm{UCRIT} = \frac{v_{lim}}{\mu} \tag{19}$$

3.6 Saturation voltage

The maximum current that can flow in the channel occurs when velocity is saturated:

$$I_D = -W v_{\lim} Q'_{ID} \tag{20}$$

Equating (16) to (20) one can calculate Q'$_{IDSAT}$, the minimum inversion charge density at the drain required to allow for a current equal to I_D (see appendix 2)

$$Q'_{IDSAT} = Q'_{IS} - nC'_{OX}\phi_t - Q'_A\left[1-\sqrt{1-\frac{2\left(Q'_{IS} - nC'_{OX}\phi_t\right)}{Q'_A}+\frac{\left(nC'_{OX}\phi_t\right)^2}{Q'^{\,2}_A}}\right] \tag{21}$$

V_{DSSAT} is calculated from equation (2).

3.7 Channel length modulation [4, 5, 11]

The channel length modulation is modeled by

$$\Delta L = \mathrm{LAMBDA}.L_C.\ln\left[1+\frac{\left(V_{DS} - V'_{DS}\right)}{L_C.\mathrm{UCRIT}}\right] \tag{22}$$

with

$$L_C = \sqrt{\frac{\varepsilon_o.\varepsilon_{Si}.x_j}{C'_{OX}}} \tag{23}$$

V'$_{DS}$ is given by equation (A4) in appendix 1, using L_{eff} instead of L_{eq} for the calculation of V_{DSSAT}.

3.8 Effective channel length and width [5]

$$W_{eff} = NP(W + DW) \tag{24}$$

$$L_{eff} = NS(L + DL) \tag{25}$$

3.9 Transconductances

The transconductances, which are the derivatives of the current with respect to the voltages, must be exact for a reliable and faster convergence of the DC analysis. The transconductances have been computed by taking into account all the parameters which represent the variation of the current as a function of the terminal voltages.

$$g_{md} = \frac{dI_D}{dV_D} \tag{26}$$

$$g_{ms} = -\frac{dI_D}{dV_S} \tag{27}$$

$$g_{mg} = \frac{dI_D}{dV_G} \tag{28}$$

3.10 Derivatives of the charge densities

The derivatives of the (shifted) charge densities are written in a very simple form [3], which has been used in the equations for the intrinsic capacitances.

$$\frac{dQ'_{F(R)}}{dV_{S(D)}} = n.C'_{OX} \cdot \frac{Q'_{IS(D)}}{Q'_{F(R)}} \tag{29}$$

3.11 Intrinsic charges

$$Q_I = -W_{eff} L_{eff} \left(\frac{2}{3} \frac{Q'^2_F + Q'_F . Q'_R + Q'^2_R}{Q'_F + Q'_R} + n.C'_{OX} . \phi_t \right) \tag{30}$$

$$Q_B = -W_{eff} L_{eff} C'_{OX} \left[(n-1)\phi_t + \frac{GAMMA^2}{2.(n-1)} \right] - \frac{n-1}{n} Q_I \tag{31}$$

$$Q_G = Q_B - Q_I \tag{32}$$

$$Q_S = -W_{eff} L_{eff} \left[\frac{6.Q'^3_F + 12.Q'_R.Q'_F{}^2 + 8.Q'^2_R.Q'_F + 4.Q^3_R}{15.\left(Q'_F + Q'_R\right)^2} + \frac{n.C'_{OX}.\phi_t}{2} \right] \tag{33}$$

$$Q_D = Q_I - Q_S \tag{34}$$

3.12 Intrinsic capacitances

$$C_{gs} = \frac{2.W_{eff} L_{eff}}{3.n} \left[1 - \frac{Q'^2_R}{\left(Q'_F + Q'_R\right)^2} \right] \frac{dQ'_F}{dV_S} \tag{35}$$

$$C_{gd} = \frac{2.W_{eff} L_{eff}}{3.n} \left[1 - \frac{Q'^2_F}{\left(Q'_F + Q'_R\right)^2} \right] \frac{dQ'_R}{dV_D} \tag{36}$$

$$C_{gb} = \frac{GAMMA}{2\sqrt{PHI + V_P} + GAMMA} \left(C_{ox} - C_{gs} - C_{gd} \right) \tag{37}$$

$$C_{gg} = C_{gs} + C_{gd} + C_{gb} \tag{38}$$

$$C_{bs} = (n-1).C_{gs} \tag{39}$$

$$C_{bd} = (n-1).C_{gd} \tag{40}$$

$$C_{bg} = C_{gb} \tag{41}$$

$$C_{bb} = C_{bd} + C_{bg} + C_{bs} \tag{42}$$

$$C_{ss} = \frac{2}{15} W_{eff} L_{eff} \left[\frac{3.Q'^3_F + 9.Q'_R.Q'_F{}^2 + 8.Q'^2_R.Q'_F}{\left(Q'_F + Q'_R\right)^3} \right] \frac{dQ'_F}{dV_S} \tag{43}$$

$$C_{sd} = -\frac{4}{15} W_{eff} L_{eff} \left[\frac{Q'^3_R + 3.Q'_F.Q'_R{}^2 + Q'^2_F.Q'_R}{\left(Q'_F + Q'_R\right)^3} \right] \frac{dQ'_R}{dV_D} \tag{44}$$

$$C_{sg} = \frac{C_{ss} - C_{sd}}{n} \tag{45}$$

$$C_{sb} = (n - 1)C_{sg} \tag{46}$$

$$C_{dd} = C_{gd} + C_{bd} + C_{sd} \tag{47}$$

$$C_{dg} = C_{gg} - C_{bg} - C_{sg} \tag{48}$$

$$C_{db} = C_{bb} - C_{gb} - C_{sb} \tag{49}$$

$$C_{ds} = C_{dd} - C_{dg} - C_{db} \tag{50}$$

APPENDIX 1 - SMOOTHING FUNCTIONS

To avoid overflow, the denominators of the expressions presented in this document cannot be equal to zero. To avoid y=x to be zero when x→0, the following approximation is used [4].

$$y = \frac{1}{2}\left(x + \sqrt{x^2 + 4\delta^2}\right) \tag{A1}$$

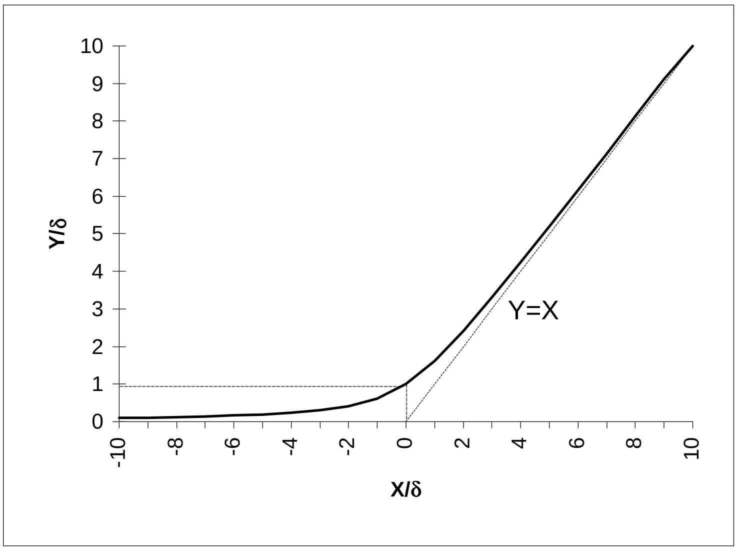

Fig. A1 - The smoothing function of eq. (A1).

The equivalent channel length (L_{eq}) is obtained by using the function (A1) with x = L' and δ = $L_{min.}$

$$L_{MIN} = \frac{L_{eff}}{10} \tag{A2}$$

$$L' = L_{eff} - \Delta L \tag{A3}$$

For both the calculation of Q'_R and ΔL the channel voltage drop V'_{DS} should be smoothly clamped at V_{DSSAT}, by means of equations (A4) to (A6) [8] (Fig. A2).

$$V'_{DS} = f_D - \sqrt{f_D{}^2 - V_{DS} V_{DSSAT}} \tag{A4}$$

$$f_D = \frac{1}{2}\left[V_{DS} + (1+s)V_{DSSAT}\right] \tag{A5}$$

$$V'_{DB} = V'_{DS} + V_{SB} \tag{A6}$$

where s is a fitting parameter equal to 0.01.

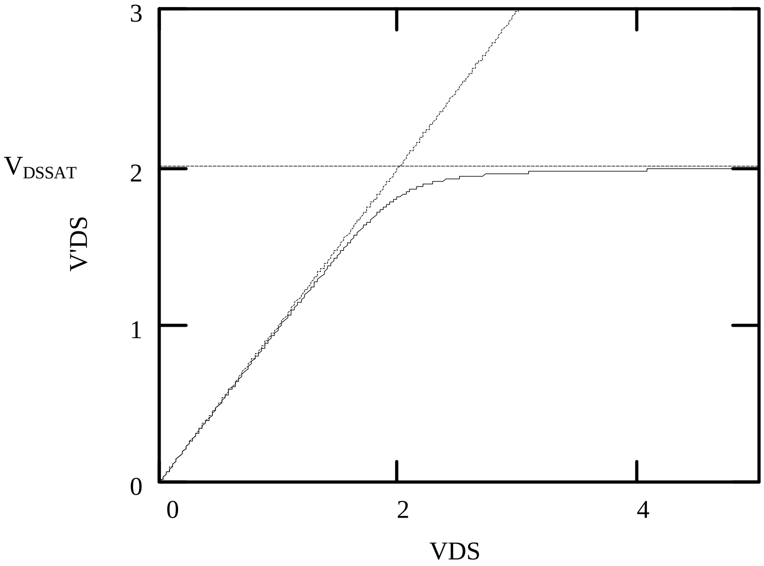

Fig.A2 - V'$_{DS}$ given by (A4)

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