



Chapter 16

Selecting a MOSFET Model

Now that you know more about MOSFET models from Chapter 15, “Introducing MOSFET.” it will be easier for you to choose which type of models you require for your needs.

This chapter lists the various MOSFET models, and provides the specifications for each model. The following topics are covered in this chapter:

- [Level 1 IDS: Schichman-Hodges Model](#)
- [Level 2 IDS: Grove-Frohman Model](#)
- [Level 3 IDS: Empirical Model](#)
- [Level 4 IDS: MOS Model](#)
- [Level 5 IDS Model](#)
- [Level 6 and Level 7 IDS: MOSFET Model](#)
- [Level 7 IDS Model](#)
- [Level 8 IDS Model](#)
- [Level 13 BSIM Model](#)
- [Level 27 SOSFET Model](#)
- [Level 28 Modified BSIM Model](#)
- [Level 38 IDS: Cypress Depletion Model](#)
- [Level 39 BSIM2 Model](#)
- [Level 40 HP a-Si TFT Model](#)
- [Level 47 BSIM3 Version 2 MOS Model](#)
- [Level 49 BSIM3 Version 3 MOS Model](#)
- [Level 50 Philips MOS9 Model](#)
- [Comparing MOS Models](#)

Level 1 IDS: Schichman-Hodges Model

This section describes the parameters and equations for the Level 1 IDS: Schichman-Hodges model.

Level 1 Model Parameters

The Level 1 model parameters follow.

Basic Model Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	DC model selector. Level 1 is the Schichman-Hodges model.
COX	F/m ²	3.453e-4	oxide capacitance per unit gate area. If COX is not specified, it is calculated from TOX.
<i>KP (BET, BETA)</i>	A/V ²		intrinsic transconductance parameter. If KP is not specified and UO and TOX are entered, the parameter is computed from: $KP = UO \cdot COX$ <p>The default=2.0718e-5 (NMOS), 8.632e-6 (PMOS).</p>
LAMBDA (LAM, LA)	V ⁻¹	0.0	channel-length modulation
TOX	m	1e-7	gate oxide thickness
UO	cm ² / (V·s)		carrier mobility

Effective Width and Length Parameters

Name(Alias)	Units	Default	Description
DEL	m	0.0	channel length reduction on each side. $DEL_{scaled} = DEL \cdot SCALM$
LD (DLAT, LATD)	m		lateral diffusion into channel from source and drain diffusion. If LD and XJ are unspecified, LD Default=0.0. When LD is unspecified but XJ is specified, LD is calculated as: LD Default=0.75 · XJ $LD_{scaled} = LD \cdot SCALM$
LDAC	m		This parameter is the same as LD, but if LDAC is in the .MODEL statement, it replaces LD in the L_{eff} calculation for AC gate capacitance.
LMLT		1.0	length shrink factor
WD	m	0.0	lateral diffusion into channel from bulk along width $WD_{scaled} = WD \cdot SCALM$
WDAC	m		This parameter is the same as WD, but if WDAC is in the .MODEL statement, it replaces WD in the W_{eff} calculation for AC gate capacitance.
WMLT		1.0	diffusion layer and width shrink factor

Name(Alias)	Units	Default	Description
XJ	m	0.0	metallurgical junction depth: $XJ_{\text{scaled}} = XJ \cdot \text{SCALM}$
XL (DL, (LDEL)	m	0.0	accounts for masking and etching effects: $XL_{\text{scaled}} = XL \cdot \text{SCALM}$
XW (DW, WDEL)	m	0.0	accounts for masking and etching effects: $XW_{\text{scaled}} = XW \cdot \text{SCALM}$

Threshold Voltage Parameters

Name(Alias)	Units	Default	Description
GAMMA	$V^{1/2}$	0.5276	body effect factor. If GAMMA is not specified, it is calculated from NSUB (See "Common Threshold Voltage Parameters" on page 15-52).
NFS (DFS, NF, DNF)	$\text{cm}^{-2} \cdot V$ 1	0.0	fast surface state density
NSUB (DNB, NB)	cm^{-3}	1e15	bulk surface doping. NSUB is calculated from GAMMA if not specified.
PHI	V	0.576	surface inversion potential –PH is calculated from NSUB if not specified (See "Common Threshold Voltage Parameters" on page 15-52).
VTO (VT)	V		zero-bias threshold voltage. If not specified, it is calculated. (See "Common Threshold Voltage Parameters" on page 15-52).

The Level 1 MOSFET model should be used when accuracy is less important than simulation turn-around time. For digital switching circuits, especially when only a “qualitative” simulation of timing and function is needed, Level 1 run-time can be about half that of a simulation using the Level 2 model. The agreement in timing is approximately 10%. The Level 1 model, however, results in severe inaccuracies in DC transfer functions of TTL-compatible input buffers, if these buffers are present in the circuit.

The channel-length modulation parameter LAMBDA is equivalent to the inverse of the Early voltage for the bipolar transistor. LAMBDA is a measure of the output conductance in saturation. When this parameter is specified, the MOSFET has a finite but constant output conductance in saturation. If LAMBDA is not input, the Level 1 model assumes zero output conductance.

Level 1 Model Equations

The Level 1 model equations follow.

IDS Equations

In the Level 1 model the carrier mobility degradation and the carrier saturation effect and weak inversion model are not included. This model determines the DC current as follows:

Cutoff Region, $v_{gs} \leq v_{th}$

$$I_{ds} = 0.0$$

Linear Region, $v_{ds} < v_{gs} - v_{th}$

$$I_{ds} = KP \cdot \frac{W_{eff}}{L_{eff}} \cdot (1 + LAMBDA \cdot v_{ds}) \cdot \left(v_{gs} - v_{th} - \frac{v_{ds}}{2} \right) \cdot v_{ds}$$

Saturation Region, $v_{ds} \geq v_{gs} - v_{th}$

$$I_{ds} = \frac{KP}{2} \cdot \frac{W_{eff}}{L_{eff}} \cdot (1 + LAMBDA \cdot v_{ds}) \cdot (v_{gs} - v_{th})^2$$

Effective Channel Length and Width

The model calculates the effective channel length and width from the drawn length and width as follows:

$$L_{eff} = L_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot (LD_{scaled} + DEL_{scaled})$$

$$W_{eff} = M \cdot (W_{scaled} WMLT + XW_{scaled} - 2 \cdot WD_{scaled})$$

Threshold Voltage, v_{th}

$$v_{sb} \geq 0$$

$$v_{th} = v_{bi} + GAMMA \cdot (PHI + v_{sb})^{1/2}$$

$$v_{sb} < 0$$

$$v_{th} = v_{bi} + GAMMA \cdot \left(PHI^{1/2} + 0.5 \frac{v_{sb}}{PHI^{1/2}} \right)$$

Where the built-in voltage v_{bi} is defined as:

$$v_{bi} = v_{fb} + PHI$$

or

$$v_{bi} = VTO - GAMMA \cdot PHI^{1/2}$$

Note: See "Common Threshold Voltage Parameters" on page 15-52 for calculation of VTO, GAMMA, and PHI if they are not specified.

Saturation Voltage, v_{sat}

The saturation voltage for the Level 1 model is due to channel pinch off at the drain side and is computed by:

$$v_{sat} = v_{gs} - v_{th}$$

In the Level 1 model, the carrier velocity saturation effect is not included.

Level 2 IDS: Grove-Frohman Model

This section describes the parameters and equations for the Level 2 IDS: Grove-Frohman model.

Level 2 Model Parameters

The Level 2 model parameters follow.

Basic Model Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	DC model selector. Level 2 is the Grove-Frohman model.
COX	F/m ²	3.453e-4	oxide capacitance per unit gate area. This parameter is calculated from TOX if not specified.
ECRIT (ESAT)	V/cm	0.0	critical electric field for carrier velocity saturation. From Grove:electrons 6e4 holes 2.4e4
			Use zero to indicate an infinite value. ECRIT is preferred over VMAX because the equation is more stable. ECRIT is estimated as: ECRIT = 100 · (VMAX / UO)
KP (BET, BETA)	A/V ²	2.0e-5	intrinsic transconductance. If KP is not specified and UO and TOX are entered, KP is calculated from KP = UO · COX
LAMBDA (LAM, LA)	V ⁻¹	0.0	channel length modulation

Name(Alias)	Units	Default	Description
NEFF		1.0	total channel charge (fixed and mobile) coefficient
TOX	m	1e-7	gate oxide thickness
VMAX (VMX, VSAT)	m/s	0.0	maximum drift velocity of carriers. Use zero to indicate an infinite value.

Effective Width and Length Parameters

Name(Alias)	Units	Default	Description
DEL	m	0.0	channel length reduction on each side: $DEL_{scaled} = DEL \cdot SCALM$
LD (DLAT, LADT)	m		lateral diffusion into channel from source and drain diffusion. If LD and XJ are unspecified, LD default=0.0. When LD is unspecified but XJ is specified, LD is calculated from: XJ . The default= $0.75 \cdot XJ$. $LD_{scaled} = LD \cdot SCALM$
LDAC	m		This parameter is the same as LD, but if LDAC is included in the .MODEL statement, it replaces LD in the $Leff$ calculation for AC gate capacitance.
LMLT		1.0	length shrink factor
LREF	m	0.0	channel length reference $LREF_{scaled} = LREF \cdot SCALM$
WD	m	0.0	lateral diffusion into channel from bulk along width $WD_{scaled} = WD \cdot SCALM$

Name(Alias)	Units	Default	Description
WDAC	m		This parameter is the same as WD, but if WDAC is included in the .MODEL statement, it replaces WD in the Weff calculation for AC gate capacitance.
WMLT		1.0	diffusion layer and width shrink factor
WREF	m	0.0	channel width reference $WREF_{scaled} = WREF \cdot SCALM$
XJ	m	0.0	metallurgical junction depth $XJ_{scaled} = XJ \cdot SCALM$
<i>XL (DL, LDEL)</i>	m	0.0	length bias accounts for masking and etching effects $XL_{scaled} = XL \cdot SCALM$
<i>XW (DW, WDEL)</i>	m	0.0	width bias accounts for masking and etching effects $XW_{scaled} = XW \cdot SCALM$

Threshold Voltage Parameters

Name(Alias)	Units	Default	Description
DELTA		0.0	narrow width factor for adjusting threshold
GAMMA	$V^{1/2}$	0.5276	body effect factor. This parameter is calculated from NSUB if not specified (see "Common Threshold Voltage Parameters" on page 15-52).
LND	$\mu m/V$	0.0	ND length sensitivity
LN0	μm	0.0	N0 length sensitivity
ND	V^{-1}	0.0	drain subthreshold factor
N0		0.0	gate subthreshold factor. Typical value=1.

Name(Alias)	Units	Default	Description
NFS (DFS, NF, DNF)	$\text{cm}^{-2} \cdot \text{V}^{-1}$	0.0	fast surface state density
NSUB (DNB, NB)	cm^{-3}	1e15	bulk surface doping. If NSUB is not specified, it is calculated from GAMMA.
PHI	V	0.576	surface inversion potential. If PHI is not specified, it is calculated from NSUB (see "Common Threshold Voltage Parameters" on page 15-52).
VTO(VT)	V		zero-bias threshold voltage. If it is not specified, it is calculated (see "Common Threshold Voltage Parameters" on page 15-52).
WIC		0.0	subthreshold model selector
WND	$\mu\text{m}/\text{V}$	0.0	ND width sensitivity.
WN0	μm	0.0	N0 width sensitivity

Mobility Parameters

Name(Alias)	Units	Default	Description
MOB		0.0	mobility equation selector. This parameter can be set to MOB=0 or MOB=7. If MOB=7, the model is changed, which also affects the channel length calculation. Note: MOB=7 operates as a flag. It invokes the channel length modulation and mobility equations of MOSFET Level 3.
THETA	V^{-1}	0.0	mobility modulation. THETA is used only when MOB=7. A typical value in this application is THETA=5e-2.

Name(Alias)	Units	Default	Description
UCRIT	V/cm	1.0e4	critical field for mobility degradation, UCRIT. The parameter is the limit at which the surface mobility UO begins to decrease in accordance with the empirical relation given later.
UEXP (F2)		0.0	critical field exponent in the empirical formula which characterizes surface mobility degradation
UO (UB, UBO)	cm ² / (V·s)	600 (N) 250 (P)	low-field bulk mobility. This parameter is calculated from KP if KP is input.
UTRA		0.0	transverse field coefficient

Note: SPICE does not use UTRA. HSPICE uses it if supplied, but issues a warning because UTRA can hinder convergence.

The mobility parameters are best determined by curve fitting. In most cases UTRA should be specified between 0.0 and 0.5. Nonzero values for UTRA can result in negative resistance regions at the onset of saturation.

Level 2 Model Equations

The Level 2 model equations follow.

IDS Equations

The following section describes the way the Level 2 MOSFET model calculates the drain current of n-channel and p-channel MOSFETs.

Cutoff Region, $v_{gs} \leq v_{th}$

$$I_{ds} = 0 \quad (\text{see subthreshold current})$$

On Region, $v_{gs} > v_{th}$

$$I_{ds} = \beta \cdot \left\{ \left(v_{gs} - v_{bi} - \frac{\eta \cdot v_{de}}{2} \right) \cdot v_{de} - \frac{2}{3} \cdot \gamma \cdot [(PHI + v_{de} + v_{sb})^{3/2} - (PHI + v_{sb})^{3/2}] \right\}$$

where

$$v_{de} = \min(v_{ds}, v_{dsat})$$

$$\eta = 1 + DELTA \cdot \frac{\pi \cdot \epsilon_{si}}{4 \cdot COX \cdot W_{eff}}$$

$$\beta = KP \cdot \frac{W_{eff}}{L_{eff}}$$

Effective Channel Length and Width

The model calculates effective channel length and width from the drawn length and width as follows:

$$L_{eff} = L_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot (LD_{scaled} + DEL_{scaled})$$

$$W_{eff} = M \cdot (W_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled})$$

$$LREF_{eff} = LREF_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot (LD_{scaled} + DEL_{scaled})$$

$$WREF_{eff} = M \cdot (WREF_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled})$$

Threshold Voltage, v_{th}

The model parameter VTO is an extrapolated zero-bias threshold voltage of a large device. The effective threshold voltage, including the device size effects and the terminal voltages, is calculated by:

$$v_{th} = v_{bi} + \gamma \cdot (PHI + v_{sb})^{1/2}$$

where

$$v_{bi} = VTO - GAMMA \cdot (PHI)^{1/2} + (\eta - 1) \cdot (PHI + v_{sb})$$

The narrow width effect is included through v_{bi} and η . To include the narrow width effect, specify the model parameter DELTA. The short-channel effect is included through the effective γ . To include short-channel effects, the model parameter XJ must be greater than zero. Then:

$$\gamma = GAMMA \cdot \left\{ 1 - \frac{XJ_{scaled}}{2 \cdot L_{eff}} \cdot \left[\left(1 + \frac{2 \cdot W_s}{XJ_{scaled}} \right)^{1/2} + \left(1 + \frac{2 \cdot W_d}{XJ_{scaled}} \right)^{1/2} - 2 \right] \right\}$$

The depletion widths, W_s and W_d , are determined by:

$$W_s = \left[\frac{2 \cdot E_{si}}{q \cdot NSUB} \cdot (PHI + v_{sb}) \right]^{1/2}$$

$$W_d = \left[\frac{2 \cdot E_{si}}{q \cdot NSUB} \cdot (PHI + v_{ds} + v_{sb}) \right]^{1/2}$$

HSPICE calculates parameters such as VTO, GAMMA, and PHI unless you specify them. The model uses these parameters to calculate threshold voltage. (See “Common Threshold Voltage Parameters” on page 15-52).

Saturation Voltage, v_{dsat}

If you do not specify the model parameter VMAX, the program computes the saturation voltage due to channel pinch off at the drain side. By including the corrections for small-size effects, v_{sat} is:

$$v_{sat} = \frac{v_{gs} - v_{bi}}{\eta} + \frac{1}{2} \left(\frac{\gamma}{\eta} \right)^2 \cdot \left\{ 1 - \left[1 + 4 \cdot \left(\frac{\eta}{\gamma} \right)^2 \cdot \left(\frac{v_{gs} - v_{bi}}{\eta} + PHI + v_{sb} \right) \right] \right\}^{1/2}$$

$$v_{dsat} = v_{sat}$$

If you specify ECRIT, the program modifies v_{sat} to include carrier velocity saturation effect.

$$v_{dsat} = v_{sat} + v_c - (v_{sat}^2 + v_c^2)^{1/2}$$

where

$$v_c = ECRIT \cdot L_{eff}$$

Note: If VMAX is specified, a different v_{dsat} calculation is performed. Refer to the Vladimirescu document¹ for details.

Mobility Reduction, u_{eff}

The mobility of carriers in the channel decreases as the carriers' speeds approach their scattering limited velocity. In HSPICE the mobility degradation for the Level 2 MOS model uses two different equations, depending on the mobility equation selector value of MOB.

If MOB=0, (default)

$$u_{eff} = UO \cdot \left[\frac{UCRIT \cdot E_{si}}{COX \cdot (v_{gs} - v_{th} - UTRA \cdot v_{ds})} \right]^{UEXP}$$

Since u_{eff} is less than UO , the program uses the above equation if the bracket term is less than one; otherwise the program uses $u_{eff}=UO$.

If $MOB=7$, $THETA \neq 0$

$$u_{eff} = \frac{UO}{1 + THETA \cdot (v_{gs} - v_{th})}$$

$v_{gs} < v_{th}$, $u_{eff} = UO$

If $MOB=7$, $THETA=0$

$$u_{eff} = UO \cdot \left[\frac{UCRIT \cdot E_{si}}{COX \cdot (v_{gs} - v_{th})} \right]^{UEXP}$$

If $MOB=7$, $VMAX > 0$

$$u_{eff} = \frac{u_{eff}}{1 + u_{eff} \cdot \frac{v_{de}}{VMAX \cdot L_{eff}}}$$

Channel Length Modulation

The Level 2 MOS model includes the channel length modulation effect by modifying the I_{ds} current as follows:

$$I_{ds} = \frac{I_{ds}}{1 - \lambda \cdot v_{ds}}$$

The model calculates the value of λ if you do not specify the model parameter LAMBDA.

LAMBDA > 0

$$\lambda = LAMBDA$$

VMAX>0, NSUB >0, and LAMBDA≤0

$$\lambda = \frac{X_d}{NEFF^{1/2} \cdot L_{eff} \cdot v_{ds}} \cdot \left\{ \left[\left(\frac{VMAX \cdot X_d}{2 \cdot NEFF^{1/2} \cdot u_{eff}} \right)^2 + v_{ds} - v_{dsat} \right]^{1/2} - \frac{VMAX \cdot X_d}{2 \cdot NEFF^{1/2} \cdot u_{eff}} \right\}$$

VMAX=0, NSUB>0, and LAMBDA ≤ 0

If MOB=0

$$\lambda = \frac{X_d}{L_{eff} \cdot v_{ds}} \cdot \left\{ \frac{v_{ds} - v_{dsat}}{4} + \left[1 + \left(\frac{v_{ds} - v_{dsat}}{4} \right)^2 \right]^{1/2} \right\}^{1/2}$$

If MOB=7

$$\lambda = \frac{X_d}{L_{eff} \cdot v_{ds}} \cdot \left\{ \left[\frac{v_{ds} - v_{dsat}}{4} + \left(1 + \left(\frac{v_{ds} - v_{dsat}}{4} \right)^2 \right)^{1/2} \right]^{1/2} - 1 \right\}$$

where X_d is defined by:

$$X_d = \left(\frac{2 \cdot E_{si}}{q \cdot NSUB} \right)^{1/2}$$

The above equations do not include the effect of the field between gate and drain and gate and pinch-off point, respectively. They tend to overestimate the output conductance in the saturation region.

The modification of I_{ds} by factor $(1 - \lambda \cdot v_{ds})$ is equivalent to replacing L_{eff} with:

$$L_e = L_{eff} - \lambda \cdot v_{ds} \cdot L_{eff}$$

To prevent the channel length (L_e) from becoming negative, HSPICE limits the value of L_e as follows:

If $L_e < x_{wb}$, then L_e is replaced by:

$$\frac{xwb}{1 + \frac{xwb - Le}{xwb}}$$

where:

$$xwb = X_d \cdot PB^{1/2}$$

Subthreshold Current, I_{ds}

This region of operation is characterized by the fast surface states model parameter, NFS. For NFS>0 the model determines the modified threshold voltage (v_{on}) as follows:

$$v_{on} = v_{th} + fast$$

where:

$$fast = vt \cdot \left[\eta + (PHI + v_{sb})^{1/2} \cdot \frac{\partial \gamma}{\partial v_{sb}} + \frac{\gamma}{2 \cdot (PHI + v_{sb})^{1/2}} + \frac{q \cdot NFS}{COX} \right]$$

and vt is the thermal voltage.

The I_{ds} current for $v_{gs} < v_{on}$ is given by:

$$I_{ds} = I_{ds}(v_{on}, v_{de}, v_{sb}) \cdot e^{\frac{v_{gs} - v_{on}}{fast}}$$

$v_{gs} \geq v_{on}$

$$I_{ds} = I_{ds}(v_{gs}, v_{de}, v_{sb})$$

where

$$v_{de} = \min(v_{ds}, v_{dsat})$$

Note: The modified threshold voltage (v_{on}), due to NFS specification, is also used in strong inversion instead of v_{th} , mainly in the mobility equations.

If WIC=3, the model calculates the subthreshold current differently. In this case the I_{ds} current is:

$$I_{ds} = I_{ds}(v_{gs}, v_{de}, v_{sb}) + isub(N0_{eff}, ND_{eff}, v_{gs}, v_{ds})$$

The $N0_{eff}$ and ND_{eff} are functions of effective device width and length.

Level 3 IDS: Empirical Model

This sections provides the Level 3 IDS: Empirical model parameters and equations.

Level 3 Model Parameters

The Level 3 model parameters follow.

Basic Model Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	DC model selector. LEVEL=3 is an empirical model.
COX	F/m ²	3.453e-4	oxide capacitance per unit gate area. If this parameter is not specified, it is calculated from TOX.
DERIV		1	derivative method selector DERIV=0: analytic DERIV=1: finite difference
KAPPA	V ⁻¹	0.2	saturation field factor. This parameter is used in the channel length modulation equation.
KP (BET, BETA)	A/V ²	2.0e-5	intrinsic transconductance parameter. If this parameter is not specified and UO and TOX are entered, KP is calculated from KP = UO · COX
TOX	m	1e-7	gate oxide thickness
VMAX (VMX)	m/s	0.0	maximum drift velocity of carriers. Use zero to indicate an infinite value.

Effective Width and Length Parameters

Name(Alias)	Units	Default	Description
DEL	m	0.0	channel length reduction on each side
			$DEL_{scaled} = DEL \cdot SCALM$
LD (DLAT, LATD)	m		lateral diffusion into channel from source and drain diffusion, If LD and XJ are unspecified, LD Default= 0.0. If LD is unspecified but XJ is specified, LD is calculated from XJ as $LD = 0.75 \cdot XJ$.
LDAC	m		This parameter is the same as LD, but if LDAC is included in the .MODEL statement, it replaces LD in the L_{eff} calculation for AC gate capacitance.
LREF	m	0.0	channel length reference
			$LREF_{scaled} = LREF \cdot SCALM$
LMLT		1.0	length shrink factor
WD	m	0.0	lateral diffusion into channel width from bulk
			$WD_{scaled} = WD \cdot SCALM$
WDAC	m		This parameter is the same as WD, but if WDAC is included in the .MODEL statement, it replaces WD in the W_{eff} calculation for AC gate capacitance.
WMLT		1.0	diffusion layer and width shrink factor

Name(Alias)	Units	Default	Description
WREF	m	0.0	channel width reference $WREF_{scaled} = WREF \cdot SCALM$
XJ	m	0.0	metallurgical junction depth $XJ_{scaled} = XJ \cdot SCALM$
XL (DL, LDEL)	m	0.0	length bias accounts for masking and etching effects $XL_{scaled} = XL \cdot SCALM$
XW (DW, WDEL)	m	0.0	width bias accounts for masking and etching effects $XW_{scaled} = XW \cdot SCALM$

Threshold Voltage Parameters

Name(Alias)	Units	Default	Description
DELTA		0.0	narrow width factor for adjusting threshold
ETA		0.0	static feedback factor for adjusting threshold
GAMMA	$V^{1/2}$	0.5276	body effect factor. This parameter is calculated from NSUB if not specified (See "Common Threshold Voltage Parameters" on page 15-52).
LND	$\mu m/V$	0.0	ND length sensitivity
LNO	μm	0.0	N0 length sensitivity
ND	V^{-1}	0.0	drain subthreshold factor
N0		0.0	gate subthreshold factor (typical value=1)

Name(Alias)	Units	Default	Description
NFS (DFS,NF, DNF)	$\text{cm}^{-2}\cdot\text{V}^{-1}$	0.0	fast surface state density
NSUB (DNB, NB)	cm^{-3}	1e15	bulk surface doping. This parameter is calculated from GAMMA if not specified.
PHI	V	0.576	surface inversion potential. This parameter is calculated from NSUB if not specified (see "Common Threshold Voltage Parameters" on page 15-52).
VTO (VT)	V		zero-bias threshold voltage. This parameter is calculated if not specified (see "Common Threshold Voltage Parameters" on page 15-52).
WIC		0.0	sub-threshold model selector
WND	$\mu\text{m}/\text{V}$	0.0	ND width sensitivity
WNO	μm	0.0	N0 width sensitivity

Mobility Parameters

Name(Alias)	Units	Default	Description
THETA	V^{-1}	0.0	mobility degradation factor
UO (UB,UBO)	$\text{cm}^2/(\text{V}\cdot\text{s})$	600(N) 250(P)	low field bulk mobility. This parameter is calculated from KP if KP is specified.

Level 3 Model Equations

The Level 3 model equations follow.

IDS Equations

The following describes the way the Level 3 MOSFET model calculates the drain current, I_{ds} .

Cutoff Region, $v_{gs} \leq v_{th}$

$$I_{ds} = 0 \quad (\text{See subthreshold current})$$

On Region, $v_{gs} > v_{th}$

$$I_{ds} = \beta \cdot \left(v_{gs} - v_{th} - \frac{1 + fb}{2} \cdot v_{de} \right) \cdot v_{de}$$

where

$$\begin{aligned} \beta &= KP \cdot \frac{W_{eff}}{L_{eff}} \\ &= u_{eff} \cdot COX \cdot \frac{W_{eff}}{L_{eff}} \end{aligned}$$

$$v_{de} = \min(v_{ds}, v_{dsat})$$

and

$$fb = f_n + \frac{GAMMA \cdot f_s}{4 \cdot (PHI + v_{sb})^{1/2}}$$

Note: In the above equation the factor 4 should be 2, but since SPICE uses a factor of 4, HSPICE uses factor of 4 as well.

The narrow width effect is included through the f_n parameter:

$$f_n = \frac{DELTA}{W_{eff}} \cdot \frac{1}{4} \cdot \frac{2\pi \cdot E_{si}}{COX}$$

The term f_s expresses the effect of the short channel and is determined as:

$$f_s = 1 - \frac{XJ_{scaled}}{L_{eff}} \cdot \left\{ \frac{LD_{scaled} + W_c}{XJ_{scaled}} \cdot \left[1 - \left(\frac{W_p}{XJ_{scaled} + W_p} \right)^2 \right]^{1/2} - \frac{LD_{scaled}}{XJ_{scaled}} \right\}$$

$$W_p = X_d \cdot (PHI + v_{sb})^{1/2}$$

$$X_d = \left(\frac{2 \cdot E_{si}}{q \cdot NSUB} \right)^{1/2}$$

$$W_c = XJ_{scaled} \cdot \left[0.0631353 + 0.8013292 \cdot \left(\frac{W_p}{XJ_{scaled}} \right) - 0.01110777 \cdot \left(\frac{W_p}{XJ_{scaled}} \right)^2 \right]$$

Effective Channel Length and Width

The model determines effective channel length and width in the Level 3 model as follows:

$$L_{eff} = L_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot (LD_{scaled} + DEL_{scaled})$$

$$W_{eff} = M \cdot (W_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled})$$

$$LREF_{eff} = LREF_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot (LD_{scaled} + DEL_{scaled})$$

$$WREF_{eff} = M \cdot (WREF_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled})$$

Threshold Voltage, v_{th}

The effective threshold voltage, including the device size and terminal voltage effects, is calculated by:

$$v_{th} = v_{bi} - \frac{8.14e-22 \cdot ETA}{COX \cdot L_{eff}^3} \cdot v_{ds} + GAMMA \cdot f_s \cdot (PHI + v_{sb})^{1/2} + f_n \cdot (PHI + v_{sb})$$

where

$$v_{bi} = v_{fb} + PHI$$

or

$$v_{bi} = VTO - GAMMA \cdot PHI^{1/2}$$

The VTO is the extrapolated zero-bias threshold voltage of a large device. If VTO, GAMMA, and PHI are not specified, HSPICE computes them (see “Common Threshold Voltage Parameters” on page 15-52).

Saturation Voltage, v_{dsat}

For the Level 3 model, HSPICE determines saturation voltage due to channel pinch-off at the drain side. The model uses the parameter VMAX to include the reduction of the saturation voltage due to carrier velocity saturation effect.

$$v_{sat} = \frac{v_{gs} - v_{th}}{1 + f_b}$$

$$v_{dsat} = v_{sat} + v_c - (v_{sat}^2 + v_c^2)^{1/2}$$

where

$$v_c = \frac{VMAX \cdot L_{eff}}{us}$$

The surface mobility parameter “us” is defined in the next section. If the model parameter VMAX is not specified, then:

$$v_{dsat} = v_{sat}$$

Effective Mobility, u_{eff}

The model defines the carrier mobility reduction due to the normal field as the effective surface mobility (us).

$v_{gs} > v_{th}$

$$us = \frac{UO}{1 + THETA \cdot (v_{gs} - v_{th})}$$

The model determines the degradation of mobility due to the lateral field and the carrier velocity saturation if you specify the VMAX model parameter.

VMAX > 0

$$u_{eff} = \frac{us}{1 + \frac{vde}{v_c}}$$

otherwise,

$$u_{eff} = us$$

Channel Length Modulation

For $v_{ds} > v_{dsat}$, the channel length modulation factor is computed. The model determines the channel length reduction (ΔL) differently, depending on the VMAX model parameter value.

VMAX = 0

$$\Delta L = X_d \cdot [KAPPA \cdot (v_{ds} - v_{dsat})]^{1/2}$$

VMAX>0

$$\Delta L = -\frac{E_p \cdot X_d^2}{2} + \left[\left(\frac{E_p \cdot X_d^2}{2} \right)^2 + KAPPA \cdot X_d^2 \cdot (v_{ds} - v_{dsat}) \right]^{1/2}$$

where E_p is the lateral electric field at the pinch off point. Its value is approximated by:

$$E_p = \frac{v_c \cdot (v_c + v_{dsat})}{L_{eff} \cdot v_{dsat}}$$

The current I_{ds} in the saturation region is computed as:

$$I_{ds} = \frac{I_{ds}}{1 - \frac{\Delta L}{L_{eff}}}$$

In order to prevent the denominator from going to zero, HSPICE limits the ΔL value as follows:

If

$$\Delta L > \frac{L_{eff}}{2}$$

then

$$\Delta L = L_{eff} - \frac{\left(\frac{L_{eff}}{2} \right)^2}{\Delta L}$$

Subthreshold Current, I_{ds}

This region of operation is characterized by the model parameter for fast surface state (NFS). The modified threshold voltage (v_{on}) is determined as follows:

NFS>0

$$v_{on} = v_{th} + fast$$

where

$$fast = v_{tm} \cdot \left[1 + \frac{q \cdot NFS}{COX} + \frac{GAMMA \cdot f_s \cdot (PHI + v_{sb})^{1/2} + f_n \cdot (PHI + v_{sb})}{2 \cdot (PHI + v_{sb})} \right]$$

The current I_{ds} is given by:

$v_{gs} < v_{on}$

$$I_{ds} = I_{ds}(v_{on}, v_{de}, v_{sb}) \cdot e^{\frac{v_{gs} - v_{on}}{fast}}$$

$v_{gs} \geq v_{on}$

$$I_{ds} = I_{ds}(v_{gs}, v_{de}, v_{sb})$$

Note: The model does not use the modified threshold voltage in strong inversion.

If WIC=3, the model calculates subthreshold current differently. In this case, the I_{ds} current is:

$$I_{ds} = I_{ds}(v_{gs}, v_{de}, v_{sb}) + isub(N0_{eff}, ND_{eff}, v_{gs}, v_{ds})$$

Subthreshold current $isub$ for LEVEL=3 is the same as for LEVEL=13 (see page -117).

$N0_{eff}$ and ND_{eff} are functions of effective device width and length.

Compatibility Notes

This section describes compatibility issues.

HSPICE versus SPICE3

Differences between HSPICE and Berkeley SPICE3 can arise in the following situations:

Small XJ

HSPICE and SPICE3 differ for small values of XJ, typically less than 0.05 microns. Such small values for XJ are physically unreasonable and should be avoided. XJ is used to calculate the short-channel reduction of the GAMMA effect,

$$GAMMA \rightarrow f_s \cdot GAMMA$$

f_s is normally less than or equal to 1. For very small values of XJ, f_s can be greater than one. HSPICE imposes the limit $f_s \leq 1.0$, while SPICE3 allows $f_s > 1.0$.

ETA

HSPICE uses 8.14 as the constant in the ETA equation, which provides the variation in threshold with v_{ds} . Berkeley SPICE3 uses 8.15.

Solution: To convert a SPICE3 model to HSPICE, multiply ETA by 815/814.

NSUB Missing

When NSUB is missing in SPICE3, the KAPPA equation becomes inactive. In HSPICE, a default NSUB is generated from GAMMA, and the KAPPA equation is active.

Solution: If NSUB is missing in the SPICE3 model, set KAPPA=0 in the HSPICE model.

LD Missing

If LD is missing, HSPICE uses the default $0.75 \cdot XJ$. SPICE3 defaults LD to zero.
Solution: If LD is missing in the SPICE3 model, set LD=0 in the HSPICE model.

Constants

Boltzmann constant $k = 1.3806226e-23 \text{ J} \cdot \text{K}^{-1}$

Electron charge $e = 1.6021918e-19 \text{ C}$

Permittivity of silicon dioxide $\epsilon_{\text{ox}} = 3.45314379969e-11 \text{ F/m}$

Permittivity of silicon $\epsilon_{\text{si}} = 1.035943139907e-10 \text{ F/m}$

Example of Temperature Compensation

The example below verifies temperature dependence for Level 3.

Input file

```
$ test of temp dependence for Level=3 Tlevc=0 Tlev=1
.option ingold=2 numdgt=6
.temp 25 100
vd d 0 5
vg g 0 2
m1 d g 0 0 nch w=10u L=1u
.op
.print id=lx4(m1) vdsat=lv10(m1)
.model nch nmos level=3 tlev=1 tlevc=0 acm=3
+ uo=600 tox=172.6572
+ vto=0.8 gamma=0.8 phi=0.64
+ kappa=0 xj=0
+ nsub=1e16 rsh=0
+ tcv=1.5e-3 bex=-1.5
.end
```

This simple model, with XJ=0 and KAPPA=0, has a saturation current

$$I_{ds} = \frac{\beta \cdot 0.5 \cdot (v_{gs} - v_{tm})^2}{1 + \beta}$$

$$\beta = COX \cdot \left(\frac{W}{L}\right) \cdot UO(t) \quad \beta = \frac{GAMMA}{(4 \cdot \sqrt{\phi(t)})}$$

Using the model parameters in the input file and the equations from the previous page,

$$\beta = (1.2e - 3) \cdot \left(\frac{t}{t_{ref}}\right)^{BEX}$$

$$v_{tm} = 0.8 - TCV \cdot (t - t_{ref})$$

$$\phi(t) = 0.64 \cdot \left(\frac{t}{t_{ref}}\right)^{-v_{therm}} \cdot \left(e_{garg} + 3 \cdot \log\left(\frac{t}{t_{ref}}\right)\right)$$

At room temperature,

$$\beta = (1.2e - 3)$$

$$v_{tm} = 0.8$$

$$\phi(t) = 0.64$$

$$I_{ds} = (1.2e - 3) \cdot 0.5 \cdot \frac{(2 - 0.8)^2}{1 + \frac{0.2}{\sqrt{0.64}}} = 6.912e - 4$$

At T=100,

$$\beta = 1.2e - 3 \cdot (1.251551)^{-1.5} = 0.570545e - 4$$

$$v_{tm} = 0.8 - (1.5e - 3) \cdot 75 = 0.6875$$

$$egarg = 9.399920 \quad vtherm = 3.215466e - 2$$

$$phi(t) = 0.64 \cdot 1.251551 - 0.3238962 = 0.4770964$$

$$I_{ds} = beta \cdot 0.5 \cdot \frac{(2 - vt)^2}{1 + \frac{0.2}{\sqrt{phi(t)}}} = 5.724507e - 4$$

HSPICE results:

T=25, id=6.91200e-04

T=100, id=5.72451e-04

These results are in agreement with the hand calculations.

Level 4 IDS: MOS Model

The Level 4 MOS model is the same as the Level 2 model, with the following exceptions:

- No narrow width effects: $\eta = 1$
- No short-channel effects: $\gamma = \text{GAMMA}$
- For lateral diffusion, $LD_{\text{scaled}} = LD \cdot XJ \cdot \text{SCALM}$. The LD default = 0.75 if XJ is specified and 0 if XJ is not specified.
- TPG, the model parameter for type of gate materials, defaults to zero (AL gate). The default is 1 for other levels. This parameter computes VTO if that model parameter is not specified (see “Using Common Threshold Voltage Equations” on page 15-52).

Level 5 IDS Model

This section describes the Level 5 IDS model parameters and equations.

Note: This model uses micrometer units rather than the typical meter units. Units and defaults are often unique in Level 5. The option SCALM is ineffective for this level.

Level 5 Model Parameters

The Level 5 model parameters follow.

Basic Model Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	model level selector
DNB (NSUB)	cm ⁻³	0.0	surface doping
DP	μm	1.0	implant depth (depletion model only)
ECV	V/μm	1000	critical field
NI	cm ⁻²	2e11	implant doping (depletion model only)
PHI	V	0.8	built-in potential
TOX	Å	0.0	oxide thickness
TUH		1.5	implant channel mobility temperature exponent (depletion model only)
ZENH		1.0	mode flag (enhancement). Set ZENH=0.0 for depletion mode.

Effective Width and Length Parameters

Name(Alias)	Units	Default	Description
DEL (WDEL)	μm	0.0	channel length reduction on each side
LATD (LD)	μm	$1.7 \cdot \text{XJ}$	lateral diffusion on each side
LMLT		1.0	length shrink factor
OXETCH	μm	0.0	oxide etch
WMLT		1.0	diffusion layer and width shrink factor

Threshold Voltage Parameters

Name(Alias)	Units	Default	Description
FSS (NFS)	$\text{cm}^{-2} \cdot \text{V}$ 1	0.0	number of fast surface states
NWM		0.0	narrow width modifier
SCM		0.0	short-channel drain source voltage multiplier
VT (VTO)	V	0.0	extrapolated threshold voltage
XJ	μm	1.5	junction depth

Mobility Parameters

Name(Alias)	Units	Default	Description
FRC	$\text{\AA} \cdot \text{s} / \text{cm}^2$	0.0	field reduction coefficient
FSB	$\text{V}^{1/2} \cdot \text{s} / \text{cm}^2$	0.0	lateral mobility coefficient

Name(Alias)	Units	Default	Description
UB (UO)	cm ² / (V·s)	0.0	low field bulk mobility
UH	cm ² / (V·s)	900 (N) 300 (P)*	implant - channel mobility * (For depletion model only)
VST	cm/s	0.0	saturation velocity

Capacitance Parameters

Name(Alias)	Units	Default	Description
AFC		1.0	area factor for MOSFET capacitance
CAPOP		6	gate capacitance selector
METO	μm	0.0	metal overlap on gate

The Level 5 MOSFET model has been expanded to include two modes: enhancement and depletion. These two modes are accessed by the flag mode parameter, ZENH.

ZENH=1 This enhancement model (default mode) is a portion of HSPICE MOS5 and is identical to AMI SPICE MOS Level 4.

ZENH=0 This depletion model is revised in HSPICE (from previous depletion mode) and is identical to AMI SPICE MOS Level 5.

The HSPICE enhancement and depletion models are basically identical to the AMI models. However, certain aspects have been revised to enhance performance. Using the HSPICE enhancement and depletion models provides access to HSPICE features as described below.

The HSPICE version of the enhancement and depletion models allows the choice of either SPICE-style or ASPEC-style temperature compensation. For Level 5, the default is TLEV=1, invoking ASPEC style temperature compensation. Setting TLEV=0 invokes SPICE-style temperature compensation.

CAPOP=6 represents AMI Gate Capacitance in HSPICE. CAPOP=6 is the default setting for Level 5 only. The level 5 models can also use CAPOP =1, 2, 3.

The parameter ACM defaults to 0 in Level 5, invoking SPICE-style parasitics. ACM also can be set to 1 (ASPEC) or to 2 (HSPICE). All MOSFET models follow this convention.

The HSPICE option SCALE can be used with the Level 5 model; however, option SCALM cannot be used due to the difference in units.

You *must* specify the following parameters for MOS Level 5: VTO (VT), TOX, UO (UB), FRC, and NSUB (DNB).

IDS Equations

The Level 5 IDS equations follow.

Cutoff Region, $v_{gs} \leq v_{th}$

$$I_{ds} = 0 \quad (\text{See “” on page -42})$$

On Region, $v_{gs} > v_{th}$

$$I_{ds} = \beta \cdot \left\{ \left(v_{gs} - v_{bi} - \frac{v_{de}}{2} \right) \cdot v_{de} - \frac{2}{3} \cdot \gamma \cdot [(\Phi_f + v_{de} + v_{sb})^{3/2} - (\Phi_f + v_{sb})^{3/2}] \right\}$$

where

$$v_{de} = \min(v_{ds}, v_{dsat})$$

$$\beta = UB_{eff} \cdot c_{ox} \cdot \frac{W_{eff}}{L_{eff}}$$

$$\Phi_f = 2 \cdot v_{tm} \cdot \ln\left(\frac{DNB}{ni}\right)$$

and gate oxide capacitances per unit area are calculated by:

$$c_{ox} = \frac{E_{ox}}{TOX \cdot 1E-10} \text{ F/m}$$

Effective Channel Length and Width

The effective channel length and width in the Level 5 model is determined as follows.

$$W_{eff} = W_{scaled} \cdot WMLT + OXETCH$$

$$L_{eff} = L_{scaled} \cdot LMLT - 2 \cdot (LATD + DEL)$$

Threshold Voltage, v_{th}

The model parameter VTO is an extrapolated zero-bias threshold voltage of a large device. The effective threshold voltage, including the device size effects and the terminal voltages, is given by:

$$v_{th} = v_{bi} + \gamma \cdot (\Phi_f + v_{sb})^{1/2}$$

where

$$v_{bi} = v_{fb} + \Phi_f = VTO - \gamma_0 \cdot \Phi_f^{1/2}$$

$$\gamma_0 = \frac{(2 \cdot E_{si} \cdot q \cdot DNB)^{1/2}}{c_{ox}}$$

Note: For Level 5 model, you must specify DNB and VTO parameters. The HSPICE program computes γ_0 using DNB and ignores the GAMMA model parameter.

The effective body effect (γ), including the device size effects, is computed as follows.

$$\gamma = \gamma_0 \cdot (1 - scf) \cdot (1 + ncf)$$

If $SCM \leq 0$,

$$scf = 0$$

otherwise,

$$scf = \frac{XJ}{L_{eff}} \cdot \left\{ \left[1 + \frac{2xd}{XJ} \cdot (SCM \cdot v_{ds} + v_{sb} + \Phi_f)^{1/2} \right]^{1/2} - 1 \right\}$$

If $NWM \leq 0$,

$$ncf = 0$$

otherwise,

$$ncf = \frac{NWM \cdot X_d \cdot (\Phi_f)^{1/2}}{W_{eff}}$$

where

$$X_d = \left(\frac{2 \cdot E_{si}}{q \cdot DNB} \right)^{1/2}$$

Saturation Voltage, v_{dsat}

The saturation voltage due to channel pinch-off at the drain side is computed by:

$$v_{sat} = v_{gs} - v_{bi} + \frac{\gamma^2}{2} \cdot \left\{ 1 - \left[1 + \frac{4}{\gamma^2} \cdot (v_{gs} - v_{bi} + \Phi_f + v_{sb}) \right]^{1/2} \right\}$$

$$v_{dsat} = v_{sat}$$

If ECV is not equal to 1000, then the program modifies v_{sat} to include carrier velocity saturation effect

$$v_{dsat} = v_{sat} + v_c - (v_{sat}^2 + v_c^2)^{1/2}$$

where

$$v_c = ECV \cdot L_{eff}$$

Mobility Reduction, UB_{eff}

The mobility degradation effect in the Level 5 model is computed by:

$$UB_{eff} = \frac{1}{\frac{1}{UB} + \frac{FRC \cdot (v_{gs} - v_{th})}{TOX} + \frac{vde}{VST \cdot L_e} + FSB \cdot v_{sb}^{1/2}}$$

where

$$L_e = L_{eff} \quad \text{linear region}$$

$$L_e = L_{eff} - \Delta L \quad \text{saturation region}$$

The channel length modulation effect (ΔL) is defined in the following section.

Channel Length Modulation

The Level 5 model includes the channel length modulation effect by modifying the I_{ds} current as follows:

$$I_{ds} = \frac{I_{ds}}{1 - \frac{\Delta L}{L_{eff}}}$$

where

$$\Delta L = 1e4 \cdot \left[\frac{2.73e3 \cdot XJ}{DNB \cdot \ln\left(\frac{1e20}{DNB}\right)} \right]^{1/3} \cdot [(v_{ds} - v_{dsat} + PHI)^{1/3} - PHI^{1/3}]$$

The ΔL is in microns, assuming XJ is in microns and DNB is in cm^{-3} .

Subthreshold Current, I_{ds}

This region of operation is characterized by the Fast Surface State (FSS) if it is greater than $1e10$. Then the effective threshold voltage, separating the strong inversion region from the weak inversion region, is determined as follows:

$$v_{on} = v_{th} + fast$$

where

$$fast = v_{tm} \cdot \left[1 + \frac{q \cdot FSS}{cox} + \frac{\gamma}{2 \cdot (\Phi_f + v_{sb})^{1/2}} \right]$$

and v_t is the thermal voltage.

The I_{ds} is given by:

Weak Inversion Region, $v_{gs} < v_{th}$

$$I_{ds} = (v_{on}, v_{de}, v_{sb}) \cdot e^{\frac{v_{gs} - v_{on}}{fast}}$$

Strong Inversion Region, $v_{gs} \geq v_{th}$

$$I_{ds} = I_{ds}(v_{gs}, v_{de}, v_{sb})$$

Note: The modified threshold voltage (v_{on}) produced by FSS is also used in strong inversion; that is, in the mobility equations, v_{on} is used instead of v_{th} .

Depletion Mode DC Model ZENH=0

The Level 5 MOS model uses depletion mode devices as the load element in contemporary standard n-channel technologies². This model was formulated assuming a silicon gate construction with an ion implant used to obtain the depletion characteristics. A special model is required for depletion devices because the implant used to create the negative threshold also results in a complicated impurity concentration profile in the substrate. The implant profile changes the basis for the traditional calculation of the bulk charge, QB. The additional charge from the implant, QBI, must be calculated.

This implanted layer also causes the formation of an additional channel, offering a conductive pathway through the bulk silicon, as well as through the surface channel. This second pathway can cause difficulties when trying to model a depletion device with existing MOS models. The bulk channel is partially shielded from the oxide interface by the surface channel, and the mobility of the bulk silicon can be substantially higher. Yet with all the differences, a depletion model still can share the same theoretical basis as the Ihantola and Moll gradual channel model.

The depletion model differs from the Ihanola and Moll model as follows:

- Implant charge accounted for
- Finite implant thickness (DP)
- Two channels are assumed: a surface channel and a bulk channel
- Bulk channel has a bulk mobility (UH)
- Bulk gain is assumed to be different from surface gain

In the depletion model, the gain is lower at low gate voltages and higher at high gate voltages. This variation in gain is the reason the enhancement models cannot generate an accurate representation for a depletion device. The physical model for a depletion device is basically the same as an enhancement model, except that the depletion implant is approximated by a one-step profile with a depth DP.

Due to the implant profile, the drain current equation must be calculated by region. MOSFET device model Level 5 has three regions: depletion, enhancement, and partial enhancement.

Depletion Region, $v_{gs} - v_{fb} < 0$

The low gate voltage region is dominated by the bulk channel.

Enhancement Region, $v_{gs} - v_{fb} > 0$, $v_{ds} < v_{gs} - v_{fb}$

The region is defined by high gate voltage and low drain voltage. In the enhancement region, both channels are fully turned on.

Partial enhancement region, $v_{gs} - v_{fb} > 0$, $v_{ds} > v_{gs} - v_{fb}$

The region has high gate and drain voltages, resulting in the surface region being partially turned on and the bulk region being fully turned on.

IDS Equations, Depletion Model Level 5

The IDS equations for a Level 5 depletion model follow.

Depletion, $v_{gs}-v_{fb} < 0$

$$I_{ds} = \beta_1 \cdot \left\{ q \cdot NI \cdot vde + cav \cdot \left[(v_{gs} - v_{fb}) \cdot vde - \frac{vde^2}{2} \right] \right. \\ \left. \frac{2}{3} \cdot cav \cdot \gamma \cdot [(vde + v_{sb} + \Phi_d)^{3/2} - (v_{sb} + \Phi_d)^{3/2}] \right\}$$

Enhancement, $v_{gs}-v_{fb} \ vde > 0$

$$I_{ds} = \beta_1 \cdot \left\{ q \cdot NI \cdot vde - \frac{2}{3} \cdot cav \cdot \gamma \cdot [(vde + v_{sb} + \Phi_d)^{3/2} - (v_{sb} + \Phi_d)^{3/2}] \right\} \\ + \beta \cdot \left[(v_{gs} - v_{fb}) \cdot vde - \frac{vde^2}{2} \right]$$

Partial Enhancement, $v_{gs}-v_{fb} < vde$

$$I_{ds} = \beta_1 \cdot \left\{ q \cdot NI \cdot vde + cav \cdot \left[(v_{gs} - v_{fb}) \cdot vde - \frac{vde^2}{2} \right] \right. \\ \left. - \frac{2}{3} \cdot cav \cdot \gamma \cdot [(vde + v_{sb} + \Phi_d)^{3/2} - (v_{sb} + \Phi_d)^{3/2}] \right\} \\ + \left(\frac{1}{2} \beta - \beta_1 \cdot cav \right) \cdot (v_{gs} - v_{fb})^2$$

where

$$\beta_1 = UH \cdot \frac{W_{eff}}{L_{eff}}$$

$$\beta = UB_{eff} \cdot c_{ox} \cdot \frac{W_{eff}}{L_{eff}}$$

$$c_{av} = \frac{c_{ox} \cdot c_s}{c_{ox} + c_s}$$

$$c_s = \frac{2.77E_{si}}{DP \cdot 1e-4}$$

$$\Phi_d = v_{tm} \cdot \ln\left(\frac{DNB \cdot nd}{ni^2}\right)$$

$$nd = \frac{NI \cdot 1e4}{DP}$$

and

$$v_{de} = \min(v_{ds}, v_{dsat})$$

The saturation voltage, threshold voltage, and effective γ are described in the following sections.

Threshold Voltage, v_{th}

The model parameter VTO is an extrapolated zero-bias threshold voltage for a large device. The effective threshold voltage, including the device size effects and the terminal voltages, is calculated as follows:

$$v_{th} = v_{fb} - \beta d \cdot [v_{ch} - \gamma \cdot (\Phi_d + v_{sb})^{1/2}]$$

where

$$v_{fb} = VTO + \beta d \cdot (v_{ch} - \gamma_0 \cdot \Phi_d^{1/2})$$

$$\beta d = \frac{UH \cdot cav}{UB \cdot cox}$$

$$v_{ch} = \frac{q \cdot NI}{cav}$$

$$\gamma_0 = \frac{(2 \cdot E_{si} \cdot q \cdot na1)^{1/2}}{cav}$$

$$na1 = \frac{nd \cdot DNB}{nd + DNB}$$

$$nd = \frac{NI}{DP \cdot 1e-4}$$

The effective γ , including small device size effects, is computed as follows:

$$\gamma = \gamma_0 \cdot (1 - scf) \cdot (1 + ncf)$$

where

If $SCM \leq 0$,

$$scf = 0$$

otherwise,

$$scf = \frac{XJ}{L_{eff}} \cdot \left\{ \left[1 + \frac{2xd}{XJ} \cdot (SCM \cdot v_{ds} + v_b + \Phi_d)^{1/2} \right]^{1/2} - 1 \right\}$$

If $NWM \leq 0$,

$$ncf = 0$$

otherwise,

$$ncf = \frac{NWM \cdot X_d \cdot \Phi_d^{1/2}}{W_{eff}}$$

where

$$X_d = \left(\frac{2 \cdot E_{si}}{q \cdot DNB} \right)^{1/2}$$

Note: When $v_{gs} \leq v_{th}$, the surface is inverted and a residual DC current exists. When v_{sb} is large enough to make $v_{th} > v_{in_{th}}$, then v_{th} is used as the inversion threshold voltage. In order to determine the residual current, $v_{in_{th}}$ is inserted into the I_{ds} , v_{sat} , and mobility equation in place of v_{gs} (except for v_{gs} in the exponential term of the subthreshold current). The inversion threshold voltage at a given v_{sb} is $v_{in_{th}}$, which is computed as:

$$v_{inth} = v_{fb} - \frac{q \cdot NI}{C_{OX}} - v_{sb}$$

Saturation Voltage, v_{dsat}

The saturation voltage (v_{sat}) is determined as:

$$v_{sat} = v_{gs} - v_{fb} + v_{ch} + \frac{\gamma^2}{2} \cdot \left\{ 1 - \left[1 + \frac{4}{\gamma^2} \cdot (v_{gs} - v_{fb} + v_{ch} + v_{sb} + \Phi_d) \right]^{1/2} \right\}$$

$$v_{dsat} = v_{sat}$$

IF ECV is not equal to 1000 (V/ μ m), HSPICE modifies v_{sat} to include the carrier velocity saturation effect.

$$v_{dsat} = v_{sat} + v_c - (v_{sat} + v_c)^{1/2}$$

where

$$v_c = ECV \cdot L_{eff}$$

Mobility Reduction, UB_{eff}

The surface mobility (UB) is dependent upon terminal voltages as follows:

$$UB_{eff} = \frac{1}{\frac{1}{UB} + \frac{FRC \cdot (v_{gs} - v_{th})}{TOX} + \frac{v_{de}}{VST \cdot l_e} + FSB \cdot v_{sb}^{1/2}}$$

where

$$L_e = L_{eff} \quad \text{Linear region}$$

$$L_e = L_{eff} - \Delta L \quad \text{Saturation region}$$

The channel length modulation effect (ΔL) is defined next.

Channel Length Modulation

The channel length modulation effect is included by modifying the I_{ds} current as:

$$I_{ds} = \frac{I_{ds}}{1 - \frac{\Delta L}{L_{eff}}}$$

where

$$\Delta L = 1e4 \cdot \left[\frac{2.73e3 \cdot XJ}{na1 \cdot \ln\left(\frac{1e20}{na1}\right)} \right]^{1/3} \cdot [(v_{ds} - v_{dsat} + PHI)^{1/3} - PHI^{1/3}]$$

The ΔL parameter is in microns, assuming XJ is in microns and $na1$ is in cm^{-3} .

Subthreshold Current, I_{ds}

When device leakage currents become important for operation near or below the normal threshold voltage, the subthreshold characteristics are considered. The HSPICE Level 5 model uses the subthreshold model only if the number of fast surface states (that is, the FSS) is greater than $1e10$. An effective threshold voltage (v_{on}) is then determined:

$$v_{on} = v_{th} + fast$$

where

$$fast = v_{tm} \cdot \left[1 + \frac{q \cdot FSS}{cox} + \frac{\gamma}{2 \cdot (\Phi_d + v_{sb})^{1/2}} \right]$$

If $v_{on} < v_{in_{th}}$, then $v_{in_{th}}$ is substituted for v_{on} .

Note: The HSPICE Level 5 model uses the following subthreshold model only if $v_{gs} < v_{on}$ and the device is either in partial or full enhancement mode. Otherwise, it use the model in enhancement mode ($ZENH=1$). The

subthreshold current calculated below includes the residual DC current.

If $v_{gs} < v_{on}$ then,

Partial Enhancement, $v_{gs} - v_{fb} < v_{de}$

$$I_{ds} = \beta 1 \cdot \left\{ q \cdot NI \cdot v_{de} + cav \cdot \left[(v_{on} - v_{fb}) \cdot v_{de} - \frac{v_{de}^2}{2} \right] \right. \\ \left. - \frac{2}{3} \cdot cav \cdot \gamma \cdot [(v_{de} + v_{sb} + \Phi_d)^{3/2} - (v_{sb} + \Phi_d)^{3/2}] \right\} \\ + \frac{1}{2} \cdot \left(\beta \cdot e^{\frac{v_{gs} - v_{on}}{fast}} - \beta 1 \cdot cav \right) \cdot (v_{on} - v_{fb})^2$$

Full Enhancement, $v_{gs} - v_{fb} \quad v_{de} > 0$

$$I_{ds} = \beta 1 \cdot \left\{ q \cdot NI \cdot v_{de} - \frac{2}{3} \cdot cav \cdot \gamma [(v_{de} + v_{sb} + \Phi_d)^{3/2} - (v_{sb} + \Phi_d)^{3/2}] \right\} \\ + \beta \cdot \left[(v_{on} - v_{fb}) \cdot v_{de} - \frac{v_{de}^2}{2} \right] \cdot e^{\frac{v_{gs} - v_{on}}{fast}}$$

Example of Level 5 Model

```

FILE ML5IV.SP HSPICE LEVEL 5 MODEL EXAMPLES
*OUTPUT CHARACTERISTICS FOR ENHANCEMENT & DEPLETION
MODE
.OPT ACCT LIST CO=132
.OP
VDS 3 0 .1
VGS 2 0
M1 1 2 0 0 MODEN L=20U W=20U

```

Enhancement Mode

```

.MODEL MODEN NMOS LEVEL=5
+ VT=.7 TOX=292 FRC=2.739E-2 DNB=2.423E16 UB=642.8
+ OXETCH=-.98 XJ=.29 LATD=.34 ECV=4 VST=5.595E7
+ FSB=7.095E-5 SCM=.4 FSS=2.2E11 NWM=.93 PHI=.61
+ TCV=1.45E-3 PTC=9E-5 BEX=1.8
*
VIDS 3 1
.DC VGS 0 5 0.2
.PRINT DC I(VIDS) V(2)
.PLOT DC I(VIDS)
$$$$$$
.ALTER
$$$$$$
M1 1 2 0 0 MODDP L=20U W=20U

```

Depletion Mode

```

.MODEL MODDP NMOS LEVEL=5 ZENH=0.
+ VT=-4.0 FRC=.03 TOX=800 DNB=6E14 XJ=0.8 LATD=0.7
+ DEL=0.4 CJ=0.1E-3 PHI=0.6 EXA=0.5 EXP=0.5 FSB=3E-5
+ ECV=5 VST=4E7 UB=850 SCM=0.5 NI=5.5E11 DP=0.7
UH=1200
*
.END

```

Level 6 and Level 7 I_{DS} : MOSFET Model

These models represent ASPEC, MSINC, and ISPICE MOSFET model equations. The only difference between Level 6 and Level 7 equations is the handling of the parasitic elements and the method of temperature compensation. See [Mobility Parameters, -11](#) and [Channel Length Modulation, -16](#) for those model parameters.

Level 6 and Level 7 Model Parameters

The Level 6 and Level 7 model parameters are listed in this section.

Basic Model Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	IDS equation selector
			LEVEL=6
			Lattin-Jenkins-Grove model, using ASPEC-style parasitics
			Note: When option ASPEC is invoked, the program automatically selects Level 6. However, specifying Level 6 does not automatically invoke option ASPEC. (For complete information, see the end of the Level 6 section.)
			LEVEL=7
			Lattin-Jenkins-Grove model, using SPICE-style parasitics

Name(Alias)	Units	Default	Description
CLM (GDS)		0.0	channel length modulation equation selector
DNB (NSUB)	$1/\text{cm}^3$	$1.0\text{e}15$	substrate doping
DNS (NI)	$1/\text{cm}^3$	0.0	Surface substrate doping
ECRIT (ESAT)	V/cm	0.0	drain-source critical field. Use zero to indicate an infinite value, typically 40,000 V/cm .
GAMMA	$\text{V}^{1/2}$		body effect factor. If this parameter is not input, GAMMA is calculated from DNB.
			GAMMA is the body effect when $v_{sb} < V_{B0}$.
			If $v_{sb} > V_{B0}$, LGAMMA is used.
			Using GAMMA, LGAMMA, and V_{B0} allows a two-step approximation of a non-homogeneous substrate.
LGAMMA	$\text{V}^{1/2}$	0.0	This parameter is the body effect factor when $v_{sb} > V_{B0}$.
			When the Poon-Yau GAMMA expression is used, LGAMMA is junction depth, in microns. In this case LGAMMA is multiplied by SCALM.
MOB		0.0	mobility equation selector
NWM		0.0	narrow width modulation of GAMMA
SCM		0.0	short-channel modulation of GAMMA
UO (UB, UBO)	$\text{cm}^2/(\text{V}\cdot\text{s})$	600 (N) 250 (P)	This parameter is the low field bulk mobility. It is calculated from KP if KP is supplied.

Name(Alias)	Units	Default	Description
UPDATE		0.0	<p>selector for different version of Level 6 model. For UPDATE=1 and 2 alternate saturation voltage, mobility equation (MOB=3) and series resistances RS and RD are modified to be compatible with ASPEC.</p> <p>UPDATE=1 provides continuous Multi-Level GAMMA model.</p>
VB0 (VB)	V	0.0	<p>reference voltage for GAMMA switch.</p> <p>If $v_{sb} < VB0$, GAMMA is used.</p> <p>If $v_{sb} > VB0$, LGAMMA is used in the i_{ds} equation.</p>
VMAX (VMX)	cm/s	0.0	<p>maximum drift velocity of carriers. Whether or not VMAX is set determines which calculation scheme is used for v_{dsat}. Use zero to indicate an infinite value. Typical values:</p> <p>electrons 8.4e6 cm/s</p> <p>holes 4.3e6 cm/s</p>

Effective Length and Width Parameters

Name(Alias)	Units	Default	Description
DEL	m	0.0	channel length reduction on each side. DEL is applicable in most MOSFET models. An exception is the BSIM (Level 13) model, where DEL is not present. DELscaled = DEL · SCALM
LD (DLAT, LATD)	m		lateral diffusion into channel from source and drain diffusion. If LD and XJ are unspecified, LD Default=0.0. When LD is unspecified but XJ is specified, LD is calculated from XJ. LD Default=0.75 · XJ. LDscaled = LD · SCALM
LDAC	m		This parameter is the same as LD, but if LDAC is included in the .MODEL statement, it replaces LD in the Leff calculation for AC gate capacitance.
LREF	m	0.0	channel length reference LREFscaled = LREF · SCALM
LMLT		1.0	length shrink factor
WD	m	0.0	lateral diffusion into channel from bulk along width WDscaled = WD · SCALM

Name(Alias)	Units	Default	Description
WDAC	m		This parameter is the same as WD, but if WDAC is included in the .MODEL statement, it replaces WD in the Weff calculation for AC gate capacitance.
WMLT		1.0	diffusion layer and width shrink factor
WREF	m	0.0	channel width reference WREFscaled = WREF · SCALM
XJ	m	0.0	metallurgical junction depth XJscaled = XJ · SCALM
XL (DL, LDEL)	m	0.0	accounts for masking and etching effects XLscaled = XL · SCALM
XW (DW, WDEL)	m	0.0	accounts for masking and etching effects XWscaled = XW · SCALM

Threshold Voltage Parameters

Name(Alias)	Units	Default	Description
FDS		0.0	field, drain to source, controls reduction of threshold due to source-drain electric field
LND	$\mu\text{m}/\text{V}$	0.0	ND length sensitivity
LN0	μm	0.0	N0 length sensitivity
ND	$1/\text{V}$	0.0	drain subthreshold factor. Typical value=1.
N0		0.0	gate subthreshold factor. Typical value=1.
NFS (DFS, NF)	$\text{cm}^{-2} \cdot \text{V}^{-1}$	0.0	fast surface state density

Name(Alias)	Units	Default	Description
NWE	m	0.0	narrow width effect, direct compensation of VTO NWEScaled = NWE · SCALM
UFDS		0.0	high field FDS
VFDS	V	0.0	reference voltage for selection of FDS OR UFDS: FDS used if $v_{ds} \leq VFDS$ UFDS used if $v_{ds} > VFDS$
VSH	V	0.0	threshold voltage shifter for zero-bias threshold voltage (VTO) reduction as a function of the ratio of LD to Leff
VTO (VT)	V		zero-bias threshold voltage. This parameter is calculated if not specified (see "Common Threshold Voltage Parameters" on page 15-52).
WEX			weak inversion exponent
WIC		0.0	subthreshold model selector
WND	$\mu\text{m}/\text{V}$	0.0	ND width sensitivity
WNO	μm	0.0	N0 width sensitivity

Alternate Saturation Model Parameters

Name(Alias)	Units	Default	Description
KA		1.0	alternate saturation model: short-channel vds scaling factor coefficient

Name(Alias)	Units	Default	Description
KU		0.0	lateral field mobility parameter
MAL		0.5	alternate saturation model: short-channel vds scaling factor exponent
MBL		1.0	exponent for mobility reduction due to source-drain electric field
NU		1.0	mobility reduction due to source-drain electric field

UPDATE Parameter for Level 6 and Level 7

The general form of the I_{ds} equation for Level 6 is the same as the Level 2 MOS model, but the small size effects, mobility reduction, and channel length modulation are included differently. Also, you can use Level 6 models to model the MOS transistors with ion-implanted channels through the multi-level GAMMA capability.

The Level 6 model represents the ASPEC, MSINC, and ISPICE programs MOSFET model. Use the enhanced model parameter UPDATE to invoke different versions of the Level 6 model, described below.

UPDATE=0

This is the original Level 6 model in HSPICE which is not quite compatible with the ASPEC model. It has some discontinuities in weak inversion, mobility equations (MOB=3), and multi-Level GAMMA equations.

UPDATE=1

This enhanced version of the Level 6 model contains improved multi-level GAMMA equations. The saturation voltage, drain-source current, and conductances are continuous.

UPDATE=2

This version of the Level 6 model is compatible with the ASPEC model. The multi-level GAMMA model is not continuous, which is the case in the ASPEC program. See "ASPEC Compatibility" on page 16-88.

Set UPDATE to 1.0 to implement changes to the device equations. Set UPDATE to 1.0 or 2 to implement the default handling of RS and RD are implemented. These values and changes provide a more accurate ASPEC model.

UPDATE=1 or 2 then,

$$\text{TOX} = 690$$

$$\text{UO (UB)} = 750 \text{ cm}^2 / (\text{V} \cdot \text{s}) \text{ (N-ch)}$$

$$\text{UTRA (F3)} = 0.5$$

UPDATE=0 then,

$$\text{TOX} = 1000$$

$$\text{UO (UB)} = 600 \text{ cm}^2 / (\text{V} \cdot \text{s}) \text{ (N-ch)}$$

$$\text{UTRA (F3)} = 0.0$$

Calculation of RD and RS in the MOSFET changes as follows when LDIF is not specified:

UPDATE=1 or 2 and LDIF=0,

$$RD = \frac{(RD + NRD \cdot RL)}{M}$$

$$RS = \frac{(RS + NRS \cdot RL)}{M}$$

Note: The ASPEC program does not use the multiplier M .

LDIF \neq 0,

$$RD = \frac{LATD_{scaled} + LDIF_{scaled}}{W_{eff}} \cdot RD + NRD \cdot \frac{RL}{M}$$

$$RS = \frac{LATD_{scaled} + LDIF_{scaled}}{W_{eff}} \cdot RS + NRS \cdot \frac{RL}{M}$$

The vde in the mobility equations for alternate saturation model changes as follows:

$$vde = \min\left(\frac{vds}{vfa}, v_{sat}\right), UPDATE = 1 \text{ or } 2$$

$$vde = \min(vds, vfa \cdot v_{sat}), UPDATE = 0$$

The saturation voltage in the impact ionization equation is as follows:

$$vdsat = vfa \cdot v_{sat}, \quad UPDATE = 1 \text{ or } 2$$

$$vdsat = v_{sat}, \quad UPDATE = 0$$

Mobility equation MOB=3 changes as follows:

UPDATE= 1 or 2 and $(vgs - vth)^{F2} > VF1$,

$$u_{eff} = \frac{UB}{F4 + (F1 - F3) \cdot VF1 + F3 \cdot (vgs - vth)^{F2}}$$

UPDATE= 0 and $(vgs - vth)^{F2} > VF1$,

$$u_{eff} = \frac{UB}{F4 + F3 \cdot (vgs - vth)^{F2}}$$

Level 6 Model Equations, UPDATE=0,2

IDS Equations

$$ids = \beta \cdot \left\{ \left(vgs - vbi - \frac{\eta \cdot vde}{2} \right) \cdot vde - \frac{2}{3} \cdot \gamma \cdot [(PHI + vde + vsb)^{3/2} - (PHI + vsb)^{3/2}] \right\}$$

where

$$vde = \min(vds, vdsat)$$

$$\eta = 1 + \frac{NWEscaled}{weff}$$

$$\beta = ueff \cdot COX \cdot \frac{weff}{Leff}$$

Include the narrow-width effect through η , vbi , and γ values. For the narrow-width effect, specify model parameters NWE and/or NWM. Include the short-channel effect through parameters vbi and γ .

Effective Channel Length and Width

The model calculates effective channel length and width from the drawn length and width as follows:

$$leff = Lscaled \cdot LMLT + XLscaled - 2 \cdot (LDscaled + DELscaled)$$

$$weff = M \cdot (Wscaled \cdot WMLT + XWscaled - 2 \cdot WDscaled)$$

$$LREFeff = LREFscaled \cdot LMLT + XLscaled - 2 \cdot (LDscaled + DELscaled)$$

$$WREFeff = M \cdot (WREFscaled \cdot WMLT + XWscaled - 2 \cdot WDscaled)$$

Threshold Voltage, v_{th}

The model determines effective threshold voltage as follows:

$$v_{th} = v_{bi} + \gamma \cdot (PHI + v_{sb})^{1/2}$$

The built-in voltage v_{bi} and γ is computed differently depending on the specified model parameters.

Single-Gamma, $VBO=0$

When model parameter VBO is zero, the single-gamma model is used. In this case the model treats the parameter $LGAMMA$ as a junction depth. It then modifies the $GAMMA$ parameter for short-channel effect by the scf factor, which is computed using the Poon and Yau formulation. In this case $LGAMMA$ is multiplied by the $SCALM$ option.

$$scf = 1 - \frac{LGAMMA}{l_{eff}} \cdot \left\{ \left[1 + \frac{2 \cdot LAMBDA}{LGAMMA} \cdot (PHI + v_{sb})^{1/2} \right]^{1/2} - 1 \right\}$$

Specify the model parameter XJ to modify the model parameter $GAMMA$ by the short-channel factor (gl).

$$gl = 1 - \frac{XJ_{scaled}}{l_{eff}} \cdot \left\{ \left[1 + \frac{2 \cdot LAMBDA}{XJ_{scaled}} \cdot (PHI + v_{sb} + SCM \cdot v_{ds})^{1/2} \right]^{1/2} - 1 \right\}$$

The gl factor generally replaces the scf factor for the multilevel $GAMMA$ model.

The model also includes the narrow-width effect by modifying $GAMMA$ with the gw factor, which is computed as:

$$gw = \frac{1 + NWM \cdot xd}{w_{eff}}$$

where

$$xd = \left(\frac{2 \cdot \epsilon_{si}}{q \cdot DNB} \right)^{1/2}$$

Finally, the effective γ , including short-channel and narrow width effects, is:

$$\gamma = GAMMA \cdot gw \cdot gl \cdot scf$$

Effective Built-in Voltage, v_{bi}

The model includes the narrow-width effect, which is the increase in threshold voltage due to extra bulk charge at the edge of the channel, by modifying v_{bi} if you specify the model parameter NWE.

The short-channel effect, which is the decrease in threshold voltage due to the induced potential barrier-lowering effect, is included through v_{bi} modification. To include this effect, you must specify the model parameter FDS and/or UFDS and VFDS.

The expressions for v_{bi} , which sum up the above features, are:

$v_{ds} \leq VFDS$, or $VFDS=0$

$$v_{bi} = VTO - \gamma \cdot PHI^{1/2} + (\eta - 1) \cdot (PHI + v_{sb}) - \frac{LD_{scaled}}{Leff} \cdot VSH - \frac{\epsilon_{si}}{COX \cdot Leff} \cdot FDS \cdot v_{ds}$$

$v_{ds} > VFDS$

$$v_{bi} = VTO - \gamma \cdot PHI^{1/2} + (\eta - 1) \cdot (PHI + v_{sb}) - \frac{LD_{scaled}}{leff} \cdot VSH - \frac{\epsilon_{si}}{COX \cdot Leff} \cdot [(FDS - UFDS) \cdot VFDS + UFDS \cdot v_{ds}]$$

The above equations describe piecewise linear variations of v_{bi} as a function of v_{ds} . If you do not specify VFDS, the first equation for v_{bi} is used.

Note: HSPICE calculates model parameters such as VTO, PHI, and GAMMA, if they are not user-specified (see "Common Threshold Voltage Parameters" on page 15-52).

Multi-Level Gamma, $V_{BO} > 0$

Use Multi-Level Gamma to model MOS transistors with Ion-Implanted channels. The doping concentration under the gate is approximated as step functions. GAMMA and LGAMMA, respectively, represent the corresponding body effects coefficients for the implant layer and the substrate. Figure 16-1 shows the variation of v_{th} as a function of v_{sb} for Multi-Level Gamma.

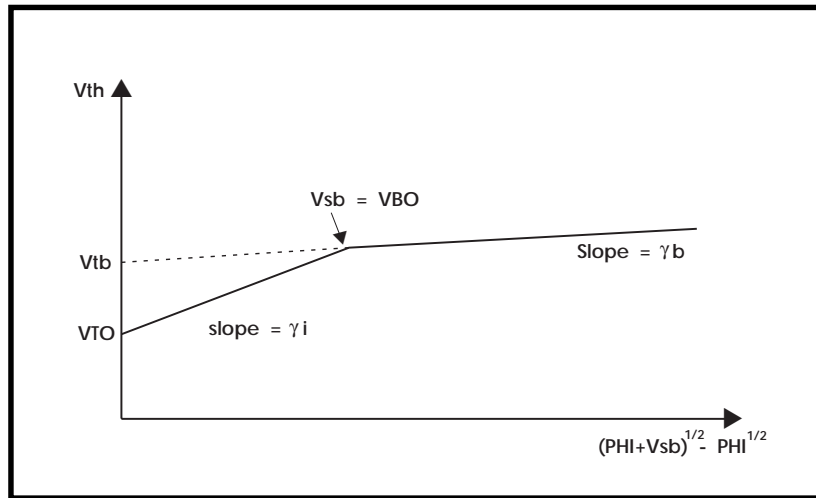


Figure 16-1: Threshold Voltage Variation

The threshold voltage equations for different regions are as follows:

Channel Depletion Region is in the Implant Layer, $v_{sb} \leq V_{BO}$

$$\gamma = \gamma_i$$

$$v_{th} = v_{bi} + \gamma_i \cdot (v_{sb} + PHI)^{1/2}$$

$$v_{bi} = V_{TO} - \gamma_i \cdot (PHI)^{1/2}$$

Channel Depletion Region is Expanded into the Bulk, $v_{sb} > V_{BO}$

$$\gamma = \gamma_b$$

$$v_{th} = v_{bi} + \gamma_b \cdot (v_{sb} + PHI)^{1/2}$$

$$v_{bi} = v_{tb} - \gamma_b \cdot (PHI)^{1/2}$$

In order for the threshold voltage to be continuous at $v_{sb}=V_{BO}$, v_{tb} must be:

$$v_{tb} = V_{TO} + (\gamma_i - \gamma_b) \cdot [(V_{BO} + PHI)^{1/2} - (PHI)^{1/2}]$$

The γ_i and γ_b are effective values of GAMMA and LGAMMA, respectively. The model computes them as γ in single-gamma models, except the scf factor is 1.0.

$$\gamma_i = GAMMA \cdot g_w \cdot g_l$$

$$\gamma_b = LGAMMA \cdot g_w \cdot g_l$$

Effective Built-in Voltage, v_{bi} for $V_{BO} > 0$

For $v_{ds} \leq V_{FDS}$,

if $v_{sb} \leq V_{BO}$,

$$v_{bi} = V_{TO} - \gamma_i \cdot (PHI)^{1/2} + (\eta - 1) \cdot (PHI + v_{sb}) - \frac{LD_{scaled}}{Leff} \cdot V_{SH} - \frac{\epsilon_{si}}{COX \cdot Leff} \cdot FDS$$

if $v_{sb} > V_{BO}$,

$$v_{bi} = V_{TO} - \gamma_b \cdot (PHI)^{1/2} + (\gamma_i - \gamma_b) \cdot [(V_{BO} + PHI)^{1/2} - (PHI)^{1/2}] + (\eta - 1) \\ + (PHI + v_{sb}) - \frac{LD_{scaled}}{Leff} \cdot V_{SH} - \frac{\epsilon_{si}}{COX \cdot Leff} \cdot FDS \cdot v_{ds}$$

For $v_{ds} > V_{FDS}$,

if $v_{sb} \leq V_{BO}$,

$$v_{bi} = V_{TO} - \gamma_i \cdot (PHI)^{1/2} + (\eta - 1) \cdot (PHI + v_{sb}) - \frac{LD_{scaled}}{Leff} \cdot V_{SH} - \frac{\epsilon_{si}}{COX \cdot Leff} \cdot [(FDS - UFDS) \cdot VFDS + UFDS \cdot v_{ds}]$$

if $v_{sb} > V_{BO}$,

$$v_{bi} = V_{TO} - \gamma_b \cdot (PHI)^{1/2} + (\gamma_i - \gamma_b) \cdot [(V_{BO} + PHI)^{1/2} - (PHI)^{1/2}] + (\eta - 1) \cdot PHI + v_{sb} - \frac{LD_{scaled}}{Leff} \cdot V_{SH} - \frac{\epsilon_{si}}{COX \cdot Leff} \cdot [(FDS - UFDS) \cdot VFDS + UFDS \cdot v_{ds}]$$

Saturation Voltage, v_{dsat} (UPDATE=0,2)

The saturation voltage due to channel pinch-off at the drain side is determined by:

$$v_{sat} = \frac{v_{gs} - v_{bi}}{\eta} + \frac{1}{2} \left(\frac{\gamma}{\eta} \right)^2 \cdot \left\{ 1 - \left[1 + \left(\frac{2 \cdot \eta}{\gamma} \right)^2 \cdot \left(\frac{v_{gs} - v_{bi}}{\eta} + PHI + v_{sb} \right) \right]^{1/2} \right\}$$

The reduction of saturation voltage due to the carrier velocity saturation effect is included as follows:

$$v_{dsat} = v_{sat} + v_c - (v_{sat}^2 + v_c^2)^{1/2}$$

where v_c is determined if model parameter $ECRIT > 0$, or $V_{MAX} > 0$, and $KU \leq 1$. If both $ECRIT$ and V_{MAX} are specified, then only the V_{MAX} equation is used. However, the V_{MAX} equation is not used if $MOB=4$ or $MOB=5$, since these mobility equations already contain a velocity saturation term.

$$v_c = ECRIT \cdot Leff$$

or

$$v_c = \frac{V_{MAX} \cdot L_{eff}}{u_{eff}}$$

Because $v_{sb} > V_{BO}$, γ is switched from γ_i to γ_b , the i_{ds} , v_{sat} , and conductances are not continuous. This problem is demonstrated in the following example. To correct the discontinuity problem, specify model parameter UPDATE=1. The next section discusses this improvement.

Example of Multi-Level Gamma Model, UPDATE=0

```

$ TGAM2.SP---MULTI-LEVEL GAMMA MODEL, UPDATE=0
* THIS DATA IS FOR THE COMPARISON OF MULTI-LEVEL
GAMMA
* UPDATE=0 OR 2 AND THE IMPROVED MULTI-LEVEL GAMMA
UPDATE=1.
*
.OPTIONS ASPEC NOMOD POST VNTOL=.1U RELI=.001
RELV=.0001
*
.MODEL NCH NMOS BULK=99 UPDATE=0
+ FDS=0.9 KU=1.6 MAL=0.5 MOB=1 CLM=1
+ LATD=0.2 PHI=0.3 VT=0.9 GAMMA=0.72 LGAMMA=0.14
+ VB0=1.2 F1=0.08 ESAT=8.6E+4 KL=0.05
+ LAMBDA=3.2U UB=638 F3=0.22
+ KA=0.97 MBL=0.76 NFS=1.0E+12 WIC=0
+ LDEL=0.084 WDEL=0.037 TOX=365 VSH=0.7
*
VD 1 0 5
VB 0 99 0
VG 2 0 1
MA 1 2 0 99 NCH 26.0 1.4
.DC VB 1.0 1.3 .01
.PRINT IDS=PAR('I(MA)') VTH=PAR('LV9(MA)')
VDSAT=PAR('LV10(MA)')
.PRINT GM=PAR('LX7(MA)') GDS=PAR('LX8(MA)')

```

```
GMBS=PAR ( 'LX9 (MA) ' )
.END
```

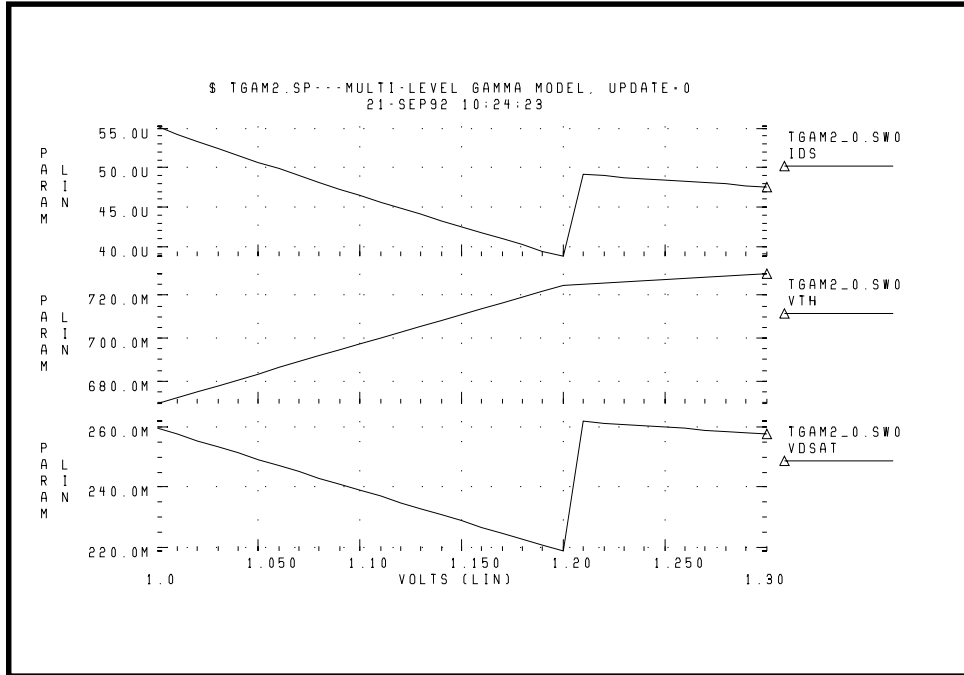


Figure 16-2: Variation of I_{DS} , V_{TH} and V_{DSAT} for $UPDATE=0$

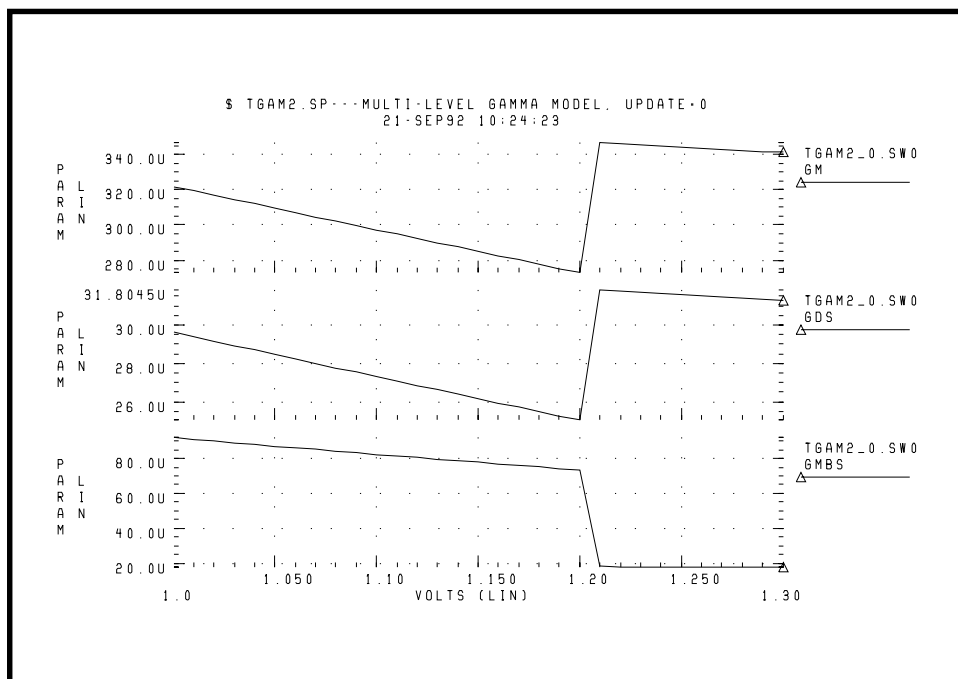


Figure 16-3: Variation of GM, GDS and GMBS for UPDATE=0

Each plot compares I_{DS} , V_{TH} , V_{DSAT} , GM, GDS and GMBS as a function of v_{sb} for UPDATE=0.

Improved Multi-Level Gamma, UPDATE=1

As demonstrated in previous sections, the regular Multi-Level Gamma displays some discontinuities in saturation voltage and drain current. This is because when v_{sb} is less than V_{BO} , γ is set to γ_i and used in i_{ds} and v_{sat} calculation. This is not correct; if $(v_{ds} + v_{sb})$ exceeds V_{BO} , the depletion regions at drain side expands into the substrate region, which means γ_b must be used instead of γ_i in v_{sat} computation. Since $v_{sat} = v_{gs} - v_{th}$ (drain), the threshold voltage at drain is computed using γ_i for $v_{sb} < V_{BO}$. As a result, the existing model overestimates the threshold voltage, ($\gamma_i > \gamma_b$), and, in turn, underestimates the saturation voltage and the drain current in the saturation region.

This causes a discontinuous increase in the saturation drain current crossing from the region $v_{sb} < V_{BO}$ to the region $v_{sb} > V_{BO}$.

There are two major differences between the improved Multi-Level model and the regular Multi-Level model: the saturation voltage equation and the drain current equations. To use the improved model, set the model parameter to UPDATE=1.

Example of Multi-Level Gamma Model, UPDATE=2

```

$ TGAM2.SP---MULTI-LEVEL GAMMA MODEL, UPDATE=2
* THIS DATA IS FOR THE COMPARISON OF MULTI-LEVEL
  GAMMA
* UPDATE=0 OR 2 AND THE IMPROVED MULTI-LEVEL GAMMA
  UPDATE=1.
*
.OPTIONS ASPEC NOMOD POST VNTOL=.1U RELI=.001
RELV=.0001
*
.MODEL NCH NMOS BULK=99 UPDATE=1
+ FDS=0.9 KU=1.6 MAL=0.5 MOB=1 CLM=1
+ LATD=0.2 PHI=0.3 VT=0.9 GAMMA=0.72 LGAMMA=0.14
+ VB0=1.2 F1=0.08 ESAT=8.6E+4 KL=0.05
+ LAMBDA=3.2U UB=638 F3=0.22
+ KA=0.97 MBL=0.76 NFS=1.0E+12 WIC=0
+ LDEL=0.084 WDEL=0.037 TOX=365 VSH=0.7
*
VD 1 0 5
VB 0 99 0
VG 2 0 1
MA 1 2 0 99 NCH 26.0 1.4
.DC VB 1.0 1.3 .01
.PRINT IDS=PAR('I(MA)') VTH=PAR('LV9(MA)')
VDSAT=PAR('LV10(MA)')
.PRINT GM=PAR('LX7(MA)') GDS=PAR('LX8(MA)')
GMBS=PAR('LX9(MA)')
.END

```

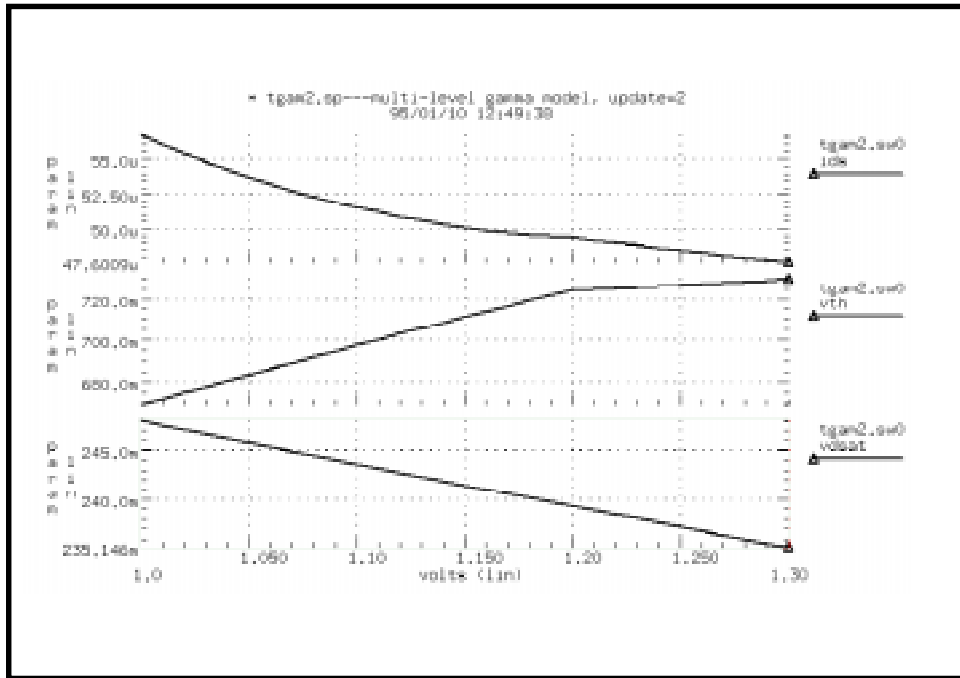


Figure 16-4: Variation of I_{DS} , V_{TH} and V_{DSAT} for UPDATE=2

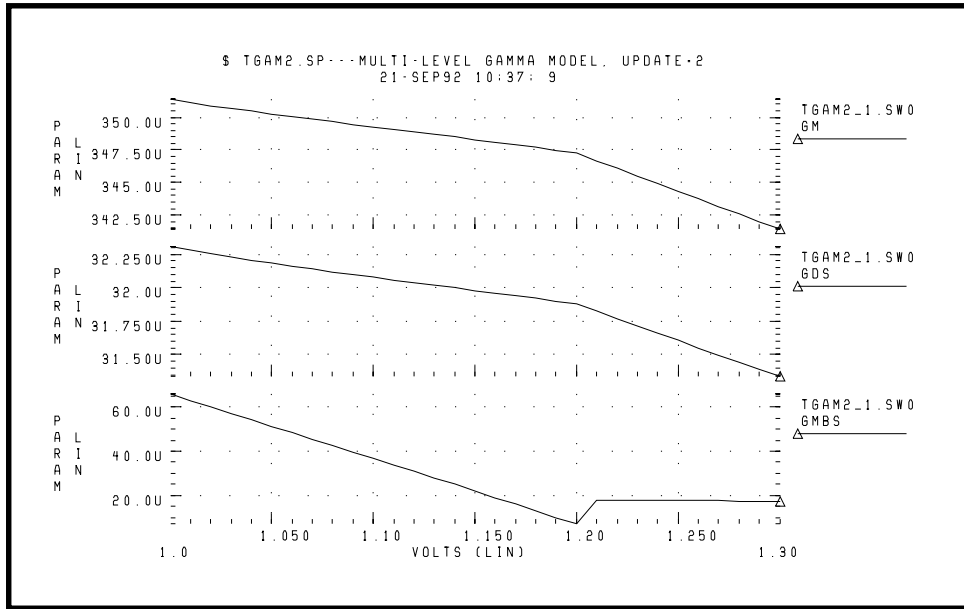


Figure 16-5: Variation of GM, GDS and GMBS for UPDATE=2

Each plot compares I_{DS} , V_{TH} , V_{DSAT} , GM, GDS and GMBS as a function of v_{sb} for UPDATE=1.

Saturation Voltage, v_{sat}

To get the right value for v_{sat} , two trial values of v_{sat} corresponding to γ_i and γ_b are calculated:

$$v_{sat1} = \frac{v_{gs} - v_{bi1}}{\eta} + \frac{1}{2} \left(\frac{\gamma_i}{\eta} \right)^2 \cdot \left\{ 1 - \left[1 + \left(\frac{2 \cdot \eta}{\gamma_i} \right)^2 \cdot \left(\frac{v_{gs} - v_{bi1}}{\eta} + PHI + v_{sb} \right) \right]^{1/2} \right\}$$

$$v_{sat2} = \frac{v_{gs} - v_{bi2}}{\eta} + \frac{1}{2} \left(\frac{\gamma_b}{\eta} \right)^2 \cdot \left\{ 1 - \left[1 + \left(\frac{2 \cdot \eta}{\gamma_b} \right)^2 \cdot \left(\frac{v_{gs} - v_{bi2}}{\eta} + PHI + v_{sb} \right) \right]^{1/2} \right\}$$

v_{bi1} and v_{bi2} are built in potentials corresponding to γ_i and γ_b , respectively.

If $(v_{dsat1} + v_{sb}) \leq V_{BO}$, then $v_{dsat} = v_{dsat1}$

If $(v_{dsat2} + v_{sb}) > V_{BO}$, then $v_{dsat} = v_{dsat2}$

Note: The v_{sat} is modified by v_c for carrier velocity saturation effects to obtain v_{dsat} .

Level 6 I_{DS} Equations, UPDATE=1

There are three equations for i_{ds} depending upon the region of operation. The model derives these equations by integrating the bulk charge $(v_{gs} - v_{th}(v) - v)$ from the source to the drain.

For $v_{sb} < V_{BO} - v_{de}$, the model forms an entire gate depletion region in the implant layer.

$$i_{ds} = \beta \cdot \left\{ \left(v_{gs} - v_{bi1} - \frac{\eta \cdot v_{de}}{2} \right) \cdot v_{de}^{-\frac{2}{3}} \cdot \gamma_i \cdot \left[(PHI + v_{de} + v_{sb})^{3/2} - (PHI + v_{sb})^{3/2} \right] \right\}$$

where v_{bi1} is the same as v_{bi} for $v_{sb} \leq V_{BO}$.

For $v_{sb} \geq V_{BO}$, the entire gate depletion region expands into the bulk area.

$$i_{ds} = \beta \cdot \left\{ \left(v_{gs} - v_{bi2} - \frac{\eta \cdot v_{de}}{2} \right) \cdot v_{de}^{-\frac{2}{3}} \cdot \gamma_b \cdot \left[(PHI + v_{de} + v_{sb})^{3/2} - (PHI + v_{sb})^{3/2} \right] \right\}$$

where v_{bi2} is the same as v_{bi} for $v_{sb} > V_{BO}$.

$$i_{ds} = \beta \cdot \left\{ \left(v_{gs} - v_{bi2} - \frac{\eta \cdot v_{de}}{2} \right) \cdot v_{de}^{-\frac{2}{3}} \cdot \gamma_i \cdot \left[(V_{BO} + PHI)^{3/2} - (v_{sb} + PHI)^{3/2} \right] \right. \\ \left. + (\gamma_i - \gamma_b) \cdot (V_{BO} + PHI)^{1/2} \cdot (V_{BO} - v_{sb}) \right\}$$

For $VBO - v_{de} < v_{sb} < VBO$, the source side gate depletion region is in the implant layer, but the drain side gate depletion region is expanded into the bulk area.

Alternate DC Model, (ISPICE model)

If model parameter $KU > 1$, this model is invoked. Then, the model computes v_{fu} and v_{fa} scale factors to scale both the v_{ds} voltage and the i_{ds} current. These scale factors are functions of $ECRIT$ and v_{gs} voltage. The v_{fa} and v_{fu} factors are defined as follows:

$$v_{fu} = 1 - \frac{KU}{(\alpha^2 + KU^2)^{1/2} + \alpha(KU - 1)}$$

$$v_{fa} = KA \cdot v_{fu}^{(2 \cdot MAL)}$$

where

$$\alpha = \frac{ECRIT \cdot Leff}{v_{gs} - v_{th}}$$

Note: v_{fu} factor is always less than one.

The current i_{ds} is modified as follows:

NU=1

$$i_{ds} = v_{fu}^{(2 \cdot MBL)} \cdot i_{ds}$$

For $NU=0$, the factor $v_{fu}^{(2 \cdot MBL)}$ is set to one.

The current i_{ds} is a function of effective drain to source voltage, v_{de} , which is determined as:

$$v_{de} = \min(v_{ds}/v_{fa}, v_{sat})$$

and

$$v_{dsat} = v_{fa} \cdot v_{sat}$$

This alternate model is generally coupled with the mobility normal field equations (MOB=3) and the channel length modulation drain field equation (CLM=3). The vde value used in the mobility equations is:

$$le = \min(vds, vfa \cdot vsa, UPDATE=0)$$

$$ds = \min(vds/vfa, vsa, UPDATE=1,2)$$

Subthreshold Current, ids

This region of operation is characterized by the choice of two different equations, selected through the model parameter WIC (Weak Inversion Choice).

WIC can be designated as follows:

WIC=0 no weak inversion (default)

WIC=1 ASPEC-style weak inversion

WIC=2 enhanced HSPICE-style weak inversion

In addition to WIC, set the parameter NFS. NFS represents the number of fast states per centimeter squared. Reasonable values for NFS range from 1e10 to 1e12.

WIC=0, no weak inversion.

WIC=1, the threshold voltage vth is increased by the term fast.

$$von = vth + fast$$

where

$$fast = vt \cdot \left[1 + \frac{q \cdot NFS}{COX} + \frac{\gamma}{2 \cdot (vsb + PHI)^{1/2}} \right]$$

and vt is the thermal voltage.

The current ids for $vgs < von$ is given by:

$$ids = ids(von, vde, vsb) \cdot e^{\frac{vgs - von}{fast}}$$

if $v_{gs} > v_{on}$, then

$$i_{ds} = i_{ds}(v_{gs}, v_{ds}, v_{sb})$$

Note: The modified threshold voltage (v_{on}) is not used for strong inversion conditions.

WIC=2

The subthreshold region is limited between cutoff and strong inversion regions. Although it appears that, if the gate voltage is less than $v_{th}-PHI$, there can be no weak inversion conduction, there still can be diffusion conduction from the drain-to-bulk rather than drain-to-source.

$$v_{on} = v_{th} + fast$$

where

$$fast = v_t \cdot \left[1 + \frac{q \cdot NFS}{COX} + \frac{\gamma}{2 \cdot (v_{sb} + PHI)^{1/2}} \right]$$

Cutoff Region, $v_{gs} \leq v_{th} - PHI$

$$i_{ds} = 0$$

Weak Inversion, $v_{th} - PHI < v_{gs} \leq v_{on}$

$$i_{ds} = i_{ds}(v_{on}, v_{ds}, v_{sb}) \cdot \left(1 - \frac{v_{on} - v_{gs}}{fast + PHI} \right)^{WEX}$$

Strong Inversion, $v_{gs} > v_{on}$

$$i_{ds} = i_{ds}(v_{gs}, v_{ds}, v_{sb})$$

Note: The modified threshold voltage (v_{on}) is not used in strong inversion conditions.

If $WIC=3$, the subthreshold current is calculated differently. In this case, the ids current is:

$$ids = ids(vgs, vde, vsb) + isub(N0eff, NDeff, vgs, vds)$$

The $N0eff$ and $NDeff$ are functions of effective device width and length.

Effective Mobility, $ueff$

All mobility equations have the general form:

$$ueff = UO \cdot factor$$

$ueff$ Effective mobility at analysis temperature.

$factor$ Mobility degradation factor, see the following sections.
Default=1.0

Use model parameter MOB to select the mobility modulation equation used by HSPICE as follows:

$MOB\ 0$	no mobility reduction (default)
$MOB\ 1$	Gm equation
$MOB\ 2$	Frohman-Bentchkowski equation
$MOB\ 3$	normal field equation
$MOB\ 4$	universal field mobility reduction
$MOB\ 5$	universal field mobility reduction with independent drain field
$MOB\ 6$	modified $MOB\ 3$ equations (lateral field effect included)
$MOB\ 7$	modified $MOB\ 3$ equations (lateral field effect not included)

These equations are described in the following sections.

MOB=0 Default, No Mobility

factor = 1.0 No mobility reduction

MOB=1 Gm Equation

Name(Alias)	Units	Default	Description
F1	1/V	0.0	gate field mobility reduction
UTRA (F3)	factor	0.0	source-drain mobility reduction factor

The MOB=1 equation is useful for transistors with constant source-to-bulk voltage, since the factor does not contain a v_{sb} term. Use of this equation can result in over-estimation of mobility for small gate voltages and large back-bias such as depletion pull-ups.

$$factor = \frac{1}{1 + F1 \cdot (v_{gs} - v_{b1} - F3 \cdot v_{de})}$$

$$v_{de} = \min(v_{ds}, v_{dsat})$$

Note: If the alternate saturation model is used, v_{de} is different for UPDATE=0 and UPDATE=1. See "Alternate DC Model, (ISPIICE model)" on page 16-75. Also, if $V_{MAX} > 0$, then $v_{de} = \min(v_{ds}, v_{sat})$, and if V_{MAX} is not specified, then $v_{de} = \min(v_{ds}, v_{dsat})$.

MOB=2 Frohman-Bentchkowski Equation

Name(Alias)	Units	Default	Description
F1	V/cm	0.0	critical gate-bulk electric field at which mobility reduction becomes significant

Name(Alias)	Units	Default	Description
UEXP (F2)		0.0	mobility exponent. Use 0.36 factor for n-channel and 0.15 for p-channel.
UTRA (F3)	factor	0.0	source-drain mobility reduction factor
VMAX (VMX)	cm/s	0.0	maximum drift velocity of carriers. Whether or not VMAX is set determines which calculation scheme is used for vdsat. Use zero to indicate an infinite value.

Mobility reduction equation ($MOB=2^3$ produces good results for high gate voltages and drain fields with constant back-bias. This equation is typically used for p-channel pull-ups and n-channel pull-downs. Specify a value for VMAX to cause the proper calculation scheme to be used for vdsat. $MOB=2$ corresponds to MSINC UN=2 and is the SPICE default.

$$factor = \left[\frac{F1 \cdot \epsilon si}{COX \cdot (vgs - vbi - F3 \cdot vde)} \right]^{F2}$$

where vde is defined the same as for $MOB=1$ equation.

MOB=3 Normal Field Equation

Name(Alias)	Units	Default	Description
<i>F1</i>	1/V	0.0	low-field mobility multiplier
<i>F4</i>		1.0	mobility summing constant
<i>UEXP (F2)</i>		0.0	mobility exponent
<i>UTRA (F3)</i>	1/V	0.0	high-field mobility multiplier
<i>VF1</i>	V	0.0	low to high field mobility (voltage switch)

This equation is the same as MSINC UN=1.

$$(vgs - vth)^{F2} \leq VF1,$$

$$factor = \frac{1}{F4 + F1 \cdot (vgs - vth)^{F2}}$$

If UPDATE=0, and $(vgs-vth)^{F2} > VF1$,

$$factor = \frac{1}{F4 + F3 \cdot (vgs - vth)^{F2}}$$

If UPDATE=1, 2 and $(vgs-vth)^{F2} > VF1$,

$$factor = \frac{1}{F4 + (F1 - F3) \cdot VF1 + F3 \cdot (vgs - vth)^{F2}}$$

MOB=4 and MOB=5 Universal Field Mobility Reduction

Name(Alias)	Units	Default	Description
ECRIT	V/cm	0.0	critical electric drain field for mobility reduction. Use zero to indicate an infinite value.
F1	V/cm	0.0	source-drain mobility reduction field (typical value 1e4 to 5e8)
MOB		0.0	mobility equation selector. Set MOB=4 for critical field equation, or set MOB=5 for critical field equation with independent drain field.
UEXP (F2)	$1/V^{1/2}$	0.0	bulk mobility reduction factor (typical value 0 to 0.5)
UTRA (F3)	V/cm	0.0	critical electric drain field for mobility reduction

The MOB=4 equation is the same as the MSINC UN=3 equation. The MOB=5 equation is the same as MOB=4 except that F3 substitutes for ECRIT in the expression for v_c .

The MOB=5 equation provides a better fit for CMOS devices in the saturation region. Do not specify a value for VMAX since velocity saturation is handled in the mobility equation.

$$factor = \frac{1}{1 + \frac{COX}{F1 \cdot \epsilon_{ox}} \cdot (vgs - cth) + \frac{vde}{vc} + F2 \cdot (vsb + PHI)^{1/2}}$$

If MOB=4,

$$vc = ECRIT \cdot Leff$$

If MOB=5,

$$vc = F3 \cdot Leff$$

Note: If you use the alternate saturation model, vde is different for UPDATE=0 and UPDATE=1, 2.

MOB=6, 7 Modified MOB=3

This mobility equation is the same as MOB=3, except the equation uses VTO instead of vth. When MOB=6 is used, the current ids also is modified as follows:

$$ids = \frac{ids}{1 + F1 \cdot \left(vgs - vth - \frac{vde}{2} \right) + \frac{UTRA}{Leff} \cdot vde}$$

Channel Length Modulation

The basic MOSFET current equation for ids describes a parabola, where the peak corresponds to the drain-to-source saturation voltage (vdsat). Long-channel MOSFETs generally demonstrate ideal behavior. For vds voltages greater than vdsat, there is no increase in the ids current. As the channel length decreases, the current in the saturation region continues to increase. This increase in current is modeled as a decrease in the effective channel length. Except for CLM=5 and 6, the channel length modulation equations are only

calculated when the device is in the saturation region. HSPICE provides several channel length modulation equations; all (except for CLM=5) modify the i_{ds} equation as follows:

$$i_{ds} = \frac{i_{ds}}{1 - \frac{\Delta L}{L_{eff}}}$$

ΔL is the change in channel length due to MOSFET electric fields.

Use model parameter CLM to designate the channel length modulation equation HSPICE uses as follows:

CLM = 0	no channel length modulation (default)
CLM = 1	one-sided step depletion layer drain field equation
CLM = 2	Frohman's electrostatic fringing field equation
CLM = 3	one-sided step depletion layer drain field equation, with carrier velocity saturation
CLM = 4	Wang's equation: linearly-graded depletion layer
CLM = 5	Meta-Software's channel length modulation
CLM = 6	Meta-Software's ΔL equations

These equations and the associated model parameters are discussed in the following sections.

CLM=0 No Channel Modulation - Default

$$\Delta L = 0$$

This is the default channel length equation, representing no channel length modulation; it corresponds to MSINC GDS=0.0

CLM=1 Step Depletion Equation

Name(Alias)	Units	Default	Description
<i>KL</i>		0.0	empirical constant (saturation voltage)
<i>LAMBDA</i> (<i>LAM</i> , <i>LA</i>)	cm/V ^{1/2}	1.137e-4	channel length modulation (–s calculated from NSUB unless specified) default LAMBDA corresponds to default NSUB value

$$\Delta L = LAMBDA \cdot (vds - vdsat)^{1/2} \cdot \left(\frac{vdsat}{vsat}\right)^{KL}$$

If not user-specified, LAMBDA is calculated as:

$$LAMBDA = \left(\frac{2 \cdot \epsilon si}{q \cdot DNB}\right)^{1/2}$$

This is a one-sided step depletion region formulation by Grove: ΔL varies with the depletion layer width, which is a function of the difference between the effective saturation voltage ($vdsat$) and the drain-to-source channel voltage (vds). This equation is typically used for long channels and high dopant concentrations. This corresponds to GDS=1 in MSINC.

CLM=2 Electrostatic Fringing Field

Name(Alias)	Units	Default	Description
<i>A1</i>		0.2	first fringing field factor gate-drain
<i>A2</i>		0.6	second fringing field factor gate- $vdsat$

$$\Delta L = \frac{\epsilon si}{COX} \cdot \frac{vds - vdsat}{A1 \cdot (vds - vgs + vbi) + A2 \cdot (vgs - vbi - vdsat)}$$

The fringing field equation, or electrostatic channel length reduction, developed by Frohman-Bentchkowski, is most often used for modeling short-channel enhancement transistors. In MSINC, the equivalent equation is $GDS=2$.

CLM=3 Carrier Velocity Saturation

Name(Alias)	Units	Default	Description
KA		1.0	vds scaling factor for velocity saturation
KCL		1.0	exponent for vsb scaling factor
KU		0.0	velocity saturation switch. If $KU \leq 1$, the standard velocity saturation equation is used.
LAMBDA (LAM, LA)	cm/V ^{1/2}	1.137e-4	channel length modulation. This parameter is calculated from NSUB if not specified. The default LAMBDA corresponds to the default NSUB value.
MAL		0.5	vds exponent for velocity saturation
MCL		1.0	short channel exponent

$$L = vfu^{(2 \cdot MCL)} \cdot LAMBDA \cdot$$

$$[(vds - vfa \cdot vsat + KCL \cdot vsb + PHI)^{1/2} - (KCL \cdot vsb + PHI)^{1/2}]$$

This equation is an extension of the first depletion layer equation, CLM=1, and includes the effects of carrier velocity saturation and the source-to-bulk voltage (vsb) depletion layer width. It represents the basic ISPIECE equation. See “Alternate DC Model, (ISPIECE model)” on page 16-75 for definitions of vfa and vfu.

CLM=4, Wang's Equation

Name(Alias)	Units	Default	Description
A1	m	0.2	junction depth
			A1scaled = A1 SCALM
DND	cm ⁻³	1e20	drain diffusion concentration

Linearly-Graded Depletion Layer

$$\Delta L = \left[\frac{2.73e5 \cdot A1scaled}{DNB \cdot \ln\left(\frac{DND}{DNB}\right)} \right]^{1/3} \cdot [(vds - vdsat + PHI)^{1/3} - PHI^{1/3}]$$

Wang's equation allows the inclusion of junction characteristics in the calculation of channel length modulation. The equation assumes that the junction approximated a linearly-graded junction and provides a value of 0.33 for the exponent. This equation is similar to MSINC GDS=3.

CLM=5, HSPICE Channel Length Modulation

Name(Alias)	Units	Default	Description
LAMBDA	amp/V ²	0	constant coefficient
VGLAM	1/V	0	constant coefficient

When CLM=5, the current i_{ds} is increased by i_{dssat} , given as:

$$i_{dssat} = \frac{w_{eff}}{L_{eff}} \cdot LAMBDA \cdot vds \cdot (vgs - vth) \cdot [1 + VGLAM \cdot (vgs - vth)]$$

$$ids = ids + idssat$$

Note: The equation adds the idssat term to ids in all regions of operation. Also, LAMBDA is a function of temperature.

CLM=6, HSPICE ΔL Equation

Name(Alias)	Units	Default	Description
LAMBDA	$1/V^{KL}$	0	vds coefficient
LAM1	1/m	0	channel length coefficient
KL		0	vds exponent
VGLAM	1/V	0	gate drive coefficient

Unlike the other CLMs, this equation calculates the channel length modulation (ΔL) in all regions of operations and uses it to modify current ids.

$$\Delta L = \frac{Leff \cdot LAMBDA \cdot vds^{KL} \cdot [1 + VGLAM \cdot (vgs - vth)]}{1 + LAM1 \cdot Leff}$$

and

$$ids = \frac{ids}{1 - \frac{\Delta L}{Leff}}$$

Note: LAMBDA is a function of temperature.

ASPEC Compatibility

Make MOSFET models compatible with ASPEC by specifying ASPEC=1 in the .OPTION statement and LEVEL=6 in the associated MOSFET model statement.

If you assign the element parameters without keynames, you must use the parameter sequence given in the general format. HSPICE assigns parameters in the order they are listed in the element statement. Errors occur if parameter names are also element keynames.

When Option ASPEC is in effect, a number of program variations occur. The MOSFET model parameter LEVEL is set to 6.

Note: Setting LEVEL=6 in the model does not invoke ASPEC.

ASPEC sets the following options:

MOSFET Option	WL = 1
General Options	SCALE = 1e-6
	SCALM = 1e-6

Since the ASPEC option sets the SCALE and SCALM options, it effectively changes the default units of any parameters affected by these options; use parameter values consistent with these scaling factors.

ASPEC sets the following model parameter defaults:

LEVEL	=	6
ACM	=	1
CJ	=	0.0
IS	=	0.0
NSUB	=	1e15

Note: NSUB is not be calculated from GAMMA, if UPDATE=1 or 2.

PHI	=	$1 \cdot \Phi_f$ (the Fermi potential)
TLEV	=	1
TLEVC	=	1

TLEV (TLEVC in turn, selects the ASPEC method of temperature update for the parameters CJ, CJSW, PB, PHP, VTO, and PHI.

Note: If PHI is entered explicitly, however, it is not updated for temperature. SCALM does not effect the scaling of parameters for the ASPEC mode. If SCALM is specified when using ASPEC, HSPICE generates an error stating that SCALM is ignored.

Level 7 IDS Model

The Level 7 model is the same as the Level 6 model except for the value of PHI.

If PHI is specified, then

For LEVEL=6,

$$\Phi_s = \frac{PHI}{2}, \text{ where } \Phi_s \text{ is the surface potential.}$$

For LEVEL=7,

$$\Phi_s = PHI$$

To transform a Level 7 equation to Level 6, make the following substitution:

$$PHI \rightarrow 2 \cdot PHI$$

To transform a Level 6 model into a Level 7 model, make the following substitution:

$$PHI(\text{Level } 7) = PHI(\text{Level } 6)/2$$

Level 8 IDS Model

The Level 8 model, derived from research at Intersil and General Electric, is an enhanced version of the Level 2 ids equation. Level 2 differs from Level 8 in the following areas: the effective substrate doping, threshold voltage, effective mobility, channel length modulation, and subthreshold current.

Level 8 Model Parameters

This section lists the Level 8 model parameters.

Basic DC Model Parameters

Name(Alias)	Units	Default	Description
LEVEL		1.0	IDS equation selector. Use Level 8 for the advanced model using finite differences.
COX	F/m ²	3.45314 e-4	oxide capacitance per unit gate area. This parameter is calculated from TOX if not specified.
ECRIT (ESAT)	V/cm	0.0	critical electric field for carrier velocity saturation, from Grove: electrons 6e4 holes 2.4e4 Use zero to indicate an infinite value.
SNVB	1/ (V·cm ³)	0.0	Slope of doping concentration versus vsb (element parameter). (Multiplied by 1e6)
TOX	m	1e-7	oxide thickness
VMAX (VMX, VSAT)	m/s	0.0	maximum drift velocity of carriers. Use zero to indicate an infinite value.

Effective Channel Width and Length Parameters

Name(Alias)	Units	Default	Description
DEL	m	0.0	channel length reduction on each side. DEL is applicable in most MOSFET models. An exception is the BSIM (Level 13) model, where DEL is not present. DELscaled = DEL · SCALM
LD (DLAT, LATD)	m		lateral diffusion into channel from source and drain diffusion. If LD and XJ are unspecified, LD default=0.0. When LD is unspecified, but XJ is specified, LD default=0.75 · XJ. LDscaled = LD · SCALM.
LDAC	m		This parameter is the same as LD, but if LDAC is included in the .MODEL statement, it replaces LD in the Leff calculation for AC gate capacitance.
WD	m	0.0	lateral diffusion into channel from bulk along width WDscaled = WD · SCALM
WDAC	m		This parameter is the same as WD, but if WDAC is included in the .MODEL statement, it replaces WD in the Weff calculation for AC gate capacitance.
LMLT		1.0	length shrink factor
LREF	m	0.0	channel length reference LREFscaled = LREF · SCALM
WMLT		1.0	diffusion layer and width shrink factor

Name(Alias)	Units	Default	Description
WREF	m	0.0	channel width reference WREFscaled = WREF · SCALM
XJ	m	0.0	metallurgical junction depth XJscaled = XJ · SCALM
XL (DL, LDEL)	m	0.0	accounts for masking and etching effects XLscaled = XL · SCALM
XW (WDEL, DW)	m	0.0	accounts for masking and etching effects XWscaled = XW · SCALM

Threshold Voltage Parameters

Name(Alias)	Units	Default	Description
CAV		0.0	thermal voltage multiplier for the weak inversion equation
DELTA		0.0	narrow width factor for adjusting threshold
ETA		0.0	drain-induced barrier lowering (DIBL) effect coefficient for threshold voltage
GAMMA	$V^{1/2}$		body effect factor. This parameter is calculated from NSUB if not specified (see "Common Threshold Voltage Parameters" on page 15-52).
LND	$\mu\text{m}/V$	0.0	ND length sensitivity

Name(Alias)	Units	Default	Description
LN0	μm	0.0	N0 length sensitivity
ND	$1/V$	0.0	drain subthreshold factor (typical value=1)
N0		0.0	gate subthreshold factor (typical value=1)
WIC		0.0	sub-threshold model selector
WND	$\mu\text{m}/V$	0.0	ND width sensitivity
WN0	μm	0.0	N0 width sensitivity
NFS (DFS, NF, DNF)	$\text{cm}^{-2}\cdot V^{-1}$	0.0	fast surface state density
NSUB (DNB, NB)	cm^{-3}	1e15	bulk surface doping. This parameter is calculated from GAMMA if not specified.
PHI	V	0.576	surface inversion potential. This parameter is calculated from NSUB if not specified (see "Common Threshold Voltage Parameters" on page 15-52).
VTO(VT)	V		zero-bias threshold voltage. This parameter is calculated if not specified (see "Common Threshold Voltage Parameters" on page 15-52).

Mobility Parameters

Name(Alias)	Units	Default	Description
MOB		6.0	Mobility equation selector (can be set to 2, 3, 6, or 7 in Level 8)
UCRIT	V/cm	1e4	MOB=6, UEXP>0 Critical field for mobility degradation, UEXP operates as a switch.
			MOB=6, UEXP≤0 Critical field for mobility degradation. Typical value is $0.01 V^{-1}$.

Name(Alias)	Units	Default	Description
UEXP (F2)		0.0	critical field exponent in mobility degradation
UTRA	m/V	0.0	transverse field coefficient (mobility)
UO (UB, UBO)	cm ² / (V·s)	600 (N) 250 (P)	low field bulk mobility. This parameter is calculated from KP (BETA) if KP (BETA) is input.

Channel Length Modulation Parameters

Name(Alias)	Units	Default	Description
A1		0.2	channel length modulation exponent (CLM=8)
CLM		7	channel length modulation equation selector
LAM1	1/m	0.0	channel length modulation length correction
LAMBDA (LAM, LA)		0.0	channel length modulation coefficient

Level 8 Model Equations

This section lists the Level 8 model equations.

IDS Equations

Level 8 ids equations are the same as the Level 2 model. These equations are repeated here for convenience.

Cutoff Region, $v_{gs} \leq v_{th}$

$$ids = 0 \quad (\text{See subthreshold current})$$

On Region, $v_{gs} > v_{th}$

$$ids = \beta \cdot \left\{ \left(v_{gs} - v_{th} - \frac{\eta \cdot v_{de}}{2} \right) \cdot v_{de} - \frac{2}{3} \cdot \gamma \cdot [(\Phi + v_{de} + v_{sb})^{3/2} - (\Phi + v_{sb})^{3/2}] \right\}$$

where

$$v_{de} = \min(v_{ds}, v_{dsat})$$

$$\eta = 1 + DELTA \cdot \frac{\pi \cdot \epsilon_{si}}{4 \cdot COX \cdot W_{eff}}$$

$$\beta = KP \cdot \frac{W_{eff}}{L_{eff}}$$

Effective Channel Length and Width

The model calculates effective channel length and width from the drawn length and width as follows:

$$L_{eff} = L_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot (LD_{scaled} + DEL_{scaled})$$

$$W_{eff} = M \cdot (W_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled})$$

$$LREF_{eff} = LREF_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot (LD_{scaled} + DEL_{scaled})$$

$$WREF_{eff} = M \cdot (WREF_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled})$$

Effective Substrate Doping, nsub

Specify the model parameter SNVB to vary substrate doping concentration linearly as a function of vsb.

$$nsub = NSUB + SNVB \cdot vsb$$

The γ , Φ , and xd parameters are computed using the above equation for $nsub$.

$$\gamma = \frac{\sqrt{2 \cdot \epsilon_{si} \cdot q \cdot nsub}}{COX}$$

$$\Phi = 2 \cdot vt \cdot \ln\left(\frac{nsub}{ni}\right)$$

$$xd = \sqrt{\frac{2 \cdot \epsilon_{si}}{q \cdot nsub}}$$

If SNVB is zero, then $\gamma = \text{GAMMA}$. The γ value is adjusted for short-channel effect the same way as the Level 2 model. Also, Φ is calculated using NSUB.

Threshold Voltage, v_{th}

Specify ETA to include the threshold voltage reduction due to potential barrier lowering effect.

$$v_{bi} = VTO - \gamma \cdot \sqrt{\Phi} - \frac{8.14e-22 \cdot ETA}{COX \cdot L_{eff}^3} \cdot v_{ds} + (\eta - 1) \cdot (v_{sb} + \Phi)$$

$$v_{th} = v_{bi} + \gamma \cdot \sqrt{v_{sb} + \Phi}$$

The γ is modified for short-channel effect, the same as in the Level 2 model, to get effective γ .

Saturation Voltage v_{dsat}

The saturation voltage v_{sat} is computed the same as in the Level 2 model. The carrier velocity effect is included only when ECRIT is greater than zero.

ECRIT > 0,

$$v_{dsat} = v_{sat} + v_c - \sqrt{v_{sat}^2 + v_c^2}$$

where

$$v_c = ECRIT \cdot L_{eff}$$

ECRIT ≤ 0 or MOB=7,

$$v_{dsat} = v_{sat}$$

v_{sat} is computed as in the Level=2 model (See page -15).

Effective Mobility, μ_{eff}

The mobility equation selector MOB controls the mobility reduction equations. In the Level 8 model, set MOB to 2, 3, 6, or 7. Default=6.

MOB=2 Mobility Reduction

$$u_{eff} = UO \cdot \left[\frac{\epsilon_{se} \cdot UCRIT}{COX \cdot (vgs - vth - UTRA \cdot vde)} \right]^{UEXP}$$

MOB=3 Mobility Reduction

$$u_{eff} = \frac{UO}{1 + \frac{2.1e-8 \cdot (vgs + vth + egfet - \Phi)}{6 \cdot TOX}}$$

where *egfet* is the silicon energy gap at the analysis temperature.

$$egfet = 1.16 - \frac{7.02e-4 \cdot t^2}{t + 1108}$$

where *t* is the temperature in degrees Kelvin.

If VMAX>1,

$$u_{eff} = \frac{u_{eff}}{1 + \frac{u_{eff}}{VMAX \cdot L_{eff}} \cdot vde}$$

MOB=6 Mobility Reduction

For UEXP>0,

$$\text{If } (vgs - vth) > \frac{\epsilon_{si} \cdot UCRIT}{COX}$$

$$\text{then } u_{eff} = \frac{UO \cdot \left[\frac{\epsilon_{si} \cdot UCRIT}{COX \cdot (vgs - vth)} \right]^{UEXP}}{1 + \frac{UTRA}{L_{eff}} \cdot vde}$$

otherwise,
$$u_{eff} = \frac{UO}{1 + \frac{UTRA}{L_{eff}} \cdot vde}$$

For UEXP=0

$$u_{eff} = \frac{UO}{[1 + UCRIT \cdot (vgs - vth)] \cdot \left(1 + \frac{UTRA}{L_{eff}} \cdot vde\right)}$$

UCRIT for UEXP=0 has a dimension of (1/V).

MOB=7 Mobility Reduction

$$u_{eff} = \frac{UO}{1 + UTRA \cdot \left(vgs - vbi - \eta \cdot \frac{vde}{2} + \frac{body}{vde}\right)}$$

where

$$body = \frac{2}{3} \cdot \gamma \cdot [(vde + vsb + \Phi)^{3/2} - (vsb + \Phi)^{3/2}]$$

Channel Length Modulation

The equation selector CLM controls the channel length modulation equations. In the Level 8 model, set CLM to 6, 7, and 8. Default=7.

CLM=6 SPICE Channel Length Modulation

If LAMBDA=0,

$$\lambda = \frac{xd}{l_{eff} \cdot vds} \cdot \sqrt{\frac{vds - vdsat}{4}} + \sqrt{1 + \left(\frac{vds - vdsat}{4}\right)^2}$$

otherwise,

$$\lambda = LAMBDA$$

then,

$$\Delta L = \frac{\lambda \cdot L_{eff} \cdot vds}{1 + LAM1 \cdot L_{eff}}$$

Note: The Level 2 model has no LAM1 term.

The current is modified for channel length modulation effect in entire regions as:

$$ids = \frac{ids}{1 - \frac{\Delta L}{L_{eff}}}$$

CLM=7 Intersil Channel Length Modulation

The ΔL is only computed for the saturation region.

vds > vdsat

$$\Delta L = \frac{LAMBDA \cdot L_{eff}}{1 + LAM1 \cdot L_{eff}} \cdot (vds - vdsat)$$

and

$$ids = \frac{ids}{L - \frac{\Delta L}{L_{eff}}}$$

CLM=8

The ΔL is only computed for the saturation region.

vds > vdsat

$$\Delta L = \frac{L_{eff}}{1 + \frac{(1 + LAM1 \cdot L_{eff}) \cdot (1 + vde)^{A1}}{LAMBDA \cdot (vds - vde)}}$$

and

$$ids = \frac{ids}{1 - \frac{\Delta L}{L_{eff}}}$$

Subthreshold Current Ids

The Level 8 model has different subthreshold current equations, depending on the value of model parameter CAV.

Define:

$$fast = vt \cdot \left[\eta + \frac{q \cdot NFS}{COX} + \frac{\gamma}{2 \cdot (vsb + \Phi)^{1/2}} + \frac{\epsilon_{si} \cdot q \cdot SNVB \cdot \sqrt{vsb + \Phi}}{\gamma \cdot COX^2} \right]$$

CAV≠0

$$von = vth + CAV \cdot fast$$

Subthreshold Region, vgs < von

If vgs > vth

$$ids = ids(von, vde, vsb) \cdot e^{\left(-1 - \frac{CAV}{2}\right)} \cdot e^{\left\{ \left[\frac{1}{fast} - \frac{(CAV - 2) \cdot (vgs - vth)}{2 \cdot CAV^2 \cdot fast^2} \right] (vgs - vth) \right\}}$$

If vgs ≤ vth

$$ids = ids(von, vde, vsb) \cdot e^{\left(-1 - \frac{CAV}{2}\right)} \cdot e^{\left(\frac{vgs - vth}{fast}\right)}$$

CAV=0

If CLM=8,

$$von = vth + 3 \cdot fast$$

otherwise,

$$von = vth + 2 \cdot fast$$

Subthreshold Region, vgs < von

$$ids = ids(von, vde, vsb) \cdot e^{\left(\frac{vgs - von}{fast}\right)}$$

If WIC=3, the subthreshold current is calculated differently. In this case the ids current is:

$$ids = ids(vgs, vde, vsb) + isub(N0eff, NDeff, vgs, vds)$$

N0eff and NDeff are functions of effective device width and length.

Level 13 BSIM Model

The HSPICE Level 13 MOSFET model is an adaptation of BSIM (Berkeley Short Channel IGFET) from SPICE 2G.6 (SPICE). The model is formulated on the device physics of small-geometry MOS transistors. To invoke the subthreshold region, set the model parameter N0 (low field weak inversion gate drive coefficient) to less than 200. The HSPICE wire model (from resistor element), which is compatible with SPICE BSIM interconnect model for polysilicon and metal layers, simulates resistors and capacitors generated with interconnect. The HSPICE capacitor model (from capacitor element) simulates capacitors generated with interconnect. The HSPICE MOSFET diffusion model is compatible with the SPICE BSIM diffusion model.

Two different types of formats are available for specifying the BSIM model parameters. Enter the model parameters as a sequence of numbers similar to SPICE, or set them using model parameter assignments. When converting from SPICE to HSPICE, the keyletter for the MOSFET device is S for SPICE BSIM and M for HSPICE. (Refer to the example of HSPICE BSIM model circuit file at the end of this section.) Some model parameter names have been modified due to the SPICE BSIM model installation in HSPICE.

BSIM Model Features

- vertical field dependence of carrier mobility
- carrier velocity saturation
- drain-induced barrier lowering
- depletion charge sharing by source and drain
- non-uniform doping profile for ion-implanted devices
- channel length modulation
- subthreshold conduction
- geometric dependence of electrical parameters

Level 13 Model Parameters

Note: When reading parameter names, be aware of the difference in appearance between the upper case letter O, the lower case letter o, and the number zero (0).

For reference purposes only, the default values below are obtained from a medium size n-channel MOSFET device.

All Level 13 parameters should be specified using NMOS conventions, even for PMOS (for example, $ETA0=0.02$, not $ETA0=-0.02$).

Transistor Process Parameters

Name(Alias)	Units	Default	Description
LEVEL		1	MOSFET model level selector, set to 13 for the HSPICE BSIM model
CGBOM, (CGBO)	F/m	2.0e-10	gate-to-bulk parasitic capacitance (F/m of length)
CGDOM, (CGDO)	F/m	1.5e-9	gate-to-drain parasitic capacitance (F/m of width)
CGSOM, (CGSO)	F/m	1.5e-9	gate-to-source parasitic capacitance (F/m of width)
DL0	μm	0.0	difference between drawn poly and electrical
DW0	μm	0.0	difference between drawn diffusion and electrical
DUM1		0.0	dummy (not used)
DUM2		0.0	dummy (not used)
ETA0		0.0	linear vds threshold coefficient
LETA	mm	0.0	length sensitivity
WETA	μm	0.0	width sensitivity
K1	$V^{1/2}$	0.5	root-vs _b threshold coefficient

Name(Alias)	Units	Default	Description
LK1	$V^{1/2}\cdot\mu\text{m}$	0.0	length sensitivity
WK1	$V^{1/2}\cdot\mu\text{m}$	0.0	width sensitivity
K2		0.0	linear vsb threshold coefficient
LK2	μm	0.0	length sensitivity
WK2	μm	0.0	width sensitivity
MUS	$\text{cm}^2/(\text{V}\cdot\text{s})$	600	high drain field mobility
LMS (LMUS)	$\mu\text{m}\cdot\text{cm}^2/(\text{V}\cdot\text{s})$	0.0	length sensitivity
WMS (WMUS)	$\mu\text{m}\cdot\text{cm}^2/(\text{V}\cdot\text{s})$	0.0	width sensitivity
MUZ	$\text{cm}^2/(\text{V}\cdot\text{s})$	600	low drain field first order mobility
LMUZ	$\mu\text{m}\cdot\text{cm}^2/(\text{V}\cdot\text{s})$	0.0	length sensitivity
WMUZ	$\mu\text{m}\cdot\text{cm}^2/(\text{V}\cdot\text{s})$	0.0	width sensitivity
N0		0.5	low field weak inversion gate drive coefficient (a value of 200 for N0 disables weak inversion calculation)
LN0		0.0	length sensitivity
WN0		0.0	width sensitivity
NB0		0.0	Vsb reduction to low field weak inversion gate drive coefficient
LNB		0.0	length sensitivity
WNB		0.0	width sensitivity
ND0		0.0	Vds reduction to low field weak inversion gate drive coefficient

Name(Alias)	Units	Default	Description
LND		0.0	length sensitivity
WND		0.0	width sensitivity
PHI0	V	0.7	two times the Fermi potential
LPHI	V· μm	0.0	length sensitivity
WPHI	V· μm	0.0	width sensitivity
TREF	°C	25.0	reference temperature of model (local override of TNOM)
TOXM, (TOX)	μm , (m)	0.02	gate oxide thickness (TOXM or TOX > 1 is interpreted as Angstroms)
U00	1/V	0.0	gate field mobility reduction factor
LU0	$\mu\text{m}/\text{V}$	0.0	length sensitivity
WU0	$\mu\text{m}/\text{V}$	0.0	width sensitivity
U1	$\mu\text{m}/\text{V}$	0.0	drain field mobility reduction factor
LU1	$\mu\text{m}^2/\text{V}$	0.0	length sensitivity
WU1	$\mu\text{m}^2/\text{V}$	0.0	width sensitivity
VDDM	V	50	critical voltage for high drain field mobility reduction
VFB0 (VFB)	V	-0.3	flatband voltage
LVFB	V· μm	0.0	length sensitivity
WVFB	V· μm	0.0	width sensitivity
X2E	1/V	0.0	Vsb correction to linear vds threshold coefficient
LX2E	$\mu\text{m}/\text{V}$	0.0	length sensitivity
WX2E	$\mu\text{m}/\text{V}$	0.0	width sensitivity
X2M (X2MZ)	$\text{cm}^2/(\text{V}^2\cdot\text{s})$	0.0	Vsb correction to low field first order mobility
LX2M (LX2MZ)	$\mu\text{m}\cdot\text{cm}^2/(\text{V}^2\cdot\text{s})$	0.0	length sensitivity

Name(Alias)	Units	Default	Description
WX2M (WX2MZ)	$\mu\text{m}\cdot\text{cm}^2/(\text{V}^2\cdot\text{s})$	0.0	width sensitivity
X2MS	$\text{cm}^2/(\text{V}^2\cdot\text{s})$	0.0	V _{bs} reduction to high drain field mobility
LX2MS	$\mu\text{m}\cdot\text{cm}^2/(\text{V}^2\cdot\text{s})$	0.0	length sensitivity
WX2MS	$\mu\text{m}\cdot\text{cm}^2/(\text{V}^2\cdot\text{s})$	0.0	width sensitivity
X2U0	$1/\text{V}^2$	0.0	V _{sb} reduction to GATE field mobility reduction factor
LX2U0	$\mu\text{m}/\text{V}^2$	0.0	length sensitivity
WX2U0	$\mu\text{m}/\text{V}^2$	0.0	width sensitivity
X2U1	$\mu\text{m}/\text{V}^2$	0.0	V _{sb} reduction to DRAIN field mobility reduction factor
LX2U1	$\mu\text{m}^2/\text{V}^2$	0.0	length sensitivity
WX2U1	$\mu\text{m}^2/\text{V}^2$	0.0	width sensitivity
X3E	$1/\text{V}$	0.0	V _{ds} correction to linear v _{ds} threshold coefficient
LX3E	$\mu\text{m}/\text{V}$	0.0	length sensitivity
WX3E	$\mu\text{m}/\text{V}$	0.0	width sensitivity
X3MS	$\text{cm}^2/(\text{V}^2\cdot\text{s})$	5.0	V _{ds} reduction to high drain field mobility
LX3MS	$\mu\text{m}\cdot\text{cm}^2/(\text{V}^2\cdot\text{s})$	0.0	length sensitivity
WX3MS	$\mu\text{m}\cdot\text{cm}^2/(\text{V}^2\cdot\text{s})$	0.0	width sensitivity
X3U1	$\mu\text{m}/\text{V}^2$	0.0	V _{ds} reduction to drain field mobility reduction factor
LX3U1	$\mu\text{m}^2/\text{V}^2$	0.0	length sensitivity
WX3U1	$\mu\text{m}^2/\text{V}^2$	0.0	width sensitivity

Name(Alias)	Units	Default	Description
XPART		1.0	selector for gate capacitance charge-sharing coefficient

Diffusion Layer Process Parameters

Name(Alias)	Units	Default	Description
CJW, (CJSW)	F/m	0.0	zero-bias bulk junction sidewall capacitance
CJM, (CJ)	F/m ²	4.5e-5	zero-bias bulk junction bottom capacitance
DS	m	0.0	average variation of size due to side etching or mask compensation (not used)
IJS, (JS)	A/m ²	0	bulk junction saturation current
JSW	A/m	0.0	sidewall bulk junction saturation current
MJ0, (MJ)		0.5	bulk junction bottom grading coefficient
MJW, (MJSW)		0.33	bulk junction sidewall grading coefficient
PJ, (PB)	V	0.8	bulk junction bottom potential
PJW, (PHP)	V	0.8	bulk junction sidewall potential
RSHM, (RSH)	ohm/sq	0.0	sheet resistance/square
WDF	m	0.0	default width of the layer (not used)

Note: The wire model includes poly and metal layer process parameters.

Basic Model Parameters

Name(Alias)	Units	Default	Description
LD (DLAT, LATD)	m		lateral diffusion into channel from source and drain diffusion. If LD and XJ are unspecified, then LD default=0.0. When LD is unspecified but XJ is specified, LD is calculated from XJ. LD Default=0.75 · XJ. $LD_{scaled} = LD \cdot SCALM$
LDAC	m		This parameter is the same as LD, but if LDAC is included in the .MODEL statement, it replaces LD in the L_{eff} calculation for AC gate capacitance.
LMLT		1.0	length shrink factor
LREF	m	0.0 *	channel length reference $LREF_{scaled} = LREF \cdot SCALM$
WD	m	0.0	lateral diffusion into channel from bulk along width $WD_{scaled} = WD \cdot SCALM$
WDAC	m		This parameter is the same as WD, but if WDAC is included in the .MODEL statement, it replaces WD in the W_{eff} calculation for AC gate capacitance.
WMLT		1.0	diffusion layer and width shrink factor

Name(Alias)	Units	Default	Description
XL (DL, LDEL)	m	0.0	accounts for masking and etching effects XLscaled = XL · SCALM
XW (DW, WDEL)	m	0.0	accounts for masking and etching effects XWscaled = XW · SCALM
WREF	m	0.0 *	reference channel width WREFscaled = WREF · SCALM

*Note: *If LREF and WREF are not defined in the model, they take a value of infinity. The default of 0.0 is for HSPICE only.*

Temperature Parameters

Name(Alias)	Units	Default	Description
BEX		-1.5	temperature exponent for MUZ and MUS mobility parameters
FEX		0.0	temperature exponent for mobility reduction factor U1
TCV	V/°K	0.0	flat-band voltage temperature coefficient
TREF	°C	25	temperature at which parameters are extracted. This parameter defaults to the option TNOM, which defaults to 25 °C.

Sensitivity Factors of Model Parameters

For transistors, denote the L (channel length) and W (channel width) sensitivity factors of a basic electrical parameter are denoted by adding the characters 'L' and 'W' at the start of the name. For example, VFB0 sensitivity factors are LVFB and WVFB. If A0 is a basic parameter, then LA and WA are the corresponding L and W sensitivity factors of this parameter. LA and WA cannot be scaled using option SCALM in HSPICE. The model uses the general formula below to obtain this parameter value.

$$A = A0 + LA \cdot \left(\frac{1}{Leff} - \frac{1}{LREFeff} \right) + WA \cdot \left(\frac{1}{Weff} - \frac{1}{WREFeff} \right)$$

LA and WA are specified in units of microns times the units of A0.

The left side of the equation represents the effective model parameter value after device size adjustment. All the effective model parameters are in lower case and start with the character "z", followed by the parameter name.

Examples:

$$VFB0 = -0.350v$$

$$LVFB = -0.1v\mu$$

$$WVFB = 0.08v \cdot \mu$$

$$Leff = 1 \cdot 10^{-6}m = 1\mu$$

$$Weff = 2 \cdot 10^{-6}m = 2\mu$$

$$LREFeff = 2 \cdot 10^{-6}m = 2\mu$$

$$WREFeff = 1 \cdot 10^{-5}m = 10\mu$$

$$z_{vfb} = VFB0 + LVFB \cdot \left(\frac{1}{Leff} - \frac{1}{LREFeff} \right) + WVFB \cdot \left(\frac{1}{Weff} - \frac{1}{WREFeff} \right)$$

$$z_{vfb} = -0.35v + -0.1v \cdot \mu \cdot \left(\frac{1}{1\mu} - \frac{1}{2\mu} \right) + 0.08v \cdot \mu \cdot \left(\frac{1}{2\mu} - \frac{1}{10\mu} \right)$$

$$z_{vfb} = -0.35v - 0.05v + 0.032v$$

$$z_{vfb} = -0.368v$$

.MODEL VERSION Changes to BSIM Models

The VERSION parameter to the .MODEL statement allows portability of Level 13 BSIM and Level 39 BSIM2 models between HSPICE versions. Using the VERSION parameter in a Level 13 .MODEL statement results in the following changes to the BSIM model:

Model version Effect of VERSION on BSIM model

9007Blevel 13 BSIM model introduced: no changes

9007Dremoves the K2 limit

92Achanges the TOX parameter default from 1000 A to 200 A

92Badds the K2LIM parameter, which specifies the K2 limit

93Aintroduces gds constraints

93A.02VERSION parameter introduced

95.1fixes nonprinting TREF and incorrect GMBS problems

96.1Flatband voltage temperature adjustment has been changed.

Level 13 Equations

This section lists the Level 13 model equations.

Effective Channel Length and Width

The effective channel length and width for Level 13 is determined differently, depending on the specified model parameters.

If $DL0$ is specified then,

$$L_{eff} = L_{scaled} \cdot LMLT - DL0 \cdot 1e-6$$

$$LREF_{eff} = LREF_{scaled} \cdot LMLT - DL0 \cdot 1e-6$$

Otherwise, if XL or LD is specified,

$$L_{eff} = L_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot LD_{scaled}$$

$$LREF_{eff} = LREF_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot LD_{scaled}$$

If $DW0$ is specified, then

$$W_{eff} = W_{scaled} \cdot WMLT - DW0 \cdot 1e-6$$

$$WREF_{eff} = WREF_{scaled} \cdot WMLT - DW0 \cdot 1e-6$$

Otherwise, if XW or WD is specified, then

$$W_{eff} = W_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled}$$

$$WREF_{eff} = WREF_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled}$$

IDS Equations

The device characteristics are modeled by process-oriented model parameters, which are mapped into model parameters at a specific bias voltage. The ids equations are as follows:

Cutoff Region, $v_{gs} \leq v_{th}$

$$i_{ds} = 0 \quad (\text{see subthreshold current})$$

On Region, $v_{gs} > v_{th}$

For $v_{ds} < v_{dsat}$, triode region:

$$i_{ds} = \frac{\beta}{1 + x_{u1} \cdot v_{ds}} \cdot \left[(v_{gs} - v_{th}) \cdot v_{ds} - \frac{body}{2} \cdot v_{ds}^2 \right]$$

For $v_{ds} \geq v_{dsat}$, saturation region:

$$i_{ds} = \frac{\beta}{2 \cdot body \cdot arg} \cdot (v_{gs} - v_{th})^2$$

where

$$\beta = u_{eff} \cdot COX \cdot \frac{W_{eff}}{L_{eff}}$$

$$u_{eff} = \frac{u_0}{1 + x_{u0} \cdot (v_{gs} - v_{th})}$$

$$x_{u0} = z_{u0} - z_{x2u0} \cdot v_{sb}$$

The carrier mobility, u_0 , is calculated by quadratic interpolation through three data points.

$$u_0|_{v_{ds}=0} = MUZ - z_{x2mz} \cdot v_{sb}$$

$$u_0|_{v_{ds}=VDDM} = z_{mus} - z_{x2ms} \cdot v_{sb}$$

and the sensitivity of u_0 to v_{ds} at $v_{ds}=VDDM$, which is z_{x3ms} .

The “body” factor is calculated by:

$$body = 1 + \frac{g \cdot zk1}{2 \cdot (zphi + vsb)^{1/2}}$$

where

$$g = 1 - \frac{1}{1.744 + 0.8364 \cdot (zphi + vsb)}$$

The “arg” term in saturation region current is calculated by:

$$arg = \frac{1}{2} \cdot [1 + vc + (1 + 2 \cdot vc)^{1/2}]$$

where

$$vc = \frac{xu1 \cdot (vgs - vth)}{body}$$

and

$$xu1 = zu1 - zx2u1 \cdot vsb + zx3u1 \cdot (vds - VDDM), \quad UPDATE=2$$

$$xu1 = \frac{zu1 - zx2u1 \cdot vsb + zx3u1 \cdot (vds - VDDM)}{Leff}, \quad UPDATE=0, 1$$

Threshold Voltage

The threshold voltage can be expressed as:

$$vth = zvfb + zphi + gamma \cdot (zphi + vsb)^{1/2} - xeta \cdot vds$$

where

$$gamma = zk1 - zk2 \cdot (zphi + vsb)^{1/2}$$

and

$$xeta = zeta - zx2e \cdot vsb + zx3e \cdot (vds - VDDM), \quad UPDATE=0, 2$$

$$xeta = zeta + zx2e \cdot (zphi + vsb) + zx3e \cdot (vds - VDDM), \quad UPDATE=1$$

Saturation Voltage (vdsat)

The saturation voltage in the BSIM model is calculated as follows:

$$vdsat = \frac{vgs - vth}{body \cdot arg^{1/2}}$$

Subthreshold Current ids

The subthreshold current isub is calculated when zn0 is less than 200 as follows:

$$isub = \frac{Ilim \cdot Iexp}{Ilim + Iexp}$$

where

$$Iexp = \beta_o \cdot vt^2 \cdot e^{1.8} \cdot e^{\frac{vgs - vth}{xn \cdot vt}} \cdot \left(1 - e^{-\frac{vds}{vt}}\right)$$

$$Ilim = 4.5 \cdot \beta_o \cdot vt^2$$

$$\beta_o = uo \cdot COX \cdot \frac{Weff}{Leff}$$

and

$$xn = zn0 - znb \cdot vsb + znd \cdot vds$$

Note: The current isub also is added to the ids current in the strong inversion.

Resistors and Capacitors Generated with Interconnects

See the HSPICE wire model table (resistor element) for the model parameters used.

Resistances:

$$r = RSH \cdot \frac{Leff}{Weff}$$

Capacitances:

$$c = COX \cdot Leff \cdot Weff + 2 \cdot CAPSW \cdot (Leff + Weff)$$

Temperature Effect

$$MUZ(t) = MUZ \cdot \left(\frac{t}{tnom} \right)^{BEX} \quad UPDATE=0, 1$$

$$zmus(t) = zmus \cdot \left(\frac{t}{tnom} \right)^{BEX} \quad UPDATE=0, 1$$

$$uo(t) = uo \left(\frac{t}{tnom} \right)^{BEX} \quad UPDATE=2$$

$$xu1(t) = xu1 \cdot \left(\frac{t}{tnom} \right)^{FEX}$$

$$zvfb(t) = zvfb - \Delta t \cdot TCV$$

where

$$\Delta t = t - tnom$$

Charge-Based Capacitance Model

The HSPICE Level 13 capacitance model conserves charge and has nonreciprocal attributes. Using charge as the state variable guarantees charge conservation. You can get total stored charge in each of the gate, bulk, and channel regions by integrating the distributed charge densities/area of the active region.

The channel charge is partitioned into drain and source components in two physically significant methods by using the model parameter XPART: 40/60, or 0/100 in the saturation region, which smoothly changes to 50/50 in the triode region. XPART=0 selects 40/60 drain/source charge-partitioning in the saturation region, while XPART=1 and XPART=0.5 select 0/100 and 50/50 for drain/source charge-partitioning in the saturation region, respectively.

Define:

$$v_{tho} = z_{vfb} + z_{phi} + z_{k1} \cdot (z_{phi} + v_{sb})^{1/2}$$

$$cap = COX \cdot Leff \cdot Weff$$

$$v_{pof} = \frac{v_{gs} - v_{tho}}{body}$$

$$argx = \frac{body \cdot v_{ds}}{12 \cdot (v_{gs} - v_{tho} - 0.5 \cdot body \cdot v_{ds})}$$

If $(v_{gs} - v_{tho} - 0.5 \cdot body \cdot v_{ds}) \leq 1e-8$ then,

$$argx = \frac{1}{6}$$

$$argy = \frac{(v_{gs} - v_{tho})^2 - 0.75 \cdot body \cdot (v_{gs} - v_{tho}) \cdot v_{ds} + 0.15 \cdot body^2 \cdot v_{ds}^2}{6 \cdot (v_{gs} - v_{tho} - 0.5 \cdot body \cdot v_{ds})^3}$$

If $(v_{gs} - v_{tho} - 0.5 \cdot body \cdot v_{ds}) \leq 1e-8$ then,

$$argy = \frac{4}{15}$$

Regions Charge Expressions

Accumulation Region, $v_{gs} \leq v_{tho}$, $v_{gs} \leq z_{vfb} - v_{sb}$

$$Qg = cap \cdot (v_{gs} - z_{vfb} + v_{sb})$$

$$Qb = -qg$$

$$Qs = 0$$

$$Qd = 0$$

Subthreshold Region, $v_{gs} \leq v_{tho}$, $v_{gs} > z_{vfb} - v_{sb}$

$$= \frac{cap \cdot zk1}{2} \cdot \left\{ [(zk1)^2 + 4(v_{gs} - z_{vfb} + v_{sb})]^{1/2} - zk1 \right.$$

$$Qb = -qg$$

$$Qs = 0$$

50/50 Channel-Charge Partitioning for Drain and Source, XPART=.5

Triode Region, $v_{gs} > v_{tho}$, $v_{ds} \leq v_{pof}$

$$Qg = cap \cdot (v_{gs} - z_{vfb} - z_{phi} - 0.5 \cdot v_{ds} + v_{ds} \cdot argx)$$

$$Qb = cap \cdot [-v_{tho} + z_{vfb} + z_{phi} + (1 - body) \cdot (0.5 - argx) \cdot v_{ds}]$$

$$Qd = -0.5 \cdot (qg + qb)$$

$$Qs = Qd$$

Saturation Region, $v_{gs} > v_{th0}$, $v_{ds} > v_{pof}$

$$Q_g = cap \cdot \left(v_{gs} - z_{vfb} - z_{phi} - \frac{v_{gs} - v_{th0}}{3 \cdot body} \right)$$

$$Q_b = cap \cdot \left[z_{vfb} + z_{phi} - v_{th0} + (1 - body) \cdot \frac{(v_{gs} - v_{th0})}{3 \cdot body} \right]$$

$$Q_d = -\frac{cap}{3} \cdot (v_{gs} - v_{th0})$$

$$Q_s = Q_d$$

40/60 Channel-Charge Partitioning for Drain and Source, XPART=0**Triode Region, $v_{gs} > v_{th0}$, $v_{ds} \leq v_{pof}$**

$$Q_g = cap \cdot (v_{gs} - x_{vfb} - z_{phi} - 0.5 \cdot v_{ds} + argx \cdot v_{ds})$$

$$Q_b = cap \cdot [-v_{th0} + z_{vfb} + z_{phi} + (1 - body) \cdot (0.5 - argx) \cdot v_{ds}]$$

$$Q_d = -(cap \cdot [0.5 \cdot (v_{gs} - v_{th0} - body \cdot v_{ds}) + body \cdot argy \cdot v_{ds}])$$

$$Q_s = -(Q_g + Q_b + Q_d)$$

Saturation Region, $v_{gs} > v_{th0}$, $v_{ds} > v_{pof}$

$$Q_g = cap \cdot \left(v_{gs} - z_{vfb} - z_{phi} - \frac{v_{gs} - v_{th0}}{3 \cdot body} \right)$$

$$Q_b = cap \cdot \left[z_{vfb} + z_{phi} - v_{th0} + (1 - body) \cdot \frac{(v_{gs} - v_{th0})}{3 \cdot body} \right]$$

$$Q_d = -\frac{4 \cdot cap}{15} \cdot (v_{gs} - v_{th0})$$

$$Q_s = \frac{3}{2} \cdot Q_d$$

0/100 Channel-Charge Partitioning for Drain and Source, XPART=1

Triode Region, $v_{gs} > v_{tho}$, $v_{ds} \leq v_{pof}$

$$Q_g = cap \cdot (v_{gs} - z_{vfb} - z_{phi} - 0.5 \cdot v_{ds} + v_{ds} \cdot argx)$$

$$Q_b = cap \cdot [-v_{tho} + z_{vfb} + z_{phi} + (1 - body) \cdot (0.5 - argx) \cdot v_{ds}]$$

$$Q_d = -(cap \cdot [0.5 \cdot (v_{gs} - v_{tho}) - body \cdot v_{ds} \cdot (0.75 - 1.5 \cdot argx)])$$

$$Q_s = -(Q_g + Q_b + Q_d)$$

Saturation Region, $v_{gs} > v_{tho}$, $v_{ds} > v_{pof}$

$$Q_g = cap \cdot \left(v_{gs} - z_{vfb} - z_{phi} - \frac{v_{gs} - v_{tho}}{3 \cdot body} \right)$$

$$Q_b = cap \cdot \left[z_{vfb} + z_{phi} - v_{tho} + (1 - body) \cdot \frac{(v_{gs} - v_{tho})}{3 \cdot body} \right]$$

$$Q_d = 0$$

$$Q_s = -Q_g - Q_b$$

Prevention of Negative Output Conductance

HSPICE internally protects against conditions in the Level 13 model that would cause convergence problems due to negative output conductance. The constraints imposed are:

$$ND \geq 0$$

$$MUS \geq MUZ + X3MS + VDD(M/2)$$

These constraints are imposed after length and width adjustment and *VBS* dependence. This feature is gained at the expense of some accuracy in the saturation region, particularly at high *Vgs*. Consequently, BSIM1 models might need to be requalified in the following situations:

1. Devices exhibit self-heating during characterization, which causes declining I_{ds} at high V_{ds} . This would not occur if the device characterization measurement sweeps V_{ds} .
2. The extraction technique produces parameters that result in negative conductance.
3. Voltage simulation is attempted outside the characterized range of the device.

Example Calculations Using Level 13 Equations

To verify the equations, it is helpful to do very simple tests using HSPICE and check the results with a hand calculator. Check threshold, *vdsat*, and *ids* for a very simple model, with many parameters set to zero. There is no series resistance, *RSH*=0. Diode current has been turned off, *JS*=*JSW*=*IS*=0. The Level 13 subthreshold current has been turned off by *n0*=200. The geometry parameters are set to zero, so *Leff*=*L*=1u, *Weff*=*W*=1u.

A value of *TOX* has been chosen to give

$$cox = \frac{2.00000e - 3F}{m^2}$$

The test is at *vbs*=-0.35, so that *phi-vbs*=1.0:

```

$ t1
.option ingold=2 numdgt=6
vd d 0 5
vg g 0 5
vb b 0 -0.35
m1 d g 0 b nch w=10u L=1u
.dc vd 4 5 1
.print ids=lx4(m1) vth=lv9(m1) vdsat=lv10(m1)
.model nch nmos level=13
+ vfb0=-0.4 lvfb=0 wvfb=0
+ phi0=0.65 lphi=0 wphi=0
+ k1=0.5 lk1=0 wk1=0
+ k2=0 lk2=0 wk2=0
+ eta0=1e-3 leta=0 weta=0
+ muz=600 mus=700 x3ms=10
+ xl=0 ld=0 xw=0 wd=0
+ u00=0 lu0=0 wu0=0
+ u1=0 lu1=0 wu1=0
+ tox=172.657
+ acm=2 rsh=0 js=0 jsw=0 is=0 n0=200
.end

```

Results from HSPICE

```

ids          vth          vdsat
1.09907e-02  7.45000e-01  3.69000e+00

```

Calculations at vgs=vds=5, vbs=-0.35

$$\phi - v_{bs} = 1$$

$$v_{th} = -0.4 + 0.65 + (0.5 \cdot 1) - (ETA \cdot v_{ds}) = 0.75 - (0.001 \cdot v_{ds}) = 0.745$$

$$g = 1 - \frac{1}{(1.744 + 0.8364 \cdot 1)} = 0.612463$$

$$body = 1 + \frac{g \cdot 0.5}{(2 \cdot 1)} = 1 + 0.25 \cdot g = 1.153116$$

$$vc = 0 \quad arg = 1$$

$$vdsat = \frac{(vgs - vth)}{body \cdot \sqrt{arg}} = \frac{(5 - 0.745)}{body} = 3.69000$$

At vds=VDDM (default VDDM=5), mobility=mus=700

$$ids = cox \cdot \left(\frac{W_{eff}}{L_{eff}} \right) \cdot 700 \cdot \frac{(vgs - vth)^2}{(2 \cdot body \cdot arg)}$$

$$ids = \left(\frac{10 \cdot 700 \cdot 4.255^2}{2 \cdot 1.15311 \cdot 1} \right) \cdot cox = 54953.36 \cdot cox$$

$$ids = 1.09907e - 2$$

These calculations agree with the HSPICE results given above.

Compatibility Notes

Model Parameter Naming

The following names are HSPICE-specific: U00, DL0, DW0, PHI0, ETA0, NB0, ND0. A zero was added to the SPICE names to avoid conflicts with other standard HSPICE names. For example, U0 cannot be used because it is an alias for UB, the mobility parameter in many other levels. DL cannot be used because it is an alias for XL, a geometry parameter available in all levels.

HSPICE supports the use of DL0 and DW0, but the use of XL, LD, XW, WD is recommended instead (noting the difference in units).

Watch the units of TOX. It is safest to enter a number greater than one, which is always interpreted as Angstroms.

To avoid negative gds:

1. Set X3U1, LX3U1 and WX3U1 to zero.
2. Check that
 $zx3ms \geq 0$, where $zx3ms = X3MS$, with L, W adjustment
3. Check that
 $zmuz + VDDM \cdot zx3ms < zmus$

SPICE/HSPICE Parameter Differences

A cross-reference table for UCB's BSIM1 and Meta-Software's Level 13 model parameters is provided for comparison. Units are given in brackets. The HSPICE parameter name is given only if it differs from the SPICE name. The model specifies units for HSPICE parameters only if they differ from SPICE's. HSPICE aliases are in parentheses. Note that some HSPICE aliases match the SPICE names.

An asterisk (*) in front of a UCB SPICE name denotes an incompatibility between the HSPICE name and the UCB SPICE name (that is, the HSPICE alias does not match, or units are different).

Even when there is a difference in parameter name between HSPICE and SPICE, the corresponding L and W sensitivity parameter names might not differ. L and W sensitivity parameters are only listed for the few cases for which there is a difference.

Table 16-1: – Comparison of HSPICE Parameters with UCB SPICE 2 and 3

UC Berkeley SPICE 2, 3	Meta-Software HSPICE
VFB [V]	VFB0 (VFB)
PHI [V]	PHI0
K1 [V ^{1/2}]	same
K2	same

Table 16-1: – Comparison of HSPICE Parameters with UCB SPICE 2 and 3

UC Berkeley SPICE 2, 3	Meta-Software HSPICE
* ETA	ETA0
MUZ [$\text{cm}^2/\text{V}\cdot\text{s}$]	same
* DL [μm]	DL0
* DW [μm]	DW0
* U0 [$1/\text{V}$]	U00
* U1 [μ/V]	same
X2MZ [$\text{cm}^2/\text{V}^2\cdot\text{s}$]	X2M (X2MZ)
LX2MZ [$\mu\text{m}\cdot\text{cm}^2/\text{V}^2\cdot\text{s}$]	X2M (LX2MZ)
WX2MZ [$\mu\text{m}\cdot\text{cm}^2/\text{V}^2\cdot\text{s}$]	WX2M (WX2MZ)
X2E [$1/\text{V}$]	same
X3E [$1/\text{V}$]	same
X2U0 [$1/\text{V}^2$]	same
X2U1 [$\mu\text{m}/\text{V}^2$]	same
MUS [$\text{cm}^2/\text{V}\cdot\text{s}$]	same
LMUS [$\mu\text{m}\cdot\text{cm}^2/\text{V}\cdot\text{s}$]	LMS (LMUS)
WMUS [$\mu\text{m}\cdot\text{cm}^2/\text{V}\cdot\text{s}$]	WMS (WMUS)
X2MS [$\text{cm}^2/\text{V}^2\cdot\text{s}$]	same
X3MS [$\text{cm}^2/\text{V}^2\cdot\text{s}$]	same
X3U1 [$\mu\text{m}/\text{V}^2$]	same
* TOX [μm]	TOXM[μ] (TOX[m])
* TEMP [$^{\circ}\text{C}$]	TREF
* VDD [V]	VDDM
CGDO [F/m]	CGDOM (CGDO)

Table 16-1: – Comparison of HSPICE Parameters with UCB SPICE 2 and 3

UC Berkeley SPICE 2, 3	Meta-Software HSPICE
CGSO [F/m]	CGSOM (CGSO)
CGBO [F/m]	CGBOM (CGBO)
XPART	same
N0	same
* NB	NB0
* ND	ND0
RSH [ohm/sq]	RSHM (RSH)
JS [A/m ²]	IJS (JS)
PB [V]	PJ (PB)
MJ	MJ0 (MJ)
* PBSW [V]	PJW (PHP)
MJSW	MJW (MJSW)
CJ [F/m ²]	CJM (CJ)
CJSW [F/m]	CCJW (CJSW)
* WDF [m]	–
* DELL [m]	–

In UCB SPICE, you must specify all BSIM model parameters. In HSPICE, there are defaults for the parameters.

Parasitics

ACM > 0 invokes HSPICE parasitic diodes. ACM=0 (default) is SPICE style.

Temperature Compensation

The model reference temperature TNOM's default is 25°C in HSPICE unless “.OPTION SPICE” is set, causing TNOM to default to 27°C. This option also sets some other SPICE compatibility parameters. HSPICE TNOM is set in an .OPTION line in the netlist and can always be overridden locally (that is, for a model) with model parameter TREF. (The model “reference temperature” means that the model parameters were extracted at and are valid at that temperature.)

In UCB SPICE, TNOM (default 27°C) is not effective for BSIM, and the model parameter TEMP is used instead (and must be specified) as both the model reference temperature and analysis temperature. The analysis at TEMP only applies to thermally activated exponentials in the model equations. There is no adjustment of model parameter values with TEMP. It is assumed that the model parameters were extracted at TEMP, TEMP being both the reference and the analysis temperature.

In contrast to UCB SPICE's BSIM, HSPICE Level 13 does provide for temperature analysis. The default analysis temperature is 25°C in HSPICE (and 27°C in UCB SPICE for all model levels except for BSIM, as explained in the previous paragraph). Use a .TEMP statement in the HSPICE netlist to change the HSPICE analysis temperature.

HSPICE provides two temperature coefficients for the Level 13 model, TCV and BEX. Threshold voltage is adjusted by

$$v_{th}(t) = v_{th} - TCV \cdot (t - t_{nom})$$

There are two implementations of the BEX factor, selected by the UPDATE parameter, which is described in the next section. The mobility in BSIM is a combination of five quantities: MUZ, zmus, z3ms, zx2mz, and zx2ms.

BEX Usage

$$MUZ(t) = MUZ \cdot \left(\frac{t}{t_{nom}} \right)^{BEX}$$

$$z_{mus}(t) = z_{mus} \cdot \left(\frac{t}{t_{nom}}\right)^{BEX}$$

$$z_{x3ms}(t) = z_{x3ms} \cdot \left(\frac{t}{t_{nom}}\right)^{BEX}$$

$$z_{x2mz}(t) = z_{x2mz} \cdot \left(\frac{t}{t_{nom}}\right)^{BEX}$$

$$z_{x2ms}(t) = z_{x2ms} \cdot \left(\frac{t}{t_{nom}}\right)^{BEX}$$

Note: This is equivalent to multiplying the final mobility by the $\left(\frac{t}{t_{nom}}\right)^{BEX}$ factor.

UPDATE Parameter

The UPDATE parameter selects between variations of the BSIM equations. UPDATE=0 is the default, which is consistent with UCB SPICE3. UPDATE=3 also is consistent with UCB SPICE3 and BEX usage.

Here is the sequence of UPDATE choices, which were responses to specific customer requests.

UPDATE=0	UCB compatible, previous BEX usage
UPDATE=1	Special X2E equation, previous BEX usage
UPDATE=2	Remove 1/Leff in U1 equation, present BEX usage
UPDATE=3	UCB compatible, present BEX usage

Explanations

The normal X2E equation is

$$xeta = zeta - (zx2e \cdot vsb) + zx3e \cdot (vds - VDDM)$$

The special X2E equation, for UPDATE=1 only, is

$$\eta = z_{e0} + z_{x2e} \cdot (z_{phi} + v_{sb}) + z_{x3e} \cdot (v_{ds} - V_{DDM})$$

The special X2E equation was requested to match a parameter extraction program. Whenever you use a parameter extraction program, the equations should be checked carefully.

The original U1 equation divides by L_{eff} in microns,

$$x_{u1} = \frac{(z_{u1} - (z_{x2u1} \cdot v_{sb}) + z_{x3u1} \cdot (v_{ds} - V_{DDM}))}{L_{eff}}$$

This is one of the few places where L_{eff} enters explicitly into the BSIM equations; usually the L_{eff} variation is handled by the L-adjustment model parameters, such as LU1. Physically x_{u1} should decrease as $1/L_{eff}$ at long channels, but when dealing with short-channel devices, you can turn off this variation. Set UPDATE=2 to remove the $1/L_{eff}$ factor in the x_{u1} equation.

UPDATE=2 introduces the present BEX usage as the $1/L_{eff}$ removal ability. UPDATE=3 provides the present BEX usage with the previous x_{u1} equation.

Example of IDS and VGS Curves for PMOS and NMOS

FILE:ML13IV.SP IDS AND VGS CURVES FOR PMOS AND NMOS

Two Different Types Of Model Parameter Formats Used

```
.OPTIONS ACCT LIST NOPAGE
.OP
.DC VDDN 0 5.0 .1 VBBN 0 -3 -3

*N-CHANNEL IDS CURVES (VD=0 to 5, VG=1,2,3,4,5,
VB=0,-3)
.PRINT DC I(VN1) I(VN2) I(VN3) I(VN4) I(VN5) V(90)
.PLOT DC I(VN1) I(VN2) I(VN3) I(VN4) I(VN5)

*P-CHANNEL IDS CURVES (VD=0 to -5, VG=-1,-2,-3,-4,-
5, VB=0,3)
.PRINT DC I(VP1) I(VP2) I(VP3) I(VP4) I(VP5) V(90)
```

```
.PLOT DC I(VP1) I(VP2) I(VP3) I(VP4) I(VP5)
```

VGS Curves

```
.PRINT DC I(VN6) I(VP6)
```

```
.PLOT DC I(VN6) I(VP6)
```

```
* N-CHANNEL LX7=GM (VD=5,      VG=0 to ->5, VS=0,
VB=0,-3)
```

```
* N-CHANNEL LX8=GD (VD=0 to 5,VG=5,      VS=0,
VB=0,-3)
```

```
* N-CHANNEL LX9=GB (VD=5,      VG=5,      VS=0,VB=0
to -5)
```

```
.PLOT DC LX7(M21) LX8(M5) LX9(M31)
```

```
* P-CHANNEL LX7=GM (VD=0,      VG=0->-5,  VS=-5
VB=0,3)
```

```
* P-CHANNEL LX8=GD (VD=0 to -5,VG=-5,    VS=-5,
VB=0,3)
```

```
* P-CHANNEL LX9=GB (VD=0,      VG=0,      VS=-5,
VB=0- >5)
```

```
.PLOT DC LX7(M22) LX8(M15) LX9(M32)
```

```
*
```

```
VDDN 99 0 5.0
```

```
VBBN 90 0 0
```

```
EPD 98 0 99 0 -1
```

```
EPB 91 0 90 0 -1
```

```
V1 1 0 1
```

```
V2 2 0 2
```

```
V3 3 0 3
```

```
V4 4 0 4
```

```
V5 5 0 5
```

```
V11 11 0 -1
```

```
V12 12 0 -2
```

```
V13 13 0 -3
```

V14 14 0 -4

V15 15 0 -5

*

VN1 99 31 0

VN2 99 32 0

VN3 99 33 0

VN4 99 34 0

VN5 99 35 0

M1 31 1 0 90 PC_NM1 8U 8U

M2 32 2 0 90 PC_NM1 8U 8U

M3 33 3 0 90 PC_NM1 8U 8U

M4 34 4 0 90 PC_NM1 8U 8U

M5 35 5 0 90 PC_NM1 8U 8U

*

VP1 98 41 0

VP2 98 42 0

VP3 98 43 0

VP4 98 44 0

VP5 98 45 0

M11 41 11 0 91 PC_PM1 8U 8U

M12 42 12 0 91 PC_PM1 8U 8U

M13 43 13 0 91 PC_PM1 8U 8U

M14 44 14 0 91 PC_PM1 8U 8U

M15 45 15 0 91 PC_PM1 8U 8U

GM Test

VN6 5 36 0

VP6 0 46 0

M21 36 99 0 90 PC_NM1 8U 8U

M22 46 98 15 91 PC_PM1 8U 8U

GM B CVN7 5 37 0

```

VP7  0 47 0
M31  37  5  0 98 PC_NM1  8U 8U
M32  47  0 15 99 PC_PM1  8U 8U

```

.PROCESS PC Filename=M57R

```

* Preliminary MOSIS BSIM parameters for SPICE3:
* The following parameters were extracted from a
MOSIS
* experimental 1.2 um fabrication run.

```

For N-channel Devices

```

* NM1 PM1 PY1 ML1 ML2 DU1 DU2
*PROCESS=PC1
*RUN=m57r
*WAFER=11
*OPERATOR=david & ming
*DATE=6/12/87

```

First Model Parameter Format

```

*nmos model
.MODEL  PC_NM1 NMOS LEVEL=13 VFB0=
+-8.27348E-01, 1.42207E-01, 3.48523E-02
+ 7.87811E-01, 0.00000E+00, 0.00000E+00
+ 9.01356E-01,-1.96192E-01, 1.89222E-02
+ 4.83095E-02,-4.10812E-02,-2.21153E-02
+ 2.11768E-03, 3.04656E-04,-1.14155E-03
+ 4.93528E+02, 5.39503E-02, 4.54432E-01
+ 5.81155E-02, 4.95498E-02,-1.96838E-02
+-5.88405E-02, 6.06713E-01, 4.88790E-03
+ 9.22649E+00,-8.66150E+00, 9.55036E+00
+-7.95688E-04, 2.67366E-03, 3.88974E-03
+ 2.14262E-03,-7.19261E-04,-3.56119E-03
+ 2.05529E-03,-3.66841E-03, 1.86866E-03

```

```

+-1.64733E-02,-3.63561E-03, 3.59209E-02
+ 4.84793E+02, 3.14763E+02,-3.91874E+01
+-4.21265E+00,-7.97847E+00, 3.50692E+01
+-5.83990E+00, 6.64867E+01,-1.99620E+00
+-1.44106E-02, 8.14508E-02, 7.56591E-04
+ 2.30000E-02, 2.30000E+01, 5.00000E+00
+ 5.04000E-10, 5.04000E-10, 1.91000E-09
+ 1.00000E+00, 0.00000E+00, 0.00000E+00
+ 2.00000E+02, 0.00000E+00, 0.00000E+00
+ 0.00000E+00, 0.00000E+00, 0.00000E+00
+ 0.00000E+00, 0.00000E+00, 0.00000E+00
*n+ diffusion layer
+80.0,7.000E-004,4.20E-010,1.00E-008,0.700E000
+0.8000e000,0.5,0.33,0,0

```

PMOS Model

```

.MODEL PC_PM1 PMOS LEVEL=13 VFB0=
+-5.63441E-01,-1.06809E-01, 1.32967E-01
+ 7.46390E-01, 0.00000E+00, 0.00000E+00
+ 6.57533E-01, 1.94464E-01,-1.60925E-01
+-2.55036E-03, 1.14752E-01,-8.78447E-02
+-5.59772E-03, 2.50199E-02,-5.66587E-04
+ 1.73854E+02, 2.72457E-01, 6.57818E-01
+ 1.26943E-01, 4.25293E-02,-4.31672E-02
+-1.00718E-02, 1.50900E-01,-1.00228E-02
+ 1.03128E+01,-3.94500E+00, 1.87986E+00
+ 1.55874E-03, 4.80364E-03,-1.45355E-03
+ 4.20214E-04,-2.05447E-03,-7.44369E-04
+ 1.00044E-02,-4.43607E-03, 1.05796E-03
+-5.64102E-04, 1.97407E-03, 6.65336E-04
+ 1.77550E+02, 1.02937E+02,-2.94207E+01
+ 8.73183E+00, 1.51499E+00, 9.06178E-01
+ 1.11851E+00, 9.75265E+00,-1.88238E+00

```

```

+-4.70098E-05, 9.43069E-04, -9.19946E-05
+ 2.30000E-02, 2.30000E+01, 5.00000E+00
+ 1.00000E-09, 1.00000E-09, 1.91000E-09
+ 1.00000E+00, 0.00000E+00, 0.00000E+00
+ 2.00000E+02, 0.00000E+00, 0.00000E+00
+ 0.00000E+00, 0.00000E+00, 0.00000E+00
+ 0.00000E+00, 0.00000E+00, 0.00000E+00
*p+ diffusion layer
+140.0,4.0E-004,2.4E-010,1.00E-008,0.700E000
+0.8000e000,0.5,0.33,0,0

```

Wire Model for Poly and Metal Layers

*NOT REFERENCED BY ANY ELEMENTS IN THIS CIRCUIT,
*JUST FOR MODEL EXAMPLES.

*

```
.MODEL PC_PY1 R
```

```
*poly layer
```

```
+65.0
```

```
.MODEL PC_ML1 R
```

```
*metal layer 1
```

```
+0.200
```

```
$$$$$$$
```

```
.ALTER
```

```
$$$$$$$
```

Second Model Parameter Format

```
*nmos model
```

```
.MODEL PC_NM1 NMOS LEVEL=13
```

```
+VFB0=-8.27348E-01 LVFB=1.42207E-01 WVFB=3.48523E-02
```

```
+PHI0=7.87811E-01 LPHI=0.00000E+00
```

```
WPHI=0.00000E+00
```

```
+K1=9.01356E-01 LK1=-1.96192E-01 WK1=1.89222E-02
```

```
+K2=4.83095E-02 LK2=-4.10812E-02 WK2=-2.21153E-
```



```

02
+ETA0=2.11768E-03  LETA=3.04656E-04  WETA=-1.14155E-
03
+MUZ=4.93528E+02  DL0=5.39503E-02  DW0=4.54432E-01
+U00=5.81155E-02  LU0=4.95498E-02  WU0=-1.96838E-
02
+U1=-5.88405E-02  LU1=6.06713E-01  WU1=4.88790E-03
+X2M=9.22649E+00  LX2M=-8.66150E+00
WX2M=9.55036E+00
+X2E=-7.95688E-04  LX2E=2.67366E-03  WX2E=3.88974E-
03
+X3E=2.14262E-03  LX3E=-7.19261E-04  WX3E=-3.56119E-
03
+X2U0=2.05529E-03  LX2U0=-3.66841E-03  WX2U0=1.86866E-
03
+X2U1=-1.64733E-02  LX2U1=-3.63561E-03  WX2U1=3.59209E-
02
+MUS=4.84793E+02  LMS=3.14763E+02  WMS=-
3.91874E+01
+X2MS=-4.21265E+00  LX2MS=-7.97847E+00
WX2MS=3.50692E+01
+X3MS=-5.83990E+00  LX3MS=6.64867E+01  WX3MS=-
1.99620E+00
+X3U1=-1.44106E-02  LX3U1=8.14508E-02  WX3U1=7.56591E-
04
+TOXM=2.30000E-02  TEMPM=2.30000E+01
VDDM=5.00000E+00
+CGDOM=5.04000E-10  CGSOM=5.04000E-10  CGBOM=1.91000E-
09
+XPART=1.00000E+00  DUM1=0.00000E+00
DUM2=0.00000E+00
+N0=2.00000E+02  LN0=0.00000E+00  WNO=0.00000E+00
+NB0=0.00000E+00  LNB=0.00000E+00  WNB=0.00000E+00
+ND0=0.00000E+00  LND=0.00000E+00  WND=0.00000E+00

```

N+ Diffusion Layer

+RSHM=80.0	CJM=7.000E-004	CJW=4.20E-010
+IJS=1.00E-008	PJ=0.700E000	
+PJW=0.8000E000	MJ0=0.5	MJW=0.33
+WDF=0	DS=0	

PMOS Model

```
.MODEL PC_PM1 PMOS LEVEL=13
+VFB0=-5.63441E-01 LVFB=-1.06809E-01 WVFB=1.32967E-01
+PHI0=7.46390E-01 LPHI=0.00000E+00 WPHI=0.00000E+00
+K1=6.57533E-01 LK1=1.94464E-01 WK1=-1.60925E-01
+K2=-2.55036E-03 LK2=1.14752E-01 WK2=-8.78447E-02
+ETA0=-5.59772E-03 LETA=2.50199E-02 WETA=-5.66587E-04
+MUZ=1.73854E+02 DL0=2.72457E-01 DW0=6.57818E-01
+U00=1.26943E-01 LU0=4.25293E-02 WU0=-4.31672E-02
+U1=-1.00718E-02 LU1=1.50900E-01 WU1=-1.00228E-02
+X2M=1.03128E+01 LX2M=-3.94500E+00 WX2M=1.87986E+00
+X2E=1.55874E-03 LX2E=4.80364E-03 WX2E=-1.45355E-03
+X3E=4.20214E-04 LX3E=-2.05447E-03 WX3E=-7.44369E-04
+X2U0=1.00044E-02 LX2U0=-4.43607E-03 WX2U0=1.05796E-03
+X2U1=-5.64102E-04 LX2U1=1.97407E-03 WX2U1=6.65336E-04
+MUS=1.77550E+02 LMS=1.02937E+02 WMS=-2.94207E+01
+X2MS=8.73183E+00 LX2MS=1.51499E+00 WX2MS=9.06178E-01
+X3MS=1.11851E+00 LX3MS=9.75265E+00 WX3MS=-1.88238E+00
+X3U1=-4.70098E-05 LX3U1=9.43069E-04 WX3U1=-9.19946E-05
+TOXM=2.30000E-02 TEMPM=2.30000E+01 VDDM=5.00000E+00
+CGDOM=1.00000E-09 CGSOM=1.00000E-09 CGBOM=1.91000E-09
+XPART=1.00000E+00 DUM1=0.00000E+00 DUM2=0.00000E+00
+N0=2.00000E+02 LN0=0.00000E+00 WN0=0.00000E+00
+NB0=0.00000E+00 LNB=0.00000E+00 WNB=0.00000E+00
+ND0=0.00000E+00 LND=0.00000E+00 WND=0.00000E+00
*p+ diffusion layer
+RSHM=140.0 CJM=4.0E-004 CJW=2.4E-010
+IJS=1.00E-008 PJ=0.700E000
+PJW=0.8000E000 MJ0=0.5 MJW=0.33
+WDF=0 DS=0
```

Wire Model for Poly and Metal Layers

*NOT REFERENCED BY ANY ELEMENTS IN THIS CIRCUIT,
*JUST FOR MODEL EXAMPLES.

```
*  
.MODEL PC_PY1 R  
*poly layer  
+RSH=65.0  
.MODEL PC_ML1 R  
*metal layer 1  
+RSH=0.200  
*  
.END
```

Level 27 SOSFET Model

A three-terminal silicon-on-sapphire (SOS) FET transistor model is available in HSPICE⁴. This SOSFET model is based on a sapphire insulator that isolates the substrate and models the behavior of SOS devices more accurately than standard MOSFET models with physically-unreal parameter values. The SOSFET model also includes a charge conservation model (Ward and Dutton model based).

Because the defaults of the SOSFET model parameters are channel-length dependent, you must specify the model parameter SOSLEV to select either the 5 μm or 3 μm processing model.

Setting SOSLEV=1 selects the 5 μm model; otherwise the 3 μm model is automatically set, including the second order effects (default=3 μm).

Note: There is no bulk node specification for this model. If bulk nodes are specified, HSPICE ignores them.

This model does not use the model parameter ACM because the model includes no junction diodes. Also, the model parameter CAPOP only accepts a value of 7. Seven is its own charge conservation model, which cannot be used by the other level MOSFET models.

Temperature compensation equations for SOSFET model parameters VTO and UO are the same as those used for the MOSFET model.

Note: The model provides a special option for bulk nodes for silicon on sapphire. In the model definition, when you specify -1 for the bulk node, the model generates a special node for each element. This bulk node is named in the form, B#<element name>, where the element name is that of the defined element. Use this name in any statement, such as a .PRINT statement, to refer to the element's bulk node.

General form

```
.MODEL mname PMOS <LEVEL=27> <SOSLEV=val>
<pname1=val1>...
```

or

```
.MODEL mname NMOS <LEVEL=27> <SOSLEV=val>
<pname=val1>...
```

<i>mname</i>	the model name
<i>PMOS</i>	identifies a p-channel MOSFET model
<i>NMOS</i>	identifies an n-channel MOSFET model
<i>LEVEL</i>	model level selector
<i>SOSLEV</i>	selects the processing model. If you set SOSLEV=1, the default=5 μ m. The automatic default=3 μ m.
<i>pname</i>	parameter model

Level 27 Model Parameters**5 μ m Model Parameters**

Name(Alias)	Units	Default	Description
CGDO	F/m		gate-drain overlap capacitance per unit channel width. The default=3.1e-10 (n-type), 2.2e-10 (p-type).
CGSO	F/m		gate-source overlap capacitance per unit channel width. The default=3.1e-10 (n-type), 2.2e-10 (p-type).
LD	m		lateral diffusion. The default=0.6 μ (n-type), 0.3 μ (p-type).
RSH	ohm/ sq		drain and source diffusion sheet resistance. The default=25 (n-type), 100 (p-type).
SOSLEV		1	model index
TOX	m	7.0e-8	oxide thickness

Name(Alias)	Units	Default	Description
UO	cm ² / (V·s)		surface mobility. The default=350 (n-type), 220 (p-type).
VTO	V		threshold voltage. The default=1.25 (n-type), -1.25 (p-type).

3 μm Model Parameters

Name(Alias)	Units	Default	Description
A	m/V	0.1μm	channel length shortening coefficient (2nd effect)
ALPHA	V/m		threshold voltage length dependence. The default=0.15μ (n-type), 0.18μ (p-type).
CAPOP		7	capacitance model selector
CGDO	F/m		gate-drain overlap capacitance per unit channel width. The default=4.6e-10 (n-type), 3.6e-10 (p-type).
CGSO	F/m		gate-source overlap capacitance per unit channel width. The default=4.6e-10 (n-type), 3.6e-10 (p-type).
EC	V/m		critical electric field for velocity saturation (2nd effect). The default=3.0e6 (n-type), 7.5e6 (p-type).
FB			body effect coefficient (2nd effect). The default=0.15 (n-type), 0 (p-type).
LD	m		lateral diffusion. The default=0.3μ (n-type), 0.2μ (p-type).
LEVEL		27	model level selector
RSH	ohm/sq		drain and source diffusion sheet resistance. The default=25 (n-type), 80 (p-type).

Name(Alias)	Units	Default	Description
SOSLEV		2	model index
THETA	1/V		Mobility degradation coefficient (2nd effect). The default=0.055 (n-type), 0.075 (p-type).
TOX	m	3.4e-8	oxide thickness
UO	cm ² / (V·s)		surface mobility. The default=370 (n-type), 215 (p-type).
VTO	V		threshold voltage. The default=0.83 (n-type), -0.74 (p-type).

Example of NMOS and PMOS SOSFETs

*FILE ML27IV.SP: IDS AND VGS CURVES FOR NMOS AND PMOS SOSFETS.

.OPTIONS ACCT LIST NOPAGE NOMOD

.OP

.DC VDDN 0 5.0 .1

* N-CHANNEL IDS CURVES (VD=0->5, VG=1,2,3,4,5)

.PRINT DC I(VN1) I(VN2) I(VN3) I(VN4) I(VN5)

.PLOT DC I(VN1) I(VN2) I(VN3) I(VN4) I(VN5)

* P-CHANNEL IDS CURVES (VD=0->-5, VG=-1,-2,-3,-4,-5)

.PRINT DC I(VP1) I(VP2) I(VP3) I(VP4) I(VP5)

.PLOT DC I(VP1) I(VP2) I(VP3) I(VP4) I(VP5)

* V G S CURVES

.PRINT DC I(VN6) I(VP6)

.PLOT DC I(VN6) I(VP6)

* N-CHANNEL LX7=GM (VD=5, VG=0->5, VS=0)

* N-CHANNEL LX8=GD (VD=0->5, VG=5, VS=0)

```
* N-CHANNEL LX9=GB (VD=5,      VG=5,      VS=0)
.PLOT DC LX7 (M21) LX8(M5) LX9(M31)
```

```
* P-CHANNEL LX7=GM (VD=0,      VG=0->-5, VS=-5)
* P-CHANNEL LX8=GD (VD=0->-5,  VG=-5,    VS=-5)
* P-CHANNEL LX9=GB (VD=0,      VG=0,     VS=-5)
.PLOT DC LX7(M22) LX8(M15) LX9(M32)
```

```
*
```

```
VDDN 99 0 5.0
```

```
EPD 98 0 99 0 -1
```

```
V1 1 0 1
```

```
V2 2 0 2
```

```
V3 3 0 3
```

```
V4 4 0 4
```

```
V5 5 0 5
```

```
V11 11 0 -1
```

```
V12 12 0 -2
```

```
V13 13 0 -3
```

```
V14 14 0 -4
```

```
V15 15 0 -5
```

```
*
```

```
VN1 99 31 0
```

```
VN2 99 32 0
```

```
VN3 99 33 0
```

```
VN4 99 34 0
```

```
VN5 99 35 0
```

```
M1 31 1 0 N1 8U 8U
```

```
M2 32 2 0 N1 8U 8U
```

```
M3 33 3 0 N1 8U 8U
```

```
M4 34 4 0 N1 8U 8U
```

```
M5 35 5 0 N1 8U 8U
```



```

*
VP1 98 41 0
VP2 98 42 0
VP3 98 43 0
VP4 98 44 0
VP5 98 45 0

M11 41 11 0 P1 8U 8U
M12 42 12 0 P1 8U 8U
M13 43 13 0 P1 8U 8U
M14 44 14 0 P1 8U 8U
M15 45 15 0 P1 8U 8U
*
G M Test
VN6 5 36 0
VP6 0 46 0
M21 36 99 0 N1 8U 8U
M22 46 98 15 P1 8U 8U
*
G M B Test
VN7 5 37 0
VP7 0 47 0
M31 37 5 0 98 N1 8U 8U
M32 47 0 15 99 P1 8U 8U
*
.MODEL N1 NMOS LEVEL=27 SOSLEV=2
+VTO=0.814 TOX=0.34E-7 THETA=0.55E-1
+FB=0.15 EC=0.3E7 A=0.1E-6
+UO=370 CGSO=0.46E-9 CGDO=0.46E-9
+RSH=25 LD=0.3E-6
*
.MODEL P1 PMOS LEVEL=27 SOSLEV=2
+VTO=-0.7212 TOX=0.34E-7 THETA=0.75E-1

```

```
+FB=0.0 EC=0.75E7 A=0.1E-6  
+UO=215 CGSO=0.36E-9 CGDO=0.36E-9  
+RSH=80 LD=0.2E-6  
*  
.END
```

Non-Fully Depleted SOI Model

When using HSPICE for SOS/SOI applications, several approaches are currently available. HSPICE has a 3-terminal SOS model (LEVEL=27) that is stable for circuit design usage, but has some limitations. The model does not have provisions for depleted bulk. Use it only with non-fully depleted applications and where kink effects are not considered.

The following circuit example is a 4-terminal SOI model for incompletely depleted bulk with kink effect. The example uses a subcircuit to allow a parasitic capacitance to the substrate. In this example, the bulk is considered to be the region under the channel. The substrate is assumed to be the conductive layer under the insulator.

For SOI, the insulator is usually silicon dioxide and the substrate is silicon. For SOS, the insulator is sapphire and the substrate is the metal that contacts the back of the integrated circuit die.

Model Components

The model consists of the following subcomponents:

- Core IDS model: any level works since the impact ionization and weak inversion models are common to all DC levels. The example uses a LEVEL=3 DC MOS model.
- Subthreshold model: the model parameter WIC=3 allows the older models to use the more advanced models found in the BSIM (LEVEL=13, LEVEL=28) models. Model parameter N0 should have a typical value around 1.0.

- Impact ionization model: set the parameters ALPHA and VCR to enable the impact ionization model. Impact ionization is available to all MOS DC equations. Typical values are ALPHA=0.1 and VCR=18.
- Charge conservation gate cap model (CAPOP=9 XQC=.4) keeps the floating bulk node from obtaining extreme values.
- The automatic periphery diode area calculation method (ACM) is set to 3 to allow automatic calculation of the source and drain resistances and diode junction leakage and capacitance. (ACM=3 CJ=0 CJSW=0 CJGATE=4e-10 JS=0 JSW=1e-9 LD=.1u HDIF=1.5u RS=40 RD=40 N=1).

Note: It is assumed that the source/drain diffusions extend to the buried oxide; thus, the area part of the diode has no capacitance to bulk. Linear capacitors to the substrate, however, are included in the subcircuit.

Obtaining Model Parameters

Use the HSPICE optimizing capabilities to obtain the core IDS model parameters.

Use the optimizer to get the core model, subthreshold, and impact ionization parameters. The subthreshold model selected is an improved BSIM type of model that was altered for the older models. The impact ionization model is similar to the Intel model.

The charge conservation model is more charge conserving than the original Ward-Dutton model in SPICE 2G6.

The automatic diode area and resistance calculation estimates the junction capacitance, saturation current, and resistance as a function of the transistor width. The parameters VNDS and NDS allow for a piecewise linear approximation to the reverse junction current characteristics.

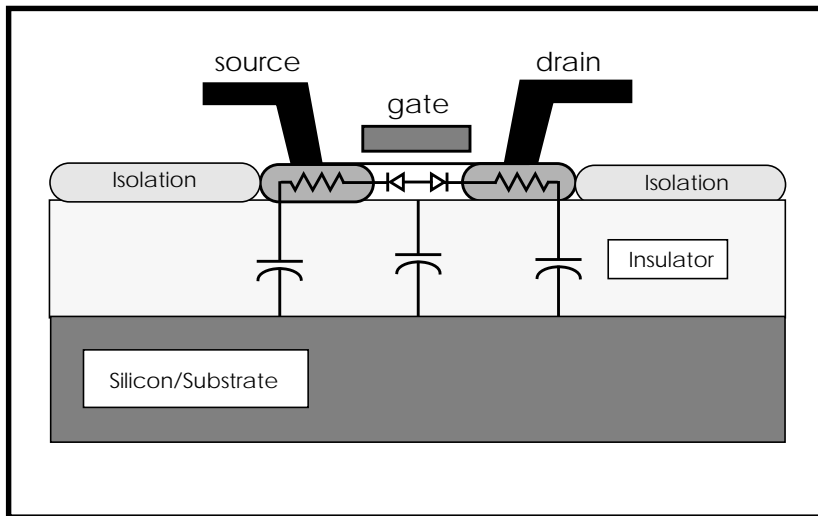


Figure 16-6: – Non-fully depleted SOI Model

Example for Non-Fully Depleted Case

```

ssoi.sp level=3 floating bulk model
** non-fully depleted
* test 1st order soi model with floating substrate
.option nomod post

* substrate capacitance 3.45e-11 is for SiO2
.param t_sub_ox=.5u    subcap='3.45e-11/t_sub_ox'
+ hdif=1.5u

.global substrate
.dc vd 0 5 0.1 sweep vg 1.5 3.5 0.5
.print id=i(xm1.m) vds=v(d) vgs=v(g)
.param vds=0 vgs=0 vbs=0
vd d gnd vds
vg g gnd vgs
vs s gnd 0
vsub substrate gnd vbs

```

```

xml  d g s  nch w=50u L=5u

.macro nch d g s  w=10u l=2u
* macro definition for fet+ parasitic cap to
substrate
* assumes existance of undepleted bulk
  m d g s  b nch w=w L=L
  cx d substrate  c='w*2*hdif*subcap'
  cx s substrate  c='w*2*hdif*subcap'
  cx b substrate  c='w*L*subcap'
.eom

.model  nch nmos  level=3
+ lmin=.5u lmax=100u wmin=.5u wmax=500u $model
selector
+ ld=0.1u  wd=.15u xl=0 xw=0      $diffusion+photobias
+ acm=3    hdif=hdif rsh=30 rs=10k rd=10k  $resistors
+ ldif=0.1u
$junction cap (ACM=3 (h9007 only) allows diode on
gate edge
+ cj=0 cjsw=0 cgate=0.4e-9 mjsw=0.33 php=0.6
+ js=0 jsw=1e-9  n=1 vnds=.5 nds=1      $junction
leakage
+   bex=-1.5 tcv=2m                      $temperature
+   tox=200 capop=9  xqc=.4  meto=0.08u  $gate cap
+   alpha=0.1      vcr=18                      $impact
ionization

+   vto=0.7  phi=1 gamma=1                $threshold
+   eta=10    xj=0.1u                      $threshold
+   wic=3 n0=0.9  nd=0                    $subthreshold
+   uo=400          theta=1m              $dc mobility
+   vmax=100k  kappa=0                    $dc saturation
.end

```

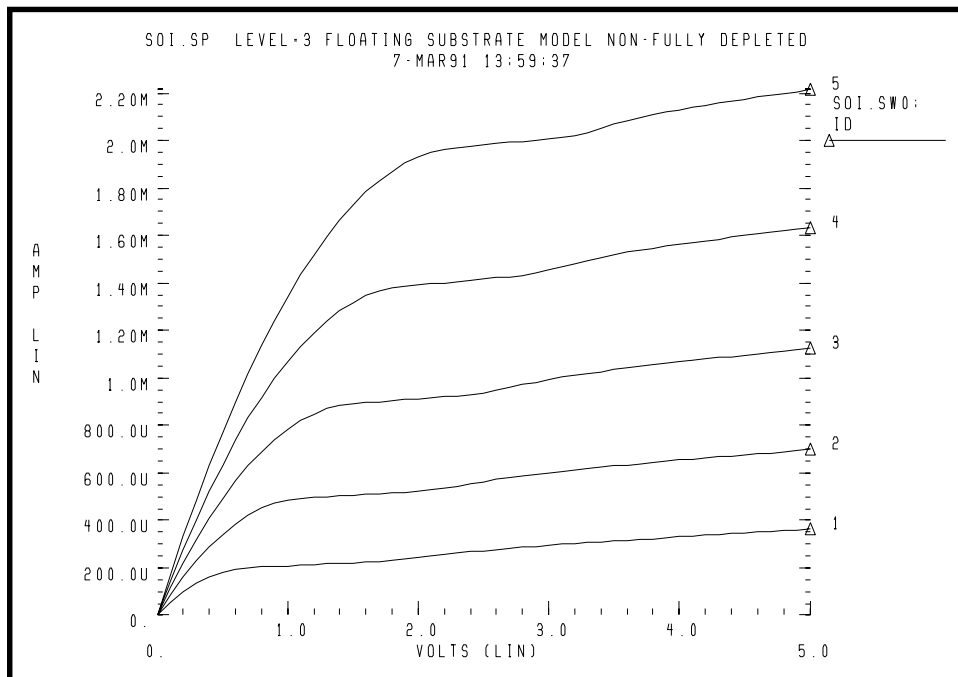


Figure 16-7: – Level 3 Floating Bulk Model

Fully Depleted SOI Model Considerations

Fully-depleted transistors require additional modeling equations. The first order effects are:

- Threshold sensitivity to the substrate
- No kink current
- Depletion capacitance hits a minimum determined by the silicon thickness

Lack of these effects is not a serious problem for an inverter circuit because the source-to-substrate voltage does not move. Digital circuits with good gate drive are not seriously affected because a large gate voltage renders the small V_{th} shift to a small change in I_{DS} current.

Analog amplifiers with transistors at back-bias and low gate voltages and similar circuits can be affected by the substrate threshold sensitivity.

Level 28 Modified BSIM Model

This section lists the Level 28 parameters and equations for the modified BSIM model.

Level 28 Features

The following are the significant features of the Level 28 model.

- vertical field dependence of carrier mobility
- carrier velocity saturation
- drain-induced barrier lowering
- depletion charge sharing by source and drain
- nonuniform doping profile for ion-implanted devices
- channel length modulation
- subthreshold conduction
- geometric dependence of electrical parameters

Level 28 Model Parameters

The Level 28 model parameters follow.

Transistor Process Parameters

Name (Alias)	Units	Default	Description
LEVEL		1	MOSFET model level selector. Set this parameter to 28 for this HSPICE model.
B1		0.0	lower vdsat transition point
LB1	μm	0.0	length sensitivity
WB1	μm	0.0	width sensitivity
B2		1	upper vdsat transition point

Name (Alias)	Units	Default	Description
LB2	μm	0.0	length sensitivity
WB2	μm	0.0	width sensitivity
CGBO	F/m	2.0e-10	gate-to-bulk parasitic capacitance (F/m of length)
CGDO	F/m	1.5e-9	gate-to-drain parasitic capacitance (F/m of width)
CGSO	F/m	1.5e-9	gate-to-source parasitic capacitance (F/m of width)
ETA0		0.0	linear vds threshold coefficient
LETA	μm	0.0	length sensitivity
WETA	μm	0.0	width sensitivity
ETAMN		0.0	minimum linear vds threshold coefficient
LETAMN	μm	0.0	length sensitivity
WETAMN	μm	0.0	width sensitivity
GAMMN	$V^{1/2}$	0.0	minimum root-vsbs threshold coefficient
LGAMN	$V^{1/2}\cdot\mu\text{m}$	0.0	length sensitivity
WGAMN	$V^{1/2}\cdot\mu\text{m}$	0.0	width sensitivity
K1	$V^{1/2}$	0.5	root-vsbs threshold coefficient
LK1	$V^{1/2}\cdot\mu\text{m}$	0.0	length sensitivity
WK1	$V^{1/2}\cdot\mu\text{m}$	0.0	width sensitivity
K2		0.0	linear vsb threshold coefficient
LK2	μm	0.0	length sensitivity
WK2	μm	0.0	width sensitivity
MUZ	$\text{cm}^2/V\cdot\text{s}$	600	low drain field first order mobility

Name (Alias)	Units	Default	Description
LMUZ	$\mu\text{m}\cdot\text{cm}^2/\text{V}\cdot\text{s}$	0.0	length sensitivity
WMUZ	$\mu\text{m}\cdot\text{cm}^2/\text{V}\cdot\text{s}$	0.0	width sensitivity
N0		200	low field weak inversion gate drive coefficient (value of 200 for N0 disables weak inversion calculation)
LNO	μm	0.0	length sensitivity
WNO	μm	0.0	width sensitivity
NB0		0.0	Vsb reduction to low field weak inversion gate drive coefficient
LNB	μm	0.0	length sensitivity
WNB	μm	0.0	width sensitivity
ND0		0.0	Vds reduction to low field weak inversion gate drive coefficient
LND	μm	0.0	length sensitivity
WND	μm	0.0	width sensitivity
PHI0	V	0.7	two times the Fermi potential
LPHI	$\text{V}\cdot\mu\text{m}$	0.0	length sensitivity
WPHI	$\text{V}\cdot\mu\text{m}$	0.0	width sensitivity
TOXM (TOX)	μm (m)	0.02	gate oxide thickness (if TOXM or TOX > 1, Angstroms is assumed)
U00	1/V	0.0	gate field mobility reduction factor
LU0	$\mu\text{m}/\text{V}$	0.0	length sensitivity
WU0	$\mu\text{m}/\text{V}$	0.0	width sensitivity
U1	1/V	0.0	drain field mobility reduction factor

Name (Alias)	Units	Default	Description
LU1	$\mu\text{m}/\text{V}$	0.0	length sensitivity
WU1	$\mu\text{m}/\text{V}$	0.0	width sensitivity
VDDM	V	5.0	critical voltage for high drain field mobility reduction
VFB0 (VFB)	V	-0.3	flatband voltage
LVFB	$\text{V}\cdot\mu\text{m}$	0.0	length sensitivity
WVFB	$\text{V}\cdot\mu\text{m}$	0.0	width sensitivity
WFAC		4	weak inversion factor
LWFAC	μm	0.0	length sensitivity
WWFAC	μm	0.0	width sensitivity
WFACU		0.0	second weak inversion factor
LWFACU	μm	0.0	length sensitivity
WWFACU	μm	0.0	width sensitivity
X2E	$1/\text{V}$	0.0	Vsb correction to linear vds threshold coefficient
LX2E	$\mu\text{m}/\text{V}$	0.0	length sensitivity
WX2E	$\mu\text{m}/\text{V}$	0.0	width sensitivity
X2M (X2MZ)	$\text{cm}^2/\text{V}^2\cdot\text{s}$	0.0	Vsb correction to low field first order mobility
LX2M (LX2MZ)	$\mu\text{m}\cdot\text{cm}^2/\text{V}^2\cdot\text{s}$	0.0	length sensitivity
WX2M (WX2MZ)	$\mu\text{m}\cdot\text{cm}^2/\text{V}^2\cdot\text{s}$	0.0	width sensitivity
X2U0	$1/\text{V}^2$	0.0	Vsb reduction to GATE field mobility reduction factor

Name (Alias)	Units	Default	Description
LX2U0	$\mu\text{m}/\text{V}^2$	0.0	length sensitivity
WX2U0	$\mu\text{m}/\text{V}^2$	0.0	width sensitivity
X2U1	$\mu\text{m}/\text{V}^2$	0.0	Vsb reduction to DRAIN field mobility reduction factor
LX2U1	$\mu\text{m}^2/\text{V}^2$	0.0	length sensitivity
WX2U1	$\mu\text{m}^2/\text{V}^2$	0.0	width sensitivity
X33M	$\text{cm}^2/\text{V}^2\cdot\text{s}$	0.0	gate field reduction of X3MS
LX33M	$\mu\text{m}\cdot\text{cm}^2/\text{V}^2\cdot\text{s}$	0.0	length sensitivity
WX33M	$\mu\text{m}\cdot\text{cm}^2/\text{V}^2\cdot\text{s}$	0.0	width sensitivity
X3E	$1/\text{V}$	0.0	Vds correction to linear vds threshold coefficient
LX3E	$\mu\text{m}/\text{V}$	0.0	length sensitivity
WX3E	$\mu\text{m}/\text{V}$	0.0	width sensitivity
X3MS	$\text{cm}^2/\text{V}^2\cdot\text{s}$	5.0	Vds correction for high drain field mobility
LX3MS	$\mu\text{m}\cdot\text{cm}^2/\text{V}^2\cdot\text{s}$	0.0	length sensitivity
WX3MS	$\mu\text{m}\cdot\text{cm}^2/\text{V}^2\cdot\text{s}$	0.0	width sensitivity
X3U1	$1/\text{V}^2$	0.0	Vds reduction to drain field mobility reduction factor
LX3U1	$\mu\text{m}/\text{V}^2$	0.0	length sensitivity
WX3U1	$\mu\text{m}/\text{V}^2$	0.0	width sensitivity
XPART		1.0	selector for gate capacitance charge sharing coefficient

Notes:

1. When reading parameter names, be aware of the difference in appearance between the capital letter O, and the number zero 0.
2. All Level 28 parameters should be specified using NMOS conventions, even for PMOS—for example, $ETA0 = 0.02$, not $ETA0 = -0.02$.
3. The WL-product sensitivity parameter is available for any parameter with an L and W sensitivity. Replace the leading “L” of the L sensitivity parameter name with a “P”.

Basic Model Parameters

Name (Alias)	Units	Default	Description
LD (DLAT, LATD)	m		lateral diffusion into channel from source and drain diffusion. If LD and XJ are unspecified, the LD default=0.0. When LD is unspecified but XJ is specified, LD is calculated from XJ. The LD default=0.75 XJ. $LD_{scaled} = LD \cdot SCALM$
LDAC	m		This parameter is the same as LD, but if LDAC is included in the .MODEL statement, it replaces LD in the L_{eff} calculation for AC gate capacitance.
LMLT		1.0	length shrink factor
LREF	m	0.0	reference channel length $LREF_{scaled} = LREF \cdot SCALM$

Name (Alias)	Units	Default	Description
XLREF	m	0.0	difference between physical (on wafer) and drawn reference channel length $XLREF_{scaled} = XLREF \cdot SCALM$
WD	m	0.0	lateral diffusion into channel from bulk along width $WD_{scaled} = WD \cdot SCALM$
WDAC	m		This parameter is the same as WD, but if WDAC is in the .MODEL statement, it replaces WD in the Weff calculation for AC gate capacitance.
WMLT		1.0	diffusion layer and width shrink factor
XL (DL, LDEL)	m	0.0	accounts for masking and etching effects $XL_{scaled} = XL \cdot SCALM$
XW (DW, WDEL)	m	0.0	accounts for masking and etching effects $XW_{scaled} = XW \cdot SCALM$
WREF	m	0.0	reference channel width $WREF_{scaled} = WREF \cdot SCALM$
XWREF	m	0.0	difference between physical (on wafer) and drawn reference channel width $XWREF_{scaled} = XWREF \cdot SCALM$

Temperature Parameters

Name (Alias)	Units	Default	Description
BEX		-1.5	temperature exponent for MUZ, X2M, X3MS, X33M mobility parameters
FEX		0.0	temperature exponent for mobility reduction factor U1
TCV	V°K	0.0	flat-band voltage temperature coefficient

Sensitivity Factors of Model Parameters

For transistors, the L (channel length), W (channel width), and WL-product sensitivity factors of a basic electrical parameter are denoted by adding the characters 'L', 'W', and 'P', respectively, at the start of the name, and often dropping any ending "0". For example, VFB0 sensitivity factors are LVFB, WVFB, and PVFB. If A0 is a basic parameter, LA, WA and PA are the corresponding sensitivity factors of this parameter (note that LA, WA and PA cannot be scaled using option SCALM in HSPICE). Then the model uses the following general formula to obtain the parameter value.

The left side of the equation represents the effective model parameter value after device size adjustment. All the effective model parameters are in lower case and start with the character 'z', followed by the parameter name.

$$\begin{aligned}
 za = A0 + LA \cdot \left[\frac{1}{Leff} - \frac{1}{LREFeff} \right] + WA \cdot \left[\frac{1}{Weff} - \frac{1}{WREFeff} \right] \\
 + PA \cdot \left[\frac{1}{Leff} - \frac{1}{LREFeff} \right] \cdot \left[\frac{1}{Weff} - \frac{1}{WREFeff} \right]
 \end{aligned}$$

LA and WA are specified in units of microns times the units of A0. PA is specified in units of square microns times the units of A0.

If you set LREF or WREF=0, you effectively set the parameter to infinity. This is the default.

Examples

$$VFB0 = -0.350v$$

$$LVFB = -0.1v\mu$$

$$WVFB = 0.08v \cdot \mu$$

$$Leff = 1 \cdot 10^{-6}m = 1\mu$$

$$Weff = 2 \cdot 10^{-6}m = 2\mu$$

$$LREff = 2 \cdot 10^{-6}m = 2\mu$$

$$WREff = 1 \cdot 10^{-5}m = 10\mu$$

$$z_{vfb} = VFB0 + LVFB \cdot \left(\frac{1}{Leff} - \frac{1}{LREff} \right) + WVFB \cdot \left(\frac{1}{Weff} - \frac{1}{WREff} \right)$$

$$z_{vfb} = -0.35v + -0.1v \cdot \mu \cdot \left(\frac{1}{1\mu} - \frac{1}{2\mu} \right) + 0.08v \cdot \mu \cdot \left(\frac{1}{2\mu} - \frac{1}{10\mu} \right)$$

$$z_{vfb} = -0.35v - 0.05v + 0.032v$$

$$z_{vfb} = -0.368v$$

Level 28 Model Equations

The Level 28 model equations follow.

Effective Channel Length and Width

The effective channel length and width for Level 28 is determined to be consistent with the Level 3 model. L, W and the multiplier M are from the .MODEL statement in the netlist. SCALE and SCALM are options. When no scaling options or multipliers are used,

$$L_{eff} = L + XL - 2 \cdot LD \quad W_{eff} = W + XW - 2 \cdot WD$$

Note: If LDAC and WDAC are included in the .MODEL statement,

$$L_{eff} = L + XL - 2 \cdot LDAC \quad W_{eff} = W + XW - 2 \cdot WDAC$$

General form

$$L_{scaled} = L \cdot SCALE$$

$$W_{scaled} = W \cdot SCALE$$

$$XL_{scaled} = XL \cdot SCALM$$

$$LD_{scaled} = LD \cdot SCALM$$

$$XW_{scaled} = XW \cdot SCALM$$

$$WD_{scaled} = WD \cdot SCALM$$

$$L_{eff} = L_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot LD_{scaled}$$

$$LREF_{eff} = LREF_{scaled} \cdot LMLT + XLREF_{scaled} - 2 \cdot LD_{scaled}$$

$$W_{eff} = M \cdot (W_{scaled} \cdot WMLT + XWREF_{scaled} - 2 \cdot WD_{scaled})$$

$$WREF_{eff} = M \cdot (WREF_{scaled} \cdot WMLT + XW_{scaled} - 2 \cdot WD_{scaled})$$

Threshold Voltage

Effective model parameter values for threshold voltage after device size adjustment are *zphi*, *zvfb*, *zk1*, *zk2*, *zeta*, *zx2e*, *zx3e*, *zgammn*, and *zetamn*. They are calculated from the model parameters *PHI0*, *VFB0*, *K1*, *K2*, *ETA0*, *X2E*, *X3E*, *GAMMN*, *ETAMN*, and their respective length and width sensitivity parameters.

$$xbs = (zphi - vbs)^{1/2}$$

$$xeta = zeta + zx2e \cdot vbs + zx3e \cdot vds$$

$$vth = zvfb + zphi + zk1 \cdot xbs - zk2 \cdot xbs^2 - xeta \cdot vds$$

This equation is quadratic in x_{bs} and v_{ds} . It is joined to linear equations at $d(v_{th})/d(x_{bs}) = z_{gammn}$ and at $d(v_{th})/d(v_{ds}) = -z_{etamn}$, which prevents the quadratics from going in the wrong direction.

Both $gammn$ and $etamn$ default to zero and typically do not affect behavior in the normal operating region.

Effective Mobility

The effective model parameter values for mobility after device size adjustment are z_{muz} , z_{x2m} , z_{x3m} , z_{x33m} , z_{u0} , and z_{x2u0} . They are calculated from the model parameters MUZ , $X2M$, $X3M$, $X33M$, $U00$, $X2U0$, and their respective length and width sensitivity parameters.

$$v_{gst} = v_{gs} - v_{th}$$

$$c_{x3ms} = \frac{z_{x33ms}}{(muz + z_{x33m} \cdot v_{gst})}$$

$$m_{eff} = (z_{muz} + z_{x2m} \cdot v_{bs})$$

$$\cdot (1 + c_{x3ms} \cdot (VDDM + v_{ds} - (VDDM \cdot VDDM + v_{ds} \cdot v_{ds})^{1/2}))$$

$$x_{u0} = z_{u0} + z_{x2u0} \cdot v_{bs}$$

$$u_{eff} = \frac{m_{eff}}{(1 + x_{u0} \cdot v_{gst})}$$

$$beta = u_{eff} \cdot COX \cdot \frac{W_{eff}}{L_{eff}}$$

Saturation Voltage (v_{dsat})

The effective model parameter values for saturation voltage after device size adjustment are $zu1$, $zx2u1$, and $zx3u1$. They are calculated from the model parameters $U1$, $X2U1$, $X3U1$ and their respective length and width sensitivity parameters.

$$xbs = (zphi - v_{bs})^{1/2}$$

$$g = 1 - \frac{1}{(1.744 + 0.8364 \cdot xbs^2)}$$

$$body = \frac{1 + g \cdot zk1}{(2 \cdot xbs)}$$

$$xu1 = zu1 + vbs \cdot zx2u1$$

$$rx = (body^2 + zu1 \cdot 2 \cdot body \cdot v_{gst} + zx3u1 \cdot 4 \cdot v_{gst}^2)^{1/2}$$

$$v_{dsat} = \frac{2 \cdot v_{gst}}{(body + rx)}$$

This is the value of v_{ds} that makes the partial derivative of

$$I_{ds}, v_{gst}, v_{bs} = (v_{gst} - body/2 \cdot v_{ds}) \cdot \frac{v_{ds}}{(1 + (xu1 + zx3u1 \cdot v_{ds}))}$$

with respect to v_{ds} equal to zero.

Transition Points

The effective model parameter values for transition points after device size adjustment are $zb1$ and $zb2$. They are calculated from the model parameters $B1$, $B2$, and their respective length and width sensitivity parameters.

$$v1 = v_{dsat} - zb1 \cdot \frac{v_{dsat}}{1 + v_{dsat}}$$

$$v2 = v_{dsat} + zb2 \cdot v_{gst}$$

Strong Inversion Current

For $v_{ds} < v1$,

$$= \beta \cdot (v_{gst} - body/2 \cdot v_{ds}) \cdot \frac{v_{ds}}{(1 + (zu1 + zx3u1 \cdot v_{ds}))}$$

The v_{ds} derivative varies approximately linearly between $v1$ and $v2$.

For $v_{ds} > v2$, i_{ds} is a function of β and v_{gst} only. If $zb1$ and $zb2$ are both positive, their main effect is to increase the current in saturation.

Weak Inversion Current

The effective model parameter values for weak inversion current after device size adjustment are $zn0$, znb , znd , $zwfac$ and $zwfacu$. They are calculated from the model parameters $N0$, $ND0$, $NB0$, $WFAC$, $WFACU$, and their respective length and width sensitivity parameters.

The weak inversion current is calculated when $zn0$ is less than 200. It is added to the strong inversion current,

$$I_{total} = I_{strong} + I_{weak} \cdot \left(1 - \exp\left(\frac{-v_{ds}}{v_{therm}}\right)\right)$$

In deep subthreshold,

$$x_n = zn0 + znb \cdot v_{bs} + znd \cdot v_{ds}$$

$$v_{therm} = \frac{KT}{Q}$$

$$xweak = \frac{(v_{gs} - vt)}{(xn \cdot vtherm)}$$

$$Iweak = const \cdot exp(xweak)$$

The modification of this formula near threshold is controlled by zwfac and zwfacu. Just above threshold, the device is in saturation:

$$Istrong = const \cdot xweak^2$$

so Iweak needs an $xweak^2$ term to cancel the kink in gm at threshold. Then Iweak goes to zero for $xweak > A0$, which is at a small voltage above threshold. Iweak has four regions:

(1) $xweak < -zwfac + A0$

$$Iweak = const \cdot exp(xweak)$$

(2) $-zwfac + A0 < xweak < 0$

$$Iweak = const \cdot exp(xweak - const \cdot wf)$$

where wf is the integral with respect to xweak of

$$dwf = \frac{(xweak + zwfac - A0)^2}{[(1 + xweak + zwfac - A0)(1 + zwfacu \cdot (xweak + zwfac - A0))]}$$

(3) $0 < x_{weak} < A_0$

$$I_{weak} = (\text{same formula as in region 2}) - \text{const} \cdot x_{weak}^2$$

(4) $A_0 < x_{weak}$

$$I_{weak} = 0$$

A_0 and the constants in the formulas above are not model parameters, but are uniquely determined by continuity conditions at the boundaries between regions.

Level 38 IDS: Cypress Depletion Model

The Level 38 Cypress Depletion MOSFET model (Cypress Semiconductor Corporation) is a further development of the HSPICE Level 5 model and features:

- BSIM-style length and width sensitivities
- Degraded body effect at high substrate bias (second GAMMA)
- Empirical fitting parameters for I_{ds} current calculations in the depletion mode of operations
- A comprehensive surface mobility equation
- Drain-induced barrier lowering

At the default parameter settings, the Level 38 model is basically backwards-compatible with Level 5 /ZENH=0.0, with the exception of the surface mobility degradation equation (see the discussion below). Refer to the documentation for Level 5 for the underlying physics that forms the foundation for the Huang-Taylor construct.

In Level 38, the temperature compensation for threshold is ASPEC-style, concurring with the default in Level 5. This section introduces and documents model parameters unique to this depletion model and additional temperature compensation parameters.

Level 38 allows the use of all HSPICE capacitance options (CAPOP). CAPOP=2 is the default setting for Level 38. By setting CAPOP=6 (AMI capacitance model), Level 38 capacitance calculations become identical to those of Level 5.

The parameter ACM default (ACM=0 in Level 38) invokes SPICE-style parasitics. ACM also can be set to 1 (ASPEC), or to 2 (HSPICE). All MOSFET models follow this convention.

HSPICE option SCALE can be used with the Level 5 model. However, option SCALM cannot be used due to the difference in units. Option DERIV cannot be used.

The following parameters *must* be specified for MOS Level 38: VTO (VT), TOX, UO (UB), FRC, ECV, and NSUB (DNB).

As with Level 5, the Ids current is calculated according to three gate voltage regions:

Depletion Region, $v_{gs} - v_{fb} < 0$

The low gate voltage region dominated by the bulk channel.

Enhancement Region, $v_{gs} - v_{fb} > 0$, $v_{ds} < v_{gs} - v_{fb}$

The region defined by high gate voltage and low drain voltage. In the enhancement region, both channels are fully turned on.

Partial enhancement region, $v_{gs} - v_{fb} > 0$, $v_{ds} > v_{gs} - v_{fb}$

The region with high gate and drain voltages, resulting in the surface region being partially turned on and the bulk region being fully turned on.

To better model depletion region operations, empirical fitting constants have been added to the original Huang-Taylor mechanism to account for the effects caused by nonuniform channel implants and also to make up for an oversight in the average capacitance construct⁵. For the enhancement region, a significantly more elaborate surface mobility model is used.

Body effect in Level 38 is calculated in two regions⁶:

Bulk body effect, $v_{sb} - v_{sbc} > 0$.

With sufficiently high (and negative) substrate bias (exceeding v_{sbc}), the depletion region at the implanted channel-substrate junction reaches the Si-oxide interface. Under such circumstances, the free carriers can only accumulate at the interface (like in an enhancement device) and the body effect is determined by the bulk doping level.

Implant-dominated body effect, $v_{sb}-v_{sbc} < 0$

Before reaching v_{sbc} , and as long as the implant dose overwhelms the substrate doping level, the body effect of the depletion mode device is dominated by the deeply “buried” transistor due to the implant. The body effect coefficient $\bar{\gamma}$ is proportional to both the substrate doping and, to first order, the implant depth. In this model level, the “amplification” of the body effect due to deep implant is accounted for by an empirical parameter, BetaGam.

Model parameters that start with L or W represent geometric sensitivities. In the model equations, a quantity denoted by zX (X being the variable name) is determined by three model parameters: the large-and-wide channel case value X and length and width sensitivities LX and WX, according to $zX=X+LX/L_{eff}+WX/W_{eff}$. For example, the zero field surface mobility is given by

$$zUO = UO + \frac{LUO}{l_{eff}} + \frac{WUO}{w_{eff}}$$

Note: This model uses mostly micrometer units rather than the typical meter units. Units and defaults are often unique in Level 38. The I_{ds} derivatives that give small signal gains gm, gds, and gmbs are calculated using the finite difference method. The options SCALM and DERIV are ineffective for this model.

Level 38 Model Parameters

The Level 38 model parameters follow.

Basic Model Parameters

Name (Alias)	Units	Default	Description
LEVEL		1.0	model level selector. This parameter is set to 38 for this model.
DNB (NSUB)	cm ⁻³	0.0	surface doping density.
DP	μm	1.0	implant depth
ECV	V/μm	1000	critical field
KCS		2.77	implant capacitance integration constant
NI	cm ⁻²	2e11	implant doping
PHI	V	0.8	built-in potential
TOX	Å	0.0	oxide thickness

Effective Width and Length Parameters

Name (Alias)	Units	Default	Description
DEL (WDEL)	m	0.0	channel length reduction on each side
LATD (LD)	m	1.7 · XJ	lateral diffusion on each side
LDAC	m		This parameter is the same as LD, but if LDAC is included in the .MODEL statement, it replaces LD in the Leff calculation for AC gate capacitance.

Name (Alias)	Units	Default	Description
LMLT		1.0	length shrink factor
OXETCH	μm	0.0	oxide etch
WMLT		1.0	diffusion layer and width shrink factor

Threshold Voltage Parameters

Name (Alias)	Units	Default	Description
FSS (NFS)	$\text{cm}^{-2}\cdot\text{V}^{-1}$	0.0	number of fast surface states
NWM		0.0	narrow width modifier
SCM		0.0	short-channel drain source voltage multiplier
BetaGam		1.0	body effect transition ratio
LBetaGam	μm	0.0	BetaGam dependence on channel length
WBetaGam	μm	0.0	BetaGam dependence on channel width
DVSBC	V	0.0	empirical body effect transition voltage adjustment
LDVSBC	$\text{V}\cdot\mu\text{m}$	0.0	L-dependent body effect transition voltage adjustment
WDVSBC	$\text{V}\cdot\mu\text{m}$	0.0	W-dependent body effect transition voltage adjustment
TDVSBC	V/K	0.0	body effect transition voltage shift due to temperature
VT (VTO)	V	0.0	extrapolated threshold voltage
LVT (LVTO)	$\text{V}\cdot\mu\text{m}$	0.0	VT dependence on channel length
WVT (WVTO)	$\text{V}\cdot\mu\text{m}$	0.0	VT dependence on channel width

Name (Alias)	Units	Default	Description
ETA		0.0	channel-length independent drain-induced barrier lowering
LETA(DIBL)	μm	0.0	channel-length dependent drain-induced barrier lowering
WETA	μm	0.0	channel-width dependent drain-induced barrier lowering
DVIN	V	0.0	empirical surface inversion voltage adjustment
XJ	μm	1.5	junction depth

Mobility Parameters

Name (Alias)	Units	Default	Description
FRC	$\text{\AA}\cdot\text{s}/\text{cm}^2$	0.0	field reduction coefficient
LFRC	$10^{-4}\text{\AA}\cdot\text{s}/\text{cm}$	0.0	FRC sensitivity to effective channel length
WFRC	$10^{-4}\text{\AA}\cdot\text{s}/\text{cm}$	0.0	FRC sensitivity to effective channel width
VFRC	$\text{\AA}\cdot\text{s}/(\text{cm}^2\cdot\text{V})$	0.0	field reduction coefficient variation due to drain bias
LVFRC	$10^{-4}\text{\AA}\cdot\text{s}/(\text{cm}\cdot\text{V})$	0.0	VFRC sensitivity to effective channel length

Name (Alias)	Units	Default	Description
WVFRC	$10^{-4} \text{Å}\cdot\text{s}/(\text{cm}\cdot\text{V})$	0.0	VFRC sensitivity to effective channel width
BFRC	$\text{Å}\cdot\text{s}/(\text{cm}^2\cdot\text{V})$	0.0	field reduction coefficient variation due to substrate bias.
LBFRC	$10^{-4} \text{Å}\cdot\text{s}/(\text{cm}\cdot\text{V})$	0.0	BFRC sensitivity to effective channel length
WBFRC	$10^{-4} \text{Å}\cdot\text{s}/(\text{cm}\cdot\text{V})$	0.0	BFRC sensitivity to effective channel width
FSB	$\text{V}^{1/2}\cdot\text{s}/\text{cm}^2$	0.0	substrate bias-induced mobility degradation coefficient
LFSB	$10^{-4} \text{V}^{1/2}\cdot\text{s}/\text{cm}$	0.0	FSB sensitivity to effective channel length
WFSB	$10^{-4} \text{V}^{1/2}\cdot\text{s}/\text{cm}$	0.0	FSB sensitivity to effective channel width
UO (UB)	$\text{cm}^2/(\text{V}\cdot\text{s})$	600	low field bulk mobility
LUO(LUB)	$\text{cm}^2\cdot\mu\text{m}/(\text{V}\cdot\text{s})$	0.0	UO sensitivity to effective channel length
WUO(WUB)	$\text{cm}^2\cdot\mu\text{m}/(\text{V}\cdot\text{s})$	0.0	UO sensitivity to effective channel width
FRCEX(F1EX)		0.0	temperature coefficient for <i>FRC</i>

Name (Alias)	Units	Default	Description
UH	cm ² / (V·s)	900	implant-channel mobility
KBeta1		1.0	effective implant-channel mobility modifier
LKBeta1	μm	0.0	length-dependent implant-channel mobility modifier
WKBeta1	μm	0.0	width-dependent implant-channel mobility modifier
KI0(KIO)		1.0	residue current coefficient
LKI0(LKIO)	μm	0.0	length-dependent residue current coefficient
WKI0(WKIO)	μm	0.0	width-dependent residue current coefficient
HEX(TUH)		-1.5	implant channel mobility temperature exponent
BEX		-1.5	surface channel mobility temperature exponent
VST	cm/s	0.0	saturation velocity
UHSAT	μm/V	0.0	implant-channel mobility saturation factor

Capacitance Parameters

Name (Alias)	Units	Default	Description
AFC		1.0	area factor for MOSFET capacitance
CAPOP		6	gate capacitance selector
METO	μm	0.0	metal overlap on gate

Level 38 Model Equations

The Level 38 model equations follow.

IDS Equations

Depletion, $v_{gs} - v_{fb} < 0$

$$ids = \beta_1 \cdot \left\{ q \cdot zKI0 \cdot NI \cdot vde + cav \cdot \left[(vgs - vfb) \cdot vde - \frac{vde^2}{2} \right] \right. \\ \left. - \frac{2}{3} \cdot cav \cdot \bar{\gamma} \cdot [(vde + vsb + Phid)^{3/2} - (vsb + Phid)^{3/2}] + Icrit \right\}$$

Enhancement, $v_{gs} - v_{fb} \geq 0$

$$ids = \beta_1 \cdot \left\{ q \cdot zKI0 \cdot NI \cdot vde - \frac{2}{3} \cdot cav \cdot \bar{\gamma} \cdot [(vde + vsb + Phid)^{3/2} - (vsb + Phid)^{3/2}] + Icrit \right. \\ \left. + \beta \cdot \left[(vgs - vfb) \cdot vde - \frac{vde^2}{2} \right] \right\}$$

Partial Enhancement, $v_{gs} - v_{fb} < vde$

$$ids = \beta_1 \cdot \left\{ q \cdot zKI0 \cdot NI \cdot vde + cav \cdot \left[(vgs - vfb) \cdot vde - \frac{vde^2}{2} \right] \right. \\ \left. - \frac{2}{3} \cdot cav \cdot \bar{\gamma} \cdot [(vde + vsb + Phid)^{3/2} - (vsb + Phid)^{3/2}] + Icrit \right\}$$

$$+ \left(\frac{1}{2} \beta - \frac{1}{2} \beta_1 \cdot cav \right) \cdot (vgs - vfb)^2$$

where

$$\beta_1 = \frac{zKBeta1}{1 + UHSAT \cdot \frac{vde}{Leff}} \cdot UH \cdot \frac{Weff}{Leff}$$

$$\beta = UBeff \cdot cox \cdot \frac{Weff}{Leff}$$

$$cav = \frac{cox \cdot cs}{cox + cs}$$

$$cs = \frac{KCS \cdot \epsilon_{si}}{DP \cdot 1e-4}$$

$$Phid = vt \cdot \ln \left(\frac{DNB \cdot nd}{ni^2} \right)$$

$$nd = \frac{NI \cdot 1e4}{DP}$$

and

$$vde = \min(vds, vdsat)$$

The temperature dependence of the mobility terms assume the ordinary exponential form:

$$UH(t) = UH(tnom) \cdot \left(\frac{t}{tnom} \right)^{TUH}$$

$$zUO(t) = zUO(tnom) \cdot \left(\frac{t}{tnom}\right)^{TUH}$$

The continuity term at the body effect transition point is given by

$$I_{crit} = -\frac{2}{3} \cdot cav \cdot [(vde + vsbc + Phid)^{3/2} - (vsbc + Phid)^{3/2}] \cdot \gamma \cdot \left(\frac{1}{zBetaGam} - 1\right)$$

for $v_{sb} > v_{sbc}$; $I_{crit} = 0$ otherwise.

The saturation voltage, threshold voltage, body effect transition voltage, and body effect coefficient $\bar{\gamma}$ are described in the following sections.

Threshold Voltage, v_{th}

The model parameter VTO, often called the “pinch-off”, is a zero-bias threshold voltage extrapolated from a large device operating in the depletion mode. The effective pinch-off threshold voltage, including the device size effects and the terminal voltages, is given by:

$$v_{th} = v_{fb} - \beta_d \cdot [v_{ch} - \bar{\gamma} \cdot (Phid + vsb)^{1/2} + v_{crit}]$$

where

$$v_{fb} = zVTO - zETA \cdot v_{ds} + \beta_d \cdot (v_{ch} - \gamma_0 \cdot Phid^{1/2})$$

$$v_{crit} = \left(\gamma - \frac{\bar{\gamma}}{zBetaGam}\right) \cdot (Phid + vsbc)^{1/2} \text{ for } v_{sb} > v_{sbc}; \text{ 0 otherwise.}$$

$$\beta_d = \frac{UH \cdot cav}{zUO \cdot cox}$$

$$v_{ch} = \frac{q \cdot NI}{cav}$$

$$\gamma_0 = \frac{(2 \cdot \epsilon_{si} \cdot q \cdot na1)^{1/2}}{cav}$$

$$na1 = \frac{nd \cdot DNB}{nd + DNB}$$

$$nd = \frac{NI}{DP \cdot 1e-4}$$

The effective $\bar{\gamma}$, including small device size effects, is computed as follows:

$$\bar{\gamma} = \frac{\gamma}{zBetaGam} \text{ for } vsb > vsbc, \text{ and } =g \text{ otherwise.}$$

$$\gamma = \gamma_0 \cdot (1 - scf) \cdot (1 + ncf)$$

where

If $SCM \leq 0$,

$$scf = 0$$

otherwise,

$$scf = \frac{XJ}{Leff} \cdot \left\{ \left[1 + \frac{2xd}{XJ} \cdot (SCM \cdot vds + vsb + Phid)^{1/2} \right]^{1/2} - 1 \right\}$$

If $NWM \leq 0$,

$$ncf = 0$$

otherwise,

$$ncf = \frac{NWM \cdot xd \cdot (Phid)^{1/2}}{Weff}$$

where

$$xd = \left(\frac{2 \cdot \epsilon si}{q \cdot DNB} \right)^{1/2}$$

The body effect transition point is calculated as follows:

$$V_{sbc} = \frac{qDP^2}{2\epsilon si} \left(\frac{NI}{DP \cdot 1e-4} - DNB \right) + zDVSBC + TDVSBC \cdot (t-tnom) - Phid$$

When $v_{gs} \leq v_{th}$, the surface is inverted and a residual DC current exists. When v_{sb} is large enough to make $v_{th} > v_{inth}$, then v_{th} is used as the inversion threshold voltage.

In order to determine the residual current, v_{inth} is inserted into the i_{ds} , v_{sat} , and mobility equation in place of v_{gs} (except for v_{gs} in the exponential term of the subthreshold current). The inversion threshold voltage at a given v_{sb} is v_{inth} , which is computed as:

$$v_{inth} = v_{fb} - \frac{q \cdot NI}{c_{ox}} - v_{sb} + DVIN - zETA \cdot v_{ds}$$

Saturation Voltage, v_{dsat}

The saturation voltage v_{sat} is determined by:

$$v_{sat} = v_{gs} - v_{fb} + v_{ch} + \frac{\gamma^2}{2} \cdot \left\{ 1 - \left[1 + \frac{4}{\gamma^2} \cdot (v_{gs} - v_{fb} + v_{ch} + v_{sb} + Phid) \right]^{1/2} \right\}$$

$$v_{dsat} = v_{sat}$$

HSPICE modifies v_{sat} to include carrier velocity saturation effect:

$$v_{dsat} = v_{sat} + v_c - (v_{sat}^2 + v_c^2)^{1/2}$$

where

$$v_c = ECV \cdot Leff$$

Mobility Reduction, UBeff

The surface mobility UB is dependent upon terminal voltages as follows:

$$UB_{eff} = \frac{1}{\frac{1}{zUO} + \frac{(zFRC + zVFRC \cdot vde + zBFRC \cdot vsb) \cdot (vgs - vfb)}{TOX}} + \bar{v}$$

where

$$Le = Leff \quad \text{Linear region}$$

$$Le = Leff - \Delta L \quad \text{Saturation region}$$

and at elevated temperatures

$$zFRC(t) = zFRC(tnom) \cdot \left(\frac{t}{tnom} \right)^{FRCEX}$$

The ΔL is the channel length modulation effect, defined in the next section. Note that v_{fb} assumes the role of v_{th} in the Level 5 mobility equation. The degradation parameters are semi-empirical and grouped together according to their (linearized) mathematical dependencies instead of physical origin to better provide parameter extraction.⁷

Channel Length Modulation

The channel length modulation effect is included by modifying the ids current as follows:

$$ids = \frac{ids}{1 - \frac{\Delta L}{Leff}}$$

where

$$\Delta L = 1e4 \cdot \left[\frac{2.73e3 \cdot XJ}{na1 \cdot \ln\left(\frac{1e20}{na1}\right)} \right]^{1/3} \cdot [(vds - vdsat + PHI)^{1/3} - PHI^{1/3}]$$

The ΔL is in microns, assuming XJ is in microns and na1 is in cm^{-3} .

Subthreshold Current, ids

When device leakage currents become important for operation near or below the normal threshold voltage, the model considers the subthreshold characteristics. In the presence of surface states, the effective threshold voltage von is determined by:

$$von = \max(vth, vinth) + fast$$

where

$$fast = vt \cdot \left[1 + \frac{q \cdot FSS}{cox} + \frac{\gamma}{2 \cdot (Phid + vsb)^{1/2}} \right]$$

If $vgs < von$, then

Partial Enhancement, $0 < vgs - vfb < vde$

$$ids = \beta 1 \cdot \left\{ q \cdot zKIO \cdot NI \cdot vde + cav \cdot \left[(von - vfb) \cdot vde - \frac{vde^2}{2} \right] \right. \\ \left. - \frac{2}{3} \cdot cav \cdot \bar{\gamma} \cdot [(vde + vsb + Phid)^{3/2} - (vsb + Phid)^{3/2}] + Icrit \right\} \\ + \frac{1}{2} \cdot \left(\beta \cdot e^{\frac{vgs - von}{fast}} - \beta 1 \cdot cav \right) \cdot (von - vfb)^2$$

Full Enhancement, $v_{gs} - v_{fb} - v_{de} > 0$

$$ids = \beta 1 \cdot \left\{ q \cdot zKI0 \cdot NI \cdot vde - \frac{2}{3} \cdot cav \cdot \bar{\gamma} \cdot [(vde + vsb + Phid)^{3/2} - (vsb + Phid)^{3/2}] \right. \\ \left. + \beta \cdot \left[(von - vfb) \cdot vde - \frac{vde^2}{2} \right] \cdot e^{\frac{vgs - von}{fast}} \right.$$

Depletion, $v_{gs} - v_{fb} < 0$

$$ids = \beta 1 \cdot \left\{ q \cdot zKI0 \cdot NI \cdot vde + cav \cdot \left[(vgs - vfb) \cdot vde - \frac{vde^2}{2} \right] \right.$$

$$\left. - \frac{2}{3} \cdot cav \cdot \bar{\gamma} \cdot [(vde + vsb + Phid)^{3/2} - (vsb + Phid)^{3/2}] + Icrit \right\} \cdot e^{\frac{vgs - von}{fast}}$$

Example Model File

```

$ file Depstor.mod
.MODEL DEPSTOR NMOS LEVEL=38
* PARASITIC ELEMENTS
+ ACM=1
+ LD=0.15u WD=0.2u $ for LEFF AND WEFF
+ CJ=0.3E-16 MJ=0.4 PB=0.8 JS=2.0E-17 $ INTRINSIC
DIODE
+ CJSW=0 MJSW=0.3
+ BULK=98 $ DEFAULT NODE FOR SUBSTRATE
* THRESHOLD
+ VTO=-2.5 LVT=-0.25 WVT=0
+ leta=0.02 eta=0.0 weta=0.0

```

```

+ TCV=0.003$ TEMPERATURE COEFFICIENT
*   MISC
+ DVIN=0.5 PHI=0.75
+ NFS=2e10 DNB=3.0E16

```

Mobility Model

```

+ UH= 1300
+ UO=495   FRC= 0.020 FSB=5e-5   VFRC=-1e-
4         BFRC=-0
+ LUO=-100 LFRC=.03   LFSB=-1e-5   LVFRC=-
.002     LBFRC=-1e-3
+ WUO=-30  WFRC=-0.01 WFSB=5e-5   WVFRC=-0.00
         WBFRC=-0.4e-3
+ KIO=.9KBETA1=.5
+ LKIO=0.16LKBETA1=-0.15
+ WKIO=0.0WKBETA1=-0.0
+ BEX=-1.3 TUH=-1.0 Frcex=1.0

```

Body Effect

```

+ NWM=0.5SCM=.1
+ DVSBC=0.1LDVSBC=0 WDVSB=0
+ TDVSBC=.002
+ BetaGam=0.9LBetaGam=-.2 WBetaGam=.1

```

Saturation

```

+ ECV=2.9VST=8000UHSAT=0
* CHANNEL LENGTH MODULATION
+ XJ= 0.1
* OXIDE THICKNESS AND CAPACITANCE
+ TOX=165 CGSO=0 CAPOP=2
* CHANNEL IMPLANT
+ NI=1.5e12KCS=3 DP=0.25
* .END

```

Level 39 BSIM2 Model

The BSIM2 (Berkeley Short-Channel IGFET Model 2)^{8,9} is available in HSPICE as Level 39. Meta-Software's implementation of this model is based on Berkeley SPICE 3E2.

Provide input to the model by assigning model parameters, as for other HSPICE models. Tabular model entry without model parameter names (as used for BSIM1) is *not* allowed for BSIM2.

Level 39 Model Parameters

The following is a list of the BSIM2 parameters, their units, their HSPICE defaults (if any), and their descriptions. There are 47 BSIM2-specific parameters listed in the following table. Considering that three of the parameters (TEMP, DELL, DFW) are not used in HSPICE and, considering the width and length sensitivity parameters associated with all the remaining parameters except the first six (TOX, VDD, VGG, VBB, DL, DW), the total parameter count is 120. (Unlike Berkeley SPICE, HSPICE has L and W sensitivity for MU0). This count does not include the "generic" MOS parameters listed in a later table or the WL-product sensitivity parameters, which are Meta-Software enhancements.

BSIM2 Model Parameters

Name (Alias)	Units	Default	Description
TOX	m	0.02	gate oxide thickness. (TOX > 1 is assumed to be in Angstroms)
TEMP	C	-	NOT USED IN HSPICE (see the following compatibility notes)
VDD	V	5	drain supply voltage (NMOS convention)
VGG	V	5	gate supply voltage (NMOS convention)
VBB	V	-5	body supply voltage (NMOS convention)

Name (Alias)	Units	Default	Description
DL	μ	0	channel length reduction
DW	μ	0	channel width reduction
VGHIGH	V	0	upper bound of the weak-strong inversion transition region
VGLOW	V	0	lower bound of same
VFB	V	-0.3	flat band voltage
PHI	V	0.8	surface potential
K1	V^{-1}	0.5	body effect coefficient
K2	-	0	second order body effect coefficient (for nonuniform channel doping)
ETA0	-	0	drain-induced barrier lowering coefficient.
ETAB	V^{-1}	0	sensitivity of drain-induced barrier lowering coefficient to V_{bs}
MU0	$cm^2/V \cdot s$	400	low-field mobility
MU0B	$cm^2/V^2 \cdot s$	0	sensitivity of low-field mobility to V_{bs}
MUS0	$cm^2/V \cdot s$	600	high drain field mobility
MUSB	$cm^2/V^2 \cdot s$	0	sensitivity of high drain field mobility to V_{bs}
MU20	-	0	empirical parameter for output resistance
MU2B	V^{-1}	0	sensitivity of empirical parameter to V_{bs}
MU2G	V^{-1}	0	sensitivity of empirical parameter to V_{gs}
MU30	$cm^2/V^2 \cdot s$	0	empirical parameter for output resistance

Name (Alias)	Units	Default	Description
MU3B	$\text{cm}^2/\text{V}^3\cdot\text{s}$	0	sensitivity of empirical parameter to V_{bs}
MU3G	$\text{cm}^2/\text{V}^3\cdot\text{s}$	0	sensitivity of empirical parameter to V_{gs}
MU40	$\text{cm}^2/\text{V}^3\cdot\text{s}$	0	empirical parameter for output resistance
MU4B	$\text{cm}^2/\text{V}^4\cdot\text{s}$	0	sensitivity of empirical parameter to V_{bs}
MU4G	$\text{cm}^2/\text{V}^4\cdot\text{s}$	0	sensitivity of empirical parameter to V_{gs}
UA0	V^{-1}	0	first-order vertical-field mobility reduction factor
UAB	V^{-2}	0	sensitivity of first-order factor to V_{bs}
UB0	V^{-2}	0	second-order vertical-field mobility reduction factor
UBB	V^{-3}	0	sensitivity of second-order factor to V_{bs}
U10	V^{-1}	0	high drain field (velocity saturation) mobility reduction factor
U1B	V^{-2}	0	sensitivity of mobility reduction factor to V_{bs}
U1D	V^{-2}	0	sensitivity of mobility reduction factor to V_{ds}
N0	-	0.5	subthreshold swing coefficient
NB	$\text{V}^{1/2}$	0	sensitivity of subthreshold swing to V_{bs}
ND	V^{-1}	0	sensitivity of subthreshold swing to V_{ds}
VOF0	-	0	threshold offset (normalized to NKT/q) for subthreshold.
VOFB	V^{-1}	0	sensitivity of offset to V_{bs} .
VOFD	V^{-1}	0	sensitivity of offset to V_{ds} .
AI0	-	0	impact ionization coefficient.
AIB	V^{-1}	0	sensitivity of impact ionization coefficient to V_{bs} .

Name (Alias)	Units	Default	Description
BI0	V	0	impact ionization exponent.
BIB	-	0	sensitivity of impact ionization exponent to V_{bs} .
DELL	m	-	length reduction of source drain diffusion. NOT USED IN HSPICE!
WDF	m	-	default width. NOT USED IN HSPICE. Use ".OPTION DEFW=#" in the netlist instead.

All BSIM2 parameters should be specified according to NMOS convention, even for a PMOS model. Examples: VDD=5, not -5, and VBB=-5, not 5, and ETA0=0.02, not -0.02.

Also see the notes following the last table in this section.

Other SPICE Parameters

The following generic SPICE MOS parameters are used with BSIM2 in Berkeley SPICE 3. All are also HSPICE parameters that can be used with HSPICE's BSIM2. See "Gate Capacitance Modeling" on page 16-272 and "MOSFET Diode Model Selection" on page 15-29 for more information.

Generic SPICE MOS Parameters

Name(Alias)	Units	Default	Description
CGDO	F/m	-	gate-drain overlap capacitance.
			calculated if not specified and if LD or METO, and TOX are.

Name(Alias)	Units	Default	Description
CGSO	F/m	-	gate-source overlap capacitance. This parameter is calculated if not specified and if LD or METO, and TOX are.
CGBO	F/m	-	gate-bulk overlap capacitance. This parameter is calculated if not specified and if WD and TOX are.
RSH	ohm/sq	0	source/drain sheet resistance.
JS	A/m ²	0	source/drain bulk diode reverse saturation current density.
PB	V	0.8	source/drain bulk junction potential.
PBSW	V	PB	sidewall junction potential
CJ	F/m ²	0	source/drain bulk zero-bias junction capacitance
CJSW	F/m	0	sidewall junction capacitance
MJ	-	0.5	source/drain bulk junction grading coefficient
MJSW		0.33	sidewall junction grading coefficient

Additionally, source/drain bulk diode sidewall reverse saturation current density, JSW[A/m], is available in HSPICE.

Other HSPICE Model Parameters Affecting BSIM2

The following HSPICE MOS model parameters are needed to use some HSPICE enhancements, such as LDD-compatible parasitics, model parameter geometry adjustment relative to a reference device, impact ionization modeling with bulk-source current partitioning, and element temperature adjustment of key model parameters.

This is a partial list. For complete information, see “Effective Length and Width for AC Gate Capacitance Calculations” on page 15-103, “Drain and Source Resistance Model Parameters” on page 15-32, “Impact Ionization Model Parameters” on page 15-55, and “Temperature Parameters” on page 15-107. See “.MODEL VERSION Changes to BSIM2 Models” on page 16-197 for information about how the .MODEL statement VERSION parameter changes the BSIM2 model depending on the model version number.

HSPICE Model Parameters

Name(Alias)	Units	Default	Description
ACM	-	0	MOS S/D parasitics selector. ACM=0 is SPICE style. ACM=2 or 3 is recommended for LDD.
SPICE3	-	0	SPICE3 model compatibility selector. For accurate SPICE3 BSIM2, set SPICE3=1.
DERIV	-	0	derivative selector: DERIV=0 ⇒ analytic. DERIV=1 ⇒ finite difference
CAPOP	-	*	MOS gate cap model selector: CAPOP=39 for BSIM2, CAPOP=13 for BSIM1, CAPOP=4 is a synonym for CAPOP=13. * If SPICE3=0, default CAPOP=13. If SPICE3=1, default CAPOP=39.
LMLT	-	1.0	gate length shrink factor
XL	m	0	difference between physical (on wafer) and drawn channel length. This parameter is used for L_{eff} calculation only if DL=0. $XL_{\text{scaled}} = XL \cdot SCALM$
LD	m	0	lateral diffusion under gate (per side) of S/D junction. This parameter is used for L_{eff} calculation only if DL=0. $LD_{\text{scaled}} = LD \cdot SCALM$

Name(Alias)	Units	Default	Description
LDAC	m		This parameter is the same as LD, but if LDAC is included in the .MODEL statement, it replaces LD in the L_{eff} calculation for AC gate capacitance.
XW	m	0	difference between physical (on wafer) and drawn S/D active width. This parameter is used for W_{eff} calculation only if DW=0. $XW_{scaled} = XW \cdot SCALM$
WMLT	-	1.0	diffusion and gate width shrink factor
WD	m	0	channel stop lateral diffusion under gate (per side). This parameter is used for W_{eff} calculation only if DW=0. WD scaled=WD · SCALM
WDAC	m		This parameter is the same as WD, but if WDAC is included in the .MODEL statement, it replaces WD in the W_{eff} calculation for AC gate capacitance.
LREF	m	0 (●)	reference channel length for length adjustment of BSIM model parameters. For Berkeley compatibility (LREF-> ∞), use LREF=0. $LREF_{scaled} = LREF \cdot SCALM$
XLREF	m	0.0	difference between physical and drawn reference channel length
WREF	m	0 (●)	reference device width for width adjustment of BSIM model parameters. For Berkeley compatibility (WREF-> ∞), use WREF=0. $WREF_{scaled} = WREF \cdot SCALM$
XWREF	m	0.0	difference between physical and drawn reference channel width
DELVTO	V	0	threshold voltage shift. This parameter is "type" sensitive. For example, DELVTO>0 increases the magnitude of n-channel threshold and decreases the magnitude of p-channel threshold. It adds to the element-line DELVTO parameter.

Name(Alias)	Units	Default	Description
ALPHA	V ⁻¹	0	impact ionization coefficient. This parameter has associated geometry sensitivity parameters. Choose between BSIM2 (A10>0 and HSPICE (ALPHA>0) impact ionization modeling. <i>Do not use both.</i>
VCR	V	0	impact ionization critical voltage. This parameter has associated geometry sensitivity parameters.
IIRAT	-	0	impact ionization source bulk current partitioning factor. One corresponds to 100% source. Zero corresponds to 100% bulk.
TCV	V/C	0	zero-bias threshold voltage temperature coefficient. The sign of TCV is adjusted automatically for NMOS and PMOS to make threshold decrease in magnitude with rising temperature.
BEX	-	-1.5	temperature exponent for mobility
FEX	-	0	temperature exponent for velocity saturation
Px	[x]/μμ ²	0	Px is Meta-Software's proprietary WL-product sensitivity parameter for x, where x is a model parameter with length and width sensitivity.

Level 39 Model Equations

In the following expressions, model parameters are in all upper case Roman. It is assumed that all model parameters have already been adjusted for geometry, and that those without a trailing “0” have already been adjusted for bias, as appropriate. The exceptions are U1 and N, whose bias dependences are given explicitly below.

Threshold voltage, V_{th} :

$$V_{th} = V_{bi} + K1 \sqrt{PHI - V_{bs}} - K2(PHI - V_{bs}) - ETA \cdot V_{ds}$$

where

$$V_{bi} = VFB + PHI$$

Strong inversion ($V_{gs} > V_{th} + VGHIGH$):

Linear region ($V_{ds} < V_{dsat}$) drain-source current I_{DS} :

$$I_{DS} = \frac{\beta' \left(V_{gs} - V_{th} - \frac{a}{2} V_{ds} \right) V_{ds}}{1 + UA(V_{gs} - V_{th}) + UB(V_{gs} - V_{th})^2 + U1 \cdot V_{ds}}$$

where

$$V_{dsat} = \frac{V_{gs} - V_{th}}{a \sqrt{K}},$$

$$K = \frac{1 + V_c + \sqrt{1 + 2V_c}}{2},$$

$$V_c = \frac{U_{1S}(V_{gs} - V_{th})}{a[1 + UA(V_{gs} - V_{th}) + UB(V_{gs} - V_{th})^2]},$$

$$U_{1S} = U10 + U1B \cdot V_{bs},$$

$$U1 = U_{1S} \left[1 - \Theta(V_{dsat} - V_{ds}) \frac{U1D(V_{ds} - V_{dsat})^2}{V_{dsat}^2} \right]$$

where $\Theta(x)$ is the usual unit step function,

$$\beta' = \beta_0 + \beta_1 \tanh\left(MU2 \frac{V_{ds}}{V_{dsat}}\right) + \beta_3 V_{ds} - \beta_4 V_{ds}^2$$

$$\beta_0 = \frac{W_{eff}}{L_{eff}} MU \cdot C_{ox} ,$$

$$\beta_1 = \beta_S - (\beta_0 + \beta_3 VDD - \beta_4 VDD^2),$$

$$\beta_i = \frac{W_{eff}}{L_{eff}} MU_i \cdot C_{ox}, \quad i = S, 3, 4 ,$$

$$a = 1 + \frac{gK1}{2\sqrt{PHI - V_{bs}}},$$

and

$$g = 1 - \frac{1}{1.744 + 0.8364(PHI - V_{bs})}$$

Saturation ($V_{ds} > V_{dsat}$) drain-source current, I_{DS} :

$$I_{DS} = \frac{\beta'(V_{gs} - V_{th})^2}{2aK[1 + UA(V_{gs} - V_{th}) + UB(V_{gs} - V_{th})^2]} \cdot (1 + f)$$

where the impact ionization term, f is

$$f = AI \cdot e^{\frac{-BI}{V_{ds} - V_{dsat}}}$$

Weak Inversion ($V_{gs} < V_{th} + VGLOW$; $[VGLOW < 0]$):

Subthreshold drain-source current, I_{ds} :

$$I_{DS} = \beta' \cdot V_{tm}^2 \cdot \exp\left(\frac{V_{gs} - V_{th}}{N \cdot V_{tm}} + VOFF\right) \cdot \left[1 - \exp\left(-\frac{V_{ds}}{V_{tm}}\right)\right] \cdot (1 + f)$$

$$\text{where } V_{tm} = \frac{kT}{q} \text{ and } N = N0 + \frac{NB}{\sqrt{PHI - V_{bs}}} + ND \cdot V_{ds}$$

Strong inversion-to-weak inversion transition region ($V_{th} + VGLOW \leq V_{gs} \leq \zeta_{th} + VGHIGH$):

$$V_{geff}(V_{gst}) = \sum_{j=0}^3 C_j V_{gst}^j$$

replaces $V_{gst} = V_{gs} - V_{th}$ in the linear or saturation drain currents, based on $V_{dsat}(V_{geff})$. At the lower boundary $V_{gs} - V_{th} = VGLOW$, the saturation equation is assumed to be valid for all V_{ds} (that is, $V_{dsat}(V_{geff}(VGLOW)) \approx 0$), to allow a match to the subthreshold equation given above. The coefficients C_j of the cubic spline V_{geff} are internally determined by the conditions that I_{DS} and dI_{ds}/dV_{gs} both be continuous at the boundaries $V_{gs} = V_{th} + VGLOW$ and $V_{gs} = V_{th} + VGHIGH$.

Effective Length and Width

If DL is nonzero:

$$L_{eff} = L_{scaled} \cdot LMLT - DL$$

$$LREF_{eff} = LREF_{scaled} \cdot LMLT - DL$$

Otherwise,

$$L_{eff} = L_{scaled} \cdot LMLT + XL_{scaled} - 2 \cdot LD_{scaled}$$

$$LREF_{eff} = LREF_{scaled} \cdot LMLT + XLREF_{scaled} - 2 \cdot LD_{scaled}$$

If DW is nonzero:

$$W_{eff} = (W_{scaled} \cdot WMLT - DW) \cdot M$$

$$WREF_{eff} = (WREF_{scaled} \cdot WMLT - DW) \cdot M$$

Otherwise,

$$W_{eff} = (W_{scaled} \cdot WMLT + XW - 2 \cdot WD_{scaled}) \cdot M$$

$$WREF_{eff} = (WREF_{scaled} \cdot WMLT + XWREF_{scaled} - 2 \cdot WD_{scaled}) \cdot M$$

Geometry and Bias Adjustment of Model Parameters

Most of the BSIM2 parameters have associated width and length sensitivity parameters. Meta-proprietary WL-product sensitivity parameters can also be specified. If P is a parameter, then its associated width, length, and WL-product sensitivity parameters are WP, LP, and PP, respectively. The value of the parameter P' adjusted for width, length, and WL-product is:

$$P' = P + WP \cdot \left(\frac{1}{W_{eff}} - \frac{1}{WREF_{eff}} \right) + LP \cdot \left(\frac{1}{L_{eff}} - \frac{1}{LREF_{eff}} \right) \\ + PP \cdot \left(\frac{1}{W_{eff}} - \frac{1}{WREF_{eff}} \right) \cdot \left(\frac{1}{L_{eff}} - \frac{1}{LREF_{eff}} \right)$$

The WREF and LREF terms do not appear in Berkeley SPICE. They are effectively infinite, which is the HSPICE default.

The following BSIM2 parameters have no associated geometry sensitivity parameters:

TOX, TEMP (not used), VDD, VGG, VBB, DL, and DW.

The BSIM2 parameters ending in "0" are assumed to be valid at zero bias, and they have associated bias sensitivities, as given in the BSIM2 parameter table.

If PB, PD, and PG are the geometry-adjusted v_{bs} -, v_{ds} -, and v_{gs} - sensitivity parameters, respectively, associated with the geometry-adjusted zero-bias parameter P0, then in general the bias-dependent parameter P is given by

$$P = P0 + PB \cdot V_{bs} + PD \cdot V_{ds} + PG \cdot V_{gs}$$

The exceptions are the velocity saturation factor U1 and the subthreshold swing coefficient N. Expressions for their bias dependences is given later.

Compatibility Notes

SPICE3 Flag

If model parameter SPICE3=0 (default), certain Meta-Software corrections to the BSIM2 equations are effective. If SPICE3 is set to 1, the equations used are as faithful as possible to the BSIM2 equations for SPICE3E2. Even in this mode, certain numerical problems have been addressed and should not be noticeable under normal circumstances.

Temperature

The model reference temperature TNOM's default is 25°C in HSPICE unless “.OPTION SPICE” is set. In this case TNOM defaults to 27° C. This option also sets some other SPICE compatibility parameters. HSPICE's TNOM is set in an “.OPTION” line in the netlist and can be overridden locally (that is, for a model) with model parameter TREF. (“Reference temperature” means that the model parameters were extracted at, and are therefore valid at, that temperature.)

In UCB SPICE 3, TNOM (default 27° C) is not effective for the BSIM models, and model parameter TEMP is used (and must be specified) as both the model reference temperature and analysis temperature. The analysis at TEMP only applies to thermally-activated exponentials in the model equations. There is no adjustment of model parameter values with TEMP. It is assumed that the model parameters were extracted at TEMP, TEMP being both the reference and analysis temperature.

For model levels *other than* 4 (BSIM1) and 5 (BSIM2) in UCB SPICE3, key model parameters are adjusted for the difference between TEMP (default 27°C) and TNOM, and TEMP is specified in the netlist with “.TEMP #”, just as in HSPICE.

In contrast to UCB SPICE’s BSIM models, HSPICE Level 39 does provide for temperature analysis. The default analysis temperature is 25°C in HSPICE. Set “.TEMP #” in the HSPICE netlist to change the HSPICE analysis temperature (TEMP as a model parameter is NOT USED). HSPICE provides temperature adjustment of key model parameters, as explained later.

Parasitics

ACM > 0 invokes HSPICE MOS source-drain parasitics. ACM=0 (default) is SPICE style. See “HSPICE Enhancements” on page 16-200.

Gate Capacitance Selection

CAPOP=39 selects the BSIM2 charge-conserving capacitance model as shipped with Berkeley SPICE 3E2. This is the default selection if SPICE3=1 is set. Please note that XPART (charge-sharing flag) is currently not a BSIM2 model parameter, despite its specification in the sample BSIM2 input decks shipped with Berkeley SPICE 3E. It appears that its use in SPICE 3E was as a printback debug aid. Saturation charge sharing appears to be fixed at 60/40 (S/D) in the BSIM2 capacitance model. Charge equations are given later under “”. See also “Modeling Guidelines and Removal of Mathematical Anomalies” on page 16-203.

Other CAPOPs can be chosen. CAPOP=13 (recommended) selects Meta’s BSIM1-based charge-conserving capacitance model that is in common usage with HSPICE MOS Levels 13 (BSIM1) and Level 28 (modified BSIM1). This option is the default selection if SPICE3=0. With this capacitance model, charge sharing can be adjusted using model parameters XPART or XQC. See “Level 13 BSIM Model” on page 16-104 *for more information*.

Unused Parameters

SPICE model parameters DELL (S/D diode length reduction) and WDF (default device width) are not used in HSPICE. The function of DELL in SPICE 3E cannot be determined. A default width can be specified in HSPICE on the .OPTION line as DEFW (which defaults to 100 μ).

.MODEL VERSION Changes to BSIM2 Models

HSPICE provides a VERSION parameter to the .MODEL statement, which allows portability of Level 13 BSIM and Level 39 BSIM2 models between HSPICE versions. Using the VERSION parameter in a Level 13 .MODEL statement results in the following changes to the BSIM model:

Model version Effect of VERSION on BSIM2 model

92Alevel 39 BSIM2 model introduced: no changes

92Bno changes

93Aintroduces gds constraints,
fixes WMU3B parameter defect,
fixes PMU0 parameter “O” versus “0” defect, and
introduces MU4 parameter defect

93A.02VERSION parameter introduced,
fixes MU4 parameter defect

95.1fixes defects that cause PMUSB, LDAC, WDAC parameter problems
fixes GMBS defect when gds constraints are used

96.1limited ETA+ ETAB · vb5 \geq 0

Prevention of Negative Output Conductance

HSPIICE internally protects against conditions in the Level 13 model that cause convergence problems due to negative output conductance. The constraints imposed are:

$$MU2 \geq 0 \quad ND \geq 0 \quad AI \geq 0$$

These constraints are imposed after length and width adjustment and VBS dependence. This feature is gained at the expense of some accuracy in the saturation region, particularly at high V_{gs} . Consequently, BSIM2 models might need to be requalified in the following situations:

1. Devices exhibit self-heating during characterization, which causes declining I_{ds} at high V_{ds} . This would not occur if the device characterization measurement sweeps V_{ds} .
2. The extraction technique produces parameters that result in negative conductance.
3. Voltage simulation is attempted outside the characterized range of the device.

Charge-based Gate Capacitance Model (CAPOP=39)

The BSIM2 gate capacitance model conserves charge and has non-reciprocal attributes. The use of charges as state variables guarantees charge conservation. Charge partitioning is fixed at 60/40 (S/D) in saturation and is 50/50 in the linear region. $Q_s = -(Q_g + Q_d + Q_b)$ in all regions.

Accumulation region ($V_{gs} < V_{bs} + VFB$):

$$Q_g = C_{ox} W_{eff} \cdot L_{eff} (V_{gs} - V_{bs} - VFB)$$

$$Q_b = -Q_g$$

$$Q_d = 0$$

Subthreshold region ($V_{bs} + VFB < V_{gs} < V_{th} + VGLOW$):

$$Q_g = C_{ox} W_{eff} \cdot L_{eff} (V_{gs} - V_{bs} - VFB)$$

$$\cdot \left[1 - \frac{V_{gs} - V_{bs} - VFB}{V_{gs} - V_{bs} - VFB - V_{gst}} + \frac{1}{3} \left\{ \frac{V_{gs} - V_{bs} - VFB}{V_{gs} - V_{bs} - VFB - V_{gst}} \right\}^2 \right]$$

$$Q_b = -Q_g$$

$$Q_d = 0$$

Saturation region ($V_{ds} > V_{dsat}$):

$$Q_g = \frac{2}{3} C_{ox} W_{eff} \cdot L_{eff} \cdot V_{gst} + Q_{bulk}$$

where

$$Q_{bulk} = \frac{1}{3} C_{ox} W_{eff} \cdot L_{eff} [V_{th} - V_{bs} - VFB]$$

$$Q_b = -Q_{bulk}$$

$$Q_d = -\frac{4}{10} \cdot \frac{2}{3} C_{ox} W_{eff} \cdot L_{eff} \cdot V_{gst} = \left(-\frac{4}{15} \right) C_{ox} W_{eff} \cdot L_{eff} \cdot V_{gst}$$

Linear region ($V_{ds} < V_{dsat}$):

$$Q_g = \frac{2}{3} C_{ox} W_{eff} \cdot L_{eff} \cdot V_{gst} \cdot \left[\frac{3 \left(1 - \frac{V_{ds}}{V_{dsat}} \right) + \left(\frac{V_{ds}}{V_{dsat}} \right)^2}{2 - \frac{V_{ds}}{V_{dsat}}} \right] + Q_{bulk}$$

$$Q_b = -Q_{bulk}$$

$$Q_d = -\frac{1}{3} C_{ox} W_{eff} \cdot L_{eff} \cdot V_{gst}$$

$$\cdot \left[\frac{3 \left(1 - \frac{V_{ds}}{V_{dsat}} \right) + \left(\frac{V_{ds}}{V_{dsat}} \right)^2}{2 - \frac{V_{ds}}{V_{dsat}}} + \frac{\frac{V_{ds}}{V_{dsat}} \left(1 - \frac{V_{ds}}{V_{dsat}} \right) + 0.2 \left(\frac{V_{ds}}{V_{dsat}} \right)^2}{\left(2 - \frac{V_{ds}}{V_{dsat}} \right)^2} \right] + Q_{bulk}$$

HSPICE Enhancements

In the following expressions, model parameters are in all upper case Roman. It is assumed that all model parameters without a trailing “0” have already been adjusted for both geometry and bias, as appropriate.

Temperature Effects

TLEV=1 is enforced for LEVEL=39. No other TLEV value is currently allowed.

Threshold voltage for Level 39 TLEV=1 is adjusted according to:

$$V_{th}(T) = V_{bi}(T) + K1 \cdot \sqrt{\phi(T) - V_{bs}} - K2 \cdot (\phi(T) - V_{bs}) - ETA \cdot V_{ds}$$

where

$$V_{bi}(T) = V_{to}(T) - K1 \cdot \sqrt{\phi(T)} + K2 \cdot \phi(T),$$

$$V_{to}(T) = V_{to} - TCV \cdot (T - T_{nom}),$$

and the nominal-temperature, zero-bias threshold voltage is given by

$$\begin{aligned} V_{to} &= V_{bi} + K1 \cdot \sqrt{PHI} - K2 \cdot PHI \\ &= VFB + PHI + K1 \cdot \sqrt{PHI} - K2 \cdot PHI, \end{aligned}$$

and $\phi(T)$ is calculated according to the value of TLEV as specified.

Mobility is adjusted according to

$$\mu(T) = \mu(T_{nom}) \cdot \left(\frac{T}{T_{nom}}\right)^{BEX} \text{ where } \mu = \frac{\beta'}{C_{ox}(W_{eff}/L_{eff})}$$

Velocity saturation is adjusted through UIS according to

$$UIS(T) = UIS \cdot \left(\frac{T}{T_{nom}}\right)^{FEX}$$

In addition, all of the usual HSPICE adjustments to capacitances and parasitic diodes and resistors are effective.

Alternate Gate Capacitance Model

Select CAPOP=13 for Meta-Software's charge-conserving capacitance model, widely used with LEVEL=13 (BSIM1) and LEVEL=28 (improved BSIM1). See "Level 13 BSIM Model" on page 16-104 for more details.

Impact Ionization

You can select HSPICE impact ionization modeling (instead of BSIM2's) by leaving AI0=0 and specifying model parameters ALPHA [$\text{ALPHA} \cdot (V_{ds} - V_{dsat})$ replaces AI in equation for f in the BSIM2 equations section above], VCR (replaces BI), and IIRAT (multiplies f).

HSPICE impact ionization modeling differs from BSIM2's in two ways:

1. There is a bias term, $V_{ds} - V_{dsat}$, multiplying the exponential, as well as ALPHA.
2. The impact ionization component of the drain current can be partitioned between the source and the bulk with model parameter IIRAT. IIRAT multiplies f in the saturation I_{ds} equation. Thus, the fraction IIRAT of the impact ionization current goes to the source, and the fraction 1-IIRAT goes to the bulk, adding to I_{DB} . IIRAT defaults to zero (that is, 100% of impact ionization current goes to the bulk).

BSIM2's impact ionization assumes that all of the impact ionization current is part of I_{DS} . In other words, it flows to the source. This assumption can lead to inaccuracies in, for example, cascode circuits. See "Impact Ionization Equations" on page 15-55 for more details.

Parasitic Diode for Proper LDD Modeling

HSPICE has alternative MOS parasitic diodes to replace SPICE-style MOS parasitic diodes. These alternatives allow for geometric scaling of the parasitics with MOS device dimension, proper modeling of LDD parasitic resistances, allowance for shared sources and drains, and allowance for different diode sidewall capacitances along the gate edge and field edge.

The MOS parasitic diode is selected with model parameter ACM. ACM=0 (default) chooses SPICE style. The alternatives likely to be of most interest to the BSIM2 user are ACM=2 and 3.

ACM=2 allows for diode area calculation based on W, XW, and HDIF (contact to gate spacing). The calculation can be overridden from the element line. It further allows specification of LDIF (spacer dimension) and RS, RD (source and drain sheet resistance under the spacer) for LDD devices, as well as RSH (sheet resistance of heavily doped diffusion). Thus, total parasitic resistance of LDD devices is properly calculated.

ACM=3 uses all the features of ACM=2 and, in addition, its calculations of diode parasitics takes into account the sharing of source/drains, and different junction sidewall capacitances along the gate and field edges. Specify source/drain sharing from the element line with parameter GEO.

See "MOSFET Diode Model Selection" on page 15-29 for more details.

Skewing of Model Parameters

The BSIM2 model file, like any other HSPICE model, can be set up for skewing to reflect process variation. Worst-case or Monte-Carlo analysis can be performed, based on fab statistics. For more information, see Chapter 9, "AC Sweep and Signal Analysis."

HSPICE Optimizer

The BSIM2 model, like any other HSPICE model, can be tied into the HSPICE optimizer for fitting to actual device data.

For more information, see Chapter 11, “Optimizing Performance.” An example fit appears at the end of this section.

Modeling Guidelines and Removal of Mathematical Anomalies

Because of the somewhat arbitrary geometric and bias adjustments given to BSIM2 parameters, they can take on non-physical or mathematically unallowed values in Berkeley SPICE 3. This can lead to illegal function arguments, program crashes, and unexpected model behavior (for example, negative conductance). The following guidelines and corrections must be satisfied at all geometries of interest and at biases, up to double the supply voltages (that is, to $V_{ds} = 2 \cdot VDD$, $V_{gs} = 2 \cdot VGG$, and $V_{bs} = 2 \cdot VBB$).

To avoid drain current discontinuity at $V_{ds} = V_{dsat}$, be sure that $BI \neq 0$ if $AI0 \neq 0$.

To prevent negative g_{ds} , be sure that $ETA > 0$ and that $MU3 > 0$ and $MU4 < MU3 / (4 * VDD)$. This should ensure positive g_{ds} at biases up to double the supply voltages. To simplify matters, set all $MU4$ parameters to zero. You can obtain reasonably good fits to submicron devices without using $MU4$ ¹⁰.

In HSPICE, $U1S$ is prevented from becoming negative. A negative $U1S$ is physically meaningless and causes negative arguments in a square root function in one of the BSIM2 equations. It is also recommended that $U1D$ be kept less than unity (between 0 and 1).

For reasonable V_{th} behavior, make sure that $K1 - 2K2 \cdot \sqrt{PHI - V_{bs}} \geq 0$.

For the equations to make sense, the following must hold: $N > 0$, $VGLOW \leq 0$, and $VGHIGH \geq 0$.

The BSIM2 gate capacitance model of SPICE 3E tends to display negative C_{gs} in subthreshold. This appears to be due to $C_{gg} \rightarrow 0$ as $V_{gs} \rightarrow V_{th}$ by construction of the gate charge equation, so that $C_{gs} = C_{gg} - C_{gd} - C_{gb} \rightarrow -C_{gd} - C_{gb} \approx -C_{gb}$.

Therefore the use of CAPOP=13 (default) is recommend until an improved BSIM2 gate capacitance model is released by Berkeley.

Modeling Example

The following is the result of fitting data from a submicron channel-length NMOS device to BSIM2. The fitting was performed with Meta-Software's ATEM characterization software and the HSPICE optimizer.

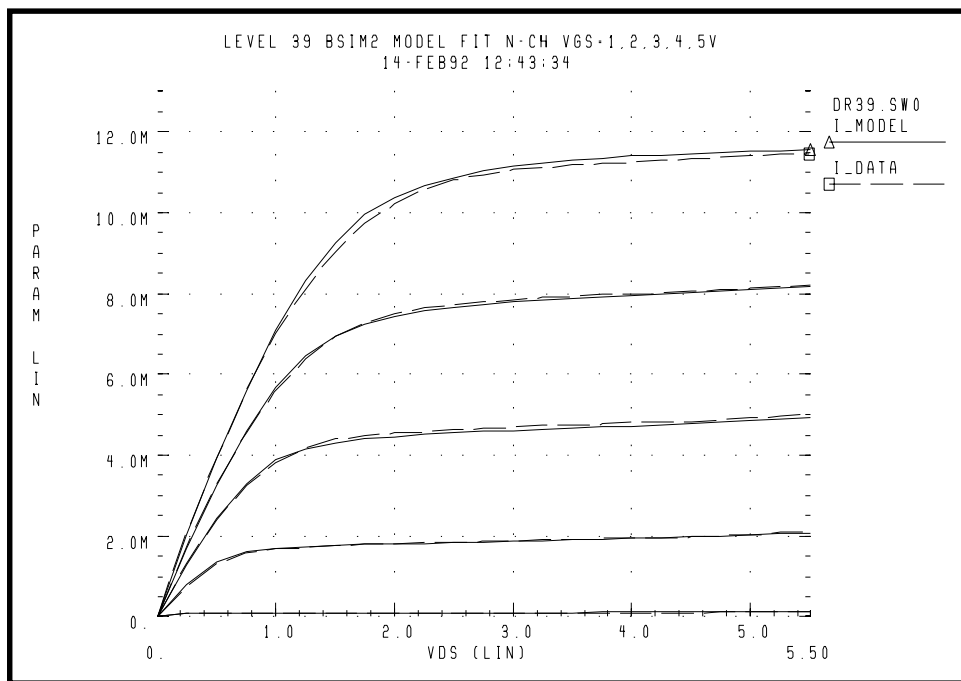


Figure 16-8: $-I_{DS}$ vs. V_{ds} for $V_{gs} = 1, 2, 3, 4, 5V$; BSIM2 Model vs. Data

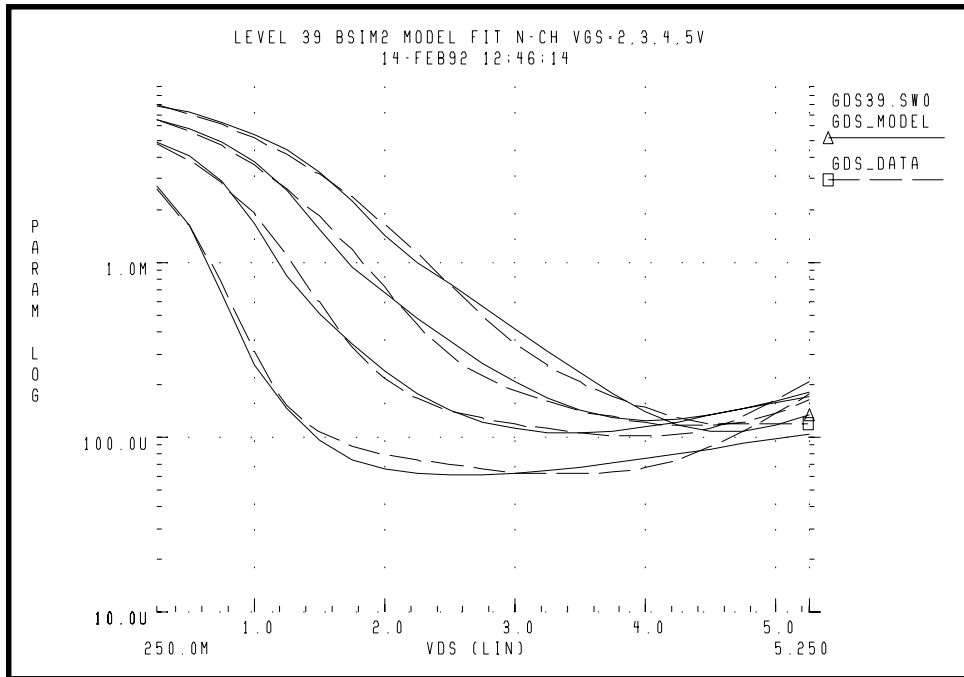


Figure 16-9: $-g_{ds}$ vs. V_{ds} for $V_{gs} = 2, 3, 4, 5V$; BSIM2 Model vs. Data, LOG scale

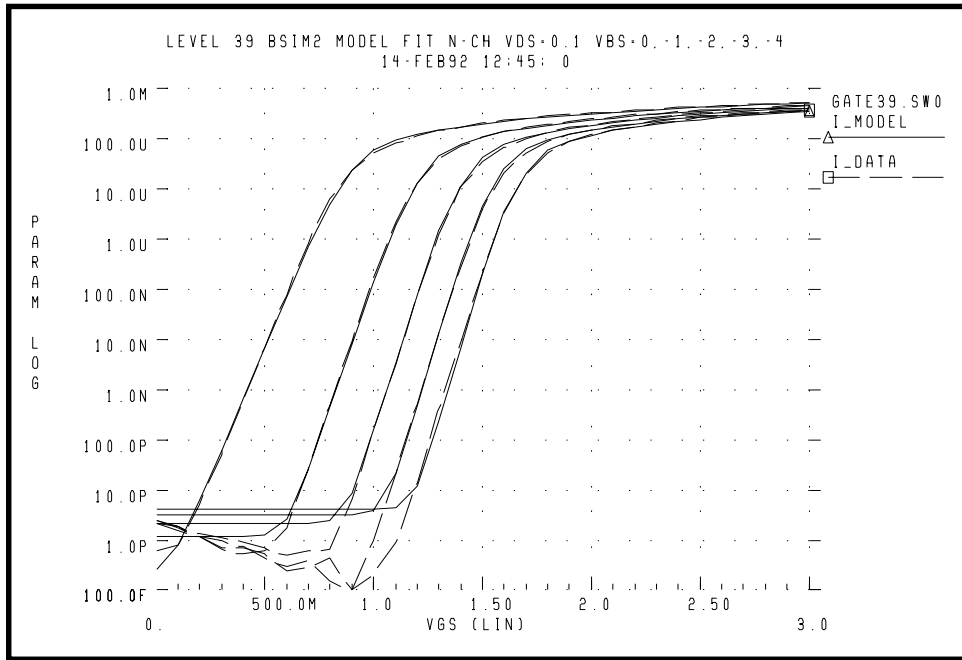


Figure 16-10: – I_{DS} vs. V_{GS} for $V_{ds} = 0.1V$, $V_{bs} = 0, -1, -2, -3, -4V$, Showing Subthreshold Region; Model vs. Data

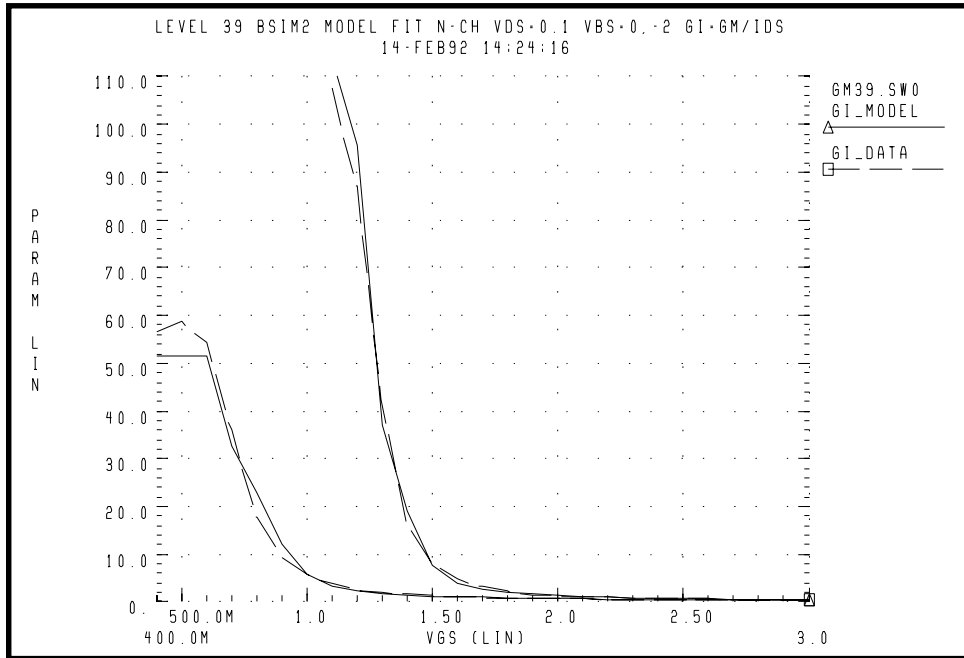


Figure 16-11: $-gm/I_{DS}$ vs. V_{gs} for $V_{ds} = 0.1V$, $V_{bs} = 0, -2V$; BSIM2 Model vs. Data

Example of Typical BSIM2 Model Listing

In this example, geometry sensitivities are set to zero because a fit at only one geometry has been performed. Note the extra HSPICE parameters for LDD, temperature, and geometry.

```
.MODEL NCH NMOS LEVEL = 39
+ TOX = 2.000000E-02    TEMP = 2.500000E+01
+ VDD = 5.000000E+00    VGG = 5.000000E+00    VBB = -
5.000000E+00
+ DL = 0.000000E+00    DW = 0.000000E+00
+ VGHIGH = 1.270000E-01 LVGHIGH= 0.000000E+00
WVGHIGH= 0.000000E+00
+ VGLLOW = -7.820000E-02 LVGLLOW = 0.000000E+00 WVGLLOW
= 0.000000E+00
```

+ VFB = -5.760000E-01	LVFB = 0.000000E+00	WVFB = 0.000000E+00
+ PHI = 6.500000E-01	LPHI = 0.000000E+00	WPHI = 0.000000E+00
+ K1 = 9.900000E-01	LK1 = 0.000000E+00	WK1 = 0.000000E+00
+ K2 = 1.290000E-01	LK2 = 0.000000E+00	WK2 = 0.000000E+00
+ ETA0 = 4.840000E-03	LETA0 = 0.000000E+00	WETA0 = 0.000000E+00
+ ETAB = -5.560000E-03	LETAB = 0.000000E+00	WETAB = 0.000000E+00
+ MU0 = 3.000000E+02		
+ MU0B = 0.000000E+00	LMU0B = 0.000000E+00	WMU0B = 0.000000E+00
+ MUS0 = 7.050000E+02	LMUS0 = 0.000000E+00	WMUS0 = 0.000000E+00
+ MUSB = 0.000000E+00	LMUSB = 0.000000E+00	WMUSB = 0.000000E+00
+ MU20 = 1.170000E+00	LMU20 = 0.000000E+00	WMU20 = 0.000000E+00
+ MU2B = 0.000000E+00	LMU2B = 0.000000E+00	WMU2B = 0.000000E+00
+ MU2G = 0.000000E+00	LMU2G = 0.000000E+00	WMU2G = 0.000000E+00
+ MU30 = 3.000000E+01	LMU30 = 0.000000E+00	WMU30 = 0.000000E+00
+ MU3B = 0.000000E+00	LMU3B = 0.000000E+00	WMU3B = 0.000000E+00
+ MU3G = -2.970000E+00	LMU3G = 0.000000E+00	WMU3G = 0.000000E+00
+ MU40 = 0.000000E+00	LMU40 = 0.000000E+00	WMU40 = 0.000000E+00
+ MU4B = 0.000000E+00	LMU4B = 0.000000E+00	WMU4B = 0.000000E+00


```

0.000000E+00
+ MU4G = 0.000000E+00    LMU4G = 0.000000E+00    WMU4G =
0.000000E+00
+ UA0 = 0.000000E+00    LUA0 = 0.000000E+00    WUA0 =
0.000000E+00
+ UAB = 0.000000E+00    LUAB = 0.000000E+00    WUAB =
0.000000E+00
+ UB0 = 7.450000E-03    LUB0 = 0.000000E+00    WUB0 =
0.000000E+00
+ UBB = 0.000000E+00    LUBB = 0.000000E+00    WUBB =
0.000000E+00
+ U10 = 0.000000E+00    LU10 = 7.900000E-01    WU10 =
0.000000E+00
+ U1B = 0.000000E+00    LU1B = 0.000000E+00    WU1B =
0.000000E+00
+ U1D = 0.000000E+00    LU1D = 0.000000E+00    WU1D =
0.000000E+00
+ N0 = 8.370000E-01    LNO = 0.000000E+00    WNO =
0.000000E+00
+ NB = 6.660000E-01    LNB = 0.000000E+00    WNB =
0.000000E+00
+ ND = 0.000000E+00    LND = 0.000000E+00    WND =
0.000000E+00
+ VOF0 = 4.770000E-01    LVOF0 = 0.000000E+00    WVOF0 =
0.000000E+00
+ VOFB = -3.400000E-02    LVOFB = 0.000000E+00    WVOFB =
0.000000E+00
+ VOFD = -6.900000E-02    LVOFD = 0.000000E+00    WVOFD =
0.000000E+00
+ AI0 = 1.840000E+00    LAI0 = 0.000000E+00    WAI0 =
0.000000E+00
+ AIB = 0.000000E+00    LAIB = 0.000000E+00    WAIB =
0.000000E+00
+ BI0 = 2.000000E+01    LBI0 = 0.000000E+00    WBI0 =

```

```

0.000000E+00
+ BIB = 0.000000E+00    LBIB = 0.000000E+00    WBIB =
0.000000E+00
+ DELL = 0.000000E+00    WDF = 0.000000E+00

```

Common SPICE Parameters

```

+ CGDO = 1.000000E-09    CGSO = 1.000000E-09    CGBO =
2.500000E-11
+ RSH = 3.640000E+01    JS = 1.380000E-06
+ PB = 8.000000E-01    PBSW = 8.000000E-01
+ CJ = 4.310000E-04    CJSW = 3.960000E-10
+ MJ = 4.560000E-01    MJSW = 3.020000E-01

```

Meta-Software Parameters

```

+ ACM = 3                LMLT = 8.500000E-01    WMLT =
8.500000E-01
+ XL = -5.000000E-08    LD = 5.000000E-08
+ XW = 3.000000E-07    WD = 5.000000E-07
+ CJGATE = 2.000000E-10 HDIF = 2.000000E-06    LDIF =
2.000000E-07
+ RS = 2.000000E+03    TRS = 2.420000E-03
+ RD = 2.000000E+03    TRD = 2.420000E-03
+ TCV = 1.420000E-03    BEX = -1.720000E+00    FEX = -
2.820000E+00
+ LMU0 = 0.000000E+00    WMU0 =
0.000000E+00    JSW=2.400000E-12

```

Level 40 HP a-Si TFT Model

HSPICE Level 40 is a Hewlett-Packard amorphous silicon thin-film transistor model.

Model Parameters

Name	Units	Default	Comments
UO	cm ² /V/s	1.0	mobility
VTO	V	0.0	zero voltage threshold voltage
PHI	V	0.0	surface potential
NFS	cm ²	0.0	fast surface state density
NSS	cm ²	0.0	surface state density
T1	m	280n	first thin film thickness
T2	m	0.0	second thin film thickness
E1		3.9	dielectric constant of 1st film
E2		0.0	dielectric constant of 2nd film
THETA	V ⁻¹	0.0	mobility modulation
ETA	V ⁻¹	0.0	static feedback on threshold voltage (difficulty of band bending)
VMAX	m/s	1e6	maximum drift velocity of carriers
GO	ohm ⁻¹	10e-15	conductance of TFT leakage current
DEFF		2.0	drain voltage effect for TFT leakage current
NU		0.0	first order temperature gradient
CHI		0.5	temperature exponential part
PSI		1e-20	temperature exponential part

Name	Units	Default	Comments
K2		2.0	temperature exponential part
VTIME	s	10m	voltage stress
TREF		1.5	temperature gradient of UO
RD	ohm	1.0K	(external) drain resistance
RS	ohm	1.0K	(external) source resistance
CGSO	F	1.0p	TFT gate-to-source overlap capacitance
CGDO	F	1.0p	TFT gate-to-drain overlap capacitance
CSC	F/m ²	10 μ	space charge capacitance
FREQ	Hz	400	frequency of device
FEFF		0.5	frequency effect constant
TAU	s	10n	relaxation time constant

Using the HP a-Si TFT Model in HSPICE

1. Set LEVEL=40 to identify the model as the HP a-Si TFT model.
2. The default value for L is 10 μ m, and the default value for W is 40 μ m.
3. Use the “M” designation for MOSFET rather than the “A” designation for a-Si TFT in the netlist.
4. Use the “NMOS” or “PMOS” designation for device type rather than the “NAT” or “PAT” designation. **Note:** Because of the unavailability of p-channel TFTs, PMOS model testing has been very limited.
5. The Level 40 model is a three-terminal model. No bulk node exists; therefore, no parasitic drain-bulk or source-bulk diodes are appended to the model. A fourth node can be specified, but does not affect simulation results (except for GMIN terms).
6. Parasitic resistances and overlap capacitances are constant. They are not scaled with width, length, and temperature.

7. The capacitance expressions in this model do not conserve charge.
8. The HP a-Si TFT model has a TREF parameter that is an exponent in an expression for mobility temperature dependence.

Other models use the BEX parameter for similar mobility temperature dependence expressions. The HP a-Si TFT TREF model parameter is *not the same as the reference temperature TREF* used in other models. The reference temperature for the HP a-Si TFT model is 312 K (or 38.85 °C), and cannot be modified. Experimental results from TFT manufacturers indicate that amorphous silicon materials are most stable at this temperature.

9. The default room temperature is 25° C in HSPICE, but is 27° C in some other simulators. It is a matter of choice whether or not to set the nominal simulation temperature to 27° C, by adding .OPTION TNOM=27 to the netlist. Although the *reference* temperature of the HP a-Si TFT model is fixed at 312° K (or 38.85 °C), the behavior of the model adjusts to other *simulation* temperatures that are user specified or provided by HSPICE as defaults.
10. HP's SPICE3E2 implementation of this model, on which this implementation is based, is not temperature-dependent. The Level 40 has temperature dependency enabled.
11. The default value of CAPOP is 40, which is the HP a-Si TFT non-charge-conserving capacitance model. CAPOP values of 0, 1, 2, 3, 4, 5, 9, 12, or 13 are allowed, but have not been thoroughly tested.
12. The default of DERIV is zero, the analytical method. DERIV can be set to 1 to select the finite difference method.

Effect of SCALE and SCALM

The SCALE option has the same effect for Level 40 as for other HSPICE models, such as Level 3 or Level 28. If the values of L and W are in microns rather than meters (for example, L=1 rather than L=1 μ or 1e-6), set .OPTION SCALE=1e-6.

The SCALM option is disabled in the Level 40 model. For standard HSPICE models such as Level 3, SCALM affects the scale of model parameters such as XL, XW, LD, WD, CJ, and CJSW.

Because the SCALM option is ignored by the Level 40 model, Level 40 models can be mixed in a simulation with other models in which the SCALM is set.

In general, netlists for HSPICE should be made as standard as possible. Also, it is best to convert L and W to meters scale instead of microns scale, so that the netlist can be used without the OPTION SCALE=1E-6. If these recommendations are followed, then a system-level HSPICE user can use I/O subcircuits from different vendors in one simulation.

Noise Model

The Level 40 model uses the standard NLEV=0 noise model inherited from HSPICE.

Element DELVTO

DELVTO and DTEMP on the element line can be used with Level 40.

Example HSPICE model and element statement:

```
.MODEL nch nmos level=40 UO=0.4229 VTO=1.645 PHI=1.25
NSS=0
+ NFS=2.248E+21 VMAX=1231
+ THETA=-0.01771 ETA=0.0002703 T1=2.6E-07 T2=0 E1=3.9
E2=0
+ GO=9.206E-15 NU=0 K2=2 CHI=0.5
+ PSI=1E-20 VTIME=0.01 TREF=1.5 CGSO=5.203E-14
CGDO=4.43E-14
+ CSC=0.0001447 RD=5097
+ RS=5097 FREQ=1E+06 DEFF=2.15 TAU=1.64E-07 FEFF=0.5
MCKT 1 2 3 nch L=1e-05 W=4e-05
```

Level 40 Model Equations

In the following equations, model parameters are shown in all capital letters; working variables are in lower case. Model parameters and bias voltages v_{gs} and v_{ds} are inputs. I_{ds} , g_m , and g_{ds} are the DC outputs, and the gate-to-source capacitance C_{gs} and the gate-to-drain capacitance C_{gd} are the AC outputs. Electron charge is q , Boltzmann's constant is k , and the permittivity of a vacuum is ϵ_0 .

Scaling by SCALE has been done prior to evaluation of the equations. Scaling by M is done after evaluation.

The variables $g_{m_{ift}}$ and $g_{ds_{ift}}$ are intermediate, not final, quantities.

A complete description of TFT technology and the device physics underlying these equations can be found in the Hewlett-Packard HP IC-CAP manual.

Initially, $C_{gdi} = 0$, $C_{gsi} = 0$, $\phi_i = PHI$, $v_{to} = VTO$, $u_o = UO$

If $u_o = 0$ then $u_o = 1$

C_{fm} , the dielectric capacitance per unit area, is computed as follows:

$$\text{If } T_1 \neq 0 \text{ and } T_2 \neq 0, \text{ then } C_{fm} = \frac{(\epsilon_0 \cdot E_1 \cdot E_2)}{((T_2 \cdot E_1) + (T_1 \cdot E_2))}$$

$$\text{If } T_1 = 0 \text{ and } T_2 \neq 0, \text{ then } C_{fm} = \frac{(\epsilon_0 \cdot E_2)}{T_2}$$

$$\text{If } T_2 = 0 \text{ and } T_1 \neq 0, \text{ then } C_{fm} = \frac{(\epsilon_0 \cdot E_1)}{T_1}$$

$$k_p = u_o \cdot C_{fm} \cdot 10^{-4}$$

TEMP is the HSPICE device simulation temperature, specified in °C, but converted to °K internally for the evaluation of these equations.

$$v_t = \frac{(k \cdot TEMP)}{q}$$

$$e_g = (2 \cdot 10^4 \cdot (TEMP - 312)) + 1.4$$

$$v_{to} = v_{to} + (DELVTO_{model} \cdot type) + (DELVTO_{element} \cdot type)$$

$$v_{bi} = v_{to}$$

$$ratio = \frac{TEMP}{312}$$

If $VTIME \leq 1$, then $u_o = u_o \cdot (ratio)^{TREF}$ and $k_p = k_p \cdot (ratio)^{TREF}$

Note: TREF is the Level 40 model parameter TREF, which is an exponent in temperature adjustment equations. It is not the reference temperature of this device model.

$$v_{fb} = v_{to} - (0.5 \cdot PHI) + (0.5 \cdot (1.4 - eg))$$

$$v_{bi} = v_{fb} + (0.5 + PHI \cdot ratio)$$

$$v_{to} = v_{bi} \text{ (printback definition)}$$

$$phi = phi \cdot ratio \text{ (printback definition)}$$

$$v_{fb} = v_{bi} - phi \text{ (printback definition)}$$

$$v_{dsat} = 0$$

$$beta = k_p \cdot W \cdot L$$

$$v_{th} = v_{bi} + (ETA \cdot v_{ds})$$

If $NU \neq 0$ and $K2 \neq 0$ and $PSI \neq 0$ and $VTIME > 1$, then

$$v_{th} = v_{th} + f(v_{gs}, v_{ds}, NU, K2, PSI, CHI, VTIME, TEMP)$$

$$v_{on} = v_{th}$$

If $NFS \neq 0$, then

$$x_n = 1 + \left(\frac{(q \cdot NFS \cdot 10^4 \cdot W \cdot L)}{C_{fm}} \right)$$

$$v_{on} = f(v_{th}, (v_t \cdot x_n))$$

Cutoff Region (NFS = 0, $v_{gs} \leq v_{on}$)

If $NFS = 0$ and $v_{gs} \leq v_{on}$, then

$$C_{gdi} = 0$$

$$C_{gsi} = 0$$

$$I_{ds} = GO \cdot f(v_{gs}, (DEFF \cdot v_{ds}))$$

$$g_m = GO$$

$$g_{ds} = GO \cdot DEFF$$

Noncutoff Region (NFS $\neq 0$)

If $v_{gs} > v_{on}$, then

$$v_{gsx} = v_{gs}$$

If $v_{gs} \leq v_{on}$, then

$$v_{gsx} = v_{on}$$

Mobility modulation by v_{gs} :

$$u_{eff} = f(u_o, \eta, v_{gs}, THETA)$$

If $VMAX > 0$, then

$$v_{dsc} = \frac{L \cdot VMAX}{u_{eff}}$$

$$v_{dsat} = (v_{gsx} - v_{th}) + v_{dsc} - \sqrt{((v_{gsx} - v_{th})^2 + v_{dsc}^2)}$$

$$C_{fmlw} = \frac{(C_{fm} \cdot CSC)}{(C_{fm} + CSC)} \cdot L \cdot W$$

C_{fmlw} is the series combination of the dielectric and space charge capacitance of the MIS structure.

If $v_{ds} < v_{dsat}$, then

$$v_{dsx} = v_{ds}$$

$$\epsilon_{psfm} = C_{fm} \cdot \frac{(T2 + T1)}{\epsilon_0}$$

ϵ_{psfm} is the effective equivalent dielectric constant of the insulator layers.

$$f_{val} = 0.8 + \left(\frac{\epsilon_{psfm} - 0.8}{1 + (2 \cdot \pi \cdot \text{FREQ} \cdot \text{TAU})^2} \right)$$

$$C_{gdi} = f(C_{fmlw} \cdot f(\epsilon_{fm}, 0.8) \cdot (\exp(f_{val}, \text{FEFF}, v_{gs} - v_{th} - v_{ds})))$$

$$C_{gsi} = f(C_{fmlw} \cdot f(\epsilon_{fm}, 0.8) \cdot (\exp(f_{val}, \text{FEFF}, (v_{gs} - v_{th}), v_{ds})))$$

Otherwise, $v_{ds} \geq v_{dsat}$:

$$v_{dsx} = v_{dsat}$$

$$C_{gdi} = C_{fmlw}$$

$$C_{gsi} = \frac{C_{fmlw}}{2}$$

If $v_{dsx} \neq 0$, then

$$c_{dnorm} = v_{dsx} \cdot \left(v_{gsx} - v_{th} - \frac{v_{dsx}}{2} \right)$$

Normalized drain current:

$$g_{m_{tft}} = v_{dsx}$$

$$g_{ds_{tft}} = v_{gsx} - v_{th} - v_{dsx}$$

$$cd1 = \text{beta} \cdot c_{dnorm}$$

Drain current without velocity saturation effect:

$$beta = beta \cdot fgate$$

$$idrain = beta \cdot cdnorm$$

$$gm_{ift} = (beta \cdot gm_{ift}) + (dfgdvg \cdot cd1)$$

Velocity saturation factor:

If $VMAX \neq 0$, then

$$fdrain = \frac{1}{\left(1 + \left(\frac{vdsx}{vdsc}\right)\right)}$$

$$dfddvg = -dfgdvg \cdot \frac{((fdrain)^2) \cdot vdsx}{(vdsc \cdot fgate)}$$

$$dfddvd = \frac{-(fdrain^2)}{vdsc}$$

Strong inversion current:

$$gm_{ift} = (fdrain \cdot gm_{ift}) + (dfddvg \cdot idrain)$$

$$gds_{ift} = (fdrain \cdot gds_{ift}) + (dfddvd \cdot idrain)$$

$$idrain = fdrain \cdot idrain$$

$$beta = beta \cdot fdrain$$

$$Ids = idrain \cdot f(GO, vgs, DEFF, vds)$$

$$gm = f(gm_{ift}, GO)$$

$$gds = f(gds_{ift}, GO, DEFF)$$

Weak inversion current:

If $vgs < von$, then

$$idrain = idrain \cdot \exp\left(\frac{(vgs - von)}{(vt \cdot xn)}\right)$$

$$Ids = idrain + f(GO, vgs, DEFF, vds)$$

$$gm_{ift} = \frac{idrain}{(vt \cdot xn)}$$

$$gm = f(gm_{ift}, GO)$$

$$gds_{ift} = gds_{ift} \cdot \exp\left(\frac{(vgs - von)}{(vt \cdot xn)}\right)$$

$$gds = gds_{ift} + f(GO, DEFF)$$

vdsx = 0 :

$$Ids = f(GO \cdot vgs, DEFF, vds)$$

$$gm = GO$$

$$gds_{ift} = beta \cdot (vgsx - vth)$$

If NFS ≠ 0 and vgs < von , then

$$gds_{ift} = gds_{ift} \cdot \exp\left(\frac{(vgs - von)}{(vt \cdot xn)}\right)$$

$$gds = f(gds_{ift}, GO, DEFF)$$

Cgd, Cgs

$$Cgd = Cgdi + CGDO$$

$$Cgs = Cgsi + CGSO$$

Level 40 Model Topology

Figure 16-12: shows the topology of the Level 40 model.

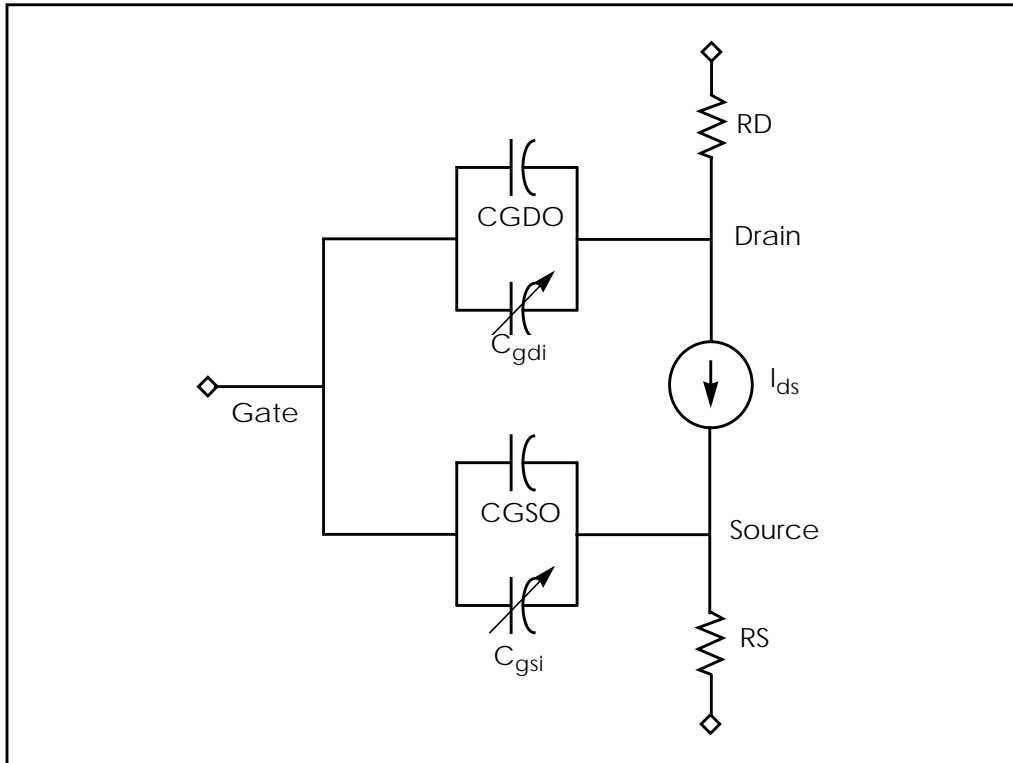


Figure 16-12: Level 40 HP a-Si TFT Topology

Level 47 BSIM3 Version 2 MOS Model

The BSIM3 version 2.0 MOS model from UC Berkeley is available as the Level 47 HSPICE model.

Level 47 Model Parameters

Name	Units	Default	Comments
VTH0	V	0.7	threshold voltage of long channel at $V_{bs} = 0$ and small V_{ds} (0.7 for n-channel, - 0.7 for p-channel)
K1	$V^{1/2}$	0.53	first-order body effect coefficient
K2		-0.0186	Second-order body effect coefficient
K3		80.0	narrow width effect coefficient
K3B	1/V	0	body width coefficient of narrow width effect
KT1	V	-0.11	temperature coefficient for threshold voltage
KT2		0.022	body bias coefficient of threshold temperature effect
GAMMA1	$V^{1/2}$	See "BSIM3 Model Equations "	Body effect coefficient, near interface
GAMMA2	$V^{1/2}$	See "Level 47 Model Equations "	body effect coefficient in the bulk
W0	m	2.5e-6	narrow width effect coefficient
NLX	m	1.74e-7	lateral nonuniform doping along channel

Name	Units	Default	Comments
TOX	m	150e-10	gate oxide thickness
XJ	m	0.15e-6	junction depth
DL	m	0.0	channel length reduction on one side (multiplied by SCALM)
DW	m	0.0	channel width reduction on one side (multiplied by SCALM)
NPEAK	cm ⁻³ (see Note 8.)	1.7e17	peak doping concentration near interface
NSUB	cm ⁻³	6.0e16	substrate doping concentration
PHI	V	See "BSIM3 Model Equations"	surface potential under strong inversion
XT	m	1.55e-7	doping depth
VBM	V	-5.0	maximum substrate bias
VBX	V	See "BSIM3 Model Equations"	V_{bs} at which the depletion width equals XT
DVT0		2.2	short-channel effect coefficient 0
DVT1		0.53	short-channel effect coefficient 1
DVT2	1/V	-0.032	short-channel effect coefficient 2
U0	m ² /Vsec (see Note 8, below)	0.067	low field mobility at T = TREF (0.067 for n-channel, 0.025 for p-channel)

Name	Units	Default	Comments
UA	m/V	2.25e-9	first-order mobility degradation coefficient
UA1	m/V	4.31e-9	temperature coefficient of UA
UB	m ² /V ²	5.87e-19	Second-order mobility degradation coefficient
UB1	m ² /V ²	-7.61e-18	temperature coefficient of UB
UC	1/V	0.0465	body bias sensitivity coefficient of mobility
UC1	1/V	-0.056	temperature coefficient of UC
VSAT	cm/sec	8e6	saturation velocity of carrier at T = TREF
AT	m/sec	3.3e4	temperature coefficient of VSAT
RDSW	ohm · μm	0.0	source drain resistance per unit width
RDS0	ohm	0.0	source drain contact resistance
LDD	m	0.0	total length of LDD region
ETA		0.3	coefficient of drain voltage reduction
ETA0		0.08	subthreshold region DIBL (Drain Induced Barrier Lowering) coefficient
ETAB	1/V	-0.07	subthreshold region DIBL coefficient
EM	V/m	4.1e7	electrical field in channel above which hot carrier effect dominates
NFACTOR		1.0	subthreshold region swing
VOFF	V	-0.11	offset voltage in subthreshold region
LITL	m		characteristic length. The default is
			$LITL = \left(\frac{\epsilon_{si} T_{ox} X_j}{\epsilon_{ox}} \right)^{1/2}$
VGLOW	V	-0.12	lower bound of the weak-strong inversion transition region

Name	Units	Default	Comments
VGHIGH	V	0.12	upper bound of the weak-strong inversion transition region
CDSC	F/m ²	2.4e-4	drain/source and channel coupling capacitance
CDSCB	F/Vm ²	0	body coefficient for CDSC
CIT	F/m ²	0.0	interface state capacitance
PCLM		1.3	coefficient of channel length modulation
PDIBL1		0.39	DIBL (Drain Induced Barrier Lowering) effect coefficient 1
PDIBL2		0.0086	DIBL effect coefficient 2
DROUT		0.56	DIBL effect coefficient 3
DSUB		DROUT	DIBL coefficient in subthreshold region
PSCBE1	V/m	4.24e8	substrate current induced body effect exponent 1
PSCBE2	m/V	1.0e-5	substrate current induced body effect coefficient 2
A0		1	bulk charge effect. The default is 4.4 for PMOS.
TNOM (TREF)	°C	25	temperature at which parameters are extracted. This parameter defaults to the option <i>TNOM</i> , which defaults to 25 °C. See 4 and 5 in "Reminders for this Installation," below.
SUBTHMO D		2	subthreshold model selector
SATMOD		2	saturation model selector
KETA	1/V	-0.047	body bias coefficient of the bulk charge effect
A1	1/V	0	first nonsaturation factor (0 for NMOS, 0.23 for PMOS)
A2		1.0	second nonsaturation factor (1.0 for NMOS, 0.08 for PMOS)
UTE		-1.5	mobility temperature exponent

Name	Units	Default	Comments
KT1L	Vm	0	channel length sensitivity of temperature coefficient for threshold voltage
UC0*	(V/m) ²		temperature coefficient
BULKMOD		1	bulk charge model selector
XPART		1	charge partitioning flag
VFB	V		flat-band voltage
PVAG		0	gate dependence of output resistance

* UC0 has no effect on the model

Using the BSIM3 Version 2 MOS Model in HSPICE

The HSPICE Level 47 model uses the same model parameters for source/drain diode current, capacitance, and resistance as do the other HSPICE MOS levels. The model parameter ACM controls the choice of source/drain equations.

The HSPICE Level 47 model also uses the same noise equations as the other levels. The parameter NLEV controls the choice of noise equations.

This model, like all models in HSPICE, can be parametrized. This is useful for modeling process skew, either by worst-case corners or by Monte Carlo. For information on worst-case and Monte Carlo analysis, see Chapter 11, “Optimizing Performance.”

Notes

1. Set LEVEL=47 to identify the model as a BSIM3 model.
2. This model is based on BSIM3 version 2.0 from UC Berkeley. Code was received from UC Berkeley in July 1994, in the form of SPICE3e2. Changes announced in a letter from UCB September 13, 1994, have been included. DC sweeps have been checked against SPICE3e2.

3. The default setting for *CAPOP* is *CAPOP*=13, which is the BSIM1 charge-conserving capacitance model. The BSIM3 capacitance model has not been installed.
4. The Level 47 model supports the model parameter name *TNOM* as an alias for *TREF*. The conventional terminology in HSPICE is *TREF*, which is supported as a model parameter in all HSPICE MOS levels. The alternative name *TNOM* is supported for Level 47, for compatibility with SPICE3.
5. The default room temperature is 25°C in HSPICE, but is 27°C in SPICE3. If the BSIM3 model parameters are specified at 27°C, *TREF*=27 should be added to the model, so that the model parameters is interpreted correctly. It is a matter of choice whether or not to set the nominal simulation temperature to 27, by adding *.OPTION TNOM=27* to the netlist. This should be done when testing HSPICE versus SPICE3.
6. The default of *DERIV* is zero, the analytical method. *DERIV* can be set to 1 for the finite difference method. The analytic derivatives in the SPICE3e2 code are not exact in some regions. Setting *DERIV*=1 gives more accurate derivatives (*GM*, *GDS*, *GMBS*), but consumes more CPU time.
7. There are three ways for the BSIM3 model to calculate V_{th} :
 - Using *K1* and *K2* values that are user specified
 - Using *GAMMA1*, *GAMMA2*, *VBM*, and *VBX* values entered in the *.MODEL* statement
 - Using *NPEAK*, *NSUB*, *XT*, and *VBM* values that are user specified
8. The model parameters *NPEAK* and *U0* can be entered in meters or centimeters. *NPEAK* is converted to cm^{-3} as follows: if *NPEAK* is greater than 1e20, it is multiplied by 1e-6. *U0* is converted to m^2/Vsec as follows: if *U0* is greater than 1, it is multiplied by 1e-4. You must enter the parameter *NSUB* in cm^{-3} units.
9. The specified value of *VTH0* for p-channel in the *.MODEL* statement should be negative.
10. The default value of *KTI* is -0.11. The negative sign ensures that the absolute value of threshold decreases with increasing temperature for NMOS and PMOS.

11. Model parameter *LITL* is not allowed to go below a minimum value of 1.0e-9 m, to avoid a possible divide by zero error.
12. *VSAT*, after temperature adjustment, is not allowed to go below a minimum value of 1.0e4 m/sec, to assure that it is positive after temperature compensation.
13. There are seven model parameters for accommodating the temperature dependencies of six temperature dependent model variables. They are *KT1* and *KT2* for *VTH*, *UTE* for *U0*, *AT* for *VSAT*, *UA1* for *UA*, *UB1* for *UB*, and *UC1* for *UC*.
14. Set up the conversion of temperature between HSPICE and SPICE3 as follows:

Example

SPICE3: .OPTIONS TEMP=125

```
.MODEL NCH NMOS LEVEL=8
+TNOM =27 . . .
```

HSPICE: .TEMP 125

```
.MODEL NCH NMOS LEVEL=47
+TREF =27 . . .
```

15. The option *SCALM* does not affect the parameters unique to this model, but it does affect the common MOS parameters, such as *XL*, *LD*, *XW*, *WD*, *CJ*, *CJSW*, *JS*, and *JSW*.
16. Level 47 uses the common HSPICE MOS parasitic models, specified by *ACM*.
17. Level 47 uses the common HSPICE MOS noise models, specified by *NLEV*.
18. *DELVTO* and *DTEMP* on the element line can be used with Level 47.
19. The impact ionization current determined by the model parameters *PSCBE1* and *PSCBE2* contributes to the drain-source current; it does not contribute to bulk current.

Leff and Weff Equations for BSIM3 Version 2.0

The standard HSPICE equations for Leff and Weff are

$$L_{\text{eff}} = L + XL - (2 \cdot LD)$$

$$W_{\text{eff}} = W + XW - (2 \cdot WD)$$

The UCB SPICE3 equations used for BSIM3 are

$$L_{\text{eff}} = L - (2 \cdot DL)$$

$$W_{\text{eff}} = W - (2 \cdot DW)$$

The units for these parameters are meters, with defaults of zero.

HSPICE uses the standard HSPICE equation for both cases, and accepting DL(DW) as the value for LD(WD). If both LD(WD) and DL(DW) are specified in an HSPICE .MODEL statement, HSPICE uses the LD(WD) value.

If LDAC and WDAC are included in the .MODEL statement,

$$L_{\text{eff}} = L + XL - 2 \cdot LDAC, \quad W_{\text{eff}} = W + XW - 2 \cdot WDAC$$

The model uses the values of LD(DL) and WD(DW) to generate defaults for CGSO, CGDO, and CGBO. The values are also used with parameters RS and RD for ACM>0.

Example

The following two models give the same HSPICE results:

```
* HSPICE style:
.MODEL n1 nmos level=47 XL=0.1e6 LD=0.15e-6
+ SatMod=2 SubthMod=2 BulkMod=1
+ CGSO=0.3e-9 CGDO=0.3e-9 CGBO=0
* SPICE3 style:
.MODEL n2 nmos level=47 LD=0.1e-6
+ SatMod=2 SubthMod=2 BulkMod=1
+ CGSO=0.3e-9 CGDO=0.3e-9 CGBO=0
```

Level 47 Model Equations

The following model equations are based on the source code of BSIM3.

Threshold Voltage

Model Parameters

V_{th0} , $K1$, $K2$, ϕ_s , N_{lx} , $K3$, W_0 , T_{ox} , V_{bi} , D_{vt0} , D_{vt1} , D_{vt2} , N_{peak} , N_{sub} , Y_1 , Y_2 , V_{bx} , V_{bm} , V_{bi} , X_t , $TREF$

$$V_{th} = V_{th0} + K1(\sqrt{\phi_s - V_{bs}} - \sqrt{\phi_s}) - K2V_{bs} + K1\left(\sqrt{1 + \frac{N_{lx}}{L_{eff}}\sqrt{\frac{\phi_s}{\phi_s - V_{bs}}}} - 1\right)\sqrt{\phi_s}$$

$$+ (K3 + K3B \cdot V_{bs}) \cdot \left(\frac{T_{ox}}{W_{eff} + W_0}\right)\phi_s - \Delta V_{th}$$

$$T_{ratio} = \frac{(TEMP + DTEMP + 273.15)}{(TREF + 273.15)}$$

$$\Delta V_{th} = \theta_{th}(L_{eff}) \cdot (V_{bi} - \phi_s)$$

$$\theta_{th}(L_{eff}) = D_{vt0} \cdot \left[\exp\left(\frac{-D_{vt1} \cdot L_{eff}}{2l_t}\right) + 2 \exp\left(\frac{-D_{vt1} \cdot L_{eff}}{l_t}\right) \right]$$

$$l_t = \sqrt{3 \cdot T_{ox} \cdot X_{dep}} \cdot (1 + D_{vt2} \cdot V_{bs})$$

$$X_{dep} = \sqrt{\frac{2 \cdot \epsilon_{si} \cdot (\phi_s - V_{bs})}{q \cdot N_{peak}}}$$

If ϕ_s is not specified as a model parameter, then

$$\phi_s = 2 \cdot V_{tm} \cdot \ln\left(\frac{N_{peak}}{n_i}\right) \quad (N_{peak} \text{ and } n_i \text{ in cm}^{-3})$$

$$V_{tm} = K \cdot T/q$$

$$n_i = 1.45e10 \cdot \left(\frac{T}{300.15}\right)^{1.5} \cdot \exp(21.5565981 - Eg/(2 \cdot V_{tm}))$$

$$Eg = 1.16 - (7.02e-4) \cdot T^2/(T + 1108.0)$$

If $K1$, $K2$ are not specified as model parameters, then they are calculated as follows:

$$K_1 = \Upsilon_2 - 2 \cdot K_2 \cdot \sqrt{\phi_s - V_{bm}}$$

$$K_2 = (\Upsilon_1 - \Upsilon_2) \cdot \frac{\sqrt{\phi_s - V_{bx}} - \sqrt{\phi_s}}{2 \cdot \sqrt{\phi_s} \cdot (\sqrt{\phi_s - V_{bm}} - \sqrt{\phi_s}) + V_{bm}}$$

$$\Upsilon_1 = \frac{\sqrt{2 \cdot q \cdot \epsilon_{si} \cdot N_{\text{peak}}}}{C_{\text{ox}}}$$

$$\Upsilon_2 = \frac{\sqrt{2 \cdot q \cdot \epsilon_{si} \cdot N_{\text{sub}}}}{C_{\text{ox}}}$$

$$V_{bx} = \phi_s - \left(\frac{q \cdot N_{\text{peak}} \cdot X_t^2}{2 \cdot \epsilon_{si}}\right)$$

If V_{bi} is not specified as a model parameter, then

$$V_{bi} = \frac{k \cdot T}{q} \cdot \ln\left(\frac{1.0e22 \cdot N_{\text{peak}}}{n_i^2}\right)$$

Mobility of Carrier

Model Parameters

$$\mu_0, U_a, U_b, U_c$$

$$\mu_{\text{eff}} = \frac{\mu_0}{1 + U_a \cdot \left(\frac{V_{gs} + V_{th}}{T_{ox}} \right) + U_b \cdot \left(\frac{V_{gs} + V_{th}}{T_{ox}} \right)^2 + U_c \cdot V_{bs}}$$

Drain Saturation Voltage

Model Parameters

$$A_0, v_{\text{sat}}, X_j, A_1, A_2, R_{ds0}, R_{dsw}$$

Rds and Pfactor:

$$R_{ds} = R_{ds0} + R_{dsw} / (1e6 \cdot W_{\text{eff}})$$

$$Pfactor = A_1 \cdot V_{gst} + A_2 \quad (\text{if } Pfactor > 1, \text{ it is set to } Pfactor = 1)$$

$$V_{gst} = V_{gs} - V_{th}$$

Vdsat for the case Rds = 0 and Pfactor = 1:

$$V_{\text{dsat}} = \frac{E_{\text{sat}} \cdot L_{\text{eff}} \cdot V_{gst}}{A_{\text{bulk}} \cdot E_{\text{sat}} \cdot L_{\text{eff}} + V_{gst}}$$

For BULKMOD = 1,

$$A_{\text{bulk}} = \left(1 + \frac{K1 \cdot A_0 \cdot L_{\text{eff}}}{(L_{\text{eff}} + T1) \cdot T1s \cdot 2} \right) / (1 + KETA \cdot V_{bs})$$

For BULKMOD = 2,

$$A_{\text{bulk}} = \left(\frac{K1 \cdot A_0 \cdot L_{\text{eff}}}{(L_{\text{eff}} + T1) \cdot \sqrt{\phi_s} \cdot 2} \right) / (1 + KETA \cdot V_{bs})$$

$$T1 = 2 \cdot \sqrt{X_j \cdot X_{\text{dep}}}$$

For $V_{bs} \leq 0$,

$$T1s = \sqrt{\phi_s - V_{bs}}$$

For $V_{bs} \geq 0$,

$$T1s = \frac{\phi_s \cdot \sqrt{\phi_s}}{V_{bs} + \frac{\phi_s}{2}}$$

$$E_{\text{sat}} = 2 \cdot \frac{v_{\text{sat}}}{\mu_{\text{eff}}}$$

V_{dsat} for the general case:

$$V_{\text{dsat}} \text{ is the solution of } Tmpa * V_{\text{dsat}} * V_{\text{dsat}} - Tmpb * V_{\text{dsat}} + Tmpc = 0$$

$$V_{\text{dsat}} = \left(Tmpb - \sqrt{Tmpb^2 - 4 \cdot Tmpa \cdot Tmpc} \right) / (2 \cdot Tmpa)$$

$$Tmpa = A_{\text{bulk}} \cdot (A_{\text{bulk}} \cdot W_{\text{eff}} \cdot v_{\text{sat}} \cdot C_{\text{ox}} \cdot R_{ds} - 1 + 1/Pfactor)$$

$$Tmpb = V_{gst} \cdot (2/Pfactor - 1) + (A_{\text{bulk}} \cdot E_{\text{sat}} \cdot L_{\text{eff}}) + (3 \cdot A_{\text{bulk}} \cdot V_{gst} \cdot W_{\text{eff}} \cdot v_{\text{sat}} \cdot C_{\text{ox}} \cdot R_{ds})$$

$$Tmpc = (V_{gst} \cdot E_{\text{sat}} \cdot L_{\text{eff}}) + (V_{gst}^2 \cdot 2 \cdot W_{\text{eff}} \cdot v_{\text{sat}} \cdot C_{\text{ox}} \cdot R_{ds})$$

Linear Region

$$I_{dslin0} = \mu_{\text{eff}} \cdot C_{\text{ox}} \cdot \frac{W_{\text{eff}}}{L_{\text{eff}}} \cdot \frac{1}{1 + V_{ds}/(E_{\text{sat}} \cdot L)} \cdot \left(V_{gst} - V_{\text{th}} - A_{\text{bulk}} \cdot \frac{V_{ds}}{2} \right) \cdot V_{ds}$$

$$I_{ds} = \frac{I_{dslin0}}{1 + \frac{R_{ds} \cdot I_{dslin0}}{V_{ds}}}$$

Saturation Region

Model Parameters

$$littl, \text{eta}, L_{dd}, E_m, D_{\text{rout}}, P_{\text{clm}}, P_{\text{dibl1}}, P_{\text{dibl2}}, P_{\text{scbe1}}, P_{\text{scbe2}}$$

Vasat and Fvag:

$$V_{\text{asat}} = \frac{E_{\text{sat}} \cdot L_{\text{eff}} + V_{\text{dsat}} + 2R_{ds} \cdot v_{\text{sat}} \cdot C_{\text{ox}} \cdot W_{\text{eff}} \cdot \left(V_{gst} - \frac{A_{\text{bulk}} \cdot V_{\text{dsat}}}{2} \right)}{2/P_{\text{factor}} - 1 + R_{ds} \cdot v_{\text{sat}} \cdot C_{\text{ox}} \cdot W_{\text{eff}} \cdot A_{\text{bulk}}}$$

$$F_{\text{vag}} = 1 + \frac{P_{\text{vag}} \cdot V_{gst}}{E_{\text{sat}} \cdot L_{\text{eff}}}$$

Early Voltage, satMod = 1:

$$V_A = V_{\text{asat}} + F_{\text{vag}} \cdot \left(\frac{1 + \text{eta} \cdot \frac{L_{dd}}{littl}}{P_{\text{clm}} \cdot A_{\text{bulk}}} \right) \cdot \left(\frac{(A_{\text{bulk}} \cdot E_{\text{sat}} \cdot L_{\text{eff}} + V_{gst} - \lambda \cdot (V_{ds} - V_{\text{dsat}})) \cdot (V_{ds} - V_{\text{dsat}})}{E_{\text{sat}} \cdot littl} \right)$$

$$\lambda = \frac{A_{\text{bulk}} \cdot E_{\text{sat}} \cdot L_{\text{eff}} + (V_{gst})}{2 \cdot littl \cdot E_m}$$

Early Voltage, satMod = 2:

$$V_A = V_{\text{asat}} + F_{\text{vag}} \cdot U_{\text{vds}} \cdot \left(\frac{1}{V_{\text{aclm}}} + \frac{1}{V_{\text{adibl}}} \right)^{-1}$$

$$U_{\text{vds}} = 1 + \text{eta} \cdot \frac{L_{\text{dd}}}{l_{\text{itl}}}$$

$$V_{\text{aclm}} = \frac{1}{P_{\text{clm}}} \cdot \frac{A_{\text{bulk}} \cdot E_{\text{sat}} \cdot L_{\text{eff}} + V_{\text{gst}}}{A_{\text{bulk}} \cdot E_{\text{sat}} \cdot l_{\text{itl}}} \cdot (V_{\text{ds}} - V_{\text{dsat}})$$

$$V_{\text{adibl}} = \frac{1}{\theta_{\text{rout}}} \cdot \left[(V_{\text{gs}} - V_{\text{th}}) - \left(\frac{1}{A_{\text{bulk}} \cdot V_{\text{dsat}}} + \frac{1}{V_{\text{gst}}} \right)^{-1} \right]$$

$$\theta_{\text{rout}} = P_{\text{dibl1}} \cdot \left[\exp\left(\frac{-D_{\text{rout}} \cdot L_{\text{eff}}}{2 \cdot l_t}\right) + 2 \exp\left(\frac{-D_{\text{rout}} \cdot L_{\text{eff}}}{l_t}\right) \right] + P_{\text{dibl2}}$$

$$V_{\text{ahce}} = \left[\frac{P_{\text{scbe2}}}{L_{\text{eff}}} \cdot \exp\left(\frac{-P_{\text{scbe1}} \cdot l_{\text{itl}}}{V_{\text{ds}} - V_{\text{dsat}}}\right) \right]^{-1}$$

Drain Current

$$I_{\text{dsat}} = W_{\text{eff}} \cdot v_{\text{sat}} \cdot C_{\text{ox}} \cdot (V_{\text{gs}} - V_{\text{th}} - A_{\text{bulk}} \cdot V_{\text{dsat}}) \cdot P_{\text{factor}}$$

$$P_{\text{factor}} = A_1 \cdot V_{\text{gst}} + A_2$$

$$I_{\text{ds}} = I_{\text{dsat}} \cdot \left(1 + \frac{V_{\text{ds}} - V_{\text{dsat}}}{V_A} \right) \cdot \left(1 + \frac{V_{\text{ds}} - V_{\text{dsat}}}{V_{\text{ahce}}} \right)$$

Subthreshold Region

Model Parameters

$Nfactor$, C_{dsc} , C_{dscb} , V_{off} , C_{it} , D_{sub} , eta_0 , eta_b

n and DIBL:

$$n = 1 + \frac{Nfactor \cdot 1.034e-10}{X_{dep} \cdot C_{ox}} + \frac{(C_{dsc} + C_{dscb} \cdot V_{bs}) \cdot \left[\exp\left(\frac{-L_{eff}}{2 \cdot l_t}\right) + 2 \exp\left(\frac{-L_{eff}}{l_t}\right) \right] + C_{it}}{C_{ox}}$$

$$DIBL = (eta_0 + eta_b \cdot V_{bs}) \cdot \left[\exp\left(\frac{-D_{sub} \cdot L_{eff}}{2 \cdot l_{t0}}\right) + 2 \exp\left(\frac{-D_{sub} \cdot L_{eff}}{l_{t0}}\right) \right]$$

$$l_{t0} = \sqrt{3 \cdot T_{ox} \cdot X_{dep0}}$$

$$X_{dep0} = \sqrt{\frac{2 \cdot \epsilon_{si} \cdot \phi_s}{q \cdot N_{peak}}}$$

If subthMod = 0,

$$I_{ds} = g_m = g_{ds} = g_{mb} = 0$$

If subthMod = 1,

$$I_{ds} = \frac{I_{limit} \cdot I_{exp}}{I_{limit} + I_{exp}} \cdot \left[1 - \exp\left(\frac{-V_{ds}}{V_{tm}}\right) \right]$$

$$I_{limit} = \frac{9}{2} \cdot u_0 \cdot \sqrt{\frac{q \epsilon_{si} \cdot N_{peak}}{2 \cdot \phi_s}} \cdot \frac{W_{eff}}{L_{eff}} \cdot V_{tm}^2$$

$$I_{exp} = u_0 \cdot \sqrt{\frac{q \cdot \epsilon_{si} \cdot N_{peak}}{2 \cdot \phi_s}} \cdot \frac{W_{eff}}{L_{eff}} \cdot V_{tm}^2 \cdot \exp\left(\frac{V_{gs} - V_{th} - V_{off} + DIBL \cdot V_{ds}}{n \cdot V_{tm}}\right)$$

If subthMod = 2,

$$I_{ds} = u0 \cdot \sqrt{\frac{q \cdot \epsilon_{si} \cdot N_{peak}}{2 \cdot \phi_s}} \cdot \frac{W_{eff}}{L_{eff}} \cdot V_{tm}^2 \cdot \left[1 - \exp\left(\frac{-V_{ds}}{V_{tm}}\right) \right] \cdot \exp\left(\frac{V_{gs} - V_{th} - V_{off} + DIBL \cdot V_{ds}}{n \cdot V_{tm}}\right)$$

Transition Region (for subthMod = 2 only)

Model Parameters

$$V_{gshigh}, V_{gslow}$$

$$I_{ds} = (1-t)^2 \cdot I_{dslow} + 2 \cdot (1-t) \cdot t \cdot I_p + t^2 \cdot I_{dshigh}$$

$$t = \left(\frac{V_p - V_{gslow}}{V_{gslow} - 2 \cdot V_p + V_{gshigh}} \right) \cdot \left(\sqrt{1 + \frac{(V_{gslow} - 2 \cdot V_p + V_{gshigh})(V_{gs} - V_{th} - V_{gslow})}{(V_p - V_{gslow})^2}} - 1 \right)$$

$$V_p = \frac{(g_{mhigh} \cdot V_{gshigh} - g_{mlow} \cdot V_{gslow}) - (I_{dshigh} - I_{dslow})}{g_{mhigh} - g_{mlow}}$$

$$I_p = I_{dslow} + g_{mlow} \cdot (V_p - V_{gslow})$$

Temperature Compensation

Model Parameters

$$A_r, U_{a1}, U_{b1}, U_{c1}, KT1, KT2, UTE$$

$$V_{th}(temp) = V_{th}(tref) + (KT1 + KT2 \cdot V_{bs}) \cdot (T_{ratio} - 1)$$

$$u0(temp) = u0(tref) \cdot (T_{ratio})^{UTE}$$

$$V_{sat}(temp) = V_{sat}(tref) - A_r \cdot (T_{ratio} - 1)$$

$$U_a(temp) = U_a(tref) + U_{a1} \cdot (T_{ratio} - 1)$$

$$U_b(temp) = U_b(tref) + U_{b1} \cdot (T_{ratio} - 1)$$

$$U_c(temp) = U_c(tref) + U_{c1} \cdot (T_{ratio} - 1)$$

Sample PMOS Model

The following is an example of a PMOS model. Note that VTH0 is negative.

```
.model pch PMOS level=47
+Tnom=27.0
+Npeak= 1.5E+23  Tox=7.0E-09  Xj=1.0E-07
+d1= 0.2E-06  dw=-0.1E-06
+SatMod= 2  SubthMod= 2  BulkMod= 1
+Vth0= -.8  Phi= .7  K1= .5  K2=0.03  K3= 0
+Dvt0= 48  Dvt1= .6  Dvt2=-5e-4
+Nlx=0  W0= 0
+Vsat= 9E6  Ua= 1E-09  Ub= 0  Uc= -3E-02
+Rds0= 180  Rdsw= 0  U0= 7E-03
+A0= .87
+Voff=-.07  NFactor= 1.5  Cit=-3E-05
+Cdsc= 6E-02  Vglow=-.12  Vghigh= .12
+Pclm= 77  Pdibl1= 0  Pdibl2= 2E-011
+Drout= 0  Pscbe1= 0  Pscbe2= 1E-28
+Eta= 0  Litl= 4.5E-08
+Em= 0  Ldd= 0
+kt1=-.3  kt2=-.03
+At= 33000
+Ua1= 4E-09  Ub1= 7E-18  Uc1= 0
```

Level 49 BSIM3 Version 3 MOS Model

The BSIM3v3 MOS model from UC Berkeley has been installed as Level 49 in Star-Hspice. Level 49 is compliant with the Berkeley release except for some differences in default values and the absence of the non-quasi static (NQS) capacitance model.

Level 49 also provides enhancements to the standard BSIM3 model including the Star-Hspice junction and noise models and can be parametrized.

Parameterization is useful for modeling process skew, either by worst-case corners or Monte Carlo analysis. See Chapter 9, “Parametric Variation and Statistical Analysis,” for information on worst-case and Monte Carlo analysis. Specific level 49 enhancements and differences between level 49 and Berkeley-BSIM3v3 are discussed below.

Version

The model parameter, VERSION, selects among the various Berkeley releases of BSIM3v3 as follows:

- Version 3.0 Berkeley (October 31, 1995) default for HSPICE96.1,96.2,96.3
- Version 3.1 Berkeley (December 12, 1997) default for HSPICE97.1,97.2
- Version 3.11 Berkeley (December 12, 1997) default for HSPICE97.4
- Version 3.1 is maintained for compatibility with the older Star-Hspice version. In order to realize the 97.4 enhancements and bug fixes make sure that VERSION is set or defaults to 3.11.

Model Parameter Defaults

The following parameter default values deviate from the Berkeley BSIM3v3 default values and should be set explicitly in the model card:

VERSION, SFVTFLAG, ACM, NQS=0, XPART, CAPMOD, JS, CJ, CJSW

Star-Hspice Enhancements

The performance of level 49 has been improved by reducing model equation complexity, replacing some calculations with spline functions, and optimizing the compiler. The result is a reduction in simulation time of up to 35% (for both 3.11 and 3.1 versions) compared to previous releases while maintaining accuracy to 5 digits or better. The use of spline functions can be disabled by setting the model parameter, SFVTFLAG=0, in the model card. The default value, SFVTFLAG=1, enables the spline functions.

In the 12/10/96 release of BSIM3v3, Berkeley offers the BSIM1 capacitance model as CAPMOD=0. In the 3.1 and 3.11 versions in Star-Hspice we offer a modified BSIM1 capacitance model based on the Star-Hspice CAPOP=13 model. The current default is CAPMOD=0 for VERSION=3.1, 3.11 and CAPMOD=1 for VERSION=3.0.

The capacitance model CAPMOD=0 normally calculates the threshold voltage as $V_{th} = v_{fbc} + \phi + k1 * \sqrt{\phi - v_{bs}}$, where v_{fbc} is the model parameter VFBCV. This has the effect of eliminating any dependence on the parameter VTH0. To allow capacitance dependence on VTH0 please set the model parameter VFBFLAG=1. The capacitance model CAPMOD=0 will calculate the threshold voltage as $V_{th} = v_{fb} + \phi + k1 * \sqrt{\phi - v_{bs}}$, where v_{fb} is identical to the flatband voltage used in the drain current calculations. This setting will show capacitance dependence on VTH0. The VFBFLAG default value is 0.

Either Berkeley BSIM3v3 or standard Star-Hspice MOSFET junction diode models can be used in Level 49. Specifying ACM=0,1,2,3 will invoke the standard Star-Hspice junction model (see pg.15-19 to 15-36). The default ACM is zero.

The Berkeley BSIM3v3 junction model can be invoked by setting ACM=10,11,12,13. In addition, setting ACM=10-13 provides external source and drain parasitic resistances. These parasitic resistance equations are calculated using the corresponding ACM=0-3 parasitic resistance equations (see pg.15-19 to 15-36).

Note: ACM=10-13 only apply Star-Hspice area calculation equations to the parasitic resistors, R_s and R_d .

Star-Hspice equations are not used in calculating areas and perimeters for the Berkeley junction models. Note the following parameters are ignored when using ACM=0-3: NJ, CJSWG, PBSWG, MJSWG. The following parameters are ignored when using ACM=10-13: PHP, CJGATE.

The Star-Hspice noise equations (see pg. 15-71 to 15-73) are invoked when the parameter NLEV is specified in the model card. If NLEV is not specified, the Berkeley noise equations are invoked.

Printback of all model parameters with units is now enabled. The printback also indicates whether Berkeley or Star-Hspice junction diodes are invoked and which parameters are not used (e.g. CJGATE is not used when ACM=0-3).

Level 49 Model Parameters

The Level 49 model parameters are described in this section.

Model Flags

Name	Units	Default	Comments
<i>VERSION</i>	-	3.11	Selects from BSIM3 Versions 3.0, 3.1, 3.11 (version=3.11 is the HSPICE97.4 equivalent to BSIM3v3 version 3.1)
<i>PARAMCHK</i>	-	0	PARAMCHK=1 will check some model parameters for range compliance
<i>BINFLAG</i>	-	0	Uses wref, lref when set > 0.9
<i>MOBMOD</i>	-	1	mobility model selector
<i>CAPMOD</i>	-	0	Selects from Charge models 0,1,2 (default deviates from BSIM3v3 = 2)
<i>NOIMOD</i>	-	1	Berkeley noise model flag
<i>NLEV</i>	-	0 (off)	Star-Hspice noise model flag (non-zero overrides NOIMOD) (Star-Hspice specific)

<i>NQSMOD</i>	-	0 (off)	NQS Model is not supported in Level 49
<i>SFVTFLAG</i>	-	1 (on)	Spline function for Vth (Star-Hspice specific)
<i>VFBFLAG</i>	-	0 (off)	UFB selector for CAPMOD=0 (Star-Hspice specific)

Basic Model Parameters

Name	Units	Default	Comments
<i>TOX</i>	m	150e-10	gate oxide thickness
<i>XJ</i>	m	0.15e-6	junction depth
<i>NGATE</i>	cm ⁻³	infinite	Poly gate doping concentration
<i>VTH0</i> (<i>VTHO</i>)	V	0.7	threshold voltage of long channel device at $V_{bs} = 0$ and small V_{ds} (typically 0.7 for n-channel, - 0.7 for p-channel)
<i>NSUB</i>	cm ⁻³	6.0e16	substrate doping concentration
<i>NCH</i>	cm ⁻³ (see Note 6)	1.7e17	peak doping concentration near interface
<i>NLX</i>	m	1.74e-7	lateral nonuniform doping along channel
<i>K1</i>	V ^{1/2}	0.50	first-order body effect coefficient
<i>K2</i>	-	-0.0186	second-order body effect coefficient
<i>K3</i>	-	80.0	narrow width effect coefficient
<i>K3B</i>	1/V	0	body width coefficient of narrow width effect
<i>W0</i>	m	2.5e-6	narrow width effect coefficient

Name	Units	Default	Comments
<i>DVT0W</i>	1/m	0	narrow width coefficient 0, for V_{th} , at small L
<i>DVT1W</i>	1/m	5.3e6	narrow width coefficient 1, for V_{th} , at small L
<i>DVT2W</i>	1/V	-0.032	narrow width coefficient 2, for V_{th} , at small L
<i>DVT0</i>	-	2.2	short channel effect coefficient 0, for V_{th}
<i>DVT1</i>	-	0.53	short channel effect coefficient 1, for V_{th}
<i>DVT2</i>	1/V	-0.032	short channel effect coefficient 2, for V_{th}
<i>ETA0</i>	-	0.08	subthreshold region DIBL (Drain Induced Barrier Lowering) coefficient
<i>ETAB</i>	1/V	-0.07	subthreshold region DIBL coefficient
<i>DSUB</i>	-	DROUT	DIBL coefficient exponent in subthreshold region
<i>VBM</i>	V	-3.0	maximum substrate bias, for V_{th} calculation
<i>U0</i>	cm ² /V/ sec	670 nmos 250 pmos	low field mobility at $T = TREF = TNOM$
<i>UA</i>	m/V	2.25e-9	first-order mobility degradation coefficient
<i>UB</i>	m ² /V ²	5.87e-19	second-order mobility degradation coefficient
<i>UC</i>	1/V	-4.65e-11 or -0.0465	body bias sensitivity coefficient of mobility -4.65e-11 for MOBMOD=1,2 or, -0.0465 for MOBMOD = 3
<i>A0</i>	-	1.0	bulk charge effect coefficient for channel length

Name	Units	Default	Comments
AGS	1/V	0.0	gate bias coefficient of Abulk
BO	m	0.0	bulk charge effect coefficient for channel width
B1	m	0.0	bulk charge effect width offset
KETA	1/V	-0.047	body-bias coefficient of bulk charge effect
VOFF	V	-0.08	offset voltage in subthreshold region
VSAT	m/sec	8e4	saturation velocity of carrier at $T = TREF = TNOM$
A1	1/V	0	first nonsaturation factor
A2	-	1.0	second nonsaturation factor
RDSW	ohm · μm	0.0	parasitic source drain resistance per unit width
PRWG	1/V	0	gate bias effect coefficient of RDSW
PRWB	$1/V^{1/2}$	0	body effect coefficient of RDSW
WR	-	1.0	width offset from Weff for Rds calculation
NFACTOR	-	1.0	subthreshold region swing
CIT	F/m ²	0.0	interface state capacitance
CDSC	F/m ²	2.4e-4	drain/source and channel coupling capacitance
CDSCD	F/Vm ²	0	drain bias sensitivity of CDSC
CDSCB	F/Vm ²	0	body coefficient for CDSC
PCLM	-	1.3	coefficient of channel length modulation values ≤ 0 will result in an error message and program exit.

Name	Units	Default	Comments
<i>PDIBLC1</i>	-	0.39	DIBL (Drain Induced Barrier Lowering) effect coefficient 1
<i>PDIBLC2</i>	-	0.0086	DIBL effect coefficient 2
<i>PDIBLCB</i>	1/V	0	body effect coefficient of DIBL effect coefficients
<i>DROUT</i>	-	0.56	length dependence coefficient of the DIBL correction parameter in R_{out}
<i>PSCBE1</i>	V/m	4.24e8	substrate current induced body effect exponent 1
<i>PSCBE2</i>	V/m	1.0e-5	substrate current induced body effect coefficient 2
<i>PVAG</i>	-	0	gate dependence of Early voltage
<i>DELTA</i>	V	0.01	effective Vds parameter
<i>ALPHA0</i>	m/V	0	the first parameter of impact ionization current
<i>BETA0</i>	V	30	the second parameter of impact ionization current
<i>RSH</i>	0.0	ohm/square	source/drain sheet resistance in ohm per square

AC and Capacitance Parameters

Name	Units	Default	Comments
<i>XPART</i>	-	1	charge partitioning rate flag (default deviates from BSIM3V3=0)
<i>CGSO</i>	F/m	p1 (see Note1)	non-LDD region source-gate overlap capacitance per unit channel length
<i>CGDO</i>	F/m	p2 (see Note2)	non-LDD region source-gate overlap capacitance per unit channel length
<i>CGBO</i>	F/m	0	gate-bulk overlap capacitance per unit channel length
<i>CGS1</i>	F/m	0.0	lightly doped source-gate overlap region capacitance
<i>CGD1</i>	F/m	0.0	lightly doped drain-gate overlap region capacitance
<i>CKAPPA</i>	F/m	0.6	coefficient for lightly doped region overlap capacitance fringing field capacitance
<i>CF</i>	F/m	(see Note3)	fringing field capacitance
<i>CLC</i>	m	0.1e-6	constant term for the short channel model
<i>CLE</i>	-	0.6	exponential term for the short channel model

Length and Width Parameters

Name	Units	Default	Comments
<i>WINT</i>	m	0.0	width offset fitting parameter from I-V without bias
<i>WLN</i>	-	1.0	power of length dependence of width offset
<i>WW</i>	m^{WWN}	0.0	coefficient of width dependence for width offset
<i>WWN</i>	-	1.0	power of width dependence of width offset.
<i>WWL</i>	$m^{WWN} * m^{WLN}$	0.0	coefficient of length and width cross term for width offset
<i>DWG</i>	m/V	0.0	coefficient of Weff's gate dependence
<i>DWB</i>	$m/V^{1/2}$	0.0	coefficient of Weff's substrate body bias dependence
<i>LINT</i>	m	0.0	length offset fitting parameter from I-V without bias
<i>LL</i>	m^{LLN}	0.0	coefficient of length dependence for length offset
<i>LLN</i>	-	1.0	power of length dependence of length offset
<i>LW</i>	m^{LWN}	0.0	coefficient of width dependence for length offset
<i>LWN</i>	-	1.0	power of width dependence of length offset
<i>LWL</i>	$m^{LWN} * m^{LLN}$	0.0	coefficient of length and width cross term for length offset
<i>DLC</i>	m	LINT	length offset fitting parameter from CV
<i>DWC</i>	m	WINT	width offset fitting parameter from CV

Temperature Parameters

Name	Units	Default	Comments
<i>KT1</i>	V	0.0	temperature coefficient for Vth
<i>KT1L</i>	m-V	0.0	temperature coef. for channel length dependence of Vth
<i>KT2</i>	-	0.022	body bias coefficient of Vth temperature effect
<i>UTE</i>	-	-1.5	mobility temperature exponent
<i>UA1</i>	m/V	4.31e-9	temperature coefficient for UA
<i>UB1</i>	(m/V) ²	-7.61e-18	temperature coefficient for UB
<i>UC1</i>	m/V ²	-5.69e-11	temperature coefficient for UC
<i>AT</i>	m/sec	3.3e4	temperature coefficient for saturation velocity
<i>PRT</i>	ohm-um	0	temperature coefficient for RDSW
<i>XTI</i>	-	3.0	junction current temperature exponent

Bin Description Parameters

Name	Units	Default	Comments
<i>LMIN</i>	m	0.0	maximum channel length
<i>LMAX</i>	m	1.0	maximum channel length
<i>WMIN</i>	m	0.0	minimum channel width
<i>WMAX</i>	m	1.0	maximum channel width
<i>BINUNIT</i>	-	0	assumes weff,leff,wref,lref units are in microns when BINUNIT=1 or meters otherwise

Process Parameters

Name	Units	Default	Comments
<i>GAMMA1</i>	$V^{1/2}$	see Note 8	body effect coefficient near the surface
<i>GAMMA2</i>	$V^{1/2}$	see Note 9	body effect coefficient in the bulk
<i>VBX</i>	V	see Note 10	VBX at which the depletion region width equals XT
<i>XT</i>	m	1.55e-7	doping depth
<i>VBI</i>	V	see Note 11	drain and source junction built-in potential

Noise Parameters

Name	Units	Default	Comments
<i>NIOA</i>	-	1.0e20 nmos 9.9e18 pmos	body effect coefficient near the surface
<i>NOIB</i>	-	5.0e4 nmos 2.4e3 pmos	body effect coefficient in the bulk
<i>NOIC</i>	-	-1.4e-12 nmos 1.4e-12 pmos	VBX at which the depletion region width equals XT
<i>EM</i>	V/m	4.1e ⁷	doping depth
<i>AF</i>	-	1.0	drain and source junction built-in potential
<i>KF</i>	-	1.0	flicker exponent
<i>EF</i>	-	0.0	flicker noise parameter

Junction Parameters

Name	Units	Default	Comments
<i>ACM</i>	-	0	Area calculation method selector (Star-Hspice specific)
<i>JS</i>	A/m ²	0.0	bulk junction saturation current (Default deviates from BSIM3v3 = 1.0e ⁻⁴)
<i>JSW</i>	A/m	0.0	sidewall bulk junction saturation current
<i>NJ</i>	-	1	emission coefficient (not used with ACM=3)
<i>CJ</i>	F/m ²	5.79e ⁻⁴	zero-bias bulk junction capacitance (Default deviates from BSIM3v3 = 5.0e ⁻⁴)
<i>CJSW</i>	F/m	0.0	zero-bias sidewall bulk junction capacitance (Default deviates from BSIM3v3 = 5.0e ⁻¹⁰)
<i>CJSWG</i>	F/m	<i>CJSW</i>	zero-bias gate-edge sidewall bulk junction capacitance (not used with ACM=0-3)
<i>PB, PHIB</i>	V	1.0	bulk junction contact potential
<i>PBSW</i>	V	1.0	sidewall bulk junction contact potential
<i>PBSWG</i>	V	<i>PBSW</i>	gate-edge sidewall bulk junction contact potential (not used with ACM=0-3)
<i>MJ</i>	-	0.5	bulk junction grading coefficient
<i>MJSW</i>	-	0.33	sidewall bulk junction grading coefficient
<i>MJSWG</i>	-	<i>MJSW</i>	gate-edge sidewall bulk junction grading coefficient (not used with ACM=0-3)

NQS Parameters

Name	Units	Default	Comments
<i>ELM</i>	-	5.0	Elmore constant (Star-Hspice currently does not support the NQS model)

Notes

1. If C_{gso} is not given, it is calculated as follows:

If ($d1c$ is given and is greater than 0.0), then,

$$cgso = p1 = \max(0, d1c * cox - cgs1)$$

Otherwise, $cgso = 0.6 * xj * cox$

2. If C_{gdo} is not given, it is calculated as follows:

if ($d1c$ is given and is greater than 0.0), then,

$$cgdo = p2 = \max(0, d1c * cox - cgd1)$$

Otherwise $cgdo = 0.6 * xj * cox$

3. If C_f is not given, it is calculated using:

$$C_f = \frac{2\epsilon_{ox}}{\pi} \log\left(1 + \frac{4 \times 10^{-7}}{T_{ox}}\right)$$

4. If V_{th0} is not specified in the .MODEL statement, it is calculated with $V_{fb} = -1$, using:

$$V_{th0} = V_{fb} + \phi_s + K_1 \sqrt{\phi_s}$$

5. If K_1 and K_2 are not given, they are calculated using:

$$K_1 = GAMMA_2 + 2K_2 \sqrt{\phi_s - V_{bs}}$$

$$K_2 = \frac{(GAMMA_2 - GAMMA_1)(\sqrt{\phi_s - V_{bs}} - \sqrt{\phi_s})}{2\sqrt{\phi_s}(\sqrt{\phi_s - V_{bm}} - \sqrt{\phi_s}) + V_{bm}}$$

6. If n_{ch} is not given, and $GAMMA_1$ is given, n_{ch} is calculated from:

$$n_{ch} = \frac{GAMMA_1^2 C_{OX}^2}{2q\epsilon_{si}}$$

If both n_{ch} and $GAMMA_1$ are not given, n_{ch} defaults to 1.7e17 per cubic meter and $GAMMA_1$ is calculated from n_{ch} .

7. If PHI is not given, it is calculated using:

$$\phi_s = 2 \frac{k_B T}{q} \log\left(\frac{n_{ch}}{n_i}\right)$$

$$n_i = 1.45 \times 10^{10} \left(\frac{T}{300.15}\right)^{1.5} \exp\left(21.5565981 - \frac{qE_g(T)}{2k_B T}\right)$$

$$E_g(T) = 1.16 - \frac{7.02 \times 10^{-4} T^2}{T + 1108}$$

8. If $GAMMA_1$ is not given, it is calculated using:

$$GAMMA_1 = \frac{\sqrt{2q\epsilon_{si} n_{ch}}}{C_{ox}}$$

9. If $GAMMA_2$ is not given, it is calculated using:

$$GAMMA_2 = \frac{\sqrt{2q\epsilon_{si} n_{sub}}}{C_{ox}}$$

10. If V_{bx} is not given, it is calculated using:

$$V_{bx} = \phi_s - \frac{qn_{ch} X_t^2}{2\epsilon_{si}}$$

11. If V_{bi} is not given, it is calculated using:

$$V_{bi} = \frac{k_B T}{q} \log \left(\frac{n_c h^N N_{DS}}{n_i^2} \right)$$

where N_{DS} is $1e20/c^2$

Level 49 uses the BSIM3.V3 capacitance model. However, it does not support the nonquasistatic (NQS) capacitance model. The Level 49 model supports the model parameter name TNOM as an alias for TREF. The conventional terminology in Star-Hspice is TREF, which is supported as a model parameter in all Star-Hspice MOS levels. The alternative name TNOM is supported for Level 49, for compatibility with SPICE3.

The default room temperature is 25°C in Star-Hspice, but is 27°C in SPICE3. If the BSIM3 model parameters are specified at 27°C, TNOM=27 should be added to the model, so that the model parameters are interpreted correctly. It is a matter of choice whether or not to set the nominal simulation temperature to 27, by adding .OPTION TNOM=27 to the netlist. Add this option when testing Star-Hspice versus SPICE3.

DELVTO and DTEMP on the element line can be used with Level 49.

The conversion of temperature setup between Star-Hspice and SPICE3 is as follows:

```
SPICE3:  .OPTIONS TEMP=125
         .MODEL NCH NMOS LEVEL=8
         +  TNOM =27 ...
```

```
Star-Hspice:.TEMP 125
           .MODEL NCH NMOS LEVEL=49
           +  TNOM =27 ...
```

The option SCALM does not affect the parameters unique to this model, but it does affect the common MOS parameters, such as CJ, CJSW, JS, and JSW.

There are three ways for the BSIM3 model to calculate V_{th} using:

- $K1$ and $K2$ values that are user specified
- $GAMMA1$, $GAMMA2$, VBM , and VBX values entered in the .MODEL statement
- $NPEAK$, $NSUB$, XT , and VBM values that are user specified

The model parameter $U0$ can be entered in meters or centimeters. $U0$ is converted to $m^2/Vsec$ as follows: if $U0$ is greater than 1, it is multiplied by $1e-4$. The parameter $NSUB$ must be entered in cm^{-3} units.

Specify a negative value of $VTH0$ for p-channel in the .MODEL statement.

The impact ionization current determined by the model parameters $PSCBE1$ and $PSCBE2$ contributes to the bulk current.

The units for the LWP geometry parameters can be selected to be in microns by setting the model parameter $BINUNIT = 1$. For other choices of $BINUNIT$ the lengths are in units of meters. The Star-Hspice parameters XL and $XLREF$ are handled in a manner consistent with other models, and they produce shifts in parameter values without disrupting the continuity across bin boundaries.

Level 49 Equations

The effective channel length and width used in all model equations are:

$$L_{eff} = L_{drawn} - 2dL$$

$$W_{eff} = W_{drawn} - 2dW$$

$$W'_{eff} = W_{drawn} - 2dW'$$

where the unprimed W_{eff} is bias-dependent, and the primed quantity is bias-independent.

$$dW = dW' + dW_g V_{gsteff} + dW_b (\sqrt{\phi_s - V_{bseff}} - \sqrt{\phi_s})$$

$$dW' = W_{int} + \frac{W_L}{L_{WLN}} + \frac{W_W}{W_{WWN}} + \frac{W_{WL}}{L_{WLN} W_{WWN}}$$

$$dL = L_{int} + \frac{L_L}{L_{LLN}} + \frac{L_W}{W_{LWN}} + \frac{L_{WL}}{L_{LLN} W_{LWN}}$$

Note: A detailed discussion of the BSIM3 Version 3 equations is available from the BSIM3 site: <http://www-device.eecs.berkeley.edu/~bsim3/get.html>

Example .MODEL CARDS NMOS Model

```

.model nch nmos level=49
+ Tnom=27.0
+ nch=1.024685E+17 tox=1.00000E-08 xj=1.00000E-07
+ lint=3.75860E-08 wint=-2.02101528644562E-07
+ vth0=.6094574 k1=.5341038 k2=1.703463E-03 k3=-17.24589
+ dvt0=.1767506 dvt1=.5109418 dvt2=-0.05
+ nlx=9.979638E-08 w0=1e-6
+ k3b=4.139039
+ vsat=97662.05 ua=-1.748481E-09 ub=3.178541E-18 uc=1.3623e-10
+ rdsw=298.873 u0=307.2991 prwb=-2.24e-4
+ a0=.4976366
+ keta=-2.195445E-02 a1=.0332883 a2=.9
+ voff=-9.623903E-02 nFactor=.8408191 cit=3.994609E-04
+ cdsc=1.130797E-04
+ cdscb=2.4e-5
+ eta0=.0145072 etab=-3.870303E-03
+ dsub=.4116711
+ pclm=1.813153 pdiblc1=2.003703E-02 pdiblc2=.00129051
pdiblc3=-1.034e-3
+ drout=.4380235 pscbe1=5.752058E+08 pscbe2=7.510319E-05
+ pvag=.6370527 prt=68.7 ngate=1.e20 alpha0=1.e-7 beta0=28.4
+ prwg=-0.001 ags=1.2
+ dvt0w=0.58 dvt1w=5.3e6 dvt2w=-0.0032
+ kt1=-.3 kt2=-.03
+ at=33000
+ ute=-1.5
+ ual=4.31E-09 ub1=7.61E-18 uc1=-2.378e-10
+ kt1l=1e-8
+ wr=1 b0=1e-7 b1=1e-7 dwg=5e-8 dwb=2e-8 delta=0.015
+ cgdl=1e-10 cgsl=1e-10 cgbo=1e-10 xpart=0.0
+ cgdo=0.4e-9 cgso=0.4e-9
+ clc=0.1e-6
+ cle=0.6
+ ckappa=0.6

```


Example PMOS Model

This is an example of a PMOS model. Note that VTH0 is negative.

```
.model pch PMOS level=49
+ Tnom=27.0
+ nch=5.73068E+16 tox=1.00000E-08 xj=1.00000E-07
+ lint=8.195860E-08 wint=-1.821562E-07
+ vth0=-.86094574 k1=.341038 k2=2.703463E-02 k3=12.24589
+ dvt0=.767506 dvt1=.65109418 dvt2=-0.145
+ nlx=1.979638E-07 w0=1.1e-6
+ k3b=-2.4139039
+ vsat=60362.05 ua=1.348481E-09 ub=3.178541E-19 uc=1.1623e-10
+ rdsw=498.873 u0=137.2991 prwb=-1.2e-5
+ a0=.3276366
+ keta=-1.8195445E-02 a1=.0232883 a2=.9
+ voff=-6.623903E-02 nFactor=1.0408191 cit=4.994609E-04
+ cdsc=1.030797E-3
+ cds cb=2.84e-4
+ eta0=.0245072 etab=-1.570303E-03
+ dsub=.24116711
+ pclm=2.6813153 pdiblc1=4.003703E-02 pdiblc2=.00329051
pdiblc3=-2.e-4
+ drout=.1380235 pscbe1=0 pscbe2=1.e-28
+ pvag=-.16370527
+ prwg=-0.001 ags=1.2
+ dvt0w=0.58 dvt1w=5.3e6 dvt2w=-0.0032
+ kt1=-.3 kt2=-.03 prt=76.4
+ at=33000
+ ute=-1.5
+ ua1=4.31E-09 ub1=7.61E-18 uc1=-2.378e-10
+ kt11=0
+ wr=1 b0=1e-7 b1=1e-7 dwg=5e-8 dwb=2e-8 delta=0.015
+ cgd1=1e-10 cgs1=1e-10 cgbo=1e-10 xpart=0.0
+ cgdo=0.4e-9 cgso=0.4e-9
+ clc=0.1e-6
+ cle=0.6
+ ckappa=0.6
```

Level 50 Philips MOS9 Model

The Philips MOS Model 9, Level 902, is available as Level 50 in HSPICE (based on the “Unclassified Report NL-UR 003/94” by R.M.D.A. Velghe, D.B.M. Klaassen, and F.M. Klaassen).

The model has been installed in its entirety, except for the gate noise current.

The Philips document does not describe built-in parasitic diodes. Standard HSPICE parasitic diode equations, using parameters JS, JSW, N, CJ, CJSW, CJGATE, MJ, MJSW, PB, PHP, ACM, HDIF have been added. The older parameter IS is not used.

Level 50 Model Parameters

Name	Units	Default(N)	Default(P)	Comments
LER	m	1.1e-6	1.25e-6	reference Leff
WER	m	20.0e-6	20.0e-6	reference Weff
LVAR	m	-220.0e-9	-460.0e-9	variation in gate length
LAP	m	100.0e-9	25.0e-9	lateral diffusion per side
WVAR	m	-25.0e-9	-130.0e-9	variation in active width
WOT	m	0.0	0.0	channel-stop diffusion per side
TR	°C	21.0	21.0	reference temperature for model
VTOR	V	730.0e-3	1.1	threshold voltage at zero bias
STVTO	V/K	-1.2e-3	-1.7e-3	temperature dependence of VTO
SLVTO	Vm	-135.0e-9	35.0e-9	length dependence of VTO
SL2VTO	Vm ²	0.0	0.0	second length dependence of VTO
SWVTO	Vm	130.0e-9	50.0e-9	width dependence of VTO
KOR	V ^{-1/2}	650.0e-3	470.0e-3	low-back-bias body factor

Name	Units	Default(N)	Default(P)	Comments
SLKO	$V^{-1/2}m$	-130.0e-9	-200.0e-9	length dependence of KO
SWKO	$V^{-1/2}m$	2.0e-9	115.0e-9	width dependence of KO
KR	$V^{-1/2}$	110.0e-3	470.0e-3	high-back-bias body factor
SLK	$V^{-1/2}m$	-280.0e-9	-200.0e-9	length dependence of K
SWK	$V^{-1/2}m$	275.0e-9	115.0e-9	width dependence of K
PHIBR	V	650.0e-3	650.0e-3	strong inversion surface potential
VSBXR	V	660.0e-3	0.0	transition voltage for dual-k-factor model
SLVSBX	Vm	0.0	0.0	length dependence of VSBX
SWVSBX	Vm	-675.0e-9	0.0	width dependence of VSBX
BETSQ	AV^{-2}	83.0e-6	26.1e-6	gain factor of infinite square transistor
ETABET	-	1.6	1.6	exponent of temperature dependence of gain factor
THE1R	V^{-1}	190.0e-3	190.0e-3	gate-induced mobility reduction coefficient
STTHE1R	V^{-1}/K	0.0	0.0	temperature dependence coefficient of THE1R
SLTHE1R	$V^{-1}m$	140.0e-9	70.0e-9	length dependence coefficient of THE1R
STLTHE1	$V^{-1}m/K$	0.0	0.0	temperature dependence of, length dependence of THE1R
SWTHE1	$V^{-1}m$	-58.0e-9	-80.0e-9	width dependence coefficient of THE1R
THE2R	$V^{-1/2}$	12.0e-3	165.0e-3	back-bias induced mobility reduction coefficient
STTHE2R	$V^{-1/2}/K$	0.0	0.0	temperature dependence coefficient of THE2R

Name	Units	Default(N)	Default(P)	Comments
SLTHE2R	$V^{-1/2}m$	-33.0e-9	-75.0e-9	length dependence coefficient of <i>THE2R</i>
STLTHE2	$V^{-1/2}m/K$	0.0	0.0	temperature dependence of, length dependence of <i>THE2R</i>
SWTHE2	$V^{-1/2}m$	30.0e-9	20.0e-9	width dependence coefficient of <i>THE2R</i>
THE3R	V^{-1}	145.0e-3	27.0e-3	lateral field induced mobility reduction coefficient
STTHE3R	V^{-1}/K	-660.0e-6	0.0	temperature dependence coefficient of <i>THE3R</i>
SLTHE3R	$V^{-1}m$	185.0e-9	27.0e-9	length dependence coefficient of <i>THE3R</i>
STLTHE3	$V^{-1}m/K$	-620.0e-12	0.0	temperature dependence of, length dependence of <i>THE3R</i>
SWTHE3	$V^{-1}m$	20.0e-9	11.0e-9	width dependence coefficient of <i>THE3R</i>
GAM1R	-	145.0e-3	77.0e-3	drain-induced threshold shift coefficient, for high gate drive
SLGAM1	-	160.0e-9	105.0e-9	length dependence of <i>GAM1R</i>
SWGAM1	-	-10.0e-9	-11.0e-9	width dependence of <i>GAM1R</i>
ETADSR	-	600.0e-3	600.0e-3	exponent of drain dependence of <i>GAM1R</i>
ALPR	-	3.0e-3	44.0e-3	channel length modulation factor
ETAALP	-	150.0e-3	170.0e-3	exponent of length dependence of <i>ALPR</i>
SLALP	-	-5.65e-3	9.0e-3	coefficient of length dependence of <i>ALPR</i>
SWALP	m	1.67e-9	180.0e-12	coefficient of width dependence of <i>ALPR</i>

Name	Units	Default(N)	Default(P)	Comments
VPR	V	340.0e-3	235.0e-3	characteristic voltage for channel length modulation
GAMOOOR	-	18.0e-3	7.0e-3	drain-induced threshold shift coefficient, at zero gate drive, and zero back-bias
SLGAMOO	m ²	20.0e-15	11.0e-15	length dependence of <i>GAMOOOR</i>
ETAGAMR	-	2.0	1.0	exponent of back-bias dependence of zero gate-drive, drain-induced threshold shift
MOR	-	500.0e-3	375.0e-3	subthreshold slope factor
STMO	K ⁻¹	0.0	0.0	temperature dependence coefficient of <i>MOR</i>
SLMO	m ^{1/2}	280.0e-6	47.0e-6	length dependence coefficient of <i>MOR</i>
ETAMR	-	2.0	1.0	exponent of back-bias dependence of subthreshold slope
ZET1R	-	420.0e-3	1.3	weak-inversion correction factor
ETAZET	-	170.0e-3	30.0e-3	exponent of length dependence of <i>ZET1R</i>
SLZET1	-	-390.0e-3	-2.8	length dependence coefficient of <i>ZET1R</i>
VSBT	V	2.1	100.0	limiting voltage for back-bias dependence
SLVSBT	Vm	-4.4e-6	0.0	length dependence of <i>VSBT</i>
A1R	-	6.0	10.0	weak avalanche current factor
STA1	K ⁻¹	0.0	0.0	temperature coefficient of <i>A1R</i>
SLA1	m	1.3e-6	-15.0e-6	length dependence of <i>A1R</i>
SWA1	m	3.0e-6	30.0e-6	width dependence of <i>A1R</i>

Name	Units	Default(N)	Default(P)	Comments
A2R	V	38.0	59.0	exponent of weak-avalanche current
SLA2	Vm	1.0e-6	-8.0e-6	length dependence of A2R
SWA2	Vm	2.0e-6	15.0e-6	width dependence of A2R
A3R	-	650.0e-3	520.0e-3	factor of minimum drain bias above which avalanche sets in
SLA3	m	-550.0e-9	-450.0e-9	length dependence of A3R
SWA3	m	0.0	-140.0e-9	width dependence of A3R
TOX	m	25.0e-9	25.0e-9	oxide thickness
COL	F/m	320.0e-12	320.0e-12	gate overlap capacitance per unit width
NTR	J	24.4e-21	21.1e-21	thermal noise coefficient
NFR	V ²	70.0e-12	21.4e-12	flicker noise coefficient

Using the Philips MOS9 Model in HSPICE

1. Set LEVEL=50 to identify the model as the Philips MOS Model 9.
2. The default room temperature is 25 °C in HSPICE, but is 27 °C in most other simulators. When comparing to other simulators, set the simulation temperature to 27 with .TEMP 27 or with .OPTION TNOM=27.
3. The model parameter set should always include the model reference temperature, TR, which corresponds to TREF in other levels in HSPICE. The default for TR is 21.0 °C, to match the Philips simulator.
4. The model has its own charge-based capacitance model. The CAPOP parameter, which selects different capacitance models, is ignored for this model.
5. The model uses analytical derivatives for the conductances. The DERIV parameter, which selects the finite difference method, is ignored for this model.

6. DTEMP can be used with this model. It is set on the element line and increases the temperature of individual elements relative to the circuit temperature.
7. Since defaults are nonzero, it is strongly recommended that every model parameter listed in the table above be set in the .MODEL statement.

Example HSPICE Model Statement

```
.model nch nmos level=50
+ ler = 1e-6 wer = 10e-6
+ lvar = 0.0 lap = 0.05e-6
+ wvar = 0.0 wot = 0.0
+ tr = 27.00
+ vtor = 0.8 stvto = 0 slvto = 0 sl2vto= 0
+ swvto = 0
+ kor = 0.7 slko = 0 swko = 0
+ kr = 0.3 slk = 0 swk = 0
+ phibr = 0.65
+ vsbxr = 0.5 slvsbx = 0 swvsbx= 0
+ betsq = 120e-6
+ etabet = 1.5
+ the1r = 0.3
+ stthe1r = 0 slthe1r = 0 stlthe1= 0 swthe1 = 0
+ the2r = 0.06
+ stthe2r = 0 slthe2r = 0 stlthe2 = 0 swthe2 = 0
+ the3r = 0.1
+ stthe3r = 0 slthe3r = 0 stlthe3 = 0 swthe3 = 0
+ gam1r = 0.02 slgam1 = 0 swgam1 = 0
+ etadsr= 0.60
+ alpr = 0.01
+ etaalp = 0 slalp = 0 swalp = 0
+ vpr = 0.4
+ gamoor = 0.006
+ slgamoo = 0
```

```
+ etagamr = 2.0
+ mor = 0.5 stmo = 0 slmo = 0
+ etamr = 2.0
+ zet1r = 1.0
+ etazet = 0.5
+ slzet1 = 0
+ vsbtr = 2.5
+ slvsbt = 0
+ alr = 10 sta1 = 0 sla1 = 0 swa1 = 0
+ a2r = 30 sla2 = 0 swa2 = 0
+ a3r = 0.8 sla3 = 0 swa3 = 0
+ tox = 15.00e-9
+ col = 0.3e-9
+ ntr = 2.0e-20
+ nfr = 5.0e-11
+ acm=2 hdif=1u js=1e-3
+ cj=1e-3 mj=0.5 pb=0.8
+ cjsw=1e-9 cjgate=1e-9 mjsw=0.3 php=0.8
```

Comparing MOS Models

This section reviews the history, motivation, strengths and weaknesses of the most commonly used MOS models in Star-Hspice:

Level 2	SPICE Level 2
Level 3	SPICE Level 3
Level 13	BSIM1
Level 28	Meta-Software proprietary model, based on BSIM1
Level 39	BSIM2

History and Motivation

This section describes the history of and motivation for using MOS models in Star-Hspice.

HSPICE Model Enhancements

In order to satisfy the needs of customers, Avant! modified the standard SPICE models. The modifications are in the areas of:

- Drawn dimensions with corrections for photolithography and diffusion
- Corrections for optical shrink
- Model-independent process variation parameters
- Uniform subthreshold equations
- Charge-conserving capacitance equations
- Impact ionization with selectable source/bulk partitioning of the excess drain current
- Enhanced temperature relationships

Level 2

The Level 2 model is an enhanced Grove equation. It is the most common of MOS equations in all simulators.

The basic current equation with the 3/2-power terms was developed by Ihanola and Moll in 1964. Channel length modulation was added by Reddi and Sah in 1965. The vertical field reduction was added by Crawford in 1967. The ECRIT parameter was added by Klassen in 1978.

Level 3

The Level 3 model was developed by Liu in 1981. It is computationally more efficient, replacing the 3/2-power terms with a first-order Taylor expansion. The drain-induced barrier lowering effect (ETA parameter) was added.

The Level 3 models is impressively physical, modeling two-dimensional effects based on junction depth and depletion depths.

Level 13 - BSIM

The BSIM1 model was developed by Sheu, Scharfetter, Poon and Hu at Berkeley in 1984, for higher accuracy modeling of short-channel devices. The approach is empirical rather than physical. It uses polynomials frequently. This makes it easier to write a parameter extraction program, but the polynomials often behave badly. For example, a quadratic function of V_{DS} is used for mobility. Parameters specify the values at $V_{DS}=0$ and 5 and the slope at $V_{DS}=5$; unfortunately, values that look reasonable can produce a quadratic that is non-monotonic, giving a $G_{DS}<0$ problem.

The HSPICE implementation of BSIM1 as Level 13 removed discontinuities in the current function, added temperature parameters, and added diode and capacitance models consistent with other models. The Berkeley version did not include temperature parameters.

Level 28

Level 28 is a proprietary HSPICE model for submicron devices, designed to fix the following problems in BSIM1:

- Negative GDS
- Bad behavior of some polynomial expressions
- A kink in GM at threshold

Level 28 is based on BSIM1, but some of the parameters are quite different. A BSIM1 parameter set cannot be used as a Level 28 model. The Level 28 model is designed for optimization; there is no simple extraction program. It has proven stable for automated model parameter generation.

Optimization of Level 28 models to IDS, GDS, GM data is accomplished routinely by Meta-Labs.

Level 39

The BSIM2 model was developed by Duster, Jeng, Ko, and Hu, and released in SPICE3 in 1991. It is designed for deep sub-micron devices. It uses a cubic spline to give smooth weak inversion transition and has many additional parameters for improved accuracy. The GDS transition at VDSAT is markedly smoother than in BSIM1.

Future for Model Developments

This sequence of models shows a trend towards empirical rather than physical models, and an ever-increasing number of parameters. It is unfortunate to lose contact with the physics, but it can be unavoidable, because the physics has become less universal. Short-channel devices are much more sensitive to the detail of the process. I-V curves from different manufacturers show qualitative differences in the shape of the curves. Therefore, the models need to be very flexible, requiring a large number of empirical parameters.

Model Equation Evaluation Criteria

This section describes the following aspects of the model equations:

- potential for good fit to data
- ease of fitting to data
- robustness and convergence properties
- behavior follows actual devices in all circuit conditions
- ability to simulate process variation
- gate capacitance modeling

Some of these aspects depend on general HSPICE features that are the same for all levels. Others result in simple objective measures for comparing the levels. These measures are summarized in the “– Comparison of HSPICE Parameters with UCB SPICE 2 and 3” on page 16-126.

Potential for Good Fit to Data

Generally, the model with the largest number of parameters has the potential to give the best fit. For the purpose of comparing the models, the number of parameters are counted in two ways.

Measure: Number of Parameters

Only the drain current parameters are counted, not the diode or series resistance, nor gate capacitance and impact ionization parameters, since these are almost the same for all levels.

Level 2: VTO, PHI, GAMMA, XJ, DELTA, UO, ECRIT, UCRIT, UTRA, UEXP, NSUB, LAMBDA, NFS (total=13).

Level 3: VTO, PHI, GAMMA, XJ, DELTA, ETA, UO, THETA, VMAX, NSUB, KAPPA, NFS (total=12).

Level 13: VFB0, PHI0, K1, K2, ETA0, X2E, X3E, MUZ, X2M, X3MS, MUS, X2MS, U00, X2U0, U1, X2U1, X3U1, N0, ND0, NB0, plus L- and W- variation parameters (total = $20 \times 3 = 60$).

Level 28: similar to Level 13, minus MUS, X2MS, plus X33M, WFAC, WFACU (total = $21 \times 3 = 63$).

Level 39: VGHIGH, VGLow, VFB, K1, K2, ETA0, ETAB, MU0, MU0B, MUS0, MUSB, MU20, MU2B, MU2G, MU30, MU3B, MU40, MU4B, MU4G, UAO, UAB, UB0, UBB, U10, U1B, U1D, N0, NB, ND, plus L- and W- parameters (total = $33 \times 3 = 99$).

Measure: Minimal Number of Parameters

The minimal number of parameters is defined as the subset of the above set of parameters that would normally be needed to fit a specific W/L device. For Level 2, 3 DELTA is dropped, which is a W-effect parameter. For Level 13 and 28, the L- and W- terms are dropped, as are X2E, X3E, ND0, which are second-order effects. For Level 39, ETAB, MU40, MU4B, MU4G, ND are dropped. The resulting minimal parameter counts for the five models are Level 2=12, Level 3=11, Level 13=17, Level 28=18, and Level 39=28.

Ease of Fit to Data

Generally, the larger the “minimal number of parameters”, the more time needs to be spent fitting the data. The systematic L and W effect parameters of Level 13, 28, and 39 makes fitting easier because optimization can be done to individual W/L devices. Then the final model parameters, with L and W terms, can be calculated from the individual models. On the other hand, the more physical parameters of Level 2 and 3 are helpful because it is easier to predict the value from a knowledge of the process, before fitting to I-V data. Examples of physical parameters are junction depths and doping concentrations.

Measure: Physical Percentage of Parameters

Starting with the minimal set of parameters, the percentage that are physical are calculated. For Level 2— PHI, XJ, UO, ECRIT, NSUB, and NFS are physical, while VTO, GAMMA, UCRIT, UTRA, UEXP, LAMBDA are empirical, which gives 50% physical parameters. For level 3— PHI, XJ, UO, VMAX, NSUB, NFS are physical, which gives 55%. For Levels 13, 28, and 39—only PHI0 and MUZ are physical, giving 12%, 11%, and 7% physical parameters, respectively.

Robustness and Convergence Properties

A discontinuity in the derivatives GM, GDS, GMBS can cause convergence problems. Also, since real devices have continuous derivatives, a discontinuity leads to a large inaccuracy in the derivatives near that region. This can be annoying to an analog designer looking at a plot of gain versus bias, for example. The most common important discontinuities are GDS at $v_{ds}=v_{dsat}$, and GM at $v_{gs}=v_{th}$. The Level 2 and 3 models have these discontinuities, while the Level 13, 28, and 39 models do not.

However, the Level 13 model (BSIM1) often produces a negative GDS, which is obviously inaccurate, and causes oscillation, which can lead to convergence failure or a “timestep too small” error. It is possible for a Level 13 model to avoid negative GDS, but it depends on complex relationships between the parameters MUZ, X2M, MUS, X2MS, X3MS, U1, X2U1, X3U1. Usually, a negative GDS can be removed by setting $X3MS=0$, but this lowers the accuracy of the model in the linear region. The Level 39 (BSIM2) model also is capable of producing negative GDS unless you select parameters carefully. The Level 28 model does not give negative GDS.

The BSIM1 model has a continuous GM at $v_{gs}=v_{th}$, but a plot of GM/IDS versus VGS shows a kink, while data from real devices is monotonic. This kink is annoying to analog designers working with devices in the weak and medium inversion region. Level 28 and 39 have solved this problem, at the cost of additional parameters.

There are three more important measures, as follows:

Measure: Continuous Derivatives

Levels 2 and 3 fail. Levels 13, 28, and 39 pass.

Measure: Positive GDS

Levels 13 and 39 fail. Levels 2, 3, and 28 pass.

Measure: Monotonic GM/IDS in weak inversion

Levels 2, 3, and 13 fail. Levels 28 and 39 pass.

Behavior Follows Actual Devices In All Circuit Conditions

A model can give a very good fit to IDS data in the normal operating region and still fail to be useful for simulating some circuits.

The first criterion of this type is that the model should have good temperature dependence. HSPICE provides temperature-dependence parameters for threshold voltage and mobility for all levels. The Level 13, 28 and 39 models also have an FEX parameter that controls VDSAT variation with temperature.

The next most important criterion is that the model should have subthreshold current to provide accurate analog simulation. Even for digital circuits it aids in convergence. Fortunately, all of these models have subthreshold current.

Impact ionization causes a drain-to-bulk current that has a strong effect on cascode circuits. HSPICE provides parameters ALPHA and VCR for this current, which can be used for all levels.

The BSIM2 model has a more complex impact ionization model, with parameters AI0, AIB, BI0, BIB, but in the Berkeley SPICE3 release this current was all assigned to drain-to-source current, IDS. Using the HSPICE parameters ALPHA and VCR, the impact ionization current is assigned to IDB, which is essential for cascode simulation. The HSPICE parameter IIRAT allows the model to divide the current between IDS and IDB, if needed.

Ability to Simulate Process Variation

Usually, full model parameter extraction or optimization is only done on a small number of test wafers. Statistical data on process variation is gathered by in-fabrication measurements (for example, TOX) and simple electrical measurements (for example, VT), made on a large number of wafers. This statistical data gives variances that are used to simulate process variation, using a worst-case, Monte-Carlo, or Taguchi methodology.

In order to do this simulation, models must be modified to take into account variations in TOX, thresholds, line widths, and sheet resistance. In HSPICE, we have made the different levels similar in their use of these parameters. All of the models discussed here accept the following parameters: TOX, DELVTO, XL, XW, RSH. The DELVTO model parameter shifts the threshold.

For the Level 2 and 3 models, setting DELVTO=0.1 is equivalent to adding 0.1 to VTO; for the Level 13, 28, 39 models, it is equivalent to adding 0.1 to VFB0. The parameters XL and XW represent line width variation. The equation for effective channel length is:

$$L_{eff} = L + XL - 2 \cdot LD$$

The Berkeley BSIM1 and BSIM2 models use $L_{eff} = L - DL$. The DL and DW parameters (DL0, DW0 for BSIM1) are supported in HSPICE for compatibility, using XL, LD, XW, WD is recommended instead. In HSPICE, the geometry parameters (XL, LD, XW, WD) and the parasitic parameters (CJ, MJ, CJSW, MJSW, RSH) are kept simple and level-independent to use process variation information consistently.

Gate Capacitance Modeling

Level 2 and 3 were released in Berkeley SPICE with the Meyer model for gate capacitance. This model is non-charge-conserving and sets $dQG/dVD = dQD/dVG$, which is not valid in a real device, although provides an adequate response for most digital simulations. The BSIM1 and BSIM2 models were released from Berkeley with charge-conserving, non-symmetric capacitance models.

In HSPICE, several choices of capacitance models are available; the range of choices and the default varies with the model chosen. The default for Levels 2 and 3 is still the Meyer model, but you can also select a charge-conserving Ward-Dutton model.

Level Comparisons

Table 16-2:

Level	2	3	13	28	39
number of parameters	13	12	60	63	99
minimal number of parameters	12	11	17	18	28
physical parameters	50%	55%	12%	11%	7%
continuous derivatives	no	no	yes	yes	yes
positive GDS	yes	yes	no	yes	no
monotonic GM/IDS	no	no	no	yes	yes

Outline of Optimization Procedure

1. Extract XL, LD, XW, WD, TOX, RSH, CGSO, CGDO, CGBO, CJ, MJ, CJSW, MJSW from resistor and capacitor data, and plots of Beta vs. W, L.
2. For each W/L device,
 - a. Extract VT versus VBS from IDS vs. VGS data.
 - b. Calculate ETA from log(IDS) vs. VGS plots at VDS=0.1, 5.0.
 - c. Fit VT parameters to the VT vs. VBS data.
 - d. Optimize the rest of the parameters, except L and W sensitivity parameters, to IDS, GDS, GM vs. VGS, VDS, VBS data.
3. For each W/L device, calculate L and W sensitivity parameters from the optimized parameters of nearby devices.
4. Fit the models together into one model using the HSPICE Lmin, Lmax, Wmin, Wmax feature.

Examples of Data Fitting

The following plots show fits of Levels 2, 3, 13, 28, 39 to data from a submicron device, fabricated by a modern CMOS process. All of the models were optimized to the same data. Similar optimization files were used, optimizing different parameters. The HSPICE impact ionization model, with parameters ALPHA, VCR, was used in all models except Level 39, which has its own impact ionization parameters.

The problem of negative GDS in Level 13 was avoided by improved optimization of parameter values, but the GDS discontinuity in Level 3 and the GM discontinuity in Level 2 could not be avoided.

Model versus data plots are presented for drain and gate sweeps. These are followed by close-up plots of the models with small step size to show GM and GDS problems with the individual levels.

Level 28, 2, 3 - Ids Model vs. Data

- Ids vs. Vds at Vgs=1, 2, 3, 4, 5, Vbs=0
- Fits to IDS only (not GDS and GM) would have looked better for these plots, but would not have been acceptable for analog design.

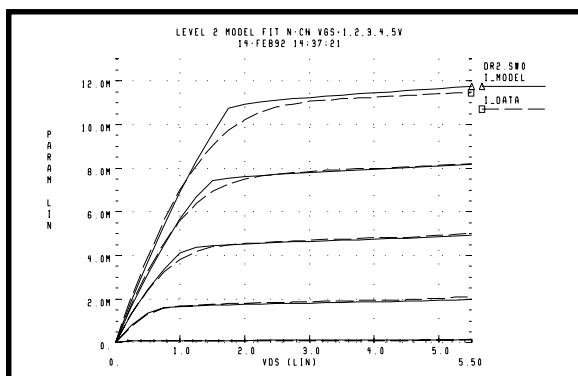


Figure 16-13: – Level 2 Ids Model vs. Data Curves

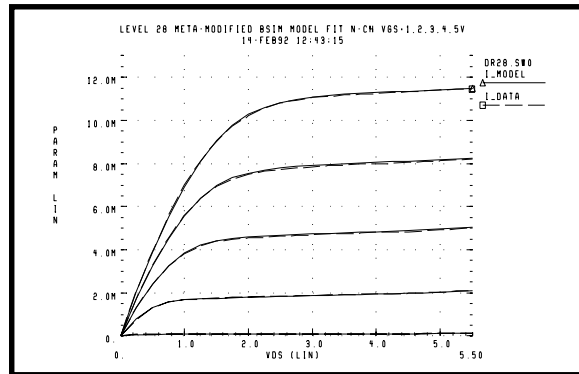


Figure 16-14: – Level 28 Ids Model vs. Data Curves

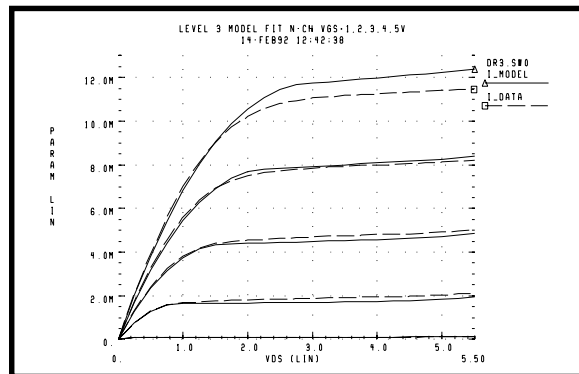


Figure 16-15: – Level 3 Ids Model vs. Data Curves

Level 13, 28, 39 - Ids Model vs. Data

- Ids vs. Vds at Vgs= 1, 2, 3, 4, 5, Vbs=0

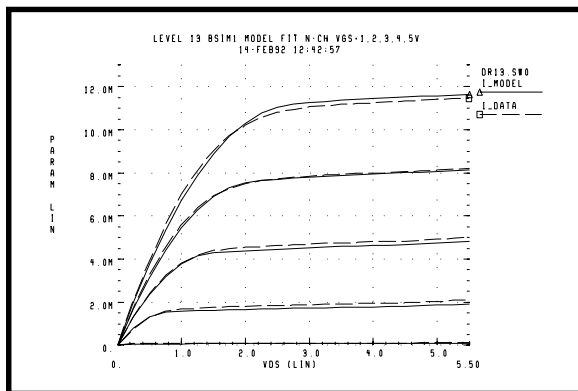


Figure 16-16: – Level 13 Ids vs. Vds Curves

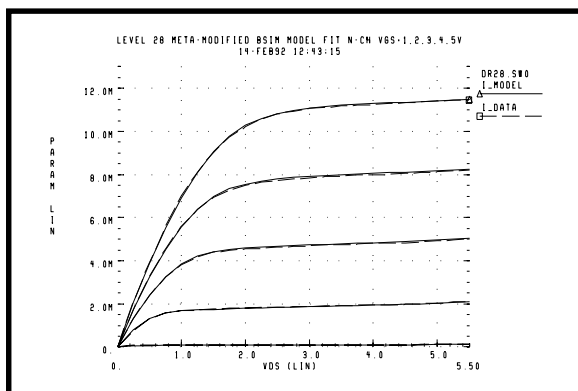


Figure 16-17: – Level 28 Ids vs. Vds Curves

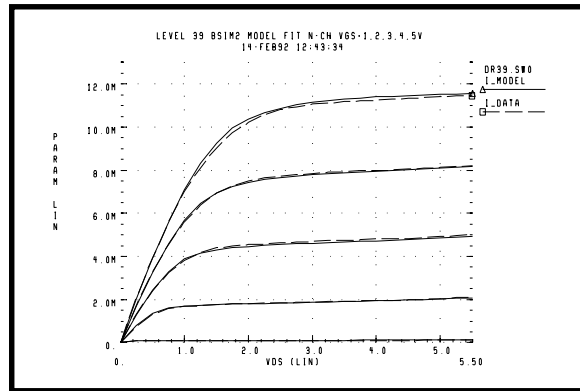


Figure 16-18: – Level 39 Ids vs. Vds Curves

Level 28, 2, 3 - Gds Model vs. Data

- gds -vs.- Vds at Vgs=2, 3, 4, 5, Vbs=0
- This plot shows the inability of Level 2 and 3 to model GDS accurately.

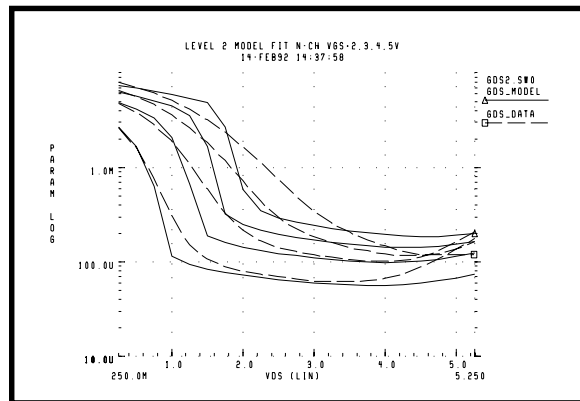


Figure 16-19: – Level 2 gds vs. Vds Curves

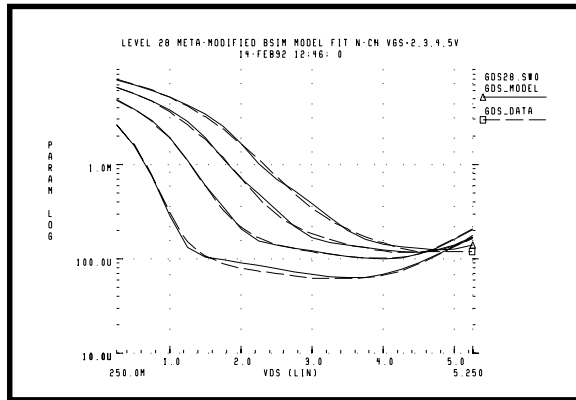


Figure 16-20: – Level 28 gds vs. Vds Curves

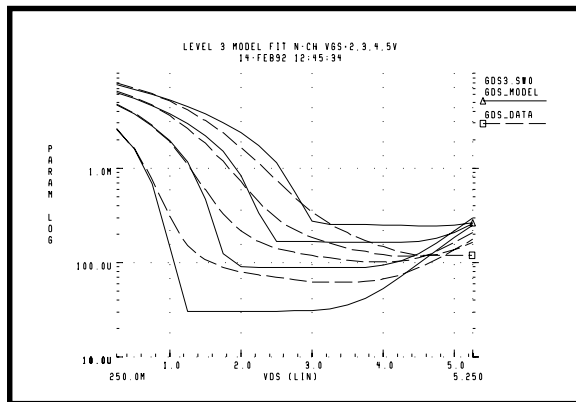


Figure 16-21: – Level 3 gds vs. Vds Curves

Level 13, 28, 39 - Gds Model vs. Data

- $g_{ds} = \text{vs. } V_{ds}$ at $V_{gs}=2, 3, 4, 5, V_{bs}=0$
- These models still have a small change in slope of G_{ds} at V_{dsat} , more visible for the Level 13 model than for Level 28 or 39.

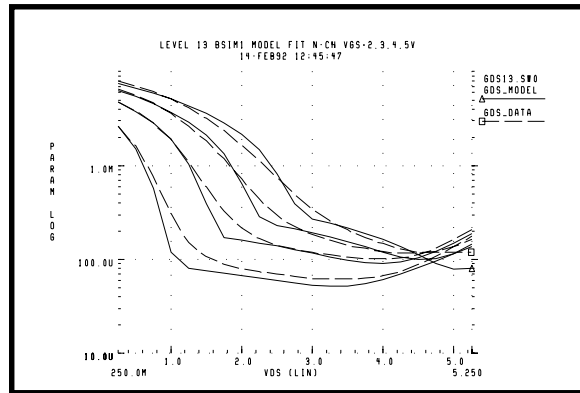


Figure 16-22: – Level 13 gds vs. Vds Curves

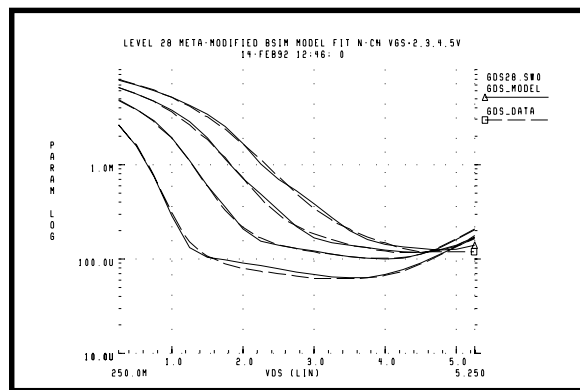


Figure 16-23: – Level 28 gds vs. Vds Curves

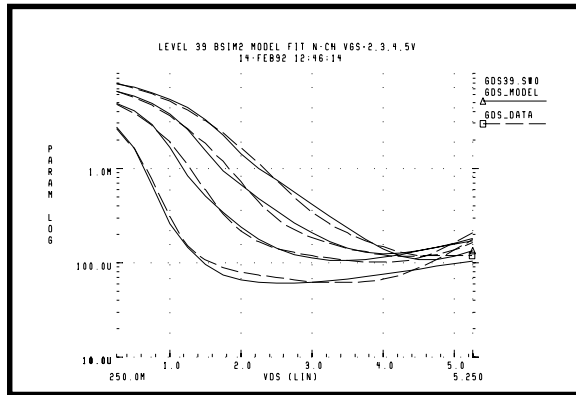


Figure 16-24: – Level 39 gds vs. Vds Curves

Level 2, 3, 28 - Ids Model vs. Data

- Ids -vs.- Vgs at Vds=0.1, Vgs =0, -1, -2, -3, -4

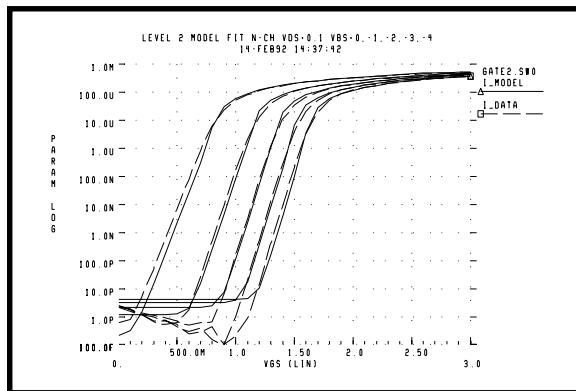


Figure 16-25: – Level 2 Ids vs. Vgs Curves

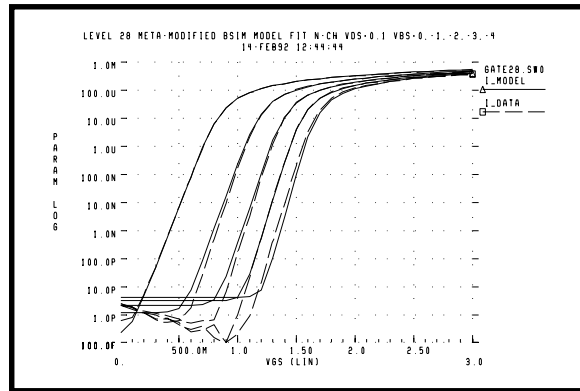


Figure 16-26: – Level 28 Ids vs. Vgs Curves

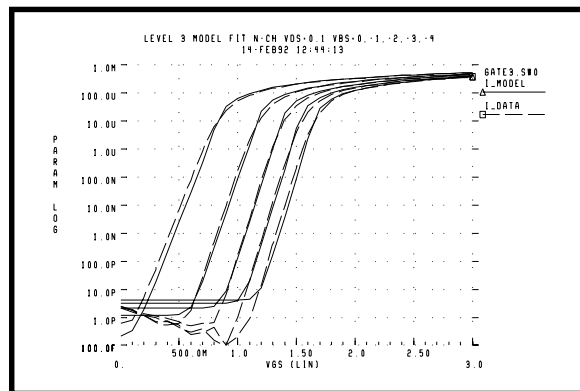


Figure 16-27: – Level 3 Ids vs. Vgs Curves

Level 13, 28, 39 - Ids Model vs. Data

- Ids -vs.- Vgs at Vds=0.1, Vbs =0, -1, -2, -3, -4

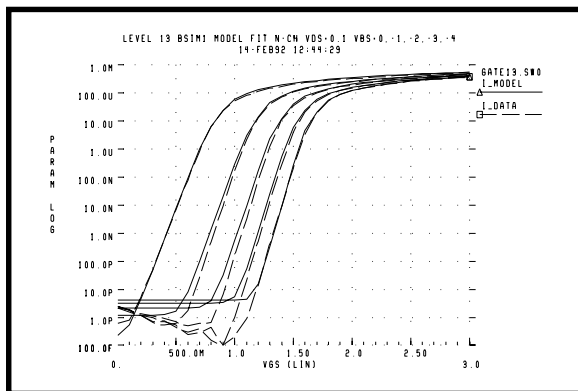


Figure 16-28: – Level 13 Ids vs. Vgs Curves

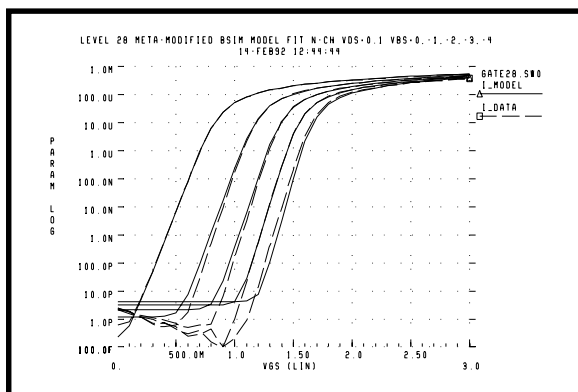


Figure 16-29: – Level 28 Ids vs. Vgs Curves

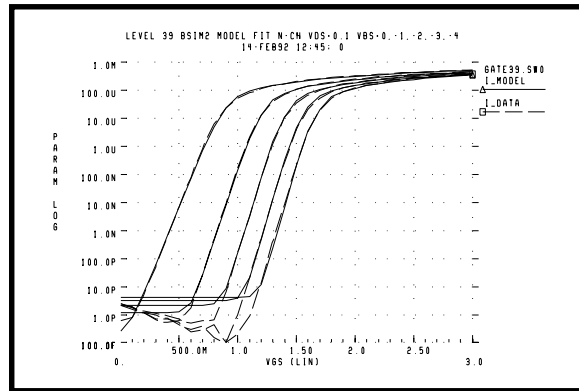


Figure 16-30: – Level 39 Ids vs. Vgs Curves

Level 2, 3, 28 - Gm/Ids Model vs. Data

- gm/Ids -vs- Vgs at Vds=0.1, Vbs =0, -2
- The Level 2 and 3 models have spikes at Vgs=Vth. The data, and the Level 28 model, is monotonic decreasing.

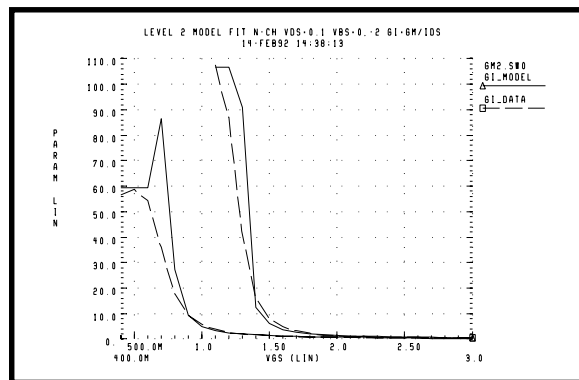


Figure 16-31: – Level 2 gm/Ids vs. Vgs Curves

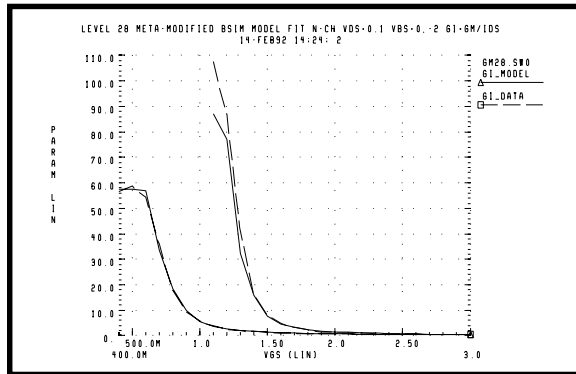


Figure 16-32: – Level 28 gm/Ids vs. Vgs Curves

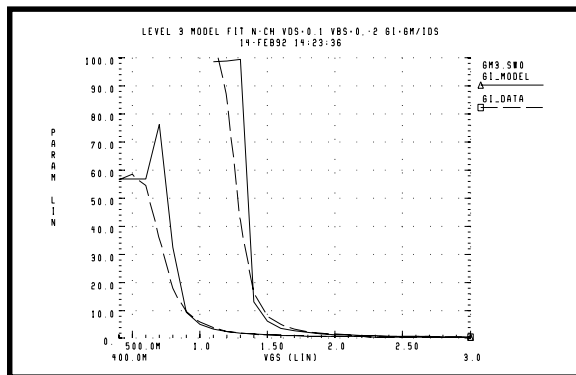


Figure 16-33: – Level 3 gm/Ids vs. Vgs Curves

Level 13, 28, 39 - Gm/Ids Model vs. Data

- gm/Ids -vs.- Vgs at Vds=0.1, Vbs =0, -2
- Level 13 has a kink at Vth, which is not visible at this resolution. Level 28 and 39 are monotonic.

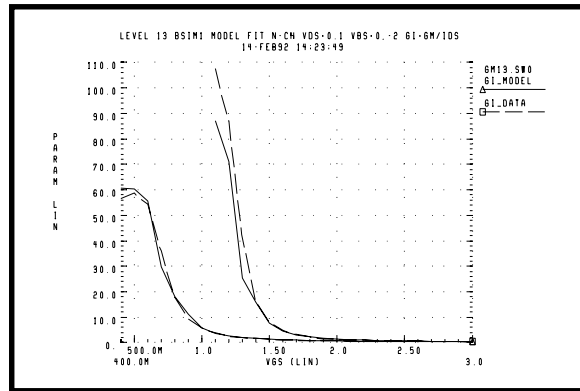


Figure 16-34: – Level 13 gm/Ids vs. Vgs Curves

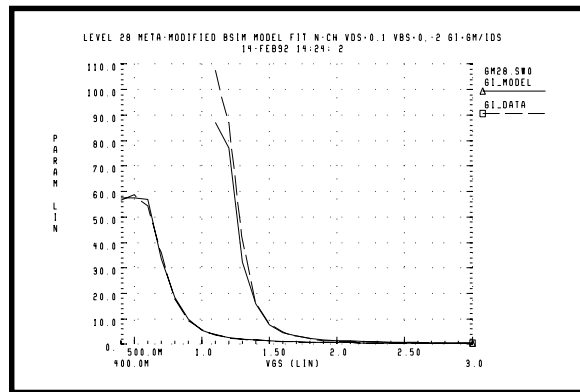


Figure 16-35: – Level 28 gm/Ids vs. Vgs Curves

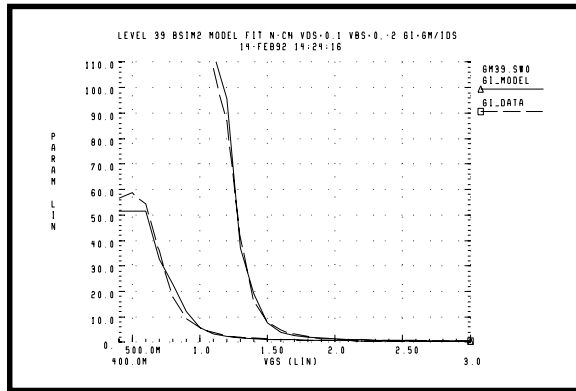


Figure 16-36: – Level 39 gm/Ids vs. Vgs Curves

Gds vs. Vds at Vgs=4, Vbs=0

- This plot shows the behavior of gds at the linear to saturation transition. The Level 3 model has a gds discontinuity.

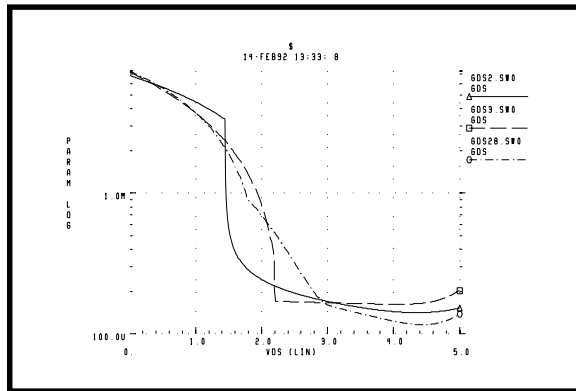


Figure 16-37: – Levels 2, 3, 28 gds vs. Vds Curves

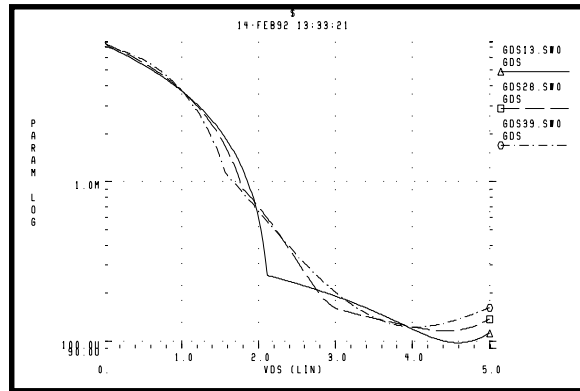


Figure 16-38: – Levels 13, 28, 39 gds vs. Vds Curves

Gm/Ids vs. Vgs at Vds=0.1, Vbs=0, 2

- This plot shows a gm discontinuity in the Level 2 model, related to parameters UCRIT and UEXP.

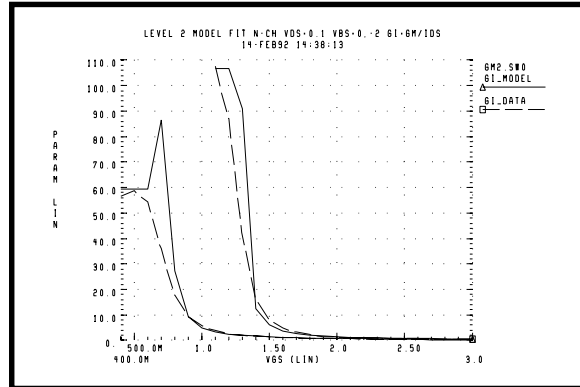


Figure 16-39: – Level 2 gm/Ids vs. Vgs Curves

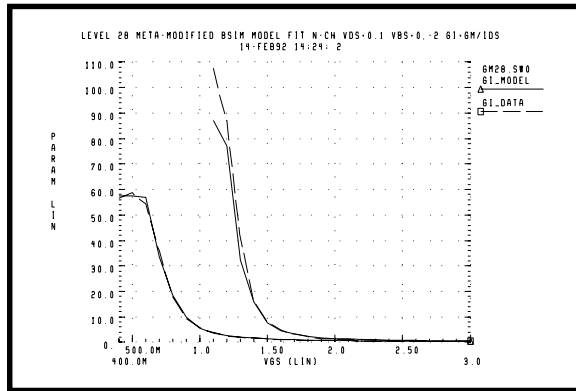


Figure 16-40: – Level 28 gm/Ids vs. Vgs Curves

Gm/Ids vs. Vgs at Vds=0.1, Vbs=0

- This plot shows the ratio gm/Ids in the weak inversion transition region. The Level 2, 3, and 13 models have kinks near threshold, while Levels 28 and 39 are monotonic.

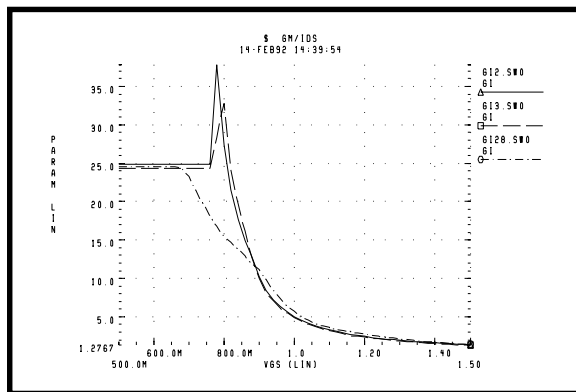


Figure 16-41: – Levels 2, 3, 28 gm/Ids vs. Vgs Curves

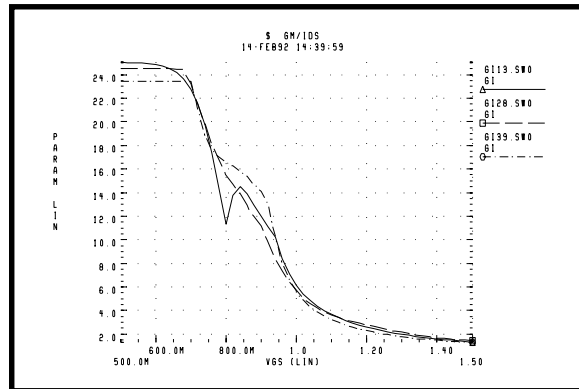


Figure 16-42: – Levels 13, 28, 39 gm/lDs vs. Vgs Curves

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