N Channel MOSFET BSIM4 model mosnbsim4

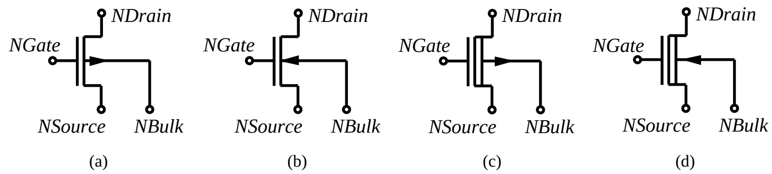

Figure 1: N Channel MOSFET BSIM4 model

Form: `mosnbsim4`:⟨`instance name`⟩ n_1 n_2 n_3 n_4 ⟨`parameter list`⟩

n_1 is the drain node,
n_2 is the gate node,
n_3 is the source node,
n_4 is the bulk node.

Model Parameters:

Parameter	Description	Default	Units
TOXE	Electrical gate equivalent oxide thickness	3.0e-9	m
TOXP	Physical gate equivalent oxide thickness	TOXE	m
EPSROX	Gate dielectric constant relative to vacuum	3.9	-
VFB	Flat-band voltage	-1.0	V
VTH0	Long-channel threshold voltage	0.7	V
NGATE	Poly Si gate doping concentration	0.0	cm^{-3}
XL	Channel length offset due to mask/etch effect	0.0	m
XW	Channel width offset due to mask/etch effect	0.0	m
NF	Number of device fingers	1.0	-
W	Width of the device	5.0e-6	m
L	Length of the device	5.0e-6	m
DWG	Coefficient of gate bias dependence of Weff	0.0	m/V
DWB	Coefficient of body bias dependence of Weff	0.0	m/V
WINT	Channel-width offset parameter	0.0	m
WLN	Power of length dependence of width offset	1.0	m
WL	Coefficient of length dependence for width offset	0.0	m
WWN	Power of width dependence of width offset	1.0	m
WW	Coefficient of width dependence for width offset	0.0	m
WWL	Coefficient of length and width cross term dependence for width offset		m
LINT	Channel-length offset parameter	0.0	m
LLN	Power of length dependence for length offset	0.0	m
LL	Coefficient of length dependence for length offset	0.0	m
LW	Coefficient of width dependence for length offset	0.0	m
LWN	Power of width dependence for length offset	1.0	m
LWL	Coefficient of length and width cross term dependence for length offset	0.0	m
K1	First-order body bias coefficient	0.0	$V^{-0.5}$
K2	Second-order body bias coefficient	0.0	-

Table 1: MOS Model Parameter table 1

Parameter	Description	Default	Units
LPEB	Lateral non-uniform doping effect on K1	0.0	m
LPE0	Lateral non-uniform doping parameter at Vbs=0	1.74e-7	m
K3	Narrow width coefficient	80.0	-
K3B	Body effect coefficient of K3	0.0	V^{-1}
W0	Narrow width parameter	2.5e-6	m
DVT0W	First coefficient of narrow width effect on threshold voltage for small channel length	0.0	-
DVT0	First coefficient of short channel effect on threshold	2.2	-
DVT1W	Second coefficient of narrow width effect on threshold voltage for small channel length	5.3e6	-
DVT1	Second coefficient of short channel effect on threshold	0.53	-
DSUB	DIBL coefficient exponent in sub-threshold region	0.56	-
ETA0	DIBL coefficient in sub-threshold region	0.56	-
ETAB	Body-bias coefficient for the sub-threshold region	-0.07	-
TOXM	$T_{\rm ox}$ at which parameters are extracted	TOXE	m
T	Temperature	300.0	^oK
NDEP	Channel doping concentration at depletion edge for zero body bias	1.7e17	cm^{-3}
PHIN	Non-uniform vertical doping effect on surface potential	0.0	V
VBM	Maximum applied body bias in VTH0 calculation	-3.0	V
NSUB	Substrate doping concentration	6.0e16	cm^{-3}
DVT2W	Body-bias coefficient of narrow width effect for small channel length	-0.032	-
NSD	Source/drain doping concentration	1.0e20	cm^{-3}
DVT2	Body-bias coefficient of short-channel effect on threshold	-0.032	-
MINV	V_{gsteff} fitting parameter for moderate inversion condition	-0.0	-
NFACTOR	Subthreshold swing factor	1.0	-
CDSC	Coupling capacitance between source/drain and channel	1.0	F/m^2
CDSCD	Drain-bias sensitivity of CDSC	2.4e-4	F/Vm^2
CDSCB	Body-bias sensitivity of CDSC	0.0	F/Vm^2
CIT	Interface trap capacitance	0.0	F/m^2

Table 2: MOS Model Parameter table 2

Parameter	Description	Default	Units
KETA	Body-bias coefficient of bulk charge effect	-0.047	V^{-1}
B0	Bulk charge effect coefficient for channel width	0.0	m
B1	Bulk charge effect width offset	0.0	m
A0	Coefficient of channel-length dependence bulk charge effect	1.0	-
AGS	Coefficient of V_{gs} dependence of bulk charge effect	0.0	V^{-1}
XJ	S/D junction depth	1.5e-7	m
U0	Low-field mobility	0.067	m^2/Vs
UA	Coefficient of first-order mobility degradation due to vertical field	1.0e-15	m/V
UB	Coefficient of second-order mobility degradation due to vertical field	1.0e-19	m^2/V^2
UC	Coefficient of mobility degradation due to body-bias effect	-0.0465e-9	m/V
EU	Exponent for mobility degradation	1.67	-
DELTA	Parameter for DC V_{dseff}	0.01	V
PDITS	Impact of drain-induced threshold shift on R_{out}	0.0	V^{-1}
FPROUT	Effect of pocket implant on Rout degradation	0.0	$V/m^0.5$
PDITSL	Channel-length dependence of drain-induced V_{th} shift for R_{out}	0.0	m^{-1}
PDITSD	V_{ds} dependence of drain-induced V_{th} shift for Rout	0.0	V^{-1}
PSCBE2	Second substrate current induced body-effect parameter	1.0e-5	m/V
PSCBE1	First substrate current induced body-effect parameter	4.24e8	V/m
PDIBLCB	Body bias coefficient of DIBL effect on Rout	0.0	V^{-1}
PVAG	Gate-bias dependence of Early voltage	0.0	-
PDIBL1	Parameter for DIBL effect on R_{out}	0.0	-
PDIBL2	Parameter for DIBL effect on R_{out}	0.0	-
AGS	Coefficient of V_{gs} dependence of bulk charge effect	0.0	V^{-1}
DROUT	Channel-length dependence of DIBL effect on R_{out}	0.56	-
PCLM	Channel length modulation parameter	1.3	-
A1	First non-saturation effect parameter	0.0	V^{-1}
A2	Second non-saturation factor	1.0	-

Table 3: MOS Model Parameter table 3

Parameter	Description	Default	Units
`RDWMIN`	Lightly-doped drain resistance per unit width at high $V_{\rm gs}$ and zero V_{bs}	0.0	Ω
`RDSW`	Zero bias lightly-doped drain resistance per unit width	200.0	Ω
`PRWG`	Gate-bias dependence of LDD resistance	1.0	V^{-1}
`PRWB`	Body-bias dependence of LDD resistance	0.0	$V^{-0.5}$
`WR`	Channel-width dependence parameter of LDD resistance	1.0	m
`WLC`	Coefficient of length dependence for CV channel width offset	WL	m
`WWC`	Coefficient of width dependence for CV channel width offset	WW	m
`WWLC`	Coefficient of length and width cross term dependence for CV channel width offset	WWL	m
`DWJ`	Offset of the S/D junction width	WINT	m
`CLC`	Constant term for the short channel model	1.0e-7	m
`CLE`	Exponential term for the short channel model	0.6	-
`NOFF`	CV parameter in $V_{gsteffCV}$ for weak to strong inversion	1.0	-
`VOFFCV`	CV parameter in $V_{gsteffCV}$ for weak to strong inversion	0.0	V
`CF`	Fringing field capacitance	0.0	F/m
`CKAPPAD`	Coefficient of bias-dependent overlap capacitance for the drain side	0.6	V
`CKAPPAS`	Coefficient of bias-dependent overlap capacitance for the source side	0.6	V
`LLC`	Coefficient of length dependence on CV channel length offset	0.0	m
`LWC`	Coefficient of width dependence on CV channel length offset	0.0	m
`LWLC`	Coefficient of length and width cross term dependence on CV channel length offset	0.0	m
`WWLC`	Coefficient of length and width cross term dependence on CV channel width offset	0.0	m
`VOFF`	Offset voltage in the subthreshold region for large W and L	-0.08	V
`VOFFL`	Channel length dependence of `VOFF`	0.0	V

Table 4: MOS Model Parameter table 4

Parameter	Description	Default	Units
POXEDGE	Factor for the gate oxide thickness in S/D overlap regions	1.0	-
TOXREF	Nominal gate oxide thickness for gate dielectric tunnelling current model	3.0e-9	m
NTOX	Exponent for gate oxide ratio	1.0	-
DLCIG	Source/drain overlap length for I_{gs} and I_{gd}	LINT	m
AIGSD	parameter for I_{gs} and I_{gd}	0.43	$(Fs^2/g)^{0.5}m^{-1}$
BIGSD	parameter for I_{gs} and I_{gd}	0.054	$(Fs^2/g)^{0.5}m^{-1}$
CIGSD	parameter for I_{gs} and I_{gd}	0.075	$(Fs^2/g)^{0.5}m^{-1}$
MOIN	Coefficient for gate-bias dependent surface potential	15.0	-
VSAT	Saturation velocity	8.0e4	m/s
PDITSD	V_{ds} dependence of drain induced V_{th} shift for Rout	0.0	V^{-1}
AIGC	Parameter for I_{gcs} and I_{gcd}	0.43	$(Fs^2/g)^{0.5}m^{-1}$
BIGC	Parameter for I_{gcs} and I_{gcd}	0.054	$(Fs^2/g)^{0.5}m^{-1}$
CIGC	Parameter for I_{gcs} and I_{gcd}	0.075	$(Fs^2/g)^{0.5}m^{-1}$
NIGC	Parameter for I_{gcs} I_{gcd}, I_{gs} and I_{gd}	1.0	$(Fs^2/g)^{0.5}m^{-1}$
PIGCD	V_{ds} dependence of I_{gcs} and I_{gcd}	1.0	-
DVTP0	First coefficient of drain induced V_{th} shift due to long channel pocket devices	0.0	m
DVTP1	First coefficient of drain induced V_{th} shift due to long channel pocket devices	0.0	V^{-1}
PRT	Temperature coefficient for RDSW	0.0	$\Omega - m$
AT	Temperature coefficient for saturation velocity	3.3e4	m/s
XT	Doping Depth	1.55e-7	m
ALPHA0	First parameter of impact ionization current	0.0	Am/V
ALPHA1	I_{sub} parameter for length scaling	0.0	A/V
BETA0	Second parameter of impact ionization current	30.0	V
AGIDL	Pre-exponential coefficient for GIDL	0.0	A/V
BGIDL	Exponential coefficient for GIDL	2.3e9	V/m
CGIDL	Parameter for body-bias effect on GIDL	0.5	V^3
EGIDL	Fitting parameter for band bending for GIDL	0.8	V
ACDE	Exponential coefficient for charge thickness	1.0	m/V
DLC	Channel length offset parameter	LINT	m
DWC	Channel width offset parameter	WINT	m

Table 5: MOS Model Parameter table 5

Parameter	Description	Default	Units
AIGBACC	Parameter for I_{gb} in accumulation	0.43	m^{-1}
BIGBACC	Parameter for I_{gb} in accumulation	0.054	$m^{-1}V^{-1}$
CIGBACC	Parameter for I_{gb} in accumulation	0.075	V^{-1}
NIGBACC	Parameter for I_{gb} in accumulation	1.0	-
AIGBINV	Parameter for I_{gb} in inversion	0.35	m^{-1}
BIGBINV	Parameter for I_{gb} in inversion	0.03	$m^{-1}V^{-1}$
CIGBINV	Parameter for I_{gb} in inversion	0.006	V^{-1}
EIGBINV	Parameter for I_{gb} in inversion	1.1	V
NIGBINV	Parameter for I_{gb} in inversion	3.0	-
KT1	Temperature coeff for V_{TH}	-0.11	V
KT1L	Channel length for KT1	0.0	Vm
KT2	Body bias coeff for V_{TH} temp effect	0.022	-

Table 6: MOS Model Parameter table 6

Description:
The BSIM4 model takes a lot of it's characteristics from it's predecessor, BSIM3 but also adds enough functionality to name it with a new model number. It uses many new parameters and replaces some old BSIM3 parameters. It uses a newly formulated smoothing function for gate-source voltage. It uses more than 200 parameters, uses charge conserving equations for calculation of various capacitances, has a single equation for modeling current in all regions of transistor operation, has better modeling for gate currents, for external parasitics, noise, temperature and mobility. This chapter deals with the equations and features of this advanced transistor model that have been modeled in *f*REEDA™.
Channel Width and Length:
The effective channel lengths and widths are less than the values of L and W on account of diffusion effects. XL and XW are parameters that account for the channel length/width offset due to mask/etch effects and process nonuniformity. The terms dL and dW are provided for user convenience. They are turned off by default. The effective length L_{EFF} is represented as

$$L_{\mathrm{EFF}} = \mathtt{L} + 2\mathtt{XL} - 2\Delta L_{\mathrm{geom}} \tag{1}$$

where

$$\Delta L_{\mathrm{geom}} = \frac{\mathtt{LL}}{L^{\mathtt{LLN}}} + \frac{\mathtt{LW}}{W^{\mathtt{LWN}}} + \frac{\mathtt{LWL}}{L^{\mathtt{LLN}}W^{\mathtt{LWN}}} \tag{2}$$

The effective width is represented as

$$W_{\mathrm{EFF}} = \frac{W}{\mathtt{NF}} + \mathtt{XW} - 2\Delta W_{\mathrm{geom}} - 2\Delta W_{\mathrm{biasdep}} \tag{3}$$

where

$$\Delta W_{\mathrm{geom}} = \frac{\mathtt{WL}}{L^{\mathtt{WLN}}} + \frac{\mathtt{WW}}{W^{\mathtt{WWN}}} + \frac{\mathtt{WWL}}{L^{\mathtt{WLN}}W^{\mathtt{WWN}}} \tag{4}$$

$$\Delta W_{\mathrm{biasdep}} = \mathtt{DWG}(V_{\mathrm{GSTeff}}) + \mathtt{DWB}(\sqrt{2\phi_f - V_{\mathrm{BSeff}}} - \sqrt{2\phi_f}) \tag{5}$$

Threshold Voltage:
This model attempts to accurately model threshold voltage and include various channel effects such as DIBL (Drain Induced Barrier Lowering), Non-uniform vertical doping, body-effect, charge sharing between the source and drain, short-channel and pocket implant effects.
Effective Bulk-Source Voltage:
V_{BSeff} is calculated in order to prevent the body bias from taking unreasonably high values during simulation. It provides an upper limit on the value of body bias.

$$V_{\mathrm{BSeff}} = V_{\mathrm{bc}} + \frac{(V_{\mathrm{BS}} - V_{\mathrm{bc}} - 0.001) + \sqrt{(V_{\mathrm{BS}} - V_{\mathrm{bc}} - 0.001)^2 - 4\,V_{\mathrm{bc}}\,0.001}}{2} \tag{6}$$

where $V_{\rm bc}$, which represents the maximum allowable $V_{\rm BS}$ is given by

$$V_{\rm bc} = 0.9.(2\phi_f - \frac{\texttt{K1}^2}{4\texttt{K2}^2}) \tag{7}$$

The threshold voltage is evaluated as

$$\begin{aligned} V_{\rm TH} \quad = \quad & \texttt{VTH0} + \delta_{\rm NP}.(\Delta V_{\rm T,BodyEffect} - \Delta V_{\rm T,ChargeSharing} - \Delta V_{\rm T,DIBL} \\ & + \Delta V_{\rm T,ReverseShortChannel} + \Delta V_{\rm T,NarrowWidth} + \Delta V_{\rm T,SmallSize} \\ & - \Delta V_{\rm T,PocketImplant}) \end{aligned} \tag{8}$$

In certain cases, devices are operated with a positive value of $V_{\rm BS}$. In these cases, the threshold voltage reduces and drive current increases. The parameters K1 and K2 control the value of the body effect term and it is modeled by

$$\begin{aligned} \Delta V_{\rm T,BodyEffect} \quad = \quad & [\texttt{K1} \, \frac{\texttt{TOXE}}{\texttt{TOXM}} \, \sqrt{2\phi_f - V_{\rm BSeff}} - \texttt{K1}\sqrt{2\phi_f}] \, \sqrt{1 + \frac{\texttt{LPEB}}{L_{\rm EFF}}} \\ & - \texttt{K2} \, V_{\rm BSeff} \, \frac{\texttt{TOXE}}{\texttt{TOXM}} \end{aligned} \tag{9}$$

In modern technologies, the threshold voltage first increases as the effective length decreases before it takes on it's expected trend of decrease as effective length decreases. To correctly model the temporary increase of threshold voltage the term used is

$$\Delta V_{\rm T,ReverseShortChannel} = \texttt{K1} \, \frac{\texttt{TOXE}}{\texttt{TOXM}} \, (\sqrt{1 + \frac{\texttt{LPE0}}{L_{\rm EFF}}} - 1) \, \sqrt{2\phi_f} \tag{10}$$

As the channel becomes shorter, the threshold voltage becomes more dependent on the channel length (SCE, short channel effects) and on DIBL. As the product of effective length and width reduces, the exponents in Equation 11 reduce and assume a finite value. This suggests that there is a shift in threshold voltage for smaller devices. The value can be controlled by the parameters DVT0W and DVT1W. SCE are represented as

$$\begin{aligned} \Delta V_{\rm T,SmallSize} \quad = \quad & \texttt{DVT0W} \, [\exp(-\texttt{DVT1W} \, \frac{W_{\rm EFF} \, L_{\rm EFF}}{2L_{\rm tw}}) \\ & +2 \, \exp(-\texttt{DVT1W} \, \frac{W_{\rm EFF} \, L_{\rm EFF}}{2L_{\rm tw}})] \, (V_{\rm bi} - 2\phi_f) \end{aligned} \tag{11}$$

As $V_{\rm DS}$ increases in short channel devices, there is a non-trivial change in the surface potential. As a result, the barrier blocking the carriers in the drain from entering the channel diminishes and the device turns on sooner. Since this barrier lowering is induced by drain source voltage, this effect is called Drain Induced Barrier Lowering. To model DIBL, the following term is used.

$$\begin{aligned} \Delta V_{\rm T,DIBL} \quad = \quad & [\exp(-\texttt{DSUB} \, \frac{L_{\rm EFF}}{2L_{\rm t0}}) + 2\exp(-\texttt{DSUB} \, \frac{L_{\rm EFF}}{2L_{\rm t0}})] \\ & \times (\texttt{ETA0} + \texttt{ETAB} \, V_{\rm BSeff}) \, V_{\rm DS} \end{aligned} \tag{12}$$

The actual depletion region in the channel is larger than what is usually assumed because of fringing fields. Thus, as the channel width decreases, there is a net increase in the threshold voltage. This is modeled by

$$\Delta V_{\rm T,NarrowWidth} = (\texttt{K3} + \texttt{K3B} \, V_{\rm BSeff}) \, \frac{\texttt{TOXE}}{W_{\rm EFF} + \texttt{W0}} \tag{13}$$

The influence of charge sharing effects between the source and drain depends greatly on the size of the channel. It's value increases as the channel lengths reduce. The effect of charge sharing on threshold voltage is controlled by parameters DVT0, DVT1 and DVT2. When the effective channel length is small, the exponents assume a finite value and have a direct bearing on the value of threshold voltage. Increased charge sharing tends to reduce the value of threshold voltage and it is represented as

$$\Delta V_{\rm T,ChargeSharing} = \texttt{DVT0} \frac{0.5}{\cosh(\texttt{DVT1} \, L_{\rm EFF}/L_t) - 1} (V_{\rm bi} - 2\phi_f) \tag{14}$$

$\Delta V_{\mathrm{T,PocketImplant}}$ is defined after the calculation of ideality factor n. The built in potential is given as

$$V_{\mathrm{bi}} = \frac{k[T+273.15]}{q} \ln \frac{(\mathtt{NDEP}\ \mathtt{NSD})}{n_i^2} \tag{15}$$

The characteristic length is given by:

$$L_t = \begin{cases} \sqrt{\epsilon_s X_{\mathrm{dep}}/C_{\mathrm{oxe}}}\,(1+\mathtt{DVT2}\ V_{\mathrm{BSeff}}) & \mathtt{DVT2}\ V_{\mathrm{BSeff}} \geq -0.5 \\ \sqrt{\epsilon_s X_{\mathrm{dep}}/C_{\mathrm{oxe}}}\,(1+3\ \mathtt{DVT2}\ V_{\mathrm{BSeff}}) \\ \times(3+8\,\mathtt{DVT2}\,V_{\mathrm{BSeff}})^{-1} & \mathtt{DVT2}\ V_{\mathrm{BSeff}} < 0.5 \end{cases} \tag{16}$$

$$L_{\mathrm{t0}} = \sqrt{\frac{\epsilon_s\ X_{\mathrm{dep0}}}{C_{\mathrm{oxe}}}} \tag{17}$$

where

$$C_{\mathrm{oxe}} = \frac{\epsilon_{\mathrm{ox}}}{\mathtt{TOXE}} \tag{18}$$

$$L_{\mathrm{tw}} = \begin{cases} \sqrt{\epsilon_s X_{\mathrm{dep}}/C_{\mathrm{oxe}}}\,(1+\mathtt{DVT2W}\ V_{\mathrm{BSeff}}) & \mathtt{DVT2W}\ V_{\mathrm{BSeff}} \geq -0.5 \\ \sqrt{\epsilon_s X_{\mathrm{dep}}/C_{\mathrm{oxe}}}\,(1+3\ \mathtt{DVT2W}\ V_{\mathrm{BSeff}}) \\ \times(3+8\,\mathtt{DVT2W}\,V_{\mathrm{BSeff}})^{-1} & \mathtt{DVT2W}\ V_{\mathrm{BSeff}} < 0.5 \end{cases} \tag{19}$$

$$X_{\mathrm{dep}} = \sqrt{\frac{2\epsilon_s(2\phi_f - V_{\mathrm{BSeff}})}{q\ \mathtt{NDEP}}} \tag{20}$$

$$X_{\mathrm{dep0}} = \sqrt{\frac{2\epsilon_s(2\phi_f)}{q\ \mathtt{NDEP}}} \tag{21}$$

Effective Gate Source voltage:
Care is taken in Equation 23 to make sure that the voltage across the poly-silicon gate does not exceed the silicon band gap voltage.

$$V_{\mathrm{poly}} = \frac{q\ \epsilon_s\ \mathtt{NGATE}\ C_{\mathrm{oxe}}^2\ 10^6}{2}\left[\sqrt{1+\frac{2(V_{\mathrm{GS}}-V_{\mathrm{FB}}-2\phi_f)}{q\ \epsilon_s\ \mathtt{NGATE}\ C_{\mathrm{oxe}}^2\ 10^6}}-1\right]^2 \tag{22}$$

$$V_{\mathrm{PolyEff}} = 1.12 - 0.5\ (1.12 - V_{\mathrm{poly}} - \delta + \sqrt{(1.12 - V_{\mathrm{poly}} - \delta)^2 + 4\ \delta\ 1.12}) \tag{23}$$

$$V_{\mathrm{GSeff}} = V_{\mathrm{GS}} - V_{\mathrm{PolyEff}} \tag{24}$$

Effective V_{GS} - V_{TH} Smoothing Function:
This function smoothes out the characteristics between the subthreshold and the strong inversion operating regions. It is approximately equal to $V_{\mathrm{GS}} - V_{\mathrm{T}}$ in strong inversion but becomes proportional to $\exp[q(V_{\mathrm{GS}} - V_{\mathrm{T}})/nkT]$ in the subthreshold region.

$$V_{\mathrm{GSTeff}} = \frac{n\frac{kT}{q}\ln(1+\exp(\frac{m}{n}\frac{V_{\mathrm{GSeff}}-V_{\mathrm{T}}}{nkT/q}))}{m+n\frac{C_{\mathrm{oxe}}}{C_{\mathrm{dep0}}}\exp[-\frac{(1-m)(V_{\mathrm{GSeff}}-V_{\mathrm{T}})-V_{\mathrm{off}}}{nkT/q}]} \tag{25}$$

where

$$m = \frac{1}{2} + \frac{\arctan(\mathtt{MINV})}{\pi} \tag{26}$$

$$V_{\mathrm{off}} = \mathtt{VOFF} + \frac{\mathtt{VOFFL}}{L_{\mathrm{EFF}}} \tag{27}$$

$$C_{\mathrm{dep0}} = \frac{\epsilon_s}{X_{\mathrm{dep0}}} \tag{28}$$

$$C_{\mathrm{dep}} = \frac{\epsilon_s}{X_{\mathrm{dep}}} \tag{29}$$

The ideality factor n is

$$n = 1 + \mathtt{NFACTOR}\,\frac{C_{\mathrm{dep}}}{C_{\mathrm{oxe}}}\,\frac{\mathtt{CDSC} + \mathtt{CDSCD}\,V_{\mathrm{DS}} + \mathtt{CDSCB}\,V_{\mathrm{BSeff}}}{C_{\mathrm{oxe}}} \tag{30}$$

$$\times\frac{0.5}{\cosh(\mathtt{DVT1}\,L_{\mathrm{EFF}}/L_t - 1)} + \frac{\mathtt{CIT}}{C_{\mathrm{oxe}}} \tag{31}$$

As mentioned earlier, the ΔV_{T} correction due to pocket implant requires the knowledge of the ideality factor n. Pocket implants near the source and drain regions increase the drive currents. They also increase the drain conductance. The pocket implant correction is modeled as

$$\Delta V_{\mathrm{T,PocketImplant}} = n\frac{kT}{q}\ln[\frac{L_{\mathrm{EFF}}}{L_{\mathrm{EFF}} + \mathtt{DVTP0}\,(1 + \exp(-\mathtt{DVTP1}\,V_{\mathrm{DS}}))}] \tag{32}$$

Mobility characteristics:
The mobility equations are based on the universal-mobility theorem which predicts the mobility degradation with increasing V_{GS}. As an electron moves along the channel due to the lateral electric field, it is also attracted to the gate due to the normal electric field. This causes the electron to drift toward the gate and results in mobility degradation. This effect is modeled in the equations for mobility. We first define a variable TEMP.

$$\mathtt{TEMP} = (\mathtt{UA} + \mathtt{UC}\,V_{\mathrm{BSeff}})\,(\frac{V_{\mathrm{GSTeff}} + V_{\mathrm{T-fb-}\phi}}{\mathtt{TOXE}})^{\mathtt{EU}} \tag{33}$$

where EU is set to zero if the user suppiled value is negative and

$$V_{\mathrm{T-fb-}\phi} = \begin{cases} 2\,(\mathtt{VTH0} - V_{\mathrm{FB}} - 2\phi_f) & \text{for NMOS} \\ 2.5\,(\mathtt{VTH0} - V_{\mathrm{FB}} - 2\phi_f) & \text{for PMOS} \end{cases} \tag{34}$$

The effective mobility of the model takes the generalized form

$$\mu_{\mathrm{eff}} = \frac{\mathtt{U0}}{\mathtt{Denom}} \tag{35}$$

where

$$\mathtt{Denom} = \begin{cases} 1 + \mathtt{TEMP} & \text{if } \mathtt{TEMP} \geq -0.8 \\ (0.6 + \mathtt{TEMP})/(7 + 10\,\mathtt{TEMP}) & \text{if } \mathtt{TEMP} < -0.8 \end{cases} \tag{36}$$

Current characteristics:
Effective Internal Source-Drain Resistance:
This model only models an internal drain to source resistance, R_{DS} given by

$$R_{\mathrm{DS}} = \frac{\mathtt{RDSWMIN} + \mathtt{RDSW} \times 0.5\,[\mathtt{TEMP} + \sqrt{\mathtt{TEMP}^2 + 0.01}]}{(10^6 \times W_{\mathrm{EFFCJ}})^{WR}} \tag{37}$$

Bulk-Charge coefficient:
The bulk-charge coefficient should always have a real physical value, i.e. greater than zero. BSIM4 ensures that this value is always greater than zero. It is an intermediate variable that aids in the evaluation of current and saturation voltage.

$$\begin{aligned} A_{\mathrm{bulk}} &= [1 - F_{\mathrm{doping}} \times [\frac{\mathtt{A0}\,L_{\mathrm{EFF}}}{L_{\mathrm{EFF}} + 2\sqrt{\mathtt{XJ}\,X_{\mathrm{dep}}}} \\ &\quad (1 - \mathtt{AGS}\,V_{\mathrm{GSTeff}}(\frac{L_{\mathrm{EFF}}}{L_{\mathrm{EFF}} + 2\sqrt{\mathtt{XJ}\,X_{\mathrm{dep}}}})^2) + \frac{\mathtt{B0}}{W_{\mathrm{EFF}} + \mathtt{B1}}]] \\ &\quad \times\frac{1}{1 + \mathtt{KETA}\,V_{\mathrm{BSeff}}} \end{aligned} \tag{38}$$

where

$$F_{\text{doping}} = \sqrt{1 + \frac{\texttt{LPEB}}{L_{\text{EFF}}}} \times \frac{\texttt{K1}}{2\sqrt{2\phi_f - V_{\text{BSeff}}}} \frac{\texttt{TOXE}}{\texttt{TOXM}} + \texttt{K2}\,\frac{\texttt{TOXE}}{\texttt{TOXM}} - \texttt{K3} \times \frac{\texttt{TOXE}}{W_{\text{EFF}} + \texttt{W0}}\, 2\,\phi_f \tag{39}$$

Drain Saturation Voltage:
The value of the drain voltage in the saturation region is given by

$$\epsilon_{\text{sat}} = \frac{2\ \texttt{VSAT}}{\mu_{\text{eff}}} \tag{40}$$

If $R_{\text{DS}} = 0$, then

$$V_{\text{DSsat}} = \frac{\epsilon_{\text{sat}}\ L_{\text{EFF}}\ (V_{\text{GSTeff}} + 2kT/q)}{A_{\text{bulk}}\ \epsilon_{\text{sat}}\ L_{\text{EFF}} + (V_{\text{GSTeff}} + 2kT/q)} \tag{41}$$

If $R_{\text{DS}} \neq 0$, then,

$$V_{\text{DSsat}} = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \tag{42}$$

$$a = A_{\text{bulk}}^2\ W_{\text{EFF}}\ \texttt{VSAT}\ C_{\text{oxe}}\ R_{\text{DS}} + (\frac{1}{\lambda} - 1)\ A_{\text{bulk}} \tag{43}$$

$$b = -[(V_{\text{GSTeff+2kT/q}})\ (\frac{2}{\lambda} - 1) + A_{\text{bulk}}\ \epsilon_{\text{sat}}\ L_{\text{EFF}} + 3\ A_{\text{bulk}}\ (V_{\text{GSTeff+2kT/q}})\ W_{\text{EFF}}\ \texttt{VSAT}\ C_{\text{oxe}}\ R_{\text{DS}}] \tag{44}$$

$$c = (V_{\text{GSTeff+2kT/q}})\ \epsilon_{\text{sat}}\ L_{\text{EFF}} + 2(V_{\text{GSTeff+2kT/q}})^2 W_{\text{EFF}}\ \texttt{VSAT}\ C_{\text{oxe}}\ R_{\text{DS}} \tag{45}$$

where λ is determined by parameters `A1` and `A2`.
Effective Drain to Source Voltage:
V_{DSeff} varies between 0 (when $V_{\text{DS}} = 0$) and V_{DSsat} in the saturation region, where V_{DS} is fairly high. It is a smoothing function defined to smooth out the transition between the linear and saturation regions. The parameter `DELTA` can be varied between 0.1 and 0.001 to get greater control of the transition between the linear and saturation region.

$$V_{\text{DSeff}} = V_{\text{DSsat}} - 0.5\ (V_{\text{DSsat}} - V_{\text{DS}} - \texttt{DELTA} + \sqrt{(V_{\text{DSsat}-\text{V}_{\text{DS}}-\texttt{DELTA}})^2 + 4\ \texttt{DELTA}\ \text{V}_{\text{DSsat}}}) \tag{46}$$

Effective oxide calculation:
The drain current, in BSIM4, has a significant amount of drain current in the strong inversion region. It calculates the maximum probability of carrier distribution occurs at a distance X_{DC} away from the interface. The oxide capacitance for the inversion calculation is given by

$$C_{\text{ox}} = \frac{\epsilon_{\text{ox}}}{\texttt{TOXP}} \parallel \frac{\epsilon_s}{X_{\text{DC}}} \tag{47}$$

where

$$X_{\text{DC}} = \begin{cases} 1.9 \times 10^{-9} \times [1 + \frac{V_{\text{GSTeff}} + 4(\texttt{VTH0} - V_{\text{FB}} - 2\phi_f)}{2 \times 10^8\ \texttt{TOXP}}]^{-0.7} & (V_{\text{TH0}} - V_{\text{FB}} - 2\phi_f) \geq 0 \\ 1.9 \times 10^{-9} \times [1 + V_{\text{GSTeff}}/(2 \times 10^8\ \texttt{TOXP})]^{-0.7} & (V_{\text{TH0}} - V_{\text{FB}} - 2\phi_f) < 0 \end{cases} \tag{48}$$

Current Calculations:
This is the dominant portion of drain current. It flows from the drain to the source through the channel.

$$\begin{aligned} I_{\mathrm{DS}} &= \frac{I_{\mathrm{DS0}}}{1+\frac{R_{\mathrm{DS}} I_{\mathrm{DS0}}}{V_{\mathrm{DSeff}}}} \left(1+\frac{1}{C_{\mathrm{clm}}}\ln\frac{V_A}{V_{\mathrm{Asat}}}\right) \times \left(1+\frac{V_{\mathrm{DS}}-V_{\mathrm{DSeff}}}{V_{\mathrm{ADIBL}}}\right) \\ &\quad \times\left(1+\frac{V_{\mathrm{DS}}-V_{\mathrm{DSeff}}}{V_{\mathrm{ADITS}}}\right) \times \left(1+\frac{V_{\mathrm{DS}}-V_{\mathrm{DSeff}}}{V_{\mathrm{ASCBE}}}\right) \times \mathtt{NF} \end{aligned} \tag{49}$$

where the ideal long channel current in the absence of channel length modulation and DIBL effects is given by

$$I_{\mathrm{DS0}} = \frac{W_{\mathrm{EFF}}\,\mu_{\mathrm{eff}}\,C_{\mathrm{ox}}\,V_{\mathrm{GSTeff}}}{L_{\mathrm{EFF}}\,[1+V_{\mathrm{DSeff}}/(\epsilon_{\mathrm{sat}} L_{\mathrm{EFF}})]}\left[1-\frac{A_{\mathrm{bulk}}\,V_{\mathrm{DSeff}}}{2(V_{\mathrm{GSTeff}}+2kT/q)}\right] V_{\mathrm{DSeff}} \tag{50}$$

There Early voltage is given as

$$V_A = V_{\mathrm{Asat}} + V_{\mathrm{ACLM}} \tag{51}$$

where V_{Asat} calculates the ideal early voltage in the absence of short channel effects and V_{ACLM} models channel length modulation.

$$\begin{aligned} V_{\mathrm{Asat}} &= \frac{\epsilon_{\mathrm{sat}}\,L_{\mathrm{EFF}} + V_{\mathrm{DSsat}} + 2R_{\mathrm{DS}}\,\mathtt{VSAT}\,C_{\mathrm{oxe}} W_{\mathrm{EFF}}\,V_{\mathrm{GSTeff}}}{2/\lambda - 1 + R_{\mathrm{DS}}\,\mathtt{VSAT}\,C_{\mathrm{oxe}}\,W_{\mathrm{EFF}}\,A_{\mathrm{bulk}}} \\ &\quad \times\left[1-\frac{A_{\mathrm{bulk}}\,V_{\mathrm{DSsat}}}{2\,(V_{\mathrm{GSTeff}}+2kT/q)}\right] \end{aligned} \tag{52}$$

The degradation factor due to pocket implantation is given by

$$F_p = \begin{cases} (1+\mathtt{FPROUT}\,\sqrt{L_{\mathrm{EFF}}}/(V_{\mathrm{GSTeff}}+2kT/q))^{-1} & \mathtt{FPROUT} > 0 \\ 1 & \mathtt{FPROUT} \le 0 \end{cases} \tag{53}$$

To account for the effects of gate-bias on the slope of I_{DS} in the saturation region, we use

$$F_{\mathrm{VG}} = \begin{cases} 1+\mathtt{PVAG}\,V_{\mathrm{GSTeff}}/(\epsilon_{\mathrm{sat}}\,L_{\mathrm{EFF}}) & \mathtt{PVAG}\,V_{\mathrm{GSTeff}}/(\epsilon_{\mathrm{sat}}\,L_{\mathrm{EFF}}) > -0.9 \\ 0.8+\mathtt{PVAG}\,V_{\mathrm{GSTeff}}/(\epsilon_{\mathrm{sat}}\,L_{\mathrm{EFF}}) & \\ \times(17+20\,\mathtt{PVAG}\,V_{\mathrm{GSTeff}}/(\epsilon_{\mathrm{sat}}\,L_{\mathrm{EFF}}))^{-1} & \end{cases} \tag{54}$$

$$C_{\mathrm{clm}} = \begin{cases} \mathtt{TEMP} & \mathtt{PCLM} > 0 \textit{ and } (V_{\mathrm{DS}}-V_{\mathrm{DSeff}}) > 10^{-10} \\ 5.834617425\times 10^{14} & \end{cases} \tag{55}$$

where

$$\mathtt{TEMP} = \frac{F_p}{\mathtt{PCLM}\,L_{\mathrm{itl}}} F_{\mathrm{VG}} \times \left(1+\frac{R_{\mathrm{DS}}\,I_{\mathrm{DS0}}}{V_{\mathrm{DSeff}}}\right) \times \left(L_{\mathrm{EFF}}+\frac{V_{\mathrm{DSsat}}}{\epsilon_{\mathrm{sat}}}\right) \tag{56}$$

$$\begin{aligned} \theta_{\mathrm{rout}} &= \mathtt{PDIBLC1}\times[\exp(-\mathtt{DROUT}\,L_{\mathrm{EFF}}/2L_{\mathrm{t0}}) + 2\exp(-\mathtt{DROUT}\,L_{\mathrm{EFF}}/2L_{\mathrm{t0}})] \\ &\quad +\mathtt{PDIBLC2} \end{aligned} \tag{57}$$

The effect of DIBL on Early voltage is modeled as:

$$V_{\mathrm{ADIBL}} = \begin{cases} V_{\mathrm{GSTeff}} + 2kT/q/(\theta_{\mathrm{rout}}(1+\mathtt{PDIBLCB}\,V_{\mathrm{BSeff}})) \times F_{\mathrm{VG}} & \\ \times[1-A_{\mathrm{bulk}}V_{\mathrm{DSsat}}/(A_{\mathrm{bulk}}V_{\mathrm{DSsat}}+V_{\mathrm{GSTeff}}+2kT/q)] & \theta_{\mathrm{rout}} \ge 0 \\ 5.834617425\times 10^{10} & \theta_{\mathrm{rout}} < 0 \end{cases} \tag{58}$$

The effect of DITS (Drain-induced Threshold Shift) due to pocket implant is modeled by

$$V_{\mathrm{ADITS}} = \begin{cases} \frac{F_p}{\mathtt{PDITS}}[1+(1+\mathtt{PDITSL}\,L_{\mathrm{EFF}})\times\exp(\mathtt{PDITSD}\,V_{\mathrm{DS}})] & \mathtt{PDITS} > 0 \\ 5.834617425\times 10^{14} & \textit{else} \end{cases} \tag{59}$$

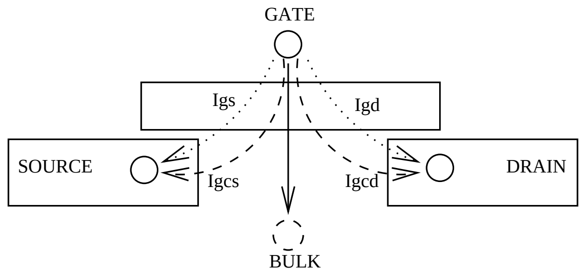

Figure 2: Schematic of the gate current distribution in the FET

Substrate current has an effect on Early voltage and it is modeled by SCBE (Substrate Current Induced Body Effect).

$$V_{\text{ASCBE}} = \begin{cases} \frac{L_{\text{EFF}}}{\texttt{PSCBE2}} \exp(\texttt{PSCBE2}\, L_{\text{itl}}/(V_{\text{DS}} - V_{\text{DSeff}})) & \texttt{PSCBE2} > 0 \\ 5.834617425 \times 10^{10} & \textit{else} \end{cases} \tag{60}$$

where

$$L_{\text{itl}} = \sqrt{\epsilon_s/\epsilon_{\text{ox}} \times \texttt{TOXE}\,\texttt{XJ}} \tag{61}$$

Substrate Currents:
The substrate currents comprise of two parts, one due to Impact Ionization and the other due to GIDL. When V_{DS} is high, a large voltage is dropped across the depletion region near the drain. This field accelerates the electrons as they are moving in the channel. When they generate sufficient energy, the collide with the semiconductor crystal and generate electron-hole pairs. This current that is generated flows towards the substrate. This forms the Impact Ionization current and is denoted by I_{sub}.

$$\begin{aligned} I_{\text{sub}} &= \texttt{NF} \times (\frac{\texttt{ALPHA0}}{L_{\text{EFF}}} + \texttt{ALPHA1})(V_{\text{DS}} - V_{\text{DSeff}}) \exp[-\frac{\texttt{BETA0}}{V_{\text{DS}} - V_{\text{DSeff}}}] \\ & \frac{I_{\text{DS0}}}{1 + \frac{R_{\text{DS}} I_{\text{DS0}}}{V_{\text{DSeff}}}} (1 + \frac{1}{C_{\text{clm}}} \ln \frac{V_A}{V_{\text{Asat}}}) \times (1 + \frac{V_{\text{DS}} - V_{\text{DSeff}}}{V_{\text{ADIBL}}}) \\ & \times (1 + \frac{V_{\text{DS}} - V_{\text{DSeff}}}{V_{\text{ADITS}}}) \end{aligned} \tag{62}$$

The contribution due to GIDL is given by

$$\begin{aligned} I_{\text{gidl}} &= \texttt{NF} \times \texttt{AGIDL}\, W_{\text{EFFCJ}} [\frac{V_{\text{DS}} - V_{\text{GSeff}} - \texttt{EGIDL}}{3\, \texttt{TOXE}}] \\ & \times \exp(\frac{-3\, \texttt{TOXE} \times \texttt{BGIDL}}{V_{\text{DS}} - V_{\text{GSeff}} - \texttt{EGIDL}}) \\ & \frac{V_{\text{DB}}^3}{\texttt{CGIDL} + V_{\text{DB}}^3} \end{aligned} \tag{63}$$

Gate Currents:
As the oxide layer becomes progressively thinner, the tunnelling currents flowing through the oxide become more significant. This model considers four tunnelling currents as shown in Fig 2.

I_{gd} is the tunnelling current between the gate and the heavily-doped drain. I_{gcd} denotes the current that flows from the gate to the channel and then to the drain. Likewise, I_{gs} and I_{gcs} are similar tunnelling currents, but associated with the source junction. The current I_{gb} represents the current flowing from the gate to the bulk.
The voltage drop across the oxide is given by

$$V_{\text{ox}} = V_{\text{FB}} - V_{\text{FBeff}} + \texttt{K1}\, \sqrt{\phi_s} + V_{\text{GSTeff}} \tag{64}$$

The first two terms of the above equation represent voltage dropped in the accumulation region or V_{oxacc} and the depletion/inversion region or V_{oxdepinv}. The two channel tunnelling components are given by

$$I_{\mathrm{gcs}} = I_{\mathrm{gc}} \times \frac{-1 + \mathtt{PIGCD}\, V_{\mathrm{DS}} + \exp(-\mathtt{PIGCD}\, V_{\mathrm{DS}} + 10^{-4})}{(\mathtt{PIGCD}\, V_{\mathrm{DS}})^2 + 2 \times 10^{-4}} \tag{65}$$

$$I_{\mathrm{gcd}} = I_{\mathrm{gc}} \times \frac{1 - (1 + \mathtt{PIGCD}\, V_{\mathrm{DS}}) + \exp(-\mathtt{PIGCD}\, V_{\mathrm{DS}} + 10^{-4})}{(\mathtt{PIGCD}\, V_{\mathrm{DS}})^2 + 2 \times 10^{-4}} \tag{66}$$

Both these currents have dependencies on the drain-source voltage V_{DS}. Generally, these currents do not sum up to I_{gc}. However, when V_{DS} is zero, they are identical to each other and equal to half of I_{gc}, which is given by

$$\begin{aligned} I_{\mathrm{gc}} &= \mathtt{NF}\, W_{\mathrm{EFF}}\, L_{\mathrm{EFF}} \frac{A}{(\mathtt{TOXE})^2} \left(\frac{\mathtt{TOXREF}}{\mathtt{TOXE}}\right)^{\mathtt{NTOX}} V_{\mathrm{GSeff}} \\ &\quad \times \mathtt{NIGC} \frac{kT}{q} \ln[1 + \exp(\frac{q(V_{\mathrm{GSeff}} - \mathtt{VTHO})}{kT.\mathtt{NIGC}})] \\ &\quad \exp[-B.\mathtt{TOXE}(\mathtt{AIGC} - \mathtt{BIGC} V_{\mathrm{oxdepinv}}).(1 + \mathtt{CIGC} V_{\mathrm{oxdepinv}})] \end{aligned} \tag{67}$$

The coefficients used in the above equations are

$$A = 4.97232 \times 10^{-7} \tag{68}$$

$$B = 7.45669 \times 10^{11} \tag{69}$$

The currents associated with the gate and source/drain regions is given by

$$\begin{aligned} I_{\mathrm{gs}} &= \mathtt{NF}\, W_{\mathrm{EFF}}\, \mathtt{DLCIG} \frac{A}{(\mathtt{TOXE\ POXEDGE})^2} \left(\frac{\mathtt{TOXREF}}{\mathtt{TOXE\ POXEDGE}}\right)^{\mathtt{NTOX}} V_{\mathrm{GS}} \times V'_{\mathrm{GS}} \\ &\quad \exp[-B\, \mathtt{TOXE\ POXEDGE}(\mathtt{AIGSD} - \mathtt{BIGSD}\, V_{\mathrm{GS}}) \\ &\quad (1 + \mathtt{CIGSD}\, V'_{\mathrm{GS}})] \end{aligned} \tag{70}$$

$$V'_{\mathrm{GS}} = \sqrt{(V_{\mathrm{GS}} - V_{\mathrm{fbsd}})^2 + 10^{-4}} \tag{71}$$

$$\begin{aligned} I_{\mathrm{gd}} &= \mathtt{NF}\, W_{\mathrm{EFF}}\, \mathtt{DLCIG} \frac{A}{(\mathtt{TOXE\ POXEDGE})^2} \left(\frac{\mathtt{TOXREF}}{\mathtt{TOXE\ POXEDGE}}\right)^{\mathtt{NTOX}} V_{\mathrm{GD}} \times V'_{\mathrm{GD}} \\ &\quad \exp[-B\, \mathtt{TOXE\ POXEDGE}(\mathtt{AIGSD} - \mathtt{BIGSD}\, V_{\mathrm{GD}}) \\ &\quad (1 + \mathtt{CIGSD}\, V'_{\mathrm{GD}})] \end{aligned} \tag{72}$$

$$V'_{\mathrm{GD}} = \sqrt{(V_{\mathrm{GD}} - V_{\mathrm{fbsd}})^2 + 10^{-4}} \tag{73}$$

The resultant dc equivalent circuit for the transistor is shown in Figure 3

Charge computation and Conservation:

Basic Formulation:

To ensure charge conservation, terminal charges are used as state variables along with terminal voltages. Q_g, Q_s, Q_d and Q_b are the charges associated with the gate, source, drain and bulk terminals respectively. The gate charge comprises of the inversion charge Q_{inv}, the accumulation charge Q_{acc} and the substrate depletion charge Q_{sub}.

The channel charge comes from the source and drain terminals while the accumulation and substrate charge is associated with the substrate.

$$\begin{aligned} Q_g &= -(Q_{\mathrm{sub}} + Q_{\mathrm{inv}} + Q_{\mathrm{acc}}) \\ Q_b &= Q_{\mathrm{acc}} + Q_{\mathrm{sub}} \\ Q_{\mathrm{inv}} &= Q_d + Q_s \end{aligned} \tag{74}$$

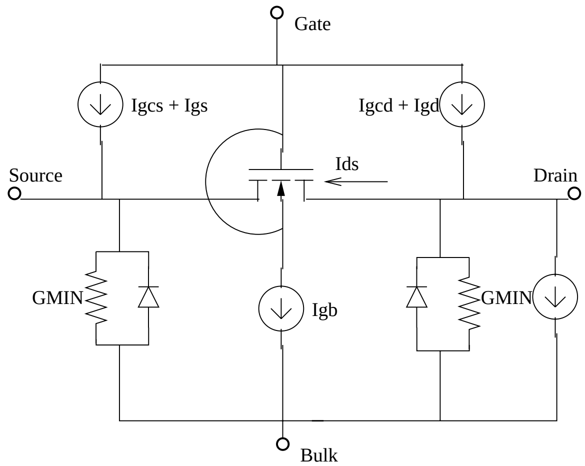

Figure 3: Schematic of the dc equivalent circuit

The substrate charge can be divided further into two components: the substrate charge at zero source-drain bias (Q_{sub0}) and a non-uniform substrate charge in the presence of a drain bias (δQ_{sub}). The gate charge now becomes

$$Q_g = -(Q_{\mathrm{sub0}} + \delta Q_{\mathrm{sub}} + Q_{\mathrm{inv}} + Q_{\mathrm{acc}}) \tag{75}$$

The total charge is computed by integrating the charge along the channel. SPICE3 provides three options in BSIM4 whereby a user can select the percentage of charge distribution between the source and drain. The options are a 0/100 distribution which implies that no channel charge is associated with the source and it is all assigned to the drain, a 50/50 partition which divides the charges equally between the source and drain and a 40/60 partition wherein the total charge in the channel is divided in a 40:60 ratio between the source and drain. *f*REEDA™uses a 40/60 charge partitioning scheme between the source and drain terminals because that is the closest to a physical situation in the channel.

Effective V_{BS}, V_{GB}:

This is a smoothing function required for C-V calculations.

$$V_{\mathrm{BSeffCV}} = \begin{cases} V_{\mathrm{BSeff}} & V_{\mathrm{BSeff}} < 0 \\ \phi_s - \frac{\phi_s}{\phi_s + V_{\mathrm{BSeff}}} & V_{\mathrm{BSeff}} \geq 0 \end{cases} \tag{76}$$

$$V_{\mathrm{GBeffCV}} = V_{gse} - V_{\mathrm{BSeffCV}} \tag{77}$$

Effective $V_{\mathrm{GS}} - V_{\mathrm{T}}$:

This is also a smoothing function used in the C-V calculation.

$$V_{\mathrm{GSTeffCV}} = \mathtt{NOFF}\,\frac{nkT}{q}\,\ln[1 + \exp(\frac{V_{\mathrm{GSeff}} - V_{\mathrm{T}} - \mathtt{VOFFCV}}{\mathtt{NOFF}\,nkT/q})] \tag{78}$$

Modified Bulk Charge coefficient:

For C-V calculations, the reduced bulk charge coefficient is used instead of the coefficient used in the DC calculations.

$$\begin{aligned} A_{\mathrm{bulk0}} &= [1 - F_{\mathrm{doping}} \times [\frac{\mathtt{A0}\,L_{\mathrm{EFF}}}{L_{\mathrm{EFF}} + 2\sqrt{\mathtt{XJ}\,X_{\mathrm{dep}}}} + \frac{\mathtt{B0}}{W_{\mathrm{EFF}} + \mathtt{B1}}]] \\ &\times \frac{1}{1 + \mathtt{KETA}\,V_{\mathrm{BSeff}}} \end{aligned} \tag{79}$$

Using this value of reduced bulk-charge coefficient, the bulk-charge coefficient for C-V calculations is given by

$$A_{\mathrm{bulkCV}} = A_{\mathrm{bulk0}}[1 + (\frac{\mathtt{CLC}}{L_{\mathrm{EFF}}})^{\mathtt{CLE}}] \tag{80}$$

The Terminal Charges:
The effective oxide thickness

$$C'_{\text{oxeff}} = \frac{\epsilon_{\text{ox}}}{\texttt{TOXP}} \| \frac{\epsilon_s}{X_{\text{DCeff}}} \tag{81}$$

where

$$\begin{aligned} X_{\text{DCeff}} &= X_{\text{DCmax}} \\ &- \frac{X_{\text{DCmax}} - X_{\text{DC}} - \delta_x + \sqrt{(X_{\text{DCmax}} - X_{DC} - \delta_x)^2 + 4\,\delta_x\, X_{\text{DCmax}}}}{2} \end{aligned} \tag{82}$$

The various terms inside the above equation are given by

$$X_{\text{DC}} = \frac{L_{\text{Deb}}}{3} \exp[\texttt{ACDE}(\frac{\texttt{NDEP}}{2 \times 10^{16}})^{-0.25}\ \frac{V_{\text{GBeff}} - V_{\text{fbzb}}}{10^8 \times \texttt{TOXP}}] \tag{83}$$

$$L_{\text{Deb}} = \sqrt{\frac{\epsilon_s\ k[T + 273.15]/q}{q\texttt{NDEP}10^6}} \tag{84}$$

$$X_{\text{DCmax}} = \frac{L_{\text{Deb}}}{3} \tag{85}$$

$$\delta_x = 10^{-3}\texttt{TOXP} \tag{86}$$

The effective oxide is re-calculated for evaluation of the accumulation charge.

$$C_{\text{oxeff}} = C'_{\text{oxeff}} \times W_{\text{EFF}} \times L_{\text{EFF}} \times \texttt{NF} \tag{87}$$

The accumulation charge is given by

$$Q_{\text{acc}} = C_{\text{oxeff}}\ (V_{\text{FBeffCV}} - V_{\text{FBCV}}) \tag{88}$$

The substrate charge is given by

$$Q_{\text{sub0}} = C_{\text{oxeff}}\ (\texttt{K1}\frac{\texttt{TOXE}}{\texttt{TOXM}})\ \sqrt{\phi_{\text{s,dep}}} \tag{89}$$

When the transistor enters the sub-threshold region, another value of X_{DC} is required. This value is used in the evaluation of Q_{inv} and δQ_{sub}.

$$C'_{\text{oxinv}} = \frac{\epsilon_{\text{ox}}}{\texttt{TOXP}} \| \frac{\epsilon_s}{X_{\text{DCinv}}} \tag{90}$$

where

$$X_{\text{DCinv}} = \begin{cases} 1.9 \times 10^{-9} & \\ \times[1 + \frac{V_{\text{GSTeffCV}} + 4(\texttt{VTH0} - V_{\text{FB}} - 2\phi_f)}{2 \times 10^8\ \texttt{TOXP}}]^{-0.7} & (V_{\text{TH0}} - V_{\text{FB}} - 2\phi_f) \geq 0 \\ & \\ 1.9 \times 10^{-9} & \\ \times[1 + V_{\text{GSTeffCV}}/(2 \times 10^8\ \texttt{TOXP})]^{-0.7} & (V_{\text{TH0}} - V_{\text{FB}} - 2\phi_f) < 0 \end{cases} \tag{91}$$

The above equation is identical to X_{DC} used for I-V calculations, except that V_{GSTeff} is replaced by V_{GSTeffCV}.

$$C_{\text{oxinv}} = C'_{\text{oxinv}} \times W_{\text{EFF}} \times L_{\text{EFF}} \times \texttt{NF} \tag{92}$$

In addition to the new X_{DC}, the surface potential is not constant as in the I-V case and needs to be re-calculated.

$$\phi_\delta = \begin{cases} \frac{kT}{q} \ln[1 + V_{\text{GSTeffCV}}(V_{\text{GSTeffCV}} + 2\texttt{K1}\ (\texttt{TOXE/TOXM})\ (\phi_s))] & \\ -\frac{kT}{q}\ \ln[\texttt{MOIN}\ \texttt{K1}^2(\texttt{TOXE/TOXM})^2\ (kT/q)] & \texttt{K1} > 0 \\ & \\ \frac{kT}{q} \ln[1 + V_{\text{GSTeffCV}}(V_{\text{GSTeffCV}} + \sqrt{\phi_s})/(0.25 \times \texttt{MOIN}(kT/q))] & \texttt{K1} \leq 0 \end{cases} \tag{93}$$

$$V_{\text{DSsatCV}} = \frac{V_{\text{GSTeffCV}} - \phi_\delta}{A_{\text{bulkCV}}} \tag{94}$$

$$V_{\rm DSeffCV} = V_{\rm DSsatCV} - \frac{V_{\rm DSsatCV} - V_{\rm DS} - 0.02}{2} - \sqrt{\frac{(V_{\rm DSsatCV} - V_{\rm DS} - 0.02)^2 + 4\ 0.02\ V_{\rm DSsatCV}}{2}} \tag{95}$$

Based on these calculations, the inversion charge can be written as

$$Q_{\rm inv} = -C_{\rm oxinv}[(V_{\rm GSTeffCV} - \phi_\delta - \frac{A_{\rm bulkCV}V_{\rm DSeffCV}}{2}) \frac{A^2_{\rm bulkCV}V^2_{\rm DSeffCV}}{12(V_{\rm GSTeffCV} - \phi_\delta - A_{\rm bulkCV}V_{\rm DSeffCV}/2 + 10^{-20})}] \tag{96}$$

The factor of 10^{-20} exists to mainly prevent the denominator from going to a negative value when the rest of the terms go close to zero.
The substrate charge in the presence of a drain bias is given by

$$\delta Q_{\rm sub} = C_{\rm oxinv}[\frac{1 - A_{\rm bulkCV}}{2}V_{\rm DSeffCV} \tag{97}$$

$$-\frac{(1 - A_{\rm bulkCV})\ A_{\rm bulkCV}\ V^2_{\rm DSeffCV}}{12\,(V_{\rm GSTeffCV} - \phi_\delta - A_{\rm bulkCV}\ V_{\rm DSeffCV}/2 + 10^{-20})}] \tag{98}$$

Finally, the four charges at the respective terminals are given by

$$Q_g = -Q_{\rm inv} - \delta Q_{\rm sub} + Q_{\rm acc} + Q_{\rm sub0} \tag{99}$$

$$Q_b = \delta Q_{\rm sub} - Q_{\rm acc} - Q_{\rm sub0} \tag{100}$$

For a 40/60 charge partition scheme, the charge at the source and drain regions is

$$\begin{aligned} Q_s = & -\frac{C_{\rm oxinv}}{2(V_{\rm GSTeffCV} - \phi_\delta - \frac{A_{\rm bulkCV}V_{\rm DSeffCV}}{2})^2} \\ & \times[(V_{\rm GSTeffCV} - \phi_\delta)^3 \\ & -\frac{4}{3}(V_{\rm GSTeffCV} - \phi_\delta)^2 A_{\rm bulkCV}V_{\rm DSeffCV} \\ & +\frac{2}{3}(V_{\rm GSTeffCV} - \phi_\delta)^2 A_{\rm bulkCV}V_{\rm DSeffCV} \\ & -\frac{2}{15}A^3_{\rm bulkCV}V^3_{\rm DSeffCV} \end{aligned} \tag{101}$$

$$\begin{aligned} Q_d = & -\frac{C_{\rm oxinv}}{2(V_{\rm GSTeffCV} - \phi_\delta - \frac{A_{\rm bulkCV}V_{\rm DSeffCV}}{2})^2} \\ & \times[(V_{\rm GSTeffCV} - \phi_\delta)^3 \\ & -\frac{5}{3}(V_{\rm GSTeffCV} - \phi_\delta)^2 A_{\rm bulkCV}V_{\rm DSeffCV} \\ & +(V_{\rm GSTeffCV} - \phi_\delta)^2 A_{\rm bulkCV}V_{\rm DSeffCV} \\ & -\frac{1}{5}A^3_{\rm bulkCV}V^3_{\rm DSeffCV} \end{aligned} \tag{102}$$

The net currents at the gate, source and drain is given by

$$i_G(t) = I_{\rm gcs} + I_{\rm gcd} + I_{\rm gs} + I_{\rm gd} + \frac{dQ_g}{dt} \tag{103}$$

$$i_S(t) = -I_{\rm DS} - I_{\rm gs} - I_{\rm gcs} + \frac{dQ_s}{dt} \tag{104}$$

$$i_D(t) = I_{\rm DS} + I_{\rm sub} + I_{\rm gidl} - I_{\rm gcd} - I_{\rm gd} + \frac{dQ_d}{dt} \tag{105}$$

Notes:
There is no equivalent SPICE element.

Version:
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Publications:

1. M. B. Steer, C. Christoffersen, S. Velu and N. Kriplani, "Global Modeling of RF and Microwave Circuits," Mediterranean Microwave Conf. Digest, June 2002.