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PSP-Based MOSVAR v1.0.0

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Abstract: The MOS varactor compact model is based in part on the PSP MOSFET model and is intended for analogue and RF-design. It includes dynamic inversion, finite poly doping, quantum mechanics, tunneling currents, and parasitics to model advanced MOS technologies. This manual contains a description of the PSP-based varactor model, including introduction, parameter sets, model equations, and parameter extraction procedure.

Contents

Section 1

Introduction

The PSP-based varactor model is a compact MOS model intended for analog and radio-frequency circuit design. It includes dynamic inversion, finite poly doping, quantum mechanics, gate tunneling for different polarity combinations, and parasitics to model advanced MOS technologies.

1.1 Device Structure

Figure 1.1 shows a cross section of the standard MOS varactor offered in the current MOS technologies with its equivalent circuit model overlapped on it. **g**, **bi** and **b** are the external terminals while **gii**, **gi** and **ci** are the internal nodes. See Table 1.1 for the meaning of other symbols.

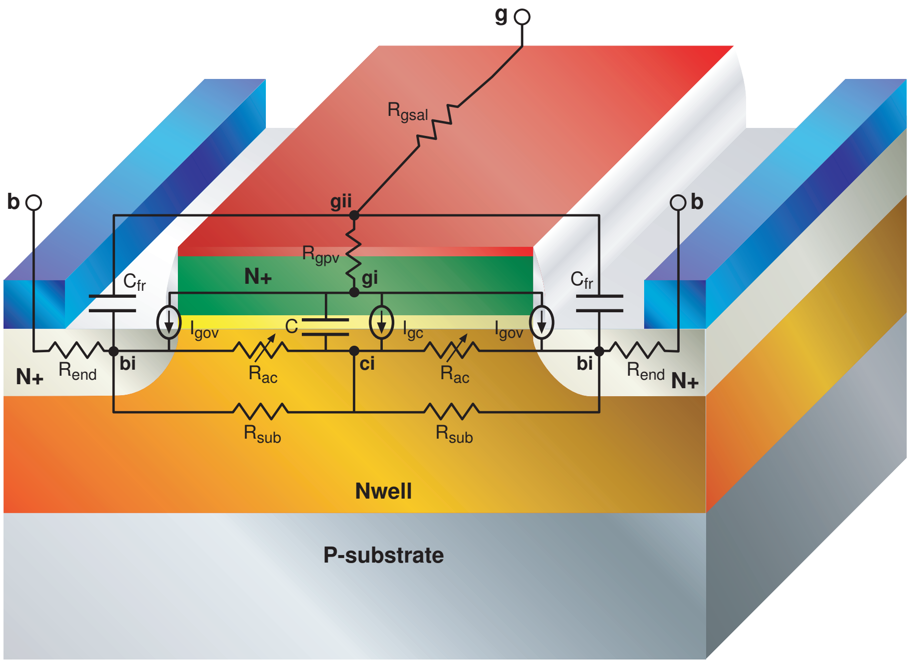

Figure 1.1: Cross section of MOS varactor with its equivalent circuit model.

Table 1.1: Components of varactor model

No.	Name	Description
1	C	Gate-channel capacitance
2	C_{fr}	Fringe and overlap capacitance
3	I_{gc}	Gate-channel current
4	I_{gov}	Gate-overlap current
5	R_{gsal}	Metal resistance
6	R_{gpv}	Poly gate resistance
7	R_{ac}	Accumulation resistance
8	R_{sub}	Substrate (in well region) resistance
9	R_{end}	End resistance

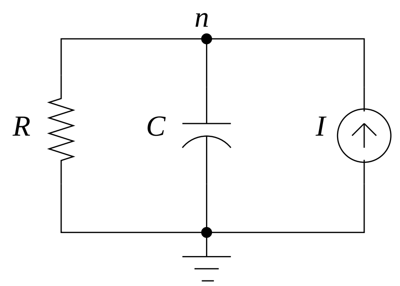

Figure 1.2: An RC circuit model used in the varactor code.

1.2 An RC Circuit Model for Inversion Charge

Figure 1.2 shows an RC circuit using in Section 4 for dynamic inversion charge [2, 3] with $R = 1\Omega, C =$ **TAU** F, which is defined in Section 2, and a current source $I = q_{i0}$ A with q_{i0} the quasi-static inversion charge (only the values of **TAU** and q_{i0} are used here) . As can be seen, it performs the operation

$$q_i = q_{i0} - \mathbf{TAU} \cdot \frac{dq_i}{dt} \tag{1.1}$$

From the internal node **n**, the calculation results can be obtained. Note that the RC circuit is used only for computing convenience, it does not exist in the physical model.

1.3 Differences with PSP MOSFET Model

Although varactor model has inherited the surface potential algorithm from the PSP model [1], there are differences between them.

1. There is no position dependence of surface potential in varactor.
2. Dynamic formation of inversion region is included in the varactor model [2, 3].

3. Different (more elaborate) parasitics are included in the varactor model.
4. The varactor model has different combinations of gate and well polarities.
5. More elaborate polysilicon space charge region model are included in the varactor model (in PSP, there is no poly space charge effect in accumulation).
6. The varactor model is global, there is no local model.
7. The varactor model has simpler parameter clamping procedure.

Section 2

Constants and Parameters

In this section, the symbolic representation, value, and description of various physical constants and parameters used in the varactor model are listed. Throughout this document, varactor parameter names are all printed in boldface capitals. Parameters for temperature scaling start with '**ST**', followed by the name of the parameter to which the temperature scaling applies.

2.1 Circuit Simulator Variables

External electrical variables

The definitions of the external electrical variables are shown in the following.

Symbol	**Unit**	**Description**
$V_{\rm G}^{\rm e}$	V	Potential applied to gate node
$V_{\rm B}^{\rm e}$	V	Potential applied to bulk node
$I_{\rm G}^{\rm e}$	A	DC current into gate node
$I_{\rm B}^{\rm e}$	A	DC current into bulk node
$S_{\rm fl}^{\rm e}$	$\rm A^2s$	Spectral density of flicker noise current in the channel
$S_{\rm id}^{\rm e}$	$\rm A^2s$	Spectral density of thermal noise current in the channel

Other circuit simulator variables

Next to the electrical variables described above, the quantities in the table below are also provided to the model by the circuit simulator.

Symbol	**Unit**	**Description**
$T_{\rm A}$	°C	Ambient circuit temperature
$f_{\rm op}$	Hz	Operation frequency

2.2 Model Constants

No.	Symbol	Unit	Value	Description
1	T_0	K	273.15	Offset between Celsius and Kelvin temperature scale
2	k_B	J/K	$1.3806505 \cdot 10^{-23}$	Boltzmann constant
3	$\hbar$	J s	$1.05457168 \cdot 10^{-34}$	Reduced Planck constant
4	q	C	$1.6021918 \cdot 10^{-19}$	Elementary unit charge
5	m_0	kg	$9.1093826 \cdot 10^{-31}$	Electron rest mass
6	ϵ_ox	F/m	$3.453 \cdot 10^{-11}$	Absolute permittivity of oxide
7	ϵ_si	F/m	$1.045 \cdot 10^{-10}$	Absolute permittivity of silicon
8	QM_N	V $\mathrm{m}^{\frac{4}{3}}\mathrm{C}^{-\frac{2}{3}}$	5.951993	Constant of quantum-mechanical behavior of electrons
9	QM_P	V $\mathrm{m}^{\frac{4}{3}}\mathrm{C}^{-\frac{2}{3}}$	7.448711	Constant of quantum-mechanical behavior of holes

2.3 Instance Parameters

No.	Name	Unit	Default	Min.	Max.	Description
1	L	m	10^{-6}	0	–	Design length of varactor
2	W	m	10^{-6}	0	–	Design width of varactor
3	m		1	0	–	Multiplicity factor
4	NGCON		1	1	2	Number of gate contacts
5	DTA	°C	0	–	–	Local temperature offset with respect to ambient circuit temperature

2.4 Special Model Parameters

No.	Name	Unit	Default	Min.	Max.	Description
1	Version		1	N/A	N/A	Model version
2	Revision		0.5	N/A	N/A	Model revision (subversion)
3	TMIN	°C	-100	-250	21	Minimum ambient temperature
4	TMAX	°C	500	21	1000	Maximum ambient temperature
5	VMAX	V	10000	0	–	Maximum voltage across node g and b

2.5 Model Parameters

No.	Name	Unit	Default	Min.	Max.	Description
1	**LEVEL**		1000	N/A	N/A	Model level
2	**TR**	°C	21	-250	1000	Nominal (reference) temperature
3	**LMIN**	m	10^{-8}	0	–	Minimum allowed drawn length
4	**LMAX**	m	$9.9 \cdot 10^{-8}$	0	–	Maximum allowed drawn length
5	**WMIN**	m	10^{-8}	0	–	Minimum allowed drawn width
6	**WMAX**	m	$9.9 \cdot 10^{-8}$	0	–	Maximum allowed drawn width
7	**TOXO**	m	$2 \cdot 10^{-9}$	$5 \cdot 10^{-10}$	$2 \cdot 10^{-8}$	Oxide thickness
8	**VFBO**	V	0.0	–	–	Flat-band voltage[1]
9	**NSUBO**	m^{-3}	$3 \cdot 10^{23}$	10^{22}	10^{25}	Substrate doping level
10	**MNSUBO**		1	1	10	Maximum change in absolute doping, limited to 1 order of magnitude up
11	**DNSUBO**		0	0	100	Doping profile slope parameter
12	**VNSUBO**		0	-5	5	Doping profile corner voltage parameter
13	**NSLPO**		0.1	0.1	1	Doping profile smoothing parameter
14	**DLQ**	m	0	–	–	Length delta for capacitor size
15	**DWQ**	m	0	–	–	Width delta for capacitor size
16	**DWR**	m	0	–	–	Width delta for substrate resistance calculation
17	**CFRL**	F/m	0	0	–	Fringing capacitance in length direction
18	**CFRW**	F/m	0	0	–	Fringing capacitance in width direction
19	**RSHG**	Ω/sq	1	0	–	Gate sheet resistance
20	**RPV**	$\Omega \cdot \mathrm{m}^2$	0	0	–	Vertical resistance down through gate
21	**REND**	Ω·m	10^{-4}	0	–	End resistance (extrinsic well res. plus vertical contact res. to well) per width
22	**RSHS**	Ω/sq	1000	0	10000	Substrate sheet resistance

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[1] In PSP, **VFBO** corresponds to NMOS and is negative of the actual value for PMOS. For varactor, one specifies the actual value.

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No.	Name	Unit	Default	Min.	Max.	Description
23	**UAC**	$m^2/V/s$	$5 \cdot 10^{-2}$	0	–	Accumulation layer zero-bias mobility
24	**UACRED**	V^{-1}	0	0	–	accumulation layer mobility degradation factor
25	**STVFB**	V/K	0	–	–	Temperature dependence of V_{fb}
26	**STRSHG**		0	–	–	Temperature dependence of R_{shg}
27	**STRPV**		0	–	–	Temperature dependence of R_{pv}
28	**STREND**		0	–	–	Temperature dependence of R_{end}
29	**STRSHS**		0	–	–	Temperature dependence of R_{shs}
30	**STUAC**		0	–	–	Temperature dependence of U_{ac}
31	**FETA**		1.0	0	–	Effective field parameter
			Switch or switch-like parameters			
32	**SWRES**		1	0	1	Switch to control series resistance: 0→ exclude;1→ include
33	**TYPE**		-1	-1	1	Substrate doping type: -1→ n-type; +1→ p-type
34	**TYPEP**		-1	-1	1	Polysilicon doping type: -1→ n-type; +1→ p-type
35	**TAU**	s	0.1	0	10	Time constant for inversion charge recombination/generation
36	**NPO**	m^{-3}	10^{27}	10^{24}	10^{27}	Polysilicon doping level
37	**QMC**		1	0	–	Quantum mechanical correction factor
38	**SWIGATE**		0	0	1	Flag for gate current: 0→turn off; 1→turn on
			Additional model parameters for gate tunneling currents			
39	**CHIBO**	V	3.1	1.0	–	Tunneling barrier height for electrons
40	**CHIBPO**	V	4.5	1.0	–	Tunneling barrier height for holes
41	**LOV**	m	0	0	–	Overlap length
42	**NOVO**	m^{-3}	$5 \cdot 10^{25}$	10^{22}	10^{26}	Effective doping level of overlap regions

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No.	Name	Unit	Default	Min.	Max.	Description
43	**IGINVLW**	A	0	0	–	ECB gate channel current pre-factor for 1 μm^2 channel area
44	**IGOVW**	A	0	0	–	ECB gate overlap current pre-factor for 1 μm wide gate overlap region
45	**GCOO**		0	-10	10	ECB gate tunneling energy adjustment
46	**GC2O**		0.375	0	10	ECB gate current slope factor
47	**GC3O**		0.063	-10	10	ECB gate current curvature factor
48	**IGCHVLW**	A	0	0	–	HVB gate channel current pre-factor for 1 μm^2 channel area
49	**IGOVHVW**	A	0	0	–	HVB gate overlap current pre-factor for 1 μm wide gate overlap region
50	**GCOHVO**		0	-10	10	HVB gate tunneling energy adjustment
51	**GC2HVO**		0.375	0	10	HVB gate current slope factor
52	**GC3HVO**		0.063	-10	10	HVB gate current curvature factor
53	**IGCEVLW**	A	0	0	–	EVB gate channel current pre-factor for 1 μm^2 channel area
54	**IGOVEVW**	A	0	0	–	EVB gate overlap current pre-factor for 1 μm wide gate overlap region
55	**GCOEVO**		0	-10	10	EVB gate tunneling energy adjustment
56	**GC2EVO**		0.375	0	10	EVB gate current slope factor
57	**GC3EVO**		0.063	-10	10	EVB gate current curvature factor

Section 3

Parameter Initializing

In this section, internal parameters, such as effective channel length and width, body factors, are initialized or calculated to prepare for the calculation of the surface potential, charges, and currents in the next section.

3.1 Capacitance of Oxide and Body Factors

$$C_{\text{ox}} = \epsilon_{\text{ox}} / \textbf{TOXO} \tag{3.1}$$

$$\gamma_{\text{s}} = \sqrt{2 \cdot q \cdot \epsilon_{\text{si}} \cdot \textbf{NSUBO}} / C_{\text{ox}} \tag{3.2}$$

$$\gamma_{\text{p}} = \sqrt{2 \cdot q \cdot \epsilon_{\text{si}} \cdot \textbf{NPO}} / C_{\text{ox}} \tag{3.3}$$

$$\gamma_{\text{ov, s}} = \sqrt{2 \cdot q \cdot \epsilon_{\text{si}} \cdot \textbf{NOVO}} / C_{\text{ox}} \tag{3.4}$$

$$\text{If } \textbf{QMC} > 0 \;\; q_{\text{q}} = \begin{cases} 0.4 \cdot \text{QMN} \cdot \textbf{QMC} \cdot (C_{\text{ox}})^{2/3}, & \text{if } \textbf{TYPE} > 0 \\ 0.4 \cdot \text{QMP} \cdot \textbf{QMC} \cdot (C_{\text{ox}})^{2/3}, & \text{otherwise} \end{cases} \tag{3.5}$$

$$\text{else} \quad q_{\text{q}} = 0 \tag{3.6}$$

$$\eta_{\mu} = \begin{cases} 0.5 \cdot \textbf{FETA}, & \text{if } \textbf{TYPE} > 0 \\ \frac{1}{3} \cdot \textbf{FETA}, & \text{otherwise} \end{cases} \tag{3.7}$$

$$norm_{\text{tox}} = \textbf{TOXO} / 10^{-9}; \tag{3.8}$$

3.2 Initializing Parameters

Temperature-Related Parameters

$$\text{TR1} = \begin{cases} \textbf{TR}, & \text{if } \textbf{TR} \geq -273 \\ -273, & \text{if } \textbf{TR} < -273 \end{cases} \tag{3.9}$$

$$T_{\mathrm{KR}} = 273.15 + \mathrm{TR1} \tag{3.10}$$

$$T_{\mathrm{KD}} = \mathrm{T_A} + \mathbf{DTA} \tag{3.11}$$

$$\Delta T = T_{\mathrm{KD}} - T_{\mathrm{KR}} \tag{3.12}$$

$$\boldsymbol{\phi}_{\mathbf{T}} = k_{\mathrm{B}} \cdot T_{\mathrm{KD}}/q \tag{3.13}$$

$$q_{\mathrm{lim2}} = 100 \cdot \boldsymbol{\phi}_{\mathbf{T}}^2 \tag{3.14}$$

$$V_{\mathrm{fb,\,T}} = \mathbf{VFBO} + \Delta T \cdot \mathbf{STVFB} \tag{3.15}$$

$$R_{\mathrm{shg,\,T}} = \mathbf{RSHG} \cdot \left(\frac{T_{\mathrm{KR}}}{T_{\mathrm{KD}}}\right)^{\mathbf{STRSHG}} \tag{3.16}$$

$$R_{\mathrm{pv,\,T}} = \mathbf{RPV} \cdot \left(\frac{T_{\mathrm{KR}}}{T_{\mathrm{KD}}}\right)^{\mathbf{STRPV}} \tag{3.17}$$

$$R_{\mathrm{end,\,T}} = \mathbf{REND} \cdot \left(\frac{T_{\mathrm{KR}}}{T_{\mathrm{KD}}}\right)^{\mathbf{STREND}} \tag{3.18}$$

$$R_{\mathrm{shs,\,T}} = \mathbf{RSHS} \cdot \left(\frac{T_{\mathrm{KR}}}{T_{\mathrm{KD}}}\right)^{\mathbf{STRSHS}} \tag{3.19}$$

$$U_{\mathrm{ac,\,T}} = \mathbf{UAC} \cdot \left(\frac{T_{\mathrm{KD}}}{T_{\mathrm{KR}}}\right)^{\mathbf{STUAC}} \tag{3.20}$$

General Parameters

$$nt0 = 4 \cdot \text{`KBOL} \cdot T_{\mathrm{KD}} \tag{3.21}$$

$$L_{\mathrm{eff}} = L + \mathbf{DLQ} \tag{3.22}$$

$$W_{\mathrm{eff}} = W + \mathbf{DWQ} \tag{3.23}$$

$$M_{\mathrm{eff}} = \text{M\_SEG} \cdot \text{` MFACTOR\_USE} \tag{3.24}$$

$$\mathrm{INV}_{\mathrm{Meff}} = 1.0 \;/\; M_{\mathrm{eff}} \tag{3.25}$$

$$E_{\mathrm{g}} = 1.179 - T_{\mathrm{KD}} \cdot \left(9.025 \cdot 10^{-5} + 3.05 \cdot 10^{-7} \cdot T_{\mathrm{KD}}\right) \tag{3.26}$$

$$r_{\mathrm{T}} = (1.045 + 4.5 \cdot 10^{-4} \cdot T_{\mathrm{KD}}) \cdot (0.523 + 1.4 \cdot 10^{-3} \cdot T_{\mathrm{KD}} - 1.48 \cdot 10^{-6} \cdot T_{\mathrm{KD}}^2) \cdot \frac{T_{\mathrm{KD}}^2}{90000} \tag{3.27}$$

$$\mathrm{INV}_{\mathrm{ni}} = 4 \cdot 10^{-26} \cdot r_{\mathrm{T}}^{-0.75} \tag{3.28}$$

$$\phi_{\mathrm{b}} = E_{\mathrm{g}} + 2 \cdot \boldsymbol{\phi}_{\mathbf{T}} \cdot \ln\left(\mathbf{NSUBO} \cdot \mathrm{INV}_{\mathrm{ni}}\right) \tag{3.29}$$

$$k_{\mathrm{se1}} = 230.26 \tag{3.30}$$

$$k_{\mathrm{se2}} = 460.52 \tag{3.31}$$

Parameters Related to Polysilicon and Overlap Regions

$$G_\mathrm{p} = \gamma_\mathrm{p}/\sqrt{\boldsymbol{\phi}_\mathbf{T}} \tag{3.32}$$

$$\xi_\mathrm{p} = 1 + G_\mathrm{p}/\sqrt{2} \tag{3.33}$$

$$x_\mathrm{mrgp} = 10^{-5} \cdot \xi_\mathrm{p} \tag{3.34}$$

$$\phi_\mathrm{p} = E_\mathrm{g} + 2 \cdot \boldsymbol{\phi}_\mathbf{T} \cdot \ln\left(\mathbf{NPO} \cdot \mathrm{INV}_\mathrm{ni}\right) \tag{3.35}$$

$$x_\mathrm{np} = \phi_\mathrm{p}/\boldsymbol{\phi}_\mathbf{T} \tag{3.36}$$

$$\Delta_\mathrm{np} = \begin{cases} \exp(-x_\mathrm{np}), & \text{if } x_\mathrm{np} < k_\mathrm{se2} \\ \dfrac{10^{-200}}{\mathrm{P3}\left(x_\mathrm{np} - k_\mathrm{se2}\right)}, & \text{otherwise} \end{cases} \tag{3.37}$$

$$G_\mathrm{ov,\,s} = \gamma_\mathrm{ov,\,s}/\sqrt{\boldsymbol{\phi}_\mathbf{T}} \tag{3.38}$$

$$\xi_\mathrm{ov,\,s} = 1 + G_\mathrm{ov,\,s}/\sqrt{2} \tag{3.39}$$

$$x_\mathrm{mrgov,\,s} = 10^{-5} \cdot \xi_\mathrm{ov,\,s} \tag{3.40}$$

$$\phi_\mathrm{b,\,ov} = E_\mathrm{g} + 6 \cdot \boldsymbol{\phi}_\mathbf{T} \tag{3.41}$$

$$x_1 = 1.25 \tag{3.42}$$

$$x_\mathrm{g1,\,ov} = x_1 + G_\mathrm{ov,\,s} \cdot \sqrt{\exp(-x_1) + x_1 - 1} \tag{3.43}$$

Fringing Capacitance

$$C_\mathrm{fr} = 2 \cdot \left(\mathbf{CFRW} \cdot W + \mathbf{CFRL} \cdot L\right) \tag{3.44}$$

Resistances

$$\text{If } \textbf{SWRES} = \text{true} \begin{cases} R_{\text{gsal}} = \dfrac{R_{\text{shg, T}} \cdot W}{L \cdot [3 + 9 \cdot (\textbf{NGCON} - 1)]} \\ R_{\text{gpv}} = \dfrac{R_{\text{pv, T}}}{W \cdot L} \\ R_{\text{end}} = \dfrac{R_{\text{end, T}}}{2 \cdot (W + \textbf{DWR})} \\ R_{\text{sub}} = \dfrac{R_{\text{shs, T}} \cdot L}{12 \cdot (W + \textbf{DWR})} \\ R_{\text{gsal}} = \text{‘ CLIP\_BOTH}(R_{\text{gsal}},\ 1.0e-03,\ 1e01) \\ R_{\text{gpv}} = \text{‘ CLIP\_BOTH}(R_{\text{gpv}},\ 1.0e-03,\ 1e02) \\ R_{\text{end}} = \text{‘ CLIP\_BOTH}(R_{\text{end}},\ 1.0e-03,\ 1e01) \\ R_{\text{sub}} = \text{‘ CLIP\_BOTH}(R_{\text{sub}},\ 1.0e-03,\ 1e03) \\ U_{\text{ac,T}} = \text{‘ CLIP\_BOTH}(U_{\text{ac,T}},\ 1.0e-03,\ 2e01) \\ G_{\text{gsal}} = 1/R_{\text{gsal}} \\ G_{\text{gpv}} = 1/R_{\text{gpv}} \\ G_{\text{end}} = 1/R_{\text{end}} \\ G_{\text{sub}} = 1/R_{\text{sub}} \\ G_{\text{ac0}} = 12 \cdot U_{\text{ac, T}} \cdot W/L \end{cases} \tag{3.45}$$

$$\text{If } \textbf{SWRES} = \text{false} \begin{cases} G_{\text{gsal}} &= 0.0 \\ G_{\text{gpv}} &= 0.0 \\ G_{\text{end}} &= 0.0 \\ G_{\text{sub}} &= 0.0 \\ G_{\text{ac0}} &= 0.0 \end{cases} \tag{3.46}$$

Gate Tunneling Parameters

$$\text{If } \mathbf{SWIGATE} = \text{true} \begin{cases} I_{\text{ginv}} = \mathbf{IGINVLW} \cdot W_{\text{eff}} \cdot L_{\text{eff}} \cdot 10^{12} \cdot \left(\dfrac{T_{\text{KD}}}{T_{\text{KR}}}\right)^{\mathbf{STIG}} \\ I_{\text{gov}} = 2 \cdot \mathbf{IGOVW} \cdot \mathbf{LOV} \cdot W_{\text{eff}} \cdot 10^{12} \cdot \left(\dfrac{T_{\text{KD}}}{T_{\text{KR}}}\right)^{\mathbf{STIG}} \\ I_{\text{gcHVB}} = \mathbf{IGCHVLW} \cdot W_{\text{eff}} \cdot L_{\text{eff}} \cdot 10^{12} \cdot \left(\dfrac{T_{\text{KD}}}{T_{\text{KR}}}\right)^{\mathbf{STIG}} \\ I_{\text{govHVB}} = 2 \cdot \mathbf{IGOVHVW} \cdot \mathbf{LOV} \cdot W_{\text{eff}} \cdot 10^{12} \cdot \left(\dfrac{T_{\text{KD}}}{T_{\text{KR}}}\right)^{\mathbf{STIG}} \\ \text{INV}_{\text{CHIB}} = 1/\mathbf{CHIBO} \\ \text{INV}_{\text{CHIB, HVB}} = 1/\mathbf{CHIBPO} \\ B_{\text{CH}} = (4/3) \cdot \mathbf{TOXO} \cdot \sqrt{2 \cdot q \cdot m_0 \cdot \mathbf{CHIBO}}\,/\hbar \\ B_{\text{OV}} = B_{\text{CH}} \\ B_{\text{CH, HVB}} = (4/3) \cdot \mathbf{TOXO} \cdot \sqrt{2 \cdot q \cdot m_0 \cdot \mathbf{CHIBPO}}\,/\hbar \\ B_{\text{OV, HVB}} = B_{\text{CH, HVB}} \\ \text{If } \mathbf{GC3O} < 0, \;\; Q_{\text{CQ}} = -0.495 \cdot \mathbf{GC2O}/\mathbf{GC3O}, \\ \text{else } \; Q_{\text{CQ}} = 0.0 \text{ , endif} \\ \alpha_{\text{b, s}} = 0.5 \cdot (E_{\text{g}} + \mathbf{TYPE} \cdot \phi_{\text{b}}) \\ \alpha_{\text{b, ov}} = 0.5 \cdot (E_{\text{g}} + \mathbf{TYPE} \cdot \phi_{\text{b, ov}}) \\ D_{\text{ch}} = \mathbf{GCOO} \cdot \boldsymbol{\phi_{\text{T}}} \\ D_{\text{ch, HVB}} = \mathbf{GCOO} \cdot \boldsymbol{\phi_{\text{T}}} \end{cases} \tag{3.47}$$

$$\text{If } \mathbf{SWIGATE} = \text{false} \begin{cases} I_{\text{ginv}} & = 0 \\ I_{\text{gov}} & = 0 \\ I_{\text{gcHVB}} & = 0 \\ I_{\text{govHVB}} & = 0 \\ \text{INV}_{\text{CHIB}} & = 0.1 \\ \text{INV}_{\text{CHIB, HVB}} & = 0.1 \\ B_{\text{CH}} & = 0 \\ B_{\text{OV}} & = 0 \\ B_{\text{CH, HVB}} & = 0 \\ B_{\text{OV, HVB}} & = 0 \\ Q_{\text{CQ}} & = 0 \\ \alpha_{\text{b, s}} & = 0 \\ \alpha_{\text{b, ov}} & = 0 \\ D_{\text{ch}} & = 0 \\ D_{\text{ch, HVB}} & = 0 \end{cases} \tag{3.48}$$

Section 4

Model Equations

4.1 Static Evaluations

$$N_{\mathrm{b,\,lim}} = \mathbf{NSUBO} \cdot \mathbf{MNSUBO} \tag{4.1}$$

$$N_{\mathrm{b1}} = \mathbf{NSUBO} \cdot [1 + \mathbf{DNSUBO} \cdot \mathrm{MAXA}(\mathbf{TYPE} \cdot (V_{\mathrm{C}} - \mathbf{VNSUBO}),\ 0,\ \mathbf{NSLPO})]\,, \tag{4.2}$$

where V_{C} is the voltage cross the capacitor C.

$$N_{\mathrm{b,\,v}} = \mathbf{NSUBO} \cdot \mathrm{MINA}(N_{\mathrm{b1}}/\mathbf{NSUBO},\ \mathbf{MNSUBO},\ 10^{-6}) \tag{4.3}$$

$$norm_{\mathrm{nsub}} = N_{\mathrm{b,\,v}}/10^{23} \tag{4.4}$$

$$\phi_{\mathrm{b1}} = E_{\mathrm{g}} + 2 \cdot \boldsymbol{\phi}_{\mathbf{T}} \cdot \ln\left(N_{\mathrm{b,\,v}} \cdot \mathrm{INV_{ni}}\right) \tag{4.5}$$

$$\gamma_{\mathrm{s1}} = \sqrt{2 \cdot q \cdot \epsilon_{\mathrm{si}} \cdot N_{\mathrm{b,\,v}}}/C_{\mathrm{ox}} \tag{4.6}$$

$$\text{If } \mathbf{QMC} > 0 \begin{cases} q_{\mathrm{b0}} = \sqrt{\gamma_s^2 \cdot \phi_b} \\ d_{\phi\mathrm{bq}} = 0.75 \cdot q_q \cdot (q_{\mathrm{b0}})^{2/3} \\ \phi_{\mathrm{b}} = \phi_{\mathrm{b1}} + d_{\phi\mathrm{bq}} \\ \gamma_{\mathrm{s}} = \gamma_{\mathrm{s1}} \cdot \left(1 + \dfrac{4}{3}\dfrac{d_{\phi\mathrm{bq}}}{q_{\mathrm{b0}}}\right) \end{cases} \tag{4.7}$$

$$G_{\mathrm{s}} = \gamma_{\mathrm{s}}/\sqrt{\boldsymbol{\phi}_{\mathbf{T}}} \tag{4.8}$$

$$\xi_{\mathrm{s}} = 1 + G_{\mathrm{s}}/\sqrt{2} \tag{4.9}$$

$$x_{\mathrm{mrgs}} = 10^{-5} \cdot \xi_{\mathrm{s}} \tag{4.10}$$

$$x_{\mathrm{ns}} = \phi_{\mathrm{b}}/\boldsymbol{\phi}_{\mathbf{T}} \tag{4.11}$$

$$\Delta_{\rm ns} = \begin{cases} \exp(-x_{\rm ns}), & \text{if } x_{\rm ns} < k_{\rm se2} \\ \dfrac{10^{-200}}{\mathrm{P3}\left(x_{\rm ns} - k_{\rm se2}\right)}, & \text{otherwise} \end{cases} \tag{4.12}$$

$$x_{\rm g1} = x_1 + G_{\rm s} \cdot \sqrt{\exp(-x_1) + x_1 - 1} \tag{4.13}$$

$$x_{\rm g1,\,ov} = x_1 + G_{\rm ov,\,s} \cdot \sqrt{\exp(-x_1) + x_1 - 1} \tag{4.14}$$

4.2 Calculation of the Surface Potential at the Channel Side

A macro $\Phi_{\rm s}$ is defined to calculate the surface potential at the channel side with output $x_{\rm s}$ and inputs: $x_{\rm g},\ x_{\rm ns},\ \Delta_{\rm ns},\ G,\ G^2,\ G^{-2},\ \xi,\ \xi^{-1},\ x_{\rm mrg}$. The definitions of the auxiliary functions MINA, MAXA, σ_1, σ_2, and others can be found in Appendix A.

$$\text{if } x_{\rm g} < -x_{\rm mrg} \begin{cases} y_{\rm g} = -x_{\rm g} \\ z = 1.25 \cdot y_{\rm g}/\xi \\ \eta = \left[z + 10 - \sqrt{(z-6)^2 + 64}\right]/2 \\ a = \left(y_{\rm g} - \eta\right)^2 + G^2 \cdot (\eta + 1) \\ c = 2 \cdot \left(y_{\rm g} - \eta\right) - G^2 \\ \tau = -\eta + \ln\left(a/G^2\right) \\ y_0 = \sigma_1(a,\, c,\, \tau,\, \eta) \\ \Delta_0 = \mathrm{expl}_{\rm high}\left(y_0\right) \\ p = 2 \cdot \left(y_{\rm g} - y_0\right) + G^2 \cdot \left[\Delta_0 - 1 + \Delta_{\rm ns} \cdot \left(1 - 1/\Delta_0\right)\right] \\ q = \left(y_{\rm g} - y_0\right)^2 + G^2 \cdot \left[y_0 - \Delta_0 + 1 + \Delta_{\rm ns} \cdot \left(1 - 1/\Delta_0 - 2 \cdot y_0\right)\right] \\ x_{\rm s} = -y_0 - \dfrac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot \left[2 - G^2 \cdot \left(\Delta_0 + \Delta_{\rm ns}/\Delta_0\right)\right]}} \end{cases} \tag{4.15}$$

$$\text{if } |x_{\rm g}| \leq x_{\rm mrg} \left\{ \; x_{\rm s} = \frac{x_{\rm g}}{\xi} \cdot \left[1 + G \cdot x_{\rm g} \cdot \frac{1 - \Delta_{\rm ns}}{\xi^2 \cdot 6 \cdot \sqrt{2}}\right] \right. \tag{4.16}$$

$$
\text{if } x_{\rm g} > x_{\rm mrg} \quad
\begin{cases}
\hat{x}_{\rm g1} = x_1 + G \cdot \sqrt{\exp(-x_1) + x_1 - 1} \\
\bar{x} = \dfrac{x_{\rm g}}{\xi} \cdot \left[1 + x_{\rm g} \cdot (\xi \cdot x_1 - \hat{x}_{\rm g1})/\hat{x}_{\rm g1}^2\right] \\
x_0 = x_{\rm g} + G^2/2 - G \cdot \sqrt{x_{\rm g} + G^2/4 - 1 + \text{expl}_{\text{low}}(-\bar{x})} \\
b_{\rm x} = x_{\rm ns} + 3 \\
\eta = \text{MINA}(x_0,\, b_{\rm x},\, 5) - \left(b_{\rm x} - \sqrt{b_{\rm x}^2 + 5}\right)/2 \\
a = (x_{\rm g} - \eta)^2 - G^2 \cdot [\exp(-\eta) + \eta - 1 - \Delta_{\rm ns} \cdot (\eta + 1)] \\
b = 1 - G^2/2 \cdot \exp(-\eta) \\
c = 2 \cdot (x_{\rm g} - \eta) + G^2 \cdot [1 - \exp(-\eta) - \Delta_{\rm ns}] \\
\tau = x_{\rm ns} - \eta + \ln\left(a/G^2\right) \\
y_0 = \sigma_2(a,\, b,\, c,\, \tau,\, \eta) \\
\Delta_0 = \begin{cases} \exp\left(y_0\right), & \text{if } y_0 < k_{\rm se1} \\ \exp\left(y_0 - x_{\rm ns}\right), & \text{if } y_0 > x_{\rm ns} - k_{\rm se1} \\ \dfrac{10^{-100}}{\text{P3}(x_{\rm ns} - y_0 - k_{\rm se1})}, & \text{otherwise} \end{cases} \\
p = 2 \cdot (x_{\rm g} - y_0) + G^2 \cdot [1 - 1/\Delta_0 + \Delta_{\rm ns} \cdot (\Delta_0 - 1)] \\
q = \left(x_{\rm g} - y_0\right)^2 - G^2 \cdot [y_0 + 1/\Delta_0 - 1 + \Delta_{\rm ns} \cdot (\Delta_0 - y_0 - 1)] \\
x_{\rm s} = y_0 + \dfrac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot [2 - G^2 \cdot (1/\Delta_0 + \Delta_{\rm ns} \cdot \Delta_0)]}}
\end{cases}
\tag{4.17}
$$

4.3 Calculation of the Surface Potential in the Overlap Regions

A macro Φ_{ov} is defined to calculate the surface potential in the overlap regions with output x_{ov} and inputs: $x_{\text{g}},\ G_{\text{ov}},\ G_{\text{ov}}^2,\ x_{\text{mrgov}},\ \xi_{\text{ov}},\ x_{\text{g1}}$.

$$
x_{\text{ov}}\left(x_{\text{g}}\right) = \begin{cases}
\text{if } x_{\text{g}} < -x_{\text{mrgov}} & \begin{cases}
y_{\text{g}} = -x_{\text{g}} \\
z = x_1 \cdot y_{\text{g}}/\xi_{\text{ov}} \\
\eta = \left[z + 10 - \sqrt{(z-6)^2 + 64}\right] \Big/ 2 \\
a = \left(y_{\text{g}} - \eta\right)^2 + G_{\text{ov}}^2 \cdot (\eta + 1) \\
c = 2 \cdot (y_{\text{g}} - \eta) - G_{\text{ov}}^2 \\
\tau = -\eta + \ln\left(a/G_{\text{ov}}^2\right) \\
y_0 = \sigma_1(a,\, c,\, \tau,\, \eta) \\
\Delta_0 = \exp\left(y_0\right) \\
p = 2 \cdot (y_{\text{g}} - y_0) + G_{\text{ov}}^2 \cdot (\Delta_0 - 1) \\
q = \left(y_{\text{g}} - y_0\right)^2 + G_{\text{ov}}^2 \cdot (y_0 - \Delta_0 + 1) \\
x_{\text{ov}} = -y_0 - \dfrac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot (2 - G_{\text{ov}}^2 \cdot \Delta_0)}}
\end{cases} \\
\text{if } |x_{\text{g}}| < x_{\text{mrgov}} & \begin{cases} x_{\text{ov}} = x_{\text{g}}/\xi_{\text{ov}} \end{cases} \\
\text{if } x_{\text{g}} > x_{\text{mrgov}} & \begin{cases}
\bar{x} = x_{\text{g}}/\xi_{\text{ov}} \cdot \left[1 + x_{\text{g}} \cdot \left(\xi_{\text{ov}} \cdot x_1 - x_{\text{g1}}\right)/x_{\text{g1}}^2\right] \\
\omega = \begin{cases} 1 - \exp\left(-\bar{x}\right), & \text{if } \bar{x} < k_{\text{se2}} \\ 1 - \dfrac{10^{-200}}{\text{P3}(\bar{x} - k_{\text{se2}})}, & \text{otherwise} \end{cases} \\
x_0 = x_{\text{g}} + G_{\text{ov}}^2/2 - G_{\text{ov}} \cdot \sqrt{x_{\text{g}} + G_{\text{ov}}^2/4 - \omega} \\
\Delta_0 = \begin{cases} \exp\left(-x_0\right), & \text{if } x_0 < k_{\text{se2}} \\ \dfrac{10^{-200}}{\text{P3}(x_0 - k_{\text{se2}})}, & \text{otherwise} \end{cases} \\
p = 2 \cdot (x_{\text{g}} - x_0) + G_{\text{ov}}^2 \cdot (1 - \Delta_0) \\
q = \left(x_{\text{g}} - x_0\right)^2 - G_{\text{ov}}^2 \cdot (x_0 + \Delta_0 - 1) \\
x_{\text{ov}} = x_0 + \dfrac{2 \cdot q}{p + \sqrt{p^2 - 2 \cdot q \cdot (2 - G_{\text{ov}}^2 \cdot \Delta_0)}}
\end{cases}
\end{cases}
\tag{4.18}
$$

4.4 Surface Potential without Poly Effect

$$V_{\text{gb1}} = \textbf{TYPE} \cdot (V_{\text{C}} - V_{\text{fb, T}}) \tag{4.19}$$

$$x_{\text{g}} = V_{\text{gb1}} / \boldsymbol{\phi_{\text{T}}} \tag{4.20}$$

The macro Φ_{s} (defined in Section 4.2) calculates the normalized surface potential (i.e., $\phi_{\text{s}}/\boldsymbol{\phi_{\text{T}}}$).

$$x_{\text{s0}} = \Phi_{\text{s}}(x_{\text{g}},\ x_{\text{ns}},\ \Delta_{\text{ns}},\ G_{\text{s}},\ G_{\text{s}}^{2},\ G_{\text{s}}^{-2},\ \xi_{\text{s}},\ \xi_{\text{s}}^{-1},\ x_{\text{mrgs}}) \tag{4.21}$$

$$\psi_{\text{s0}} = x_{\text{s0}} \cdot \boldsymbol{\phi_{\text{T}}}. \tag{4.22}$$

4.5 Surface Potential with Poly Effect

Polysilicon space charge region is one area where varactor model differs significantly from PSP model. In varactor model polysilicon is allowed to enter inversion region. Furthermore, the effect of polysilicon finite doping is included for all gate biases (in PSP polysilicon effect is not included when device operates in accumulation).

Note also that even when the frequency dependent inversion layer formation is activated in the varactor model of the active region, the polysilicon surface potential is still computed using quasi-static approximation.

When **NPO**$\geq 10^{27}$, $\psi_{\text{p0}} = 0$. The following calculates the poly surface potential when **NPO**$< 10^{27}$.

$$x_{\text{gp}} = -\textbf{TYPE} \cdot \textbf{TYPEP} \cdot (V_{\text{gb1}} - \psi_{\text{s0}})/\boldsymbol{\phi_{\text{T}}} \tag{4.23}$$

$$x_{\text{p0}} = \Phi_{\text{s}}(x_{\text{gp}},\ x_{\text{np}},\ \Delta_{\text{np}},\ G_{\text{p}},\ G_{\text{p}}^{2},\ G_{\text{p}}^{-2},\ \xi_{\text{p}},\ \xi_{\text{p}}^{-1},\ x_{\text{mrgp}}) \tag{4.24}$$

$$\psi_{\text{p0}} = -\textbf{TYPE} \cdot \textbf{TYPEP} \cdot x_{\text{p0}} \cdot \boldsymbol{\phi_{\text{T}}} \tag{4.25}$$

$$x_{\text{g}} = (V_{\text{gb1}} - \psi_{\text{p0}})/\boldsymbol{\phi_{\text{T}}} \tag{4.26}$$

$$x_{\text{s0}} = \Phi_{\text{s}}(x_{\text{g}},\ x_{\text{ns}},\ \Delta_{\text{ns}},\ G_{\text{s}},\ G_{\text{s}}^{2},\ G_{\text{s}}^{-2},\ \xi_{\text{s}},\ \xi_{\text{s}}^{-1},\ x_{\text{mrgs}}) \tag{4.27}$$

$$\psi_{\text{s0}} = x_{\text{s0}} \cdot \boldsymbol{\phi_{\text{T}}}. \tag{4.28}$$

4.6 Static Inversion Charge Calculations

The following computes surface potential-related variables and inversion charge.

$$\text{If } x_{\text{g}} \leq 0 \quad q_{\text{is}} = 0 \tag{4.29}$$

When $x_{\text{g}} > 0$ (namely the depletion and inversion regions), the following is performed to find q_{is} and q_{eff}.

$$\Delta_{\text{ls}} = 0 \tag{4.30}$$

$$\begin{cases} \text{If } x_{s0} < k_{se1} & \begin{cases} \Delta_{ls1} = \exp(x_{s0}) \\ E_s = \Delta_{ls1}^{-1} \\ \Delta_{ls} = \Delta_{ns} \cdot \Delta_{ls1} \\ D_s = \Delta_{ns} \cdot (E_s^{-1} - x_{s0} - 1) \end{cases} \\ \text{elseif } x_{s0} > x_{ns} - k_{se1} & \begin{cases} \Delta_{ls} = \exp(x_{s0} - x_{ns}) \\ E_s = \Delta_{ns}/\Delta_{ls} \\ D_s = \Delta_{ls} - \Delta_{ns} \cdot (x_{s0} + 1) \end{cases} \\ \text{else} & \begin{cases} \Delta_{ls} = \dfrac{10^{-100}}{\mathrm{P3}(x_{ns} - x_{s0} - k_{se1})} \\ E_s = \dfrac{10^{-100}}{\mathrm{P3}(x_{s0} - k_{se1})} \\ D_s = \Delta_{ls} - \Delta_{ns} \cdot (x_{s0} + 1) \end{cases} \end{cases} \tag{4.31}$$

$$\begin{cases} \text{If } x_{s0} < 10^{-5} & \begin{cases} P_s = 0.5 \cdot x_{s0}^2 \cdot \left[1 - \dfrac{1}{3} x_{s0} \cdot (1 - 0.25 \cdot x_{s0})\right] \\ D_s = \dfrac{1}{6} \Delta_{ns} \cdot x_{s0}^3 \cdot (1 + 1.75 \cdot x_{s0}) \\ S_{qs} = x_{s0} \cdot \sqrt{0.5 - \dfrac{1}{6} x_{s0} \cdot (1 - 0.25 \cdot x_{s0})} \end{cases} \\ \text{else} & \begin{cases} P_s = x_{s0} + E_s - 1 \\ S_{qs} = \sqrt{P_s} \end{cases} \end{cases} \tag{4.32}$$

$$\begin{aligned} x_{gs} &= G_s \cdot \sqrt{P_s + D_s} \\ q_{is} &= \boldsymbol{\phi}_{\mathbf{T}} \cdot G_s^2 \cdot D_s/(x_{gs} + G_s \cdot S_{qs}) \end{aligned} \tag{4.33}$$

The normalized static inversion charge is

$$Q_{i0} = -q_{is} \tag{4.34}$$

4.7 Time-Dependent Silicon Surface Potential Calculation without Poly Effect

$$x_{g,t} = (V_{gb1} + V_n)/\boldsymbol{\phi}_{\mathbf{T}}, \tag{4.35}$$

where V_n is the voltage at the internal time-constant node **n**.

$$x_s = \Phi_{ov}(x_{g,t},\ G_s,\ G_s^2,\ x_{mrgs},\ \xi_s,\ x_{g1}), \tag{4.36}$$

where Φ_{ov} calculates the normalized surface potential and is defined in Section 4.3.

$$\psi_s = x_s \cdot \boldsymbol{\phi}_{\mathbf{T}} \tag{4.37}$$

4.8 Time-Dependent Poly Surface Potential Calculation Correction

If **NPO** $\geq 10^{27}$, $\psi_{\mathrm{p}} = 0$. Otherwise, the following procedure is used.

$$x_{\mathrm{gp,\,t}} = -\mathbf{TYPE} \cdot \mathbf{TYPEP} \cdot (V_{\mathrm{gb1}} - \psi_{\mathrm{s}}) / \boldsymbol{\phi}_{\mathbf{T}} \tag{4.38}$$

$$x_{\mathrm{p}} = \Phi_{\mathrm{s}}(x_{\mathrm{gp,\,t}},\ x_{\mathrm{np}},\ \Delta_{\mathrm{np}},\ G_{\mathrm{p}},\ G_{\mathrm{p}}^2,\ G_{\mathrm{p}}^{-2},\ \xi_{\mathrm{p}},\ \xi_{\mathrm{p}}^{-1},\ x_{\mathrm{mrgp}}) \tag{4.39}$$

$$\psi_{\mathrm{p}} = -\mathbf{TYPE} \cdot \mathbf{TYPEP} \cdot x_{\mathrm{p}} \cdot \boldsymbol{\phi}_{\mathbf{T}} \tag{4.40}$$

$$x_{\mathrm{g,\,t}} = (V_{\mathrm{gb1}} + V_{\mathrm{n}} - \psi_{\mathrm{p}}) / \boldsymbol{\phi}_{\mathbf{T}} \tag{4.41}$$

$$x_{\mathrm{s}} = \Phi_{\mathrm{ov}}(x_{\mathrm{g,\,t}},\ G_{\mathrm{s}},\ G_{\mathrm{s}}^2,\ x_{\mathrm{mrgs}},\ \xi_{\mathrm{s}},\ x_{\mathrm{g1}}) \tag{4.42}$$

$$\psi_{\mathrm{s}} = x_{\mathrm{s}} \cdot \boldsymbol{\phi}_{\mathbf{T}} \tag{4.43}$$

4.9 Quantum Mechanical Corrections

$$\Delta_{\mathrm{ls}} = 0 \tag{4.44}$$

$$\begin{cases} \text{If } x_{\mathrm{s}} < k_{\mathrm{se1}} & \begin{cases} \Delta_{\mathrm{ls}} = \exp(x_{\mathrm{s}}) \\ E_{\mathrm{s}} = \Delta_{\mathrm{ls}}^{-1} \end{cases} \\ \text{elseif } x_{\mathrm{s}} > x_{\mathrm{ns}} - k_{\mathrm{se1}} & \begin{cases} \Delta_{\mathrm{ls}} = \exp(x_{\mathrm{ns}} - x_{\mathrm{s}}) \\ E_{\mathrm{s}} = \Delta_{\mathrm{ns}} \cdot \Delta_{\mathrm{ls}} \end{cases} \\ \text{else} & E_{\mathrm{s}} = \dfrac{10^{-100}}{\mathrm{P3}(x_{\mathrm{s}} - k_{\mathrm{se1}})} \end{cases} \tag{4.45}$$

$$\begin{cases} \text{If } x_{\mathrm{s}} < -x_{\mathrm{mrgs}} & \begin{cases} P_{\mathrm{s}} = E_{\mathrm{s}} + x_{\mathrm{s}} - 1.0 \\ S_{\mathrm{qs}} = -\sqrt{P_{\mathrm{s}}} \end{cases} \\ \text{else if } abs(x_{\mathrm{s}}) <= x_{\mathrm{mrgs}} & \begin{cases} P_{\mathrm{s}} = 0.5 \cdot x_{\mathrm{s}}^2 \cdot \left[1 - \dfrac{1}{3} x_{\mathrm{s}} \cdot (1 - 0.25 \cdot x_{\mathrm{s}})\right] \\ S_{\mathrm{qs}} = x_{\mathrm{s}} \cdot \sqrt{0.5 - \dfrac{1}{6} x_{\mathrm{s}} \cdot (1 - 0.25 \cdot x_{\mathrm{s}})} \end{cases} \\ \text{else} & \begin{cases} P_{\mathrm{s}} = x_{\mathrm{s}} + E_{\mathrm{s}} - 1 \\ S_{\mathrm{qs}} = \sqrt{P_{\mathrm{s}}} \end{cases} \end{cases} \tag{4.46}$$

$$\begin{aligned} q_{\mathrm{bs}} &= \boldsymbol{\phi}_{\mathbf{T}} \cdot S_{\mathrm{qs}} \cdot G_{\mathrm{s}} \\ \epsilon &= 1.62 \cdot [(1 + norm_{\mathrm{nsub}}) \cdot (1 + 0.37 \cdot norm_{\mathrm{tox}})]^2 \cdot \left(\tfrac{T_{\mathrm{KR}}}{T_{\mathrm{KD}}}\right)^{1.5} \cdot \phi_{\mathrm{T}}^2; \\ q_{\mathrm{eff}} &= \mathrm{MAXA}(q_{\mathrm{bs}}, -q_{\mathrm{bs}}, \epsilon) + \eta_{\mu} \cdot \mathrm{MAXA}(-V(b\_cn), V(b\_cn), \epsilon) \end{aligned} \tag{4.47}$$

The following $C_{\text{ox, qm}}$ calculation is for all regions ($x_{\text{g}} \leq 0$ and $x_{\text{g}} > 0$).

$$C_{\text{ox, qm}} = \begin{cases} C_{\text{ox}}, & q_{\text{q}} = 0 \\ \dfrac{C_{\text{ox}}}{1 + q_{\text{q}} \cdot \left(q_{\text{eff}}^2 + q_{\text{lim2}}\right)^{-1/6}}, & q_{\text{q}} > 0 \end{cases} \tag{4.48}$$

4.10 Accumulation Resistance Bias Dependence

$$f_{\text{rac}} = \begin{cases} \boldsymbol{\phi}_{\mathbf{T}} \cdot \exp(-10), & \text{if } x_{\text{s0}} > 10 \\ \boldsymbol{\phi}_{\mathbf{T}} \cdot \exp(-x_{\text{s0}}), & \text{otherwise} \end{cases} \tag{4.49}$$

$$q_{\text{ac}} = \gamma_s \cdot C_{\text{ox, qm}} \cdot \sqrt{f_{\text{rac}}} \tag{4.50}$$

$$m_{\text{axs}} = 0.5 \cdot \left(-V_{\text{gb1}} + \sqrt{V_{\text{gb1}}^2 + 0.04}\right) \tag{4.51}$$

$$G_{\text{ac}} = G_{\text{ac0}} \cdot q_{\text{ac}} / (1 + \mathbf{UACRED} \cdot m_{\text{axs}}) \tag{4.52}$$

4.11 Calculation of Gate Tunneling Current

A macro I_{gate} is defined as a function of I_{gin}, I_{ginHVB}, E_{g}, V_{ov}, D_{ch}, $D_{\text{ch, HVB}}$, INV_{CHIB}, $\text{INV}_{\text{CHIB, HVB}}$, **GC2O**, **GC3O**, **GC2HVO**, **GC3HVO**, Q_{CQ}, $I_{\text{g, type}}$, x_{s}, $\alpha_{\text{b, s}}$, $\alpha_{\text{b, ov}}$, $\boldsymbol{\phi}_{\mathbf{T}}^{-1}$, **TYPEP**, **TYPE**, $V_{\text{bcf, ig}}$, B_{OV}, and $B_{\text{OV, HVB}}$ as shown in the following with I_{gout} as output. It is used for the calculation of gate tunneling current. See Figure 4.1 for different gate tunneling mechanisms.

$$I_{\text{gout}} = 0 \tag{4.53}$$

$$\text{If } \mathbf{TYPEP} = 1 \begin{cases} \psi_{\text{t}} = \text{MAXA}(0,\ \ \mathbf{TYPE} \cdot V_{\text{ov}} + D_{\text{ch, HVB}},\ \ 0.01) \\ z_{\text{g}} = \sqrt{V_{\text{ov}}^2 + 10^{-6}} \cdot \text{INV}_{\text{CHIB, HVB}} \\ \text{If } \mathbf{GC3HVO} < 0 \\ \qquad z_{\text{g}} = \text{MINA}(z_{\text{g}},\ \ Q_{\text{CQ}},\ \ 10^{-6}) \\ \text{endif} \\ \Delta_{\text{si}} = \begin{cases} \exp\left[-\mathbf{TYPE} \cdot x_{\text{s}} - (E_{\text{g}} - \alpha_{\text{b,ov}} + \psi_{\text{t}}) \cdot \boldsymbol{\phi}_{\mathbf{T}}^{-1}\right], & \text{if } I_{\text{g, type}} = 0 \\ \exp\left[-\mathbf{TYPE} \cdot x_{\text{s}} - (E_{\text{g}} - \alpha_{\text{b,s}} + \psi_{\text{t}}) \cdot \boldsymbol{\phi}_{\mathbf{T}}^{-1}\right], & \text{if } I_{\text{g, type}} = 1 \end{cases} \\ \Delta_{\text{gate}} = \Delta_{\text{si}} \cdot \exp\left(\mathbf{TYPE} \cdot V_{\text{bcf, ig}} \cdot \boldsymbol{\phi}_{\mathbf{T}}^{-1}\right) \\ D = \exp\{B_{\text{OV}} \cdot [-1.5 + z_{\text{g}} \cdot (\mathbf{GC2HVO} + \mathbf{GC3HVO} \cdot z_{\text{g}})]\} \\ I_{\text{gout, HVB}} = I_{\text{ginHVB}} \cdot D \cdot \mathbf{TYPE} \cdot \ln\left(\dfrac{1.0 + \Delta_{\text{gate}}}{1.0 + \Delta_{\text{si}}}\right) \end{cases} \tag{4.54}$$

$$\psi_{\text{t}} = \text{MINA}(0,\ \ \mathbf{TYPE} \cdot V_{\text{ov}} + D_{\text{ch}},\ \ 0.01) \tag{4.55}$$

$$z_{\text{g}} = \sqrt{V_{\text{ov}}^2 + 10^{-6}} \cdot \text{INV}_{\text{CHIB}} \tag{4.56}$$

If $\mathbf{GC3O} < 0$

$$z_\text{g} = \text{MINA}(z_\text{g},\ \ Q_\text{CQ},\ \ 10^{-6}) \tag{4.57}$$

endif

$$\Delta_\text{si} = \begin{cases} \exp\left(\mathbf{TYPE} \cdot x_\text{s} + (-\alpha_\text{b,ov} + \psi_\text{t}) \cdot \boldsymbol{\phi}_\mathbf{T}^{-1}\right), & \text{if } I_\text{g, type} = 0 \\ \exp\left(\mathbf{TYPE} \cdot x_\text{s} + (-\alpha_\text{b,s} + \psi_\text{t}) \cdot \boldsymbol{\phi}_\mathbf{T}^{-1}\right), & \text{if } I_\text{g, type} = 1 \end{cases} \tag{4.58}$$

$$\Delta_\text{gate} = \Delta_\text{si} \cdot \exp\left(-\mathbf{TYPE} \cdot V_\text{bcf, ig} \cdot \boldsymbol{\phi}_\mathbf{T}^{-1}\right) \tag{4.59}$$

$$D = \exp\{B_\text{OV} \cdot [-1.5 + z_\text{g} \cdot (\mathbf{GC2O} + \mathbf{GC3O} \cdot z_\text{g})]\} \tag{4.60}$$

$$I_\text{gout, ECB} = I_\text{gin} \cdot D \cdot \mathbf{TYPE} \cdot \ln\left(\frac{1.0 + \Delta_\text{si}}{1.0 + \Delta_\text{gate}}\right) \tag{4.61}$$

$$I_\text{gout} = I_\text{gout, HVB} + I_\text{gout, ECB} \tag{4.62}$$

4.12 Gate Tunneling Current

$$V_{\text{fb, ov}} = \begin{cases} \mathbf{TYPEP} \cdot E_{\text{g}}, & \text{if } \mathbf{TYPE} \cdot \mathbf{TYPEP} = -1 \\ 0, & \text{otherwise} \end{cases} \tag{4.63}$$

$$x_{\text{g, ov}} = \mathbf{TYPE} \cdot V_{\text{C, fr}}/\boldsymbol{\phi}_{\mathbf{T}}, \tag{4.64}$$

where $V_{\text{C, fr}}$ is the voltage across the capacitance C_{fr}.

If **SWIGATE** $\neq 0$ and $I_{\text{gov}} + I_{\text{govHVB}} > 0$

$$x_{\text{ov, s0}} = \Phi_{\text{ov}}(x_{\text{g, ov}},\ G_{\text{ov, s}},\ G^2_{\text{ov, s}},\ x_{\text{mrgov, s}},\ \xi_{\text{ov, s}},\ x_{\text{g1, ov}}) \tag{4.65}$$

$$V_{\text{ov}} = \boldsymbol{\phi}_{\mathbf{T}} \cdot (x_{\text{g, ov}} - x_{\text{ov, s0}}) \tag{4.66}$$

else

$$V_{\text{ov}} = 0.0 \tag{4.67}$$

$$x_{\text{ov, s0}} = 0.0 \tag{4.68}$$

end

$$I_{\text{GC}} = 0.0 \tag{4.69}$$

$$I_{\text{GOV}} = 0.0 \tag{4.70}$$

If **SWIGATE** = true

$$V_{\text{bcf, ig}} = V_{\text{C, fr}} \cdot \mathbf{TYPE} \tag{4.71}$$

If $I_{\text{gov}} + I_{\text{govHVB}} > 0$

$$I_{\text{GOV}} = I_{\text{gate}}(I_{\text{gov}},\ I_{\text{govHVB}},\ E_{\text{g}},\ V_{\text{ov}},\ D_{\text{ch}},\ D_{\text{ch, HVB}},\ \text{INV}_{\text{CHIB}},\ \text{INV}_{\text{CHIB, HVB}},\ \mathbf{GC2O},\ \mathbf{GC3O},\ \mathbf{GC2HVO},\ \mathbf{GC3HVO},\ Q_{\text{CQ}},\ 0,\ x_{\text{ov, s0}},\ \alpha_{\text{b, s}},\ \alpha_{\text{b, ov}},\ \boldsymbol{\phi}_{\mathbf{T}}^{-1},\ \mathbf{TYPEP},\ \mathbf{TYPE},\ V_{\text{bcf, ig}},\ B_{\text{OV}},\ B_{\text{OV, HVB}}) \text{end} \tag{4.72}$$

If $I_{\text{ginv}} + I_{\text{gcHVB}} > 0$

$$V_{\text{ox}} = (x_{\text{g}} - x_{\text{s}}) \cdot \boldsymbol{\phi}_{\mathbf{T}} \tag{4.73}$$

$$I_{\text{GC}} = I_{\text{gate}}(I_{\text{ginv}},\ I_{\text{gcHVB}},\ E_{\text{g}},\ V_{\text{ox}},\ D_{\text{ch}},\ D_{\text{ch, HVB}},\ \text{INV}_{\text{CHIB}},\ \text{INV}_{\text{CHIB, HVB}},\ \mathbf{GC2O},\ \mathbf{GC3O},\ \mathbf{GC2HVO},\ \mathbf{GC3HVO},\ Q_{\text{CQ}},\ 1,\ x_{\text{s}},\ \alpha_{\text{b, s}},\ \alpha_{\text{b, ov}},\ \boldsymbol{\phi}_{\mathbf{T}}^{-1},\ \mathbf{TYPEP},\ \mathbf{TYPE},\ V_{\text{bcf,ig}},\ B_{\text{CH}},\ B_{\text{CH, HVB}}) \text{end} \tag{4.74}$$

end

Note that macro I_{gate} is defined in Section 4.11.

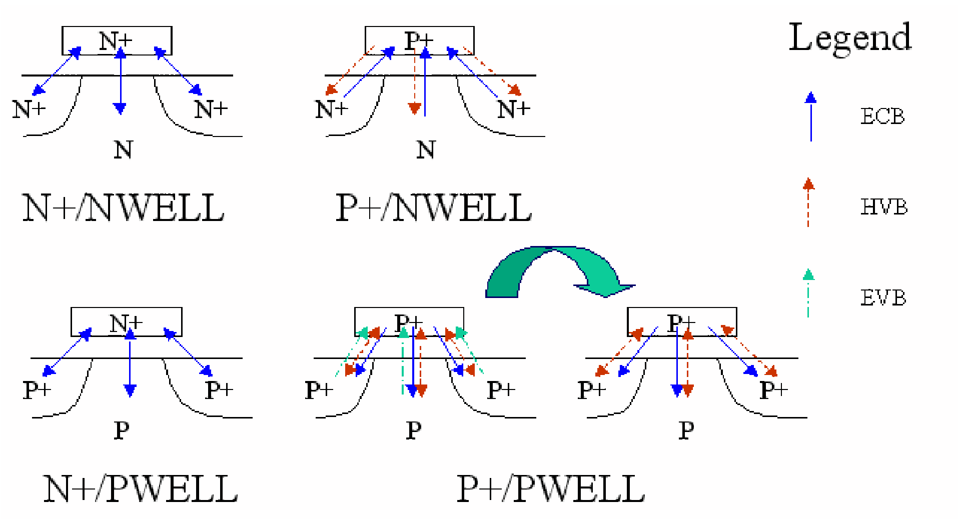

Figure 4.1: Different gate tunneling mechanisms.

4.13 Terminal Currents

4.13.1 DC Currents

Current through the gate $I_{\text{g, DC}} = \text{m} \cdot (I_{\text{GC}} + I_{\text{GOV}}),$ (4.75)

Current through the bulk $I_{\text{b, DC}} = -\text{m} \cdot (I_{\text{GC}} + I_{\text{GOV}})$ (4.76)

4.13.2 AC Currents

Current through the gate $I_{\text{g, AC}} = \text{m} \cdot \left(\frac{dQ_{\text{g}}}{dt} + \frac{dQ_{\text{fr}}}{dt} \right)$ (4.77)

Current through the bulk $I_{\text{b, AC}} = -\text{m} \cdot \left(\frac{dQ_{\text{g}}}{dt} + \frac{dQ_{\text{fr}}}{dt} \right)$ (4.78)

4.14 Terminal Charges

Total charges at the gate

$$Q_{\text{g, total}} = (V_{\text{gb1}} - \phi_{\text{s}} - \phi_{\text{p}}) \cdot L_{\text{eff}} \cdot W_{\text{eff}} \cdot C_{\text{ox, qm}} \cdot \textbf{TYPE} + C_{\text{fr}} \cdot V_{\text{C, fr}} \tag{4.79}$$

Total charges at the bulk

$$Q_{\text{b, total}} = -(V_{\text{gb1}} - \phi_{\text{s}} - \phi_{\text{p}}) \cdot L_{\text{eff}} \cdot W_{\text{eff}} \cdot C_{\text{ox, qm}} \cdot \textbf{TYPE} - C_{\text{fr}} \cdot V_{\text{C, fr}} \tag{4.80}$$

4.15 Noise

Thermal noise contributions from $rgsal$, $rgpv$, $rend$, $rsub$ and $rac0$ are calculated when **SWRES** $= 1$.

In short circuit case, noise contribution is 0. This is realized in the code by setting $ggsal$, $ggpv$, $gend$, $gsub$ and $gac0$ to 0.

Listed below are major equations for noise calculation.

$$rgsalnoise = \mathrm{m} \cdot nt0 \cdot ggsal \tag{4.81}$$

$$rgpvnoise = \mathrm{m} \cdot nt0 \cdot ggpv \tag{4.82}$$

$$rendnoise = \mathrm{m} \cdot nt0 \cdot gend \tag{4.83}$$

$$rsubnoise = \mathrm{m} \cdot nt0 \cdot gsub \tag{4.84}$$

$$rac0lnoise = \mathrm{m} \cdot nt0 \cdot gac0 \tag{4.85}$$

Appendix A

Auxiliary Equations

In this Appendix, some auxiliary functions which are used in the model equations are defined.

The MINA-smoothing function:

$$\text{MINA}\,(x,\,y,\,a) = \frac{1}{2}\cdot\left[x + y - \sqrt{(x-y)^2 + a}\right] \tag{A.1}$$

The MAXA-smoothing function:

$$\text{MAXA}\,(x,\,y,\,a) = \frac{1}{2}\cdot\left[x + y + \sqrt{(x-y)^2 + a}\right] \tag{A.2}$$

σ_1, and σ_2, which are used in the explicit approximation of surface potential:

$$\nu = a + c \tag{A.3}$$

$$\mu_1 = \frac{v^2}{\tau} + \frac{c^2}{2} - a \tag{A.4}$$

$$\sigma_1\,(a,\,c,\,\tau,\,\eta) = \frac{a\cdot\nu}{\mu_1 + (c^2/3 - a)\cdot c\cdot\nu/\mu_1} + \eta \tag{A.5}$$

$$\mu_2 = \frac{v^2}{\tau} + \frac{c^2}{2} - a\cdot b \tag{A.6}$$

$$\sigma_2\,(a,\,b,\,c,\,\tau,\,\eta) = \frac{a\cdot\nu}{\mu_2 + (c^2/3 - a\cdot b)\cdot c\cdot\nu/\mu_2} + \eta \tag{A.7}$$

A polynomial function:

$$\text{P3}(u) = 1 + u\cdot[1 + 0.5\cdot u\cdot(1 + u/3)] \tag{A.8}$$

Three functions are defined to prevent over-/under-flow for exponential functions:

$$\text{expl}(x) = \begin{cases} \exp(x), & \text{if } |x| < k_{\text{se1}} \\ \dfrac{10^{-100}}{\text{P3}(-k_{\text{se1}} - x)}, & \text{if } x < -k_{\text{se1}} \\ 10^{100}\cdot\text{P3}(x - k_{\text{se1}}), & \text{otherwise} \end{cases} \tag{A.9}$$

$$\mathrm{expl}_{\mathrm{low}}(x) = \begin{cases} \exp(x), & \text{if } x > -k_{\mathrm{se1}} \\ \dfrac{10^{-100}}{\mathrm{P3}(-k_{\mathrm{se1}} - x)}, & \text{otherwise} \end{cases} \tag{A.10}$$

$$\mathrm{expl}_{\mathrm{high}}(x) = \begin{cases} \exp(x), & \text{if } x < k_{\mathrm{se1}} \\ 10^{100} \cdot \mathrm{P3}(x - k_{\mathrm{se1}}), & \text{otherwise} \end{cases} \tag{A.11}$$

References

[1] G. Gildenblat, X. Li, W. Wu, H. Wang, A. Jha, R. van Langevelde, G.D.J. Smit, A.J. Scholten, and D.B.M. Klaassen, “PSP: An advanced surface-ptential-based MOSFET model for circuit simulation," *IEEE Trans. Electron Devices*, vol. 53, no. 9, pp. 1979-2003, Sept. 2006.

[2] J. Victory, C. McAndrew, and K. Gullapalli, “A time-dependent, surface potential based compact model for MOS capacitors,” *IEEE Electron Device Lett.*, vol. 22, no. 5, pp. 245-247, May 2001.

[3] J. Victory, Z. Yan, G. Gildenblat, C. McAndrew, and J. Zhang, “A physically based, scalable MOS varactor model and extration methodology for RF applications,” *IEEE Trans. Electron Devices*, vol. 52, no. 7, pp. 1343-1353, Jul. 2005.

[4] A. Litwin, “Overlooked interfacial silicidepolysilicon gate resistance in MOS transistors," *IEEE Trans. Electron Devices*, vol. 48, no. 12, pp. 2179-2181, Dec. 2001.

[5] A. J. Scholten, L. F. Tiemeijer, R. van Langevelde, R. J. Havens, A. T. A. Zegera-van Duijnhoven, and V. C. Venezia, “Noise modeling for RF CMOS circuit simulation," *IEEE Trans. Electron Devices*, vol. 50, no. 5, pp. 618-632, May 2001.