EKV3
MOSFET Compact Model
Model's Documentation

Model Version: 301.02
Documentation Build: 0.14b
– draft version –

Technical Report
Technical University of Crete (TUC), Greece

Antonios Bazigos, Matthias Bucher, François Krummenacher,
Jean-Michel Sallese, Ananda Roy, Christian Enz

September 2, 2008

Note to the reader

Dear reader,

this document is prepared by the EKV Team in order to accompany the Verilog-A code of the EKV3 model. Its aim is to provide helping information for the reader who wants to use and understand the model and the coding. The building of this document is still at an early stage and more things are intended to be a part of it upon its conclusion. Please, feel free to get in contact with us for any comment or question or anything else on this.

This specific version of the document describes the version 301.02 of the EKV3 model.

The EKV Team

Building date of this version of the document: September 2, 2008

Contact information:
Prof. Matthias Bucher
Technical University of Crete (TUC)
P.O. 73100 Chania, Crete, Greece
phone: + 30 28210 37210
fax: + 30 28210 37542
email: bucher@electronics.tuc.gr

Chapter 1

List of Parameters

The EKV MOSFET compact model uses a relatively low number of parameters in order to describe the electrical behaviour of a MOSFET. The parameters are hierarchically divided into instance parameters and model parameters. The first describe the geometry of each device, while the second category contains the parameters that describe a specific technology. The model parameters are further grouped according the phenomenon they are related with.

The junction diodes, formed between the source and drain nodes, on one hand, and the body of the transistor, on the other side, are naturally an element in the extrinsic part of the model. Their model parameter are considered as a subgroup of the model parameters, while their instance parameters, meaning their geometric characteristics, are calculated after the instance and model parameters.

In this chapter the whole of the parameters will be presented into tables, along with a short description and a few comment on their usage. For their default values the typical prefixes, shown also in Table 1.1, are used. All parameter names, and only parameter names, is intended to appear in typewriter fonts, like `PARAMETER`.

Table 1.1: The SI prefixes.

Prefix	Equivalent Multiplier	Prefix	Equivalent Multiplier
m	10^{-3}	k	10^{3}
μ	10^{-6}	M	10^{6}
n	10^{-9}	G	10^{9}
p	10^{-12}	T	10^{12}

1.1 Instance Parameters

The instance parameters of the model are shown in Table 1.2. The basic geometric characterisics of the device are its gate length (`L`) and gate width `W`. Note that the `W` stands for the total gate width of the device, which equals to the product of the finger width and the number of fingers (`NF`). The multiplicity factor (`M`), on the other hand, does not affect the width of each device, but just defines the repetition number of devices that are to be put in parallel.

The `AS`, `AD`, `PS` and `PD`, along with the gate width (`W`), are the geometric characterics of the junction diodes between source and body and between drain and body. They stand for the area, the non-gate-side perimeter and the gate-side perimeter of these two diodes. If these instance parameters are positive, they override the nominal values of these geometric chacteristics, that would be calculated anaytically after the model parameter `HDIF`, while if set to zero are not used. More on this can be found on the section **??**, which refers to the junction diodes.

The shallow trench that is built around the transistor for isolation affects the MOSFET's behaviour, due to stress effect. The geometric characteristics on which this effect depends, are given to the instance parameters SA and SB, while for multifinger devices also the SD is used. If SA and SB are set to zero, the effect is neglected.

Table 1.2: The instance parameters of the EKV3 model. See Figure 1.1 for more details.

Parameter	Default Value	Unit	Short Description
Basic MOSFET instance parameters.			
L	10μ	m	Gate Length
W	10μ	m	Total Gate Width
NF	1	-	Number of Fingers
M	1	-	Multiplicity Factor
Junction diodes geometric characteristics.			
AS	0	m^2	Area of Source Active Area
AD	0	m^2	Area of Drain Active Area
PS	0	m	Perimeter of Source Active Area
PD	0	m	Perimeter of Drain Active Area
Shallow trench isolation stress effect.			
SA	0	m	Distance of first gate finger from STI (one side)
SB	0	m	Distance of last gate finger from STI (other side)
SD	0	m	Distance between neighbouring gate fingers

The reader may also look into the Figure 1.1, which displays a graphical explanation for some of the instance parameters, overlaid on a simplified layout of a typical multifinger MOSFET structure. There appear the basic instance parameters of the MOSFET (L, W, NF), while the instance parameters relating to the shallow trench isolation stress effect (SA, SB, SD), are, also, shown.

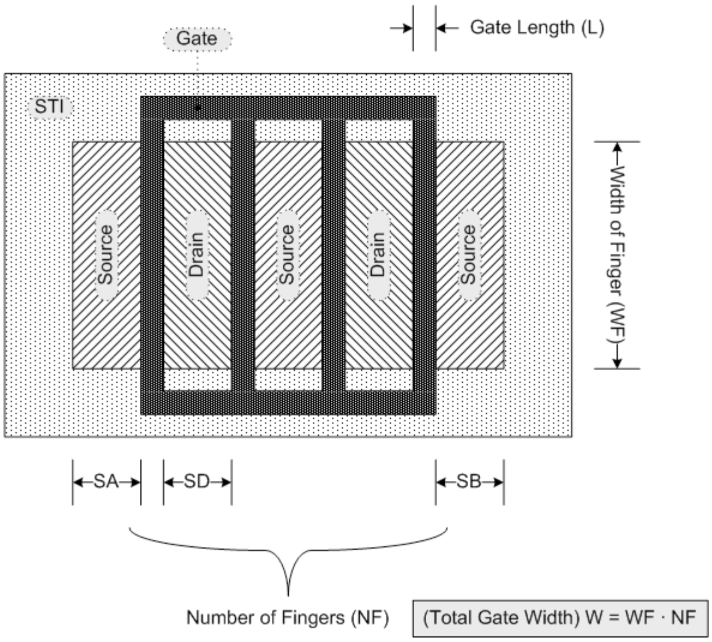

Figure 1.1: Simplified layout of a multifinger MOSFET, on which some instance parameters are displayed graphically. Note that the metal connections between the active areas of the source and drain are not shown here.

1.2 Model Parameters

The model parameters represent the behaviour of a specific technology. There is a natural categorization of these parameters into groups, according to their physical meaning and the phenomenon which they describe. There is also a set of parameters which are used as flags, for reference or for geometric scaling of the whole process, whose values are not extracted via measurements. The groups, the model parameters are divided into, are shown in Table 1.3.

Table 1.3: Model parameters are divided into the following groups.

Flags and Setup Parameters	8	Impact Ionization Current	3
Matching Parameters	3	Gate Current	4
Oxide, Substrate and Gate Doping	8	Gate Induced Drain and Source Leakage	4
Quantum Effects	3	Edge Conductance Effect	3
Mobility and reduction due to Vertical field	4	Inner Fringing Capacitances	4
Coulomb Scattering	2	STI Stress Effect	21
Drain Induced Threshold Swift	5	Length and Width Scaling Parameters	32
Small dimensions Geometrical Parameters	8	Temperature Parameters	11
Reverse Short Channel Effect	4	Flicker Noise	4
Charge Sharing Effect	5	Junction Diodes	69
Drain Induced Barrier Lowering	2	Series Resistances	8
Velocity Saturation & Channel Length Modulation	4	Overlap and Outer Fringing Capacitances	8
Inverse Narrow Width Effect	3	Gate and Substrate Resistances	13
		Temperature Scaling of Extrinsic Resistors	2
		Total:	245

1.2.1 Flags and Setup Parameters

The first group of parameters consists of some parameters of general nature. These are shown in Table 1.4, along with a short description. The `SIGN` is used to distinguish between the NMOS (`SIGN`=1) and the PMOS case (`SIGN`=-1). Since the modelling of the two cases is equivalent, `SIGN` is used for multiplication of the potential differences, at the beginning, and of the channel current, at the end of the calculations. The `TG` has non-zero value in case the material of the gate is not metal but highly doped polysilicon, thus the polysilicon depletion effect appears. The `TG`=-1 refers to a gate doping of the same type with the source and drain nodes, meaning also opposite type of the body, which is the most common case, while the `TG`=1 means the contrary. The `TNOM` stands for the reference temperature for which all the other parameters are extracted.

The geometric scaling of the process may be described with the `SCALE`, `XL` and `XW`. `SCALE` affects both dimentions analogically, while `XL` and `XW` define certain optical offsets at the length and the width of the MOSFETs, respectively. Unity value for `SCALE` and zero values for `XL` and `XW` leave the geometry of the devices unaffected.

Finally, there is a set of flag-type parameters, which enable, if equal to one, or disable, if equal to zero, certain parts of the model. The `TH_NOI` enables the thermal noise calculation, including its dependence on short channel effects, while the `NQS_NOI` enables the part of the model that calculates the non-quasi-static noise, neglecting though the short channel effects. Note that these two parameters should not be set equal to one at the same time, since this would result into introducing twice the same noise source to the circuit.

Table 1.4: Flags and Setup Parameters.

Parameter	Default Value	Unit	Short Description
SIGN	1	-	1 NMOS, -1 for PMOS
TG	-1	-	Doping Type of Gate: -1 for opposite than bulk, 1 for same with bulk, 0 for metal gate; no polysilicon depletion effect
TNOM	27.0	$^{\circ}C$	Nominal Temperature
Process geometrical scaling.			
SCALE	1.0	-	Scaling Factor for all dimensions
XL	0.0	m	Optical offset for Gate Length
XW	0.0	m	Optical offset for Gate Width
Noise flag parameters.			
TH_NOI	1.0	-	Thermal noise flag (on/off). Includes short channel effects but no NQS noise.
NQS_NOI	0.0	-	NQS noise flag (on/off). Includes thermal noise without short channel effects.

1.2.2 Matching Parameters

The model employs a statistical variation model that describes the short distance mismatch between transistors with identical geometries. The variation is inversionally proportional to the square root of the area of the gate. The model parameters that vary between the various instances are the threshold voltage (AVTO), the body effect coefficient (AGAMMA) and the mobility (AKP), as these are shown in Table 1.5.

Table 1.5: Matching Parameters.

Parameter	Default Value	Unit	Short Description
AVTO	0	-	Matching Parameter for Threshold Voltage
AGAMMA	0	-	Matching Parameter for Body Effect Coefficient
AKP	0	-	Matching Parameter for Mobility

1.2.3 Oxide, Substrate and Gate Doping related Parameters

Some parameters that describe some core physical properties of a technology are shown in Table 1.6. The capacitance per unit area of the oxide under the gate of the MOSFET (COX) is of primal importance in both the static and dynamic behaviour of the device. The nominal value of this parameter is equal to the ratio of the permitivity of the oxide (ϵ_{ox}) over the thickness of the oxide ($\mathrm{t_{ox}}$), equation (1.1).

$$\mathtt{COX} = \frac{\epsilon_{\mathrm{ox}}}{\mathrm{t_{ox}}} \tag{1.1}$$

The XJ defines the depth of the source and drain regions. The VTO is the reference parameter for threshold voltage in saturation and under $V_{SB} = 0$ bias for devices with no short or narrow channel effects. The Fermi potential of the body is given by PHIF, which nominally depends on the thermal potential ($\mathrm{U_T}$), the doping of the body ($\mathrm{N_A}$) and the intrinsic carrer concetration ($\mathrm{n_i}$) and is given by equation (1.2).

$$\mathtt{PHIF} = \mathrm{U_T} \cdot \ln \frac{\mathrm{N_A}}{\mathrm{n_i}} \tag{1.2}$$

The body effect coefficient (GAMMA) also is directly connected with N_A, equation (1.3), however, here, it is used as a free parameter in order to allow more degrees of freedom during the parameter extraction procedure and obtain a better fit of the model on the measurements.

$$\texttt{GAMMA} = \frac{\sqrt{2 \cdot q \cdot \epsilon_{si} \cdot N_A}}{\texttt{COX}} \tag{1.3}$$

In case the material of the gate is highly doped polysilicon, and not metal, the GAMMAG reflects its doping (N_G), equation (1.4). It could also be noted that an extreme high value for this parameter would remove the influnce of the effect, making the gate material resemble an ideal metal.

$$\texttt{GAMMAG} = \frac{\sqrt{2 \cdot q \cdot \epsilon_{si} \cdot N_G}}{\texttt{COX}} \tag{1.4}$$

The NO is used for fine tuning the weak inversion slope of long and wide channel devices and note that, typically, it should be left to its nominal value of unity, while in few cases it could be raised to 1.05 or so. The built-in voltage drop of the junction diodes (VBI) is typically equal to twice the Fermi potential increased by a few times the thermal potentials. Only if a positive value is given to the parameter VBI it will override its typical one.

Table 1.6: Oxide, Substrate and Gate Doping related Parameters.

Parameter	Default Value	Unit	Short Description
COX	12m	F/m^2	Oxide Capacitance per unit Area
XJ	20.0n	m	Depth of Active Areas
VTO	0.3	V	Threshold Voltage
PHIF	0.45	V	Bulk Fermi Potential
GAMMA	0.3	$\sqrt{V}$	Body Effect Coefficient
GAMMAG	4.1	$\sqrt{V}$	Body Effect Coefficient for Gate
NO	1.0	-	Long Channel Slope Factor Fine Tuning
VBI [1]	0	V	Built-in Voltage Drop

1.2.4 Quantum Effects

Quantum effects result into a lower effective value for the oxide capacitance, in both accumulation and inversion, while pinch-off voltage and surface potential are affected, too.The relating parameters are presented in Table 1.7. The AQMA and AQMI are physical constants, used as parameters for ease, relating with accumulation and inversion respectively, while ETAQM has a typical value of 3/4, is left as a fitting parameter and is used as a weight on the inversion charge in the calculation of the effective vertical field.

Table 1.7: Quantum Effects.

Parameter	Default Value	Unit	Short Description
AQMA	0.5	$V^{\frac{1}{3}}F^{-\frac{2}{3}}$	Quantum Effect Coefficient in Accumulation
AQMI	0.4	$V^{\frac{1}{3}}F^{-\frac{2}{3}}$	Quantum Effect Coefficient in Inversion
ETAQM	0.75	-	Quantum effect: Weight of inversion charge in effective vertical field calculation

[1] The value of VBI is used only if it is positive. Otherwise the built-in voltage drop is calculated after PHIF.

1.2.5 Mobility and Vertical field Mobility Effect

Mobility (μ) is passed into the model parameters via its product with the oxide capacitance per unit area (COX), forming the parameter KP, equation (1.5).

$$\mathtt{KP} = \mu \cdot \mathtt{COX} \tag{1.5}$$

The effective mobility of the device illustrates an important dependence on the vertical field of the channel. EKV3 implements a first and second order model for the mobility reduction due to vertical field, leaving separate parameters for each order, E0 and E1 repspectively. The ETA nominally is 1/2 for the NMOS transistors and 1/3 for the PMOS, but is left as a parameter for best fitting.

Table 1.8: Mobility and Vertical field Mobility Effect.

Parameter	Default Value	Unit	Short Description
KP	500.0μ	$\frac{F}{V \cdot s}$	Mobility multiplied with COX
E0	10G	V/m	First Order Coefficient for Mobility Reduction due to Vertical Field
E1	310M	V^2/m^2	Second Order Coefficient for Mobility Reduction due to Vertical Field
ETA	0.5	-	Weight of inversion change into calculation of vertical field

1.2.6 Coulomb Scattering

The Coulomb scatteting phenomenon, on the other hand, affects the mobilty of the carriers when the vertical electical field is low. Note that the effect is more intense at low temperatures, while at room temperatues might be ignored for certain technologies. The model employs two parameters for the eauation of this effect, THC and ZC, see Table 1.9. Note that a zero value of the THC will disable the influnce of Coulomb scattering.

Table 1.9: Coulomb Scattering Effect.

Parameter	Default Value	Unit	Short Description
THC	0.0	-	Coulomb Scattering Factor
ZC	1.0μ	-	Coulomb Scattering coefficient for normalized inversion charge

1.2.7 Drain Induced Threshold Swift

The pocket implants, that are created at the source and drain ends of the channel, protect mainly the short channel MOSFETs from certain short channel effects. However, their existance affect also the behaviour of long channel MOSFETs, and most importantly the output conductance ($\mathrm{g_{ds}} = \partial \mathrm{I_D} / \partial \mathrm{V_D}$) in saturation. The parameters used for this effect appear on Table 1.10. The formulation of the effect is taken from the BSIM model [1] and adapted to the context of the EKV3 model.

1.2.8 Small Dimensions Geometrical Parameters

The model uses a set of equation for calculating the effective dimensions of the gate, from the drawn dimensions. The offset is rather small, hence it is important only for devices with small length, width or both. The DL is the difference between the effective length of the gate ($\mathrm{L_{eff}}$) and

Table 1.10: Drain Induced Threshold Swift (DITS).

Parameter	Default Value	Unit	Short Description
FPROUT	1.0M	$1/\sqrt{\mathrm{m}}$	Output resistance factor for DITS effect
PDITS	0.0	-	DITS parameter
PDITSL	0.0	1/m	Length scaling factor for DITS effect
PDITSD	1.0	1/V	DITS dependence on drain bias
DDITS	0.3	-	Smoothing parameter for DITS effect

the drawn length (L_{drawn}), while the DLC allows some further fine tuning for the effective length for the dynamic behaviour ($L_{eff,c}$), see equations (1.6) and (1.7) .

$$L_{eff} = L_{drawn} + \mathtt{DL} \tag{1.6}$$

$$L_{eff,c} = L_{eff} + \mathtt{DLC} \tag{1.7}$$

The DW and DWC have similar role for the gate width (W_{eff}, W_{drawn}, $W_{eff,c}$). The WDL and LDW are scaling parameters of effective length and effective width for narrow and short channel MOSFETs, respectively, which play important role in combined short and narrow channel devices. If the simple DL scheme, equation (1.6), does not offere adequate scaling, a more complicated dependence of effective length on drawn length may be implemented with the LL and LLN. All these parameters are listed in Table 1.11.

Table 1.11: Small Dimensions Geometrical Parameters.

Parameter	Default Value	Unit	Short Description
DL	-10n	m	Difference between effective and drawn gate length
DLC	0.0	m	Fine tuning difference of effective gate length between current and capacitance behaviour
DW	-10n	m	Difference between effective and drawn gate width
DWC	0.0	m	Fine tuning difference effective gate width between current and capacitance behaviour
WDL	0.0	m^2	Width scaling for narrow devices of L_{eff}
LDW	0.0	m^2	Length scaling for short devices of W_{eff}
LL	0.0	m	Base for Exponential Dependence of L_{eff}
LLN	1.0	-	Exponent for Exponential Dependence of L_{eff}

1.2.9 Reverse Short Channel Effect

The non-homogenous longitudinal doping of the channel, due to the higher doped pocket implants at the ends of the channel, results into a dependence of the effective doping of the channel on its length, since the spread of the pockets is fixed for all geometries. This increase of the doping is reflected on an increase of the threshold voltage, the body effect coefficient and the Fermi potential. The relating parameters of this part of the model are shown in Table 1.12. The length coeffecient for the length scaling of this effect is given to the LR, while for the threshold voltage and the body effect coefficient there have been kept separated parameters, QLR and NLR respectively, for more degrees of freedom. Fermi potential follows the scaling of the body effect coefficient, when FLR keeps its nominal value of unity, but maybe also follow a different profile by modyfing FLR.

1.2.10 Charge Sharing Effect

Another short channel effect that appears in MOSFETs is the charge sharing, according to which the part of the channel that is close to its source and drain ends, is not modulated strictly by

Table 1.12: Reverse Short Channel Effect (RSCE).

Parameter	Default Value	Unit	Short Description
LR	50n	m	Length scaling coefficient for RSCE
QLR	0.5m	Vm^2/F	Threshold Voltage coefficient of RSCE
NLR	10.0m	m^2/F	Body Effect coefficient of RSCE
FLR	0.0	-	Fermi Potential coefficient of RSCE

the gate potential, but also the source and drain potentials play a role. The effect is naturally more important in short channel devices (LETA), but due to longitudinally non uniform doping, it also appears in long channel devices (LETA0), degrading the output conductance of the transistor. The LETA2 may be used for fine tuning the length scaling of the very short channel MOSFETs. The phenomenon mainly affects the body effect coefficient of the device, making it also bias dependent, and the week inversion slope (NCS). The effect also appears in narrow channel devices (WETA), since the gate contact modulates the edges of the channel differently than the rest of the channel. The above parameters are listed in Table 1.13.

Table 1.13: Charge Sharing (CHSH) Effect.

Parameter	Default Value	Unit	Short Description
LETA	0.5	-	CHSH Coefficient
LETA0	0.0	$1/m$	Lenght indepedent CHSH Coefficient
LETA2	0.0	m	Second order length scaling CHSH Coefficient
WETA	0.2	-	Narrow Channel CHSH Coefficient
NCS	1.0	-	Slope Factor Dependence on CHSH

1.2.11 Drain Induced Barrier Lowering

The drain potential, also affects importantly the pinch-off voltage (V_P). This results directly into a dependence of the threshold voltage (V_{TH}) on V_{DS}, and into a lower value of V_{TH} in saturation ($V_{TH,SAT}$) with respect to linear inversion ($V_{TH,LIN}$). This difference is controlled using the ETAD, while the SIGMAD, allows the modulation of the effect for non-zero V_{SB} values. The relating parameters appear in Table 1.14

Table 1.14: Drain Induced Barrier Lowering (DIBL).

Parameter	Default Value	Unit	Short Description
ETAD	1.0	-	DIBL Coefficient
SIGMAD	1.0	-	Body effect DIBL Coefficient

It can be noted here that the DIBL effect and the DITS effect are closely connected. Within the formulation of this model, the part of the model that refers to DITS effect deals with the output conductance degradation, mainly in long channel devices, while the DIBL effects covers the threshold voltage dependence on the drain potential for the short channel devices.

1.2.12 Velocity Saturation and Channel Length Modulation

The saturated operation of short channel transistors is dominated by the velocity saturation effect. The critical longitudinal electical field, for which the phenomenon, appears is assigned to the UCRIT. The phenomenon is accompanied by a modulation of the effective length of the channel of the MOSFET, which is controlled by the LAMBDA. The model effect uses one more parameter, the ACLM, which could be changed from its nominal value in case the fit is not adequate. The model implements a forumation of variable order, defined by DELTA, which may take values, strictly, between 1 and 2. Ideally the order of the model should be 2 for the NMOS devices, and 1 for the PMOS case, but in any case it is left as a parameter for optimum fit. The order of the effect changes the shape of the current curves during the transition from linear operation to saturation, but it also affects the length scaling of the saturation current.

Table 1.15: Velocity Saturation (VSAT) and Channel Length Modulation (CLM).

Parameter	Default Value	Unit	Short Description
UCRIT	5.0M	V/m	Critical longitudinal field of Carriers for VSAT
LAMBDA	0.5	-	Length modulation coefficient
DELTA	2.0	-	Order of VSAT model (variable order model $1 \sim 2$)
ACLM	0.83	-	Channel Length Modulation Factor

1.2.13 Inverse Narrow Width Effect

Similarly to the RSCE, there is the inverse narrow width effect. The phenomenon is connected with the isolation that is used for the MOSFETs, and changes its behaviour according to the type of the isolation, like LOCOS or STI. The formulation used by the model is the similar to the RSCE case. The `WR` defines a critical width for the scaling of the effect across the gate width, the `QWR` is connected with the dependence of the threshold voltage on the effect, while `NWR` covers the dependence of the body effect coefficient. Table 1.16 summarizes the above information.

Table 1.16: Inverse Narrow Width Effect (INWE).

Parameter	Default Value	Unit	Short Description
WR	90.0n	m	Width scaling coefficient for INWE
QWR	0.3m	Vm^2/F	Threshold Voltage coefficient of INWE
NWR	5.0m	m^2/F	Body Effect Coefficient of INWE

1.2.14 Impact Ionization Current

The saturated carriers that reach the drain side of the channel in maximum speed, are able to ionize the area. This effect results into a current from the drain node to the bulk (I_{DB}). Note that this current is added to the the drain current that flows through the drain node. The parameters of the model (`IBA`, `IBB` and `IBN`)) are listed in Table 1.17.

Table 1.17: Impact Ionization Current (IDB).

Parameter	Default Value	Unit	Short Description
IBA	0.0	$1/m$	IDB coefficient
IBB	300M	V/m	IDB exponential factor
IBN	1.0	-	IDB factor of VSAT

1.2.15 Gate Current

Along with the downscaling of the minimum gate length, the oxide gets thinner and thinner. As a result the gate current that flow due to tunneling effect through the oxide gets to be more important in modern technologies. The model of the gate current is based on the calculation of the probability of a carrier to get across the oxide, which is calculated after the silicon to oxide silicon barrier height (`XB`) and a a characteristic electrical field (`EB`). The estimation of the gate current uses also a the `KG` which is directly proportional to the gate current. Setting the latter at zero value, disables the effect. For the short channel devices the part of the oxide that overlaps with the source and drain nodes is relatively more important. The length of these to overlap regions, fitted for overlap gate current aspects (`LOVIG`), plays an important role for such geometries. See Table 1.18 for information on these parameters.

Table 1.18: Gate Current (IG).

Parameter	Default Value	Unit	Short Description
`XB`	3.1	V	$Si - SiO_2$ tunneling barrier height
`EB`	29.0G	V/m	Characteristic electrical field for gate current
`KG`	0	A/V^2	Gate Current Parameter
`LOVIG`	20.0n	m	Overlap Length for Gate current

1.2.16 Gate Induced Drain and Source Leakage

EKV3 employs a symmetrical symmetrical model for the calculation of the gate induced drain and source leakage current. The formulation is imported from the BSIM4 model [1] and adapted to the environment of the EKV3 model. This leakage current appears more profoundly much below the weak inversion region, meaning negative V_{GB} values for NMOS and positive V_{GB} values for PMOS, and increases as the bias moves further away from the weak inversion. The model uses four parameters (`AGIDL`, `BGIDL`, `CGIDL`, `EGIDL`), listed in Table 1.19. Setting `AGIDL`, will disable the phenomenon.

Table 1.19: Gate Induced Drain and Source Leakage (GIDL).

Parameter	Default Value	Unit	Short Description
`AGIDL`	0.0	A/V	Pre-exponential coefficiant for GIDL
`BGIDL`	2.3G	V/m	Exponential coefficiant for GIDL
`CGIDL`	0.5	V^3	Body effect parameter for GIDL
`EGIDL`	0.8	V	Fitting parameter for band bending for GIDL

1.2.17 Edge Conductance Effect

Another effect that appears in some modern CMOS technologies is the edge conductnce. The parts of the channel that are on the sides of the channel, are characterized by different proporties with respect to the middle and main part of the channel, forming this way some parallelel devices to the main one. This devices having, a lower pinch-off voltage (`DPHIEDGE`), thus lowers threshold voltage, and body effect coefficient (`DGAMMAEDGE`) make their appearance sooner in weak inversion. But, since their width is a portion of the while device, in strong inversion they can hardly be noticed. This parallel combination forms a step-shaped curve in weak inversion, with the current in logarithmic scale. The summed width of the two edge devices is given to the `WEDGE`. The parameters are presented in Table 1.20.

Table 1.20: Edge Conductance Effect.

Parameter	Default Value	Unit	Short Description
`WEDGE`	0.0	m	Width of edge conduction area
`DPHIEDGE`	0.0	V	Difference of Fermi potential of edge conduction area with respect to the main part of the channel
`DGAMMAEDGE`	0.0	$\sqrt{V}$	Difference of body effect coefficient between edge conduction area the main channel

1.2.18 Inner Fringing Capacitances

A parasitic bias dependent capacitance that appears in the MOSFET is the inner fringing capacitance. The element refers to the capacitance that appears between the gate node on the one side and the source and drain nodes on the other side. The curves of this electrical field are purpendicular to the gate on the gate side, pass through the oxide, and at the channel to the device turn towards the source node, on the one side, and the drain node on the other, reaching the other end at a different angle, roughly a right angle, with respect to the gate end. The value of this inner fringing capacitance is proportional to the total width of the device (via the `KJF`) and depends on the level of inversion and the ammount of the charges that will appear between the end nodes. Its maximum value appears in depletion and weak inversion while it diminishes in strong inversion and accumulation. The realating parameters appear in Table 1.21.

Table 1.21: Inner Fringing Capacitances.

Parameter	Default Value	Unit	Short Description
`KJF`	0.0	C/m	Fringing capacitance factor
`CJF`	0.0	$1/V$	Fringing capacitance bias factor
`VFR`	0.0	V	Built-in correction for fringing capacitance
`DFR`	1.0m	-	Smooth factor of fringing capacitance model

1.2.19 STI Stress Effect

It is observed that various properties, like threshold votlage and mobility, depend on the number of fingers of one device. This may be explained by considering the stress that is forced by the shallow trench isolation (STI) structure that is built around the transistor. This structure affects the closest fingers to it, which are the firsts and the lasts ones, differently that the rest of them. The model has adopted the formulation that already used by the BSIM model [1].

A single finger device has to be used for reference, and is STI geometric characteristics, meaning its `SA` and `SB` pass to the `SAREF` and `SBREF`. Comparing the behaviour of this device either with other single finger devices but with different `SA` and `SB`, with multi finger devices of various `NF`, one may extract quantitative results of the dependence of the mobility (`KKP`), the threshold votlage (`KVTO`), the body effect coefficient (`KGAMMA`), the `ETAD` of the DIBL effect (`KETAD`) and the critical longitudinal field of the VSAT model (`KUCRIT`). The model introduces on more geometric parameter defined as the distance between the edge of the transistor and the STI structure, which is normally zero, and then a list of parameters for the scaling of the effect for various geometries and temperatures, see Table 1.22 for more details.

1.2.20 Length, Width and area Scaling Parameters

Most of the above parameters, are extracted after one specific device with a certain geometry. Many of these parameters reflect properties of the whole technology so it is unnecessary to use other geometries for their extraction. Unfortunatelly, it is observed that even these properties of the technology level show some dependence on the scaling of the transistor. For the modelling of such scaling, mostly empirical models, of various complexity, are used.

For mobility a formulation that covers both dimensions is implemented. On the other hand, for threshold voltage and for the body effect coefficient the scaling model focuses on the correction of these parameters for devices with very long and wide channels. The scaling parameters, shown in Table 1.23, are completed by a list of parameters which provide a simple scaling of various parameters after which they are named. This formulation follows a scheme inversily proportional to the gate dimensions, leaving this way the behaviour of transistors with large dimensions unchanged, while it allows the fine tuning of the behaviour of short, narrow and combined short and narrow transistors.

Table 1.22: STI Stress Effect (STISE).

Parameter	Default Value	Unit	Short Description
SAREF	0.0	m	Reference distance from STI, for SA
SBREF	0.0	m	Reference distance from STI, for SB
WLOD	0.0	m	Distance between the edge device and the STI
KKP	0.0	-	KP dependence on STISE
KVTO	0.0	-	VTO dependence on STISE
KGAMMA	0.0	-	GAMMA dependence on STISE
KETAD	0.0	-	ETAD (DIBL effect) dependence on STISE
KUCRIT	0.0	-	VSAT dependence on STISE
LKKP	0.0	-	Length scaling of KP dependence on STISE
WKKP	0.0	-	Width scaling of KP dependence on STISE
PKKP	0.0	-	Area scaling of KP dependence on STISE
TKKP	0.0	-	Temperature scaling of KP dependence on STISE
LLODKKP	1.0	-	Length exponent of KP dependence on STISE
WLODKKP	1.0	-	Width exponent of KP dependence on STISE
LKVTO	0.0	-	Length scaling of VTO dependence on STISE
WKVTO	0.0	-	Width scaling of VTO dependence on STISE
PKVTO	0.0	-	Area scaling of VTO dependence on STISE
LLODKVTO	1.0	-	Length exponent of VTO dependence on STISE
WLODKVTO	1.0	-	Width exponent of VTO dependence on STISE
LODKGAMMA	1.0	-	Exponent of GAMMA dependence on STISE
LODKETAD	1.0	-	Exponent of ETAD dependence on STISE

1.2.21 Temperature Parameters

The behaviour of the MOSFET naturally depends on its temperature. Many of its properties have a physical connection with temperature which may be exploited, while for others an empirical scheme is being used for accounting their dependence on the temperature. In Table 1.24 these parameters are displayed. Their extraction has to follow the extraction of the rest parameters, at a reference temperature, given at TNOM, and typically being the room temperature, by studying measurements at higher and lower temperatures. Note that changing the values of the temperature parameters will not affect the response of the model, if the temperature of the simulation is set at the value of TNOM.

1.2.22 Flicker Noise

The flicker noise of the channel, also named $1/f$ noise, is formulated by a simple bias dependent scheme. The model allows via two parameters to adjust both the exponents of the frequency (EF), and the exponent of the transconductance (AF). The model is completed with the KF which is directly proportional to the power spectral density (PSD) of the flicker noise of the channel.

The model also introduces a flicker noise source at the gate, which is propotrional to the KGFN and to the square of the total gate current.

1.2.23 Extrinsic Part of the Model

All the above parameters refer to aspects of the MOSFET behaviour that fall within the intrinsic part of the device. Around the intrinsic part a series of extrinsic elements is placed in order to model the rest of the device. Figure 1.2 shows this distinction. The intrinsic part refers to the electrical behaviour of the channel and the area between the source and drain nodes. The

[2] The NFVTA and NFVTB were used as a pure empirical model for VTO dependence on NF before the implementation of the STI stress effect model and are considered as obsolete now. They will be discontinued in future versions.

Table 1.23: Length, Width and area Scaling Parameters.

Parameter	Default Value	Unit	Short Description
Mobility Length and Width Dependence.			
LA	1.0	m	First critical length for KP length scaling
LB	1.0	m	Second critical length for KP length scaling
KA	0.0	-	Factor for KP length scaling for LA
KB	0.0	-	Factor for KP length scaling for LB
WKP1	1.0μ	m	Width parameter for mobility profile vs. width
WKP2	0.0	-	Amplitude parameter for mobility profile vs. width
WKP3	1.0	-	Span parameter for mobility profile vs. width
Long & Wide Channel Correction for VTO *and* GAMMA.			
AVT	0.0	-	Factor for long & wide channel VTO correction
LVT	1.0	m	Length for long channel VTO correction
WVT	1.0	m	Width for wide channel VTO correction
AGAM	0.0	-	Factor for long & wide channel GAMMA correction
LGAM	1.0	m	Length for long channel GAMMA correction
WGAM	1.0	m	Width for wide channel GAMMA correction
NFVTA[2]	0	-	Number of fingers factor for VTO dependence on NF
NFVTB[2]	10k	-	Amplitude parameter for NFVTA
Length Scaling Parameters.			
LWR	0.0	m^2	Length scaling of WR
LQWR	0.0	m	Length scaling of QWR
LNWR	0.0	m	Length scaling of NWR
LDPHIEDGE	0.0	m	Length scaling of DPHIEDGE
Width Scaling Parameters.			
WLR	0.0	m^2	Width scaling of LR
WQLR	0.0	m	Width scaling of QLR
WNLR	0.0	m	Width scaling of NLR
WUCRIT	0.0	m	Width scaling of UCRIT
WLAMBDA	0.0	m	Width scaling of LAMBDA
WETAD	0.0	m	Width scaling of ETAD
WE0	0.0	m	Width scaling of E0
WE1	0.0	m	Width scaling of E1
WRLX	0.0	m	Width scaling of RLX
WUCEX	0.0	m	Width scaling of UCEX
WDPHIEDGE	0.0	m	Width scaling of DPHIEDGE
Short and Narrow Channel Fine Tuning Parameters.			
WLDPHIEDGE	0.0	m^2	Area scaling of DPHIEDGE
WLDGAMMAEDGE	0.0	m^2	Area scaling of DGAMMAEDGE

extrinsic part refers to elements that are formed outside of the area, like the overlap capacitances between the gate and the rest of the nodes, the junction diodes and the resistances due to the limited, even high, conductivity of the materials.

1.2.23.1 Junction Diodes: Assymetric model

The junction diodes are described by a typical spice model, as it is implemented in the BSIM model [?]. The formulation covers both the static and the dynamic behaviour of the diodes, and allows the assymetric characterization for the source and the drain side. In Tables 1.26 and 1.28 the parameters used for each side are listed, while Table 1.27 lists the few common parameters.

The model of the diodes is based on the division of the junction in three components. One refers to the area that exists at the bottom of the source and drain areas, the second at the

Table 1.24: Temperature Parameters.

Parameter	Default Value	Unit	Short Description
TCV	600μ	$V/°C$	Linear temperature dependence of VTO
BEX	-1.5	-	Exponential temperature dependence of KP
TETA	-0.9m	$1/°C$	Linear temperature dependence of ETA
TE0EX	0.5	-	Exponential temperature dependence of E0
TE1EX	0.5	-	Exponential temperature dependence of E1
UCEX	1.5	-	Exponential temperature dependence of UCRIT
TLAMBDA	0.0	-	Linear temperature dependence of LAMBDA
IBBT	800μ	-	Linear temperature dependence of IBB
Geometry Dependencies of Temperature Parameters.			
TCVL	0.0	$m \cdot V/°C$	Length dependence of TCV
TCVW	0.0	$m \cdot V/°C$	Width dependence of TCV
TCVWL	0.0	$m^2 \cdot V/°C$	Area dependence of TCV

Table 1.25: Flicker Noise.

Parameter	Default Value	Unit	Short Description
KF	0.0	J	Flicker noise factor
AF	1.0	-	Frequency exponent for flicker noise
EF	2.0	-	Transconductance exponent for flicker noise
KGFN	0.0	-	Gate flicker noise factor

perimeter of the drain and source areas, excluding the part of the perimeter that faces the channel, and the third includes the gate side of the perimeter. The parameters for each component should be extracted from current and capacitance measurements of diodes with at least three different geometries, preferable one with prevailing area, another with prevailing perimeter and a third with prevailing gate sided perimeter.

The current described by the model includes the carrier recombination effect, the phenomenon of trap-assisted tunneling, the breakdown and the diodes mimimum conductivity. The dynamic modelling provides a carefule and continues transition between the reverse and the forward bias of the diodes.

1.2.23.2 Series Resistances

The series resistances refer to the resistance of the active areas of the source and drain nodes that appear between the external metalic contact and the end of the actual channel.

Typical Spice Model This distance is given to the HDIF, taken from the typical spice model. The sheet resistance of this area is set by the parameter RSH. If a lightly doped area exists between the active areas and the channel, its resistance is calculated after the LDIF and the sheet resistance of RS and RD, assymetrically defined for the two sides of the channel.

Non-Geometrical Approach A simpler model may also be used for the calculation of the series resistances, which ignores the geometry of the active area calculates the series resistances with the help of the RLX which defines the resistance per width units. Also an assymetrical approach is available for this simpler model, using the RSX and RDX. If these parameters are set to a negative value, they will be ignored by the model.

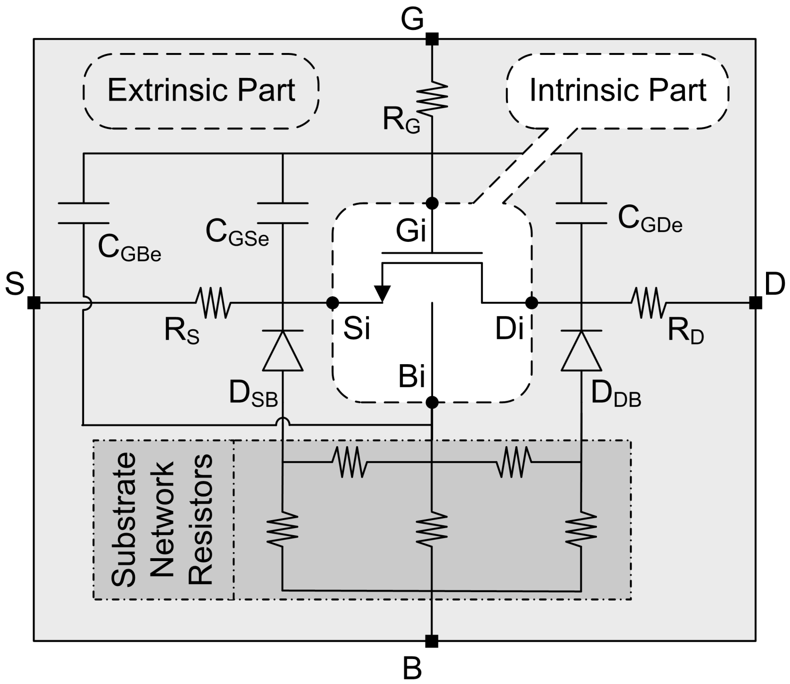

Figure 1.2: The intrinsic and the extrinsic part of the model. Note that some elements of the extrinsic network may be removed by choice of the user. The C_{GSe} consists of the overlap capacitance (C_{GSov}) and the outer fringing capacitance (C_{GSfr}) between the gate and the source. Similarly the C_{GDe} consists of the overlap capacitance (C_{GDov}) and the outer fringing capacitance (C_{GDfr}) between the gate and the drain. The C_{GBe} contains no overlap component but just the outer fringing capacitance (C_{GBfr}). The junction diodes are characterized by a leakage current and also form a parasitic capacitance between the source and drain node on one side and the substrate on the other. Finally a set of resistors is used to describe the limited conductivity of the active areas of the source and drain, of the gate material, and of the substrate.

1.2.23.3 Overlap and Outer fringing Capacitances

The overlap capacitance refers to the overlap areas that exist between the gate and the nodes at the ends of the channel. This is due to the fact that both the oxide and the gate are not strictly limited to the area above the substrate but extend a little bit further, overlapping this way the source and the drain areas. These parasitic capacitances are proportional to the overlap lentgh (`LOV`). The calculation of the overlap capacitances is based on the formulation of the charge model of the very intrinsic part of the model. The differencies are that the model focuses on a two node structure, ignoring the nodes at the ends of the channel, and, since the source and drain areas are of different type than the substrate, the `TG` should be considered opposite. A body effect coefficient (`GAMMAOV`) is defined for the source and drain region which dependes on their doping. Also the gate doping (`GAMMAGOV`) parameter is allowed to be defined differently with respect to the rest of the device.

Parallely to the above capacitances there are the parasitic outer fringing capacitences. These are model by a bias independent model that considers only geometrical aspects for their value. An outer fringing capacitance is also formed between the gate node and the substrate, proportional to the double of the gate length, which appears at the edges of the gate node, and which is more important for the narrow channel devices. The parameters of the above phenomena are jointly listed in Table 1.31.

Table 1.26: Parameters for source side junction diode.

Parameter	Default Value	Unit	Short Description
NJS	1.0	-	Slope factor for parasitic diodes (source)
JSS	0.0	A/m^2	Area component of diode current (source)
JSSWS	0.0	A/m	Perimeter component of diode current (source)
JSSWGS	0.0	A/m	Gate side component of diode current (source)
MJS	0.9	-	Area exponent of diode capacitance (source)
MJSWS	0.7	-	Perimeter exponent of diode capacitance (source)
MJSWGS	0.7	-	Gate side exponent of diode capacitance (source)
PBS	0.8	V	Area parameter of diode capacitance (source)
PBSWS	0.6	V	Perimeter parameter of diode capacitance (source)
PBSWGS	0.6	V	Gate side parameter of diode capacitance (source)
CJS	0.0	F/m^2	Area component of diode capacitance (source)
CJSWS	0.0	F/m	Perimeter component of diode capacitance (source)
CJSWGS	0.0	F/m	Gate side component of diode capacitance (source)
BVS	10.0	V	Breakdown Voltage (source)
XJBVS	0.0	-	Breakdown effect coefficient (source)
XTIS	3.0	-	Temperature dependence of diode (source)
JTSS	0.0	A/m^2	Area component of trap-assisted current (source)
JTSWS	0.0	A/m	Perimeter component of trap-assisted current (source)
JTSWGS	0.0	A/m	Gate side component of trap-assisted current (source)
XTSS	0.0	-	Temperature dependence of area component of trap-assisted current (source)
XTSSWS	0.0	-	Temperature dependence of Perimeter component of trap-assisted current (source)
XTSSWGS	0.0	-	Temperature dependence of Gate side component of trap-assisted current (source)
NJTSS	1.0	-	Area slope factor of trap-assisted current (source)
NJTSSWS	1.0	-	Perimeter slope factor of trap-assisted current (source)
NJTSSWGS	1.0	-	Gate side slope factor of trap-assisted current (source)
VTSS	0.0	V	Area voltage factor of trap-assisted current (source)
VTSSWS	0.0	V	Perimeter voltage factor of trap-assisted current (source)
VTSSWGS	0.0	V	Gate side voltage factor of trap-assisted current (source)
TNJTSS	0.0	-	Temperature dependence of NJTSS
TNJTSSWS	0.0	-	Temperature dependence of NJTSSWS
TNJTSSWGS	0.0	-	Temperature dependence of NJTSSWGS

Table 1.27: Parameters for both junction diodes.

Parameter	Default Value	Unit	Short Description
GMIN	0.0	A/V	Minimum conductance of diode (source and drain)
TCJ	0.0	$1/°C$	Temperature dependence of CJS and CJD
TCJSW	0.0	$1/°C$	Temperature dependence of CJSWS and CJSWD
TCJSWG	0.0	$1/°C$	Temperature dependence of CJSWGS and CJSWGD
TPB	0.0	$V/°C$	Temperature dependence of PBS and PBD
TPBSW	0.0	$V/°C$	Temperature dependence of PBSWS and PBSWD
TPBSWG	0.0	$V/°C$	Temperature dependence of PBSWGS and PBSWGD

1.2.23.4 Gate and Substrate Resistances

At higher frequencies it is important to include in the simulation the effects of the gate and the substrate resistances. The calculation of the gate resistance depends also on the layout of

Table 1.28: Parameters for drain side junction diode.

Parameter	Default Value	Unit	Short Description
NJD	1.0	-	Slope factor for drain diode
JSD	0.0	A/m^2	Area component of drain diode current
JSSWD	0.0	A/m	Perimeter component of drain diode current
JSSWGD	0.0	A/m	Gate side component of drain diode current
MJD	0.9	-	Area exponent of drain diode capacitance
MJSWD	0.7	-	Perimeter exponent of drain diode capacitance
MJSWGD	0.7	-	Gate side exponent of drain diode capacitance
PBD	0.8	V	Area parameter of drain diode capacitance
PBSWD	0.6	V	Perimeter parameter of drain diode capacitance
PBSWGD	0.6	V	Gate side parameter of drain diode capacitance
CJD	0.0	F/m^2	Area component of drain diode capacitance
CJSWD	0.0	F/m	Perimeter component of drain diode capacitance
CJSWGD	0.0	F/m	Gate side component of drain diode capacitance
BVD	10.0	V	Breakdown Voltage of drain diode
XJBVD	0.0	-	Breakdown effect coefficient of drain diode
XTID	3.0	-	Temperature dependence of drain diode
JTSD	0.0	A/m^2	Area component of trap-assisted current (drain)
JTSWD	0.0	A/m	Perimeter component of trap-assisted current (drain)
JTSWGD	0.0	A/m	Gate side component of trap-assisted current (drain)
XTSD	0.0	-	Temperature dependence of area component of trap-assisted drain diode current
XTSSWD	0.0	-	Temperature dependence of Perimeter component of trap-assisted drain diode current
XTSSWGD	0.0	-	Temperature dependence of Gate side component of trap-assisted drain diode current
NJTSD	1.0	-	Area slope factor of trap-assisted current (drain)
NJTSSWD	1.0	-	Perimeter slope factor of trap-assisted current (drain)
NJTSSWGD	1.0	-	Gate side slope factor of trap-assisted current (drain)
VTSD	0.0	V	Area voltage factor of trap-assisted current (drain)
VTSSWD	0.0	V	Perimeter voltage factor of trap-assisted current (drain)
VTSSWGD	0.0	V	Gate side voltage factor of trap-assisted current (drain)
TNJTSD	0.0	-	Temperature dependence of NJTSD
TNJTSSWD	0.0	-	Temperature dependence of NJTSSWD
TNJTSSWGD	0.0	-	Temperature dependence of NJTSSWGD

Table 1.29: Typical Spice Model.

Parameter	Default Value	Unit	Short Description
HDIF	0.0	m	Half length of active area
RSH	0.0	$\Omega/\square$	Square resistance of active area
LDIF	0.0	m	Length of the lightly doped area (LDD)
RS	0.0	$\Omega/\square$	LDD Source series resistance
RD	0.0	$\Omega/\square$	LDD Drain series resistance

the gate (GC), and more particularly whether the gate fingers are connect on both sides or not. The gate sheet resistance is given to the RGSH, while the KRGL1 adds a scaling dependence of the gate resistance on the length. The substrate network resistors implemented by the model is a symmetrical one, which uses five resistors. Their values again depend on the layout of the device, and more particularly on the shape of the guard ring that is built around the MOSFET.

Table 1.30: Non-Geometrical Approach.

Parameter	Default Value	Unit	Short Description
RLX	-1.0	Ω/m	Series resistance (symmetric model)
RSX	-1.0	Ω/m	Source series resistance (asymmetric model)
RDX	-1.0	Ω/m	Drain series resistance (asymmetric model)

Table 1.31: Overlap and Outer fringing Capacitances.

Parameter	Default Value	Unit	Short Description
Overlap Capacitance parameters.			
LOV	20.0n	m	Length of the overlap area
GAMMAOV	1.6	$\sqrt{V}$	Body effect coefficient of the overlap area
GAMMAGOV	10.0	$\sqrt{V}$	Body effect coefficient of the gate for the overlap area
VFBOV	0.0	V	Flat-band voltage of the overlap area
VOV	1.0	-	Bias coefficient for overlap capacitance
Outer fringing Capacitance parameters.			
CGSO	0.0	F/m	Gate to source outer fringing capacitance
CGDO	0.0	F/m	Gate to drain outer fringing capacitance
CGBO	0.0	F/m	Gate to bulk outer fringing capacitance

The two resistors that are put in parallel to the channel, are considered to be equal. The above parameters are listed in Table 1.32.

Table 1.32: Gate and Substrate Resistances.

Parameter	Default Value	Unit	Short Description
Gate resistance.			
GC	1	-	Gate contacts (single sided = 1, double sided = 2)
RGSH	3.0	$\Omega/\Box$	Gate square resistance
KRGL1	0.0	$1/m^2$	Length scaling of Gate resistance
Substrate network resistances.			
RINGTYPE	1.0	-	Type of guard ring (bulk contacts) (three sides/horse shoe: 1, two sides or symmetric: 2)
RBWSH	3.0m	Ω/m	Inner-bulk to external bulk resistance
RBN	0.0	Ω	Inner-bulk to external bulk resistance per finger (for RINGTYPE=1)
RDSBSH	1.0k	$\Omega/\Box$	Drain to source substrate sheet resistance
RSBWSH	1.0m	Ω/m	Inner-bulk source side to external bulk resistance
RSBN	0.0	Ω	Inner-bulk source side to external bulk resistance per finger (for RINGTYPE=1)
RDBWSH	1.0m	Ω/m	Inner-bulk drain side to external bulk resistance
RDBN	0.0	Ω	Inner-bulk drain side to external bulk resistance per finger (for RINGTYPE=1)

1.2.23.5 Temperature Scaling of Extrinsic Resistors

At the current version of the model, the same temperature dependence is used for all the resistances. However, this is not correct since the various resistances are formed with different materials. This part will be improved in the future versions of the model. In any case, the current version of the model employs a first order dependence of the resistances on the temperature (TR) and a second order as well (TR2). The above appear in Table 1.33.

Table 1.33: Temperature Scaling of Extrinsic Resistors.

Parameter	Default Value	Unit	Short Description
`TR`	0.0	$\Omega/°C$	First order temperature coefficient of resistors
`TR2`	0.0	$\Omega/(°C)^2$	Second order temperature coefficient of resistors

Chapter 2

Equations

2.1 Modes

EKV3 model supports five versions of internal circuitry. Each version covers the needs of certain cases. These versions are listed in table 2.1. Also, some simple schematics, that correspond to each mode, are provided in figure 2.1. By commenting the proper lines at the beginning of the code of the model, the user is allowed to change between the various modes of the model. On the other hand, if the user wants to have access to all the modes simultaneously, the all the modes can be compiled but then each mode of the model will have to be under a different name. The reader is advised to look at the first lines of the main file for more details.

Mode name	short description	internal nodes
DC_S	no external resistors	0
DC	external series resistors	2
RF_S	external series resistors, gate resistor and single substrate resistor	4
RF	external series resistors, gate resistor and full substrate resistor network	6
NQS	external series resistors, gate resistor and full substrate resistor network; minimal channel segmentation	10

Table 2.1: The five modes of the EKV3 model.

2.2 Helping functions

Here a few helping functions are described.

$$\mathrm{MAX_{smooth}(a,b,c)} = \frac{1}{2}\cdot\left(\mathrm{a+b+\sqrt{(a-b)^2+c}}\right) = \mathrm{MX_S(a,b,c)} \tag{2.1}$$

$$\mathrm{MIN_{smooth}(a,b,c)} = \frac{1}{2}\cdot\left(\mathrm{a+b-\sqrt{(a-b)^2+c}}\right) = \mathrm{MN_S(a,b,c)} \tag{2.2}$$

2.3 General equations

$$\mathrm{t_{si}} = \frac{\epsilon_{\mathrm{si}}}{\mathtt{COX}} \tag{2.3}$$

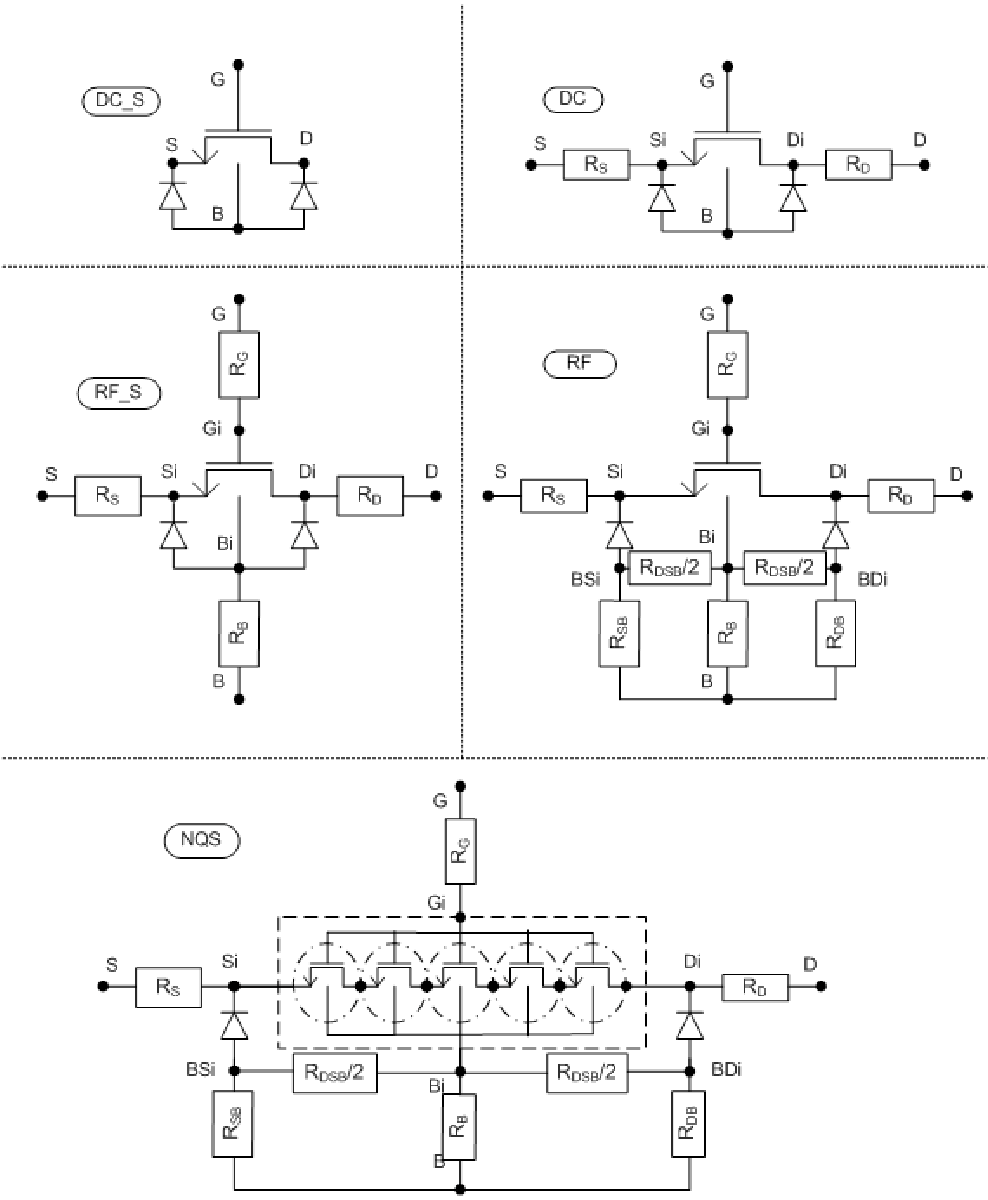

Figure 2.1: Simple schematics representing the five modes of the EKV3 model.

$$t_{ox} = \frac{\epsilon_{ox}}{\texttt{COX}} \tag{2.4}$$

$$LC = \sqrt{t_{si} \cdot \texttt{XJ}} \tag{2.5}$$

2.4 Instance level

2.4.1 Effective geometry

$$L_{scaled} = \texttt{L} \cdot \texttt{SCALE} + \texttt{XL} \tag{2.6}$$

$$W_{scaled} = \texttt{W} \cdot \texttt{SCALE} + \texttt{WL} \tag{2.7}$$

$$L_{eff} = L_{scaled} + \texttt{DL} + \frac{\texttt{WDL}}{W_{scaled}} + \frac{\texttt{LL}}{L_{scaled}^{\texttt{LLN}}} \tag{2.8}$$

$$W_{eff} = W_{scaled} + \texttt{DW} + \frac{\texttt{LDW}}{L_{scaled}} \tag{2.9}$$

$$L_{eff,C} = L_{eff} + \texttt{DLC} \tag{2.10}$$

$$W_{eff,C} = W_{eff} + \texttt{DWC} \tag{2.11}$$

2.4.2 Matching

$$VTO_a = \texttt{VTO} + \frac{\texttt{AVTO} \cdot 10^6}{\sqrt{W_{eff} \cdot L_{eff}}} \tag{2.12}$$

$$GAMMA_a = \texttt{GAMMA} + \frac{\texttt{AGAMMA} \cdot 10^6}{\sqrt{W_{eff} \cdot L_{eff}}} \tag{2.13}$$

$$KP_a = \texttt{KP}\left(1 + \frac{\texttt{AKP} \cdot 10^6}{\sqrt{W_{eff} \cdot L_{eff}}}\right) \tag{2.14}$$

2.4.3 Long and wide channel correction of VTO and GAMMA

$$\Delta VT_L = -\texttt{AVT} \cdot MX_S(\ln \frac{L_{eff}}{\texttt{LVT}}, 0, 10^{-2}) \tag{2.15}$$

$$\Delta VT_W = -\texttt{AVT} \cdot MX_S(\ln \frac{W_{eff}}{\texttt{WVT}}, 0, 10^{-2}) \tag{2.16}$$

$$\Delta GAMMA_L = -\texttt{AGAM} \cdot MX_S(\ln \frac{L_{eff}}{\texttt{LGAM}}, 0, 10^{-2}) \tag{2.17}$$

$$\Delta GAMMA_W = -\texttt{AGAM} \cdot MX_S(\ln \frac{W_{eff}}{\texttt{WGAM}}, 0, 10^{-2}) \tag{2.18}$$

2.4.4 Parameter width and length scaling

$$\mathrm{LR_g} = \mathtt{LR} + \frac{\mathtt{WLR}}{\mathrm{W_{eff}}} \tag{2.19}$$

$$\mathrm{QLR_g} = \mathtt{QLR} \cdot \left(1 + \frac{\mathtt{WQLR}}{\mathrm{W_{eff}}}\right) \tag{2.20}$$

$$\mathrm{NLR_g} = \mathtt{NLR} \cdot \left(1 + \frac{\mathtt{WNLR}}{\mathrm{W_{eff}}}\right) \tag{2.21}$$

$$\mathrm{E0_g} = \mathtt{E0} \cdot \left(1 + \frac{\mathtt{WE0}}{\mathrm{W_{eff}}}\right) \tag{2.22}$$

$$\mathrm{E1_g} = \mathtt{E1} \cdot \left(1 + \frac{\mathtt{WE1}}{\mathrm{W_{eff}}}\right) \tag{2.23}$$

$$\mathrm{UCRIT_g} = \mathtt{UCRIT} \cdot \left(1 + \frac{\mathtt{WUCRIT}}{\mathrm{W_{eff}}}\right) \tag{2.24}$$

$$\mathrm{LAMBDA_g} = \mathtt{LAMBDA} \cdot \left(1 + \frac{\mathtt{WLAMBDA}}{\mathrm{W_{eff}}}\right) \tag{2.25}$$

$$\mathrm{ETAD_g} = \mathtt{ETAD} \cdot \left(1 + \frac{\mathtt{WETAD}}{\mathrm{W_{eff}}}\right) \tag{2.26}$$

$$\mathrm{UCEX_g} = \mathtt{UCEX} \cdot \left(1 + \frac{\mathtt{WUCEX}}{\mathrm{W_{eff}}}\right) \tag{2.27}$$

$$\mathrm{WR_g} = \mathtt{WR} + \frac{\mathtt{LWR}}{\mathrm{L_{eff}}} \tag{2.28}$$

$$\mathrm{QWR_g} = \mathtt{QWR} \cdot \left(1 + \frac{\mathtt{LQWR}}{\mathrm{L_{eff}}}\right) \tag{2.29}$$

$$\mathrm{NWR_g} = \mathtt{NWR} \cdot \left(1 + \frac{\mathtt{LNWR}}{\mathrm{L_{eff}}}\right) \tag{2.30}$$

$$\mathrm{TCV_g} = \mathtt{TCV} + \frac{\mathtt{TCVL}}{\mathrm{L_{eff}}} + \frac{\mathtt{TCVW}}{\mathrm{W_{eff}}} + \frac{\mathtt{TCVWL}}{\mathrm{W_{eff}} \cdot \mathrm{L_{eff}}} \tag{2.31}$$

2.4.5 Reverse short channel effect (RSCE)

$$\Delta\mathrm{VT_{RSCE}} = \frac{2 \cdot \mathrm{QLR_g} \cdot \left(1 - \exp\left(\left(\frac{\mathrm{L_{eff}}}{\mathrm{LR_g}}\right)^2\right)\right)}{\mathtt{COX} \cdot \frac{\mathrm{L_{eff}}}{\mathrm{LR_g}}} \tag{2.32}$$

$$\mathrm{GAMMA_{RSCE}} = \sqrt{1.0 + \frac{2 \cdot \mathrm{NLR_g} \cdot \left(1 - \exp\left(\left(\frac{\mathrm{L_{eff}}}{\mathrm{LR_g}}\right)^2\right)\right)}{\mathtt{COX} \cdot \frac{\mathrm{L_{eff}}}{\mathrm{LR_g}}}} \tag{2.33}$$

$$\Delta\Phi_{\mathrm{f,RSCE}} = \mathrm{U_T} \cdot \mathtt{FLR} \cdot \ln\left(1 + \frac{2 \cdot \mathrm{NLR_g} \cdot \left(1 - \exp\left(\left(\frac{\mathrm{L_{eff}}}{\mathrm{LR_g}}\right)^2\right)\right)}{\mathtt{COX} \cdot \frac{\mathrm{L_{eff}}}{\mathrm{LR_g}}}\right) \tag{2.34}$$

2.4.6 Inverse narrow width effect (INWE)

$$\Delta VT_{INWE} = -\frac{2 \cdot QWR_g \cdot \left(1 - \exp\left(\left(\frac{W_{eff}}{WR_g}\right)^2\right)\right)}{\mathtt{COX} \cdot \frac{W_{eff}}{WR_g}} \tag{2.35}$$

$$GAMMA_{INWE} = \frac{1}{\sqrt{1.0 + \frac{2 \cdot NWR_g \cdot \left(1 - \exp\left(\left(\frac{W_{eff}}{WR_g}\right)^2\right)\right)}{\mathtt{COX} \cdot \frac{W_{eff}}{WR_g}}}} \tag{2.36}$$

2.4.7 Mobility scaling

$$KP_l = \frac{1}{\left(1 + \frac{\mathtt{KA} \cdot \mathtt{LA}}{L_{eff}}\right) \cdot \left(1 - \exp\left(-\frac{L_{eff}}{\mathtt{LA}}\right)\right) + \left(1 + \frac{\mathtt{KB} \cdot \mathtt{LB}}{L_{eff}}\right) \cdot \left(1 - \exp\left(-\frac{L_{eff}}{\mathtt{LB}}\right)\right)} \tag{2.37}$$

$$KP_w = 1 + \mathtt{WKP2} \cdot \exp\left(-\left(\frac{\ln\left(\frac{W_{eff}}{\mathtt{WKP1}}\right)}{\mathtt{WKP3}}\right)^2\right) \tag{2.38}$$

2.4.8 Shallow Trench Isolation Stress effect

$$\begin{aligned} KKP_{STI} = & 1 + \mathtt{LKKP} \cdot L_{scaled}^{-\mathtt{LLODKKP}} + \mathtt{WKKP} \cdot (W_{scaled} + \mathtt{WLOD})^{-\mathtt{WLODKKP}} + \\ & + \mathtt{PKKP} \cdot L_{scaled}^{-\mathtt{LLODKKP}} \cdot (W_{scaled} + \mathtt{WLOD})^{-\mathtt{WLODKKP}} \end{aligned} \tag{2.39}$$

$$KP_{STI} = \frac{1 + \frac{\mathtt{KKP}}{KKP_{STI}} \cdot \left(\sum_{i=0}^{i=\mathtt{NF}-1} \frac{1}{\mathtt{SA} + \frac{1}{2}L_{scaled} + i \cdot (\mathtt{SD} + L_{scaled})} + \frac{1}{\mathtt{SB} + \frac{1}{2}L_{scaled} + i \cdot (\mathtt{SD} + L_{scaled})}\right)}{1 + \frac{\mathtt{KKP}}{KKP_{STI}} \cdot \frac{1}{\mathtt{SAREF} + \frac{1}{2}L_{scaled}} + \frac{1}{\mathtt{SBREF} + \frac{1}{2}L_{scaled}}} \tag{2.40}$$

$$UCRIT_{STI} = \frac{1 + \mathtt{KUCRIT} \cdot \left(\sum_{i=0}^{i=\mathtt{NF}-1} \frac{1}{\mathtt{SA} + \frac{1}{2}L_{scaled} + i \cdot (\mathtt{SD} + L_{scaled})} + \frac{1}{\mathtt{SB} + \frac{1}{2}L_{scaled} + i \cdot (\mathtt{SD} + L_{scaled})}\right)}{1 + \mathtt{KUCRIT} \cdot \left(\frac{1}{\mathtt{SAREF} + \frac{1}{2}L_{scaled}} + \frac{1}{\mathtt{SBREF} + \frac{1}{2}L_{scaled}}\right)} \tag{2.41}$$

$$\begin{aligned} KVTO_{STI} = & 1 + \mathtt{LKVTO} \cdot L_{scaled}^{-\mathtt{LLODKVTO}} + \mathtt{WKVTO} \cdot (W_{scaled} + \mathtt{WLOD})^{-\mathtt{WLODKVTO}} + \\ & + \mathtt{PKVTO} \cdot L_{scaled}^{-\mathtt{LLODKVTO}} \cdot (W_{scaled} + \mathtt{WLOD})^{-\mathtt{WLODKVTO}} \end{aligned} \tag{2.42}$$

$$\begin{aligned} \Delta VT_{STI} = & \frac{\mathtt{KVTO}}{KVTO_{STI}} \cdot \left(\sum_{i=0}^{i=\mathtt{NF}-1} \frac{1}{\mathtt{SA} + \frac{1}{2}L_{scaled} + i \cdot (\mathtt{SD} + L_{scaled})} + \frac{1}{\mathtt{SB} + \frac{1}{2}L_{scaled} + i \cdot (\mathtt{SD} + L_{scaled})} \right. \\ & \left. - \frac{1}{\mathtt{SAREF} - \frac{1}{2}L_{scaled}} + \frac{1}{\mathtt{SBREF} + \frac{1}{2}L_{scaled}}\right) \end{aligned}$$

(2.43)

$$\Delta\mathrm{GAMMA_{STI}} = \frac{\mathtt{KGAMMA}}{\mathrm{KVTO_{STI}^{\mathtt{LODKGAMMA}}}} \cdot \cdot \left(\sum_{i=0}^{i=\mathtt{NF}-1} \frac{1}{\mathtt{SA} + \frac{1}{2}\mathrm{L_{scaled}} + i \cdot (\mathtt{SD} + \mathrm{L_{scaled}})} + \frac{1}{\mathtt{SB} + \frac{1}{2}\mathrm{L_{scaled}} + i \cdot (\mathtt{SD} + \mathrm{L_{scaled}})} - \frac{1}{\mathtt{SAREF} - \frac{1}{2}\mathrm{L_{scaled}}} + \frac{1}{\mathtt{SBREF} + \frac{1}{2}\mathrm{L_{scaled}}} \right) \tag{2.44}$$

$$\Delta\mathrm{ETAD_{STI}} = \frac{\mathtt{KETAD}}{\mathrm{KVTO_{STI}^{\mathtt{LODKETAD}}}} \cdot \cdot \left(\sum_{i=0}^{i=\mathtt{NF}-1} \frac{1}{\mathtt{SA} + \frac{1}{2}\mathrm{L_{scaled}} + i \cdot (\mathtt{SD} + \mathrm{L_{scaled}})} + \frac{1}{\mathtt{SB} + \frac{1}{2}\mathrm{L_{scaled}} + i \cdot (\mathtt{SD} + \mathrm{L_{scaled}})} - \frac{1}{\mathtt{SAREF} - \frac{1}{2}\mathrm{L_{scaled}}} + \frac{1}{\mathtt{SBREF} + \frac{1}{2}\mathrm{L_{scaled}}} \right) \tag{2.45}$$

2.4.9 Instance level parameters

$$\mathrm{VTO_g} = \mathrm{VTO_a} + \Delta\mathrm{VT_L} + \Delta\mathrm{VT_W} + \Delta\mathrm{VT_{RSCE}} + \Delta\mathrm{VT_{INWE}} + \Delta\mathrm{VT_{STI}} \tag{2.46}$$

$$\mathrm{GAMMA_g} = \mathrm{GAMMA_a} \cdot \mathrm{GAMMA_{RSCE}} \cdot \mathrm{GAMMA_{INWE}} + \Delta\mathrm{GAMMA_L} + \Delta\mathrm{GAMMA_W} + \Delta\mathrm{GAMMA_{STI}} \tag{2.47}$$

$$\Phi_{\mathrm{f,g}} = \mathtt{PHIF} + \Delta\Phi_{\mathrm{f,RSCE}} \tag{2.48}$$

$$\mathrm{KP_g} = \mathtt{KP} \cdot \mathrm{KP_l} \cdot \mathrm{KP_w} \cdot \mathrm{KP_{STI}} \tag{2.49}$$

$$\mathrm{ETAD_{g,STI}} = \mathrm{ETAD_g} + \Delta\mathrm{ETAD_{STI}} \tag{2.50}$$

$$\mathrm{UCRIT_{g,STI}} = \mathrm{UCRIT_g} \cdot \mathrm{UCRIT_{STI}} \tag{2.51}$$

2.4.10 Temperature scaling

$$\Delta\mathrm{T} = \mathrm{T} - \mathtt{TNOM} \tag{2.52}$$

$$\mathrm{rT} = \frac{\mathrm{T}}{\mathtt{TNOM}} \tag{2.53}$$

$$\mathrm{VTO_{gt}} = \mathrm{VTO_g} - \mathrm{TCV_g} \cdot \Delta\mathrm{T} \tag{2.54}$$

$$\mathrm{KP_{gt}} = \mathrm{KP_g} \cdot \mathrm{rT}^{\mathtt{BEX}} \tag{2.55}$$

$$\mathrm{ETA_t} = \mathtt{ETA} - \mathtt{TETA} \cdot \Delta\mathrm{T} \tag{2.56}$$

$$\mathrm{E0_{gt}} = \mathrm{E0_g} \cdot \mathrm{rT}^{\mathtt{TE0EX}} \tag{2.57}$$

$$\mathrm{E1_{gt}} = \mathrm{E1_g} \cdot \mathrm{rT}^{\mathtt{TE1EX}} \tag{2.58}$$

$$\Phi_{\mathrm{f,gt}} = \Phi_{\mathrm{f,g}} \cdot \mathrm{rT} - \frac{\mathrm{E_g(T)} - \mathrm{E_g}(\mathtt{TNOM}) \cdot \mathrm{rT} - 3 \cdot \mathrm{U_T} \cdot \ln \mathrm{rT}}{2} \tag{2.59}$$

2.4.11 Normalizing

$$\phi_\mathrm{f} = \frac{\Phi_{\mathrm{f,gt}}}{\mathrm{U_T}} \tag{2.60}$$

$$\mathrm{vto} = \frac{\mathrm{VTO_{gt}}}{\mathrm{U_T}} \tag{2.61}$$

$$\gamma = \frac{\mathrm{GAMMA_g}}{\sqrt{\mathrm{U_T}}} \tag{2.62}$$

$$\gamma_\mathrm{g} = \frac{\mathtt{GAMMAG}}{\sqrt{\mathrm{U_T}}} \tag{2.63}$$

$$\gamma_\mathrm{ov} = \frac{\mathtt{GAMMAOV}}{\sqrt{\mathrm{U_T}}} \tag{2.64}$$

$$\mathrm{vfb_{ov}} = \frac{\mathtt{VFBOV}}{\mathrm{U_T}} \tag{2.65}$$

$$\mathrm{ucrit} = \frac{\mathtt{UCRIT}_{\mathrm{g},\mathtt{STI}}}{\mathrm{U_T}} \tag{2.66}$$

$$\mathrm{xb} = \frac{\mathtt{XB}}{\mathrm{U_T}} \tag{2.67}$$

$$\mathrm{ub} = \frac{\mathtt{EB} \cdot \mathrm{t_{ox}}}{\mathtt{XB}} \tag{2.68}$$

2.4.12 Slope factor n_{Q0}

$$\mathrm{n_{Q0}} = \begin{cases} 1 + \dfrac{\gamma}{2 \cdot \sqrt{2 \cdot \phi_\mathrm{f}}}, & \text{if } \mathtt{TG} = 0 \text{ or } 1 \\ \dfrac{1}{1 + \dfrac{\gamma^2}{\gamma_\mathrm{g}^2} \cdot \dfrac{2 \cdot \sqrt{2 \cdot \phi_\mathrm{f}}}{\gamma}} + \dfrac{\gamma}{2 \cdot \sqrt{2 \cdot \phi_\mathrm{f}}}, & \text{if } \mathtt{TG} = -1 \end{cases} \tag{2.69}$$

2.4.13 Quantum mechanic effect

$$\alpha_{\mathrm{qma}} = \mathtt{AQMA} \cdot \frac{\mathtt{COX}^{2/3}}{\mathrm{U_T^{1/3}}} \cdot \mathtt{ETAQM}^{2/3} \tag{2.70}$$

$$\delta_{\mathrm{qmi}} = \frac{1}{3} \cdot \mathtt{AQMI} \cdot \frac{\gamma \cdot \mathtt{COX}}{2 \cdot \phi_{\mathrm{f}} \cdot \sqrt{\mathrm{U_T}}} \left(\frac{2 \cdot \mathtt{ETAQM} \cdot \mathrm{n_{Q0}} \cdot \sqrt{2 \cdot \phi_{\mathrm{f}}}}{\gamma} - 1 \right) \tag{2.71}$$

$$\Delta\Psi_0 = \mathtt{AQMI} \cdot \frac{2}{3} \cdot \left(\gamma \cdot \mathtt{COX} \cdot \sqrt{2 \cdot \phi_{\mathrm{f}}} \right)^{2/3} \tag{2.72}$$

$$\Delta\psi_0 = \frac{\Delta\Psi_0}{\mathrm{U_T}} \tag{2.73}$$

$$\phi = 2 \cdot \phi_{\mathrm{f}} + \ln\left(4 \cdot \mathrm{n_{Q0}} \cdot \frac{\sqrt{2 \cdot \phi_{\mathrm{f}}}}{\gamma} \right) + \Delta\psi_0 \tag{2.74}$$

2.4.14 Normalization factor for charges

$$\mathrm{Q_0} = -\mathrm{W_{eff,C}} \cdot \mathtt{NF} \cdot \mathrm{L_{eff,C}} \cdot \mathrm{U_T} \cdot \frac{\mathtt{COX}}{1 + \delta_{\mathrm{qmi}}} \frac{\mathrm{W_{eff}} - \mathtt{WEDGE}}{\mathrm{W_{eff}}} \tag{2.75}$$

$$\mathrm{Q_{0,OV}} = -\mathrm{W_{eff,C}} \cdot \mathtt{NF} \cdot \mathtt{LOV} \cdot \mathrm{U_T} \cdot \frac{\mathtt{COX}}{1 + \delta_{\mathrm{qmi}}} \tag{2.76}$$

2.4.15 Normalization of potentials

$$\mathrm{v_g} = \frac{\mathrm{V_{GB}}}{\mathrm{U_T}} \tag{2.77}$$

$$\mathrm{v_d} = \begin{cases} \dfrac{\mathrm{V_{DB}}}{\mathrm{U_T}}, & \text{if } \mathrm{V_D} \geq \mathrm{V_S} \\ \dfrac{\mathrm{V_{SB}}}{\mathrm{U_T}}, & \text{if } \mathrm{V_D} < \mathrm{V_S} \end{cases} \tag{2.78}$$

$$\mathrm{v_s} = \begin{cases} \dfrac{\mathrm{V_{SB}}}{\mathrm{U_T}}, & \text{if } \mathrm{V_D} \geq \mathrm{V_S} \\ \dfrac{\mathrm{V_{DB}}}{\mathrm{U_T}}, & \text{if } \mathrm{V_D} < \mathrm{V_S} \end{cases} \tag{2.79}$$

2.4.16 Charge sharing effect

$$\mathrm{CHSH_L} = \mathtt{LETA0} + \frac{\mathtt{LETA}}{\mathrm{L_{eff}}} + \frac{\mathtt{LETA2}}{\mathrm{L_{eff}^2}} \tag{2.80}$$

$$\mathrm{CHSH_W} = \frac{\mathtt{WETA}}{\mathrm{W_{eff}}} \tag{2.81}$$

$$\mathrm{NUV} = \mathtt{N0} + 3 \cdot \mathtt{NCS} \cdot \mathrm{t_{ox}} \cdot \mathrm{CHSH_L} \tag{2.82}$$

$$\mathrm{A_1} = 1 - \frac{\mathrm{CHSH_L} \cdot \mathrm{t_{si}}}{\gamma} \left(\sqrt{\mathrm{MX_S}\left(\mathrm{v_{bi}} + \mathrm{v_s}, 0, \mathrm{U_T^2}\right)} + \sqrt{\mathrm{MX_S}\left(\mathrm{v_{bi}} + \mathrm{v_d}, 0, \mathrm{U_T^2}\right)} \right) \tag{2.83}$$

$$A_2 = 2 \cdot A_1 - 1 + 2 \cdot CHSH_W \cdot \frac{\sqrt{\phi}}{\gamma} \tag{2.84}$$

$$A_3 = 1 + CHSH_W \cdot t_{si} \cdot \frac{\gamma}{\gamma_g} \cdot A_2 \tag{2.85}$$

$$\gamma_{chsh} = \gamma \cdot \frac{A_1}{1 + CHSH_W} \tag{2.86}$$

$$\gamma_{eff} = \gamma \cdot \frac{A_1}{A_3} \tag{2.87}$$

$$A_{1,0} = 1 - 2 \cdot \frac{CHSH_L \cdot t_{si}}{\gamma} \cdot \sqrt{v_{bi}} \tag{2.88}$$

$$A_{2,0} = 2 \cdot A_{1,0} - 1 + 2 \cdot CHSH_W \cdot \frac{\sqrt{\phi}}{\gamma} \tag{2.89}$$

$$A_{3,0} = 1 + CHSH_W \cdot t_{si} \cdot \frac{\gamma^2}{\gamma_g^2} \cdot A_{2,0} \tag{2.90}$$

$$\gamma_{chsh,0} = \gamma \cdot \frac{A_{1,0}}{1 + CHSH_W} \tag{2.91}$$

2.4.17 Flat-band voltage

$$\begin{aligned} v_{fb} = & v_{to} - \phi \cdot \left(1 + CHSH_W \cdot t_{si} + \frac{\gamma^2}{\gamma_g^2} \cdot \left(1 - 2 \cdot CHSH_L \cdot t_{si} \cdot \frac{\sqrt{v_{bi}}}{\gamma}\right)^2\right) - \\ & -\gamma \cdot \left(1 - 2 \cdot CHSH_L \cdot \frac{\sqrt{v_{bi}}}{\gamma} \cdot \sqrt{\phi}\right) \end{aligned} \tag{2.92}$$

2.4.18 Effective gate-voltage

$$v'_g = v_g - v_{fb} \tag{2.93}$$

$$v'_{g,chsh} = \frac{v'_g}{1 + CHSH_W \cdot t_{si}} \tag{2.94}$$

$$v'_{g,chsh,pd} = \frac{v'_g}{A_3} \tag{2.95}$$

$$v'_{g,chsh,pd,0} = \frac{v'_g}{A_{3,0}} \tag{2.96}$$

2.4.19 Pinch-off surface potential

2.4.19.1 Approximation around zero

$$\psi_{\mathrm{po}} = \mathrm{MX_S}\left(\mathrm{v}'_{\mathrm{g,chsh}} - 6\cdot\left(1+\frac{\gamma_{\mathrm{chsh}}}{\sqrt{2}}\right), 0, 6\cdot \mathrm{v}'_{\mathrm{g,chsh}}\right) \tag{2.97}$$

$$\psi_{\mathrm{po,0}} = \mathrm{MX_S}\left(\mathrm{v}'_{\mathrm{g,chsh}} - 6\cdot\left(1+\frac{\gamma_{\mathrm{chsh,0}}}{\sqrt{2}}\right), 0, 6\cdot \mathrm{v}'_{\mathrm{g,chsh}}\right) \tag{2.98}$$

2.4.19.2 Exact solution

$$\psi_{\mathrm{p}} = \begin{cases} -\ln\left(1-\psi_{\mathrm{po}}+\left(\dfrac{\psi_{\mathrm{po}}-\mathrm{v}'_{\mathrm{g,chsh}}}{\gamma_{\mathrm{chsh}}}\right)^2\right), & \text{if } \mathrm{v}'_{\mathrm{g}} < 0 \\ \left(\sqrt{\mathrm{v}_{\mathrm{g,chsh,pd}} - 1 + \exp\left(-\psi_{\mathrm{po}}\right) + \dfrac{\gamma_{\mathrm{eff}}^2}{4}} - \dfrac{\gamma_{\mathrm{eff}}}{2}\right)^2 + 1 - \exp\left(-\psi_{\mathrm{po}}\right), & \text{if } \mathrm{v}'_{\mathrm{g}} \geq 0 \end{cases} \tag{2.99}$$

$$\psi_{\mathrm{p,0}} = \begin{cases} -\ln\left(1-\psi_{\mathrm{po,0}}+\left(\dfrac{\psi_{\mathrm{po,0}}-\mathrm{v}'_{\mathrm{g,chsh}}}{\gamma_{\mathrm{chsh,0}}}\right)^2\right), & \text{if } \mathrm{v}'_{\mathrm{g}} < 0 \\ \left(\sqrt{\mathrm{v}_{\mathrm{g,chsh,pd,0}} - 1 + \exp\left(-\psi_{\mathrm{po,0}}\right) + \dfrac{\gamma_{\mathrm{chsh,0}}^2}{4}} - \dfrac{\gamma_{\mathrm{chsh,0}}}{2}\right)^2 + 1 - \exp\left(-\psi_{\mathrm{po,0}}\right), & \text{if } \mathrm{v}'_{\mathrm{g}} \geq 0 \end{cases} \tag{2.100}$$

2.4.20 Pinch-off voltage

$$\mathrm{v_p} = \psi_{\mathrm{p}} - \phi \tag{2.101}$$

2.4.21 Slope factor n_v

$$\mathrm{n_v} = \mathrm{A_3} + \gamma\cdot\frac{\mathrm{A_1}}{2\cdot\sqrt{\psi_{\mathrm{p}}}} \tag{2.102}$$

2.4.22 Drain induced barrier lowering effect

$$\mathrm{l_0} = \mathrm{ETAD_{g,STI}}\cdot \mathrm{t_{si}}\cdot\sqrt{\frac{2\cdot\sqrt{\phi}}{\gamma}} \tag{2.103}$$

$$\mathrm{v_o} = 4 + 40\cdot\frac{\mathrm{l_0}}{\mathrm{L_{eff}}} \tag{2.104}$$

$$\mathrm{dv} = \mathrm{MN_S}(\mathrm{v_p}, \mathrm{MN_S}(\mathrm{v_s}, \mathrm{v_d}, \mathrm{v_o^2}), \mathrm{v_o^2}) \tag{2.105}$$

$$\delta\psi_{\mathrm{s}} = \exp\left(-\frac{\mathrm{L_{eff}}}{2\cdot \mathrm{l_0}}\right)\cdot\left(2+\mathtt{SIGMAD}\cdot\frac{\mathrm{L_{eff}}}{2\cdot \mathrm{l_0}}\cdot\frac{\mathrm{dv}}{2\cdot\phi}\right)\cdot\sqrt{(\mathrm{nul}+\mathrm{v_s}-\mathrm{dv})\cdot(\mathrm{nul}+\mathrm{v_d}-\mathrm{dv})} \tag{2.106}$$

2.4.23 Normalized source inversion charge

$$q(v) = \left| \begin{array}{l} \text{if } \frac{v}{NUV} < -0.6 \\ \quad z_1 = \frac{1}{4} \cdot (\frac{v}{NUV} - 1.4 + \sqrt{\frac{v}{NUV} \cdot (\frac{v}{NUV} - 0.384936) + 9.662671}) \\ \quad z_2 = \frac{\frac{v}{NUV} - (2 \cdot z_1 + \ln z_1)}{2 \cdot z_1 + 1} \\ \quad z_1(1 + z_2 \cdot (1 + 0.07 \cdot z_2)) \cdot NUV \\ \text{if } \frac{v}{NUV} \geq -0.6 \\ \quad z_{1,ln} = 0.5 \cdot (\frac{v}{NUV} - 0.201491 - \sqrt{\frac{v}{NUV} \cdot (\frac{v}{NUV} - 0.402982) + 2.446562}) \\ \quad z_1 = \frac{1}{4} \cdot (\frac{v}{NUV} - 1.4 + \sqrt{\frac{v}{NUV} \cdot (\frac{v}{NUV} - 0.384936) + 9.662671}) \\ \quad z_2 = \frac{\frac{v}{NUV} - (2 \cdot \exp(z_{1,ln}) + z_{1,ln})}{2z_1 + 1} \\ \quad z_1(1 + z_2 \cdot (1 + 0.483 \cdot z_2)) \cdot NUV \end{array} \right. \tag{2.107}$$

$$q_s = q(v_p + \delta\psi_s - v_s) \tag{2.108}$$

2.4.23.1 Normalized forward current

$$i_f = q_s + q_s^2 \tag{2.109}$$

2.4.24 Velocity saturation

$$e_{clm} = \frac{2}{u_{crit} \cdot L_{eff}} \tag{2.110}$$

$$q_{sat} = \frac{2 \cdot e_{clm} \cdot i_f}{e_{clm} + 2 + 2 \cdot e_{clm} \cdot q_s + \sqrt{(e_{clm} + 2)^2 + 8 \cdot e_{clm} \cdot q_s}} \tag{2.111}$$

$$v_{d,sat} = v_p - \frac{(2 \cdot q_{sat} + \ln q_{sat})(1 + e_{clm} \cdot (q_s - q_{sat}))}{\sqrt{1 + \frac{2 \cdot (e_{clm} \cdot (2 - \mathtt{DELTA}) \cdot (q_s - q_{sat}))^2}{0.1 + e_{clm} \cdot (2 - \mathtt{DELTA}) \cdot (q_s - q_{sat})}} + e_{clm} \cdot (q_s - q_{sat})} \tag{2.112}$$

$$v_{ds,sat} = MX_S(v_{d,sat} - v_s, 3, 4) \tag{2.113}$$

$$dv = \frac{\mathtt{ACLM}}{\mathtt{DELTA}} \cdot \frac{4 \cdot q_{sat} + \mathtt{DELTA}}{q_s + 1} \tag{2.114}$$

$$\begin{aligned} v'_d =& \frac{1}{2} \cdot \sqrt{\left((v_d - v_s) \cdot \sqrt{1 + \frac{4 \cdot dv}{v_{ds,sat}}} + v_{ds,sat}\right)^2 + 4 \cdot dv \cdot v_{ds,sat}} - \\ & -\frac{1}{2} \cdot \sqrt{\left((v_d - v_s) \cdot \sqrt{1 + \frac{4 \cdot dv}{v_{ds,sat}}} - v_{ds,sat}\right)^2 + 4 \cdot dv \cdot v_{ds,sat}} + v_s \end{aligned} \tag{2.115}$$

2.4.24.1 Channel length modulation

$$u_{clm} = \frac{e_{clm} \cdot L_{eff}}{L_C \cdot (v_d - v'_d)} \tag{2.116}$$

$$\alpha_{clm} = \frac{L_C}{L_{eff} - 2 \cdot L_C} \tag{2.117}$$

$$\delta L = \mathrm{LAMBDA}_{g,t} \cdot L_C \cdot \ln \frac{\alpha_{clm} + u_{clm} + \sqrt{u_{clm}^2 + 2 \cdot \alpha_{clm} \cdot u_{clm} + 1}}{\alpha_{clm} + 1} \tag{2.118}$$

2.4.25 Normalized drain inversion charge

$$q_d = q(v_p + \delta\psi_s - v'_d) \tag{2.119}$$

2.4.25.1 Normalized forward current

$$i_r = q_d + q_d^2 \tag{2.120}$$

2.4.26 Slope factor n_Q

$$\psi_{sa} = \psi_p - q_s - q_d \tag{2.121}$$

$$n_Q = \begin{cases} \text{if } \mathtt{TG} < 0 \\ \dfrac{1 + \dfrac{\gamma^2}{\gamma_g^2} + \dfrac{\mathtt{GAMMA}}{\sqrt{U_T}(\sqrt{\psi_p} + \sqrt{\psi_{sa}})}}{\dfrac{1}{2} + \dfrac{\gamma^2}{\gamma_g^2}\dfrac{\sqrt{U_T}\sqrt{\psi_{sa}}}{\mathtt{GAMMA}} + \sqrt{\left(\dfrac{1}{2} + \dfrac{\gamma^2}{\gamma_g^2}\dfrac{\sqrt{U_T}\sqrt{\psi_{sa}}}{\mathtt{GAMMA}}\right)^2 + \left(1 + \dfrac{\gamma^2}{\gamma_g^2} + \dfrac{\mathtt{GAMMA}}{\sqrt{U_T}(\sqrt{\psi_p} + \sqrt{\psi_{sa}})}\right)\dfrac{q_s + q_d}{\gamma_g^2}}} \\ \text{if } \mathtt{TG} \geq 0 \\ 1 + \dfrac{\mathtt{GAMMA}}{\sqrt{U_T} \cdot (\sqrt{\psi_p} + \sqrt{\psi_{sa}})} \end{cases} \tag{2.122}$$

2.4.27 Charge model

$$v_o = v'_{g,chsh} - \psi_{p,0} \tag{2.123}$$

2.4.27.1 Quantum mechanic effect

$$q_{bo} = v'_{g,chsh} - \psi_p, \quad \text{if } v'_g < 0 \tag{2.124}$$

$$q_{bo} = \frac{v'_{g,chsh}}{1 + \dfrac{\gamma^2}{\gamma_g^2}} - \psi_{po}, \quad \text{if } v'_g < 0 \tag{2.125}$$

$$\delta\psi_{\mathrm{v}} = \alpha_{\mathrm{qma}} \cdot \left(\left(\sqrt{\frac{\mathrm{q_{bo}}^2}{4} + 4 \cdot \alpha_{\mathrm{qma}} \cdot \gamma_{\mathrm{chsh}}^2} - \frac{\mathrm{q_{bo}}}{2} \right)^{2/3} - \left(\sqrt{\frac{9 \cdot \gamma_{\mathrm{chsh}}^2}{2} + 4 \cdot \alpha_{\mathrm{qma}} \cdot \gamma_{\mathrm{chsh}}^2} - \frac{3 \cdot \gamma_{\mathrm{chsh}}}{\sqrt{2}} \right)^{2/3} \right) \tag{2.126}$$

$$\mathrm{v_{o,qm}} = \mathrm{v_o} + \delta\psi_{\mathrm{v}} \tag{2.127}$$

2.4.27.2 Q_S, Q_D, Q_G, Q_B

$$\mathrm{q_S} = \frac{\mathrm{n_Q}}{3 \cdot (1 + \delta \mathrm{q_{mi}})} \cdot \left(2 \cdot \mathrm{q_s} + \mathrm{q_d} + \frac{(1 + \frac{4}{5} \cdot \mathrm{q_s} + \frac{6}{5} \cdot \mathrm{q_d}) \cdot (\mathrm{q_s} - \mathrm{q_d})^2}{2 \cdot (\mathrm{q_s} + \mathrm{q_d} + 1)^2} \right) \tag{2.128}$$

$$\mathrm{q_D} = \frac{\mathrm{n_Q}}{3 \cdot (1 + \delta \mathrm{q_{mi}})} \cdot \left(\mathrm{q_s} + 2 \cdot \mathrm{q_d} + \frac{(1 + \frac{6}{5} \cdot \mathrm{q_s} + \frac{4}{5} \cdot \mathrm{q_d}) \cdot (\mathrm{q_s} - \mathrm{q_d})^2}{2 \cdot (\mathrm{q_s} + \mathrm{q_d} + 1)^2} \right) \tag{2.129}$$

$$\mathrm{q_G} = \begin{cases} \text{if } \mathtt{TG} < 0 \\ \dfrac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_s}}{1 + \delta_{\mathrm{qmi}}}}{1 + 2 \cdot \sqrt{\frac{1}{4} + \frac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_s}}{1 + \delta_{\mathrm{qmi}}}}{\gamma_{\mathrm{g}}^2}}} + \dfrac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_d}}{1 + \delta_{\mathrm{qmi}}}}{1 + 2 \cdot \sqrt{\frac{1}{4} + \frac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_d}}{1 + \delta_{\mathrm{qmi}}}}{\gamma_{\mathrm{g}}^2}}} + \\ + \dfrac{1}{3 \cdot (1 + \delta_{\mathrm{qmi}})} \cdot \dfrac{(\mathrm{q_s} - \mathrm{q_d})^2}{\left(\sqrt{\frac{1}{4} + \frac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_s}}{1 + \delta_{\mathrm{qmi}}}}{\gamma_{\mathrm{g}}^2}} + \sqrt{\frac{1}{4} + \frac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_d}}{1 + \delta_{\mathrm{qmi}}}}{\gamma_{\mathrm{g}}^2}} \right)^3} \cdot \\ \cdot \dfrac{4}{5} \cdot \left(\sqrt{\frac{1}{4} + \frac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_s}}{1 + \delta_{\mathrm{qmi}}}}{\gamma_{\mathrm{g}}^2}} + \sqrt{\frac{1}{4} + \frac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_d}}{1 + \delta_{\mathrm{qmi}}}}{\gamma_{\mathrm{g}}^2}} \right)^2 + \\ + \dfrac{4}{5} \cdot \sqrt{\frac{1}{4} + \frac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_s}}{1 + \delta_{\mathrm{qmi}}}}{\gamma_{\mathrm{g}}^2}} \cdot \sqrt{\frac{1}{4} + \frac{\mathrm{v_{o,qm}} + \frac{2 \cdot \mathrm{q_d}}{1 + \delta_{\mathrm{qmi}}}}{\gamma_{\mathrm{g}}^2}} + \dfrac{2}{\gamma_{\mathrm{g}}^2} \\ \text{if } \mathtt{TG} \geq 0 \\ \mathrm{v_{o,qm}} + \mathrm{q_s} + \mathrm{q_s} + \dfrac{1}{3 \cdot (1 + \delta_{\mathrm{qmi}})} \cdot \dfrac{(\mathrm{q_s} - \mathrm{q_d})^2}{\mathrm{q_s} + \mathrm{q_d} + 1} \end{cases} \tag{2.130}$$

$$\mathrm{q_I} = \mathrm{q_S} + \mathrm{q_D} \tag{2.131}$$

$$\mathrm{q_B} = \mathrm{q_G} - \mathrm{q_S} - \mathrm{q_D} \tag{2.132}$$

2.4.28 Mobility effects

2.4.28.1 Coulomb scattering

$$\beta_{\mathrm{coul}} = \frac{\mathtt{THC}}{(1 + \mathrm{n_v} \cdot \mathtt{ZC} \cdot \mathrm{q_s}) \cdot (1 + \mathrm{n_v} \cdot \mathtt{ZC} \cdot \mathrm{q_d})} \tag{2.133}$$

2.4.28.2 Vertical field effect

$$\mathrm{e_{q0}} = \mathrm{q_B} + \mathrm{ETA_t} \cdot \mathrm{n_v} \cdot \mathrm{q_I} \tag{2.134}$$

$$\begin{aligned}\mathrm{e_{q1}} =& \left(\gamma_{\mathrm{eff}} \cdot \sqrt{\psi_{\mathrm{p}}} + \mathrm{n_v} \cdot (1 - \mathrm{ETA_t}) - 1\right)^2 + (\mathrm{n_v} \cdot (1 - \mathrm{ETA_t}) - 1)^2 \cdot (1 + 2 \cdot \mathrm{i_f} + 2 \cdot \mathrm{i_r}) - \\ & - \frac{8}{3} \cdot (\mathrm{n_v} \cdot (1 - \mathrm{ETA_t}) - 1) \cdot (\gamma_{\mathrm{eff}} \cdot \sqrt{\psi_{\mathrm{p}}} + \mathrm{n_v} \cdot (1 - \mathrm{ETA_t}) - 1) \cdot \\ & \cdot \frac{\mathrm{i_f} + \mathrm{i_r} + 0.5 + \sqrt{(\mathrm{i_f} + 0.25) \cdot (\mathrm{i_r} + 0.25)}}{\sqrt{\mathrm{i_f} + 0.25} + \sqrt{\mathrm{i_r} + 0.25}}\end{aligned} \tag{2.135}$$

$$\beta_{\mathrm{rvf,coul}} = \frac{1 + \dfrac{\mathrm{U_T}}{\mathrm{E0_{g,t}} \cdot \mathrm{t_{si}}} \cdot \gamma_{\mathrm{eff}} \cdot \sqrt{\phi} + \left(\dfrac{\mathrm{U_T}}{\mathrm{E1_{g,t}} \cdot \mathrm{t_{si}}} \cdot \gamma_{\mathrm{eff}} \cdot \sqrt{\phi}\right)^2}{1 + \dfrac{\mathrm{U_T}}{\mathrm{E0_{g,t}} \cdot \mathrm{t_{si}}} \cdot \mathrm{e_{q0}} + \left(\dfrac{\mathrm{U_T}}{\mathrm{E1_{g,t}} \cdot \mathrm{t_{si}}}\right)^2 \cdot \mathrm{e_{q1}} + \beta_{\mathrm{coul}}} \tag{2.136}$$

2.4.28.3 Channel length modulation

$$\beta_{\mathrm{clm}} = \left(\sqrt{1 + \frac{2 \cdot (\mathrm{e_{clm}} \cdot (2 - \mathtt{DELTA}) \cdot (\mathrm{q_s} - \mathrm{q_d}))^2}{0.1 + \mathrm{e_{clm}} \cdot (2 - \mathtt{DELTA}) \cdot (\mathrm{q_s} - \mathrm{q_d})} + (\mathrm{e_{clm}} \cdot (\mathrm{q_s} - \mathrm{q_d}))^2}\right)^{-1} \tag{2.137}$$

2.4.28.4 Overall effect

$$\beta = \mathrm{KP_{g,t}} \cdot \beta_{\mathrm{rvf,coul}} \cdot \beta_{\mathrm{clm}} \tag{2.138}$$

2.4.29 Specific current

$$\mathrm{I_{SPEC}} = \frac{2 \cdot \mathrm{n_Q} \cdot \mathrm{U_T^2} \cdot \beta}{1 + \delta_{\mathrm{qmi}}} \cdot \frac{(\mathrm{W_{eff}} - \mathtt{WEDGE}) \cdot \mathtt{NF}}{\mathrm{L_{eff}} - \delta\mathrm{L}} \tag{2.139}$$

2.4.30 Drain induced threshold shift

$$\mathrm{va_{dits}} = \frac{\dfrac{1}{1 + \mathtt{FPROUT} \cdot \dfrac{\mathrm{L_{eff}}}{\mathrm{q_I} + 2}}}{\mathtt{PDITS}} \cdot (1 + (1 + \mathtt{PDITSL} \cdot \mathrm{L_{eff}}) \cdot \exp(\mathtt{PDITSD} \cdot (\mathrm{v_d} - \mathrm{v_s}) \cdot \mathrm{U_T})) \tag{2.140}$$

$$\mathrm{v_{ds,dits}} = \mathrm{v_{ds,sat}} - \mathrm{MX_S}(\mathrm{v_{ds,sat}} - (\mathrm{v_d} - \mathrm{v_s}) - \mathtt{DDITS}, 0, 4 \cdot \mathtt{DDITS} \cdot \mathrm{v_{ds,sat}}) \tag{2.141}$$

$$\mathrm{f_{dits}} = 1 + \frac{\mathrm{v_d} - \mathrm{v_s} - \mathrm{v_{ds,dits}}}{\mathrm{va_{dits}}} \tag{2.142}$$

2.4.31 Denormalizing

$$Q_S = q_S \cdot Q_0 \tag{2.143}$$

$$Q_D = q_D \cdot Q_0 \tag{2.144}$$

$$Q_G = -q_G \cdot Q_0 \tag{2.145}$$

$$Q_B = q_B \cdot Q_0 \tag{2.146}$$

$$I_{ds} = I_{SPEC} \cdot (i_f - i_r) \cdot f_{dits} \tag{2.147}$$

2.5 Edge Conductance

2.5.1 Normalization Factors (Edge Device)

$$I_{SPEC,edge} = \frac{2 \cdot n_Q \cdot U_T^2 \cdot \beta}{1 + \delta_{qmi}} \frac{W_{eff} \cdot \mathtt{NF}}{L_{eff} - \delta L} \cdot \frac{W_{eff} - \mathtt{WEDGE}}{W_{eff}} \tag{2.148}$$

$$Q_{0,edge} = -W_{eff,C} \cdot \mathtt{NF} \cdot L_{eff,C} \cdot U_T \cdot \frac{\mathtt{COX}}{1 + \delta_{qmi}} \cdot \frac{\mathtt{WEDGE}}{W_{eff}} \tag{2.149}$$

2.5.2 Scaling - Normalizing

$$\delta\gamma_{edge} = \frac{\mathtt{DGAMMAEDGE}}{\sqrt{U_T}} \cdot \left(1.0 + \frac{\mathtt{WLDGAMMAEDGE}}{W_{eff} \cdot L_{eff}}\right) \tag{2.150}$$

$$\delta\phi_{edge} = \frac{\mathtt{DPHIEDGE}}{U_T} \cdot \left(1.0 + \frac{\mathtt{LDPHIEDGE}}{L_{eff}}\right) \cdot \left(1.0 + \frac{\mathtt{WDPHIEDGE}}{W_{eff}}\right) \cdot \cdot \left(1.0 + \frac{\mathtt{WLDPHIEDGE}}{W_{eff} \cdot L_{eff}}\right) \tag{2.151}$$

$$\delta v_{p,edge} = -\delta\gamma_{edge} \cdot \frac{\psi_p}{\sqrt{\psi_p} + \frac{\gamma}{2}} - \delta\phi_{edge} \tag{2.152}$$

2.5.3 Normalized Inversion Charges (Edge Device)

$$q_{s,edge} = q\left(v_p + \delta v_{p,edge} + \delta\psi_s - v_s\right) \tag{2.153}$$

$$q_{d,edge} = q\left(v_p + \delta v_{p,edge} + \delta\psi_s - v_d'\right) \tag{2.154}$$

The function q(v) is displayed in the "Normalized Inversion Source Charge" subsection

2.5.4 Normalized Currents (Edge Device)

$$i_{f,edge} = q_{s,edge}^2 + q_{s,edge} \tag{2.155}$$

$$i_{r,edge} = q_{d,edge}^2 + q_{d,edge} \tag{2.156}$$

2.5.5 Drain Current (Edge Device)

$$\mathrm{I_{DS,edge}} = \mathrm{I_{SPEC,edge}} \cdot (\mathrm{i_{f,edge}} - \mathrm{i_{r,edge}}) \cdot \mathrm{f_{dits}} \tag{2.157}$$

2.5.6 Edge Device: Charge Model

$$\psi_{\mathrm{p,edge}} = \psi_{\mathrm{p}} - \delta\gamma_{\mathrm{edge}} \cdot \frac{\psi_{\mathrm{p}}}{\sqrt{\psi_{\mathrm{p}}} + \frac{\gamma}{2}} \tag{2.158}$$

$$\gamma_{\mathrm{edge}} = \gamma + \delta\gamma_{\mathrm{edge}} \tag{2.159}$$

$$\mathrm{n_{q,edge}} \tag{2.160}$$

Check function from section slope factor n_Q

$$\mathrm{Q_{S,edge}}, \mathrm{Q_{D,edge}}, \mathrm{Q_{G,edge}}, \mathrm{Q_{B,edge}} \tag{2.161}$$

Check function from section charge model $Q_S,\ Q_D,\ Q_G,\ Q_B$

2.6 Overlap Capacitances

$$\mathrm{v'_{gs,ov}} = \mathrm{v_g} - \mathtt{VOV} \cdot \mathrm{v_s} - \mathrm{vfb_{ov}} \tag{2.162}$$

if $\mathtt{TG} < 0$

$$\gamma_{\mathrm{dep,sov}} = \begin{cases} \gamma_{g,ov} & \text{if } v'_{gs,ov} \geq 0 \\ \gamma_{ov} & \text{if } v'_{gs,ov} < 0 \end{cases} \tag{2.163}$$

$$\gamma_{\mathrm{acc,sov}} = \begin{cases} \gamma_{ov} & \text{if } v'_{gs,ov} \geq 0 \\ \gamma_{g,ov} & \text{if } v'_{gs,ov} < 0 \end{cases} \tag{2.164}$$

$$\mathrm{v_{0,sov}} = \begin{cases} v'_{gs,ov} & \text{if } v'_{gs,ov} \geq 0 \\ -v'_{gs,ov} & \text{if } v'_{gs,ov} < 0 \end{cases} \tag{2.165}$$

$$\mathrm{a_{0,sov}} = 1.0 + \frac{\gamma_{\mathrm{acc,sov}}}{\sqrt{2}} \tag{2.166}$$

$$\mathrm{a_{1,sov}} = \frac{\gamma_{\mathrm{dep,sov}}}{\gamma_{\mathrm{acc,sov}}} \tag{2.167}$$

$$\mathrm{a_{2,sov}} = \frac{\mathrm{a_{0,sov}}}{\mathrm{a_{0,sov}} + \mathrm{a_{1,sov}}} \tag{2.168}$$

$$\mathrm{a_{3,sov}} = 1 + \frac{\gamma_{\mathrm{dep,sov}}}{\sqrt{2}} + \mathrm{a_{1,sov}} \tag{2.169}$$

$$\mathrm{v}_{1,\mathrm{sov}} = \frac{\mathrm{v}_{0,\mathrm{sov}}}{2} - 3 \cdot \mathrm{a}_{2,\mathrm{sov}} \cdot \mathrm{a}_{3,\mathrm{sov}} \tag{2.170}$$

$$\delta\psi_{\mathrm{gs0}} = \mathrm{v}_{1,\mathrm{sov}} + \sqrt{\mathrm{v}_{1,\mathrm{sov}}^2 + 6 \cdot \mathrm{a}_{2,\mathrm{sov}} \cdot \mathrm{a}_{3,\mathrm{sov}}} \tag{2.171}$$

$$\gamma_{\mathrm{dep2,sov}} = \gamma_{\mathrm{dep,sov}} \cdot \left(\frac{1}{2} + \frac{3}{3 \cdot \sqrt{2} \cdot \gamma_{\mathrm{acc,sov}} + \mathrm{v}_{0,\mathrm{sov}} - \delta\psi_{\mathrm{gs0}}}\right) \tag{2.172}$$

$$\mathrm{a}_{4,\mathrm{sov}} = 1 - \exp\left(-\delta\psi_{\mathrm{gs0}}\right) \tag{2.173}$$

$$\mathrm{v}_{2,\mathrm{sov}} = \mathrm{v}_{0,\mathrm{sov}} - \mathrm{a}_{4,\mathrm{sov}} \tag{2.174}$$

$$\delta\psi_{\mathrm{gs}} = \left(\frac{\mathrm{v}_{2,\mathrm{sov}}}{\gamma_{\mathrm{dep2,sov}} + \sqrt{\gamma_{\mathrm{dep2,sov}}^2 + \mathrm{v}_{2,\mathrm{sov}}}}\right)^2 + \mathrm{a}_{4,\mathrm{sov}} \tag{2.175}$$

$$\mathrm{v}_{2b,\mathrm{sov}} = \mathrm{v}_{0,\mathrm{sov}} - \delta\psi_{\mathrm{gs}} \tag{2.176}$$

$$\mathrm{v}_{3,\mathrm{sov}} = \frac{\mathrm{v}_{2b,\mathrm{sov}}}{2} \tag{2.177}$$

$$\delta\psi_{\mathrm{ox,s}} = \begin{cases} v_{3,sov} - 3 \cdot a_{0,sov} + \sqrt{\left(\dfrac{v_{3,sov}}{3 \cdot a_{0,sov}}\right)^2 - 6 \cdot v_{2b,sov}} & \text{if } v'_{gs,ov} > 0 \\ -\left(v_{3,sov} - 3 \cdot a_{0,sov} + \sqrt{\left(\dfrac{v_{3,sov}}{3 \cdot a_{0,sov}}\right)^2 - 6 \cdot v_{2b,sov}}\right) & \text{if } v'_{gs,ov} < 0 \end{cases} \tag{2.178}$$

if `TG` ≥ 0

if $\mathrm{v}'_{\mathrm{gs,ov}} \geq 0$

$$\gamma_{\mathrm{acc,sov}} = \gamma_{\mathrm{ov}} \tag{2.179}$$

$$\mathrm{v}_{0,\mathrm{sov}} = \mathrm{v}_{\mathrm{gs,ov}} \tag{2.180}$$

$$\mathrm{a}_{0,\mathrm{sov}} = 1 + \frac{\gamma_{\mathrm{acc,sov}}}{\sqrt{2}} \tag{2.181}$$

$$\mathrm{v}_{1,\mathrm{sov}} = \frac{\mathrm{v}_{0,\mathrm{sov}}}{2} - 3 \cdot \mathrm{a}_{0,\mathrm{sov}}^2 \tag{2.182}$$

$$\delta\psi_{\mathrm{gs0}} = \mathrm{v}_{1,\mathrm{sov}} + \sqrt{\mathrm{v}_{1,\mathrm{sov}}^2} \tag{2.183}$$

$$\delta\psi_{\mathrm{gs}} = 1 - \exp\left(-\delta\psi_{\mathrm{gs0}}\right) \tag{2.184}$$

$$\mathrm{v}_{2b,\mathrm{sov}} = \mathrm{v}_{0,\mathrm{sov}} - \delta\psi_{\mathrm{gs}} \tag{2.185}$$

$$\mathrm{v}_{3,\mathrm{sov}} = \frac{\mathrm{v}_{2b,\mathrm{sov}}}{2} \tag{2.186}$$

$$\delta\psi_{\mathrm{ox,s}} = \mathrm{v}_{3,\mathrm{sov}} - 2 \cdot \mathrm{a}_{0,\mathrm{sov}} + \sqrt{\left(\mathrm{v}_{3,\mathrm{sov}} + 3 \cdot \mathrm{a}_{0,\mathrm{sov}}\right)^2 - 6 \cdot \mathrm{v}_{2b,\mathrm{sov}}} \tag{2.187}$$

if $\mathrm{v}'_{\mathrm{gs,ov}} < 0$

$$\gamma_{\mathrm{dep,sov}} = \gamma_{\mathrm{ov}} \tag{2.188}$$

$$\mathrm{v}_{0,\mathrm{sov}} = -\mathrm{v}_{\mathrm{gs,ov}} \tag{2.189}$$

$$\mathrm{a}_{3,\mathrm{sov}} = 1 + \frac{\gamma_{\mathrm{dep,sov}}}{\sqrt{2}} \tag{2.190}$$

$$\mathrm{v}_{1,\mathrm{sov}} = \frac{\mathrm{v}_{0,\mathrm{sov}}}{2} - 3 \cdot \mathrm{a}_{3,\mathrm{sov}}^2 \tag{2.191}$$

$$\delta\psi_{\mathrm{gs0}} = \mathrm{v}_{1,\mathrm{sov}} + \sqrt{\mathrm{v}_{1,\mathrm{sov}}^2 + 6 \cdot \mathrm{v}_{0,\mathrm{sov}}} \tag{2.192}$$

$$\gamma_{\mathrm{dep2,sov}} = \gamma_{\mathrm{dep,sov}}2 \tag{2.193}$$

$$\mathrm{a}_{4,\mathrm{sov}} = 1 - \exp\left(-\delta\psi_{\mathrm{gs0}}\right) \tag{2.194}$$

$$\mathrm{v}_{2,\mathrm{sov}} = \mathrm{v}_{0,\mathrm{sov}} - \mathrm{a}_{4,\mathrm{sov}} \tag{2.195}$$

$$\delta\psi_{\mathrm{gs}} = \left(\frac{\mathrm{v}_{2,\mathrm{sov}}}{\gamma_{\mathrm{dep2,sov}} + \sqrt{\gamma_{\mathrm{dep2,sov}}^2 + \mathrm{v}_{2,\mathrm{sov}}}}\right)^2 + \mathrm{a}_{4,\mathrm{sov}} \tag{2.196}$$

$$\mathrm{v}_{2\mathrm{b},\mathrm{sov}} = \mathrm{v}_{0,\mathrm{sov}} - \delta\psi_{\mathrm{gs}} \tag{2.197}$$

$$\delta\psi_{\mathrm{ox,s}} = -\mathrm{v}_{2\mathrm{b},\mathrm{sov}} \tag{2.198}$$

Similar equations for drain - gate overlap capacitance.

2.6.1 Denormalizing (Overlap)

$$\mathrm{Q}_{\mathrm{S,OV}} = -\mathrm{Q}_{0,\mathrm{OV}} \cdot \delta\psi_{\mathrm{ox,s}} \tag{2.199}$$

$$\mathrm{Q}_{\mathrm{D,OV}} = -\mathrm{Q}_{0,\mathrm{OV}} \cdot \delta\psi_{\mathrm{ox,d}} \tag{2.200}$$

2.7 Fringing Capacitance

$$\mathrm{Q}_{\mathrm{S,FR}} = \mathrm{W}_{\mathrm{eff,c}} \cdot \mathtt{NF} \cdot \mathtt{KJF}\left(1 + \mathtt{CJF} \cdot \mathrm{U_T} \cdot \mathrm{v_s}\right) \cdot \sqrt{\mathrm{MX_S}\left(\mathrm{v_{bi}} + \frac{\mathtt{VFR}}{\mathrm{U_T}} + \mathrm{v_s} - (\psi_{\mathrm{p}} - 2 \cdot \mathrm{q_s}), 0, \mathtt{DFR}\right)} \tag{2.201}$$

$$\mathrm{Q}_{\mathrm{D,FR}} = \mathrm{W}_{\mathrm{eff,c}} \cdot \mathtt{NF} \cdot \mathtt{KJF}\left(1 + \mathtt{CJF} \cdot \mathrm{U_T} \cdot \mathrm{v}'_{\mathrm{d}}\right) \cdot \sqrt{\mathrm{MX_S}\left(\mathrm{v_{bi}} + \frac{\mathtt{VFR}}{\mathrm{U_T}} + \mathrm{v}'_{\mathrm{d}} - (\psi_{\mathrm{p}} - 2 \cdot \mathrm{q}'_{\mathrm{d}}), 0, \mathtt{DFR}\right)} \tag{2.202}$$

2.8 Bias-Independent Overlap Capacitances

$$\mathrm{C_{GSO}} = \mathtt{CGSO} \cdot \mathrm{W_{eff}} \tag{2.203}$$

$$\mathrm{C_{GDO}} = \mathtt{CGDO} \cdot \mathrm{W_{eff}} \tag{2.204}$$

$$\mathrm{C_{GBO}} = \mathtt{CGBO} \cdot 2 \cdot \mathrm{L_{eff}} \tag{2.205}$$

2.9 Gate Induced Drain and Source Current

$$\mathrm{v_{gs,e}} = \mathrm{v_{fb}} + \psi_\mathrm{p} - 2\cdot \mathrm{q_s} \tag{2.206}$$

$$\begin{aligned}\mathrm{I_{GIDL}} =& \mathtt{AGIDL}\cdot \mathrm{W_{eff}}\cdot \mathtt{NF}\frac{(\mathrm{v'_d}-\mathrm{v_s}-\mathrm{v_{gs,e}})\cdot \mathrm{U_T}-\mathtt{EGIDL}}{3\cdot \mathrm{T_{OX}}}\cdot \\ &\cdot \exp\left(-\frac{3\cdot \mathrm{T_{OX}}\cdot \mathtt{BGIDL}}{(\mathrm{v'_d}-\mathrm{v_s}-\mathrm{v_{gs,e}})\cdot \mathrm{U_T}-\mathtt{EGIDL}}\right)\cdot \frac{(\mathrm{v_d}\cdot \mathrm{U_T})^3}{\mathtt{CGIDL}+(\mathrm{v_d}\cdot \mathrm{U_T})^3}\end{aligned} \tag{2.207}$$

$$\mathrm{v_{gd,e}} = \mathrm{v_{fb}} + \psi_\mathrm{p} - 2\cdot \mathrm{q'_d} \tag{2.208}$$

$$\begin{aligned}\mathrm{I_{GISL}} =& \mathtt{AGIDL}\cdot \mathrm{W_{eff}}\cdot \mathtt{NF}\frac{(\mathrm{v_d}-\mathrm{v'_d}-\mathrm{v_{gd,e}})\cdot \mathrm{U_T}-\mathtt{EGIDL}}{3\cdot \mathrm{T_{OX}}}\cdot \\ &\cdot \exp\left(-\frac{3\cdot \mathrm{T_{OX}}\cdot \mathtt{BGIDL}}{(\mathrm{v_s}-\mathrm{v'_d}-\mathrm{v_{gd,e}})\cdot \mathrm{U_T}-\mathtt{EGIDL}}\right)\cdot \frac{(\mathrm{v_s}\cdot \mathrm{U_T})^3}{\mathtt{CGIDL}+(\mathrm{v_s}\cdot \mathrm{U_T})^3}\end{aligned} \tag{2.209}$$

2.10 Gate Current

if $((\psi_\mathrm{p} \geq 0)$ and $(\mathtt{TG} < 0))$ or $((\psi_\mathrm{p} < 0)$ and $(\mathtt{TG} \geq 0))$

$$\mathrm{v_1} = \sqrt{\frac{1}{4}+\frac{\mathrm{v_o}+2\cdot \mathrm{q_s}}{\gamma_\mathrm{g}^2}} \tag{2.210}$$

$$\mathrm{v_2} = \mathrm{v_1} + \frac{1}{2} \tag{2.211}$$

$$\psi_\mathrm{ox} = \frac{\mathrm{v_o}+2\cdot \mathrm{q_s}}{\mathrm{v_2}} \tag{2.212}$$

$$\delta\psi_\mathrm{dq} = \frac{2}{\mathrm{v_2}}\cdot\left(1-\frac{\mathrm{v_o}+2\cdot \mathrm{q_s}}{2\cdot \mathrm{v_1}\cdot \mathrm{v_2}\gamma_\mathrm{g}^2}\right) \tag{2.213}$$

if $((\psi_\mathrm{p} \leq 0)$ and $(\mathtt{TG} \leq 0))$ or $((\psi_\mathrm{p} > 0)$ and $(\mathtt{TG} > 0))$

$$\psi_\mathrm{ox} = \frac{\mathrm{v_o}+2\cdot \mathrm{q_s}}{\mathrm{v_2}} \tag{2.214}$$

$$\delta\psi_\mathrm{dq} = 2 \tag{2.215}$$

$$\psi_\mathrm{x} = \frac{|\psi_\mathrm{ox}|}{\mathrm{x_b}} \tag{2.216}$$

$$\mathrm{p_{tun}} = \begin{cases} \exp\left(-y_b\left(\frac{1}{1+\sqrt{1-\psi_x}}+\sqrt{1-\psi_x}\right)\right) & \text{if } \psi_x < 1 \\ \exp\left(-\frac{u_b}{\psi_x}\right) & \text{if } \psi_x > 1 \end{cases} \tag{2.217}$$

$$\mathrm{i_{go}} = \mathrm{q_s}\cdot\psi_\mathrm{ox}\cdot \mathrm{p_{tun}} \tag{2.218}$$

if $(\mathrm{v_s} = \mathrm{v_d})$ or $(\psi_{\mathrm{ox}} = 0)$

$$\mathrm{n_{igc}} = \mathrm{i_{go}} \cdot \mathrm{n_Q} \tag{2.219}$$

$$\mathrm{n_{igs}} = \frac{\mathrm{n_{igc}}}{2} \tag{2.220}$$

$$\mathrm{n_{igd}} = \mathrm{n_{igs}} \tag{2.221}$$

if $(\mathrm{v_s} \neq \mathrm{v_d})$ and $(\psi_{\mathrm{ox}} \neq 0)$

$$\delta \mathrm{q}_{\delta\xi} = \frac{\mathrm{i'_r} - \mathrm{i_f}}{1 + 2 \cdot \mathrm{q_s}} \tag{2.222}$$

$$\mathrm{a_{gc}} = \delta \mathrm{q}_{\delta\xi} \cdot \left(\frac{1}{\mathrm{q_s}} + \frac{\delta\psi_{\mathrm{dq}}}{\psi_{\mathrm{ox}}} \right) \tag{2.223}$$

if $\psi_{\mathrm{x}} < 1$

$$\mathrm{b_{gc}} = \begin{cases} \delta q_{\delta\xi} \cdot \delta\psi_{dq} \cdot \dfrac{u_b}{x_b} \cdot \dfrac{3 + \psi_x}{4 + 2\sqrt{1 - \psi_x} \cdot (2 + \psi_x)} & \text{if } \psi_{ox} > 0 \\ -\delta q_{\delta\xi} \cdot \delta\psi_{dq} \cdot \dfrac{u_b}{x_b} \cdot \dfrac{3 + \psi_x}{4 + 2\sqrt{1 - \psi_x} \cdot (2 + \psi_x)} & \text{if } \psi_{ox} < 0 \end{cases} \tag{2.224}$$

if $\psi_{\mathrm{x}} \geq 1$

$$\mathrm{b_{gc}} = \delta \mathrm{q}_{\delta\xi} \cdot \delta\psi_{\mathrm{dq}} \cdot \frac{\mathrm{u_b}}{\psi_{\mathrm{x}} + \psi_{\mathrm{ox}}} \tag{2.225}$$

$$\mathrm{n_{igc}} = \mathrm{i_{go}} \cdot \mathrm{n_Q} \cdot \frac{2 + \mathrm{a_{gc}}}{2 - \mathrm{b_{gc}}} \tag{2.226}$$

$$\mathrm{n_{igs}} = \frac{1}{2} \cdot \mathrm{i_{go}} \cdot \mathrm{n_Q} \cdot \frac{3 + \mathrm{a_{gc}}}{3 - \mathrm{b_{gc}}} \tag{2.227}$$

$$\mathrm{n_{igd}} = \mathrm{n_{igc}} - \mathrm{n_{igs}} \tag{2.228}$$

if $\mathrm{v_g} \geq \mathrm{v_{fb}}$

$$\mathrm{I_{GB}} = 0 \tag{2.229}$$

$$\mathrm{I_G} = 2 \cdot \mathtt{KG} \cdot \mathrm{W_{eff}} \cdot \mathtt{NF} \cdot \mathrm{L_{eff}} \cdot \mathrm{U_T^2} \cdot \mathrm{n_{igc}} \cdot \mathrm{p_{tun}} \cdot \mathrm{T_{OX}^{-2}} \tag{2.230}$$

$$\mathrm{I_{GD}} = 2 \cdot \mathtt{KG} \cdot \mathrm{W_{eff}} \cdot \mathtt{NF} \cdot \mathrm{L_{eff}} \cdot \mathrm{U_T^2} \cdot \mathrm{n_{igd}} \cdot \mathrm{p_{tun}} \cdot \mathrm{T_{OX}^{-2}} \tag{2.231}$$

$$\mathrm{I_{GS}} = \mathrm{I_G} - \mathrm{I_{GD}} \tag{2.232}$$

if $\mathrm{v_g} < \mathrm{v_{fb}}$

$$\mathrm{I_{GB}} = \mathtt{KG} \cdot \mathrm{W_{eff}} \cdot \mathtt{NF} \cdot \mathrm{L_{eff}} \cdot \mathrm{U_T^2} \cdot \psi_{\mathrm{ox}} \cdot |\psi_{\mathrm{ox}}| \cdot \mathrm{p_{tun}} \cdot \mathrm{T_{OX}^{-2}} \tag{2.233}$$

$$\mathrm{I_G} = 0 \tag{2.234}$$

$$\mathrm{I_{GD}} = 0 \tag{2.235}$$

$$\mathrm{I_{GS}} = 0 \tag{2.236}$$

2.10.1 Overlap Gate Current

2.10.1.1 Gate - Source (Overlap Current)

$$\psi_{\mathrm{oxr,sov}} = \begin{cases} v_g - v_s - \left(\sqrt{v_g - v_s - v_{fb,ov} + \frac{\gamma_g^2}{4}} - \frac{\gamma_g}{2}\right)^2 & \text{if } v_g - v_s > v_{fb,ov} \\ v_g - v_s + \left(\sqrt{-v_g + v_s + v_{fb,ov} + \frac{\gamma_{ov}^2}{4}} - \frac{\gamma_{ov}}{2}\right)^2 & \text{if } v_g - v_s < v_{fb,ov} \end{cases} \tag{2.237}$$

$$\psi_{\mathrm{xr,sov}} = \frac{|\psi_{\mathrm{oxr,sov}}|}{\mathrm{x_b}} \tag{2.238}$$

$$\mathrm{p_{tun,sov}} = \begin{cases} \exp\left(-y_b\left(\frac{1}{1+\sqrt{1-\psi_{xr,sov}}} + \sqrt{1-\psi_{xr,sov}}\right)\right) & \text{if } \psi_{xr,sov} < 1 \\ \exp\left(-\frac{u_b}{\psi_{xr,sov}}\right) & \text{if } \psi_{xr,sov} > 1 \end{cases} \tag{2.239}$$

$$\mathrm{I_{GSOV}} = \mathtt{KG} \cdot \mathrm{W_{eff}} \cdot \mathtt{NF} \cdot \mathtt{LOVIG} \cdot \psi_{\mathrm{oxr,sov}} \cdot |\psi_{\mathrm{oxr,sov}}| \cdot \mathrm{U_T^2} \cdot \mathrm{p_{tun}} \cdot \mathrm{T_{OX}^{-2}} \tag{2.240}$$

2.10.1.2 Gate - Drain (Overlap Current)

Similar equations with the Gate - Source (Overlap Current)

2.11 Impact Ionization Current

$$\mathrm{v_{ib}} = \mathrm{v_d} - \mathrm{v_s} - 2 \cdot \mathtt{IBN} \cdot \mathrm{v_{ds,sat}} \tag{2.241}$$

$$\mathrm{I_{DB}} = \begin{cases} I_{DS} \cdot v_{ib} \cdot U_T \cdot \exp\left(\frac{IBB_t \cdot L_C}{v_{ib} \cdot U_T}\right) \cdot \frac{\mathtt{IBA}}{IBB_t} & \text{if } v_{ib} > 0 \\ 0 & \text{if } v_{ib} < 0 \end{cases} \tag{2.242}$$

2.12 Noise

2.12.1 Thermal Noise

$$\begin{aligned} \mathrm{g_n} =& \frac{2}{(1+\mathrm{e_{clm}}\cdot(\mathrm{q_s}-\mathrm{q_d'}))^2\cdot(\mathrm{q_s}+\mathrm{q_d'}+1)} \cdot \frac{1}{3}\cdot(\mathrm{q_s^2}+\mathrm{q_s}+\mathrm{q_d'}+\mathrm{q_d'^2}) + \mathrm{e_{clm}^2}\cdot\frac{(\mathrm{i_f}-\mathrm{i_r'})^2}{4} + \\ &+ \frac{(\mathrm{e_{clm}}\cdot(\mathrm{i_f}-\mathrm{i_r'})+1)\cdot(\mathrm{q_s}+\mathrm{q_d'})}{4} + \\ &+ \frac{\mathrm{e_{clm}}\cdot(\mathrm{i_f}-\mathrm{i_r'})-1}{8}\cdot\mathrm{e_{clm}^2}\cdot(\mathrm{i_f}-\mathrm{i_r'})\cdot(\mathrm{q_s}+\mathrm{q_d'}+1)\cdot\ln\frac{\mathrm{q_s}+\frac{1}{2}+\frac{\mathrm{e_{clm}}\cdot(\mathrm{i_f}-\mathrm{i_r'})}{2}}{\mathrm{q_d'}+\frac{1}{2}+\frac{\mathrm{e_{clm}}\cdot(\mathrm{i_f}-\mathrm{i_r'})}{2}} \end{aligned} \tag{2.243}$$

$$\mathrm{thermal} = 4\cdot\mathrm{K}\cdot\mathrm{T}\frac{\mathrm{I_{SPEC}}}{\mathrm{U_T}}\cdot\mathrm{g_n}\cdot\mathtt{TH\_NOI} \tag{2.244}$$

2.12.2 Flicker Noise

$$g_{mg} = \frac{I_{SPEC}}{U_T} \cdot \frac{q_s - q_d'}{n_v} \tag{2.245}$$

$$flicker = \frac{\mathtt{KF} \cdot g_{mg}^{\mathtt{EF}} \cdot (\delta q_{mi} + 1)}{W_{eff} \cdot \mathtt{NF} \cdot L_{eff} \cdot \mathtt{COX}} \tag{2.246}$$

$$s_{id,flicker}(f) = \frac{flicker}{f^{\mathtt{AF}}} \tag{2.247}$$

2.12.3 Induced Gate Noise

$$\omega_{spec} = \frac{\beta \cdot U_T}{\mathtt{COX} \cdot L_{eff}^2} \tag{2.248}$$

$$x_f = q_s + \frac{1}{2} \tag{2.249}$$

$$x_r = q_d' + \frac{1}{2} \tag{2.250}$$

$$s_{n,idid} = \frac{4 \cdot x_f^2 - 3 \cdot x_f + 4 \cdot x_f \cdot x_r - 3 \cdot x_r + 4 \cdot x_r^2}{6 \cdot (x_f + x_r)} \tag{2.251}$$

$$s_{n,igig} = \frac{\omega^2}{\omega_{spec}^2} \frac{16x_f^4 + 16x_r^4 + 80x_f x_r^3 + 80x_f^3 x_r + 168x_f^2 x_r^2 - 15x_r^3 - 15x_f^3 - 75x_f^2 x_r - 75x_r^2 x_f}{540 n_{q0}^2 (x_f + x_r)^5} \tag{2.252}$$

$$s_{n,ibib} = \frac{s_{n,igig}}{(n_{q0} - 1)^2} \tag{2.253}$$

$$s_{n,igid} = \frac{J \cdot \frac{\omega}{\omega_{spec}}}{18 \cdot n_{q0}} \cdot \frac{(x_f - x_r) \cdot (x_f^2 + 4 \cdot x_f \cdot x_r + x_r^2)}{(x_f + x_r)^3} \tag{2.254}$$

$$c_{igid} = J \frac{s_{n,igid}}{\sqrt{s_{n,idid} \cdot s_{n,igig}}} \tag{2.255}$$

2.12.4 Shot and Flicker Gate Noise

$$s_{ig,shot} = 2 \cdot q_e \cdot I_G \tag{2.256}$$

$$s_{ig,flicker}(f) = \frac{\mathtt{KGFN} \cdot I_G^2}{f} \tag{2.257}$$

2.13 Diodes

2.13.1 Temperature Dependence

$$\mathrm{JS_t} = \mathtt{JS} \cdot \exp\left(\frac{\frac{\mathrm{E_{g,nom}}}{\mathrm{U_{T,nom}}} - \frac{\mathrm{E_g}}{\mathrm{U_T}} + \mathtt{XTI} \cdot \frac{\mathrm{T}}{\mathrm{T_{NOM}}}}{\mathtt{ND}}\right) \tag{2.258}$$

$$\mathrm{JSW_t} = \mathtt{JSW} \cdot \exp\left(\frac{\frac{\mathrm{E_{g,nom}}}{\mathrm{U_{T,nom}}} - \frac{\mathrm{E_g}}{\mathrm{U_T}} + \mathtt{XTI} \cdot \frac{\mathrm{T}}{\mathrm{T_{NOM}}}}{\mathtt{ND}}\right) \tag{2.259}$$

$$\mathrm{JSWG_t} = \mathtt{JSWG} \cdot \exp\left(\frac{\frac{\mathrm{E_{g,nom}}}{\mathrm{U_{T,nom}}} - \frac{\mathrm{E_g}}{\mathrm{U_T}} + \mathtt{XTI} \cdot \frac{\mathrm{T}}{\mathrm{T_{NOM}}}}{\mathtt{ND}}\right) \tag{2.260}$$

$$\mathrm{PB_t} = \mathtt{PB} - \mathtt{TPB} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) \tag{2.261}$$

$$\mathrm{PBSW_t} = \mathtt{PBSW} - \mathtt{TPBSW} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) \tag{2.262}$$

$$\mathrm{PBSWG_t} = \mathtt{PBSWG} - \mathtt{TPBSWG} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) \tag{2.263}$$

$$\mathrm{CJ_t} = \mathtt{CJ} \cdot (1 + \mathtt{TCJ} \cdot (\mathrm{T} - \mathrm{T_{NOM}})) \tag{2.264}$$

$$\mathrm{CJSW_t} = \mathtt{CJSW} \cdot (1 + \mathtt{TCJSW} \cdot (\mathrm{T} - \mathrm{T_{NOM}})) \tag{2.265}$$

$$\mathrm{CJSWG_t} = \mathtt{CJSWG} \cdot (1 + \mathtt{TCJSWG} \cdot (\mathrm{T} - \mathrm{T_{NOM}})) \tag{2.266}$$

$$\mathrm{JTS_t} = \mathtt{JTS} \cdot \exp\left(\frac{\mathrm{E_{g,nom}}}{\mathrm{U_T}} \cdot \mathtt{XTS} \cdot \left(1 - \frac{\mathrm{T}}{\mathrm{T_{NOM}}}\right)\right) \tag{2.267}$$

$$\mathrm{JTSW_t} = \mathtt{JTSW} \cdot \exp\left(\frac{\mathrm{E_{g,nom}}}{\mathrm{U_T}} \cdot \mathtt{XTSW} \cdot \left(1 - \frac{\mathrm{T}}{\mathrm{T_{NOM}}}\right)\right) \tag{2.268}$$

$$\mathrm{JTSWG_t} = \mathtt{JTSWG} \cdot \exp\left(\frac{\mathrm{E_{g,nom}}}{\mathrm{U_T}} \cdot \mathtt{XTSWG} \cdot \left(1 - \frac{\mathrm{T}}{\mathrm{T_{NOM}}}\right)\right) \tag{2.269}$$

$$\mathrm{NJTS_t} = \mathtt{NJTS} \cdot \left(1 + \left(\frac{\mathrm{T}}{\mathrm{T_{NOM}}} - 1\right) \cdot \mathtt{TNJTS}\right) \tag{2.270}$$

$$\mathrm{NJTSSW_t} = \mathtt{NJTSSW} \cdot \left(1 + \left(\frac{\mathrm{T}}{\mathrm{T_{NOM}}} - 1\right) \cdot \mathtt{TNJTSSW}\right) \tag{2.271}$$

$$\mathrm{NJTSSWG_t} = \mathtt{NJTSSWG} \cdot \left(1 + \left(\frac{\mathrm{T}}{\mathrm{T_{NOM}}} - 1\right) \cdot \mathtt{TNJTSSWG}\right) \tag{2.272}$$

2.13.2 Area and Perimeter

if $\mathtt{NF}$ is even

$$\mathrm{AS} = \mathtt{HDIF} \cdot \mathrm{W_{eff}} \cdot (\mathtt{NF} + 2) \tag{2.273}$$

$$\mathrm{AD} = \mathtt{HDIF} \cdot \mathrm{W_{eff}} \cdot \mathtt{NF} \tag{2.274}$$

$$\mathrm{PS} = 2 \cdot (\mathtt{HDIF} \cdot (\mathtt{NF} + 2) + \mathrm{W_{eff}}) \tag{2.275}$$

$$\mathrm{PD} = 2 \cdot \mathtt{HDIF} \cdot \mathtt{NF} \tag{2.276}$$

if $\mathtt{NF}$ is odd

$$\mathrm{AS} = \mathtt{HDIF} \cdot \mathrm{W_{eff}} \cdot (\mathtt{NF} + 1) \tag{2.277}$$

$$\mathrm{AD} = \mathtt{HDIF} \cdot \mathrm{W_{eff}} \cdot (\mathtt{NF} + 1) \tag{2.278}$$

$$\mathrm{PS} = 2 \cdot \mathtt{HDIF} \cdot (\mathtt{NF} + 1) + \mathrm{W_{eff}} \tag{2.279}$$

$$\mathrm{PD} = 2 \cdot \mathtt{HDIF} \cdot (\mathtt{NF} + 1) + \mathrm{W_{eff}} \tag{2.280}$$

2.13.3 Junction Current

$$\mathrm{I_{S,D}} = \mathrm{JS_t} \cdot \mathrm{AD} + \mathrm{JSW_t} \cdot \mathrm{PD} + \mathrm{JSWG_t} \cdot \mathrm{W_{eff}} \cdot \mathtt{NF} \tag{2.281}$$

$$\mathrm{f_{breakdown,d}} = 1 + \mathtt{XJBV} \cdot \exp\left(-\frac{-\mathrm{V(di,b)} + \mathtt{BV}}{\mathrm{U_T} \cdot \mathtt{ND} \cdot \mathrm{T_{NOM}}}\right) \tag{2.282}$$

$$\begin{aligned}\mathrm{I_{DB,tun}} =& \mathrm{W_{eff}} \cdot \mathtt{NF} \cdot \mathrm{JTSWG_t} \cdot \left(\exp\left(\frac{\mathrm{V(di,b)} \cdot \mathrm{T}}{\mathrm{T_{NOM}} \cdot \mathrm{U_T} \cdot \mathrm{NJTSSWG_t}} \frac{\mathtt{VTSSWG}}{\mathtt{VTSSWG} + \mathrm{V(di,b)}}\right) - 1\right) \\ &+ \mathrm{PD} \cdot \mathrm{JTSW_t} \cdot \left(\exp\left(\frac{\mathrm{V(di,b)} \cdot \mathrm{T}}{\mathrm{T_{NOM}} \cdot \mathrm{U_T} \cdot \mathrm{NJTSSW_t}} \frac{\mathtt{VTSSW}}{\mathtt{VTSSW} + \mathrm{V(di,b)}}\right) - 1\right) \\ &+ \mathrm{AD} \cdot \mathrm{JT_t} \cdot \left(\exp\left(\frac{\mathrm{V(di,b)} \cdot \mathrm{T}}{\mathrm{T_{NOM}} \cdot \mathrm{U_T} \cdot \mathrm{NJTS_t}} \frac{\mathtt{VTS}}{\mathtt{VTS} + \mathrm{V(di,b)}}\right) - 1\right)\end{aligned} \tag{2.283}$$

$$\mathrm{I_{DBJ}} = \mathrm{I_{S,D}} \cdot \left(1 - \exp\left(-\frac{\mathrm{V(di,b)} \cdot \mathrm{T}}{\mathrm{T_{NOM}} \cdot \mathrm{U_T} \cdot \mathtt{ND}}\right)\right) \cdot \mathrm{f_{breakdown,d}} + \mathrm{V(di,b)} \cdot \mathtt{GMIN} \tag{2.284}$$

source, bulk current similarly

2.13.4 Junction Capacitance

if $\mathrm{V(di,b)} \geq 0$

$$\begin{aligned}\mathrm{C_{DBJ}} =& \mathrm{CJ_t} \cdot \mathrm{AD} \cdot \exp\left(\mathtt{MJ} \cdot \ln\left(1 + \frac{\mathrm{V(di,b)}}{\mathrm{PB_t}}\right)\right) + \\ &+ \mathrm{CJSW_t} \cdot \mathrm{PD} \cdot \exp\left(\mathtt{MJSW} \cdot \ln\left(1 + \frac{\mathrm{V(di,b)}}{\mathrm{PBSW_t}}\right)\right) + \\ &+ \mathrm{CJSWG_t} \cdot \mathrm{W_{eff}} \cdot \mathtt{NF} \cdot \exp\left(\mathtt{MJSWG} \cdot \ln\left(1 + \frac{\mathrm{V(di,b)}}{\mathrm{PBSWG_t}}\right)\right)\end{aligned} \tag{2.285}$$

if $\mathrm{V(di,b)} < 0$

$$\begin{aligned}
\mathrm{C_{DBJ}} = & \mathrm{CJ_t} \cdot \mathrm{AD} \cdot \left(1 - \mathtt{MJ} \cdot \frac{\mathrm{V(di,b)}}{\mathrm{PB_t}}\right) + \\
& + \mathrm{CJSW_t} \cdot \mathrm{PD} \cdot \left(1 - \mathtt{MJSW} \cdot \frac{\mathrm{V(di,b)}}{\mathrm{PBSW_t}}\right) + \\
& + \mathrm{CJSWG_t} \cdot \mathrm{W_{eff}} \cdot \mathtt{NF} \cdot \left(1 - \mathtt{MJSWG} \cdot \frac{\mathrm{V(di,b)}}{\mathrm{PBSWG_t}}\right)
\end{aligned} \tag{2.286}$$

source, bulk capacitance similarly

2.14 External Resistors (Gate, Series, Bulk)

$$\mathrm{RS} = \frac{\mathtt{HDIF} \cdot \mathtt{RSH} + \left(\mathtt{LDIF} - \frac{\mathtt{DL}}{2}\right) \cdot \mathtt{RS}}{\mathrm{W_{eff}}\mathtt{NF}} \tag{2.287}$$

$$\mathrm{RD} = \frac{\mathtt{HDIF} \cdot \mathtt{RSH} + \left(\mathtt{LDIF} - \frac{\mathtt{DL}}{2}\right) \cdot \mathtt{RD}}{\mathrm{W_{eff}}\mathtt{NF}} \tag{2.288}$$

$$\mathrm{RS_g} = \mathrm{RS} \cdot \left(1 + \frac{\mathtt{WRLX}}{\mathrm{W_{eff}}}\right) \tag{2.289}$$

$$\mathrm{RD_g} = \mathrm{RD} \cdot \left(1 + \frac{\mathtt{WRLX}}{\mathrm{W_{eff}}}\right) \tag{2.290}$$

$$\mathrm{RG} = \mathtt{RGSH} \cdot \frac{\mathrm{W_{eff}}}{3 \cdot \mathtt{GC}^2 \cdot \mathtt{NF} \cdot \mathrm{L_{eff}}} \tag{2.291}$$

$$\mathrm{RDSB} = \mathtt{RDSBSH} \cdot \frac{\mathrm{L_{eff}}}{\mathrm{L_{eff}} \cdot \mathtt{NF}} \tag{2.292}$$

if $\mathtt{RINGTYPE} = 1(\mathrm{HORSE-SHOE})$

$$\mathrm{RB} = \begin{cases} \dfrac{\mathtt{RBWSH}}{2 \cdot W_{eff}} & \text{if } \mathtt{RBN} = 0 \\ \dfrac{1}{\dfrac{2 \cdot W_{eff}}{\mathtt{RBWSH}} + \dfrac{\mathtt{NF}}{\mathtt{RBN}}} & \text{if } \mathtt{RBN} \neq 0 \end{cases} \tag{2.293}$$

if $\mathtt{NF}$ is even

$$\mathrm{RSB} = \begin{cases} \dfrac{\mathtt{RSBWSH}}{2 \cdot W_{eff}} & \text{if } \mathtt{RSBN} = 0 \\ \dfrac{1}{\dfrac{2 \cdot W_{eff}}{\mathtt{RSBWSH}} + \dfrac{\mathtt{NF}}{\mathtt{RSBN}}} & \text{if } \mathtt{RSBN} \neq 0 \end{cases} \tag{2.294}$$

$$\mathrm{RDB} = \begin{cases} \dfrac{\mathtt{RDBWSH}}{2 \cdot W_{eff}} & \text{if } \mathtt{RDBN} = 0 \\ \dfrac{1}{\dfrac{2 \cdot W_{eff}}{\mathtt{RDBWSH}} + \dfrac{\mathtt{NF}}{\mathtt{RDBN}}} & \text{if } \mathtt{RDBN} \neq 0 \end{cases} \tag{2.295}$$

if NF is odd

$$\mathrm{RSB} = \begin{cases} \dfrac{\mathtt{RSBWSH}}{W_{eff}} & \text{if } \mathtt{RSBN} = 0 \\ \dfrac{1}{\dfrac{W_{eff}}{\mathtt{RSBWSH}} + \dfrac{\mathtt{NF}}{\mathtt{RSBN}}} & \text{if } \mathtt{RSBN} \neq 0 \end{cases} \tag{2.296}$$

$$\mathrm{RDB} = \mathrm{RSB} \tag{2.297}$$

if $\mathtt{RINGTYPE} = 2(\mathrm{SYMMETRIC})$

$$\mathrm{RB} = \frac{\mathtt{RBWSH}}{2 \cdot \mathrm{W_{eff}}} \tag{2.298}$$

if NF is even

$$\mathrm{RSB} = \frac{\mathtt{RSBWSH}}{2 \cdot \mathrm{W_{eff}}} \tag{2.299}$$

$$\mathrm{RDB} = \frac{\mathtt{RDBWSH}}{2 \cdot \mathrm{W_{eff}}} \tag{2.300}$$

if NF is odd

$$\mathrm{RSB} = \frac{\mathtt{RSBWSH}}{\mathrm{W_{eff}}} \tag{2.301}$$

$$\mathrm{RDB} = \mathrm{RSB} \tag{2.302}$$

2.14.1 Temperature Dependence

$$\mathrm{RS_{gt}} = \mathrm{RS_g} \cdot (1 + \mathtt{TR} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) + \mathtt{TR2} \cdot (\mathrm{T} - \mathrm{T_{NOM}})^2) \tag{2.303}$$

$$\mathrm{RD_{gt}} = \mathrm{RD_g} \cdot (1 + \mathtt{TR} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) + \mathtt{TR2} \cdot (\mathrm{T} - \mathrm{T_{NOM}})^2) \tag{2.304}$$

$$\mathrm{RG_t} = \mathrm{RG} \cdot (1 + \mathtt{TR} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) + \mathtt{TR2} \cdot (\mathrm{T} - \mathrm{T_{NOM}})^2) \tag{2.305}$$

$$\mathrm{RB_t} = \mathrm{RB} \cdot (1 + \mathtt{TR} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) + \mathtt{TR2} \cdot (\mathrm{T} - \mathrm{T_{NOM}})^2) \tag{2.306}$$

$$\mathrm{RSB_t} = \mathrm{RSB} \cdot (1 + \mathtt{TR} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) + \mathtt{TR2} \cdot (\mathrm{T} - \mathrm{T_{NOM}})^2) \tag{2.307}$$

$$\mathrm{RDB_t} = \mathrm{RDB} \cdot (1 + \mathtt{TR} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) + \mathtt{TR2} \cdot (\mathrm{T} - \mathrm{T_{NOM}})^2) \tag{2.308}$$

$$\mathrm{RDSB_t} = \mathrm{RDSB} \cdot (1 + \mathtt{TR} \cdot (\mathrm{T} - \mathrm{T_{NOM}}) + \mathtt{TR2} \cdot (\mathrm{T} - \mathrm{T_{NOM}})^2) \tag{2.309}$$

Bibliography

[1] M. V. Dunga, W. M. Yang, X. J. Xi, J. He, W. Liu, K. M. Cao, X. Jin, J. J. Ou, M. Chan, A. M. Niknejad, and C. Hu. *BSIM4.6.1 MOSFET Model, User's Manual*. Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, 2007.

Contents