

# HiSIM\_HV 2.2.0 User's Manual

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## 1 LDMOS/HVMOS Structures

HiSIM (Hiroshima-university STARC IGFET Model) is the first complete surface-potential-based MOS-FET model for circuit simulation based on the drift-diffusion theory [1], which was originally developed by Pao and Sah [2]. The model has been extended for power MOSFETs by considering the resistance effect explicitly, which is named HiSIM\_HV [57].

There are two types of structures commonly used for high voltage applications. One is the asymmetrical laterally diffused structure called LDMOS and the other is originally the symmetrical structure, which we distinguish by referring to it as HVMOS. However, the asymmetrical HVMOS structure is also possible. HiSIM\_HV is valid for modeling all these structure types [3, 4].

The most important features of LDMOS/HVMOS devices, different from the conventional MOSFET, are originating from the drift region introduced to achieve the sustainability of high voltages. By varying the length as well as the dopant concentration of the drift region, various devices with various operating bias conditions are realized as shown in Fig. 1 for the LDMOS structure.

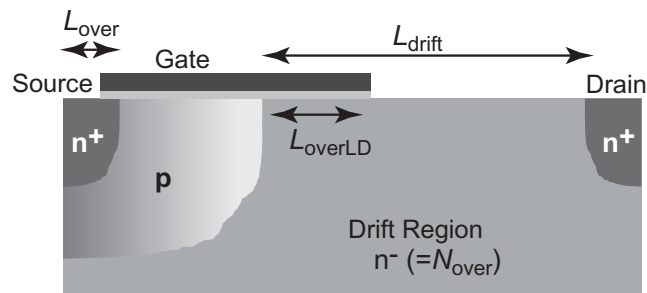


Fig. 1: Schematic of the typical LDMOS structure and device parameters.

A schematic of the general structures for LDMOS and HVMOS are shown in Fig. 2 for the n-channel case. To make the structural definition easy, Flag **COSYM** is introduced as shown in Fig. 3. **COSYM=0** refers to the asymmetrical LDMOS, and all structural parameters have to be determined independently. **COSYM=1** refers to symmetrical/asymmetrical HVMOS. If parameter values of the source side are given, they are activated. If they are not given, parameter values of the drain side are copied to the source side automatically.

Table 1 summarizes the structural parameters to be given. In case the overlap length **LOVER** is given instead of **LOVERS**, **LOVER** is taken for **LOVERS**. However, it is recommended to give **LOVERS** but not **LOVER**. Model parameters for resistances at the source side and the drain side are distinguished by **RS** and **RD** for the asymmetrical HVMOS.

HiSIM\_HV 1.2.0 includes the substrate node  $V_{sub}$  as schematically shown in Fig. 4, where model parameters **DDRIFT** and **NSUBSUB** are newly introduced for  $D_{drift}$  and  $N_{subsub}$ , respectively. The node

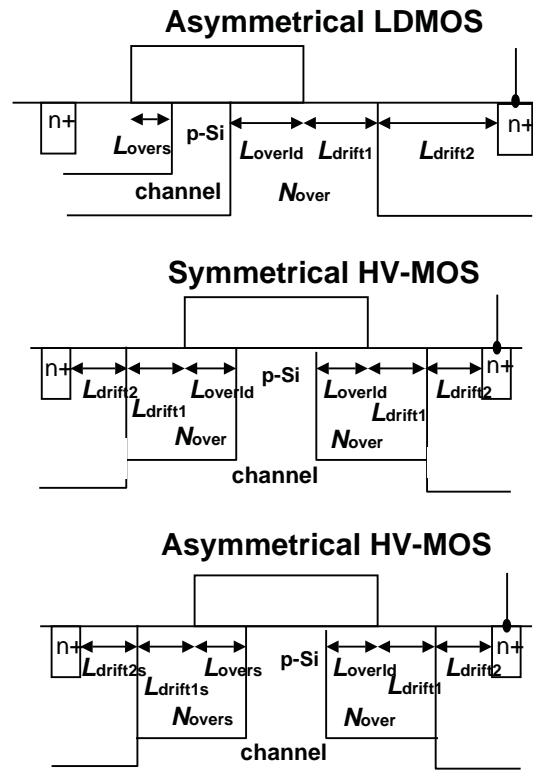


Fig. 2: Device parameters in HiSIM\_HV.

inclusion is done by selecting Flag **COSUBNODE**=0 as the 5th node.

The HiSIM\_HV model parameters introduced in section 1 are summarized in Table 2.

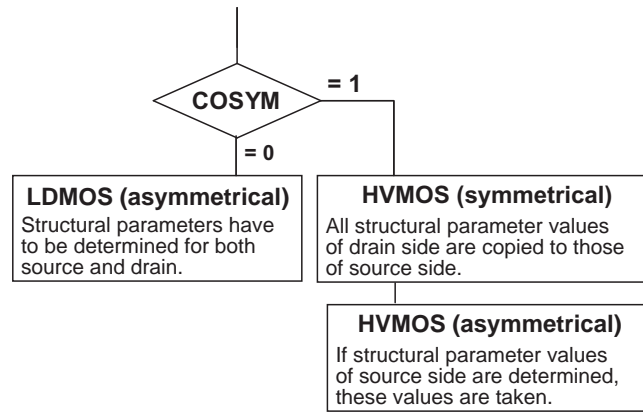


Fig. 3: Device parameters of HiSIM\_HV.

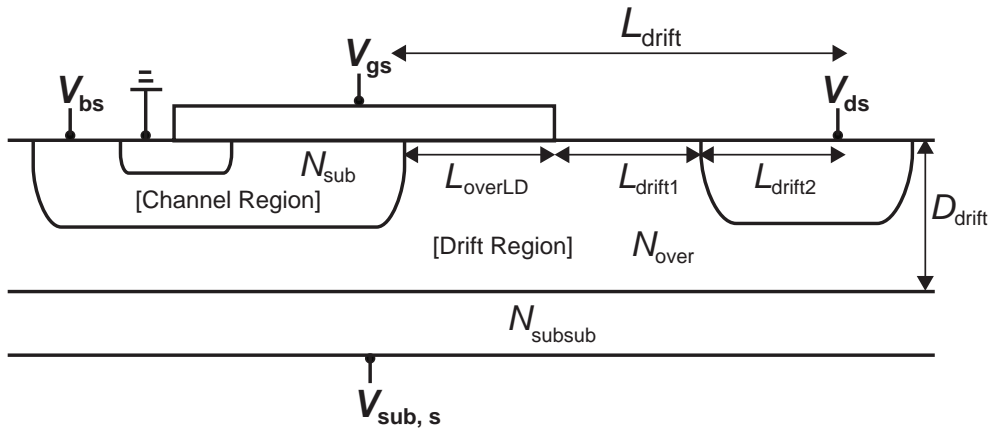


Fig. 4: Schematic of a LDMOS with the substrate node  $V_{sub,s}$ .

Table 1: HiSIM\_HV 1.2.0 model parameters introduced.

	structure	source	drain
COSYM=0	LDMOS	LOVERS RS	LOVERLD LDRIFT1 LDRIFT2 NOVER RD
COSYM=1	symmetrical HVMOS		LOVERLD LDRIFT1 LDRIFT2 NOVER RD
COSYM=1	asymmetrical HVMOS	LOVERS LDRIFT1S LDRIFT2S NOVERS RS	LOVERLD LDRIFT1 LDRIFT2 NOVER RD

Table 2: HiSIM\_HV 1.2.0 model parameters introduced in section 1 of this manual.

<b>LOVER</b>	overlap length at source side for <b>LOVERS</b>
<b>LOVERLD</b>	overlap length at drain, and at source, if <b>COSYM=1</b>
<b>LDRIFT1</b>	length of lightly doped drift region at drain, and at source, if <b>COSYM=1</b>
<b>LDRIFT2</b>	length of heavily doped drift region at drain, and at source, if <b>COSYM=1</b>
<b>NOVER</b>	impurity concentration of <b>LOVERLD</b> at drain, and at source, if <b>COSYM=1</b>
<b>LOVERS</b>	overlap length at source
<b>LDRIFT1S</b>	length of lightly doped drift region at source, if <b>COSYM=1</b> and the value is determined
<b>LDRIFT2S</b>	length of heavily doped drift region at source, if <b>COSYM=1</b> and the value is determined
<b>NOVERS</b>	impurity concentration of <b>LOVERS</b> at source, if <b>COSYM=1</b> and the value is determined
<b>VBSMIN</b>	minimum $V_{bs}$ voltage applied: No need and inactivated.
<b>DDRIFT</b>	depth of the drift region
<b>NSUBSUB</b>	impurity concentration of the substrate required for $V_{sub}$ dependence



## 2 Basic Concept

HiSIM\_HV solves the potential distribution along the surface by solving the Poisson equation iteratively including the resistance effect in the drift region, where the bias dependence of the resistance is considered. The HiSIM compact model determines the complete potential distribution along the device including the surface potential at the source side  $\phi_{S0}$ , the potential at the pinch-off point  $\phi_{SL}$ , the potential at the channel/drain junction,  $\phi_S(\Delta L)$ , and the final potential value at the drain contact  $\phi_{S0} + V_{ds}$  as shown in Fig. 5. The potential  $V_{dseff}$  is the potential value which mostly determines the device characteristics. This potential node is considered explicitly in addition to the node potential of  $V_{ds}$ . Advanced version concealing the internal node to speed up the simulation has been developed in parallel [5].

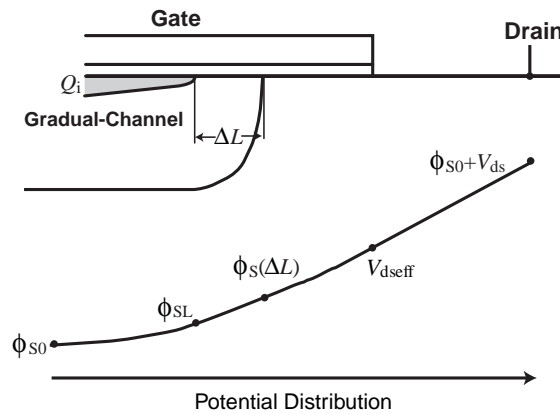


Fig. 5: Schematic of the surface potential distribution in the channel at the drain side of the LDMOS device structure.

### 3 Definition of Device Size

The effective channel length  $L_{\text{eff}}$  and width  $W_{\text{eff}}$  are calculated from the gate length  $L_{\text{gate}}$  and width  $W_{\text{gate}}$ , where  $L_{\text{gate}}$  and width  $W_{\text{gate}}$  deviate from the gate drawn length and width

$$L_{\text{gate}} = L_{\text{drawn}} + \mathbf{XL} \quad (1)$$

$$W_{\text{gate}} = \frac{W_{\text{drawn}}}{\mathbf{NF}} + \mathbf{XW} \quad (2)$$

$$L_{\text{poly}} = L_{\text{gate}} - 2 \cdot \frac{\mathbf{LL}}{(L_{\text{gate}} + \mathbf{LLD})\mathbf{LLN}} \quad (3)$$

$$W_{\text{poly}} = W_{\text{gate}} - 2 \cdot \frac{\mathbf{WL}}{(W_{\text{gate}} + \mathbf{WLD})\mathbf{WLN}} \quad (4)$$

$$L_{\text{eff}} = L_{\text{poly}} - \mathbf{XLD} - \mathbf{XLDLD} \quad (5)$$

$$W_{\text{eff}} = W_{\text{poly}} - 2 \cdot \mathbf{XWD} \quad (6)$$

$$W_{\text{eff,LD}} = W_{\text{poly}} - 2 \cdot \mathbf{XWDL D} \quad (7)$$

$$W_{\text{effc}} = W_{\text{poly}} - 2 \cdot \mathbf{XWDC} \quad (8)$$

$$(9)$$

where  $\mathbf{XLD}/\mathbf{XLDLD}$  and  $\mathbf{XWD}$  account for the overlaps of source/drain contact and the gate oxide as shown in Fig. 6. Widening of  $W_{\text{eff}}$  due to the extension of electric-force line of the drift region is considered by  $\mathbf{XWDL D}$ . The model parameter  $\mathbf{XWDC}$  is introduced to describe the different width dependence of capacitances from currents. If the value is not given, the same value as  $\mathbf{XWD}$  is taken.  $\mathbf{LL}$ ,  $\mathbf{LLD}$ ,  $\mathbf{LLN}$ ,  $\mathbf{WL}$ ,  $\mathbf{WLD}$ , and  $\mathbf{WLN}$  are further model parameters for including  $L_{\text{gate}}$  or  $W_{\text{gate}}$  dependencies on  $L_{\text{eff}}$  and  $W_{\text{eff}}$ .

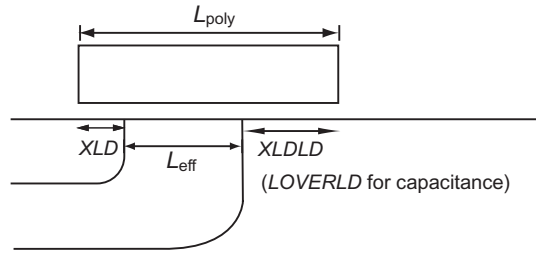


Fig. 6: Cross section of the device.

The HiSIM model parameters introduced in section 3 are summarized in Table 3.

Table 3: HiSIM model parameters introduced in section 3 of this manual. \* and # indicate minor parameters and # an instance parameter, respectively.

<b>#NF</b>	number of gate fingers
<b>XL</b>	difference between real and drawn gate length
<b>XW</b>	difference between real and drawn gate width
<b>XLD</b>	gate-overlap in length at source side
<b>XLDLD</b>	gate-overlap in length at drain side
<b>XWD</b>	gate-overlap in width
<b>XWDL</b>	widening of drift width
<b>XWDC</b>	gate-overlap in width for capacitance calculation
<b>LL</b>	coefficient of gate length modification
<b>LLD</b>	coefficient of gate length modification
<b>LLN</b>	coefficient of gate length modification
<b>WL</b>	coefficient of gate width modification
<b>WLD</b>	coefficient of gate width modification
<b>WLN</b>	coefficient of gate width modification

## 4 Charges

By applying the Gauss law, the charge density induced in the channel is derived from the Poisson equation [6]:

$$\begin{aligned}
 -(Q_B + Q_I) &= C_{\text{ox}}(V_G' - \phi_S(y)) \\
 &= \sqrt{\frac{2\epsilon_{\text{Si}}qN_{\text{sub}}}{\beta}} \left[ \exp\{-\beta(\phi_S(y) - V_{\text{bs}})\} + \beta(\phi_S(y) - V_{\text{bs}}) - 1 \right. \\
 &\quad \left. + \frac{n_{\text{p0}}}{p_{\text{p0}}} \left\{ \exp(\beta(\phi_S(y) - \phi_f(y))) - \exp(\beta(V_{\text{bs}} - \phi_f(y))) \right\} \right]^{\frac{1}{2}}
 \end{aligned}$$

$$C_{\text{ox}} = \frac{\epsilon_0 \mathbf{KAPPA}}{\mathbf{TOX}} \quad (10)$$

$$V_G' = V_{\text{gs}} - \mathbf{VFBC} + \Delta V_{\text{th}} \quad (11)$$

$$\beta = \frac{q}{kT} \quad (12)$$

where  $\mathbf{VFBC}$  is the flat-band voltage,  $\mathbf{TOX}$  is the physical gate-oxide thickness, and  $\Delta V_{\text{th}}$  is the threshold voltage shift in comparison to the threshold voltage of a long-channel transistor [10].  $\epsilon_0$  and  $\mathbf{KAPPA}$  are permittivities in vacuum and in the gate dielectric, respectively. The electron charge is denoted by  $q$ , and  $\epsilon_{\text{Si}}$  and  $N_{\text{sub}}$  are the silicon permittivity and the substrate impurity concentration, respectively. The Boltzmann constant and the lattice temperature in Kelvin are  $k$  and  $T$ , respectively. The quasi-Fermi potential  $\phi_f(y)$  preserves the following relationship:

$$\phi_f(L_{\text{eff}}) - \phi_f(0) = V_{\text{ds,mod}} \quad (13)$$

where  $V_{\text{ds,mod}}$  is introduced to fit measured transition characteristics of the channel conductance  $g_{\text{ds}}$  between the linear region and the saturation region to compensate for insufficiencies of the charge-sheet approximation as

$$V_{\text{ds,mod}} = \frac{V_{\text{ds}}}{\left[ 1 + \left( \frac{V_{\text{ds}}}{V_{\text{ds,sat}}} \right)^\Delta \right]^{\frac{1}{\Delta}}} \quad (14)$$

where

**CODDLT=0** :

$$\Delta = \frac{\mathbf{DDLTMAX} \cdot T1}{\mathbf{DDLTMAX} + T1} + 1 \quad (15)$$

$$T1 = \mathbf{DDLTSLP} \cdot L_{\text{gate}} \cdot 10^6 + \mathbf{DDLTICT} \quad (16)$$

**CODDLT=1** ( default ) :

$$\Delta = \frac{\mathbf{DDLTMAX} \cdot T1}{\mathbf{DDLTMAX} + T1} + \mathbf{DDLTICT} \quad (17)$$

$$T1 = \mathbf{DDLTSLP} \cdot L_{\text{gate}} \cdot 10^6 \quad (18)$$

and  $V_{ds,sat}$  is calculated by solving the Poisson equation analytically by neglecting the inversion carrier density [1].

The electron concentration at equilibrium condition  $n_{p0}$  is

$$n_{p0} = \frac{n_i^2}{p_{p0}} \quad (19)$$

where the intrinsic carrier concentration  $n_i$  is

$$n_i = n_{i0} T^{\frac{3}{2}} \exp\left(-\frac{E_g}{2q}\beta\right) \quad (20)$$

$p_{p0}$  is approximated to be  $N_{sub}$ , and  $E_g$  describes the temperature dependence of the bandgap (see section 14).

Analytical equations for  $Q_B$  and  $Q_I$  are derived as a function of  $\phi_{S0}$  and  $\phi_{SL}$ . The final equations for  $Q_B$ ,  $Q_I$ , and  $Q_D$  are given in Eqs. (21)- (23).

$$\begin{aligned} Q_B = & -\frac{\mu(W_{eff} \cdot \mathbf{NF})^2}{I_{ds}} \left[ const0 C_{ox}(V_G - \mathbf{VFBC}) \frac{1}{\beta} \frac{2}{3} \left[ \{\beta(\phi_S - V_{bs}) - 1\}^{\frac{3}{2}} \right]_{\phi_{S0}}^{\phi_{SL}} \right. \\ & - const0 C_{ox} \frac{1}{\beta} \frac{2}{3} \left[ \phi_S \{\beta(\phi_S - V_{bs}) - 1\}^{\frac{3}{2}} \right]_{\phi_{S0}}^{\phi_{SL}} + const0 C_{ox} \frac{1}{\beta} \frac{2}{3} \frac{1}{\beta} \frac{2}{5} \left[ \{\beta(\phi_S - V_{bs}) - 1\}^{\frac{5}{2}} \right]_{\phi_{S0}}^{\phi_{SL}} \\ & - const0^2 \frac{1}{\beta} \frac{1}{2} \left[ \beta^2(\phi_{SL} - V_{bs})^2 - 2\beta(\phi_{SL} - V_{bs}) + 1 - \beta^2(\phi_{S0} - V_{bs})^2 + 2\beta(\phi_{S0} - V_{bs}) - 1 \right] \\ & \left. - \frac{1}{\beta} \frac{\mu(W_{eff} \cdot \mathbf{NF})^2}{I_{ds}} \left[ const0 C_{ox} \frac{1}{\beta} \frac{2}{3} \{\beta(\phi_S - V_{bs}) - 1\}^{\frac{3}{2}} + \frac{1}{2} const0^2 \beta \phi_S \right]_{\phi_{S0}}^{\phi_{SL}} \right] \quad (21) \end{aligned}$$

Here  $const0$  is defined as

$$const0 = \sqrt{\frac{2\epsilon_{Si}qN_{sub}}{\beta}}$$

while  $\mu$  and  $I_{ds}$  are the carrier mobility and the drain current, respectively [7, 8].

$$Q_I = -WLC_{ox}(VgVt) \frac{2}{3} \left( \frac{1 + \alpha + \alpha^2}{1 + \alpha} \right) \quad (22)$$

$$Q_D = Q_I \left( \frac{3}{5} - \frac{1}{5} \frac{1 + 2\alpha}{(1 + \alpha)(1 + \alpha + \alpha^2)} \right) \quad (23)$$

where the surface-potential-based description derives

$$\alpha = 1 - \frac{(1 + \delta)(\phi_{SL} - \phi_{S0})}{VgVt} \quad (24)$$

$$VgVt = V_{gs} - \left( \mathbf{VFBC} + \phi_{S0} + \frac{const0}{C_{ox}} BPS0^{\frac{1}{2}} \right) \quad (25)$$

$$\delta = C0C_{ox} \frac{4}{3} \frac{1}{\beta} \frac{(BPSL^{\frac{3}{2}} - BPS0^{\frac{3}{2}})}{(\phi_{SL} - \phi_{S0})^2} - C0C_{ox} \frac{2}{\beta} \frac{(BPSL^{\frac{1}{2}} - BPS0^{\frac{1}{2}})}{(\phi_{SL} - \phi_{S0})^2} - 2C0C_{ox} \frac{BPS0^{\frac{1}{2}}}{(\phi_{SL} - \phi_{S0})} \quad (26)$$

and

$$\begin{aligned}
 C0Cox &= \frac{const0}{C_{ox}} \\
 BPSL^{\frac{1}{2}} &= \sqrt{\beta(\phi_{SL} - V_{bs}) - 1} \\
 BPS0^{\frac{1}{2}} &= \sqrt{\beta(\phi_{S0} - V_{bs}) - 1} \\
 BPSL^{\frac{3}{2}} &= (BPSL^{\frac{1}{2}})^3 \\
 BPS0^{\frac{3}{2}} &= (BPS0^{\frac{1}{2}})^3
 \end{aligned} \tag{27}$$

The HiSIM model parameters introduced in section 4 are summarized in Table 4.

Table 4: HiSIM model parameters introduced in section 4 of this manual. \* indicates minor parameters.

<b>VFBC</b>	flat-band voltage
<b>VBI</b>	built-in potential
<b>TOX</b>	physical gate-oxide thickness
<b>KAPPA</b>	dielectric constant of gate dielectric
<b>*DDLTMAX</b>	smoothing coefficient for $V_{ds}$
<b>*DDLTSLP</b>	$L_{gate}$ dependence of smoothing coefficient
<b>*DDLTICT</b>	$L_{gate}$ dependence of smoothing coefficient

## 5 Drain Current

Under the gradual-channel approximation together with approximations of an idealized gate structure and uniform channel doping, the equation for the drain current  $I_{ds}$  is written [6, 9]

$$I_{ds} = \frac{W_{\text{eff}} \cdot \mathbf{NF}}{L_{\text{eff}}} \cdot \mu \cdot \frac{I_{dd}}{\beta} \quad (28)$$

$$\begin{aligned} I_{dd} = & C_{\text{ox}}(\beta V_G' + 1)(\phi_{\text{SL}} - \phi_{\text{S0}}) - \frac{\beta}{2} C_{\text{ox}}(\phi_{\text{SL}}^2 - \phi_{\text{S0}}^2) \\ & - \frac{2}{3} \text{const0} \left[ \{\beta(\phi_{\text{SL}} - V_{\text{bs}}) - 1\}^{\frac{3}{2}} - \{\beta(\phi_{\text{S0}} - V_{\text{bs}}) - 1\}^{\frac{3}{2}} \right] \\ & + \text{const0} \left[ \{\beta(\phi_{\text{SL}} - V_{\text{bs}}) - 1\}^{\frac{1}{2}} - \{\beta(\phi_{\text{S0}} - V_{\text{bs}}) - 1\}^{\frac{1}{2}} \right] \end{aligned} \quad (29)$$

The above description includes the further approximation that the mobility  $\mu$  is independent of position along the channel  $y$ .

## 6 Threshold Voltage Shift

Different from the drift approximation, the drift-diffusion approximation does not require a threshold voltage parameter  $V_{th}$  for describing device performances. The MOSFET device parameters such as the oxide thickness  $T_{ox}$  and the substrate doping concentration  $N_{subc}$  determine the complete MOSFET behavior including the subthreshold characteristics automatically and consistently. However, HiSIM derives many detailed informations on the MOSFET fabrication technology with the  $V_{th}$  changes from a long-channel transistor ( $\Delta V_{th}$ ) as a function of gate length ( $L_{gate}$ ). The modeled  $\Delta V_{th}$  is incorporated in the  $\phi_S$  iteration as can be seen in Eq. (11), and can be viewed as consisting of two main effects or components:

(I) the short-channel effect:  $\Delta V_{th,SC}$

(II) the reverse-short-channel effect:  $\Delta V_{th,R}$  and  $\Delta V_{th,P}$

The separation into these two components ( $\Delta V_{th} = \Delta V_{th,SC} + \Delta V_{th,R}$  (or  $\Delta V_{th,P}$ )) is schematically shown in Fig. 7.

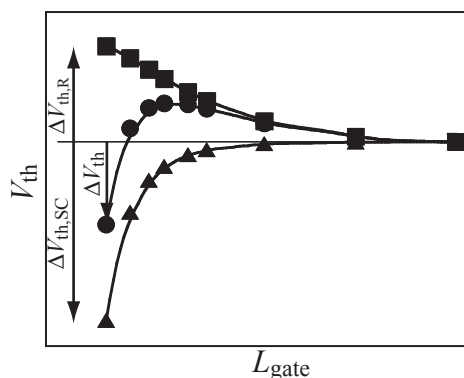


Fig. 7: Schematic plot of the separation of  $V_{th}$  into the contributions of the short-channel and the reverse-short-channel effect.

### 6.1 (I) Short-Channel Effects

All observed phenomena are caused by the lateral-electric-field contribution in the MOSFET channel, which is important even at threshold condition with small  $V_{ds}$ . Thus  $\Delta V_{th,SC}$  can be written as a function of the lateral electric field  $E_y$  by applying the Gauss law. A parabolic potential distribution along the channel is approximated, which results in a position independent gradient of the lateral electric field  $\frac{dE_y}{dy}$  [10]

$$\Delta V_{th,SC} = \frac{\epsilon_{Si}}{C_{ox}} W_d \frac{dE_y}{dy} \quad (30)$$

where  $W_d$  is the depletion-layer thickness written as



$$W_d = \sqrt{\frac{2\epsilon_{Si}(2\Phi_B - V_{bs})}{qN_{sub}}} \quad (31)$$

$$2\Phi_B = \frac{2}{\beta} \ln\left(\frac{N_{sub}}{n_i}\right) \quad (32)$$

where  $n_i$  is the intrinsic carrier density.  $\frac{dE_y}{dy}$  is derived with model parameters in the form

$$\frac{dE_y}{dy} = \frac{2(\mathbf{VBI} - 2\Phi_B)}{(L_{gate} - \mathbf{PARL2})^2} \left( \mathbf{SC1} + \mathbf{SC2} \cdot V_{ds} \cdot \{1 + \mathbf{SC4} \cdot (2\Phi_B - V_{bs})\} + \mathbf{SC3} \cdot \frac{2\Phi_B - V_{bs}}{L_{gate}} \right) \quad (33)$$

**VBI** and **PARL2** represent the built-in potential and the depletion width of the junction vertical to the channel, respectively.  $V'_G$  and *const0* were defined in Eqs. (11) and (22), respectively. The model parameter **SC1** determines the threshold voltage shift for small  $V_{ds}$  and  $V_{bs}$ , and is expected to be unity. If measured  $V_{th}$  is plotted as a function of  $V_{ds}$ , it shows nearly a linear dependence. The gradient is proportional to **SC2**. **SC3** implements a correction of the charge-sheet approximation as well as the impurity-profile gradient along the vertical direction, and is expected to be small. **PTHROU**, describing the increase of the subthreshold swing for short-channel transistors, was deleted and was modeled as the punchthrough effect.

## 6.2 (II) Reverse-Short-Channel Effects

The reverse-short-channel effect is categorized into resulting from two physical MOSFET properties:

- (i) **Impurity concentration inhomogeneity in the direction vertical to the channel (vertical channel inhomogeneity)**

(obvious in the retrograded implantation):  $\Delta V_{th,R}$

- (ii) **Impurity concentration inhomogeneity in the direction parallel to the channel (lateral channel inhomogeneity)**

(obvious in the pocket implantation):  $\Delta V_{th,P}$

- (i) **Impurity concentration inhomogeneity in the direction vertical to the channel (Retrograded Implantation)**

The above model parameters **SC3** and **SCP3** (see in 6.2. (ii)) can be successfully used, if the inhomogeneity is not extremely large.

For cases where the inhomogeneity is large or where positive  $V_{bs}$  is applied, deviation from the linearity of  $V_{th}$  as a function of  $\sqrt{2\Phi_B - V_{bs}}$  is modeled with two fitting parameters **BS1** and **BS2** as

$$Q_{Bmod} = \sqrt{2q \cdot N_{sub} \cdot \epsilon_{Si} \cdot \left( 2\Phi_B - V_{bs} - \frac{\mathbf{BS1}}{\mathbf{BS2} - V_{bs}} \right)} \quad (34)$$

where **BS1** represents the strength of the deviation and **BS2** is the starting value of  $V_{bs}$  where the deviation becomes visible. This  $Q_{Bmod}$  is incorporated into the  $\Delta V_{th}$  description as be seen in Eq. (36).

(ii) **Impurity concentration inhomogeneity in the lateral direction parallel to the channel (Pocket Implantation)**

The model equations for the  $V_{th}$  shift due to the pocket implant are:

$$\Delta V_{th,P} = (V_{th,R} - V_{th0}) \frac{\epsilon_{Si}}{C_{ox}} W_d \frac{dE_{y,P}}{dy} \quad (35)$$

$$V_{th,R} = \mathbf{VFBC} + 2\Phi_B + \frac{Q_{Bmod}}{C_{ox}} + \frac{1}{\beta} \log \left( \frac{N_{subb}}{N_{subc}} \right) \quad (36)$$

$$V_{th0} = \mathbf{VFBC} + 2\Phi_{BC} + \frac{\sqrt{2qN_{subc}\epsilon_{Si}(2\Phi_{BC} - V_{bs})}}{C_{ox}} \quad (37)$$

$$\frac{dE_{y,P}}{dy} = \frac{2(\mathbf{VBI} - 2\Phi_B)}{\mathbf{LP}^2} \left( \mathbf{SCP1} + \mathbf{SCP2} \cdot V_{ds} + \mathbf{SCP3} \cdot \frac{2\Phi_B - V_{bs}}{\mathbf{LP}} \right) \quad (38)$$

$$N_{subb} = 2 \cdot \mathbf{NSUBP} - \frac{(\mathbf{NSUBP} - N_{subc}) \cdot L_{gate}}{\mathbf{LP}} - N_{subc} \quad (39)$$

where  $N_{subc}$  is the substrate impurity concentration as defined in Eq. (76). The parameters **SCP1** - **SCP3** describe the short-channel effect caused by the potential minimum at the higher impurity concentration of the pocket.  $2\Phi_{BC}$  is the potential giving threshold condition with  $N_{subc}$  and  $2\Phi_B$  is the equivalent potential with  $N_{sub}$

$$\Phi_{BC} = \frac{2}{\beta} \ln \left( \frac{N_{subc}}{n_i} \right) \quad (40)$$

$$\Phi_B = \frac{2}{\beta} \ln \left( \frac{N_{sub}}{n_i} \right) \quad (41)$$

$$N_{sub} = \frac{N_{subc}(L_{gate} - \mathbf{LP}) + \mathbf{NSUBP} \cdot \mathbf{LP}}{L_{gate}} \quad (42)$$

As defined in Eq. (42),  $N_{sub}$  is replaced to the averaged impurity concentration in the channel and  $N_{subb}$  is introduced, beginning from channel lengths where pockets at source and drain start to overlap.

As  $V_{ds}$  approaches zero, the  $V_{th}$  dependence on  $V_{ds}$  deviates from linearity and  $V_{th}$  increases drastically as shown schematically in Fig. 8. This is modeled with two model parameters **SCP21** and **SCP22** as

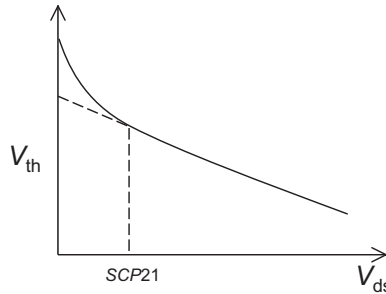


Fig. 8: Threshold voltage as a function of  $V_{ds}$ . The deviation from linearity for small  $V_{ds}$  is modeled with parameters **SCP21** and **SCP22**.

$$\Delta V_{th,P} = \Delta V_{th,P} - \frac{\mathbf{SCP22}}{(\mathbf{SCP21} + V_{ds})^2} \quad (43)$$

where **SCP21** determines the  $V_{ds}$  value at which  $V_{th}$  starts to deviate from linearity as a function of  $V_{ds}$ . The parameter **SCP22** determines the gradient of this deviation.

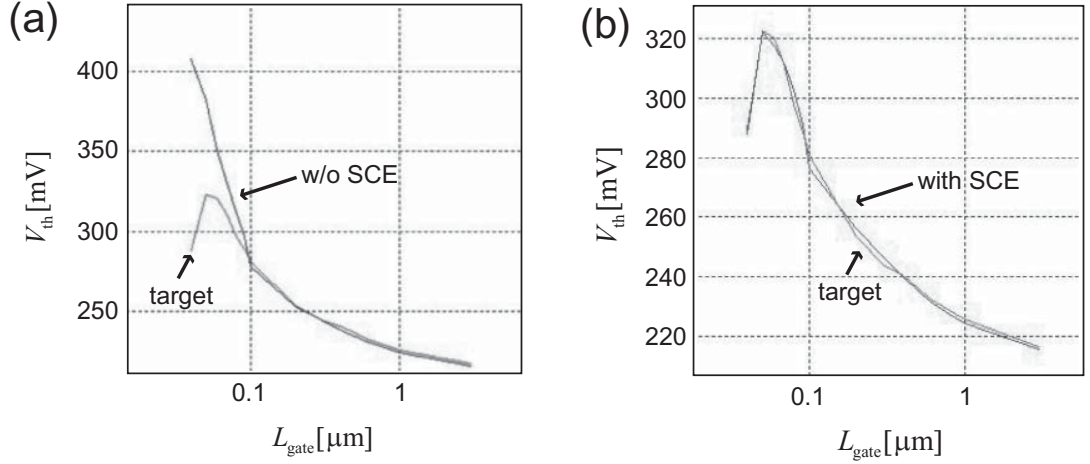


Fig. 9: Comparison of measurements and pocket-implant model for  $V_{th}$  as a function of  $L_{gate}$ . Results (a) with and (b) without short-channel effects (SCE) are shown.

$V_{th,R}$  and  $V_{th0}$ , defined in Eqs. (36) and (37), are the threshold voltages for the cases with and without pocket-implant, respectively. The overlap start of source and drain pockets causes a steep increase of  $V_{th}$  as a function of decreasing  $L_{gate}$ . This effect enables to extract **LP** from measurements. Fig. 9 compares the  $V_{th}$ - $L_{gate}$  characteristics of the developed pocket-implant model with and without inclusion of the short-channel effects (SCE). The step increase at  $L_{gate}=0.1\mu\text{m}$  in Fig. 9a means the starting of the pocket overlap, where **LP**= $0.05\mu\text{m}$ .

In some cases the pocket profile cannot be described by the single linearly decreasing form, but provides extensive tails as schematically shown in Fig. 10. Therefore, two model parameters **NPEXT** and **LPEXT** are introduced to model the pocket tails as

$$N_{sub} = N_{sub} + \frac{\mathbf{NPEXT} - N_{subc}}{\left(\frac{1}{\mathbf{xx}} + \frac{1}{\mathbf{LPEXT}}\right) L_{gate}} \quad (44)$$

where

$$\mathbf{xx} = 0.5 \cdot L_{gate} - \mathbf{LP} . \quad (45)$$

**NPEXT** is the maximum concentration of the pocket tail and **LPEXT** describes the tail extension characteristics. Usually strong pocket implantation induces a vertical impurity distribution at the same time. For fitting the measured results in such cases it is recommended to use the parameter **SCP3** together with parameters **BS1** and **BS2**.

The HiSIM model parameters introduced in section 6 are summarized in Table 5.

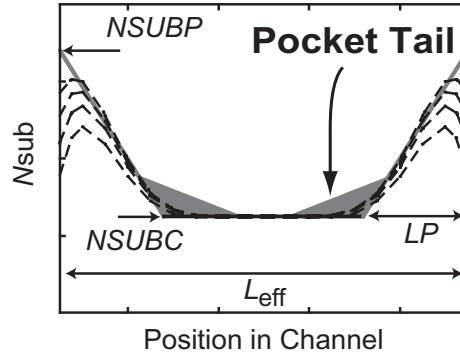


Fig. 10: Modeled pocket tail with **NPEXT** and **LPEXT**.

Table 5: HiSIM model parameters introduced in section 6 of this manual. \* indicates minor parameters.

<b>VBI</b>	built-in potential
<b>PARL2</b>	depletion width of channel/contact junction
<b>SC1</b>	magnitude of short-channel effect
<b>SC2</b>	$V_{ds}$ dependence of short-channel effect
<b>*SC3</b>	$V_{bs}$ dependence of short-channel effect
<b>*SC4</b>	$V_{bs}$ dependence of short-channel effect
<b>NSUBP</b>	maximum pocket concentration
<b>LP</b>	pocket penetration length
<b>*BS1</b>	body-coefficient modification due to impurity profile
<b>*BS2</b>	body-coefficient modification due to impurity profile
<b>SCP1</b>	magnitude of short-channel effect due to pocket
<b>SCP2</b>	$V_{ds}$ dependence of short-channel due to pocket
<b>*SCP3</b>	$V_{bs}$ dependence of short-channel effect due to pocket
<b>*SCP21</b>	short-channel-effect modification for small $V_{ds}$
<b>*SCP22</b>	short-channel-effect modification for small $V_{ds}$
<b>*NPEXT</b>	maximum concentration of pocket tail
<b>*LPEXT</b>	extension length of pocket tail

## 7 Short-Channel Effects

### 7.1 Punchthrough Effect

The origin of the punchthrough effect is the bipolar effect through source, substrate, and drain. The effect is described by a power function of the potential difference

$$POTENTIAL = (VBI - \phi_{S0})^{PTP} \quad (46)$$

The final drain current  $I_{ds}$  is written

$$I_{ds} = I_{ds} + PUNCH$$

$$PUNCH = \frac{W_{eff} \cdot \mathbf{NF}}{L_{eff}} \frac{\mu}{\beta} \cdot (\phi_{SL} - \phi_{S0})$$

$$\left\{ C_{ox} \cdot \beta \frac{\mathbf{PTL}}{(L_{gate} \cdot 10^6)^{PTLP}} \cdot POTENTIAL \cdot \left( 1 + \mathbf{PT2} \cdot V_{ds} + \frac{\mathbf{PT4} \cdot (\phi_{S0} - V_{bs})}{(L_{gate} \cdot 10^6)^{PT4P}} \right) \right\} \quad (47)$$

where model parameters **PTL**, **PTLP**, **PT2**, **PT4**, and **PT4P** are introduced.

### 7.2 Channel Conductance

The high field under the saturation condition causes the pinch-off region and the current flows away from the surface. This effect is considered as the lateral-field-induced charge for the capacitance (see section 16). The simplified formulation is applied to consider the effect as

$$I_{ds} = I_{ds} + \frac{W_{eff} \cdot \mathbf{NF}}{L_{eff}} \frac{\mu}{\beta} \cdot (\phi_{SL} - \phi_{S0}) \cdot CONDUCTANCE$$

$$CONDUCTANCE = C_{ox} \cdot \beta \frac{\mathbf{GDL}}{(L_{gate} \cdot 10^6 + \mathbf{GDLD} \cdot 10^6)^{GDLP}} \cdot V_{ds} \quad (48)$$

The HiSIM model parameters introduced in section 7 are summarized in Table 6.

Table 6: HiSIM model parameters introduced in section 7 of this manual. \* indicates minor parameters.

* <b>PTL</b>	strength of punchthrough effect
* <b>PTLP</b>	channel-length dependence of punchthrough effect
* <b>PTP</b>	strength of punchthrough effect
* <b>PT2</b>	$V_{ds}$ dependence of punchthrough effect
* <b>PT4</b>	$V_{bs}$ dependence of punchthrough effect
* <b>PT4P</b>	$V_{bs}$ dependence of punchthrough effect
* <b>GDL</b>	strength of high-field effect
* <b>GDLP</b>	channel-length dependence of high-field effect
* <b>GDLD</b>	channel-length dependence of high-field effect

## 8 Depletion Effect of the Gate Poly-Si

Carrier depletion in the gate poly-Si near the gate-oxide interface starts after the formation of the inversion layer in the substrate as shown in Fig. 11.

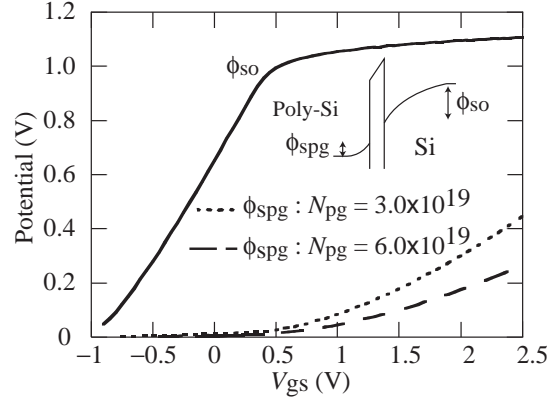


Fig. 11: Simulated surface potential at the source side ( $\phi_{S0}$ ) as a function of  $V_{gs}$ . The poly-depletion potential is also shown for two doping concentrations  $N_{pg}$  in the poly-Si.

To eliminate the necessary iteration procedure for the circuit-simulation application, the potential drop within the poly-Si  $\phi_{Spg}$  is approximated as a function of  $V_{gs}$  and  $V_{ds}$  by the simple formula of Eq. (49), and is included in the  $\Delta V_{th}$  calculation as a potential drop of  $V_{gs}$ .

$$\phi_{Spg} = \mathbf{PGD1} \left( 1 + \frac{1}{L_{gate} \cdot 10^6} \right)^{\mathbf{PGD4}} \exp \left( \frac{V_{gs} - \mathbf{PGD2}}{V} \right) \quad (49)$$

The HiSIM model parameters introduced in section 8 are summarized in Table 7.

Table 7: HiSIM model parameters introduced in section 8 of this manual. \* indicates a minor parameter.

<b>PGD1</b>	strength of poly depletion
<b>PGD2</b>	threshold voltage of poly depletion
<b>*PGD4</b>	$L_{gate}$ dependence of poly depletion

## 9 Quantum-Mechanical Effects

The main quantum-mechanical phenomenon, which has to be included into a MOSFET model for circuit simulation, is the repulsion of the channel's carrier-density peak into the substrate away from the surface. This can be described phenomenologically by an increased effective oxide thickness  $T_{\text{ox}}$  [20, 21]. The calculated  $\Delta T_{\text{ox}}-V_{\text{gs}}$  characteristics is shown in Fig. 12. Equations implemented into HiSIM for the reproduction of quantum mechanical effects are:

$$T_{\text{ox}} = \mathbf{TOX} + \Delta T_{\text{ox}} \quad (50)$$

$$\Delta T_{\text{ox}} = \frac{\mathbf{QME1}}{V_{\text{gs}} - V_{\text{th}}(T_{\text{ox}} = \mathbf{TOX}) + \mathbf{QME2}} + \mathbf{QME3} \quad (51)$$

where **QME1**, **QME2**, and **QME3** are the quantum-effect model parameters. A limiting function is introduced in the source code to avoid unreasonable  $\Delta T_{\text{ox}}$  increase below the threshold voltage.

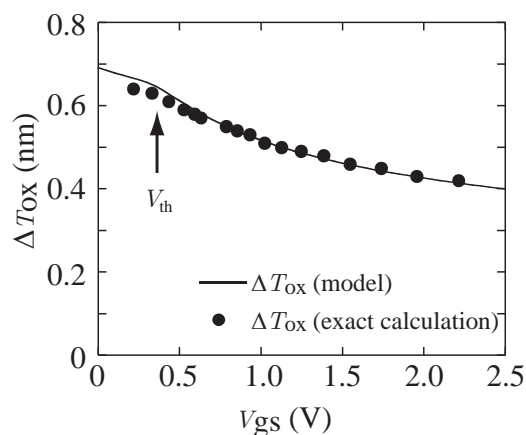


Fig. 12: Calculated  $T_{\text{ox}}$  increase by the quantum mechanical effect. The solid line shows model results with Eqs. (50) and (51). Symbols are exact calculation results by solving the Poisson equation and the Schrödinger equation simultaneously.

The HiSIM model parameters introduced in section 9 are summarized in Table 8.

Table 8: HiSIM model parameters introduced in section 9 of this manual.

<b>QME1</b>	$V_{\text{gs}}$ dependence
<b>QME2</b>	$V_{\text{gs}}$ dependence
<b>QME3</b>	minimum $T_{\text{ox}}$ modification

## 10 Mobility Model

The low-field mobility is described with the following expressions and includes the three independent mechanisms of Coulomb, phonon and surface-roughness scattering [22]:

$$\frac{1}{\mu_0} = \frac{1}{\mu_{\text{CB}}} + \frac{1}{\mu_{\text{PH}}} + \frac{1}{\mu_{\text{SR}}} \quad (52)$$

$$\mu_{\text{CB}}(\text{Coulomb}) = \mathbf{MUECB0} + \mathbf{MUECB1} \frac{Q_i}{q \cdot 10^{11}} \quad (53)$$

$$\mu_{\text{PH}}(\text{phonon}) = \frac{M_{\text{uephonon}}}{E_{\text{eff}}^{\mathbf{MUEPH0}}} \quad (54)$$

$$\mu_{\text{SR}}(\text{surface roughness}) = \frac{\mathbf{MUESR1}}{E_{\text{eff}}^{M_{\text{uesurface}}}} \quad (55)$$

where  $\mu_{\text{PH}}(\text{phonon})$  is temperature dependent as modeled in section 14.

Here  $E_{\text{eff}}$  is the effective field normal to the surface. The field are written as

$$E_{\text{eff}} = \frac{1}{\epsilon_{\text{Si}}} (N_{\text{dep}} \cdot Q_b + \mathbf{NINV} \cdot Q_i) \cdot f(\phi_S) \quad (56)$$

$$f(\phi_S) = \frac{1}{1 + (\phi_{\text{SL}} - \phi_{\text{S0}}) \cdot N_{\text{invd}}} \quad (57)$$

$$N_{\text{invd}} = \mathbf{NINVD} \quad (58)$$

where  $N_{\text{dep}}$  considers the gate length dependence with two model parameters  $\mathbf{NDEPL}$  and  $\mathbf{NDEPLP}$  as

$$N_{\text{dep}} = \mathbf{NDEP} \frac{L_{\text{gate}}^{\mathbf{NDEPLP}}}{\mathbf{NDEPL} + (L_{\text{gate}} \cdot 10^6)^{\mathbf{NDEPLP}}} \quad (59)$$

The function  $f(\phi_S)$  is introduced to reproduce the reduced resistance effect for small  $V_{\text{ds}}$  with the model parameter  $\mathbf{NINVD}$ .

The mobility universality preserves following conditions [23, 24]

$$\mathbf{MUEPH0} \simeq 0.3 \quad (60)$$

$$M_{\text{uesurface}} = 2.0 \quad (61)$$

$$\mathbf{NDEP} = 1.0 \quad (62)$$

$$\mathbf{NINV} = 0.5 \quad (63)$$

However, these parameters can be used for fitting purposes [25], if it is necessary.

The  $L_{\text{gate}}$  dependence of the mobility is considered as

$$M_{\text{uephonon}} = \mathbf{MUEPH1} \cdot \left( 1 + \frac{\mathbf{MUEPHL}}{(L_{\text{gate}} \cdot 10^6)^{\mathbf{MUEPLP}}} \right) \quad (64)$$

$$M_{\text{uesurface}} = \mathbf{MUESR0} \cdot \left( 1 + \frac{\mathbf{MUESRL}}{(L_{\text{gate}} \cdot 10^6)^{\mathbf{MUESLP}}} \right) \quad (65)$$



The high-field mobility is modeled as [26]

$$\mu = \frac{\mu_0}{\left(1 + \left(\frac{\mu_0 E_y}{V_{\max}}\right)^{\frac{BB}{BB}}\right)^{\frac{1}{BB}}} \quad (66)$$

The velocity overshoot is included in the mobility model in the following manner

$$V_{\max} = \mathbf{VMAX} \cdot \left(1 + \frac{\mathbf{VOVER}}{(L_{\text{gate}} \cdot 10^6)^{\mathbf{VOVERP}}}\right) \quad (67)$$

The HiSIM model parameters introduced in section 10 are summarized in Table 9.

Table 9: HiSIM model parameters introduced in section 10 of this manual. \* indicates minor parameters.

<b>MUECB0</b>	Coulomb scattering
<b>MUECB1</b>	Coulomb scattering
<b>MUEPH0</b>	phonon scattering
<b>MUEPH1</b>	phonon scattering
<b>*MUEPHL</b>	length dependence of phonon mobility reduction
<b>*MUEPLP</b>	length dependence of phonon mobility reduction
<b>MUESR0</b>	surface-roughness scattering
<b>MUESR1</b>	surface-roughness scattering
<b>*MUESRL</b>	length dependence of surface roughness mobility reduction
<b>*MUESLP</b>	length dependence of surface roughness mobility reduction
<b>NDEP</b>	depletion charge contribution on effective-electric field
<b>*NDEPL</b>	modification of depletion charge contribution for short-channel case
<b>*NDEPLP</b>	modification of depletion charge contribution for short-channel case
<b>NINV</b>	inversion charge contribution on effective-electric field
<b>*NINVD</b>	reduced resistance effect for small $V_{\text{ds}}$
<b>BB</b>	high-field-mobility degradation
<b>VMAX</b>	maximum saturation velocity
<b>VOVER</b>	velocity overshoot effect
<b>VOVERP</b>	$L_{\text{eff}}$ dependence of velocity overshoot

## 11 Channel-Length Modulation

The gradual-channel approximation is applied to derive analytical equations for describing device characteristics. However, this approximation is not valid for large  $V_{ds}$  causing the pinch-off phenomenon in the channel. To include the pinch-off phenomenon in HiSIM, we apply the conventional method of modeling the pinch-off region ( $\Delta L$ ) separately from the rest of the channel as depicted in Fig. 13 [28].

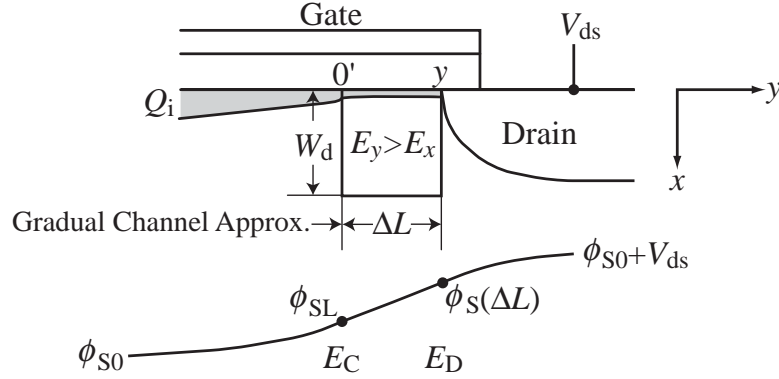


Fig. 13: Schematic showing the correlation among physical quantities in the pinch-off region.

The potential value at the end of the channel ( $\phi_S(\Delta L)$ ) lies between  $\phi_{SL}$  and  $\phi_{S0} + V_{ds}$ . The exact value is dependent on the junction profile between the channel and the drain contact. This dependence is modeled with the parameter **CLM1** as

$$\phi_S(\Delta L) = (1 - \mathbf{CLM1}) \cdot \phi_{SL} + \mathbf{CLM1} \cdot (\phi_{S0} + V_{ds}) \quad (68)$$

where **CLM1** can be interpreted to represent the hardness of the junction and must be in the range  $0 \leq \mathbf{CLM1} \leq 1$ . Here **CLM1** = 1 means that the contact profile is abrupt and the complete potential increase occurs in the  $\Delta L$  region, whereas **CLM1** = 0 corresponds to the opposite condition and there is no potential increase in the  $\Delta L$  region.

The final  $\Delta L$  is derived as

$$\Delta L = \frac{1}{2} \left[ -\frac{1}{L_{eff}} \left( 2 \frac{I_{dd}}{\beta Q_i} z + 2 \frac{N_{sub}}{\epsilon_{Si}} (\phi_S(\Delta L) - \phi_{SL}) z^2 + E_0 z^2 \right) + \sqrt{\frac{1}{L_{eff}^2} \left( 2 \frac{I_{dd}}{\beta Q_i} z + 2 \frac{N_{sub}}{\epsilon_{Si}} (\phi_S(\Delta L) - \phi_{SL}) z^2 + E_0 z^2 \right)^2 + 4 \left( 2 \frac{N_{sub}}{\epsilon_{Si}} (\phi_S(\Delta L) - \phi_{SL}) z^2 + E_0 z^2 \right)} \right] \quad (69)$$

where  $E_0$  is fixed to  $10^5$  and

$$z = \frac{\epsilon_{Si}}{\mathbf{CLM2} \cdot Q_b + \mathbf{CLM3} \cdot Q_i} \quad (70)$$

Two model parameters **CLM2** and **CLM3** are introduced to consider the uncertainty of  $Q_i$  in the pinch-off region and to counterbalance the two contributions from  $Q_b (= qN_{sub}W_d)$  and  $Q_i$ . It has to be notified that  $\Delta L$  is equal to zero, when **CLM1**=0.

Additional contributions on CLM such as the pocket effect is modeled as

$$\Delta L = \Delta L (1 + \mathbf{CLM6} \cdot (L_{\text{gate}} \cdot 10^6)^{\mathbf{CLM5}}) \quad (71)$$

It can be happen that  $L_{\text{eff}} - \Delta L$  becomes negative, if extracted **CLM5** and **CLM6** values are out of acceptable ranges. In this case HiSIM gives "warning" and fixes  $L_{\text{eff}} - \Delta L$  to  $1nm$ .

The HiSIM model parameters introduced in section 11 are summarized in Table 10.

Table 10: HiSIM model parameters introduced in section 11 of this manual.

<b>CLM1</b>	hardness coefficient of channel/contact junction
<b>CLM2</b>	coefficient for $Q_B$ contribution
<b>CLM3</b>	coefficient for $Q_I$ contribution
* <b>CLM5</b>	effect of pocket implantation
* <b>CLM6</b>	effect of pocket implantation

## 12 Narrow-Channel Effects

### 12.1 Threshold Voltage Modification

The fringing capacitances  $C_{ef}$  at the edge of the isolation is modeled [8] as

$$\Delta V_{th,W} = \left( \frac{1}{C_{ox}} - \frac{1}{C_{ox} + 2C_{ef}/(L_{eff}W_{eff})} \right) qN_{sub}W_d + \frac{\mathbf{WVTH0}}{W_{gate} \cdot 10^6} \quad (72)$$

where **WVTH0** is the parameter for including the basic width dependence and

$$C_{ef} = \frac{2\epsilon_{ox}}{\pi} L_{eff} \ln \left( \frac{2T_{fox}}{T_{ox}} \right) = \frac{\mathbf{WFC}}{2} L_{eff} \quad (73)$$

Here,  $T_{fox}$  is the thickness of the oxide at the trench edge, and **WFC** is the model parameter for including the edge-fringing-capacitance effects. The final  $\Delta V_{th}$  of Eq. (11), under inclusion of the shallow-trench-isolation effects, becomes:

$$\Delta V_{th} = \Delta V_{th,SC} + \Delta V_{th,R} + \Delta V_{th,P} + \Delta V_{th,W} - \phi_{SpG} \quad (74)$$

The width dependence of the pocket impurity concentration is modeled as

$$N_{subp} = \mathbf{NSUBP} \cdot \left( 1 + \frac{\mathbf{NSUBP0}}{(W_{gate} \cdot 10^6)^{\mathbf{NSUBWP}}} \right) \quad (75)$$

The width dependence of the substrate impurity concentration  $N_{subc}$  is also considered as

$$N_{subc} = \mathbf{NSUBC} \cdot \left( 1 + \frac{\mathbf{NSUBCW}}{(W_{gate} \cdot 10^6)^{\mathbf{NSUBCWP}}} \right) \quad (76)$$

### 12.2 Mobility Change

A reduction of  $I_{ds,sat}$  with reduced  $W_{gate}$  as indicated by curve C1 in Fig. 14 [30] is modeled by a decreasing phonon mobility with two model parameters **MUEPHW** and **MUEPWP** as

$$M_{uephonon} = M_{uephonon} \cdot \left( 1 + \frac{\mathbf{MUEPHW}}{(W_{gate} \cdot 10^6)^{\mathbf{MUEPWP}}} \right) \quad (77)$$

A start to increase for narrower  $W_{gate}$  as denoted by curve C2 is modeled as a change of the surface-roughness contribution caused by a carrier flow in increasing distance from the surface as

$$M_{uesurface} = M_{uesurface} \cdot \left( 1 + \frac{\mathbf{MUESRW}}{(W_{gate} \cdot 10^6)^{\mathbf{MUESWP}}} \right) \quad (78)$$

Further width dependences are included as

$$N_{invd} = N_{invd} \cdot \left( 1 + \frac{\mathbf{NINVDW}}{(W_{gate} \cdot 10^6)^{\mathbf{NINVDWP}}} \right) \quad (79)$$

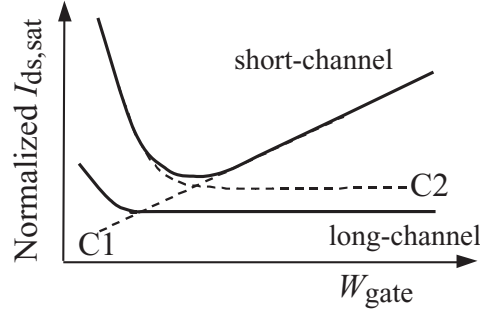


Fig. 14: Schematic of the normalized saturation current  $I_{ds,sat}$  as a function of the gate width  $W_{gate}$  for two different gate lengths  $L_{gate}$ .

### 12.3 Transistor Leakage due to Shallow Trench Isolation (STI): Hump in $I_{ds}$

The surface potential of the leakage regions at the trench edges can be derived analytically as [31]

$$\phi_{S,STI} = V'_{gs,STI} + \frac{\epsilon_{Si} Q_{N,STI}}{C'_{ox,2}} \left[ 1 - \sqrt{1 + \frac{2C'_{ox,2}}{\epsilon_{Si} Q_{N,STI}} \left( V'_{gs,STI} - V_{bs} - \frac{1}{\beta} \right)} \right] \quad (80)$$

where

$$Q_{N,STI} = q \cdot \mathbf{NSTI} \quad (81)$$

$$V'_{gs,STI} = V_{gs} - \mathbf{VFBC} + V_{th,STI} + \Delta V_{th,SCSTI} \quad (82)$$

where

$$V_{th,STI} = \mathbf{VTHSTI} - \mathbf{VDSTI} \cdot V_{ds} \quad (83)$$

and

$$\Delta V_{th,SCSTI} = \frac{\epsilon_{Si}}{C_{ox}} W_{d,STI} \frac{dE_y}{dy} \quad (84)$$

The threshold voltage for the STI effect  $\mathbf{VTHSTI}$  includes features of STI such as  $\mathbf{NSTI}$  which are different from the substrate. The depletion-layer thickness  $W_{d,STI}$  is written as

$$W_{d,STI} = \sqrt{\frac{2\epsilon_{Si}(2\Phi_{B,STI} - V_{bs})}{q\mathbf{NSTI}}}. \quad (85)$$

$\frac{dE_y}{dy}$  is described with model parameters in the same form as in section 6.1 on short-channel effects

$$\frac{dE_y}{dy} = \frac{2(\mathbf{VBI} - 2\Phi_{B,STI})}{(L_{gate,sm} - \mathbf{PARL2})^2} (\mathbf{SCSTI1} + \mathbf{SCSTI2} \cdot V_{ds}) \quad (86)$$

where

$$L_{gate,sm} = L_{gate} + \frac{\mathbf{WL1}}{wl\mathbf{WL1P}} \quad (87)$$

$$wl = (W_{\text{gate}} \cdot 10^6) \times (L_{\text{gate}} \cdot 10^6) \quad (88)$$

The modeling of the transistor leakage for STI technologies is based on the idea that the current in the subthreshold region is governed only by the diffusion term. The carrier concentration  $Q_{i,\text{STI}}$  is calculated analytically for the subthreshold region, where the STI effect is obvious [1]. The final leakage current equation is written as

$$I_{\text{ds,STI}} = 2 \frac{W_{\text{STI}}}{L_{\text{eff}} - \Delta L} \mu \frac{Q_{i,\text{STI}}}{\beta} [1 - \exp(-\beta V_{\text{ds}})] \quad (89)$$

where  $W_{\text{STI}}$  determines the width of the high-field region. The gate length dependence of  $W_{\text{STI}}$  is included as

$$W_{\text{STI}} = \mathbf{WSTI} \left( 1 + \frac{\mathbf{WSTIL}}{(L_{\text{gate,sm}} \cdot 10^6) \mathbf{WSTILP}} \right) \left( 1 + \frac{\mathbf{WSTIW}}{(W_{\text{gate,sm}} \cdot 10^6) \mathbf{WSTIWP}} \right) \quad (90)$$

## 12.4 Small Geometry

Small size devices do not show the same scaling characteristic as long-channel or wide-channel devices, but rather deviate significantly. The reason is mainly due to the resolution inaccuracy of the lithography. The small geometry effects are modeled first as the threshold voltage shift

$$\Delta V_{\text{th}} = \Delta V_{\text{th,SC}} + \Delta V_{\text{th,R}} + \Delta V_{\text{th,P}} + \Delta V_{\text{th,W}} + \Delta V_{\text{th,sm}} - \phi_{\text{SpG}} \quad (91)$$

where

$$\Delta V_{\text{th,sm}} = \frac{\mathbf{WL2}}{wl \mathbf{WL2P}} \quad (92)$$

The mobility modification due to the small device geometry is also modeled in the phonon scattering as

$$M_{\text{uephonon}} = M_{\text{uephonon}} \cdot \left( 1 + \frac{\mathbf{MUEPHS}}{wl \mathbf{MUEPSP}} \right) \quad (93)$$

$$V_{\text{max}} = V_{\text{max}} \cdot \left( 1 + \frac{\mathbf{VOVERS}}{wl \mathbf{VOVERSP}} \right) \quad (94)$$

The HiSIM model parameters introduced in section 12 are summarized in Table 11.

Table 11: HiSIM model parameters introduced in section 12 of this manual. \* indicates minor parameters.

<b>WFC</b>	threshold voltage change due to capacitance change
* <b>WVTH0</b>	threshold voltage shift
<b>NSUBC</b>	substrate-impurity concentration
* <b>NSUBCW</b>	width dependence of substrate-impurity concentration
* <b>NSUBCWP</b>	width dependence of substrate-impurity concentration
* <b>NSUBP0</b>	modification of pocket concentration for narrow width
* <b>NSUBWP</b>	modification of pocket concentration for narrow width
* <b>MUEPHW</b>	phonon related mobility reduction
* <b>MUEPWP</b>	phonon related mobility reduction
* <b>MUESRW</b>	change of surface roughness related mobility
* <b>MUESWP</b>	change of surface roughness related mobility
* <b>NINVDW</b>	width dependence on high field mobility
* <b>NINVDWP</b>	width dependence on high field mobility
* <b>VTHSTI</b>	threshold voltage shift due to STI
* <b>VDSTI</b>	threshold voltage shift dependence on $V_{ds}$ due to STI
* <b>SCSTI1</b>	the same effect as <b>SC1</b> but at STI edge
* <b>SCSTI2</b>	the same effect as <b>SC2</b> but at STI edge
<b>NSTI</b>	substrate-impurity concentration at the STI edge
<b>WSTI</b>	width of the high-field region at STI edge
* <b>WSTIL</b>	channel-length dependence of <b>WSTI</b>
* <b>WSTILP</b>	channel-length dependence of <b>WSTI</b>
* <b>WSTIW</b>	channel-width dependence of <b>WSTI</b>
* <b>WSTIWP</b>	channel-width dependence of <b>WSTI</b>
<b>WL1</b>	threshold voltage shift of STI leakage due to small size effect
<b>WL1P</b>	threshold voltage shift of STI leakage due to small size effect
<b>WL2</b>	threshold voltage shift due to small size effect
<b>WL2P</b>	threshold voltage shift due to small size effect
* <b>MUEPHS</b>	mobility modification due to small size
* <b>MUEPSP</b>	mobility modification due to small size
* <b>VOVERS</b>	modification of maximum velocity due to small size
* <b>VOVERSP</b>	modification of maximum velocity due to small size

### 13 Effects of the Source/Drain Diffusion Length for Shallow Trench Isolation (STI) Technologies

The diffusion length,  $L_{od}$  between MOSFET gate and STI edge affects the MOSFET characteristics. The influence is observed mainly in  $V_{th}$  and in the saturation current. The  $V_{th}$  change is attributed to a change of the pocket impurity concentration and modeled as

$$N_{substi} = \frac{1 + T1 \cdot T2}{1 + T1 \cdot T3} \quad (95)$$

where

$$\begin{aligned} T1 &= \frac{1}{1 + \mathbf{NSUBPSTI2}} \\ T2 &= \frac{\mathbf{NSUBPSTI1}^{\mathbf{NSUBPSTI3}}}{L_{od\_half}} \\ T3 &= \frac{\mathbf{NSUBPSTI1}^{\mathbf{NSUBPSTI3}}}{L_{od\_half\_ref}} \end{aligned} \quad (96)$$

which is used to modify the pocket concentration  $N_{subp}$  as

$$N_{subp} = N_{subp} \cdot N_{substi}. \quad (97)$$

The saturation-current change is attributed to a change of the mobility and modeled as

$$M_{uesti} = \frac{1 + T1 \cdot T2}{1 + T1 \cdot T3} \quad (98)$$

where

$$\begin{aligned} T1 &= \frac{1}{1 + \mathbf{MUESTI2}} \\ T2 &= \frac{\mathbf{MUESTI1}^{\mathbf{MUESTI3}}}{L_{od\_half}} \\ T3 &= \frac{\mathbf{MUESTI1}^{\mathbf{MUESTI3}}}{L_{od\_half\_eff}} \end{aligned} \quad (99)$$

which is used to modify the phonon mobility parameter  $M_{uephonon}$  as

$$M_{uephonon} = M_{uephonon} \cdot M_{uesti} \quad (100)$$

where  $L_{od\_half}$  and  $L_{od\_half\_eff}$  are determined in the same way as BSIM4.6.0 with model parameters **SAREF** and **SBREF** and instance parameters **SA**, **SB**, and **SD**.

The HiSIM model parameters introduced in section 13 are summarized in Table 12.



Table 12: HiSIM model parameters introduced in section 13 of this manual. # indicates instance parameters.

<b>NSUBPSTI1</b>	pocket concentration change due to diffusion-region length between gate and STI
<b>NSUBPSTI2</b>	pocket concentration change due to diffusion-region length between gate and STI
<b>NSUBPSTI3</b>	pocket concentration change due to diffusion-region length between gate and STI
<b>MUESTI1</b>	mobility change due to diffusion-region length between gate and STI
<b>MUESTI2</b>	mobility change due to diffusion-region length between gate and STI
<b>MUESTI3</b>	mobility change due to diffusion-region length between gate and STI
<b>SAREF</b>	length of diffusion between gate and STI
<b>SBREF</b>	length of diffusion between gate and STI
<b>#SA</b>	length of diffusion between gate and STI
<b>#SB</b>	length of diffusion between gate and STI
<b>#SD</b>	length of diffusion between gate and gate

## 14 Temperature Dependences

In HiSIM\_HV **TEMP** is treated as a simulation option, and temperature  $T0$  is determined as

$$T0 = \mathbf{TEMP} + \mathbf{DTEMP} \quad (101)$$

where **DTEMP** is an instance parameter describing the temperature increase from **TEMP**, thus  $T0$  is the given temperature. Whereas the temperature including the self heating effect is distinguished by  $T$

$$T = T0 + \delta T \quad (102)$$

where  $\delta T$  is the temperature increase by the self-heating effect. The temperature dependence is included automatically in the surface potentials through  $\beta$ , which is the inverse of the thermal voltage. Additionally the bandgap, the intrinsic carrier concentration, the carrier mobility, and the carrier saturation velocity are also temperature dependent. The temperature dependence of the bandgap determines the temperature dependence of  $V_{th}$  [32] and is modeled as

$$E_g = E_{g_{nom}} - \mathbf{BGTMP1} \cdot (T - \mathbf{TNOM}) - \mathbf{BGTMP2} \cdot (T - \mathbf{TNOM})^2 \quad (103)$$

$$E_{g_{nom}} = \mathbf{EG0} - 90.25 \cdot 10^{-6} \cdot \mathbf{TNOM} - 1.0 \cdot 10^{-7} \cdot \mathbf{TNOM}^2 \quad (104)$$

where  $T$  is the given temperature. The temperature dependence of the intrinsic carrier concentration is given by

$$n_i = n_{i0} \cdot T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2q}\beta\right) \quad (105)$$

The temperature dependence of the mobility and the temperature dependence of the saturation velocity have a major influence on the temperature dependence of the  $I_{ds}$ - $V_{ds}$  characteristics under the on-current condition. They are modeled as [26]:

$$\mu_{PH}(\text{phonon}) = \frac{M_{uephonon}}{(T/\mathbf{TNOM})^{\mathbf{MUETMP}} \cdot E_{eff}^{\mathbf{MUEPH0}}} \quad (106)$$

$$V_{max} = \frac{\mathbf{VMAX}}{1.8 + 0.4(T/\mathbf{TNOM}) + 0.1(T/\mathbf{TNOM})^2 - \mathbf{VTMP} \cdot (1 - T/\mathbf{TNOM})} \quad (107)$$

$$\mu_{PHdep}(\text{phonon}) = \frac{DEP_{muephonon}}{(T/\mathbf{TNOM})^{\mathbf{DEPMUETMP}} \cdot E_{eff}^{\mathbf{DEPMUEPH0}}} \quad (108)$$

$$DEP_{vmax} = \frac{\mathbf{DEPVMAX}}{1.8 + 0.4(T/\mathbf{TNOM}) + 0.1(T/\mathbf{TNOM})^2 - \mathbf{DEPVTMP} \cdot (1 - T/\mathbf{TNOM})} \quad (109)$$

The temperature dependence of the gate current is modeled by modifying the bandgap specific for the gate current as

$$E_{gp} = E_{g0} + \mathbf{EGIG} + \mathbf{IGTEMP2} \left(\frac{1}{T} - \frac{1}{\mathbf{TNOM}}\right) + \mathbf{IGTEMP3} \left(\frac{1}{T^2} - \frac{1}{\mathbf{TNOM}^2}\right) \quad (110)$$

where  $E_{g0}$  is the bandgap at **TNOM**.

**Junction Capacitance at Drain Side:**

$$\mathbf{CJ} = \mathbf{CJ} \cdot (1 + \mathbf{TCJBD} \cdot (T - \mathbf{TNOM})) \quad (111)$$

$$\mathbf{CJSW} = \mathbf{CJSW} \cdot (1 + \mathbf{TCJBDSW} \cdot (T - \mathbf{TNOM})) \quad (112)$$

$$\mathbf{CJSWG} = \mathbf{CJSWG} \cdot (1 + \mathbf{TCJBDSWG} \cdot (T - \mathbf{TNOM})) \quad (113)$$

**Junction Capacitance at Source Side:**

$$\mathbf{CJ} = \mathbf{CJ} \cdot (1 + \mathbf{TCJBS} \cdot (T - \mathbf{TNOM})) \quad (114)$$

$$\mathbf{CJSW} = \mathbf{CJSW} \cdot (1 + \mathbf{TCJBSSW} \cdot (T - \mathbf{TNOM})) \quad (115)$$

$$\mathbf{CJSWG} = \mathbf{CJSWG} \cdot (1 + \mathbf{TCJBSSWG} \cdot (T - \mathbf{TNOM})) \quad (116)$$

**Junction Current:**

$$T_{\text{tnom}} = \frac{T}{\mathbf{TNOM}} \quad (117)$$

$$j_s = \mathbf{JS0} \exp \left\{ \frac{(E_g(T = \mathbf{TNOM}) \cdot \beta(T = \mathbf{TNOM}) - E_g \beta + \mathbf{XTI} \cdot \log(T_{\text{tnom}}))}{\mathbf{NJ}} \right\} \quad (118)$$

$$j_{\text{ssw}} = \mathbf{JS0SW} \exp \left\{ \frac{(E_g(T = \mathbf{TNOM}) \cdot \beta(T = \mathbf{TNOM}) - E_g \beta + \mathbf{XTI} \cdot \log(T_{\text{tnom}}))}{\mathbf{NJSW}} \right\} \quad (119)$$

$$j_{s2} = \mathbf{JS0} \exp \left\{ \frac{(E_g(T = \mathbf{TNOM}) \cdot \beta(T = \mathbf{TNOM}) - E_g \beta + \mathbf{XTI2} \cdot \log(T_{\text{tnom}}))}{\mathbf{NJ}} \right\} \quad (120)$$

$$j_{\text{ssw}2} = \mathbf{JS0SW} \exp \left\{ \frac{(E_g(T = \mathbf{TNOM}) \cdot \beta(T = \mathbf{TNOM}) - E_g \beta + \mathbf{XTI2} \cdot \log(T_{\text{tnom}}))}{\mathbf{NJSW}} \right\} \quad (121)$$

$$\mathbf{CISB} = \mathbf{CISB} \cdot \exp \{(T_{\text{tnom}} - 1)\mathbf{CTEMP}\} \quad (122)$$

$$\mathbf{VDIFFJ} = \mathbf{VDIFFJ} \cdot (T_{\text{tnom}})^2 \quad (123)$$

In addition to the temperature dependence of the physical quantities considered, resistances include the temperature dependence, which is modeled with the given temperature to avoid complication in parameter extraction.

**CORDRIFT=1: default**

$$\mu_{\text{drift0,temp}} = \frac{\mathbf{RDRMUE}}{(T/\mathbf{TNOM})^{\mathbf{RDRMUETMP}}} \quad (124)$$

$$V_{\text{max\_drift,temp}} = \frac{\mathbf{RDRVMAX}}{1.8 + 0.4(T/\mathbf{TNOM}) + 0.1(T/\mathbf{TNOM})^2 - \mathbf{RDRVTMP} \cdot (1 - T/\mathbf{TNOM})} \quad (125)$$

$$R_{\text{drbb}} = \mathbf{RDRBB} + \mathbf{RDRBBTMP}(T - \mathbf{TNOM}) \quad (126)$$

$$(127)$$

**CORDRIFT=0: old model**

$$R_{d0,temp} = \mathbf{RDTEMP1} \cdot (T0 - \mathbf{TNOM}) + \mathbf{RDTEMP2} \cdot (T0^2 - \mathbf{TNOM}^2) \quad (128)$$

$$R_{dvd,temp} = \mathbf{RDVDTEMP1} \cdot (T0 - \mathbf{TNOM}) + \mathbf{RDVDTEMP2} \cdot (T0^2 - \mathbf{TNOM}^2) \quad (129)$$

Additional temperature dependences are also included with the given temperature in case they are needed.

$$V_{\max} = \mathbf{VMAX} \cdot (1 + \mathbf{VMAXT1} \cdot (T0 - \mathbf{TNOM}) + \mathbf{VMAXT2} \cdot (T0^2 - \mathbf{TNOM}^2)) \quad (130)$$

$$N_{\text{invd}} = N_{\text{invd}} \cdot (1 + \mathbf{NINVDT1} \cdot (T0 - \mathbf{TNOM}) + \mathbf{NINVDT2} \cdot (T0^2 - \mathbf{TNOM}^2)) \quad (131)$$

where  $T0$  in the above four equations can be replaced by  $T$  including the temperature increase due to the self-heating effect by selecting Flag **COTEMP** (see in section 24).

The HiSIM model parameters introduced in section 14 are summarized in Table 13.

Table 13: HiSIM model parameters introduced in section 14 of this manual. \* indicates minor parameters. # indicates an instance parameter.

<b>EG0</b>	bandgap
<b>BGTMP1</b>	temperature dependence of bandgap
<b>BGTMP2</b>	temperature dependence of bandgap
<b>MUETMP</b>	temperature dependence of phonon scattering
<b>TNOM</b>	temperature selected as nominal temperature value
<b>#DTEMP</b>	temperature increase from the given temperature
<b>*VTMP</b>	temperature dependence of the saturation velocity
<b>EGIG</b>	bandgap of gate current
<b>IGTEMP2</b>	temperature dependence of gate current
<b>IGTEMP3</b>	temperature dependence of gate current
<b>RDRMUE</b>	field dependent mobility in the drift region for <b>CORDRIFT=1</b>
<b>RDRMUETMP</b>	temperature dependence of resistance for <b>CORDRIFT=1</b>
<b>RDRVTMP</b>	temperature dependence of resistance for <b>CORDRIFT=1</b>
<b>RDRVMAX</b>	saturation velocity in the drift region for <b>CORDRIFT=1</b>
<b>RDTEMP1</b>	temperature dependence of resistance for <b>CORDRIFT=0</b>
<b>RDTEMP2</b>	temperature dependence of resistance for <b>CORDRIFT=0</b>
<b>RDVDTEMP1</b>	temperature dependence of resistance
<b>RDVDTEMP2</b>	temperature dependence of resistance
<b>CJ</b>	bottom junction capacitance per unit area at zero bias
<b>CJSW</b>	source/drain sidewall junction cap. grading coefficient per unit length at zero bias
<b>CJSWG</b>	source/drain sidewall junction capacitance per unit length at zero bias
<b>TCJBD</b>	temperature dependence of drain-side diode capacitance
<b>TCJBDSW</b>	temperature dependence of drain-side diode capacitance
<b>TCJBDSWG</b>	temperature dependence of drain-side diode capacitance
<b>TCJBS</b>	temperature dependence of source-side diode capacitance
<b>TCJBSSW</b>	temperature dependence of source-side diode capacitance
<b>TCJBSSWG</b>	temperature dependence of source-side diode capacitance
<b>XTI</b>	temperature coefficient for forward-current densities
<b>XTI2</b>	temperature coefficient for reverse-current densities
<b>CTEMP</b>	temperature coefficient of reverse currents
<b>NINVDT1</b>	temperature dependence of universal mobility model
<b>NINVDT2</b>	temperature dependence of universal mobility model
<b>VMAXT1</b>	temperature dependence of velocity
<b>VMAXT2</b>	temperature dependence of velocity

## 15 Resistances

Specific features of the LDMOS/HVMOS are caused by the highly resistive drift region, enabling the high-voltage application of MOSFETs.

Here the resistance model is described for the LDMOS case. For the symmetrical/asymmetrical HVMOS case, the resistance at the source side is modeled with the same equations for the drain side by fixing  $V_{ds}$  to zero.

The source and the drain resistances  $R_s$  and  $R_d$  are considered by voltage drops on each terminal as

$$V_{gs,eff} = V_{gs} - I_{ds} \cdot R_s \quad (132)$$

$$V_{ds,eff} = V_{ds} - I_{ds} \cdot (R_s + R_{drift}) \quad (133)$$

$$V_{bs,eff} = V_{bs} - I_{ds} \cdot R_s \quad (134)$$

for the DC condition, where the effective voltages are referred as internal node potential  $V_{dp}$ .

The source side resistance is written as

$$R_s = \frac{\mathbf{RS}}{W_{eff,LD} \cdot \mathbf{NF}} + \mathbf{NRS} \cdot \mathbf{RSH} \quad (135)$$

where **NRS** is an instance parameter describing the number of squares of the source diffusion, and **RSH** is its the sheet resistance of the square. The first term of the right hand side of Eq. (135) considers the resistance in the LDD region, and the second term is that in the diffusion region, which is layout dependent.

The specific feature of high-voltage MOSFETs is  $R_{drift}$ , which sustains high breakdown voltage. HiSIM\_HV 2.0.0 provides two  $R_{drift}$  options selected by Flag **CORDRIFT**. The resistance model of HiSIM\_HV 1 is activated with **CORDRIFT**=0, and the new model [55] added in HiSIM\_HV 2 is selected by **CORDRIFT**=1. To switch off the resistance effect completely, the flag **CORDRIFT** together with that of **CORSRD** must be set to zero.

The  $R_{drift}$  selection is done in three functions as depicted in Fig. 15.

### 15.1 CORDRIFT=1: default

The model concept is schematically shown in Fig. 16, where  $I_{ds}$  is written in Eq. (29), and the current flowing in the drift region  $I_{ddp}$  is modeled

$$R_{drift} = \frac{V_{ddp}}{I_{ddp}} + \mathbf{RSH} \cdot \mathbf{NRD} \quad (136)$$

$$I_{ddp} = W_{eff} \cdot X_{ov} \cdot q \cdot N_{drift} \cdot \mu_{drift} \frac{V_{ddp}}{L_{drift} + \mathbf{RDRDL1}} \quad (137)$$

where

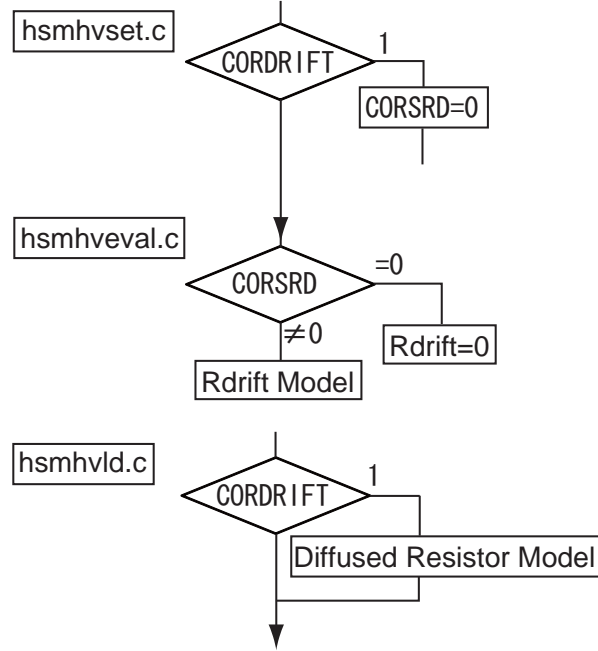


Fig. 15: Model selection done in three files.

$$L_{\text{drift}} = L_{\text{drift1}} + L_{\text{drift2}} \quad (138)$$

$$\mu_{\text{drift}} = \frac{\mu_{\text{drift0}}}{\left[ 1 + \left( \frac{\mu_{\text{drift0}}}{V_{\text{max\_drift}}} \cdot \frac{V_{\text{ddp}}}{L_{\text{drift}}} \right)^{R_{\text{drbb}}} \right]^{\frac{1}{R_{\text{drbb}}}}} \quad (139)$$

$$\mu_{\text{drift0}} = \mu_{\text{drift0,temp}} \left( 1 + \frac{\mathbf{RDRMUEL}}{(L_{\text{gate}} \cdot 10^6)^{\mathbf{RDRMUELP}}} \right) \quad (140)$$

$$V_{\text{max\_drift}} = V_{\text{max\_drift,temp}} \left( 1 + \frac{\mathbf{RDRVMAXL}}{(L_{\text{gate}} \cdot 10^6)^{\mathbf{RDRVMAXLP}}} \right) \left( 1 + \frac{\mathbf{RDRVMAXW}}{(W_{\text{gate}} \cdot 10^6)^{\mathbf{RDRVMAXWP}}} \right) \quad (141)$$

$$X_{ov} = W_0 - \mathbf{RDRCX} \cdot \left( \frac{W_0}{\mathbf{RDRDJUNC}} W_{dep} + \frac{W_0}{\mathbf{XLDLD}} W_{junc} \right) \quad (142)$$

$$W_0 = \sqrt{\mathbf{XLDLD}^2 + \mathbf{RDRDJUNC}^2} \quad (143)$$

$$W_{dep} = \sqrt{\frac{2\epsilon_{Si}(-\phi_{s,over})}{q \cdot \mathbf{NOVER}}} \quad (144)$$

$$W_{junc} = \sqrt{\frac{2\epsilon_{Si}(V_{ds} - V_{bs} + V_{bi})}{q} \cdot \frac{N_{sub}}{\mathbf{NOVER}(N_{sub} + \mathbf{NOVER})}} \quad (145)$$

$$N_{drift} = \mathbf{NOVER} \left\{ 1 + \mathbf{RDRCAR} \left( \frac{V_{ddp}}{L_{drift} - \mathbf{RDRDL2}} \right) \left( 1 - \frac{1}{1 + \frac{\mu_{drift0}}{V_{max,drift}} \cdot \frac{V_{ddp}}{L_{drift}}} \right) \right\} \\ + \left( \mathbf{RDRQOVER} \frac{-Q_{over}}{q} \right) \quad (146)$$

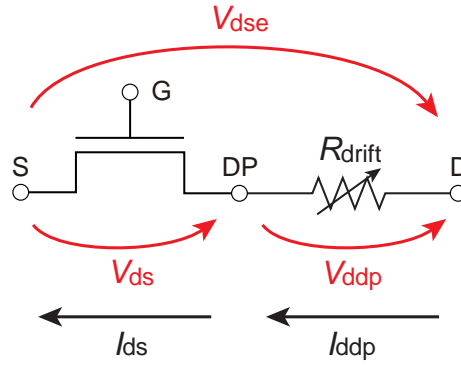


Fig. 16: Model concept.

The potential value of  $V_{ddp}$ , the difference between the internal node  $DP$  and the drain node is calculated by circuit simulator.

## 15.2 CORDRIFT=0: old model provided in HiSIM\_HV 1

The voltage drops are in principle calculated iteratively for applied voltages to keep consistency among all device performances. However, a simple analytical description is also provided. Thus, the parasitic source and drain resistances,  $R_s$  and  $R_{drift}$ , can be considered by different optional approaches. Flag **CORSRD** is provided for the selection of one of the possible approaches. **CORSRD** = 0, 1, 2, 3 means "no resistance", "external", "analytical", "external + analytical", respectively. Options to be selected by Flag **CORSRD** are summarized in Fig. 17.

In the HiSIM\_HV 1.0.2 version, the option **CORSRD**=-1 was provided as an option by introducing an internal node additionally. To keep backward compatible for such case, **CORSRD**=1 must be selected and bias independent resistance parameters, **RS** and **RD**, can be used.



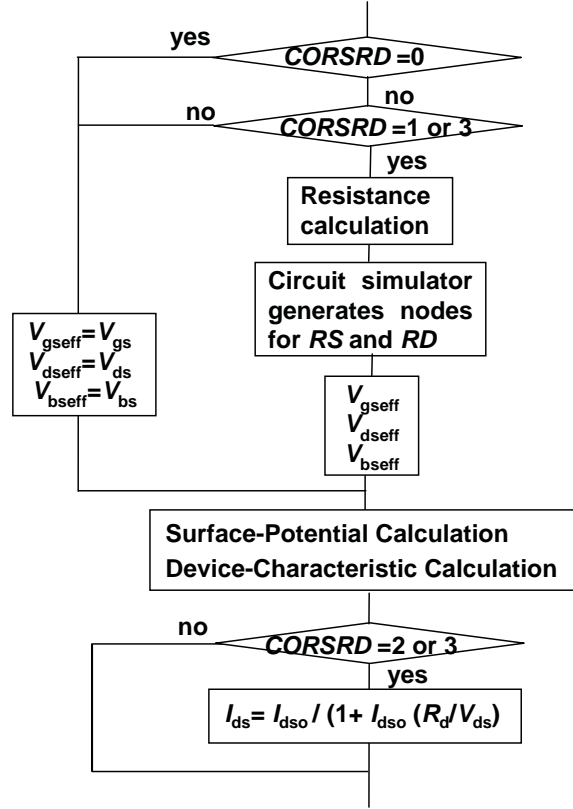


Fig. 17: Model options provided in HiSIM-LDMOS/HV for the resistance models, which are selected by Flag **CORSRD**.

**CORSRD**=2 considered only the resistance effect on the drain current as

$$I_{ds} = \frac{I_{ds0}}{1 + I_{ds0} \frac{R_d}{V_{ds}}} \quad (147)$$

where  $I_{ds0}$  is the drain current without the resistance effect and

$$R_d = \frac{1}{W_{eff}} (R'_d \cdot V_{ds}^{RD21} + V_{bs} \cdot V_{ds}^{RD22D} \cdot RD22) \quad (148)$$

$$RD23' \leq R'_d \leq RD23'(1 + RD20) \quad (149)$$

where

$$RD23' = RD23 \cdot \exp(-RD23L \cdot (L_{gate} \cdot 10^6)^{RD23LP}) \left( 1 + \frac{RD23S}{(W_{gate} \cdot 10^6 \cdot L_{gate} \cdot 10^6)^{RD23SP}} \right) \quad (150)$$

The  $V_{gs}$  dependence of  $R'_d$  is considered

$$R'_d = RD24 (V_{gs} - RD25) \quad (151)$$

The resistance effect for the case **CORSRD**=1 is described here. However, in case if it is necessary, both

resistance models (internal-node approach and analytical approach) can be applied with **CORSRD=3**.

$$R_{\text{drift}} = (R_d + V_{\text{ds}} \cdot R_{\text{DVD}}) \left( 1 + \mathbf{RDVG11} - \frac{\mathbf{RDVG11}}{\mathbf{RDVG12}} \cdot V_{\text{gs}} \right) \cdot (1 - V_{\text{bs}} \cdot \mathbf{RDVB}) \quad (152)$$

$$\cdot \left( \frac{\mathbf{LDRIFT1} + \mathbf{LDRIFT2}}{\mathbf{DDRIFT} - W_{\text{dep}}} \right) \quad (153)$$

and

$$R_d = \frac{R_{\text{d0}}}{W_{\text{eff,LD}} \cdot \mathbf{NF}} \left( 1 + \frac{\mathbf{RDS}}{(W_{\text{gate}} \cdot 10^6 \cdot L_{\text{gate}} \cdot 10^6)^{\mathbf{RDSP}}} \right) \quad (154)$$

$$R_{\text{d0}} = (\mathbf{RD} + R_{\text{d0,temp}}) f_1 \cdot f_2 \quad (155)$$

$$R_{\text{DVD}} = \frac{\mathbf{RDVD} + R_{\text{dvd,temp}}}{W_{\text{eff}}} \cdot \exp(-\mathbf{RDVDL} \cdot (L_{\text{gate}} \cdot 10^6)^{\mathbf{RDVDLP}}) \cdot \left( 1 + \frac{\mathbf{RDVDS}}{(W_{\text{gate}} \cdot 10^6 \cdot L_{\text{gate}} \cdot 10^6)^{\mathbf{RDVDSF}}} \right) \cdot f_1 \cdot f_2 \cdot f_3 \quad (156)$$

$$f_1(L_{\text{drift1}}) = \frac{\mathbf{LDRIFT1}}{1\mu\text{m}} \cdot \mathbf{RDSLP1} + \mathbf{RDICT1} \quad (157)$$

$$f_2(L_{\text{drift2}}) = \frac{\mathbf{LDRIFT2}}{1\mu\text{m}} \cdot \mathbf{RDSLP2} + \mathbf{RDICT2} \quad (158)$$

$$f_3(L_{\text{over}})^* = 1 + \left( \mathbf{RDOV11} - \frac{\mathbf{RDOV11}}{\mathbf{RDOV12}} \right) \cdot \frac{\mathbf{LOVERLD}}{1\mu\text{m}} + (1 - \mathbf{RDOV13}) \cdot \frac{\mathbf{LOVERLD}}{1\mu\text{m}} \quad (159)$$

$$W_{\text{dep}} = \sqrt{\frac{2\epsilon_{\text{Si}} \{ \mathbf{VBISUB} - (\mathbf{RDVDSUB} \cdot V_{\text{ds}} + \mathbf{RDVSUB} \cdot V_{\text{sub,s}}) \}}{q}} \cdot \sqrt{\frac{\mathbf{NSUBSUB}}{\mathbf{NOVER} \cdot (\mathbf{NSUBSUB} + \mathbf{NOVER})}} \quad (160)$$

**LDRIFT1** and **LDRIFT2** are model parameters denoting lengths of different parts of the drift region. The source resistance in the LDMOS case does not consider a drift region and has therefore no drift length parameters. It is expected that either the second term of Eq. (159) or the third term is selected. For HiSIM\_HV1.0 versions, **RDOV13** must be fixed to unity to select the second term. To select the third term **RDOV11** must be zero.

In the present and previous versions Eq. (159) is written as

$$f_3(L_{\text{over}})^* = 1 + \mathbf{RDOV11} - \frac{\mathbf{RDOV11}}{\mathbf{RDOV12}} \cdot \frac{\mathbf{LOVERLD}}{1\mu\text{m}} + (1 - \mathbf{RDOV13}) \cdot \frac{\mathbf{LOVERLD}}{1\mu\text{m}} \quad (161)$$

by mistake.

The final drift resistance  $R_{\text{drift}}$  is written as

$$R_{\text{drift}} = R_{\text{drift}} + \mathbf{RSH} \cdot \mathbf{NRD} \quad (162)$$

where **NRD** is an instance parameter describing the number of squares of the drain diffusion, and **RSH** is its the sheet resistance of the square. The first terms of the right hand side of the equation considers

the resistance in the drift region, and the second term is the that in the diffusion region, which are layout dependent.

The gate resistance becomes large as the gate width becomes large, which is the case for many RF circuits. The equation for the gate-resistance calculation is taken from the BSIM4 [33] description as

$$R_g = \frac{\mathbf{RSHG} \cdot (\mathbf{XGW} + \frac{W_{\text{eff}}}{3 \cdot \mathbf{NGCON}})}{\mathbf{NGCON} \cdot (L_{\text{drawn}} - \mathbf{XGL}) \cdot \mathbf{NF}} \quad (163)$$

where **RSHG** is the gate sheet resistance, and others are instance parameters dependent on the layout. The flag **CORG** is provided for the inclusion of gate resistance. **CORG** = 0,1 means "no", "external" gate resistance, respectively.

Model parameters for the same substrate resistance network as BSIM4 (**RBPB**, **RBPD**, **RBPS**) are included in the model parameter list, which are also treated as instance parameters.

Here summarizes the selection of the resistance model for **CORDRIFT** = 0:

**CORSRD** = 0 : no resistance

**CORSRD** = 1 : solved by circuit simulator with external nodes

All model parameters included in Eq. (135)–Eq. (160) are used.

Model parameters are:

**RS**, **NRS**, **RSH**

**RDVG11**, **RDVG12**, **RDVB**, **RDS**, **RDSP**, **NRD**

**RD**, **RDVD**, **RDVDL**, **RDVDLP**, **RDVDS**, **RDVDSP**

**RDSL1P1**, **RDICT1**, **RDSL1P2**, **RDICT2**, **RDOV11**, **RDOV12**, **RDOV13**

**RDVDSUB**, **RDVSUB**, **VBISUB**, **DDRIFT**, **NSUBSUB**

**CORSRD** = 2 : solved with the analytical equations of Eq. (147)–Eq. (151)

Model parameters are:

**RD21**, **RD22**, **RD22D**, **RD23**, **RD23L**, **RD23LP**

**RD23S**, **RD23SP**, **RD24**, **RD25**, **RD20**

**CORSRD** = 3 : Both **CORSRD** = 1 and **CORSRD** = 2 are considered.

At the starting of the parameter extraction, following model parameters are suggested to set to zero:

**RDVG11**, **RDVB**, **RDVD**

**RDTEMP1**, **RDTEMP2**, **RDVDTEMP1**, **RDVDTEMP2**

The above condition refers to the bias independent resistance.

Table 14 summarizes the minimum resistance parameters to be determined.

Table 14: HiSIM\_HV 1.2.0 resistance parameters introduced. If **RS** is not determined for the asymmetrical case, **RD** is taken.

	structure	source	drain
<b>COSYM=0</b>	<b>LDMOS</b>	<b>RS</b> (bias independent)	<b>RD</b>
<b>COSYM=1</b>	<b>symmetrical HVMOS</b>		<b>RD</b>
<b>COSYM=1</b>	<b>asymmetrical HVMOS</b>	<b>RS</b>	<b>RD</b>

The HiSIM model parameters introduced in section 15 are summarized in Table 15.

Table 15: HiSIM model parameters introduced in section 15 of this manual. # indicates instance parameters. \* indicates minor parameters.

<b>RS</b>	source-contact resistance of LDD region
<b>RSH</b>	source/drain sheet resistance of diffusion region
<b>RSHG</b>	gate sheet resistance
<b>RBPB</b>	substrate resistance network
<b>RBPD</b>	substrate resistance network
<b>RBPS</b>	substrate resistance network
<b>RBDB</b>	no more used
<b>RBSB</b>	no more used
<b>#NRS</b>	number of source squares
<b>#NRD</b>	number of drain squares
<b>#XGW</b>	distance from the gate contact to the channel edge
<b>#XGL</b>	offset of the gate length
<b>#NF</b>	number of fingers
<b>#NGCON</b>	number of gate contacts
<b>CORDRIFT=1</b>	
<b>RDRDL1</b>	effective $L_{\text{drift}}$ of current in drift region
<b>RDRDL2</b>	pinch-off length in drift region
<b>RDRCX</b>	exude of current flow from $X_{\text{ov}}$
<b>RDRCAR</b>	high field injection in drift region
<b>RDRDJUNC</b>	junction depth at channel/drift region
<b>RDRBB</b>	high field mobility in drift region
<b>RDRMUE</b>	mobility in drift region
<b>RDRVMAX</b>	saturation velocity in drift region
<b>RDRVMAXL</b>	saturation velocity $L_{\text{gate}}$ dependence
<b>RDRVMAXLP</b>	saturation velocity $L_{\text{gate}}$ dependence
<b>RDRVMAXW</b>	saturation velocity $W_{\text{gate}}$ dependence
<b>RDRVMAXWP</b>	saturation velocity $W_{\text{gate}}$ dependence
<b>RDRMUEL</b>	mobility in drift region $L_{\text{gate}}$ dependence
<b>RDRMUELP</b>	mobility in drift region $L_{\text{gate}}$ dependence
<b>RDRLOWVD1</b>	modification of $R_{\text{drift}}$ for small $V_{\text{ds}}$
<b>RDRLOWVD2</b>	modification of $R_{\text{drift}}$ for small $V_{\text{ds}}$
<b>RDRQOVER</b>	inclusion of the overlap charge into $R_{\text{drift}}$
<b>CORDRIFT=0</b>	
<b>RD</b>	drain-contact resistance of LDD region
<b>*RDVG11</b>	$V_{\text{gs}}$ dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>*RDVG12</b>	$V_{\text{gs}}$ dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>RDVD</b>	$V_{\text{ds}}$ dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>RDVB</b>	$V_{\text{bs}}$ dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>*RDS</b>	small size dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>*RDSP</b>	small size dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>*RDVDL</b>	$L_{\text{gate}}$ dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>*RDVDLP</b>	$L_{\text{gate}}$ dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>*RDVDS</b>	small size dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>*RDVDSP</b>	small size dependence of <b>RD</b> for <b>CORSRD=1,3</b>
<b>RDOV11</b>	$L_{\text{over}}$ dependence of resistance for <b>CORSRD=1,3</b>
<b>RDOV12</b>	$L_{\text{over}}$ dependence of resistance for <b>CORSRD=1,3</b>
<b>RDOV13</b>	alternative $L_{\text{over}}$ dependence model for <b>CORSRD=1,3</b>
<b>RDSL1P1</b>	<b>LDRIFT1</b> dependence of resistances for <b>CORSRD=1,3</b>
<b>RDICT1</b>	<b>LDRIFT1</b> dependence of resistances for <b>CORSRD=1,3</b>
<b>RDSL1P2</b>	<b>LDRIFT2</b> dependence of resistances for <b>CORSRD=1,3</b>
<b>RDICT2</b>	<b>LDRIFT2</b> dependence of resistances for <b>CORSRD=1,3</b>
<b>RD20</b>	<b>RD23</b> boundary for <b>CORSRD=2,3</b>
<b>RD21</b>	$V_{\text{ds}}$ dependence of <b>RD</b> for <b>CORSRD=2,3</b>
<b>RD22</b>	$V_{\text{bs}}$ dependence of <b>RD</b> for <b>CORSRD=2,3</b>
<b>RD22D</b>	$V_{\text{bs}}$ dependence of <b>RD</b> for <b>CORSRD=2,3</b> with large $V_{\text{ds}}$

<b>RD23</b>	modification of <b>RD</b> for <b>CORSRD=2,3</b>
<b>*RD23L</b>	$L_{gate}$ dependence of <b>RD23</b> boundary for <b>CORSRD=2,3</b>
<b>*RD23LP</b>	$L_{gate}$ dependence of <b>RD23</b> boundary for <b>CORSRD=2,3</b>
<b>*RD23S</b>	small size dependence of <b>RD23</b> for <b>CORSRD=2,3</b>
<b>*RD23SP</b>	small size dependence of <b>RD23</b> for <b>CORSRD=2,3</b>
<b>*RD24</b>	$V_{gs}$ dependence of <b>RD</b> for <b>CORSRD=2,3</b>
<b>*RD25</b>	$V_{gs}$ dependence of <b>RD</b> for <b>CORSRD=2,3</b>
<b>VBISUB</b>	built-in potential at the drift/substrate junction
<b>RDVDSUB</b>	$V_{ds}$ dependence of depletion width
<b>RDVSUB</b>	$V_{sub}$ dependence of depletion width
<b>DDRIFT</b>	depth of the drift region
<b>NSUBSUB</b>	impurity concentration of the substrate required for $V_{sub}$ dependence

## 16 Capacitances

### 16.1 Intrinsic Capacitances

The intrinsic capacitances are derivatives of the node charges determined as

$$\begin{aligned} C_{jk} &= \delta \frac{\partial Q_j}{\partial V_k} \\ \delta &= -1 \quad \text{for } j \neq k \\ \delta &= 1 \quad \text{for } j = k \end{aligned} \quad (164)$$

HiSIM uses analytical solutions for all 9 independent intrinsic capacitances, derived from the charges as explicit functions of the surface potentials. Therefore, there are no extra model parameters for the intrinsic capacitances except the width reduction parameter **XWDC** different from that of current **XWD**, namely  $W_{\text{eff}}$  for the total capacitance calculation instead of  $W_{\text{eff}}$ , if it is necessary.

The lateral electric field along the channel induces a capacitance  $C_{Q_y}$  which significantly affects the gate capacitance in saturation [34]. The induced charge associated with  $C_{Q_y}$  is described with the surface potential values as

$$Q_y = \epsilon_{\text{Si}} W_{\text{eff}} \cdot \text{NFW}_d \left( \frac{\phi_{\text{S0}} + V_{\text{ds}} - \phi_{\text{S}}(\Delta L)}{\text{XQY}} \right) + \frac{\text{XQY1}}{L_{\text{gate}}^{\text{XQY2}}} V_{\text{bs}} \quad (165)$$

introducing **XQY**, a parameter determining the maximum field at the channel/drain junction independent of  $L_{\text{gate}}$ . For **XQY**=0 the charge  $Q_y$  is fixed to zero.

### 16.2 Overlap Capacitances

The overlap capacitance includes three options as summarized in Fig. 18 for the drain side and Fig. 19 for the source side. If Flags **COOVLP**=**COOVLPS**=0, the overlap capacitances are treated to be constant. If **CGSO** and **CGDO** are determined, these values are taken. If they are not determined, the values are calculated with the overlap length and oxide capacitance.

If Flags **COOVLP**=**COOVLPS**=1, the bias dependent overlap capacitances are considered. Here two models are provided: One is the surface-potential-based model and the other describes with a simple  $V_{\text{gs}}$  dependence. In addition to the bias dependent capacitances, **CGSO** and **CGDO** can be also added, if they are determined.

The description is focussed on the drain side. For the source side the same calculation is performed with  $V_{\text{ds}}=0$ .

#### i) Surface-Potential-Based Model

The surface potential  $\phi_{\text{S}}$  is calculated in the same manner as in the channel region, and only the polarity is inverted from the channel. The final overlap charge equation is written with the calculated  $\phi_{\text{S}}$

a) under the depletion and the accumulation conditions

$$Q_{\text{over}} = W_{\text{eff}} \cdot \text{NF} \cdot \text{LOVERLD} \left( \sqrt{\frac{2\epsilon_{\text{Si}} q \text{NOVER}}{\beta}} \sqrt{\beta(\phi_{\text{S}} + V_{\text{ds}}) - 1} \right) \quad (166)$$

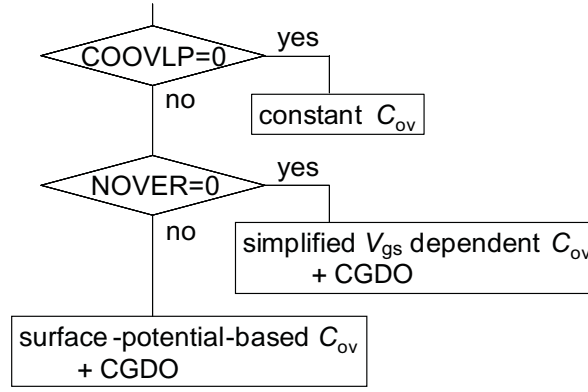


Fig. 18: Model options of the overlap capacitance at the drain side are summarized.

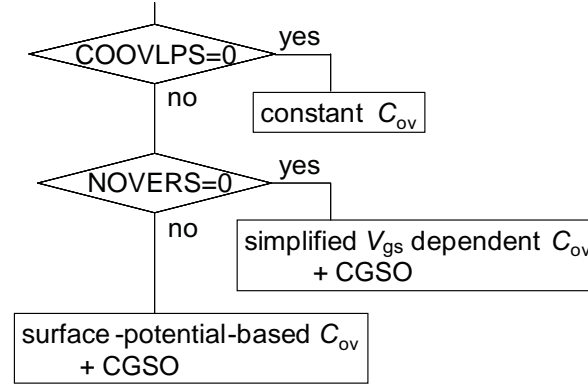


Fig. 19: Model options of the overlap capacitance at the source side are summarized.

b) under the inversion condition

$$Q_{\text{over}} = W_{\text{eff}} \cdot \mathbf{NF} \cdot \mathbf{LOVERLD} \cdot C_{\text{ox}}(V_{\text{gs}} - \mathbf{VFBOVER} - \phi_s) \quad (167)$$

where **LOVERLD** is the length of the overlap region of the gate over drain, **NOVER** is the impurity concentration in the drift region, and **VFBOVER** is the flat-band voltage in the overlap region. This model is selected, if **NOVER** is not equal to zero.

The potential distribution occurs in the drain side of the drift region underneath the gate overlap before the strong inversion is created. This induces additional charge and the overlap capacitance at the same time. This effect is modeled as

$$Q_{\text{over,d}} = Q_{\text{over,d}} + W_{\text{eff}} \cdot \mathbf{NF} \cdot \mathbf{QOVADD} \cdot \mathbf{LOVERLD} \cdot (V_{\text{dp}} - V_{\text{ch}}) \quad (168)$$

$$V_{\text{ch}} = \phi_{\text{SL}} - \phi_{\text{S0}} \quad (169)$$

Three options are provided to calculate  $\phi_s$ , which is selected by the flag **COQOVSM**:

**COQOVSM=0**: with an analytical equation excluding inversion charge

**COQOVSM=1**: with iterative procedure



**COQOVSM=2**: with an analytical equation including inversion charge

The potential value not only at the internal channel/drift junction but also that at the external node can be considered for the overlap capacitance calculation. The model parameter **CVDSOVER** has been introduced to determine the ratio of these two potential contributions as

$$C_{ov} = (1 - \mathbf{CVDSOVER}) \cdot C_{ov}(int) + \mathbf{CVDSOVER} \cdot C_{ov}(ext) \quad (170)$$

where  $C_{ov}(int)$  is the overlap capacitance value calculated with the potential value at the channel/drift junction and  $C_{ov}(ext)$  is that with the external potential value. Spikes observed in  $C_{gg}$  for  $V_{ds} \neq 0$  are determined automatically by the resistance, which is extracted with  $I - V$  characteristics. These spikes can be adjusted to measurements by **CVDSOVER** without influencing the calculated  $I - V$  characteristics.

## ii) Simplified Bias-Dependent Model

If **LOVERLD** > 0 and the flag **COOVLP** = 1, the overlap charge is modeled as

$$Q_{god} = W_{eff} \cdot \mathbf{NF} \cdot C_{ox} [(V_{gs} - V_{ds}) \mathbf{LOVERLD} - \mathbf{OVSLP} \cdot (1.2 - (\phi_{SL} - V_{ds})) \cdot (\mathbf{OVMAG} + (V_{gs} - V_{ds}))] \quad (171)$$

The overlap capacitance Flags (**COOVLP** = **COOVLPS** = 0) calculates bias-independent overlap capacitances. User-defined values can be specified using the input parameters **CGDO** and **CGSO**. If these values are not specified, the overlap capacitances are calculated using

$$C_{ov} = -\frac{\epsilon_{ox}}{\mathbf{TOX}} \mathbf{LOVERLD} \cdot W_{eff} \cdot \mathbf{NF} \quad (172)$$

The gate-to-bulk overlap capacitance  $C_{gbo,loc}$  is calculated only with a user-defined value **CGBO** using

$$C_{gbo,loc} = -\mathbf{CGBO} \cdot L_{gate} \quad (173)$$

independent of the model Flags **COOVLP** and **COOVLPS**.

## 16.3 Extrinsic Capacitances

The outer fringing capacitance is modeled as [36]

$$C_f = \frac{\epsilon_{ox}}{\pi/2} W_{gate} \cdot \mathbf{NF} \cdot \ln \left( 1 + \frac{\mathbf{TPOLY}}{T_{ox}} \right) \quad (174)$$

where **TPOLY** is the gate-poly thickness. This capacitance is bias independent.

The HiSIM model parameters introduced in section 16 are summarized in Table 16.

Table 16: HiSIM model parameters introduced in section 16 of this manual.

<b>XQY</b>	distance from drain junction to maximum electric field point
<b>*XQY1</b>	$V_{bs}$ dependence of $Q_y$
<b>*XQY2</b>	$L_{gate}$ dependence of $Q_y$
<b>LOVERLD</b>	overlap length of the drift region
<b>LOVERS</b>	overlap length of the source region
<b>LOVER</b>	overlap length of the source region, if <b>LOVERS</b> is not determined.
<b>VFBOVER</b>	flat-band voltage in overlap region
<b>*QOVADD</b>	additional overlap capacitance
<b>*CVDSOVER</b>	modification of the $C_{gg}$ spikes for $V_{ds} \neq 0$
<b>OVSLP</b>	coefficient for overlap capacitance
<b>OVMAG</b>	coefficient for overlap capacitance
<b>CGSO</b>	gate-to-source overlap capacitance
<b>CGDO</b>	gate-to-drain overlap capacitance
<b>CGBO</b>	gate-to-bulk overlap capacitance
<b>TPOLY</b>	height of the gate poly-Si

## 17 Leakage Currents

### 17.1 Substrate Current

The substrate current is modeled as

$$I_{\text{sub}} = X_{\text{sub1}} \cdot P_{\text{sisubsat}} \cdot I_{\text{ds}} \cdot \exp\left(-\frac{X_{\text{sub2}}}{P_{\text{sisubsat}}}\right) \quad (175)$$

where

$$X_{\text{sub1}} = \text{SUB1} \cdot \left(1 + \frac{\text{SUB1L}}{L_{\text{gate}}^{\text{SUB1LP}}}\right) \quad (176)$$

$$X_{\text{sub2}} = \text{SUB2} \cdot \left(1 + \frac{\text{SUB2L}}{L_{\text{gate}}}\right) \quad (177)$$

$$P_{\text{sisubsat}} = \text{SVDS} \cdot V_{\text{ds}} + \phi_{\text{S0}} - \frac{L_{\text{gate}} \cdot P_{\text{sisat}}}{X_{\text{gate}} + L_{\text{gate}}} \quad (178)$$

$$X_{\text{gate}} = \text{SLG} \cdot \left(1 + \frac{\text{SLGL}}{L_{\text{gate}}^{\text{SLGLP}}}\right) \quad (179)$$

$$P_{\text{sisat}} = V_{\text{g2}} + \frac{q \cdot \epsilon_{\text{Si}} \cdot N_{\text{sub}}}{C_{\text{ox}}^2} \cdot \left\{1 - \sqrt{1 + \frac{2C_{\text{ox}}^2}{q \cdot \epsilon_{\text{Si}} \cdot N_{\text{sub}}} \cdot \left(V_{\text{g2}} - \frac{1}{\beta} - X_{\text{vbs}} \cdot V_{\text{bs}}\right)}\right\} \quad (180)$$

$$X_{\text{vbs}} = \text{SVBS} \cdot \left(1 + \frac{\text{SVBSL}}{L_{\text{gate}}^{\text{SVBSLP}}}\right) \quad (181)$$

$$V_{\text{g2}} = \text{SVGS} \cdot \left(1 + \frac{\text{SVGSL}}{L_{\text{gate}}^{\text{SVGSLP}}}\right) \cdot \frac{W_{\text{gate}}^{\text{SVGSWP}}}{W_{\text{gate}}^{\text{SVGSWP}} + \text{SVGSW}} \cdot V_{\text{gp}} \quad (182)$$

#### 17.1.1 Impact-Ionization Induced Bulk Potential Change

The impact ionization induces electron and hole pairs, which is the origin of the substrate current. However, not only the leakage current but also the charge distribution in the bulk is changed. This induced charge redistribution affects as the bulk potential change. This is modeled in a simple way as

$$\begin{aligned} \Delta I_{\text{ds}} = & \frac{2}{3} \sqrt{\frac{2\epsilon_{\text{Si}}qN_{\text{sub}}}{\beta}} \left[ \left\{ \beta(\phi_{\text{SL}} - V_{\text{bs}}) - 1 \right\}^{\frac{3}{2}} \frac{3}{2} \frac{\beta \Delta V_{\text{bulk}}}{\beta(\phi_{\text{SL}} - V_{\text{bs}}) - 1} \right. \\ & \left. - \left\{ \beta(\phi_{\text{S0}} - V_{\text{bs}}) - 1 \right\}^{\frac{3}{2}} \frac{3}{2} \frac{\beta \Delta V_{\text{bulk}}}{\beta(\phi_{\text{S0}} - V_{\text{bs}}) - 1} \right] \\ & - \sqrt{\frac{2\epsilon_{\text{Si}}qN_{\text{sub}}}{\beta}} \left[ \left\{ \beta(\phi_{\text{SL}} - V_{\text{bs}}) - 1 \right\}^{\frac{1}{2}} \frac{1}{2} \frac{\beta \Delta V_{\text{bulk}}}{\beta(\phi_{\text{SL}} - V_{\text{bs}}) - 1} \right. \\ & \left. - \left\{ \beta(\phi_{\text{S0}} - V_{\text{bs}}) - 1 \right\}^{\frac{1}{2}} \frac{1}{2} \frac{\beta \Delta V_{\text{bulk}}}{\beta(\phi_{\text{S0}} - V_{\text{bs}}) - 1} \right] \quad (183) \end{aligned}$$

where

$$\Delta V_{\text{bulk}} = \text{IBPC1} \cdot (1 + \text{IBPC2} \cdot \Delta V_{\text{th}}) \cdot I_{\text{sub}} \quad (184)$$

where

$$IBPC1 = \mathbf{IBPC1} \cdot \left( 1 + \frac{\mathbf{IBPC1L}}{(L_{\text{gate}} \cdot 10^6)^{\mathbf{IBPC1LP}}} \right) \quad (185)$$

and  $\mathbf{IBPC1}$ ,  $\mathbf{IBPC1L}$ ,  $\mathbf{IBPC1LP}$  and  $\mathbf{IBPC2}$  are model parameters.

### Impact-Ionization in Drift Region

With increased  $V_{\text{gs}}$  the impact ionization occurs in the drift region, which shows exponential characteristics as a function of  $V_{\text{gs}}$ . This type of impact-ionization induced current is modeled as

$$I_{\text{subLD}} = I_{\text{ds}} \cdot \mathbf{SUBLD1} \cdot E_y \cdot L_{\text{drift}} \cdot \exp\left(\frac{-\mathbf{SUBLD2}}{E_y \cdot f(V_{\text{g}}V_{\text{t}})}\right) \quad (186)$$

$$E_y = \frac{V_{\text{ddp}} - \Delta V}{L_{\text{drift}}} \quad (187)$$

$$f(V_{\text{g}}V_{\text{t}}) = \sqrt{Q_{\text{I}}/q} \quad (188)$$

$$L_{\text{drift}} = \mathbf{LDRIFT1} + \mathbf{LDRIFT2} \quad (189)$$

where  $\Delta V$  is the potential change due to the stored generated carriers in the overlap region, and is modeled as

$$\Delta V = \mathbf{XPDV} \cdot T0 \cdot \mathbf{XLDLD} \cdot \exp\left(-\frac{a}{T0}\right) \quad (190)$$

$$T0 = V_{\text{ddp}} - \mathbf{XPVDTH} \cdot (1 + \mathbf{XPVDTHG} \cdot V_{\text{gs}}) \quad (191)$$

where  $a$  is unity with voltage dimension. This  $I_{\text{subLD}}$  is added to the conventional  $I_{\text{sub}}$ . The potential change  $\Delta V$  is the origin of the expansion effect [56]. The parameter  $\mathbf{SUBLD1}$  provides the  $L_{\text{gate}}$  dependence

$$\mathbf{SUBLD1} = \mathbf{SUBLD1} \cdot \left( 1 + \frac{\mathbf{SUBLD1L}}{(L_{\text{gate}} \cdot 10^6)^{\mathbf{SUBLD1LP}}} \right) \quad (192)$$

## 17.2 Gate Current

All possible gate leakage currents are schematically shown in Fig. 20.

### (i) Between Gate and Channel, $I_{\text{gate}}$

As for the current between gate and channel, ( $I_{\text{gate}}$ ) the direct-tunneling mechanism is considered [38]. Since measured  $I_{\text{gate}}$  shows nearly linear  $L_{\text{gate}}$  dependence, the tunneling is assumed to occur along the whole channel length. Thus the final description implemented in HiSIM is [39, 40]

$$I_{\text{gate}} = q \cdot \mathbf{GLEAK1} \cdot \frac{E^2}{E_{\text{gp}}^{\frac{1}{2}}} \cdot \exp\left(-\frac{E_{\text{gp}}^{\frac{3}{2}} \cdot \mathbf{GLEAK2}}{E}\right) \cdot \sqrt{\frac{Q_{\text{i}}}{\text{const0}}} \cdot W_{\text{eff}} \cdot \mathbf{NF} \cdot L_{\text{eff}} \cdot \frac{\mathbf{GLEAK6}}{\mathbf{GLEAK6} + V_{\text{ds}}} \cdot \frac{\mathbf{GLEAK7}}{\mathbf{GLEAK7} + W_{\text{eff}} \cdot \mathbf{NF} \cdot L_{\text{eff}}} \quad (193)$$

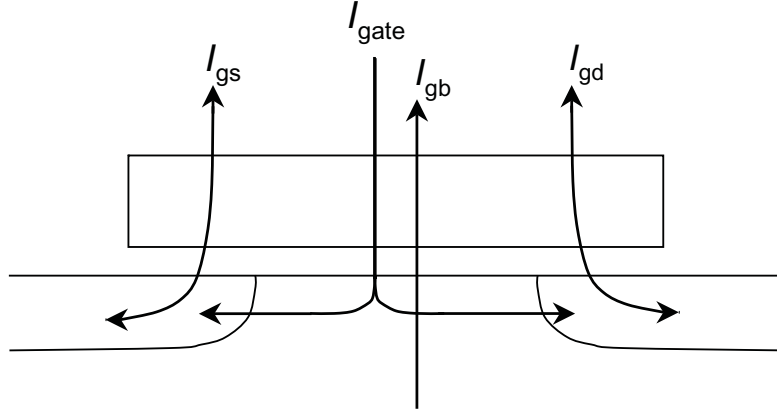


Fig. 20: Gate leakage currents considered.

where

$$E = \frac{\{V_G - \mathbf{GLEAK3} \cdot \phi_S(\Delta L)\}^2}{T_{\text{ox}}} \cdot \left(1 + \frac{E_y}{\mathbf{GLEAK5}}\right) \quad (194)$$

$$V_G = V_{\text{gs}} - \mathbf{VFBC} + \mathbf{GLEAK4} \cdot \Delta V_{\text{th}} \cdot L_{\text{eff}} \quad (195)$$

$$\Delta V_{\text{th}} = \Delta V_{\text{th,SC}} + \Delta V_{\text{th,P}} + \Delta V_{\text{th,W}} - \phi_{\text{SpG}} \quad (196)$$

**GLEAK1** – **7** are model parameters, and  $E_{\text{gp}}$  describes the temperature dependent bandgap for the gate current. The gate-channel current  $I_{\text{gate}}$  is partitioned into two terminal currents with one model parameter in the following manner.

$$I_{\text{gate}} = I_{\text{gate,s}} + I_{\text{gate,d}} \quad (197)$$

where

$$I_{\text{gate,s}} = (1 - P_{\text{artition}}) \cdot I_{\text{gate}} \quad (198)$$

$$I_{\text{gate,d}} = P_{\text{artition}} \cdot I_{\text{gate}} \quad (199)$$

where analytical description of  $P_{\text{artition}}$  is obtained by integrating the following equation

$$I_{\text{gate,d}} = \int_0^{L_{\text{eff}}} \frac{y}{L_{\text{eff}}} I_{\text{gate}}(y) dy = P_{\text{artition}} I_{\text{gate}} \quad (200)$$

The straightforward simulation result is shown in Fig. 21.

### (ii) Between Gate and Bulk, $I_{\text{gb}}$

The  $I_{\text{gb}}$  current under the accumulation condition is modeled as

$$I_{\text{gb}} = \mathbf{GLKB1} \cdot E_{\text{gb}}^2 \cdot \exp\left(-\frac{\mathbf{GLKB2}}{E_{\text{gb}}}\right) W_{\text{eff}} \cdot \mathbf{NF} \cdot L_{\text{eff}} \quad (201)$$

$$E_{\text{gb}} = -\frac{V_{\text{gs}} - \mathbf{VFBC} + \mathbf{GLKB3}}{T_{\text{ox}}} \quad (202)$$

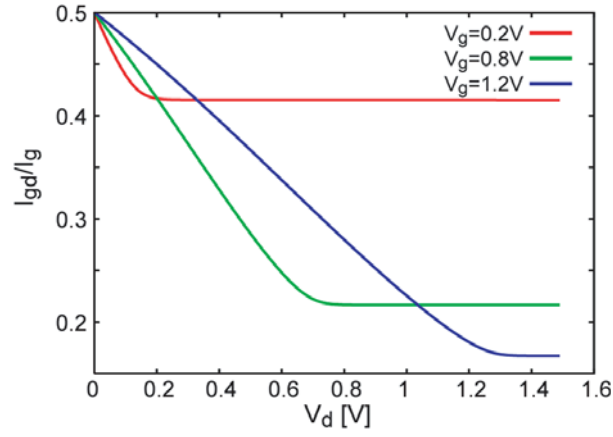


Fig. 21: Exact results of gate partitioning.

The Fowler-Nordheim tunneling mechanism is also considered

$$I_{\text{FN}} = \frac{q \cdot \mathbf{FN1} \cdot E_{\text{FN}}^2}{E_{\text{g12}}} \cdot \exp\left(-\frac{\mathbf{FN2} \cdot E_{\text{g32}}}{E_{\text{FN}}}\right) \cdot W_{\text{eff}} \cdot \mathbf{NF} \cdot L_{\text{eff}} \quad (203)$$

where

$$E_{\text{FN}} = -\frac{\mathbf{FVBS} \cdot V_{\text{bs}} - (V_{\text{gs}} - \Delta V_{\text{th,SC}} - \Delta V_{\text{th,P}}) - \mathbf{FN3}}{T_{\text{OX}}} \quad (204)$$

$$E_{\text{g32}} = E_{\text{g}} \cdot E_{\text{g12}} \quad (205)$$

$$E_{\text{g12}} = \sqrt{E_{\text{g}}} \quad (206)$$

Total substrate current is the sum of the two components as

$$I_{\text{gb}} = I_{\text{gb}} + I_{\text{FN}} \quad (207)$$

(iii) **Between Gate and Source/Drain,  $I_{\text{gs}}/I_{\text{gd}}$**

The tunneling current between the gate and the source/drain overlap region is modeled as

$$I_{\text{gs}} = \text{signGLKSD1} \cdot E_{\text{gs}}^2 \exp(T_{\text{ox}}(-\mathbf{GLKSD2} \cdot V_{\text{gs}} + \mathbf{GLKSD3})) W_{\text{eff}} \cdot \mathbf{NF} \quad (208)$$

$$E_{\text{gs}} = \frac{V_{\text{gs}}}{T_{\text{ox}}} \quad (209)$$

$$I_{\text{gd}} = \text{signGLKSD1} \cdot E_{\text{gd}}^2 \exp(T_{\text{ox}}(\mathbf{GLKSD2} \cdot (-V_{\text{gs}} + V_{\text{ds}}) + \mathbf{GLKSD3})) W_{\text{eff}} \cdot \mathbf{NF} \quad (210)$$

$$E_{\text{gd}} = \frac{V_{\text{gs}} - V_{\text{ds}}}{T_{\text{ox}}} \quad (211)$$

$$\text{sign} = +1 \quad \text{for} \quad E \leq 0$$

$$\text{sign} = -1 \quad \text{for} \quad E \geq 0$$

### 17.3 GIDL (Gate-Induced Drain Leakage)

The GIDL current is generated at the drain junction under the accumulation condition. The  $V_{ds}$  increase induces a very narrow potential well in the drain just under the gate, causing carrier generation. Therefore, the GIDL current is strongly dependent on  $V_{ds}$ . At further reduced  $V_{gs}$  values the direct gate tunneling starts to dominate the  $I_{GIDL}$  measurements, resulting in  $V_{ds}$  independence. The  $V_{ds}$  dependent  $I_{GIDL}$  is modeled here. The generation mechanism is considered to be the direct tunneling between the above mentioned narrow potential well of length  $\Delta Y$  and the ordinary drain region.

$$I_{GIDL} = \alpha I_{ds} \Delta Y \quad (212)$$

The generation occurs only in this  $\Delta Y$  region at the drain. The final equation is

$$I_{GIDL} = q \cdot \mathbf{GIDL1} \cdot \frac{E^2}{E_g^{\frac{1}{2}}} \cdot \exp\left(-\mathbf{GIDL2} \cdot \frac{E_g^{\frac{3}{2}}}{E}\right) \cdot W_{\text{eff}} \cdot \mathbf{NF} \cdot A \quad (213)$$

where

$$E = \frac{\mathbf{GIDL3} \cdot (V_{ds} + \mathbf{GIDL4}) - V'_G}{T_{\text{ox}}} \quad (214)$$

$$V'_G = V_{gs} + \Delta V_{\text{th}} \cdot \mathbf{GIDL5} \quad (215)$$

and  $A$  is introduced after BSIM4 as

$$A = \left( \frac{V_{\text{db}}^3}{V_{\text{db}}^3 + 0.5} \right) \quad (216)$$

$$V_{\text{db}} = V_{ds} - V_{bs} \quad (217)$$

Here  $\Delta V_{\text{th}}$  is defined as

$$\Delta V_{\text{th}} = \Delta V_{\text{th,SC}} + \Delta V_{\text{th,P}} \quad (218)$$

The GISL current is calculated with the same equation as the GIDL current described above. The selection either  $I_{GIDL}$  or  $I_{GISL}$  is done by the polarity of the current flow.

The HiSIM model parameters introduced in section 17 are summarized in Table 17.

Table 17: HiSIM model parameters introduced in section 17 of this manual. \* indicates minor parameters.

<b>SUB1</b>	substrate current coefficient of magnitude
<b>SUB1L</b>	$L_{gate}$ dependence <b>SUB1</b>
<b>SUB1LP</b>	$L_{gate}$ dependence <b>SUB1</b>
<b>SUB2</b>	substrate current coefficient of exponential term
<b>SUB2L</b>	$L_{gate}$ dependence of <b>SUB2</b>
<b>SVDS</b>	substrate current dependence on $V_{ds}$
<b>SLG</b>	substrate current dependence on $L_{gate}$
<b>SLGL</b>	substrate current dependence on $L_{gate}$
<b>SLGLP</b>	substrate current dependence on $L_{gate}$
<b>SVBS</b>	substrate current dependence on $V_{bs}$
<b>SVBSL</b>	$L_{gate}$ dependence of <b>SVBS</b>
<b>SVBSLP</b>	$L_{gate}$ dependence of <b>SVBS</b>
<b>SVGS</b>	substrate current dependence on $V_{gs}$
<b>SVGSL</b>	$L_{gate}$ dependence of <b>SVGS</b>
<b>SVGSLP</b>	$L_{gate}$ dependence of <b>SVGS</b>
<b>SVGSW</b>	$W_{gate}$ dependence of <b>SVGS</b>
<b>SVGSWP</b>	$W_{gate}$ dependence of <b>SVGS</b>
<b>IBPC1</b>	impact-ionization induced bulk potential change
<b>IBPC1L</b>	$L_{gate}$ length dependence of impact-ionization induced bulk potential change
<b>IBPC1LP</b>	$L_{gate}$ length dependence of impact-ionization induced bulk potential change
<b>IBPC2</b>	impact-ionization induced bulk potential change
<b>SUBLD1</b>	substrate current induced in $L_{drift}$
<b>SUBLD2</b>	substrate current induced in $L_{drift}$
<b>XPDV</b>	potential change for expansion effect
<b>XPVDTH</b>	potential change for expansion effect
<b>XPVDTHG</b>	potential change for expansion effect
<b>GLEAK1</b>	gate to channel current coefficient
<b>GLEAK2</b>	gate to channel current coefficient
<b>GLEAK3</b>	gate to channel current coefficient
<b>GLEAK4</b>	gate to channel current coefficient
<b>*GLEAK5</b>	gate to channel current coefficient ( short channel correction )
<b>*GLEAK6</b>	gate to channel current coefficient ( $V_{ds}$ dependence correction )
<b>*GLEAK7</b>	gate to channel current coefficient ( gate length and width dependence correction )
<b>*EGIG</b>	bandgap of gate leakage
<b>*IGTEMP2</b>	temperature dependence of gate leakage
<b>*IGTEMP3</b>	temperature dependence of gate leakage
<b>GLKB1</b>	gate to bulk current coefficient
<b>GLKB2</b>	gate to bulk current coefficient
<b>GLKB3</b>	flat-band shift for gate to bulk current
<b>GLKSD1</b>	gate to source/drain current coefficient
<b>GLKSD2</b>	gate to source/drain current coefficient
<b>GLKSD3</b>	gate to source/drain current coefficient
<b>GLPART1</b>	partitioning ratio of gate leakage current
<b>FN1</b>	coefficient of Fowler-Nordheim-current contribution
<b>FN2</b>	coefficient of Fowler-Nordheim-current contribution
<b>FN3</b>	coefficient of Fowler-Nordheim-current contribution
<b>FVBS</b>	$V_{bs}$ dependence of Fowler-Nordheim current
<b>GIDL1</b>	magnitude of the GIDL
<b>GIDL2</b>	field dependence of the GIDL
<b>GIDL3</b>	$V_{ds}$ dependence of the GIDL
<b>*GIDL4</b>	threshold of $V_{ds}$ dependence
<b>*GIDL5</b>	correction of high-field contribution



## 18 Source/Bulk and Drain/Bulk Diode Models

### 18.1 Diode Current

The model equations for the source/bulk and drain/bulk diode currents are based on the concepts of BSIM3v3 [42], but include a number of modifications.

The two regions denoted (a) and (b) in the schematic diagram of Fig. 22, correspond to the forward-bias current saturation and the backward-bias region, respectively. These regions are distinguished in the modeling and are treated separately according to their origins.

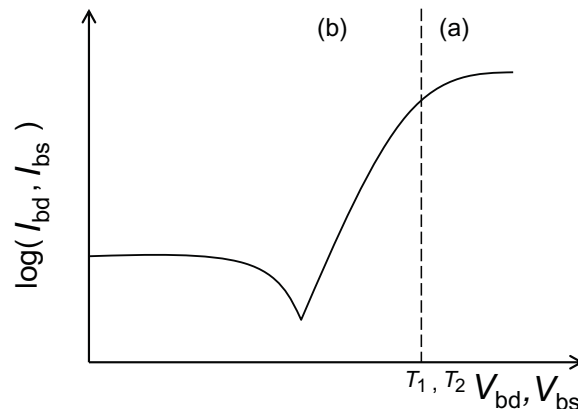


Fig. 22: The two  $I_{diode}$  currents ( $I_{bd}$  and  $I_{bs}$ ) are modeled separately in the two different operating regions (a) and (b).

The models for forward-biased current densities, describing the area and sidewall components of the source/drain regions, are given in Eqs. (219) and (220), respectively. The corresponding backward-biased current densities are given in Eqs. (221) and (222). These values include temperature dependence as described in section 14.

$$j_s = \mathbf{JS0} \quad (219)$$

$$j_{ssw} = \mathbf{JS0SW} \quad (220)$$

$$j_{s2} = \mathbf{JS0} \quad (221)$$

$$j_{ssw2} = \mathbf{JS0SW} \quad (222)$$

#### (i) Between Drain and Bulk

With these current densities and the area parameter  $AD$  and the perimeter parameter  $PD$  of the drain region, the forward and backward currents between drain and bulk are calculated as

$$I_{\text{sbd}} = AD \cdot j_s + PD \cdot j_{\text{ssw}} \quad (223)$$

$$I_{\text{sbd}2} = AD \cdot j_{s2} + PD \cdot j_{\text{ssw}2} \quad (224)$$

The resulting drain-bulk current equations in the 2 operating regions (a) and (b) are derived as follows.

a)  $V_{\text{bd}} \geq V_1$

$$\begin{aligned} I_{\text{bd}} = & I_{\text{sbd}} \left\{ \exp\left(\frac{V_1}{N_{\text{vtm}}}\right) - 1 \right\} + \frac{I_{\text{sbd}}}{N_{\text{vtm}}} \exp\left(\frac{V_1}{N_{\text{vtm}}}\right) (V_{\text{bd}} - V_1) \\ & + I_{\text{sbd}2} \cdot \mathbf{CISB} \left\{ \exp\left(-\frac{V_{\text{bd}} \mathbf{CVB}}{N_{\text{vtm}}}\right) - 1 \right\} \\ & + \mathbf{CISBK} \left\{ \exp\left(-\frac{V_{\text{bd}} \mathbf{CVB}}{N_{\text{vtm}}}\right) - 1 \right\} \end{aligned} \quad (225)$$

b)  $V_1 \geq V_{\text{bd}}$

$$\begin{aligned} I_{\text{bd}} = & I_{\text{sbd}} \left\{ \exp\left(\frac{V_{\text{bd}}}{N_{\text{vtm}}}\right) - 1 \right\} \\ & + I_{\text{sbd}2} \cdot \mathbf{CISB} \cdot \left\{ \exp\left(-\frac{V_{\text{bd}} \cdot \mathbf{CVB}}{N_{\text{vtm}}}\right) - 1 \right\} \\ & + \mathbf{CISBK} \cdot \left\{ \exp\left(-\frac{V_{\text{bd}} \cdot \mathbf{CVB}}{N_{\text{vtm}}}\right) - 1 \right\} \end{aligned} \quad (226)$$

$$N_{\text{vtm}} = \frac{\mathbf{NJ}}{\beta} \quad (227)$$

$$V_1 = N_{\text{vtm}} \cdot \log \left\{ \frac{\mathbf{VDIFFJ}}{I_{\text{sbd}}} + 1 \right\} \quad (228)$$

$$I_{\text{bd}} = I_{\text{bd}} + \mathbf{DIVX} \cdot I_{\text{sbd}2} \cdot V_{\text{bd}} \quad (229)$$

### (ii) Between Source and Bulk

The area parameter  $AS$  and the perimeter parameter  $PS$  of the source region are used to calculate the forward and backward currents between source and bulk.

$$I_{\text{sbs}} = AS \cdot j_s + PS \cdot j_{\text{ssw}} \quad (230)$$

$$I_{\text{sbs}2} = AS \cdot j_{s2} + PS \cdot j_{\text{ssw}2} \quad (231)$$

This leads to the following source-bulk current equations in the 2 operating regions (a) and (b).

a)  $V_{\text{bs}} \geq V_2$

$$\begin{aligned} I_{\text{bs}} = & I_{\text{sbs}} \left\{ \exp\left(\frac{V_2}{N_{\text{vtm}}}\right) - 1 \right\} + \frac{I_{\text{sbs}}}{N_{\text{vtm}}} \exp\left(\frac{V_2}{N_{\text{vtm}}}\right) (V_{\text{bs}} - V_2) \\ & + I_{\text{sbs}2} \cdot \mathbf{CISB} \left\{ \exp\left(-\frac{V_{\text{bs}} \mathbf{CVB}}{N_{\text{vtm}}}\right) - 1 \right\} \\ & + \mathbf{CISBK} \left\{ \exp\left(-\frac{V_{\text{bs}} \mathbf{CVB}}{N_{\text{vtm}}}\right) - 1 \right\} \end{aligned} \quad (232)$$

b)  $V_2 \geq V_{bs}$

$$\begin{aligned}
 I_{bs} = & I_{sbs} \cdot \left\{ \exp\left(\frac{V_{bs}}{N_{vtm}}\right) - 1 \right\} \\
 & + I_{sbs2} \cdot \mathbf{CISB} \cdot \left\{ \exp\left(-\frac{V_{bs} \cdot \mathbf{CVB}}{N_{vtm}}\right) - 1 \right\} \\
 & + \mathbf{CISBK} \cdot \left\{ \exp\left(-\frac{V_{bs} \cdot \mathbf{CVB}}{N_{vtm}}\right) - 1 \right\}
 \end{aligned} \tag{233}$$

$$V_2 = N_{vtm} \cdot \log\left\{\frac{\mathbf{VDIFFJ}}{I_{sbs}} + 1\right\} \tag{234}$$

$$I_{bs} = I_{bs} + \mathbf{DIVX} \cdot I_{sbs2} \cdot V_{bs} \tag{235}$$

The hard-breakdown model of the diode will be implemented in a future version of HiSIM.

## 18.2 Diode Capacitance

The diode capacitances of the source/bulk junction  $C_{apbs}$  and of the drain/bulk junction  $C_{apbd}$  are given by the following equations. These equations have the same basis as those used in BSIM3v3 [42], but include a number of minor modifications.

The notations  $\Theta = S, \theta = s$  (for source/bulk junction) and  $\Theta = D, \theta = d$  (for drain/bulk junction) apply.

$$c_{zb\theta} = \mathbf{CJ} \cdot A\Theta \tag{236}$$

(I)  $P\Theta > W_{\text{eff}}$

$$c_{zb\theta sw} = \mathbf{CJSW}(P\Theta - W_{\text{eff}} \cdot \mathbf{NF}) \tag{237}$$

$$c_{zb\theta swg} = \mathbf{CJSWG} \cdot W_{\text{eff}} \cdot \mathbf{N} \tag{238}$$

(i)  $V_{b\theta} = 0$

$$Q_{b\theta} = 0 \tag{239}$$

$$C_{apb\theta} = c_{zb\theta} + c_{zb\theta sw} + c_{zb\theta swg} \tag{240}$$

(ii)  $V_{b\theta} < 0$

a-1)  $c_{zb\theta} > 0$

$$arg = 1 - \frac{V_{b\theta}}{\mathbf{PB}} \tag{241}$$

$\alpha$ )  $\mathbf{MJ} = 0.5$

$$sarg = \frac{1}{\sqrt{arg}} \tag{242}$$

$\beta$ )  $\mathbf{MJ} \neq 0.5$

$$sarg = \exp(-\mathbf{MJ} \cdot \log(arg)) \tag{243}$$

$$Q_{b\theta} = \frac{\mathbf{PB} \cdot c_{zb\theta}(1 - arg \cdot sarg)}{1 - \mathbf{MJ}} \tag{244}$$

$$C_{apb\theta} = c_{zb\theta} \cdot sarg \tag{245}$$

a-2)  $c_{zb\theta} \leq 0$

$$Q_{b\theta} = 0 \quad (246)$$

$$C_{apb\theta} = 0 \quad (247)$$

b)  $c_{zb\theta_{sw}} > 0$

$$arg = 1 - \frac{V_{b\theta}}{\mathbf{PBSW}} \quad (248)$$

$\alpha$ )  $\mathbf{MJSW} = 0.5$

$$sarg = \frac{1}{\sqrt{arg}} \quad (249)$$

$\beta$ )  $\mathbf{MJSW} \neq 0.5$

$$sarg = \exp(-\mathbf{MJSW} \cdot \log(arg)) \quad (250)$$

$$Q_{b\theta} + = \frac{\mathbf{PBSW} \cdot c_{zb\theta_{sw}}(1 - arg \cdot sarg)}{1.0 - \mathbf{MJSW}} \quad (251)$$

$$C_{apb\theta} + = c_{zb\theta_{sw}} \cdot sarg \quad (252)$$

c)  $c_{zb\theta_{swg}} > 0$

$$arg = 1 - \frac{V_{b\theta}}{\mathbf{PBSWG}} \quad (253)$$

$\alpha$ )  $\mathbf{MJSWG} = 0.5$

$$sarg = \frac{1}{\sqrt{arg}} \quad (254)$$

$\beta$ )  $\mathbf{MJSWG} \neq 0.5$

$$sarg = \exp(-\mathbf{MJSWG} \cdot \log(arg)) \quad (255)$$

$$Q_{b\theta} + = \frac{\mathbf{PBSWG} \cdot c_{zb\theta_{swg}}(1 - arg \cdot sarg)}{1 - \mathbf{MJSWG}} \quad (256)$$

$$C_{apb\theta} + = c_{zb\theta_{swg}} \cdot sarg \quad (257)$$

(iii)  $V_{b\theta} > 0$

$$Q_{b\theta} = V_{b\theta}(c_{zb\theta} + c_{zb\theta_{sw}} + c_{zb\theta_{swg}}) + V_{b\theta}^2 \left( \frac{1}{2} \frac{c_{zb\theta} \cdot \mathbf{MJ}}{\mathbf{PB}} + \frac{1}{2} \frac{c_{zb\theta_{sw}} \cdot \mathbf{MJSW}}{\mathbf{PBSW}} + \frac{1}{2} \frac{c_{zb\theta_{swg}} \cdot \mathbf{MJSWG}}{\mathbf{PBSWG}} \right) \quad (258)$$

$$C_{apb\theta} = c_{zb\theta} + c_{zb\theta_{sw}} + c_{zb\theta_{swg}} + V_{b\theta} \left( \frac{c_{zb\theta} \cdot \mathbf{MJ}}{\mathbf{PB}} + \frac{c_{zb\theta_{sw}} \cdot \mathbf{MJSW}}{\mathbf{PBSW}} + \frac{c_{zb\theta_{swg}} \cdot \mathbf{MJSWG}}{\mathbf{PBSWG}} \right) \quad (259)$$

(II)  $P\Theta \leq W_{\text{eff}}$

$$c_{zb\theta_{swg}} = \mathbf{CJSWG} \cdot P\Theta \quad (260)$$

(i)  $V_{b\theta} = 0$

$$Q_{b\theta} = 0 \quad (261)$$

$$C_{apb\theta} = c_{zb\theta} + c_{zb\theta_{swg}} \quad (262)$$

(ii)  $V_{b\theta} < 0$

a-1)  $c_{zb\theta} > 0$ 

$$arg = 1 - \frac{V_{b\theta}}{\mathbf{PB}} \quad (263)$$

 $\alpha)$   $\mathbf{MJ} = 0.5$ 

$$sarg = \frac{1}{\sqrt{arg}} \quad (264)$$

 $\beta)$   $\mathbf{MJ} \neq 0.5$ 

$$sarg = \exp(-\mathbf{MJ} \cdot \log(arg)) \quad (265)$$

$$Q_{b\theta} = \frac{\mathbf{PB} \cdot c_{zb\theta}(1 - arg \cdot sarg)}{1 - \mathbf{MJ}} \quad (266)$$

$$C_{apb\theta} = c_{zb\theta} \cdot sarg \quad (267)$$

 a-2)  $c_{zb\theta} \leq 0$ 

$$Q_{b\theta} = 0 \quad (268)$$

$$C_{apb\theta} = 0 \quad (269)$$

 b)  $c_{zb\theta\text{swg}} > 0$ 

$$arg = 1 - \frac{V_{b\theta}}{\mathbf{PBSWG}} \quad (270)$$

 $\alpha)$   $\mathbf{MJSWG} = 0.5$ 

$$sarg = \frac{1}{\sqrt{arg}} \quad (271)$$

 $\beta)$   $\mathbf{MJSWG} \neq 0.5$ 

$$sarg = \exp(-\mathbf{MJSWG} \cdot \log(arg)) \quad (272)$$

$$Q_{b\theta} + = \mathbf{PBSWG} \cdot c_{zb\theta\text{swg}} \cdot \frac{1 - arg \cdot sarg}{1 - \mathbf{MJSWG}} \quad (273)$$

$$C_{apb\theta} + = c_{zb\theta\text{swg}} \cdot sarg \quad (274)$$

 (iii)  $V_{b\theta} > 0$ 

$$Q_{b\theta} = V_{b\theta} \cdot (c_{zb\theta} + c_{zb\theta\text{swg}}) + V_{b\theta}^2 \left( \frac{1}{2} \frac{c_{zb\theta} \cdot \mathbf{MJ}}{\mathbf{PB}} + \frac{1}{2} \frac{c_{zb\theta\text{swg}} \cdot \mathbf{MJSWG}}{\mathbf{PBSWG}} \right) \quad (275)$$

$$C_{apb\theta} = c_{zb\theta} + c_{zb\theta\text{swg}} + V_{b\theta} \left( \frac{c_{zb\theta} \cdot \mathbf{MJ}}{\mathbf{PB}} + \frac{c_{zb\theta\text{swg}} \cdot \mathbf{MJSWG}}{\mathbf{PBSWG}} \right) \quad (276)$$

The HiSIM model parameters introduced in section 18 are summarized in Table 18.

Table 18: HiSIM model parameters introduced in section 18 of this manual. # indicates instance parameters.

<b>JS0</b>	saturation current density
<b>JS0SW</b>	sidewall saturation current density
<b>NJ</b>	emission coefficient
<b>NJSW</b>	sidewall emission coefficient
<b>DIVX</b>	reverse current coefficient
<b>CISB</b>	reverse biased saturation current
<b>CVB</b>	bias dependence coefficient of <b>CISB</b>
<b>CISBK</b>	reverse biased saturation current ( at low temperature )
<b>CVBK</b>	bias dependence coefficient of <b>CISB</b> ( at low temperature )
<b>MJ</b>	bottom junction capacitance grading coefficient
<b>MJSW</b>	source/drain sidewall junction capacitance grading coefficient
<b>MJSWG</b>	source/drain gate sidewall junction capacitance grading coefficient
<b>PB</b>	bottom junction build-in potential
<b>PBSW</b>	source/drain sidewall junction build-in potential
<b>PBSWG</b>	source/drain gate sidewall junction build-in potential
<b>VDIFFJ</b>	diode threshold voltage between source/drain and substrate
<b>#AD</b>	junction area of the drain contact
<b>#PD</b>	junction periphery of the drain contact
<b>#AS</b>	junction area of the source contact
<b>#PS</b>	junction periphery of the source contact

## 19 Noise Models

### 19.1 1/f Noise Model

The 1/f noise is caused by both the carrier fluctuation and the mobility fluctuation. The final description for the drift-diffusion model is [43]

$$S_{I_{ds}} = \frac{I_{ds}^2 \mathbf{NFTRP}}{\beta f (L_{\text{eff}} - \Delta L) W_{\text{eff}} \cdot \mathbf{NF}} \left[ \frac{1}{(N_0 + N^*)(N_L + N^*)} + \frac{2\mu E_y \mathbf{NFALP}}{N_L - N_0} \ln \left( \frac{N_L + N^*}{N_0 + N^*} \right) + (\mu E_y \mathbf{NFALP})^2 \right] \quad (277)$$

where the parameters  $\mathbf{NFALP}$  and  $\mathbf{NFTRP}$  represent the contribution of the mobility fluctuation and the ratio of trap density to attenuation coefficient, respectively.  $N_0$  and  $N_L$  are carrier densities at source side and drain side or pinch-off point, respectively, as calculated in HiSIM.  $N^*$  is written as

$$N^* = \frac{C_{\text{ox}} + C_{\text{dep}} + \mathbf{CIT}}{q\beta} \quad (278)$$

where  $C_{\text{dep}}$  is the depletion capacitance calculated with  $\phi_s$ .  $\mathbf{CIT}$  is the capacitance caused by the interface-trapped carriers and is normally fixed to be zero.

$$N_{\text{flick}} = S_{I_{ds}} \cdot f^{\mathbf{FALPH}} \quad (279)$$

is calculated in HiSIM, where  $\mathbf{FALPH}$  has been introduced to model the deviation from the exact 1/f characteristic.

### 19.2 Thermal Noise Model

Van der Ziel derived the equation for the spectral density of the thermal drain-noise current at temperature  $T$  by integrating the transconductance along the channel direction  $y$  based on the Nyquist theorem [44]

$$S_{id} = \frac{4kT}{L_{\text{eff}}^2} \int g_{ds}(y) dy = 4kT g_{ds0} \gamma \quad (280)$$

Here  $k$ ,  $I_{ds}$ ,  $g_{ds}(y)$ ,  $g_{ds0}$ ,  $\gamma$  are Boltzmann's constant, drain current, position-dependent channel conductance, channel conductance at  $V_{ds} = 0$ , and drain-noise coefficient, respectively. In HiSIM the integration is performed with the surface potential  $\phi_s$  instead of the channel position as [45, 46]

$$S_{id} = \frac{4kT}{L_{\text{eff}}^2 I_{ds}} \int g_{ds}^2(\phi_s) d\phi_s \quad (281)$$

$$g_{ds}(\phi_s) = \frac{W_{\text{eff}} \cdot \mathbf{NF}}{L_{\text{eff}}} \beta \frac{d(\mu(\phi_s) f(\phi_s))}{d\phi_s} \quad (282)$$

Here  $f(\phi_s)$  is a characteristic function of HiSIM related to the carrier concentration [47]. The final equations for  $S_{id}$  in our compact-modeling approach, obtained after solving the integral of Eq. (281), become functions of the self-consistent surface potentials as well as the surface-potential derivatives at source and drain.

$$S_{id} = 4kT \frac{W_{\text{eff}} \cdot \mathbf{NFC}_{\text{ox}} V g V t \mu (1 + 3\eta + 6\eta^2) \mu_d^2 + (3 + 4\eta + 3\eta^2) \mu_d \mu_s + (6 + 3\eta + \eta^2) \mu_s}{(L_{\text{eff}} - \Delta L) 15(1 + \eta) \mu_{\text{av}}^2} \quad (283)$$

where  $\mu_s$ ,  $\mu_d$  and  $\mu_{av}$  are mobilities at the source side, the drain side, and averaged, respectively.

$$\eta = 1 - \frac{(\phi_{SL} - \phi_{S0}) + \chi(\phi_{SL} - \phi_{S0})}{V_g V_t} \quad (284)$$

$$\chi = 2 \frac{cnst0}{C_{ox}} \left[ \left[ \frac{2}{3} \frac{1}{\beta} \frac{\{\beta(\phi_{SL} - V_{bs}) - 1\}^{\frac{3}{2}} - \{\beta(\phi_{S0} - V_{bs}) - 1\}^{\frac{3}{2}}}{\phi_{SL} - \phi_{S0}} \right] - \sqrt{\beta(\phi_{S0} - V_{bs}) - 1} \right] \quad (285)$$

$V_g V_t$  is equal to the carrier density at the source side divided by the oxide capacitance.

Thus no additional model parameters are required for the thermal noise model.

$$N_{thrm1} = S_{id}/4kT \quad (286)$$

is calculated in HiSIM.

### 19.3 Induced Gate Noise Model

No additional model parameters are required for the induced gate noise model.

$$N_{igate} = S_{igate}/f^2 \quad (287)$$

is calculated in HiSIM. Explicit model equation were presented at SISPAD in 2006 [48].

### 19.4 Coupling Noise Model

No additional model parameters are required for the coupling noise model.

$$N_{cross} = \frac{S_{igid}}{\sqrt{S_{igate} \cdot S_{id}}} \quad (288)$$

is calculated in HiSIM. Explicit model equation were presented at SISPAD in 2006 [48].

The HiSIM model parameters introduced in section 19 are summarized in Table 19.

Table 19: HiSIM model parameters introduced in section 19 of this manual. \* indicates a minor parameter.

<b>NFTRP</b>	ratio of trap density to attenuation coefficient
<b>NFALP</b>	contribution of the mobility fluctuation
<b>*CIT</b>	capacitance caused by the interface trapped carriers
<b>FALPH</b>	power of $f$ describing deviation of $1/f$



## 20 Non-Quasi-Static (NQS) Model

### 20.1 Carrier Formation

To consider the carrier transit delay in HiSIM, the carrier formation is modeled as [49, 50, 51]

$$q(t_i) = \frac{q(t_{i-1}) + \frac{\Delta t}{\tau} Q(t_i)}{1 + \frac{\Delta t}{\tau}} \quad (289)$$

where  $q(t_i)$  and  $Q(t_i)$  represent the non-quasi-static and the quasi-static carrier density at time  $t_i$ , respectively, and  $\Delta t = t_i - t_{i-1}$  is valid. The delay is determined by the carrier transit delay  $\tau$  and the time interval in the circuit simulation  $\Delta t$ .

### 20.2 Delay Mechanisms

Up to weak inversion:

$$\tau_{\text{diff}} = \mathbf{DLY1} \quad (290)$$

At strong inversion:

$$\tau_{\text{cond}} = \mathbf{DLY2} \cdot \frac{Q_i}{I_{\text{ds}}} \quad (291)$$

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{diff}}} + \frac{1}{\tau_{\text{cond}}} \quad (292)$$

For the formation of bulk carriers:

$$\tau_{\text{B}} = \mathbf{DLY3} \cdot C_{\text{ox}} \quad (293)$$

where  $\mathbf{DLY3}$  is a constant coefficient and  $C_{\text{ox}}$  is the oxide capacitance. From the HiSIM\_HV 1.1.0 version this NQS model is implemented in the network form as shown in Fig. 23.

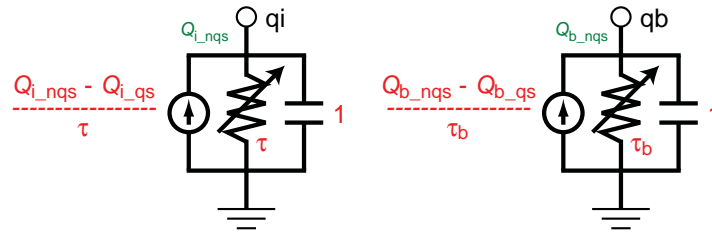


Fig. 23: NQS model implementation into circuit simulator.

### 20.3 Time-Domain Analysis

The total drain/source/bulk terminal currents are derived from the superposition of the transport current and the charging current. The transport current is a function of the instantaneous terminal voltages and is approximated by the steady-state solution. The source/drain/bulk charging currents are the time derivatives of the associated non-quasi-static charges,  $q_S$ ,  $q_D$ , and  $q_B$ , respectively.

For LDMOS/HVMOS, carrier transit delay effect in the drift region is included as the  $RC$  delay. The resistance  $R$  and the capacitance  $C$  contributing the delay are taken calculated in HiSIM\_HV. If the resistance in the drift region is large, the delay becomes automatically large.

## 20.4 AC Analysis

The load file is rewritten from the HiSIM\_HV 1.1.0 version so that the internal node is seen explicitly. Thus, the calculation procedure becomes different from the older versions, however, the formulae used for the calculation are the same.

The HiSIM model parameters introduced in section 20 are summarized in Table 20.

Table 20: HiSIM model parameters introduced in section 20 of this manual.

<b>DLY1</b>	coefficient for delay due to diffusion of carriers
<b>DLY2</b>	coefficient for delay due to conduction of carriers
<b>DLY3</b>	coefficient for RC delay of bulk carriers
<b>DLYDFT</b>	coefficient for carrier transit delay: inactivated
<b>DLYOV</b>	coefficient for RC delay of carriers: inactivated

## 21 Self-Heating Effect Model

The self-heating effect is modeled with the thermal network shown in Fig. 24. The flag **COSELFHEAT** must be equal to one and **RTH0** must not be equal to zero to activate the model. The temperature node must not be zero, if the self-heating effect is switched on. The SHE should be switched on/off only with the model flag **COSELFHEAT**. The temperature node is automatically generated in circuit simulator for each device as other bias nodes. First, the model core (HiSIMhv.eval) is called to evaluate device characteristics without heating. Then, the temperature is updated considering the self-heating effect by creating the temperature node. The model core is called again to update the device characteristics with the calculated temperature  $T$ . Under the DC condition the temperature increase is calculated analytically as

$$T = T + R_{th} \cdot I_{ds} \cdot V_{ds} \quad (294)$$

where  $R_{th}$  as well as  $C_{th}$  are a function of  $W_{eff}$  as

$$R_{th} = \frac{R_{th0}}{W_{eff}} \cdot \left( \frac{1}{\mathbf{NF}^{\mathbf{RTH0NF}}} \right) \left( 1 + \frac{\mathbf{RTH0W}}{(W_{gate} \cdot 10^6)^{\mathbf{RTH0WP}}} \right) \quad (295)$$

$$R_{th0} = \mathbf{RTH0} + \mathbf{RTHTEMP1} \cdot (T0 - \mathbf{TNOM}) + \mathbf{RTHTEMP2} \cdot (T0^2 - \mathbf{TNOM}^2) \quad (296)$$

$$C_{th} = \mathbf{CTH0} \cdot W_{eff} \quad (297)$$

The model parameter **RTH0** is fitted to measured DC data, and the model parameter **CTH0** is introduced for AC fitting.

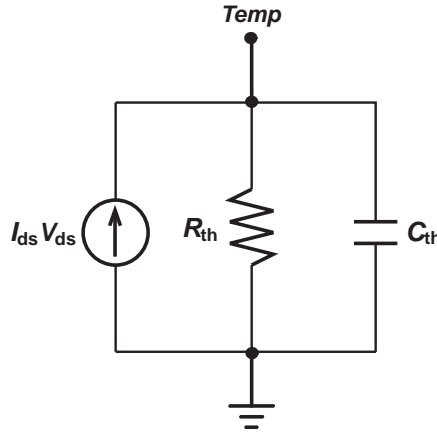


Fig. 24: Thermal Network applied for the self-heating effect.

The thermal dissipation is modeled as [54]

$$T = T + R_{th} \cdot I_{ds} \cdot V'_{ds} \quad (298)$$

$$V'_{ds} = V_{dsi} + POW_{ratio}(V_{ds} - V_{dsi}) \quad (299)$$

$$POW_{ratio} = \mathbf{POWRAT} + \mathbf{PRATTEMP1} \cdot (T0 - \mathbf{TNOM}) + \mathbf{PRATTEMP2} \cdot (T0^2 - \mathbf{TNOM}^2) \quad (300)$$

where **POWRAT** is a model parameter. The external node potential is represented by  $V_{ds}$  and the internal node potential within the drift region at the channel/drift junction is by  $V_{dsi}$ , which is calculated during the SPICE simulation.

A limiter for the temperature increase due to the self-heating effect **SHEMAX** is introduced to avoid drastic artificial temperature increase during circuit simulations.

The HiSIM model parameters introduced in section 21 are summarized in Table 21.

Table 21: HiSIM model parameters introduced in section 21 of this manual.

<b>RTH0</b>	thermal resistance
<b>RTHTEMP1</b>	temperature dependence of thermal resistance
<b>RTHTEMP2</b>	temperature dependence of thermal resistance
<b>CTH0</b>	thermal capacitance
<b>RTH0W</b>	width dependence of thermal resistance
<b>RTH0WP</b>	width dependence of thermal resistance
<b>RTH0NF</b>	number of finger dependence of thermal resistance
<b>RTH0R</b>	thermal dissipation: inactivated
<b>POWRAT</b>	thermal dissipation
<b>PRATTEMP1</b>	temperature dependence of thermal dissipation
<b>PRATTEMP2</b>	temperature dependence of thermal dissipation
<b>SHEMAX</b>	maximum temperature increase

## 22 DFM Model

To support design for manufacturability (DFM) HiSIM introduces an option for considering the variation of device parameters.

Accurate prediction of device performance for a wide range of the substrate-impurity-concentration variations is secured by introducing an impurity concentration dependent mobility due to the phonon scattering as

$$M_{\text{uephonon}} = \mathbf{MUEPH1} [\mathbf{MPHDFM} \{\ln(\mathbf{NSUBCDFM}) - \ln(N_{\text{subc}})\} + 1]$$

$$\mathbf{NSUBP} = \mathbf{NSUBP} + (N_{\text{SUBCDFM}} - N_{\text{subc}}) \quad (301)$$

$$\mathbf{NEXT} = \mathbf{NEXT} + (\mathbf{NSUBCDFM} - N_{\text{subc}}) \quad (302)$$

where **NSUBCDFM** is an instance parameter and **MPHDFM** is a model parameter describing the mobility reduction due to the increase of the substrate impurity concentration. This model is activated if the model flag **CODFM** = 1, and **NSUBCDFM** is also given.

The HiSIM model parameters introduced in section 22 are summarized in Table 22.

Table 22: HiSIM model parameters introduced in section 22 of this manual. # indicates an instance parameter.

# <b>NSUBCDFM</b>	substrate impurity concentration
<b>MPHDFM</b>	mobility dependence of $N_{\text{subc}}$ due to $\mu_{\text{phonon}}$

## 23 Depletion Mode Model Option

To support depletion mode LDMOS/HVMOS devices, an option for considering the new structure is introduced in HiSIM\_HV.

In the depletion mode LDMOS/HVMOS, an  $N^-$  layer is constructed at the channel surface of conventional LDMOS/HVMOS devices as shown Fig. 25.

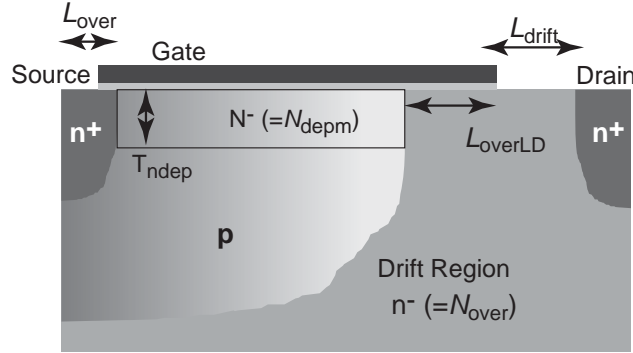


Fig. 25: Schematic of the typical depletion mode LDMOS structure and device parameters.

where  $N_{dep}$  denotes the impurity concentration of the  $N^-$  Layer, and  $T_{ndep}$  denotes the thickness of the  $N^-$  layer. This model is activated if the model flag **CODEP** = 1( default = 0 ).

Fig. 26 shows the potential and the electron carrier density distribution along the channel cross section of a depletion mode LDMOS.

In such a depletion mode LDMOS device, the electron carriers in the  $N^-$  layer strongly influence both, the current and capacitance characteristics. Therefore, the Poisson equation is solved for majority carrier under the consideration of the P/N junction depletion charge in the LDMOS/HVMOS depletion mode model.

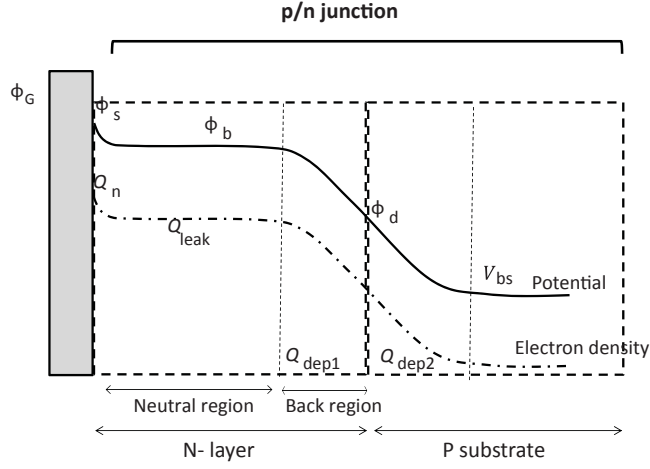


Fig. 26: Potential and electron carrier density distribution along the channel cross section of the depletion mode LDMOS.

### 23.1 DC current equation

The total drain current  $I_{ds}$  is written as follows

$$I_{ds} = \frac{W_{\text{eff,nf}}}{L_{\text{ch}}} \cdot \frac{1}{\beta} (\mu \cdot I_{dd}) + I_{ds,\text{resistor}} + I_{ds,\text{back}} \quad (303)$$

where,

$$I_{dd} = -\beta \frac{(Q_{n0} + Q_{nl})}{2} \cdot \phi_{ds} - Q_{n0} + Q_{nl} \quad (304)$$

$$I_{ds,\text{resistor}} = W_{\text{eff,nf}} \cdot Q_{\text{leak,resistor0}} \cdot \mu_{\text{leak,resistor}} \cdot \frac{V_{ds,\text{eff}}}{L_{\text{ch}}} \quad (305)$$

$$I_{ds,\text{back}} = W_{\text{eff,nf}} \cdot Q_{\text{leak,back0}} \cdot \mu_{\text{leak,back}} \cdot \frac{V_{ds,\text{eff}}}{L_{\text{ch}}} \quad (306)$$

$$Q_{\text{leak,resistor0}} = -q \cdot \text{NDEPM} \cdot (\text{TNDEP} - W_s - W_b) \quad (307)$$

$$Q_{\text{leak,back0}} = -q \cdot \text{NDEPM} \cdot \exp\{\beta(\phi_{b0} - V_{ds,\text{eff}})\} \cdot W_b \quad (308)$$

$V_{ds,\text{eff}}$  denotes the effective potential at the drain side in the resistor part and is defined as follows.

$$V_{ds,\text{eff}} = \frac{\text{DEPVDSEF2} \cdot V_{ds}}{\left[1 + \left(\frac{V_{ds}}{V_{ds,\text{sat}}}\right)^\Delta\right]^{\frac{1}{\Delta}}} \quad (309)$$

where

$$V_{ds,sat} = \left[ V_{gp} + \mathbf{DEPVDSEF1} + \frac{q\mathbf{NDEPM}\epsilon_{Si}}{C_{ox}^2} \left\{ 1 - \sqrt{1 + 2 \frac{C_{ox}^2}{q\mathbf{NDEPM}\epsilon_{Si}} \left\{ V_{gp} + \mathbf{DEPVDSEF1} - \frac{1}{\beta} - V_{bs} \right\}} \right\} \right] \quad (310)$$

$Q_{n0}$  and  $Q_{n1}$  denote the accumulation charge in the  $N^-$  layer at the source side and the drain side, respectively.  $Q_{leak,resistor0}$  denotes the charge in the resistor part at the source side. Furthermore,  $Q_{leak,back0}$  denotes the charge in the back part(see Fig. 26) at the source side.

## 23.2 Mobility model

The mobility in each part is written with following equations.

a) Surface mobility:

$$\mu = \frac{\mu_0}{\left( 1 + \left( \frac{\mu_0 E_y}{V_{max}} \right)^{\mathbf{BB}} \right)^{\frac{1}{\mathbf{BB}}}} \quad (311)$$

where,

$$Q_{iumue} = -Q_{n0} \quad (312)$$

$$R_{ns} = \frac{Q_{iumue}}{q} \quad (313)$$

$$E_{eff} = \frac{\left( \frac{\mathbf{NINV}}{\epsilon_{Si}} \right) \cdot Q_{iumue}}{1 + (\phi_{s1} - \phi_{s0}) \cdot \mathbf{NINVD}} \quad (314)$$

$$\mu_{CB} = \mathbf{MUECB0} + \mathbf{MUECB1} \cdot \frac{R_{ns}}{10^{11}} \quad (315)$$

$$\mu_{PH} = \frac{M_{uephonon}}{E_{eff} \mathbf{MUEPH0}} \quad (316)$$

$$\mu_{SR} = \frac{\mathbf{MUESR1}}{E_{eff} M_{uesurface}} \quad (317)$$

$$\frac{1}{\mu_0} = \frac{1}{\mu_{CB}} + \frac{1}{\mu_{PH}} + \frac{1}{\mu_{SR}} \quad (318)$$

b) Mobility of the resistor part:

$$\mu_{leak,resistor} = \frac{\mu_0}{\left( 1 + \left( \frac{\mu_0 E_y}{\mathbf{DEPVMAX}} \right)^{\mathbf{DEPB B}} \right)^{\frac{1}{\mathbf{DEPB B}}}} \quad (319)$$

$$(320)$$



where,

$$E_y = \frac{V_{ds,eff}}{L_{ch}} \quad (321)$$

$$Q_{iumue} = -Q_{leak,resistor0} \quad (322)$$

$$R_{ns} = \frac{Q_{iumue}}{q} \quad (323)$$

$$E_{eff} = \frac{Q_{iumue}}{1 + (\phi_{sl} - \phi_{s0}) \cdot \mathbf{NINVD}} \quad (324)$$

$$\mu_{CB} = \mathbf{DEPMUE0} + \mathbf{DEPMUE1} \cdot \frac{R_{ns}}{10^{11}} \quad (325)$$

$$\mu_{PH} = \frac{DEP_{muephonon}}{E_{eff} \mathbf{DEPMUEPH0}} \quad (326)$$

$$\frac{1}{\mu_0} = \frac{1}{\mu_{CB}} + \frac{1}{\mu_{PH}} \quad (327)$$

c) Mobilty of the back part:

$$\mu_{leak,back} = \frac{\mu_0}{\left(1 + \left(\frac{\mu_0 E_y}{\mathbf{DEPVMAX}}\right)^{\mathbf{DEPBB}}\right)^{\frac{1}{\mathbf{DEPBB}}}} \quad (328)$$

$$(329)$$

where,

$$E_y = \frac{V_{ds,eff}}{L_{ch}} \quad (330)$$

$$Q_{iumue} = -Q_{leak,back0} \quad (331)$$

$$R_{ns} = \frac{Q_{iumue}}{q} \quad (332)$$

$$E_{eff} = \frac{Q_{iumue}}{1 + (\phi_{sl} - \phi_{s0}) \cdot \mathbf{NINVD}} \quad (333)$$

$$\mu_{CB} = \mathbf{DEPMUEBACK0} + \mathbf{DEPMUEBACK1} \cdot \frac{R_{ns}}{10^{11}} \quad (334)$$

$$\mu_{PH} = \frac{DEP_{muephonon}}{E_{eff} \mathbf{DEPMUEPH0}} \quad (335)$$

$$\frac{1}{\mu_0} = \frac{1}{\mu_{CB}} + \frac{1}{\mu_{PH}} \quad (336)$$

### 23.3 Quasi-Fermi potential model

In the depletion mode LDMOS/HVMOS model, the quasi-Fermi potential( $V_{ds,mod}$ ) at the drain side is written with following equation.

$$V_{ds,mod} = \frac{V_{ds}}{\left[1 + \left(\frac{V_{ds}}{V_{ds,sat}}\right)^\Delta\right]^{\frac{1}{\Delta}}} \quad (337)$$

where

$$V_{ds,sat} = \left[ V_{gp} + \frac{q\text{NDEPM}\epsilon_{Si}}{C_{ox}^2} \left\{ 1 - \sqrt{1 + 2 \frac{C_{ox}^2}{q\text{NDEPM}\epsilon_{Si}} \left\{ V_{gp} - \frac{1}{\beta} - V_{bs} \right\}} \right\} \right] \quad (338)$$

The HiSIM model parameters introduced in section 23 are summarized in Table 23.

Table 23: HiSIM model parameters introduced in section 23 of this manual.

<b>CODEP</b>	model flag to select the depletion model
<b>NDEPM</b>	impurity concentration of the surface N <sup>-</sup> layer
<b>TNDEP</b>	thickness of the surface N <sup>-</sup> layer
<b>DEPMUE0</b>	Coulomb scattering of the resistor part
<b>DEPMUE1</b>	Coulomb scattering of the resistor part
<b>DEPMUEBACK0</b>	Coulomb scattering of the back part
<b>DEPMUEBACK1</b>	Coulomb scattering of the back part
<b>DEPMUEPH0</b>	Phonon scattering of the resistor part
<b>DEPMUEPH1</b>	Phonon scattering of the resistor part
<b>DEPVMAX</b>	saturation velocity
<b>DEPB</b>	high-field-mobility degradation
<b>DEPLEAK</b>	leakage current coefficient
<b>DEPETA</b>	$V_{ds}$ dependence of the threshold voltage shift
<b>DEPVDSEF1</b>	effective drain potential coefficient-1
<b>DEPVDSEF2</b>	effective drain potential coefficient-2
<b>DEPMUETMP</b>	temperature dependence of the phonon scattering
<b>DEPVTMP</b>	temperature dependence of the saturation velocity

## 24 Exclusion of Modeled Effects and Model Flags

1. To exclude specific modeled effects, following parameter settings should be chosen:

Short-Channel Effect	<b>SC1 = SC2 = SC3 = 0</b>
Reverse-Short-Channel Effect	<b>LP = 0</b>
Quantum-Mechanical Effect	<b>QME1 = QME3 = 0</b>
Poly-Depletion Effect	<b>PGD1 = PGD2 = 0</b>
Channel-Length Modulation	<b>CLM1 = CLM2 = CLM3 = 0</b>
Narrow-Channel Effect	<b>WFC = MUEPHW = WL1 = 0</b>
Small-Size Effect	<b>WL2 = 0</b>

Following flags are prepared to select required model options.

2. Selection for asymmetrical (LDMOS) or HV-MOS structure is done:

**COSYM = 0:** LDMOS (default)

**COSYM = 1:** symmetrical/asymmetrical HV-MOS

3. Contact resistances  $R_s$  and  $R_d$  are included:

**CORSRD = 0:** no

**CORSRD = 1 & RS/RD  $\neq$  0:** yes, as internal resistance nodes

**CORSRD = 2 & RD  $\neq$  0:** yes, analytical description

**CORSRD = 3 & RD  $\neq$  0:** yes, both internal nodes and analytical description

(default)

**CORSRD = -1 & RS/RD  $\neq$  0:** yes, as external resistance nodes

4. Overlap charges/capacitances are added to intrinsic ones:

**COADOV = 0:** no

**COADOV = 1:** yes (default)

5. Bias dependent overlap capacitance model is selected at drain side:

**COOVLP = 0:** constant overlap capacitance

**COOVLP = 1:** yes (default) including constant values as option

6. Bias dependent overlap capacitance model is selected at source side:

**COOVLPS = 0:** constant overlap capacitance (default)

**COOVLPS = 1:** yes including constant values as option

7. Method for calculating potential in overlap region is selected:

**COQOVSM = 0:** analytical equation excluding inversion charge

**COQOVSM = 1:** iterative solution (default)

**COQOVSM = 2:** analytical equation including inversion charge

8. Self-Heating Effect is considered:

**COSELFHEAT = 0:** no (default)

**COSELFHEAT = 1:** yes

9. Substrate current  $I_{\text{sub}}$  is calculated:

**COISUB** = 0: no (default)

**COISUB** = 1: yes

10. Gate current  $I_{\text{gate}}$  is calculated:

**COIIGS** = 0: no (default)

**COIIGS** = 1: yes

11. GIDL current  $I_{\text{GIDL}}$  is calculated:

**COGIDL** = 0: no (default)

**COGIDL** = 1: yes

12. STI leakage current  $I_{\text{ds,STI}}$  is calculated:

**COISTI** = 0: no (default)

**COISTI** = 1: yes

CAUTION: This model is not supported yet in the depletion mode model.

13. Non-quasi-static mode is invoked:

**CONQS** = 0: no (default)

**CONQS** = 1: yes

14. Gate-contact resistance is included:

**CORG** = 0: no (default)

**CORG** = 1: yes

15. Substrate resistance network is invoked:

**CORBNET** = 0: no (default)

**CORBNET** = 1: yes

16.  $1/f$  noise is calculated:

**COFLICK** = 0: no (default)

**COFLICK** = 1: yes

17. Thermal noise is calculated:

**COTHRML** = 0: no (default)

**COTHRML** = 1: yes

CAUTION: This model is not supported yet in the depletion mode model.

18. Induced gate and cross correlation noise are calculated:

**COIGN** = 0 || **COTHRML** = 0: no (default)

**COIGN** = 1 & **COTHRML** = 1: yes

CAUTION: This model is not supported yet in the depletion mode model.

19. Previous  $\phi_S$  is used for the iteration:

**COPPRV** = 0: no

**COPPRV** = 1: yes (default)

20. Parameter variations for the DFM support is considered:

**CODFM** = 0: no (default)

**CODFM** = 1: yes

21. Previous  $I_{ds}$  is used for calculating source/drain resistance effect ( $R_s$  and/or  $R_d \neq 0$ ): This flag is inactivated.

**COIPRV** = 0:

**COIPRV** = 1:

22. Selection for temperature dependence of models:

	$R_{d0,temp}$	$R_{dvd,temp}$	$V_{max}$	$N_{invd}$
<b>COTEMP</b> = 0:	$T$	$T0$	$T0$	$T0$ :default & backward compatible
<b>COTEMP</b> = 1:	$T0$	$T0$	$T0$	$T0$
<b>COTEMP</b> = 2:	$T$	$T$	$T$	$T$
<b>COTEMP</b> = 3:	$T$	$T$	$T0$	$T0$

where  $T$  includes the temperature increase by the self-heating effect and  $T0$  is without.

23. Selection for the 5th node:

**COSUBNODE** = 0: the 5th node is the thermal node.

**COSUBNODE** = 1: the 5th node is the  $V_{sub}$  node.

24. Selection for  $R_{drift}$  model:

**CORDRIFT** = 0: old model provided for earlier versions of HiSIM\_HV 1.

**CORDRIFT** = 1: new model (default).

25. Selection for output message whether model parameter is within recommendend range:

**COERRREP** = 0: no message is given.

**COERRREP** = 1: range check result is given (default).

26. Selection for the depletion mode model:

**CODEP** = 0: conventional HVMOS/LDMOS model (default).

**CODEP** = 1: depletion mode HVMOS/LDMOS model.

27. Selection for the  $V_{ds,sat}$  model :

**CODDLT** = 0: previous  $V_{ds,sat}$  model.

**CODDLT** = 1: new  $V_{ds,sat}$  model (default).

## 25 List of Instance Parameters

Partly the same instance-parameter names and their definitions as in the BSIM3/4 models are adopted for the convenience of HiSIM users. The HiSIM Research Group wishes to acknowledge the UC Berkeley BSIM Research Group for the introduction of these instance parameters.

<b>L</b>	gate length ( $L_{gate}$ ) default: $\mathbf{L} = 2\mu m$
<b>W</b>	gate width ( $W_{gate}$ ) default: $\mathbf{W} = 2\mu m$
	** Diode **
<b>AD</b>	area of drain junction
<b>AS</b>	area of source junction
<b>PD</b>	perimeter of drain junction
<b>PS</b>	perimeter of source junction
	** Source/Drain Resistance **
<b>NRS</b>	number of source squares
<b>NRD</b>	number of drain squares
	** Gate Resistance **
<b>XGW</b>	distance from the gate contact to the channel edge
<b>XGL</b>	offset of the gate length
<b>NF</b>	number of gate fingers
<b>M</b>	multiplication factor
<b>NGCON</b>	number of gate contacts
	** Substrate Network **
<b>RBPB</b>	substrate resistance network
<b>RBPD</b>	substrate resistance network
<b>RBPS</b>	substrate resistance network
<b>RBDB</b>	no more used
<b>RBSB</b>	no more used
	** Length of Diffusion **
<b>SA</b>	length of diffusion between gate and STI
<b>SB</b>	length of diffusion between gate and STI
<b>SD</b>	length of diffusion between gate and gate
	** Temperature **
<b>DTEMP</b>	device temperature change
	** Design for Manufacturability **
<b>NSUBCDFM</b>	substrate impurity concentration
	** Substrate Current **
<b>SUBLD1</b>	substrate current induced in $L_{drift}$ (inactivated)
<b>SUBLD2</b>	substrate current induced in $L_{drift}$ (inactivated)
	** Resistance **
<b>LDRIFT1</b>	length of lightly doped drift region (default: 0)
<b>LDRIFT2</b>	length of heavily doped drift region (default: $1 \mu m$ )
<b>LDRIFT1S</b>	length of lightly doped drift region in source side (default: 0)
<b>LDRIFT2S</b>	length of heavily doped drift region in source side (default: $1 \mu m$ )
	** Overlap **
<b>LOVER</b>	length of overlap region in source side for LDMOS
<b>LOVERLD</b>	length of overlap region in drain side
<b>LOVERS</b>	length of overlap region in source side for HVMOS
<b>COSELFHEAT</b>	flag to switch on the self-heating effect
<b>COSUBNODE</b>	flag for selection of the 5th node

<b>NPEXT</b>	maximum concentration of pocket tail
<b>FALPH</b>	power of $f$ describing deviation of $1/f$
<b>RS</b>	source-contact resistance of LDD region
<b>RD</b>	drain-contact resistance of LDD region
<b>RD22</b>	$V_{bs}$ dependence of <b>RD</b> for <b>CORSRD</b> =2,3
<b>RD23</b>	modification of <b>RD</b> for <b>CORSRD</b> =2,3
<b>RD24</b>	$V_{gs}$ dependence of <b>RD</b> for <b>CORSRD</b> =2,3
<b>RDVG11</b>	$V_{gs}$ dependence of <b>RD</b> for <b>CORSRD</b> =1,3
<b>RDICT1</b>	<b>LDRFIT1</b> dependence of resistance for <b>CORSRD</b> =1,3
<b>RDOV13</b>	alternative $L_{over}$ dependence model for <b>CORSRD</b>
<b>RDSL11</b>	<b>LDRFIT1</b> dependence of resistance for <b>CORSRD</b> =1,3
<b>RDVB</b>	$V_{bs}$ dependence of <b>RD</b> for <b>CORSRD</b> =1,3
<b>RDVD</b>	$V_{ds}$ dependence of <b>RD</b> for <b>CORSRD</b> =1,3
<b>RTH0</b>	thermal resistance
<b>VOVER</b>	velocity overshoot effect
<b>CGBO</b>	gate-to-bulk overlap capacitance
<b>CVDSOVER</b>	modification of the $C_{gg}$ spikes for $V_{ds} \neq 0$
<b>POWRAT</b>	thermal dissipation



## 26 Default Parameters and Limits of the Parameter Values

The maximum and minimum limits of the model parameter are recommended values. These values may be violated in some specific cases. "default" in remarks means that the default value is preferable.

parameter	unit	min	max	default	remarks
<b>VERSION</b>		2.10	2.20	2.10	
<b>TOX</b>	[m]			7n	
<b>XL</b>	[m]			0	
<b>XW</b>	[m]			0	
<b>XLD</b>	[m]	0	50n	0	
<b>XWD</b>	[m]	-100n	300n	0	
<b>XWDL</b>	[m]			0	given if $\neq$ <b>XWD</b>
<b>XWDC</b>	[m]	-500n	500n	0	given if $\neq$ <b>XWD</b>
<b>TPOLY</b>	[m]			$200 \times 10^{-9}$	
<b>DDRIFT</b>	[m]			0	
<b>LL</b>	[m <sup>LLN+1</sup> ]			0	
<b>LLD</b>	[m]			0	
<b>LLN</b>	[—]			0	
<b>WL</b>	[m <sup>WLN+1</sup> ]			0	
<b>WLD</b>	[m]			0	
<b>WLN</b>	[—]			0	
<b>NSUBC</b>	[cm <sup>-3</sup> ]	$1 \times 10^{16}$	$1 \times 10^{19}$	$3 \times 10^{17}$	<b>CODEP=0</b>
		$1 \times 10^{16}$	$1 \times 10^{19}$	$5 \times 10^{16}$	<b>CODEP=1</b>
<b>NSUBP</b>	[cm <sup>-3</sup> ]	$1 \times 10^{16}$	$1 \times 10^{19}$	$1 \times 10^{18}$	<b>CODEP=0</b>
		$1 \times 10^{16}$	$1 \times 10^{19}$	$1 \times 10^{17}$	<b>CODEP=1</b>
<b>DDRIFT</b>	[m]			$1.0 \times 10^{-6}$	
<b>NSUBSUB</b>	[cm <sup>-3</sup> ]			$1.0 \times 10^{15}$	required for $V_{\text{sub,s}}$ dependence
<b>LP</b>	[m]	0	300n	15n	<b>CODEP=0</b>
		0	300n	0n	<b>CODEP=1</b>
<b>*NPEXT</b>	[cm <sup>-3</sup> ]	$1 \times 10^{16}$	$1 \times 10^{18}$	$5 \times 10^{17}$	
<b>*LPEXT</b>	[m]	$1 \times 10^{-50}$	$1 \times 10^{-5}$	$1 \times 10^{-50}$	
<b>VFBC</b>	[V]	-1.2	0.0	-1.0	<b>CODEP=0</b>
		-1.2	0.8	-0.2	<b>CODEP=1</b>
<b>VBI</b>	[V]	1.0	1.2	1.1	
<b>KAPPA</b>	[—]			3.9	
<b>EG0</b>	[eV]	1.0	1.3	1.1785	
<b>BGTMP1</b>	[eV K <sup>-1</sup> ]	$50\mu$	$1000\mu$	$90.25\mu$	default
<b>BGTMP2</b>	[eV K <sup>-2</sup> ]	$-1\mu$	$1\mu$	$0.1\mu$	
<b>TNOM</b>	[°C]	22	32	27	
<b>VMAX</b>	[cm s <sup>-1</sup> ]	1MEG	20MEG	10MEG	
<b>VMAXT1</b>	[cm (sK) <sup>-1</sup> ]			0	
<b>VMAXT2</b>	[cm (sK <sup>2</sup> ) <sup>-1</sup> ]			0	
<b>VOVER</b>	[m <sup>VOVERP</sup> ]	0	4.0	0.3	
<b>VOVERP</b>	[—]	0	2.0	0.3	
<b>*VTMP</b>	[—]	-2.0	1.0	0	
<b>QME1</b>	[Vm]	0	1n	0	
<b>QME2</b>	[V]	1.0	3.0	2.0	
<b>QME3</b>	[m]	0	500p	0	
<b>PGD1</b>	[V]	0	30m	0	
<b>PGD2</b>	[V]	0	1.5	1.0	
<b>*PGD4</b>	[—]	0	3.0	0	

parameter	unit	min	max	default	remarks
<b>PARL2</b>	[m]	0	50n	10n	
<b>SC1</b>	[—]	0	10	0	
<b>SC2</b>	[V <sup>-1</sup> ]	0	1	0	
<b>*SC3</b>	[V <sup>-1</sup> m]	0	20μ	0	
<b>**SC4</b>	[1/V]	0		0	
<b>SCP1</b>	[—]	0	10	0	
<b>SCP2</b>	[V <sup>-1</sup> ]	0	1	0	
<b>*SCP3</b>	[V <sup>-1</sup> m]	0	200n	0	
<b>*SCP21</b>	[V]	0	5.0	0	
<b>*SCP22</b>	[V <sup>4</sup> ]	0	0	0	reset to zero
<b>*BS1</b>	[V <sup>2</sup> ]	0	50m	0	
<b>*BS2</b>	[V]	0.5	1.0	0.9	
<b>*PTL</b>	[V <sup>PTP-1</sup> m <sup>PTLP</sup> ]	0		0	
<b>*PTLP</b>	[—]			1.0	
<b>*PTP</b>	[—]	3.0	4.0	3.5	
<b>*PT2</b>	[V <sup>-1</sup> ]	0		0	
<b>*PT4</b>	[V <sup>-2</sup> ]	0		0	
<b>*PT4P</b>	[—]	0		1	
<b>*GDL</b>	[m <sup>GDLP</sup> ]	0	220m	0	
<b>*GDLP</b>	[—]			0	
<b>*GDLD</b>	[m]			0	
<b>MUECB0</b>	[cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ]	100	100K	1K	
<b>MUECB1</b>	[cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ]	5	10k	100	
<b>MUEPH0</b>	[—]	0.25	0.35	0.3	default
<b>MUEPH1</b>	[cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ]	2K	30K	20K(nMOS),9K(pMOS)	
<b>@</b>	(V cm <sup>-1</sup> ) <sup>MUEPH0</sup>				
<b>MUETMP</b>	[—]	0.5	2.5	1.5	
<b>*MUEPHL</b>	[μm <sup>MUEDLP</sup> ]			0	
<b>*MUEPLP</b>	[—]			1.0	
<b>MUESR0</b>	[—]	1.8	2.2	2.0	default
<b>MUESR1</b>	[cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ]	1×10 <sup>14</sup>	1×10 <sup>16</sup>	6×10 <sup>14</sup>	<b>CODEP=0</b>
<b>@</b>	(V cm <sup>-1</sup> ) <sup>MUESR0</sup>	1×10 <sup>14</sup>	1×10 <sup>16</sup>	5×10 <sup>15</sup>	<b>CODEP=1</b>
<b>*MUESRL</b>	[μm <sup>MUESLP</sup> ]			0	
<b>*MUESLP</b>	[—]			1.0	
<b>NDEP</b>	[—]	0	1.0	1.0	
<b>*NDEPL</b>	[μm <sup>NDEPLP</sup> ]			0	
<b>*NDEPLP</b>	[—]			1.0	
<b>NINV</b>	[—]	0	1.0	0.5	
<b>NINVD</b>	[1/V]	0		0.0	
<b>NINVDW</b>	[μm <sup>NINVDWP</sup> ]	0		0.0	
<b>NINVDWP</b>	[—]	0		1.0	
<b>NINVDT1</b>	[1/K]	0		0.0	
<b>NINVDT2</b>	[1/K <sup>2</sup> ]	0		0.0	
<b>BB</b>	[—]			2.0(nMOS),1.0(pMOS)	default

parameter	unit	min	max	default	remarks
<b>WFC</b>	[F m <sup>-1</sup> ]	-5.0×10 <sup>-15</sup>	1×10 <sup>-6</sup>	0	
<b>*WVTH0</b>	[V·μm]			0	
<b>*NSUBCW</b>	[μm <sup>NSUBCWP</sup> ]			0	
<b>*NSUBCWP</b>	[—]			1	
<b>*NSUBP0</b>	[cm <sup>-3</sup> ]			0	
<b>*NSUBWP</b>				1.0	
<b>*MUEPHW</b>	[μm <sup>MUEPHW</sup> ]			0	
<b>*MUEPWP</b>	[—]			1.0	
<b>*MUESRW</b>	[μm <sup>MUESRW</sup> ]			0	
<b>*MUESWP</b>	[—]			1.0	
<b>*VTHSTI</b>	[V]			0	
<b>VDSTI</b>	[—]			0	
<b>SCSTI1</b>	[—]			0	
<b>SCSTI2</b>	[V <sup>-1</sup> ]			0	
<b>NSTI</b>	[cm <sup>-3</sup> ]	1×10 <sup>16</sup>	1×10 <sup>19</sup>	5×10 <sup>17</sup>	
<b>WSTI</b>	[m]			0	
<b>WSTIL</b>	[μm <sup>WSTILP</sup> ]			0	
<b>WSTILP</b>	[—]			1.0	
<b>WSTIW</b>	[μm <sup>WSTIWP</sup> ]			0	
<b>WSTIWP</b>	[—]			1.0	
<b>WL1</b>	[μm <sup>2WL1P+1</sup> ]			0	
<b>WL1P</b>	[—]			1.0	
<b>NSUBPSTI1</b>	[m]			0	
<b>NSUBPSTI2</b>	[—]			0	
<b>NSUBPSTI3</b>	[—]			1.0	
<b>MUESTI1</b>	[m]			0	
<b>MUESTI2</b>	[—]			0	
<b>MUESTI3</b>	[—]			1.0	
<b>WL2</b>	[Vμm <sup>2WL2P</sup> ]			0	
<b>WL2P</b>	[—]			1.0	
<b>*MUEPHS</b>	[μm <sup>2MUEPSP</sup> ]			0	
<b>*MUEPSP</b>	[—]			1.0	
<b>*VOVERS</b>	[—]			0	
<b>*VOVERSP</b>	[—]			0	
<b>CLM1</b>	[—]	10m	1.0	50m	<b>CODEP=0</b>
<b>CLM2</b>	[—]	1.0	4.0	2.0	<b>CODEP=0</b>
<b>CLM3</b>	[—]	0.5	5.0	1.0	<b>CODEP=0</b>
<b>CLM5</b>	[—]	0	2.0	1.0	<b>CODEP=0</b>
<b>CLM6</b>	[μm <sup>-CLM5</sup> ]	0	20.0	0	<b>CODEP=0</b>

parameter	unit	min	max	default	remarks
SUB1	[V <sup>-1</sup> ]			10	
SUB1L	[m <sup>2WL1P+1</sup> ]			2.5×10 <sup>-3</sup>	
SUB1LP	[—]			1.0	
SUB2	[V]			25.0	
SUB2L	[m]	0	1.0	2×10 <sup>-6</sup>	
SVDS	[—]			0.8	
SLG	[m]			3×10 <sup>-8</sup>	
SLGL	[m <sup>SLGLP</sup> ]			0	
SLGLP	[—]			1.0	
SVBS	[—]			0.5	
SVBSL	[m <sup>SVBSLP</sup> ]			0	
SVBSLP	[—]			1.0	
SVGS	[—]			0.8	
SVGSL	[m <sup>SVGSLP</sup> ]			0	
SVGSLP	[—]			1.0	
SVGSW	[m <sup>SVGSWP</sup> ]			0	
SVGSWP	[—]			1.0	
IBPC1	[VA <sup>-1</sup> ]	0	1.0×10 <sup>12</sup>	0	
IBPC1L	[]				
IBPC1LP	[]				
IBPC2	[V <sup>-1</sup> ]	0	1.0×10 <sup>12</sup>	0	
SUBLD1	[V <sup>-1</sup> ]			0	
SUBLD1L	[]				
SUBLD1LP	[]				
SUBLD2	[mV <sup>-1</sup> ]			0	
XPDV	[]	0		0	
XPVDTH	[]	0		0	
XPVDTHG	[]	-1	1	0	
MPHDFM	[—]	-3	3	-0.3	
SAREF	[m]			1.0×10 <sup>-6</sup>	
SBREF	[m]			1.0×10 <sup>-6</sup>	

parameter	unit	min	max	default	remarks
<b>GLEAK1</b>	$[V^{-3/2}s^{-1}]$			50	
<b>GLEAK2</b>	$[V^{-1/2}cm^{-1}]$			10MEG	
<b>GLEAK3</b>	[—]			$60 \times 10^{-3}$	
<b>GLEAK4</b>	$[m^{-1}]$			4.0	
<b>*GLEAK5</b>	$[V m^{-1}]$			$7.5 \times 10^3$	
<b>*GLEAK6</b>	[V]			$250 \times 10^{-3}$	
<b>*GLEAK7</b>	$[m^2]$			$1 \times 10^{-6}$	
<b>*EGIG</b>	[V]			0.0	
<b>*IGTEMP2</b>	[V K]			0	
<b>*IGTEMP3</b>	$[V K^2]$			0	
<b>GLKSD1</b>	$[A m V^{-2}]$			1f	
<b>GLKSD2</b>	$[V^{-1}m^{-1}]$			$1 \times 10^3$	
<b>GLKSD3</b>	$[m^{-1}]$			$-1 \times 10^3$	
<b>GLKB1</b>	$[A V^{-2} m^{-2}]$			$5 \times 10^{-16}$	
<b>GLKB2</b>	$[m V^{-1}]$			1.0	
<b>GLKB3</b>	[V]			0	
<b>GLPART1</b>	[—]	0	1.0	0.5	
<b>FN1</b>	$[V^{-1.5} \cdot m^2]$			50	
<b>FN2</b>	$[V^{-0.5} \cdot m^{-1}]$			$170 \times 10^{-6}$	
<b>FN3</b>	[V]			0	
<b>FVBS</b>	[—]			$12 \times 10^{-3}$	
<b>GIDL1</b>	$[V^{-3/2}s^{-1}m]$			2.0	
<b>GIDL2</b>	$[V^{-0.5}m^{-1}]$			$3 \times 10^7$	
<b>GIDL3</b>	[—]			0.9	
<b>*GIDL4</b>	[V]			0	
<b>*GIDL5</b>	[—]			0.2	
<b>VBSMIN</b>	[V]				no more required
<b>VGSMIN</b>	[V]			-100(nMOS),100(pMOS)	fixed
<b>VZADD0</b>	[V]			10m	fixed
<b>PZADD0</b>	[V]			5m	fixed
<b>DDLTMAX</b>	[—]	1	10	10	
<b>DDLTSLP</b>	$[\mu m^{-1}]$	0	20	0	
<b>DDLTICT</b>	[—]	-3	20	10	

parameter	unit	min	max	default	remarks
<b>JS0</b>	[A m <sup>-2</sup> ]			0.5×10 <sup>-6</sup>	
<b>JS0SW</b>	[A m <sup>-1</sup> ]			0	
<b>NJ</b>	[—]			1.0	
<b>NJSW</b>	[—]			1.0	
<b>XTI</b>	[—]			2.0	
<b>XTI2</b>	[—]			0	
<b>DIVX</b>	[V <sup>-1</sup> ]			0	
<b>CTEMP</b>	[—]			0	
<b>CISB</b>	[—]			0	
<b>CISBK</b>	[A]			0	
<b>CVB</b>	[—]	-0.1	0.2	0	
<b>CJ</b>	[F m <sup>-2</sup> ]			5×10 <sup>-4</sup>	
<b>CJSW</b>	[F m <sup>-1</sup> ]			5×10 <sup>-10</sup>	
<b>CJSWG</b>	[F m <sup>-1</sup> ]			5×10 <sup>-10</sup>	
<b>MJ</b>	[—]			0.5	
<b>MJSW</b>	[—]			0.33	
<b>MJSWG</b>	[—]			0.33	
<b>PB</b>	[V]			1.0	
<b>PBSW</b>	[V]			1.0	
<b>PBSWG</b>	[V]			1.0	
<b>VDIFFJ</b>	[V]			0.6×10 <sup>-3</sup>	
<b>TCJBD</b>	[K <sup>-1</sup> ]			0	
<b>TCJBDSW</b>	[K <sup>-1</sup> ]			0	
<b>TCJBDSWG</b>	[K <sup>-1</sup> ]			0	
<b>TCJBS</b>	[K <sup>-1</sup> ]			0	
<b>TCJBSSW</b>	[K <sup>-1</sup> ]			0	
<b>TCJBSSWG</b>	[K <sup>-1</sup> ]			0	
<b>NFALP</b>	[cm s]			1×10 <sup>-19</sup>	
<b>NFTRP</b>	[V <sup>-1</sup> ]			10G	
<b>*CIT</b>	[F cm <sup>-2</sup> ]			0	
<b>FALPH</b>	[sm <sup>3</sup> ]			1.0	
<b>DLY1</b>	[s]			100×10 <sup>-12</sup>	
<b>DLY2</b>	[m <sup>2</sup> ]			0.7	
<b>DLY3</b>	[Ωm <sup>2</sup> ]			0.8×10 <sup>-6</sup>	
<b>XQY</b>	[m]	10n	50n	0	
<b>XQY1</b>	[F·μm <sup>XQY2-1</sup> ]	0		0	
<b>XQY2</b>	[—]	0		2	
<b>OVSLP</b>	[mV <sup>-1</sup> ]			2.1×10 <sup>-7</sup>	
<b>OVMAG</b>	[V]			0.6	
<b>CGSO</b>	[F m <sup>-1</sup> ]	0	100nm × C <sub>ox</sub>		to be set by user
<b>CGDO</b>	[F m <sup>-1</sup> ]	0	100nm × C <sub>ox</sub>		to be set by user
<b>CGBO</b>	[F m <sup>-1</sup> ]	0		0	

parameter	unit	min	max	default	remarks
<b>RS</b>	[ $\Omega\text{m}$ ]	0	10m	0	for circuit simulation instance parameter
<b>RD</b>	[ $\Omega\text{m}$ ]	0	100m	0	
<b>RSH</b>	[ $\text{V A}^{-1}\text{square}$ ]	0	500	0	
<b>RSHG</b>	[ $\text{V A}^{-1}\text{square}$ ]	0	100	0	
<b>GBMIN</b>	[—]			$1 \times 10^{-12}$	
<b>GDSLEAK</b>	[—]			0	
<b>RBPB</b>	[ $\Omega$ ]			50	
<b>RBPD</b>	[ $\Omega$ ]			50	
<b>RBPS</b>	[ $\Omega$ ]			50	
<b>RBDB</b>	[ $\Omega$ ]			50	
<b>RBSB</b>	[ $\Omega$ ]			50	
<b>RTH0</b>	[ $\text{Kcm/W}$ ]	0	10	0.1	inactivated
<b>RTHTEMP1</b>	[ $\text{Kcm/W/K}$ ]	-1	1	0	
<b>RTHTEMP2</b>	[ $\text{Kcm/W/K}^2$ ]	-1	1	0	
<b>CTH0</b>	[ $\text{Ws/(Kcm)}$ ]			$1 \times 10^{-7}$	
<b>RTH0W</b>	[ $\mu\text{m}^{\text{RTH0WP}}$ ]	-100	100	0	
<b>RTH0WP</b>	[—]	-10	10	1	
<b>RTH0NF</b>	[—]	-5	5	0	
<b>RTH0R</b>	[—]				
<b>POWRAT</b>	[—]	0	1.0	1.0	
<b>PRATTEMP1</b>	[ $1/\text{K}$ ]	-1	1	0	
<b>PRATTEMP2</b>	[ $1/\text{K}^2$ ]	-1	1	0	
<b>SHEMAX</b>	[ $\text{K}$ ]	300	900	500	
<b>XLDLD</b>	[m]	0		$1 \times 10^{-6}$	
<b>LOVERLD</b>	[m]	0		$1.0 \times 10^{-6}$	
<b>LOVERS</b>	[m]	0		30nm	
<b>LOVER</b>	[m]	0		30n	
<b>NOVER</b>	[ $\text{cm}^{-3}$ ]			$3 \times 10^{16}$	
<b>NOVERS</b>	[ $\text{cm}^{-3}$ ]			$1.0 \times 10^{17}$	
<b>VFBOVER</b>	[V]	-1.2	1	0.5	
<b>DLYDFT</b>	[ $\text{m}^2/(\text{Vs})$ ]			$5.0 \times 10^{-2}$	
<b>DLYOV</b>	[s/F]			0	
<b>QOVADD</b>	[F/m <sup>2</sup> ]			0	
<b>CVDSOVER</b>	[—]	0	1.0	0	
<b>LDRIFT1</b>	[m]	0		$1.0 \times 10^{-6}$	
<b>LDRIFT1S</b>	[m]	0		0.0	
<b>LDRIFT2</b>	[m]	0		$1.0 \times 10^{-6}$	
<b>LDRIFT2S</b>	[m]	0		$1.0 \times 10^{-6}$	
<b>**CORDRIFT=1**</b>					
<b>RDRDL1</b>	[m]			0	reset within the range
<b>RDRDL2</b>	[m]			0	
<b>RDRCX</b>	[—]	0	1	0	
<b>RDRCAR</b>	[ $\text{mV}^{-1}$ ]	0	50n	$1 \times 10^{-8}$	
<b>RDRDJUNC</b>	[m]			$1.0 \times 10^{-6}$	
<b>RDRBB</b>	[—]			1.0	
<b>RDRMUE</b>	[ $\text{m}^2(\text{V} \cdot \text{s})^{-1}$ ]	100	3K	1K	
<b>RDRMUEL</b>	[ $\mu\text{m}^{\text{RDRMUELP}}$ ]			0	
<b>RDRMUELP</b>	[—]			1	



parameter	unit	min	max	default	remarks
RDRBBTMP	[1/K]			0	
RDRMUETMP	[—]	0.0	2.0	0	
RDRVMAX	[cm s <sup>-1</sup> ]	1MEG	100MEG	30MEG	
RDRVMAXL	[ $\mu\text{m}^{\text{RDRVMAXLP}}$ ]			0	
RDRVMAXLP	[—]			1	
RDRVMAXW	[ $\mu\text{m}^{\text{RDRVMAXWP}}$ ]			0	
RDRVMAXWP	[—]			1	
RDRVTMP	[—]	-2.0	1.0	0	
RDRQOVER	[—]	0	$1 \times 10^7$	$1 \times 10^5$	
<b>**CORDRIFT=0**</b>					
RDVG11	[]	0	$V_{\text{ds,max}}/30$	0	<b>CORSRD=1,3</b>
RDVG12	[V <sup>-1</sup> ]	0	$V_{\text{ds,max}}$	100	<b>CORSRD=1,3</b>
RDVG11	[]	0	$V_{\text{ds,max}}/30$	0	<b>CORSRD=1,3</b>
RDVG12	[V <sup>-1</sup> ]	0	$V_{\text{ds,max}}$	100	<b>CORSRD=1,3</b>
RDVD	[ $\Omega/\text{V}$ ]	0	2.0	$7.0 \times 10^{-2}$	<b>CORSRD=1,3</b>
RDVB	[V <sup>-1</sup> ]	0	2.0	0	<b>CORSRD=1,3</b>
RDS	[ $\mu\text{m}^{\text{RDSP}}$ ]	-100	100	0	<b>CORSRD=1,3</b>
RDSP	[—]	-10	10	1	<b>CORSRD=1,3</b>
RDVDL	[ $\mu\text{m}^{-\text{RDVDLP}}$ ]	-100	100	0	<b>CORSRD=1,3</b>
RDVDLP	[—]	-10	10	1	<b>CORSRD=1,3</b>
RDVDS	[ $\mu\text{m}^{\text{RDVDSP}}$ ]	-100	100	0	<b>CORSRD=1,3</b>
RDVDSP	[—]	-10	10	1	<b>CORSRD=1,3</b>
RD20	[—]	0	30	0	<b>CORSRD=2,3</b>
RD21	[—]	0	1.0	1.0	<b>CORSRD=2,3</b>
RD22	[ $\Omega \text{ m}/\text{V}^{\text{RD22D}+1}$ ]	-5.0	0	0	<b>CORSRD=2,3</b>
RD22D	[—]	0	2.0	0	<b>CORSRD=2,3</b>
RD23	[ $\Omega \text{ m}/\text{V}^{\text{RD21}}$ ]	0	2.0	5m	<b>CORSRD=2,3</b>
RD23L	[ $\mu\text{m}^{-\text{RD23LP}}$ ]	-100	100	0	<b>CORSRD=2,3</b>
RD23LP	[—]	-10	10	1	<b>CORSRD=2,3</b>
RD23S	[ $\mu\text{m}^{\text{RD23SP}+1}$ ]	-100	100	0	<b>CORSRD=2,3</b>
RD23SP	[—]	-10	10	1	<b>CORSRD=2,3</b>
RD24	[ $\Omega\text{m}/\text{V}^{\text{RD21}+1}$ ]	0	0.1	0	<b>CORSRD=2,3</b>
RD25	[V]	0	$V_{\text{gs,max}}$	0	<b>CORSRD=2,3</b>
RDOV11	[—]	0	10	0	<b>CORSRD=1,3</b>
RDOV12	[—]	0	2	1.0	<b>CORSRD=1,3</b>
RDOV13	[—]	0	1.0	1.0	<b>CORSRD=1,3</b>
RDSL1P1	[—]	-10	10	0	<b>CORSRD=1,3</b>
RDICT1	[—]	-10	10	1.0	<b>CORSRD=1,3</b>
RDSL1P2	[—]	-10	10	1	<b>CORSRD=1,3</b>
RDICT2	[—]	-10	10	0	<b>CORSRD=1,3</b>
RDTEMP1	[ $\Omega\text{m}/\text{K}$ ]	$-1.0 \times 10^{-3}$	$2.0 \times 10^{-2}$	0	
RDTEMP2	[ $\Omega\text{m}/\text{K}^2$ ]	$-1.0 \times 10^{-5}$	$1.0 \times 10^{-5}$	0	
RDVDTEMP1	[ $\Omega\text{m}/(\text{VK})$ ]	$-1.0 \times 10^{-3}$	$1.0 \times 10^{-2}$	0	
RDVDTEMP2	[ $\Omega\text{m}/(\text{VK})^2$ ]	$-1.0 \times 10^{-5}$	$1.0 \times 10^{-5}$	0	
RDVDSUB	[—]			0.3	
RDVSUB	[—]			1.0	
VBISUB	[—]			0.7	
NDEPM	[cm <sup>-3</sup> ]	$5 \times 10^{15}$	$2 \times 10^{17}$	$1 \times 10^{17}$	<b>CODEP=1</b>
TNDEP	[m]	100n	1000n	200n	<b>CODEP=1</b>
DEPMUE0	[cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ]			1K	<b>CODEP=1</b>
DEPMUE1	[cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ]			0	<b>CODEP=1</b>

parameter	unit	min	max	default	remarks
<b>DEPMUEPH0</b>	[—]			0.3	<b>CODEP=1</b>
<b>DEPMUEPH1</b>	[—]	1	1.0e5	5e3	<b>CODEP=1</b>
<b>DEPVMAX</b>	[cm s <sup>-1</sup> ]			3e7	<b>CODEP=1</b>
<b>DEPLEAK</b>	[—]			0.5	<b>CODEP=1</b>
<b>DEPETA</b>	[V <sup>-1</sup> ]			0	<b>CODEP=1</b>
<b>DEPBB</b>	[—]			1	<b>CODEP=1</b>
<b>DEPVDSEF1</b>	[V]			2.0	<b>CODEP=1</b>
<b>DEPVDSEF2</b>	[—]	0.1	4.0	0.5	<b>CODEP=1</b>
<b>DEPMUETMP</b>	[—]			1.5	<b>CODEP=1</b>
<b>DEPVTMP</b>	[—]			0.0	<b>CODEP=1</b>

## 27 Overview of the Parameter-Extraction Procedure

### 27.1 General MOSFET Part

In HiSIM, device characteristics are strongly dependent on basic device parameter values, such as the impurity concentration and the oxide thickness. Therefore, the parameter-value extraction has to be repeated with measured characteristics of different devices in a specific sequence until extracted parameter values reproduce all device characteristics consistently and reliably. To achieve reliable results, it is recommended to start with initial parameter values according to the recommendations listed in the table below. Since some of the model parameters such as  $T_{ox}$  are difficult to extract, they are expected to be determined directly by dedicated measurements. Threshold voltage measurements allow to derive a rough extraction for the model parameters referred to as “basic device parameters”. The parameters identified with the symbol “\*” in the Model Parameter Table are initially fixed to zero.

Determined by dedicated measurements (not changed during extraction procedure) are used	Default values listed in the section 26 initially for the groups of parameters listed below
<b>TOX</b>	basic device parameters (not listed on left side) gate leakage GIDL source/bulk and drain/bulk diodes noise subthreshold swing non-quasi-static model overlap capacitances

The sequence of device selection for the parameter extraction is recommended in 4 steps

1. Long-Channel Devices
2. Short-Channel Devices
3. Long-Narrow Devices
4. Short-Narrow Devices

Prior to the extraction, a rough extraction with measured  $V_{th} - L_{gate}$  characteristics is recommended to get rough idea about parameter values. These parameters are usually important giving strong influence on accuracy of the total parameter extraction. The parameter extraction of the general MOSFET part is summarized in the following Table.

### 27.2 HiSIM\_HV Specific Part

Model parameters are categorized into two parts: (1) general MOSFET related parameters and (2) the HiSIM\_HV specific parameters. The HiSIM\_HV specific model parameters are extracted after the extraction of the intrinsic MOSFET part. Recommended extraction procedure is to perform first (1) and then (2). Thus the parameter extraction is done in the following sequence:

1. rough extraction of the MOSFET parameters with measured  $V_{th} - L_{gate}$
2. fine extraction with measured subthreshold in  $I_{ds} - V_{gs}$
3. extraction of mobility parameters with  $I_{ds} - V_{gs}$  and  $I_{ds} - V_{ds}$

Table 24: Summary of the 7 steps of HiSIM's Parameter Extraction Procedure.

**Step 1: Initial preparation and rough extraction**

- |  |  |
|--|--|
| 1-1. Initialize all parameters to their default values                                 |  |
| 1-2. Use the measured gate-oxide thickness for $TOX$                                   | $TOX$  |
| 1-3. Rough extraction with $V_{th}$ -dependence on $L_{gate}$<br>[ $V_{th} - V_{gs}$ ] | <b>NSUBC, VFB, SC1, SC2<br/>SC3, NSUBP, LP, SCP1<br/>SCP2, SCP3<br/>NPEXT, LPEXT</b> |
| 1-4. Quantum and poly-depletion effects [ $C_{gg} - V_{gs}$ ]                          | <b>QME1, QME2, QME3<br/>PGD1, PGD2</b>   |

**Step 2: Extraction with long and wide transistors**

- |   |  |
|---|--|
| 2-1. Fitting of sub-threshold characteristics<br>[ $I_{ds} - V_{gs}$ ]              | <b>NSUBC, VFB, MUECB0<br/>MUECB1</b>     |
| 2-2. Determination of mobility parameters for low $V_{ds}$<br>[ $I_{ds} - V_{gs}$ ] | <b>MUEPH0, MUEPH1<br/>MUESR0, MUESR1</b> |
| 2-3. Determination of mobility parameters for high $V_{ds}$ [ $I_{ds} - V_{gs}$ ]   | <b>NINV, NDEP</b>                        |

**Step 3: Extraction with medium/short length and large width transistors**

- |  |  |
|--|--|
| 3-1. Pocket-parameter extraction with medium<br>length transistors [ $I_{ds} - V_{gs}$ ]         | <b>NSUBP, LP<br/>SCP1, SCP2, SCP3<br/>NPEXT, LPEXT</b> |
| 3-2. Short-channel-parameter extraction with<br>short-length transistors [ $V_{th} - L_{gate}$ ] | <b>SC1, SC2, SC3<br/>PARL2, XLD</b>                    |
| 3-3. Mobility-parameter refinement for low $V_d$ [ $I_{ds} - V_{gs}$ ]                           | <b>MUEPHL, MUEPLP<br/>MUESRL, MUESLP</b>               |
| 3-4. Velocity parameter extraction for high $V_d$ [ $I_{ds} - V_{gs}$ ]                          | <b>VMAX, VOVER, VOVERP</b>                             |
| 3-5. Parameters for channel-length modulation [ $I_{ds} - V_{ds}$ ]                              | <b>CLM1, CLM2, CLM3</b>                                |
| 3-6. Source/drain resistances [ $I_{ds} - V_{ds}$ ]  | <b>RS, RD, RSH, NRS, NRD</b>                           |

**Step 4: Extraction of the width dependencies for long transistors**

- |   |   |
|---|---|
| 4-1. Fitting of sub-threshold width dependencies<br>[ $I_{ds} - V_{gs}$ ] | <b>NSUBC, NSUBCW, NSUBCWP<br/>WFC, XWD, WVTH0</b> |
| 4-2. Fitting of mobility width dependencies [ $I_{ds} - V_{gs}$ ]         | <b>MUEPHW, MUEPWP<br/>MUESRW, MUESWP</b>          |

**Step 5: Extraction of the width dependencies for short transistors**

- |  |                       |
|--|-----------------------|
| 5-1. Fitting of sub-threshold dependencies [ $I_{ds} - V_{gs}$ ] | <b>NSUBP0, NSUBWP</b> |
|--|-----------------------|

**Step 6: Extraction of small-geometry effects**

- |  |  |
|--|--|
| 6-1. Effective channel-length corrections        | <b>WL2, WL2P</b>                             |
| 6-2. Mobility and velocity [ $I_{ds} - V_{ds}$ ] | <b>MUEPHS, MUEPSP<br/>VOVERS<br/>VOVERSP</b> |

**Step 7: Extraction of temperature dependence with long-channel transistors**

- |  |                               |
|--|-------------------------------|
| 7-1. Sub-threshold dependencies [ $I_{ds} - V_{gs}$ ]                            | <b>BGTMP1, BGTMP2<br/>EG0</b> |
| 7-2. Mobility and maximum carrier-velocity<br>dependencies [ $I_{ds} - V_{gs}$ ] | <b>MUETMP, VTMP</b>           |

4. extraction of resistance parameters with  $I_{ds} - V_{gs}$  and  $I_{ds} - V_{ds}$
5. fine extraction of resistance with channel-conductance and trans-conductance
6. capacitance extraction

Agreement of the extraction results after the 3rd step is not sufficient especially in high  $V_{gs}$  region and low  $V_{ds}$  region. The 4th resistance-extraction step is focused on the region where the quasi-saturation effect is obvious. It is recommended to repeat the extraction steps from 3rd to 5th to achieve better fitting. The steps from 1st to 3rd are the same as the conventional extraction procedure.

The extraction of the resistance parameters are done after the model selection as summarized in Fig. 27.

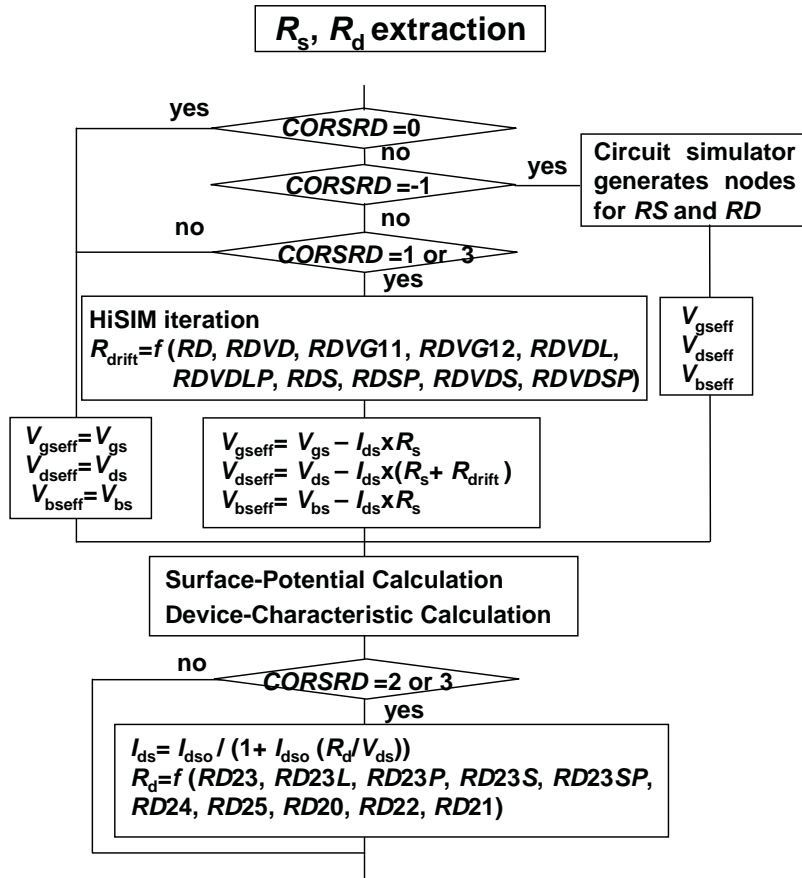


Fig. 27: Parameter extraction flow for resistance parameters. For the new resistance model (**CORDIRIFT**=1) the flag **CORSRD** is no more valid but only one extraction procedure is followed, namely the "HiSIM iteration" part with the new model equations.

If the self-heating effect is activated, all device characteristics are changed drastically. Retuning of model parameters are required. These model parameters are mostly related to the mobility and resistance models. The temperature dependent parameters are extracted without the self-heating effect with temperature dependent measurements. These values are usually not necessary to be modified after activating the self-heating effect.

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