Chapter 3: Body Currents Model

Body currents determine the body potential and therefore the drain current through the body effect. Beside the impact ionization current considered in BSIM3v3, diode (bipolar) current, GIDL, oxide tunneling and body contact current are all included in the BSIMPD model [Fig. 3.1] to give an accurate body-potential prediction in the floating body simulation [18].

3.1. Diode and Parasitic BJT Currents

In this section we describe various current components originated from **B**ody-to-**S**ource/**D**rain (B-S/D) injection, recombination in the B-S/D junction depletion region, **S**ource/**D**rain-to-**B**ody (S/D-B) injection, recombination current in the neutral body, and diode tunneling current.

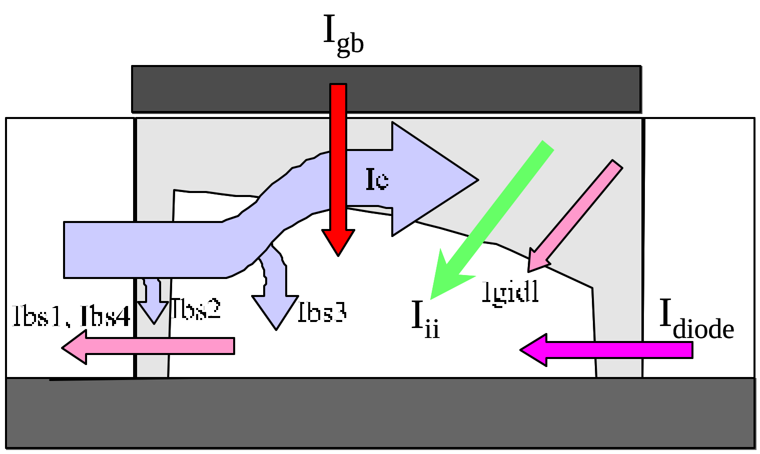

Fig. 3.1 Various current components inside the body.

The backward injection current in the B-S/D diode can be expressed as

$$
\begin{aligned}
I_{bs1} &= W_{dios} T_{si} j_{difs} \left(\exp\left(\frac{V_{bs}}{n_{diodes} V_t} \right) - 1 \right) \\
I_{bd1} &= W_{diod} T_{si} j_{difd} \left(\exp\left(\frac{V_{bd}}{n_{dioded} V_t} \right) - 1 \right)
\end{aligned} \tag{3.1}
$$

Here $n_{diodes}, j_{difs}, W_{dios}, n_{dioded}, j_{difd}, W_{diod}$ are the non-ideality factor, the saturation current, the effective B-S diode width and the B-D diode width, respectively.

The carrier recombination and trap-assisted tunneling current in the space-charge region is modeled by

$$
\begin{aligned}
I_{bs2} &= W_{dios} T_{si} j_{recs} \left(\exp\left(\frac{V_{bs}}{0.026 n_{recfs}} \right) - \exp\left(\frac{V_{sb}}{0.026 n_{recrs}} \frac{V_{rec0s}}{V_{rec0s} + V_{sb}} \right) \right) \\
I_{bd2} &= W_{diod} T_{si} j_{recd} \left(\exp\left(\frac{V_{bd}}{0.026 n_{recfd}} \right) - \exp\left(\frac{V_{db}}{0.026 n_{recrd}} \frac{V_{rec0d}}{V_{rec0d} + V_{db}} \right) \right)
\end{aligned} \tag{3.2}
$$

Here $n_{recfs}, n_{recrs}, j_{recs}, n_{recfd}, n_{recrd}, j_{recd}$ are non-ideality factors for forward bias and reverse bias, the saturation current, respectively. Note that the parameters V_{rec0s}, V_{rec0d} are provided to model the current roll-off in the high reverse bias regime.

The reverse bias tunneling current, which may be significant in junctions with high doping concentration, can be expressed as

$$
\begin{aligned}
I_{bs4} &= W_{dios} T_{si} j_{tuns} \left(1 - \exp\left(\frac{V_{sb}}{0.026 n_{tuns}} \frac{V_{tun0s}}{V_{tun0s} + V_{sb}} \right) \right) \\
I_{bd4} &= W_{diod} T_{si} j_{tund} \left(1 - \exp\left(\frac{V_{db}}{0.026 n_{tund}} \frac{V_{tun0d}}{V_{tun0d} + V_{db}} \right) \right)
\end{aligned} \tag{3.3}
$$

where j_{tuns}, j_{tund} are the saturation currents. The parameters n_{tuns}, n_{tund} and V_{tun0s}, V_{tun0d} are provided to better fit the data.

The recombination current in the neutral body can be described by

$$I_{bs3} = (1-\alpha_{bjt}) I_{ens} \left[\exp\left(\frac{V_{bs}}{n_{diodes} V_t} \right) - 1 \right] \frac{1}{\sqrt{E_{hlis} + 1}}$$

$$I_{bd3} = (1-\alpha_{bjt}) I_{end} \left[\exp\left(\frac{V_{bd}}{n_{dioded} V_t} \right) - 1 \right] \frac{1}{\sqrt{E_{hlid} + 1}}$$

$$I_{ens} = W_{eff}^{'} T_{si} j_{bjts} \left[L_{bjt0} \left(\frac{1}{L_{eff}} + \frac{1}{L_n} \right) \right]^{N_{bjt}}$$

$$I_{end} = W_{eff}^{'} T_{si} j_{bjtd} \left[L_{bjt0} \left(\frac{1}{L_{eff}} + \frac{1}{L_n} \right) \right]^{N_{bjt}}$$

$$E_{hlis} = A_{hlis\_eff} \left[\exp\left(\frac{V_{bs}}{n_{diodes} V_t} \right) - 1 \right]$$

$$E_{hlid} = A_{hlid\_eff} \left[\exp\left(\frac{V_{bd}}{n_{dioded} V_t} \right) - 1 \right]$$

$$\alpha_{bjt} = \exp\left[-0.5 \left(\frac{L_{eff}}{L_n} \right)^2 \right] \tag{3.4}$$

Here α_{bjt} is the bipolar transport factor, whose value depends on the ratio of the effective channel length L_{eff} and the minority carrier diffusion length L_n. j_{bjts} and j_{bjtd} are the saturation currents, while the parameters L_{bjt0} and N_{bjt} are provided to better fit the forward injection characteristics. Notice that E_{hlis} and E_{hlid}, determined by the parameter A_{hlis} and A_{hlid}, stand for the high level injection effect in the B-S/D diode, respectively.

The parasitic bipolar transistor current is important in transient body discharge, especially in pass-gate floating body SOI designs [7]. The BJT collector current is modeled as

$$I_c = a_{bjt} I_{en} \left\{ \exp\left[\frac{V_{bs}}{n_{diodes} V_t} \right] - \exp\left[\frac{V_{bd}}{n_{dioded} V_t} \right] \right\} \frac{1}{E_{2nd}}$$

$$E_{2nd} = \frac{E_{ely} + \sqrt{E_{ely}^{\ 2} + 4E_{hli}}}{2} \tag{3.5}$$

$$E_{ely} = 1 + \frac{V_{bs} + V_{bd}}{V_{Abjt} + A_{ely} L_{eff}}$$

$$E_{hli} = E_{hlis} + E_{hlid}$$

where E_{2nd} is composed of the Early effect E_{ely} and the high level injection roll-off E_{hli}. Note that $E_{2nd} \to E_{ely}$ as $E_{ely} >> E_{hli}$. While $E_{2nd} \to \sqrt{E_{hli}}$ as $E_{hli} >> E_{ely}$, in which case the Early voltage $V_{Abjt} + A_{ely} L_{eff}$ is high.

To sum up, the total B-S current is $I_{bs} = \sum_{i=1}^{4} I_{bsi}$, and the total B-D current is $I_{bd} = \sum_{i=1}^{4} I_{bdi}$. The total drain current including the BJT component can then be expressed as

$$I_{ds,total} = I_{ds,MOSFET} + I_c \tag{3.6}$$

3.2. New Impact Ionization Current Equation

An accurate impact ionization current equation is crucial to the PD SOI model since it may affect the transistor output characteristics through the body effect [11]. Hence in BSIMPD we use a more decent expression [22] to formulate the impact ionization current I_{ii} as

$$I_{ii} = a_0 (I_{ds,MOSFET} + F_{bjtii} I_c) \exp\left(\frac{V_{diff}}{b_2 + b_1 V_{diff} + b_0 V_{diff}^{\ 2}} \right)$$

$$V_{diff} = V_{ds} - V_{dsatii}$$

$$V_{dsatii} = VgsStep + \left[V_{dsatii0} \left(1 + T_{ii} \left(\frac{T}{T_{nom}} - 1 \right) \right) - \frac{L_{ii}}{L_{eff}} \right]$$

$$VgsStep = \left(\frac{E_{satii} L_{eff}}{1 + E_{satii} L_{eff}} \right) \left(\frac{1}{1 + S_{ii1} V_{gsteff}} + S_{ii2} \right) \left(\frac{S_{ii0} V_{gst}}{1 + S_{iid} V_{ds}} \right) \tag{3.7}$$

Here the $F_{bjtii}I_c$ term represents the contribution from the parasitic bipolar current. Notice that the classical impact ionization current model [12] adopted in BSIM3v3 is actually a special case of Eqn. (3.6) when $(b_0, b_1, b_2) = (-1,0,0)$. However, the dependence of $\log(I_{ii}/I_{ds})$ on the drain overdrive voltage V_{diff} is quite linear [22] for state-of-the-art SOI technologies due to thermally assisted impact ionization [23]. In this case, $(b_0, b_1, b_2) \cong (0,0,1)$.

The extracted saturation drain voltage V_{dsatii} depends on the gate overdrive voltage V_{gst} and L_{eff}. One can first extract the parameters $(V_{dsatii0}, L_{ii})$ by the V_{dsatii}- L_{eff} characteristics at $V_{gst} = 0$. All the other parameters $(E_{satii}, S_{ii1}, S_{ii2}, S_{ii0}, S_{iid})$ can then be determined by the plot of V_{dsatii} versus V_{gs} for different L_{eff}. Notice that a linear temperature dependence of $V_{dsatii0}$ with the parameter T_{ii} is also included.

3.3. Gate Induced Drain Leakage Current

GIDL can be important in SOI device because it can affect the body potential in the low V_{gs} and high V_{ds} regime. The formula for GIDL current is:

$$\boldsymbol{I_{GIDL} = AGIDL \cdot W_{diod} \cdot Nf \cdot \frac{V_{ds} - V_{gse} - EGIDL}{3 \cdot T_{oxe}} \cdot \exp\left(-\frac{3 \cdot T_{oxe} \cdot BGIDL}{V_{ds} - V_{gse} - EGIDL}\right) \cdot \frac{V_{db}^3}{CGIDL + V_{db}^3}} \tag{3.8}$$

where *AGIDL*, *BGIDL*, *CGIDL*, and *EGIDL* are model parameters and explained in Appendix A. *CGIDL* accounts for the body-bias dependence of *IGIDL and IGISL*.

3.4. Oxide Tunneling Current

For thin oxide (below 20Å), oxide tunneling is important in the determination of floatin-body potential [20]. In BSIMPD the following equations are used to calculate the tunneling current density J_{gb}:

In inversion,

$$
\begin{aligned}
J_{gb} &= A\frac{V_{gb}V_{aux}}{T_{ox}^{2}}\left(\frac{\mathbf{T_{oxref}}}{T_{oxqm}}\right)^{\mathbf{N_{tox}}} exp\left(\frac{-B\left(\alpha_{gb1}-\beta_{gb1}\left|V_{ox}\right|\right)T_{ox}}{1-\left|V_{ox}\right|/\mathbf{V_{gb1}}}\right)\\
V_{aux} &= \mathbf{V_{EVB}}\, ln\left(1+exp\left(\frac{\left|V_{ox}\right|-\phi_{g}}{\mathbf{V_{EVB}}}\right)\right)\\
A &= \frac{q^{3}}{8\pi h\phi_{b}}\\
B &= \frac{8\pi\sqrt{2m_{ox}}\,\phi_{b}^{3/2}}{3hq}\\
\phi_{b} &= 4.2eV\\
m_{ox} &= 0.3m_{0}
\end{aligned}
\tag{3.9}
$$

In accumulation,

$$
\begin{aligned}
J_{gb} &= A\frac{V_{gb}V_{aux}}{T_{ox}^{2}}\left(\frac{\mathbf{T_{oxref}}}{T_{oxqm}}\right)^{\mathbf{N_{tox}}} exp\left(\frac{-B\left(\alpha_{gb2}-\beta_{gb2}\left|V_{ox}\right|\right)T_{ox}}{1-\left|V_{ox}\right|/\mathbf{V_{gb2}}}\right)\\
V_{aux} &= \mathbf{V_{ECB}}V_{t}\, ln\left(1+exp\left(-\frac{V_{gb}-V_{fb}}{\mathbf{V_{ECB}}}\right)\right)\\
A &= \frac{q^{3}}{8\pi h\phi_{b}}\\
B &= \frac{8\pi\sqrt{2m_{ox}}\,\phi_{b}^{3/2}}{3hq}\\
\phi_{b} &= 3.1eV\\
m_{ox} &= 0.4m_{0}
\end{aligned}
\tag{3.10}
$$

Please see Appendix B for model parameter descriptions.

3.5. Body Contact Current

In BSIMPD, a body resistor is connected between the body (B node) and the body contact (P node) if the transistor has a body-tie. The body resistance is modeled by

$$
R_{bp} = \left(R_{body}\frac{W_{eff}^{'}}{L_{eff}}\right) \| \left(R_{halo}\frac{W_{eff}^{'}}{2}\right), R_{bodyext} = R_{bsh}N_{rb}
\tag{3.11}
$$

Here R_{bp} and $R_{bodyext}$ represent the intrinsic and extrinsic body resistance respectively. R_{body} is the intrinsic body sheet resistance, R_{halo} accounts for the effect of halo implant, N_{rb} is the number of square from the body contact to the device edge and R_{bsh} is the sheet resistance of the body contact diffusion.

The body contact current I_{bp} is defined as the current flowing through the body resistor:

$$I_{bp} = \frac{V_{bp}}{R_{bp} + R_{bodyext}} \tag{3.12}$$

where V_{bp} is the voltage across the B node and P node. Notice that $I_{bp} = 0$ if the transistor has a floating body.

3.6. Body Contact Parasitics [17]

The effective channel width may change due to the body contact. Hence the following equations are used:

$$\begin{aligned} W_{eff} &= W_{drawn} - N_{bc} dW_{bc} - (2 - N_{bc}) dW \\ W_{eff}' &= W_{drawn} - N_{bc} dW_{bc} - (2 - N_{bc}) dW' \\ W_{diod} &= W_{eff}' + P_{dbcp} \\ W_{dios} &= W_{eff}' + P_{sbcp} \end{aligned} \tag{3.13}$$

Here dW_{bc} is the width offset for the body contact isolation edge. N_{bc} is the number of body contact isolation edge. For example: $N_{bc} = 0$ for floating body devices, $N_{bc} = 1$ for T-gate structures and $N_{bc} = 2$ for H-gate structures. P_{dbcp} / P_{sbcp} represents the parasitic perimeter length for body contact at drain/source side. The body contact parasitics may affect the I-V significantly for narrow width devices [20].

After introducing all the mechanisms that contribute the body current, we can express the nodal equation (KCL) for the body node as

$$(\boldsymbol{I}_{bs} + \boldsymbol{I}_{bd}) + \boldsymbol{I}_{bp} - \boldsymbol{I}_{ii} - (\boldsymbol{I}_{dgidl} + \boldsymbol{I}_{sgidl}) - \boldsymbol{I}_{gb} = \mathbf{0} \tag{3.14}$$

Eqn. (3.14) is important since it determines the body potential through the balance of various body current components. The I-V characteristics can then be correctly predicted after this critical body potential can be well anchored.