Chapter 6: BSIMSOI –

A Unified Model for PD and FD SOI MOSFETs

Using BSIMPD as a foundation, we have developed a unified model for both PD and FD SOI circuit designs based on the concept of *body-source built-in potential lowering* [20, 25].

6.1. BSIMSOI Framework and Built-In Potential Lowering Model

As described in [20], we construct BSIMSOI based on the concept of body-source built-in potential lowering, ΔV_{bi}. There are three modes (soiMod = 0, 1, 2) in BSIMSOI: BSIMPD (soiMod = 0) can be used to model the PD SOI device, where the body potential is independent on ΔV_{bi} ($V_{BS} > \Delta V_{bi}$). Therefore the calculation of ΔV_{bi} is skipped in this mode. On the other hand, the ideal FD model (soiMod = 2) is for the FD device with body potential equal to ΔV_{bi}. Hence the calculation of body current/charge, which is essential to the PD model, is skipped. For the unified SOI model (soiMod = 1), however, both ΔV_{bi} and body current/charge are calculated to capture the floating-body behavior exhibited in FD devices. As shown in Figure 6.1, this unified model covers both BSIMPD and the ideal FD model.

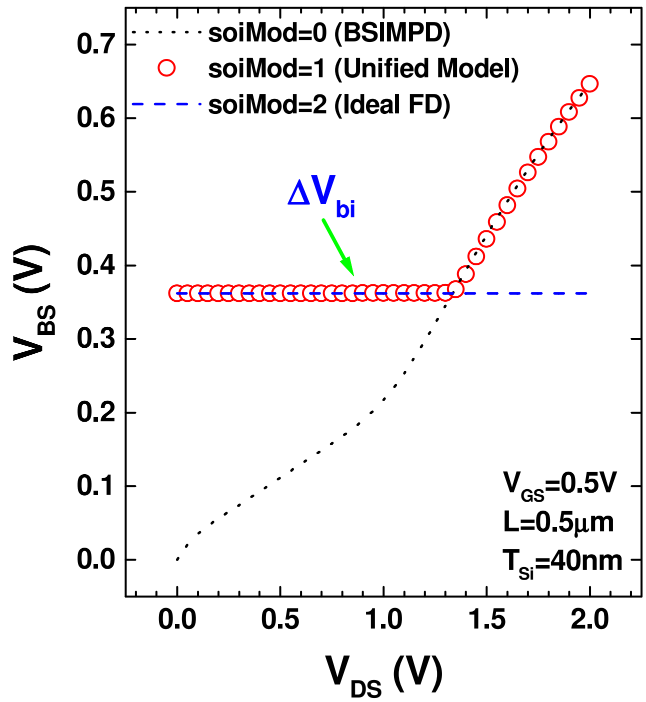

Fig. 6.1 The body potential in the unified model approaches the V_{BS} solved in BSIMPD for PD devices, while returns to ΔV_{bi} for ideal FD devices [20].

This unified model shares the same floating-body module as BSIMPD, with a generalized diode current model considering the body-source built-in potential lowering effect ($I_{BS} \propto \exp(-q\Delta V_{bi}/kT)$). Therefore, an accurate and efficient ΔV_{bi} model is crucial. The following formulation for ΔV_{bi} is mainly based on the Poisson equation and the physical characterization for ΔV_{bi}, as presented in [25].

For a given surface band bending ϕ (source reference), ΔV_{bi} can be formulated by applying the Poisson equation in the vertical direction and continuity of normal displacement at the back interface:

$$\Delta V_{bi}(\phi) = \frac{C_{Si}}{C_{Si}+C_{BOX}} \cdot \left(\phi - \frac{qN_{ch}}{2\varepsilon_{Si}} \cdot T_{Si}^{\ 2} + \Delta V_{DIBL}\right) + \eta_e\left(L_{eff}\right)\frac{C_{BOX}}{C_{Si}+C_{BOX}} \cdot \left(V_{bGS} - V_{FBb}\right)$$
$$C_{Si} = \frac{\varepsilon_{Si}}{T_{Si}}, C_{BOX} = \frac{\varepsilon_{OX}}{T_{BOX}}, C_{OX} = \frac{\varepsilon_{OX}}{T_{OX}} \qquad (6\text{-}1).$$

The first term of Equation (6-1) represents the frontgate coupling. T_{Si} is the SOI thickness. N_{ch} accounts for the effective channel doping, which may vary with channel length due to the non-uniform lateral doping effect. The second term of Equation (6-1) represents the backgate coupling (V_{bGS}). V_{FBb} is the backgate flatband voltage. Equation (6-1) shows that the impact of frontgate on ΔV_{bi} reaches maximum when the buried oxide thickness, T_{BOX}, approaches infinity.

In Equation (6-1), ΔV_{DIBL} represents the short channel effect on ΔV_{bi},

$$\Delta V_{DIBL} = D_{vbd0}\left(exp\left(-D_{vbd1}\frac{L_{eff}}{2l}\right) + 2\,exp\left(-D_{vbd1}\frac{L_{eff}}{l}\right)\right) \cdot \left(V_{bi} - 2\Phi_B\right) \qquad (6\text{-}2),$$

as addressed in [25]. Here l is the characteristic length for the short-channel-effect calculation. D_{vbd0} and D_{vbd1} are model parameters. Similarly, the following equation

$$\eta_e\left(L_{eff}\right) = K_{1b} - K_{2b} \cdot \left(exp\left(-D_{k2b}\frac{L_{eff}}{2l}\right) + 2\,exp\left(-D_{k2b}\frac{L_{eff}}{l}\right)\right) \qquad (6\text{-}3)$$

is used to account for the short channel effect on the backgate coupling, as described in [25]. D_{K1b}, D_{K2b}, K_{1b} (default 1) and K_{2b} (default 0) are model parameters.

The surface band bending, ϕ, is determined by the frontgate V_{GS} and may be approximated by

$$\phi = \begin{cases} \Phi_{ON} & \text{for } V_{GS} \geq V_T \\ \Phi_{ON} - \dfrac{C_{OX}}{C_{OX} + \left(C_{Si}^{-1} + C_{BOX}^{-1}\right)^{-1}} \cdot \left(V_T - V_{GS}\right) & \text{for } V_{GS} \leq V_T \end{cases} \qquad (6\text{-}4).$$

To improve the simulation convergency, the following single continuous function from subthreshold to strong inversion is used:

$$\phi = \Phi_{ON} - \frac{C_{OX}}{C_{OX} + \left(C_{Si}^{-1} + C_{BOX}^{-1}\right)^{-1}} \cdot N_{OFF,FD} V_t \cdot ln\left(1 + exp\left(\frac{V_{T,FD} - V_{gs\_eff} - V_{OFF,FD}}{N_{OFF,FD} V_t}\right)\right) \qquad (6\text{-}5).$$

Here V_{gs_eff} is the effective gate bias considering the poly-depletion effect. $V_{T,FD}$ is the threshold voltage at $V_{BS} = \Delta V_{bi}(\phi{=}2\Phi_B)$. $N_{OFF,FD}$ (default 1) and $V_{OFF,FD}$ (default 0) are model parameters introduced to improve the transition between subthreshold and strong inversion. V_t is the thermal voltage. Notice that the frontgate coupling ratio in the subthreshold regime approaches 1 as T_{BOX} approaches infinity.

To accurately model ΔV_{bi} and thus the device output characteristics, the surface band bending at strong inversion, Φ_{ON}, is not pinned at $2\Phi_B$. Instead, the following equation

$$\Phi_{ON} = 2\Phi_B + V_t\, ln\left(1 + \frac{V_{gsteff.FD}\left(V_{gsteff,FD} + 2K1\sqrt{2\Phi_B}\right)}{moin \cdot K1 \cdot V_t^{2}}\right) \qquad (6\text{-}6)$$

is used to account for the surface potential increment with gate bias in the strong inversion regime [4]. Here *moin* is a model parameter. K1 is the body effect coefficient. Notice that a single continuous function,

$$V_{gsteff,FD} = N_{OFF,FD} V_t \cdot ln\left(1 + exp\left(\frac{V_{gs\_eff} - V_{T,FD} - V_{OFF,FD}}{N_{OFF,FD} V_t}\right)\right) \qquad (6\text{-}7),$$

has been used to represent the gate overdrive in Equation (6-6).

6.2. Verification

The BSIMPD parameter extraction methodology presented in [20] may still be used under the unified BSIMSOI framework, provided that the link between PD and FD, ΔV_{bi}, can be accurately extracted. As described in [25], a direct probe of ΔV_{bi} can be achieved by finding the onset of the external body bias (through a body contact) after which the threshold voltage and hence the channel current of the FD SOI device is modulated. When the body contact is not available, nevertheless, model parameters related to ΔV_{bi} should be extracted based on the subthreshold characteristics of the floating-body device. As shown in Figure 6.2, the reduction of ΔV_{bi} with backgate bias is responsible for the transition from the ideal subthreshold swing (~ 60 mV/dec. at room temperature) to the non-ideal one.

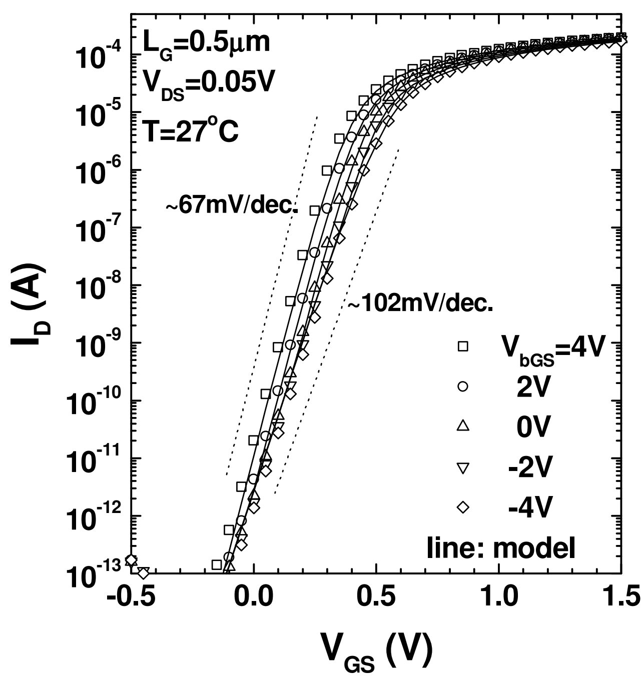

Fig. 6.2 The PD/FD transition can be captured by modeling ΔV_{bi} [20].

Figure 6.2 clearly shows that the PD/FD transition can be captured by the ΔV_{bi} approach. In other words, ΔV_{bi} is indeed an index of the degree of full depletion, as pointed out in [20, 25]. As shown in Figure 6.3, larger floating-body effect can be observed for negative backgate bias due to smaller ΔV_{bi}. In case the ΔV_{bi} value is raised by charge sharing as described in [25], it can be predicted that the short-channel device should exhibit less floating-body effect than the long-channel one due to larger ΔV_{bi}, as verified in Figure 6.4.

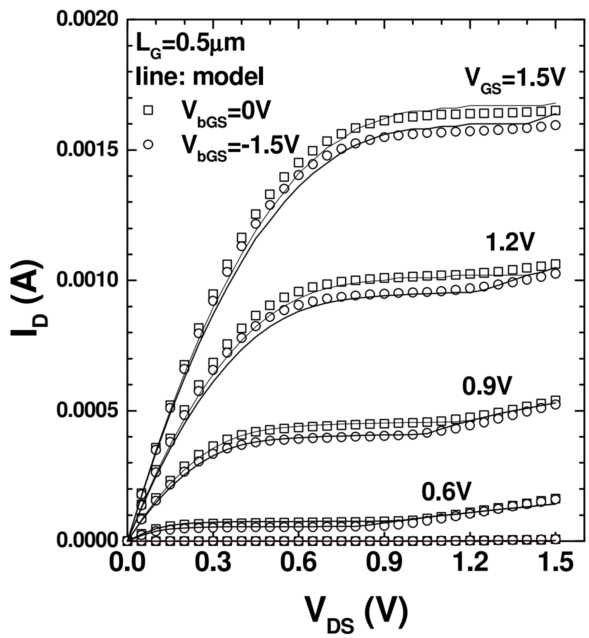

Fig. 6.3 Larger floating-body effect can be seen for the negative backgate bias (source reference) due to smaller ΔV_{bi} [20].

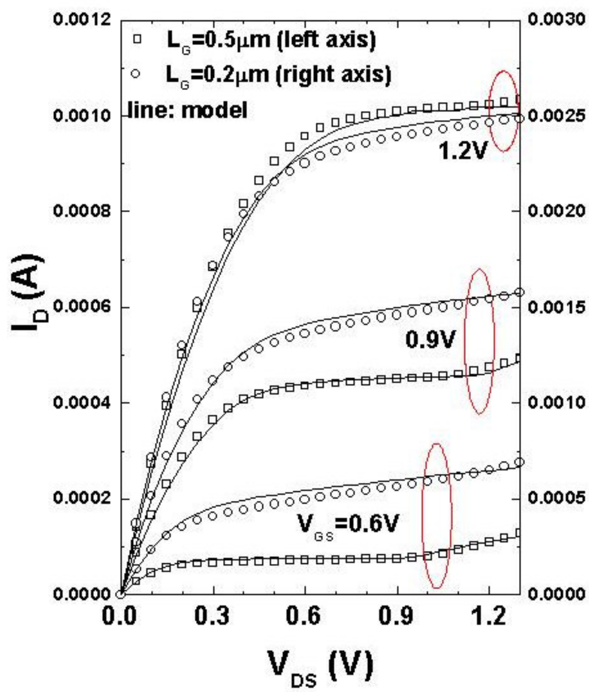

Fig. 6.4 Less floating-body effect can be seen for the short-channel device due to larger ΔV_{bi} [20].

6.3. Model Selector SOIMOD

The model selector, SoiMod, is an instance parameter and a model parameter. SoiMod will determine the operation of BSIMSOI.

If SoiMod=0 (default), the model equation is identical to BSIMPD equation.

If SoiMod=1 (unified model for PD&FD) or SoiMod=2 (ideal FD), the following equations (FD module) are added on top of BSIMPD.

$$V_{bs0} = \frac{C_{Si}}{C_{Si} + C_{BOX}} \cdot \left(phi - \frac{qN_{ch}\left(1 + N_{LX}/L_{eff}\right)}{2\varepsilon_{Si}} \cdot T_{Si}^{\;2} + V_{nonideal} + \Delta V_{DIBL} \right) + \eta_e \frac{C_{BOX}}{C_{Si} + C_{BOX}} \cdot \left(V_{es} - V_{FBb}\right)$$

$$\text{where } C_{Si} = \frac{\varepsilon_{Si}}{T_{Si}}, C_{BOX} = \frac{\varepsilon_{OX}}{T_{BOX}}, C_{OX} = \frac{\varepsilon_{OX}}{T_{OX}}$$

$$\Delta V_{DIBL} = D_{vbd0}\left(exp\left(-D_{vbd1}\frac{L_{eff}}{2l}\right) + 2\,exp\left(-D_{vbd1}\frac{L_{eff}}{l}\right)\right) \cdot \left(V_{bi} - 2\Phi_B\right)$$

$$\eta_e = K_{1b} - K_{2b} \cdot \left(exp\left(-D_{k2b}\frac{L_{eff}}{2l}\right) + 2\,exp\left(-D_{k2b}\frac{L_{eff}}{l}\right)\right)$$

$$phi = phi_{ON} - \frac{C_{OX}}{C_{OX} + \left(C_{Si}^{\;-1} + C_{BOX}^{\;-1}\right)^{-1}} \cdot N_{OFF,FD}V_t \cdot ln\left(1 + exp\left(\frac{V_{th,FD} - V_{gs\_eff} - V_{OFF,FD}}{N_{OFF,FD}V_t}\right)\right)$$

$$phi_{ON} = 2\Phi_B + V_t\, ln\left(1 + \frac{V_{gsteff.FD}\left(V_{gsteff,FD} + 2K1\sqrt{2\Phi_B}\right)}{MoinFD \cdot K1 \cdot V_t^{\;2}}\right),$$

$$V_{gsteff,FD} = N_{OFF,FD}V_t \cdot ln\left(1 + exp\left(\frac{V_{gs\_eff} - V_{th,FD} - V_{OFF,FD}}{N_{OFF,FD}V_t}\right)\right)$$

Here N_{ch} is the channel doping concentration. N_{LX} is the lateral non-uniform doping coefficient to account for the lateral non-uniform doping effect. V_{FBb} is the backgate flatband voltage. $V_{th,FD}$ is the threshold voltage at V_{bs}=V_{bs0}(phi=$2\Phi_B$). V_t is thermal voltage. K1 is the body effect coefficient.

If SoiMod=1, the lower bound of V_{bs} (SPICE solution) is set to V_{bs0}. If SoiMod=2, V_{bs} is pinned at V_{bs0}. Notice that there is no body node and body leakage/charge calculation in SoiMod=2.

The zero field body potential that will determine the transistor threshold voltage, V_{bsmos}, is then calculated by

$$\begin{aligned} V_{bsmos} &= V_{bs} - \frac{C_{Si}}{2qN_{ch}T_{Si}}\left(V_{bs0}\left(T_{OX} \to \infty\right) - V_{bs}\right)^2 \quad \text{if } V_{bs} \le V_{bs0}\left(T_{OX} \to \infty\right) \\ &= V_{bs} \quad \text{else} \end{aligned}$$

The subsequent clamping of V_{bsmos} will use the same equation that utilized in BSIMPD. Please download the BSIMPD manual at (www-device.eecs.Berkeley.edu/~bsimsoi).

If SoiMod=3 is specified, BSIMSOI will select the operation mode for the user based on the estimated value of V_{bs0} at phi=$2\Phi_B$ (bias independent), V_{bs0t}:

If $V_{bs0t} > V_{bs0fd}$, BSIMSOI will be in the ideal FD mode (SoiMod=2).

If $V_{bs0t} < V_{bs0pd}$, BSIMSOI will be in the BSIMPD mode (SoiMod=0).

Otherwise, BSIMSOI will be operated under SoiMod=1.

Notice that both V_{bs0fd} and V_{bs0pd} are model parameters.