Scalable MOSFET Short-channel Charge Model for All Regions

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Modeling Approach

- Charge models are formulated from *unified regional* approach.
- Advantages:
  - The simplest physical formulation
  - Model is easy to extend to include other effects (SCEs/non-classical model) for all regions, e.g., PAE and SCE at accumulation.
  - Accuracy requirement in surface potential can be relaxed

$$\phi_{acc} = V_{gbr} + 2v_{th}\mathcal{L}\{w\}, \left(V_{gb} < V_{fb}\right)$$

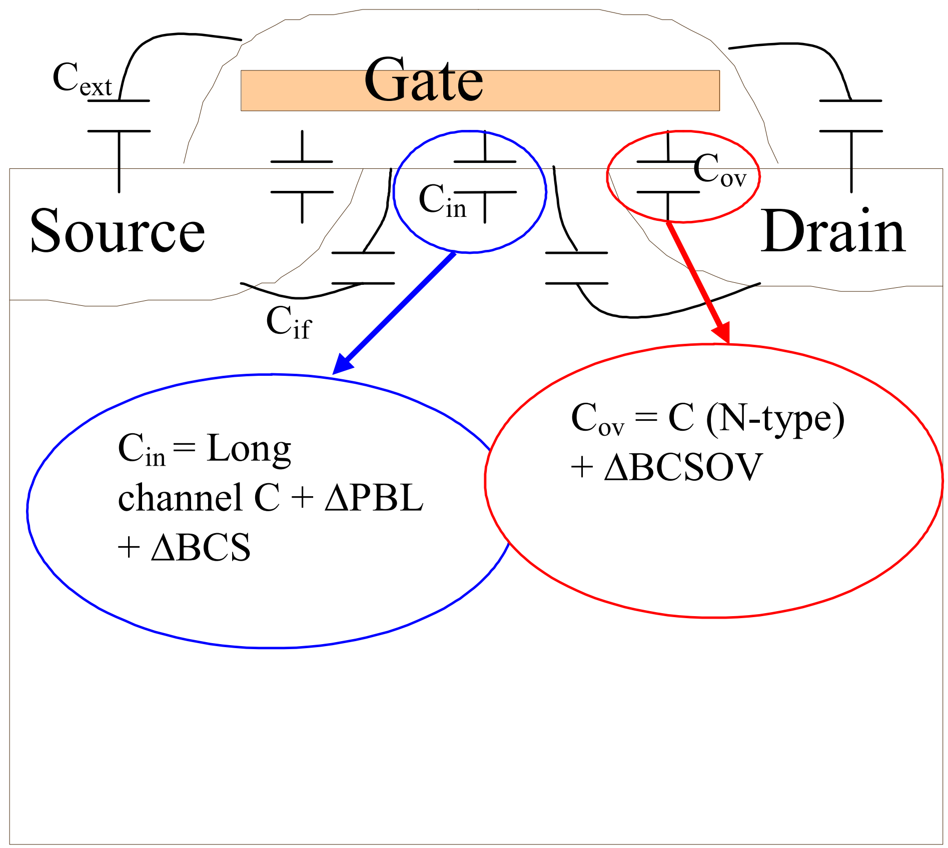
$$\phi_{sub} = \left(-\frac{\gamma}{2} + \sqrt{\frac{\gamma^2}{4} + V_{gbf}}\right)^2, \left(V_{fb} < V_{gb} < V_t\right)$$

$$\phi_{str} = \phi_{s0} + V_{cb} + \Delta, \left(V_{gb} > V_t\right)$$

Model Formulation

Short channel capacitances include:

- Intrinsic capacitance, C_{in}= Long channel capacitance + Quasi-2D Potential barrier lowering (PBL) + Bulk-charge sharing (BCS).
- Extrinsic capacitances = Overlap capacitances, C_{ov}+ Extrinsic fringing capacitance, C_{ext} + Intrinsic fringing capacitance, C_{if}



Intrinsic SC Model Quasi-2D PBL

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- Quasi-2D Poisson solution of the channel
- Assuming the maximum depletion depth, X_{dmax} for x-direction, $y(0)=V_{bi}+V_{sb}$, $y(L_{eff})=V_{bi}+V_{db}$
- A general solution exist at the minimum potential difference.

$$\phi_{acc,pbl} = \phi_{acc} + \Delta\phi_{acc}$$

$$\phi_{ds,pbl} = \phi_{ds} + \Delta\phi_{ds}$$

e.g. charge formulation in accumulation

$$Q_{B,acc} \approx -Q_{G,acc} = -C_{ox} W L_{eff}\left[V_{gb} - V_{FB} - \left(\phi_{acc} + \Delta\phi_{acc}\right)\right]$$

$$= \underbrace{-C_{ox} W L_{eff}\left(V_{gb} - V_{FB} - \phi_{acc}\right)}_{Q_{BL,acc}} + \underbrace{C_{ox} W L_{eff} \Delta\phi_{acc}}_{-\Delta Q_{B,PBL}}$$

$$V_{gb} - V_{FB} - \psi(y) + \frac{\varepsilon_{Si} X_{d\max}}{\eta C_{ox}} \frac{dE_s(y)}{dy} = \frac{Q_g + Q_{ox}}{C_{ox}}$$

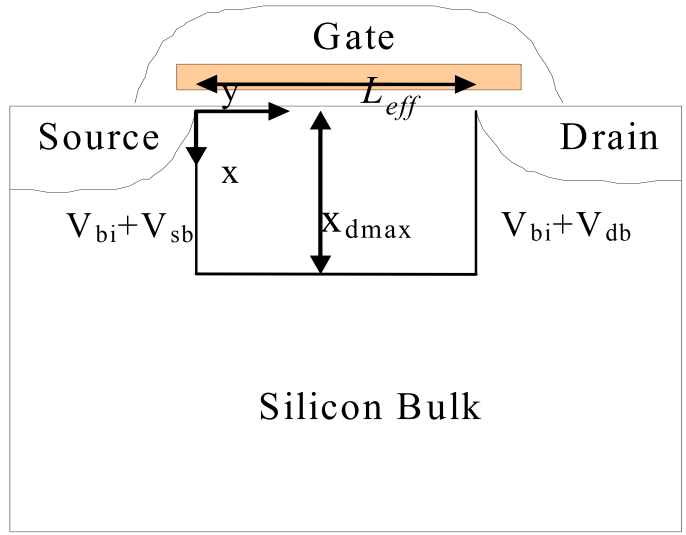

Fig. 1. Gaussian box and boundary conditions in quasi-2D analysis for PBL

BCS

- Bulk-charge sharing assumes the trapezoidal shape of depletion layer in the channel.
- Only valid when depletion layer is form when $V_{gb}>V_{FB}$
- Can be modeled with modification of body-factor

$$\gamma_{bcs} = \gamma\left(1-\frac{\lambda}{L_{eff}}\left(\frac{X_{dep,s}+X_{dep,d}}{2}\right)\right)$$

$$\phi_{ds,bcs} = \phi_{ds}\left\{\gamma_{bcs}\right\}$$

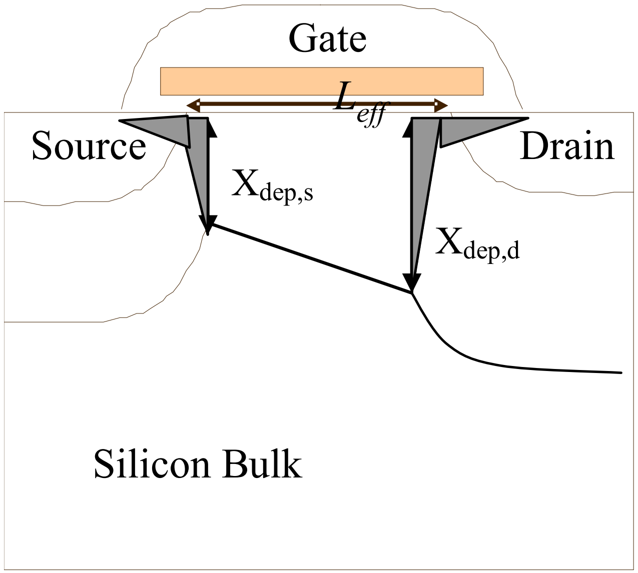

Fig. 2. Charge sharing effect in channel and overlap region at short channel

Therefore, SC intrinsic charge

$$Q_{b,L} = -C_{ox}V_{teff} \rightarrow Q_{b,sc} = -C_{ox}V_{teff}\left\{\phi_{acc}+\Delta\phi_{acc},\phi_{ds}\left\{\gamma_{bcs}\right\}+\Delta\phi_{ds}\right\}$$

$$Q_{d,L} = -C_{ox}f\left\{\phi_{ds}\right\} \rightarrow Q_{d,sc} = -C_{ox}f\left\{\phi_{ds}\left\{\gamma_{bcs}\right\}+\Delta\phi_{ds}\right\}$$

$$Q_{s,L} = -C_{ox}g\left\{\phi_{ds}\right\} \rightarrow Q_{d,sc} = -C_{ox}g\left\{\phi_{ds}\left\{\gamma_{bcs}\right\}+\Delta\phi_{ds}\right\}$$

Extrinsic Capacitances

- Overlap region: another two shorter opposite doped MOS structure.
- Become comparable to channel length at very short channel
- BCS in overlap (BCSOV) is also applied for overlap region
- Example, at source side

$$Q_{Sov,acc} = -WL_{ov}C_{ox}\left(V_{gsf} - \phi_{ov,acc}\right)$$

$$\gamma_{ov,bcs} = \gamma_{ov}\left(1 - \frac{\lambda_{ov}}{L_{ov}}\frac{X_{dov,s}}{2}\right)$$

$$Q_{Sov,sub} = -WL_{ov}C_{ox}\left(V_{gsr} - \phi_{ov,sub}\left\{\gamma_{ov,bcs}\right\}\right)$$

- Extrinsic fringing are formulated w.r.t intrinsic charge formulations

$$Q_{B,FR} = v_b Q_{B,SC}\left(C_{side} + C_{bottom}\right) / \left(L_g C_{ox}\right)$$

$$Q_{I,FR} = v_i Q_{I,SC}\left(C_{side} + C_{bottom}\right) / \left(L_g C_{ox}\right)$$

- Intrinsic fringing model the “hump” observed in the 2D-simulation result, it is empirically formulated as

$$Q_{I,IF} = -\kappa_{if} C_{IF,\max} \operatorname{erf}\left(\frac{V_{gb} - V_{FB} - \alpha_{if}}{\beta_{if}}\right)$$

- Total charge

$$Q_D = Q_{D,L}\left\{\phi_{ds}\left\{\gamma_{bcs}\right\} + \Delta\phi_{ds}\right\} + Q_{D,OV}\left\{\gamma_{ov,bcs}\right\} + 0.5Q_{I,IF} + Q_{D,FR}$$

$$Q_S = Q_{S,L}\left\{\phi_{ds}\left\{\gamma_{bcs}\right\} + \Delta\phi_{ds}\right\} + Q_{S,OV}\left\{\gamma_{ov,bcs}\right\} + 0.5Q_{I,IF} + Q_{S,FR}$$

$$Q_B = Q_{B,L}\left\{\phi_{acc} + \Delta\phi_{acc}, \phi_{ds}\left\{\gamma_{bcs}\right\} + \Delta\phi_{ds}\right\} + Q_{B,FR}$$

$$Q_G = -\left(Q_D + Q_S + Q_B + Q_{OX}\right)$$

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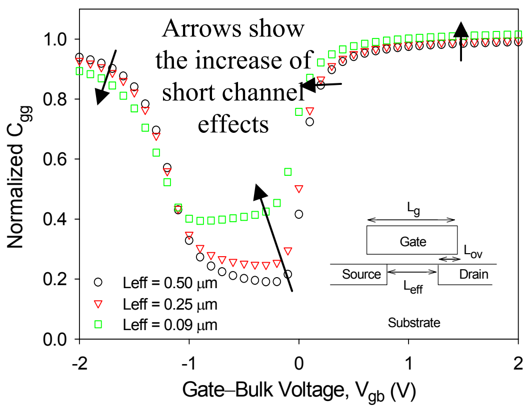
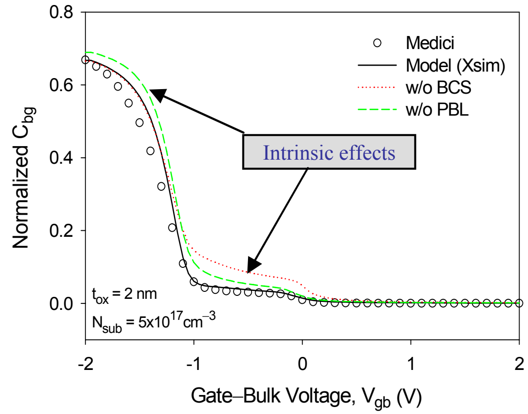
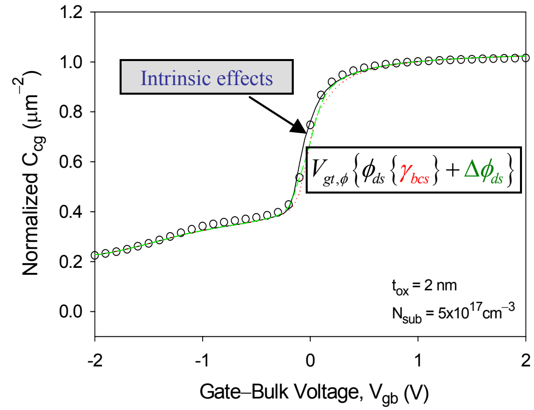
Model Behavior & Verification

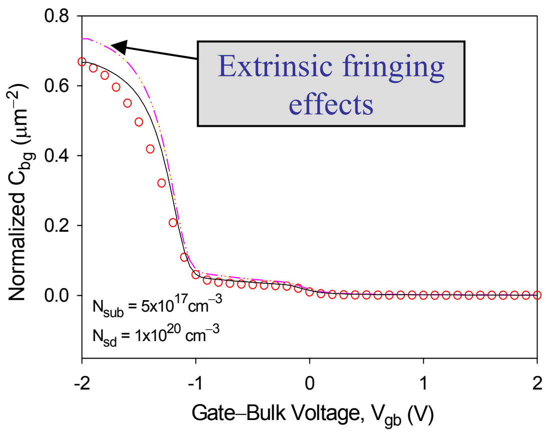
$$Q_b = -C_{ox} V_{teff} \{\phi_{acc} + \Delta\phi_{acc}, \phi_{ds}\{\gamma_{bcs}\} + \Delta\phi_{ds}\}$$





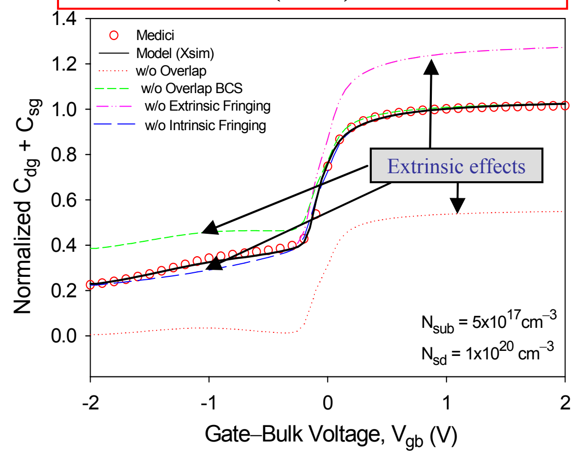


$$Q_B = Q_{B,L}\{\phi_{acc} + \Delta\phi_{acc}, \phi_{ds}\{\gamma_{bcs}\} + \Delta\phi_{ds}\} + Q_{B,FR}$$

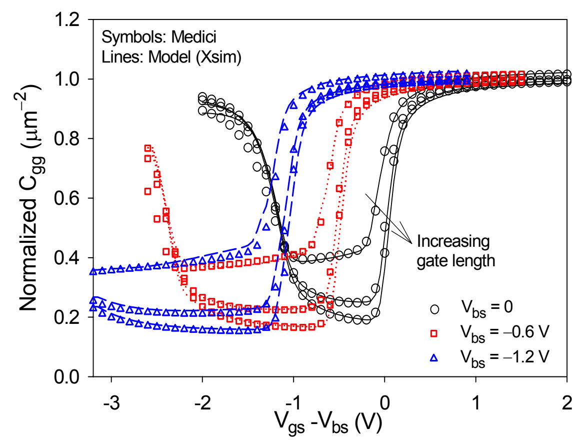


$$Q_D = Q_{D,SC} + Q_{D,OV}\{\gamma_{ov,bcs}\} + 0.5Q_{I,IF} + Q_{D,FR}$$

$$Q_S = Q_{S,SC} + Q_{S,OV}\{\gamma_{ov,bcs}\} + 0.5Q_{I,IF} + Q_{S,FR}$$



Scalable in geometry and bias



Conclusion

- Quasi-2D PBL improved the accuracy at accumulation.
- Beside Overlap capacitance, BCS in overlap region is also critical but usually ignored.
- The model is scalable for lengths and different body biases.
- More works to be done for Non-zero Vds condition.