## Physics and Engineering of CMOS Devices

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# Quasi-2D Model

### Quasi-2D Model: Concept

The charge sharing model is suitable for analyzing MOSFET operation with small drain voltage. Since in the charge sharing model the surface potential is assumed to be constant along the channel direction, the model is inaccurate at a high drain voltage. In the quasi-2D model, the Poisson's equation is solved analytically, and thus the quasi-2D model is better to analyze  $V_{th}$  shift in shorter channel MOSFETs.

Z.-H. Liu et al., "Threshold Voltage Model for Deep-Submicrometer MOSFET's," *IEEE Trans. Electron Dev.*, **40** (1), p86, 1993.

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#### Quasi-2D Model: Gauss's Law



#### Quasi-2D Model: Differential Eq.

$$\frac{d^{2}V_{s}(0, y)}{dy^{2}} + \frac{\kappa_{ox}}{\kappa_{s}} \frac{\eta}{X_{depl}t_{ox}} \left[ V_{gs} - V_{FB} - V_{s}(y) - \frac{qN_{sub}X_{depl}t_{ox}}{\kappa_{ox}\varepsilon_{0}} \right] = 0$$

$$\frac{d^{2}V_{s}(0, y)}{dy^{2}} + \frac{1}{l^{2}} \left[ V_{gs} - V_{th0} - V_{s}(y) + 2\phi_{F} \right] = 0$$

$$l = \sqrt{\frac{\kappa_{s}}{\kappa_{ox}}} \frac{X_{depl}t_{ox}}{\eta}}{V_{th0}} = V_{FB} + \frac{qN_{sub}X_{depl}t_{ox}}{\kappa_{ox}\varepsilon_{0}} + 2\phi_{F}$$

$$\frac{d^{2}V_{s}(y)}{dy^{2}} - \frac{1}{l^{2}}V(y) = -\frac{1}{l^{2}} \left[ V_{gs} - V_{th0} + 2\phi_{F} \right]$$

$$V_{s}(y) = C_{1}e^{y/l} + C_{2}e^{-y/l} + C_{3}$$

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#### **Quasi-2D Model: Boundary Condition**



#### **Quasi-2D Model: Solution**



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#### **Potential in Long Channel FETs**



## DIBL Drain Induced Barrier Lowering

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Vth Roll-off



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#### Surface Potential Minimum (V<sub>ds</sub> ~ 0)

$$V_{s\min} = V_s (y_0)$$
$$\frac{dV_s}{dy}\Big|_{y=y_0} = 0$$

When  $V_{ds} \ll V_{bi} - V_{sL}$  ,  $y_0 \approx L/2$  .

$$V_{s\min} = V_{sL} + \left[2\left(V_{bi} - V_{sL}\right) + V_{ds}\right] \frac{\sinh\left(L/2l\right)}{\sinh\left(L/l\right)}$$

At the threshold, we can expect  $V_{s\min} = 2\phi_F$ 

$$2\phi_F = V_{sL} + \left[2\left(V_{bi} - V_{sL}\right) + V_{ds}\right] \frac{\sinh\left(L/2l\right)}{\sinh\left(L/l\right)}$$

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#### Threshold Voltage Shift (V<sub>ds</sub> ~ 0)

$$2\phi_F = V_{sL} + \left[2\left(V_{bi} - V_{sL}\right) + V_{ds}\right] \frac{\sinh\left(L/2l\right)}{\sinh\left(L/l\right)}$$

$$V_{sL} = V_{gs} - V_{th0} + 2\phi_F$$

$$V_{gs} = V_{th} \left( L \right) = V_{th0} - \frac{2\left(V_{bi} - 2\phi_F\right) + V_{ds}}{2\cosh\left(\frac{L}{2l}\right) - 2}$$

When  $l \ll L$ 

$$\Delta V_{th}(L) = \frac{2(V_{bi} - 2\phi_F) + V_{ds}}{2\cosh\left(\frac{L}{2l}\right) - 2} \approx \left[2(V_{bi} - 2\phi_F) + V_{ds}\right] \left(e^{-L/2l} + 2e^{-L/l}\right)$$

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## **Plot of Threshold Voltage Roll-off**



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#### Quasi-2D Model (7): DIBL



## Threshold Voltage Shift (V<sub>ds</sub> >> 0)

The minimum of the surface potential shifts to the source side, as the drain voltage increases. Therefore, we need to accurately obtain the position giving the minimum surface potential.

 $\Delta V_{th}(L) \approx \left[3(V_{bi} - 2\phi_F) + V_{ds}\right] e^{-L/l} + 2\sqrt{(V_{bi} - 2\phi_F)(V_{bi} - 2\phi_F + V_{ds})} e^{-L/2l}$ 



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## **Saturation Velocity**

## **Velocity Saturation at High Field**



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## Empirical Formula for v-E curve



## Summary

- Quasi-2D model is introduced.
- DIBL (Drain-induced Barrier Lowering) is analyzed using the quasi-2D model.
- Exponential dependence of  $\Delta V$ th on the channel length is derived.
- Carrier velocity saturation at high field is discussed.