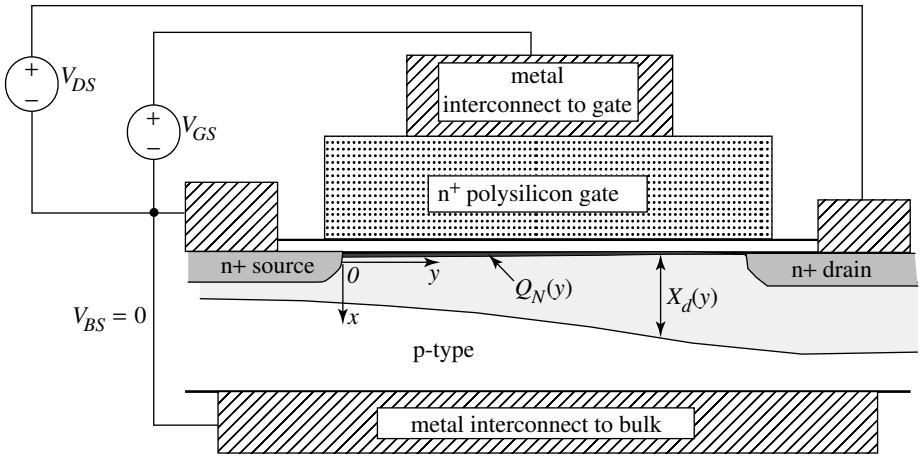
I. MOSFET Device Physics: Second Pass



A. Starting Point

$$I_D = -W v_y(y) Q_N(y)$$

B. Velocity- Assume $v_y < v_{sat}$

$$v_y = -\mu_n E_y = \mu_n \frac{dV_C(y)}{dy}$$

C. Channel Potential V_C

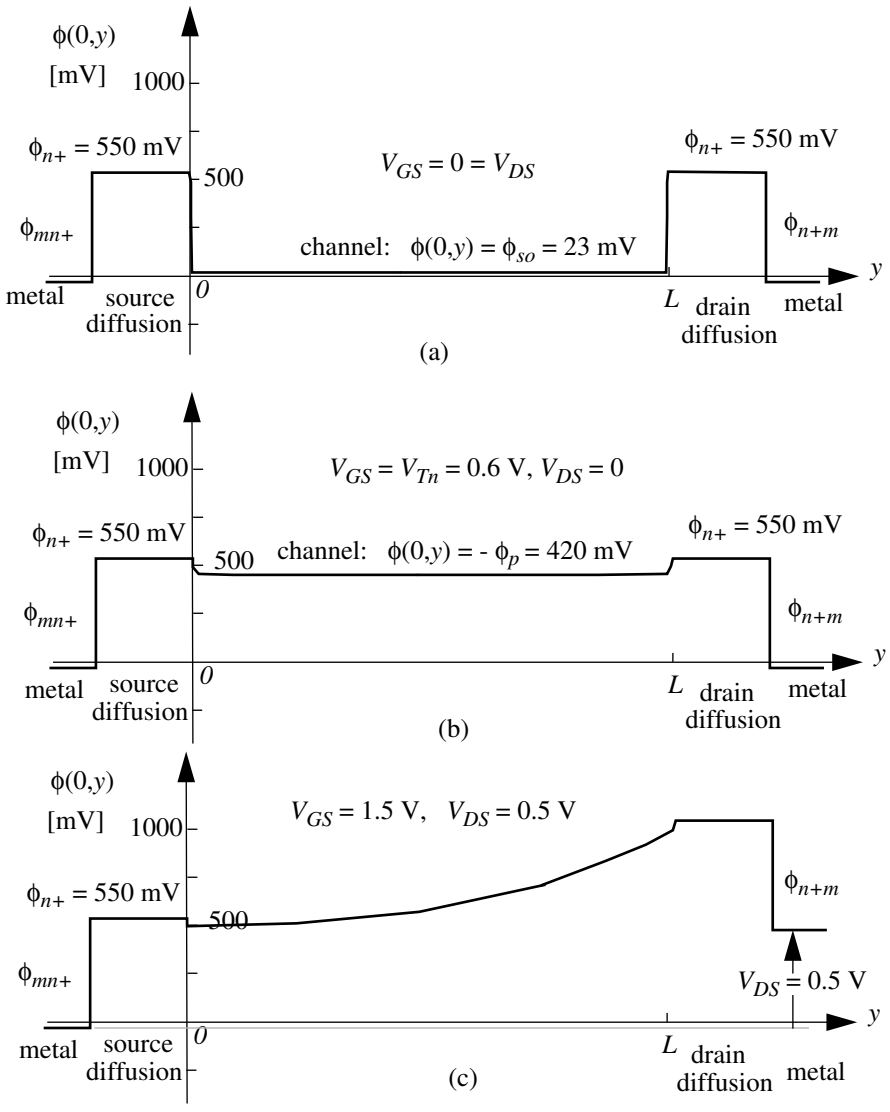
- Component of the surface potential due to drain-source voltage

D. Channel Charge

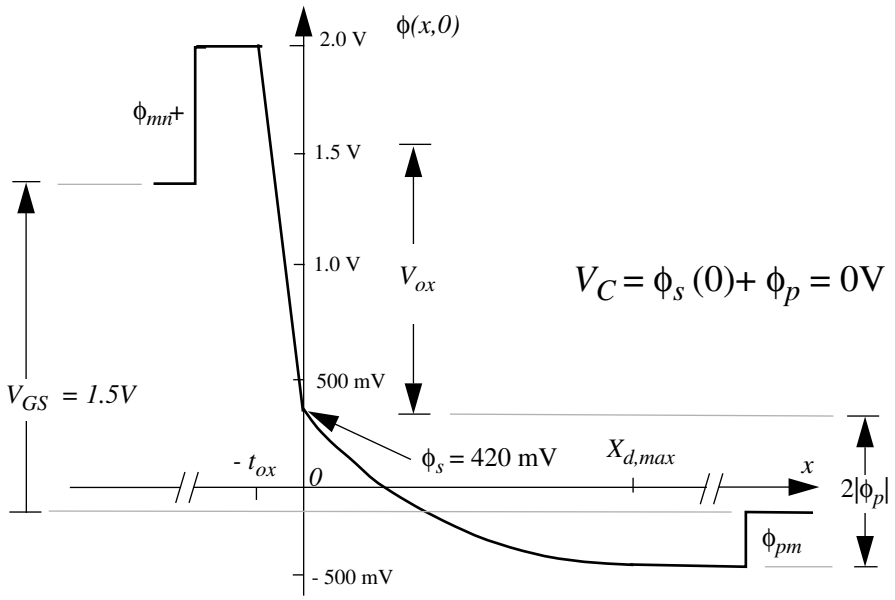
- $Q_N(y)$ varies from source-to-drain
- $Q_B(y)$ varies from source-to-drain
- $Q_G(y) = -(Q_N(y) + Q_B(y))$

E. Gradual Channel Approximation

- Apply one-dimensional results to two-dimensional MOSFET
- Lateral Field from V_{DS} has negligible effect on the vertical electrostatics. It adds its potential only at the surface of the device when the inversion layer is formed.

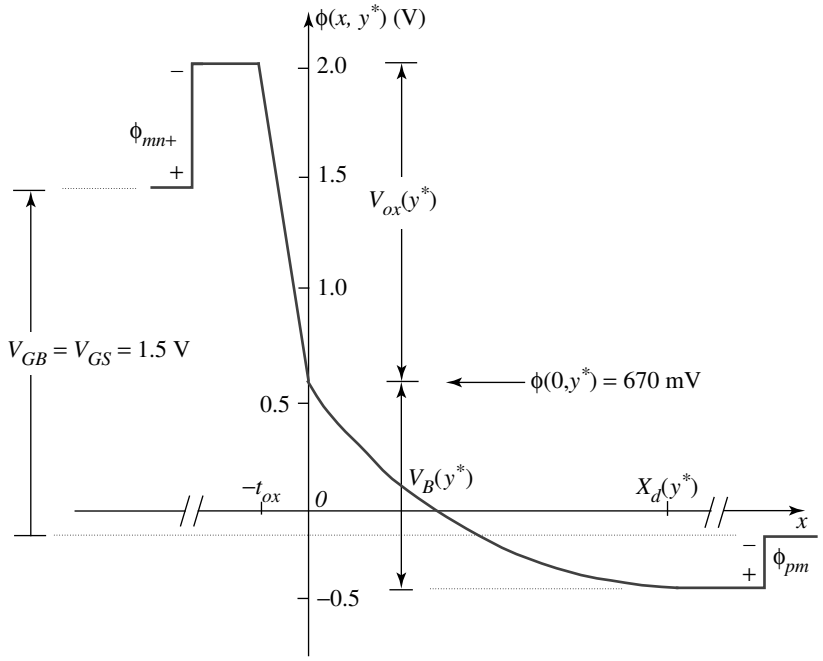


- $\phi(x,0)$ is the potential vertically at the **source end** of the device

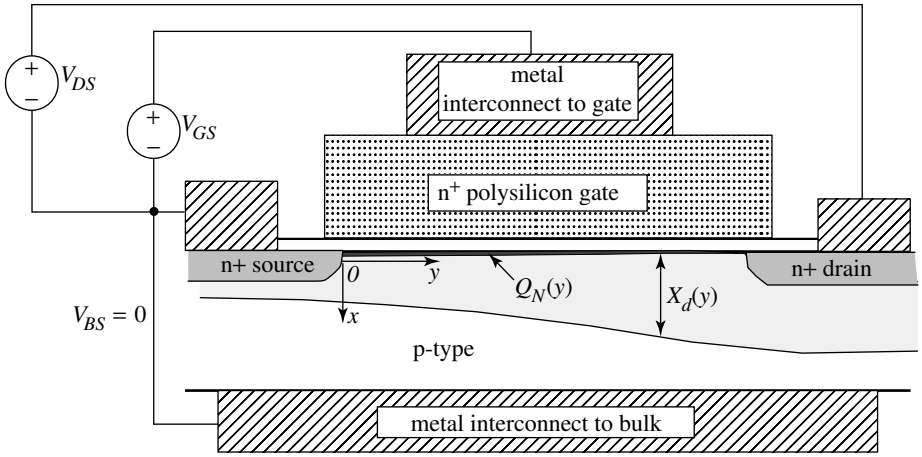


$$V_C = \phi_s(0) + \phi_p = 0\text{V}$$

- $V_C(0)$=0 V ---- $V_C(y^*)$ = 0.25V ---- $V_C(L)=V_{DS}$
- V_C referenced to Source----- ϕ_s referenced to Bulk



F. MOSFET Threshold Voltage



- Define Threshold Voltage to account for bulk charge variation along the channel

$$V_{Tn}(y) = V_{FB} - 2\phi_p + \frac{Q_B(y)}{C_{ox}} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}}\sqrt{2q\varepsilon_s N_a\left(V_C(y) - 2\phi_p\right)}$$

- Increase in Threshold Voltage along channel is due to increase in bulk charge. This effect is called - *BODY EFFECT*
- Mobile Charge including Body Effect

$$Q_N(y) = -C_{ox}\left(V_{GS} - V_{Tn}(y) - V_C(y)\right)$$

G. First Order Model

- Neglect Body Effect $Q_B(y) = Q_B(0)$ and $V_c(0) = 0$

$$V_{Tn} = V_{TOn} = V_{FB} - 2\phi_p + \frac{\sqrt{2q\varepsilon_s N_a(-2\phi_p)}}{C_{ox}}$$

- Channel Charge

$$Q_N(y) \approx -C_{ox}\left(V_{GS} - V_{Tn} - V_C(y)\right)$$

- Drain current using the Gradual Channel Approximation

$$I_D = -WQ_N(y)v_y(y) = WC_{ox}\left(V_{GS} - V_{Tn} - V_C(y)\right)\mu_n\frac{dV_C(y)}{dy}$$

- Integrate over the channel length y=0 to y=L
- $V_C(y)$ =0 V to $V_C(y)$=V_{DS}

$$\int_0^L I_D dy = \int_0^{V_{DS}} W\mu_n C_{ox}\left(V_{GS} - V_{Tn} - V_C(y)\right)dV_C$$

- Since drain current is independent of position

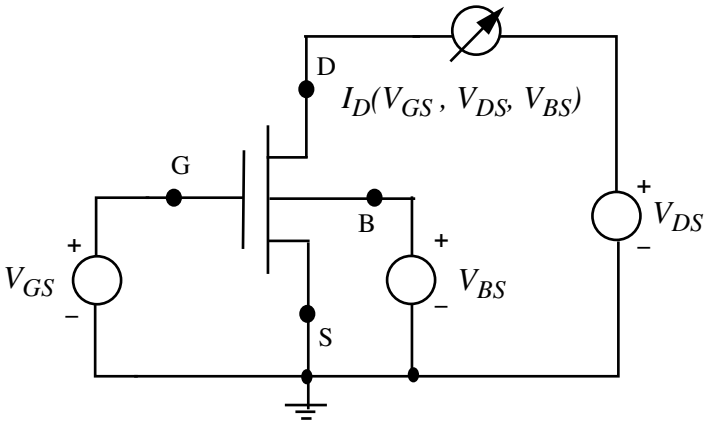
$$I_D = \left(\frac{W}{L}\right)\mu_n C_{ox}\left(V_{GS} - V_{Tn} - V_{DS}/2\right)V_{DS}$$

$$V_{DS} \leq V_{GS} - V_{Tn}$$

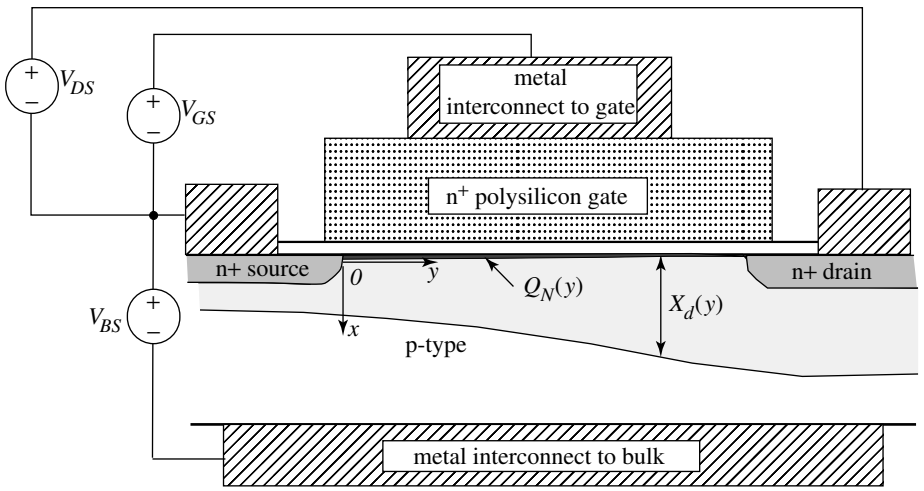
II. Backgate Effect $V_{BS} \neq 0$

A. Qualitative Description

- In some circuits, the p-type bulk region cannot be shorted to the source.
- V_{BS} must be negative in order to avoid forward bias of the source-bulk diode.



- The depletion region under the gate widens
- A larger gate voltage is needed to raise the surface potential to $-\phi_p$ and invert the surface.
- The threshold voltage increases with increasing $V_{SB} = -V_{BS}$



B. Quantitative expression:

$$V_{Tn} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}}\sqrt{(2qN_a\varepsilon_s)\,(-2\phi_p + V_{SB})}$$

- which is re-expressed in the standard form:

$$V_{Tn} = V_{TOn} + \gamma_n\left(\sqrt{-2\phi_p + V_{SB}} - \sqrt{-2\phi_p}\right)$$

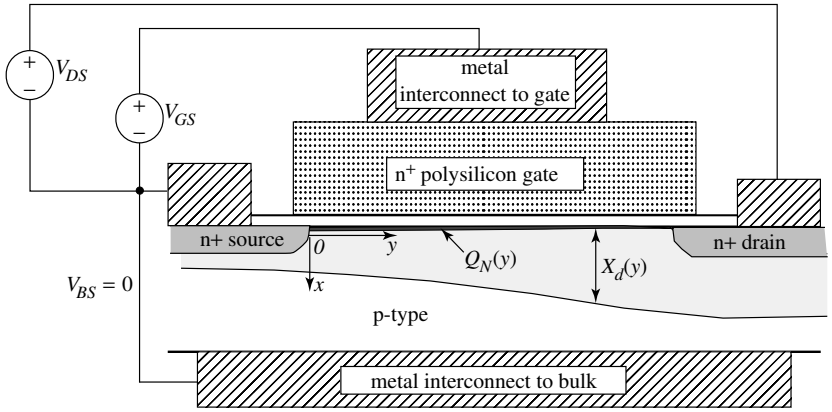
- where V_{Ton} is the threshold voltage with $V_{BS} = 0$ (standard formula)
- γ_n is the *backgate effect parameter*.

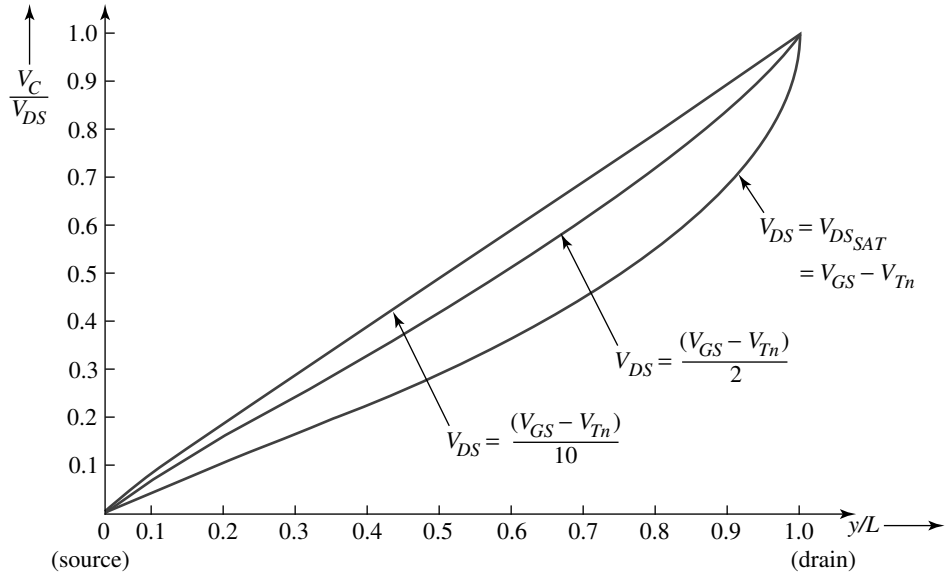
$$\gamma_n = \left(\sqrt{2qN_a\varepsilon_s}\right)/C_{ox}$$

III. Saturation

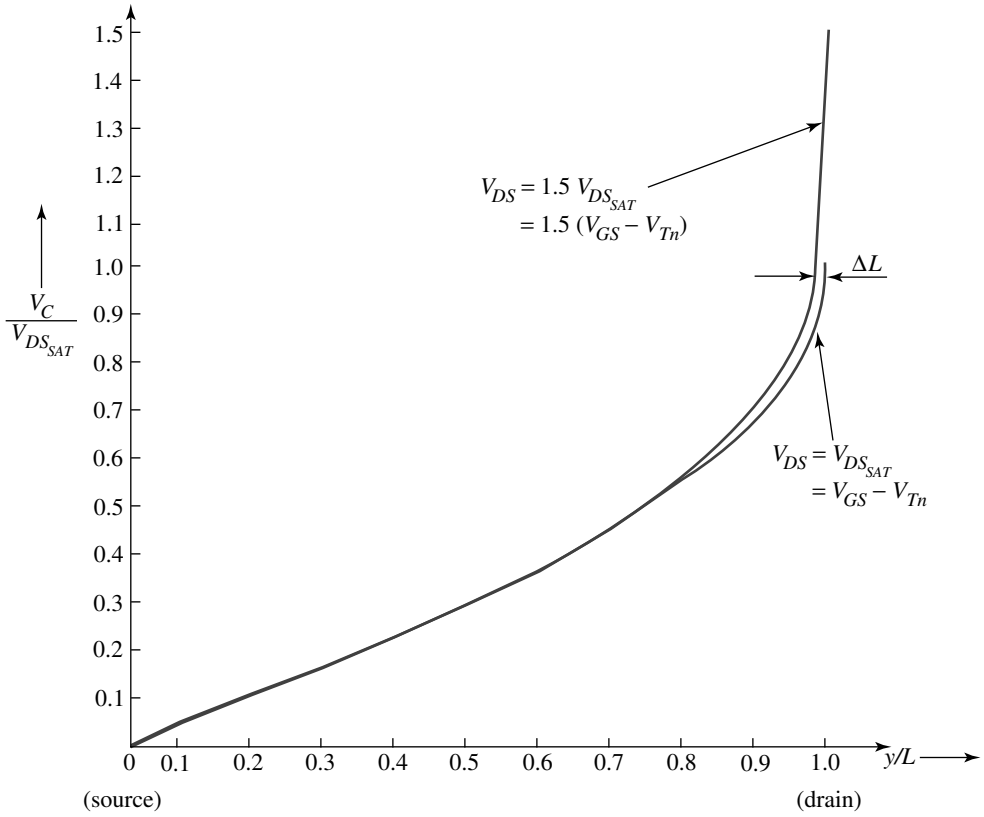
A. Replace V_{DS} with $V_{DS_{SAT}} = V_{GS} - V_{Tn}$

$$I_D = I_{D_{SAT}} = \frac{1}{2}\left(\frac{W}{L}\right)\mu_n C_{ox}\left(V_{GS} - V_{Tn}\right)^2 \text{ where } V_{DS} \geq V_{DS} = V_{GS} - V_{Tn}$$





- Increase V_{DS} above $V_{DS(sat)}$ - **Channel Length Modulation**

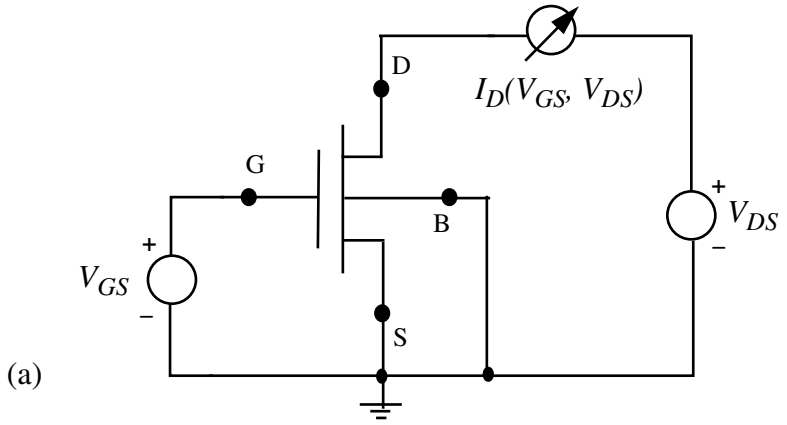


- Drain Current is modified since the channel length is shortened by

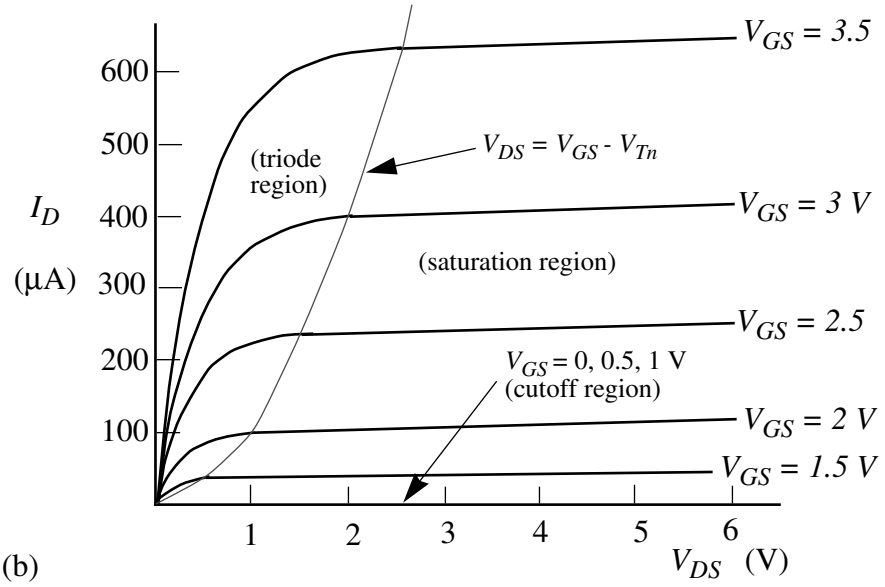
$$L - \Delta L$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L - \Delta L}\right)\left(V_{GS} - V_{Tn}\right)^2$$

B. Circuit Model for Saturation



(a)



(b)

$$I_D = \left(\frac{W}{2L}\right)\mu_n C_{ox}\left(V_{GS} - V_{Tn}\right)^2\left(1 + \lambda V_{DS}\right)$$

$$V_{Tn} = V_{TOn} + \gamma_n\left(\sqrt{-2\phi_p + V_{SB}} - \sqrt{-2\phi_p}\right)$$