Practice 3:

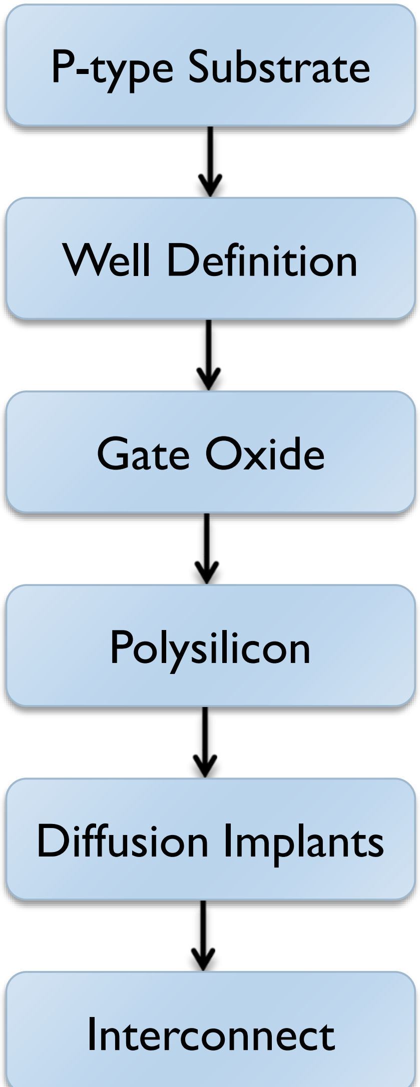
Semiconductors

VLSI Fabrication Process

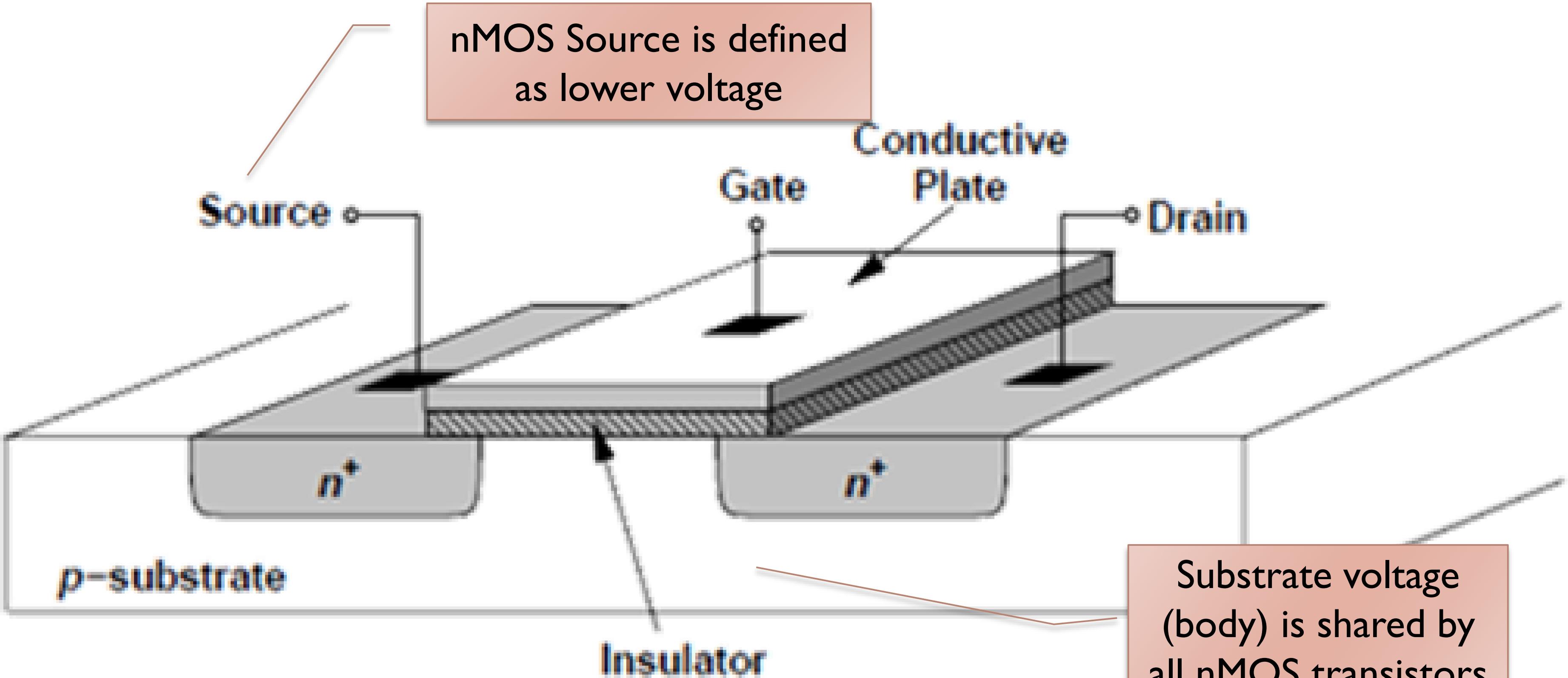
VLSI – Very Large Scale Integration

- The ability to fabricate many devices on a single substrate within a given process flow/timeframe – independent of the number of devices fabricated.
- One of the most important inventions of the 20^{th} Century.
- Similar to a printing press.

VLSI – Transistor Fabrication



VLSI – nMOS Transistor



(a) NMOS transistor as 4-terminal device

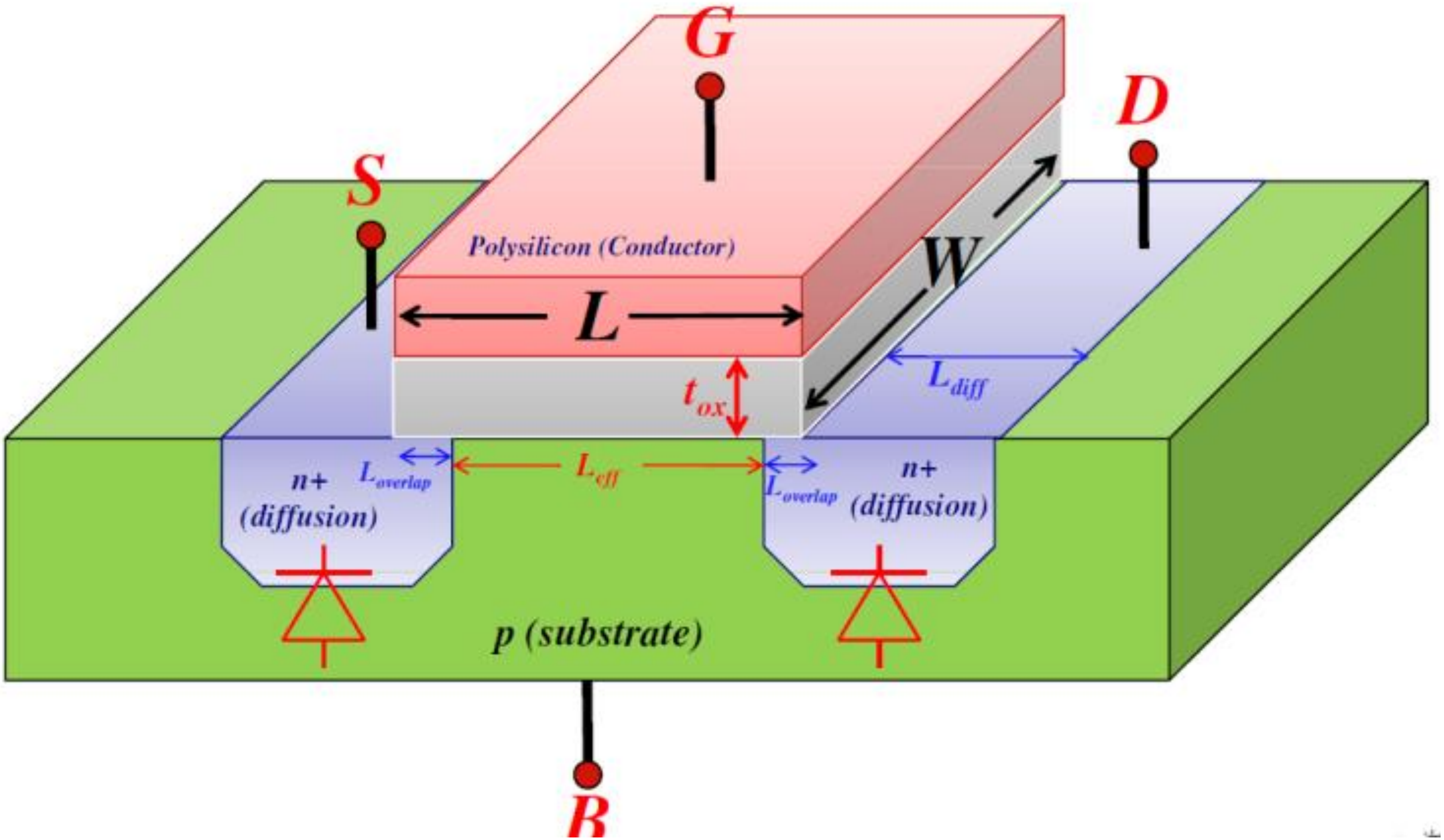
(b) NMOS transistor as 3-terminal device

(a) PMOS transistor as 4-terminal device

(d) PMOS transistor as 3-terminal device

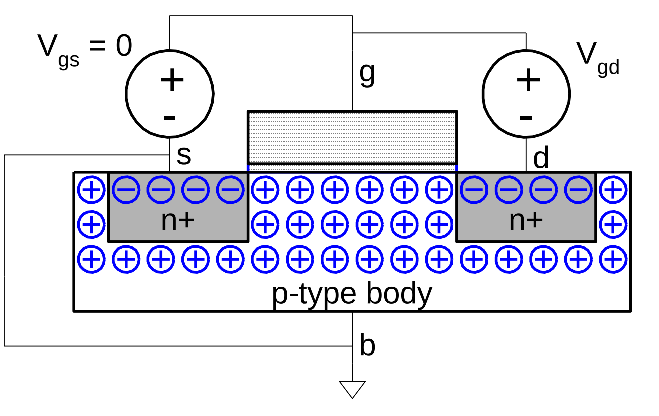
MOS Operation

MOS Operation – Terminals and Sizes



MOS Operation – Cut Off

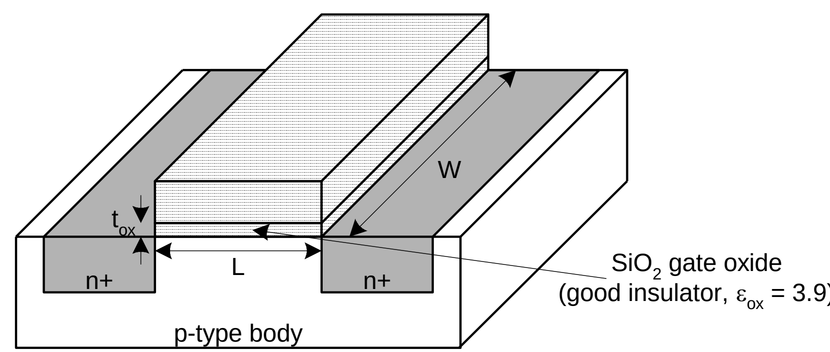
- VGS<VT
  - The channel is not Inverted.
- IDS=0



MOS Operation – Linear Region

- VGS>VT
  - The channel is Inverted.
- VDS>0
  - The channel has an equivalent resistance.
  - The current is approximately V_{DS}/R_{eq}.
- But how is this estimated?
  - We can integrate the charge over the channel, because:

$$I = Q \cdot v$$



MOS Operation – Linear Region

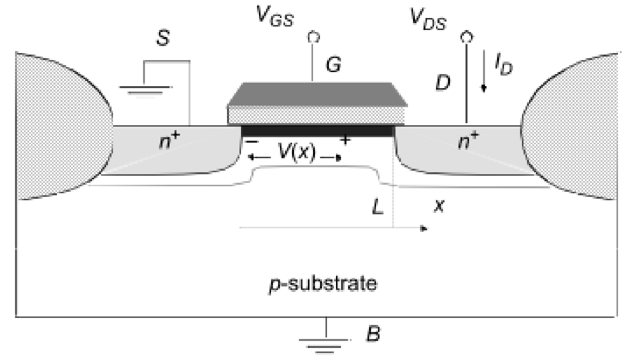
$$C_{pp} = \frac{\varepsilon \cdot A}{l}$$

- Charge Density: $\frac{Q(x)}{dx} = \frac{C(x) \cdot V(x)}{dx}$

$$C(x) \approx C_{pp\_ox} = \frac{\varepsilon_{ox}}{t_{ox}} \cdot W \cdot dx = C_{ox} W dx$$

$$V_{cap}(x) = V_{GS} - V_{XS} - V_T = V_{GS} - V(x) - V_T$$

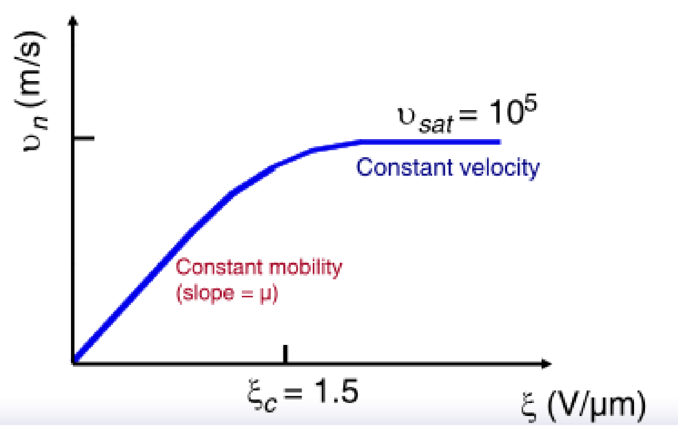
$$\frac{Q(x)}{dx} = \frac{C_{ox} W \left(V_{GS} - V(x) - V_T\right) dx}{dx}$$



- Velocity:

$$\nu(x) = \mu \cdot \xi(x) = \mu \cdot \frac{dV(x)}{dx}$$

$$\nu\left[{}^{m}\!/_{\sec}\right] = \xi\left[{}^{V}\!/_{m}\right] \cdot \mu\left[{}^{m^2}\!/_{V \cdot \sec}\right]$$



- Current estimation:

$$I(x) = Q(x) \cdot \nu(x) = C_{ox} W \left(V_{GS} - V(x) - V_T\right) \cdot \mu \frac{dV(x)}{dx}$$

MOS Operation – Linear Region

- Integrate the total current in the channel:

$$\int_{x=S}^{x=D} I(x)\,dx = \int_{V=V_S}^{V=V_D} C_{ox} W \left(V_{GS} - V(x) - V_T\right) \cdot \mu dV(x)$$

$$I_{DS} \cdot L = \mu C_{ox} W \left[\left(V_{GS} - V_T\right) V_{DS} - \frac{V_{DS}^{\;2}}{2} \right]$$

$$I_{DS} = K \left[V_{GT} V_{DS} - \frac{V_{DS}^{\;2}}{2} \right]$$

$$K \triangleq \mu C_{ox} \frac{W}{L}$$

MOS Operation – Saturation Region

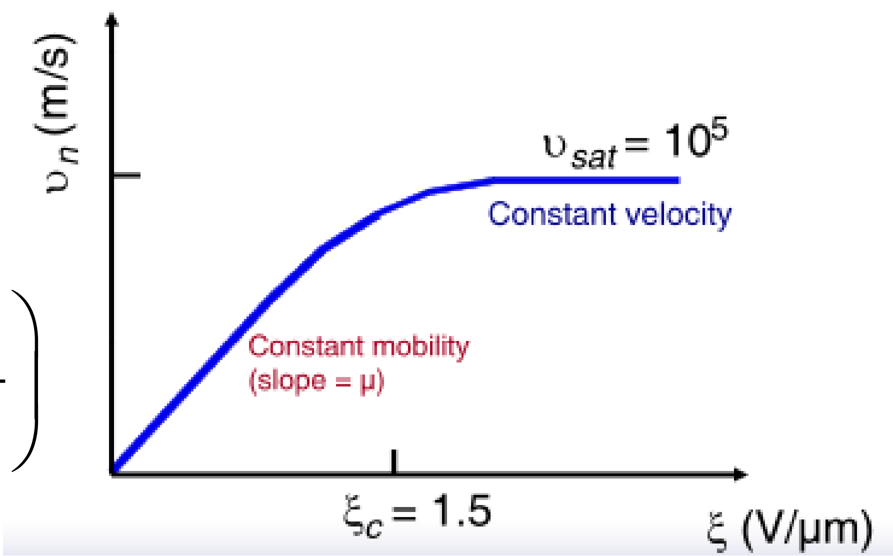
- VGS>VT
  - The channel is Inverted.
- VDS>VGS-VT
  - The channel is *pinched off*.
  - The voltage drop over the channel is constant (VGS-VT).
  - The channel resistance is almost constant.
  - Therefore the current is almost constant.

$$I_{DS} = \frac{K_N}{2}\left(V_{GS} - V_{Tn}\right)^2$$

MOS Operation – Velocity Saturation

- VGS>VT
  - The channel is Inverted.
- For a high electric field, the mobility becomes saturated.
  - We will call the VDS at which this happens "*VDSAT*"
  - Increasing VDS past VDSAT will not increase the current.

$$I_{DS} = K_N \left((V_{GS} - V_{Tn}) V_{DSATn} - \frac{V_{DSATn}^{\ 2}}{2} \right)$$



MOS Operation – Channel Length Modulation

- Is the resistance truly constant as VDS increases?
  - No, it gets smaller.
  - The depletion region of the Drain "digs in" to the channel.
  - The *effective length* is reduced.
- We call this effect "Channel Length Modulation"
  - This is almost linearly dependent on VDS.
  - We will characterize this effect with a coefficient: λ

$$I_{DS}(CLM) = I_{DS}(1 + \lambda V_{DS})$$

- *During linear operation, this effect is almost negligible…*

MOS Operation – Summary

$$V_{GT} \triangleq V_{GS} - V_T$$

$$V_{DS,eff} = \min\left(V_{DS}, V_{DSAT}, V_{GT}\right)$$

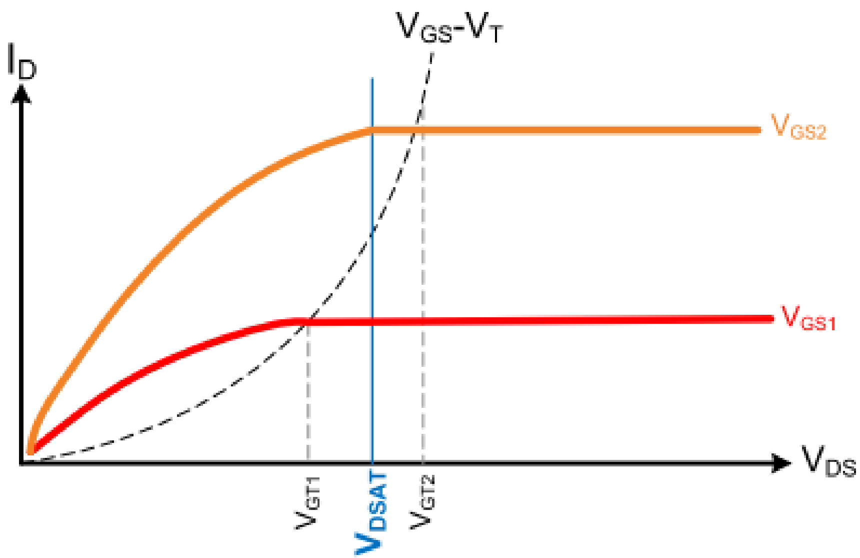
$$K_N \triangleq \mu_N C_{ox} \frac{W_N}{L_N}$$

$$I_{DS} = K_N \left(V_{GT} V_{DS,eff} - \frac{V_{DS,eff}^{\;2}}{2} \right) \left(1 + \lambda V_{DS}\right)$$

Examples

Trick Question: Moed Aleph 2009-10

מהנדס פיתוח בחברת "טרנזיסטור" בע"מ החליט לייעל את המעגלים הדיגיטליים שתוכננו בחברה . לשם כך המהנדס החליט לנצל את תכונות הטרנזיסטור **NMOS** בצורה טובה יותר. המהנדס התבונן באופיין זרם I_{DS} של הטרנזיסטור, אשר נתון באיור הבא:



להפתעתו המהנדס גילה שהמעגלים שתוכננו בחברה מנצלים רק את תכונות הטרנזיסטור כאשר V_{DS} הינו חיובי ומתעלמים לחלוטים מהערכים השליליים של V_{DS}.

עליך לצייר בצורה **איכותית** את התנהגות הזרם I_{DS} עבור מתחים שליליים של V_{DS}. **יש להסביר בקצרה.**

Example: Linear vs. Saturation

- Consider a process with:

$$L_{\min} = 0.4\mu m \quad t_{ox} = 8nm \quad \mu_n = 450\frac{cm^2}{V \cdot s} \quad V_T = 0.7V \quad \lambda \approx 0 \quad \varepsilon_{ox} = 3.45 \cdot 10^{-11}$$

- For a *long channel transistor* with $W_N/L_N = 8\mu m/0.8\mu m$:
  - Bias the transistor as a current source with of ***100μA***.

- First we will calculate the Transconductance:

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.45 \cdot 10^{-11}}{8 \cdot 10^{-9}} = 4.32 \cdot 10^{-3}\frac{F}{m^2} = 4.32\frac{\text{f}F}{\mu m^2}$$

$$k_n' = \mu_n C_{ox} = 450\frac{cm^2}{V \cdot s} \cdot 4.32\frac{\text{f}F}{\mu m^2} = 1.94 \cdot 10^{-6}\frac{F}{V \cdot s} = 194\frac{\mu A}{V^2}$$

$$k_n = k_n' W_N/L_N = 194\frac{\mu A}{V^2} \cdot \frac{8\mu m}{0.8\mu m} = 1.94m\frac{A}{V^2}$$

Example: Linear vs. Saturation

- To use our nMOS as a current source, we need to bias it in the Saturation region:

$$I_{DS} = \frac{K_N}{2}\left(V_{GS} - V_{Tn}\right)^2 = 100\mu A$$

$$V_{GS} = 1.02V$$

- But we still need to make sure we are in saturation, so:

$$V_{DS} > V_{GS} - V_T = 0.32V$$

Example: Linear vs. Saturation

- Now use the device as a resistor with ***R=1kΩ***.
  - We now want to operate our transistor in the linear region with a very small VDS.

$$I_{DS} = K_N\left[V_{GT}V_{DS} - \frac{{V_{DS}}^2}{2}\right] \approx K_N V_{GT} V_{DS}$$

$$R_{eq} = \frac{V_{DS}}{I_{DS}} \approx \frac{V_{DS}}{K_N V_{GT} V_{DS}} = \frac{1}{K_N V_{GT}} = 1000\Omega$$

$$1000 = \frac{1}{194 \cdot 10^{-6} \cdot 10\left(V_{GS} - 0.7\right)} \longrightarrow V_{GS} - 0.7 = 0.52V \longrightarrow V_{GS} = 1.22V$$

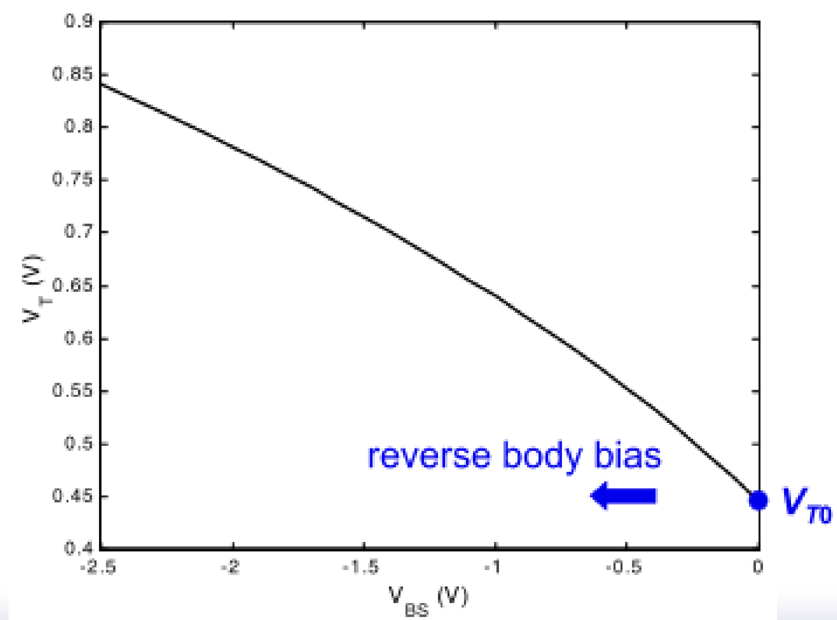
The Body Effect

The Body Effect - Introduction

- The threshold voltage (VT) of a transistor is affected by a non-zero potential between the *Source* and *Body*:

$$V_T = V_{T0} + \gamma\left(\left(\sqrt{\left|-2\Phi_F + V_{SB}\right|}\right) - \left(\sqrt{\left|-2\Phi_F\right|}\right)\right)$$

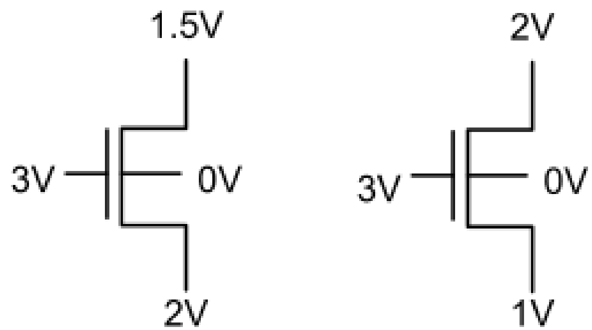
	nMOS	pMOS
Φ_F	-	+
γ	+	-
V_{SB}	+	-



The Body Effect - Example

- Moed Aleph, Semester B, 2008-9

4.2 (4) שני טרנזיסטורי NMOS חוברו כפי שמתואר באיור הבא:



טרנז' א'   טרנז' ב'

יש לסמן את התשובה הנכונה:

א. מתח הסף (V_{TH}) של טרנזיסטור א' שווה לזה של טרנזיסטור ב'

ב. מתח הסף (V_{TH}) של טרנזיסטור א' גדול מזה של טרנזיסטור ב'.

ג. מתח הסף (V_{TH}) של טרנזיסטור א' קטן מזה של טרנזיסטור ב'.

ד. אין מספיק נתונים על מנת לענות על השאלה.

The Body Effect - Example

- The threshold voltage of a pMOS was measured at standard conditions to be $V_{Tp}(V_{BS}=0)=-0.4V$.
- Given a body effect coefficient of -0.4 and Fermi Potential of 0.3V, calculate the threshold voltage with a Reverse Body Bias of 2.5V.

$$V_T = V_{T0} + \gamma\left(\left(\sqrt{\left|-2\Phi_F + V_{SB}\right|}\right) - \left(\sqrt{\left|-2\Phi_F\right|}\right)\right)$$

$$= (-0.4) - (0.4)\left(\left(\sqrt{\left|-0.6 - 2.5\right|}\right) - \left(\sqrt{\left|-0.6\right|}\right)\right)$$

$$= -0.4 - 0.4 \cdot 0.98 = -0.79V$$