VE320 Intro to Semiconductor Devices

Chapter 10

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Contents

Basic Structure

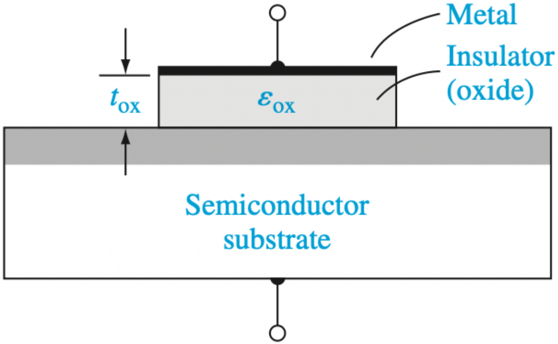


Figure: The basic MOS capacitor structure

Energy-Band Diagrams

- NMOS: P-type substrate, N-type channel

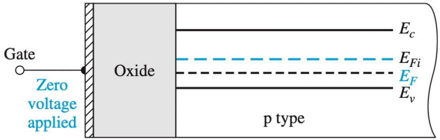


Figure: Energy-band diagram for ideal case (zero gate voltage)

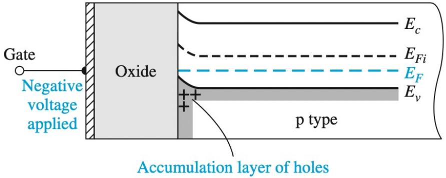


Figure: Energy-band diagram for a negative gate bias (accumulation mode)

Energy-Band Diagrams

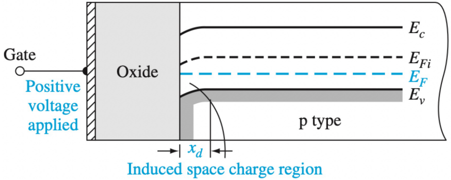


Figure: Energy-band diagram for a moderate positive gate bias (depletion mode)

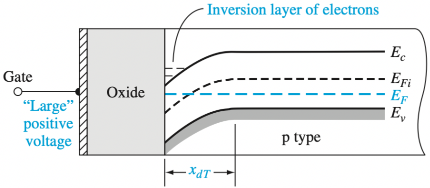
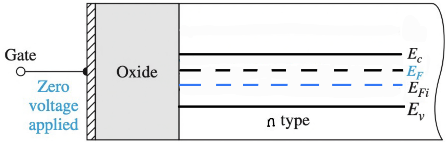


Figure: Energy-band diagram for a large positive gate bias (inversion mode)

Energy-Band Diagrams

- PMOS: N-type substrate, P-type channel



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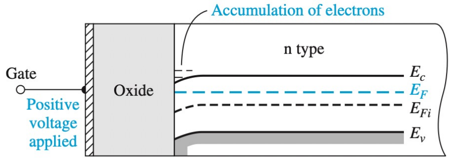


Figure: Energy-band diagram for a positive gate bias (accumulation mode)

Energy-Band Diagrams

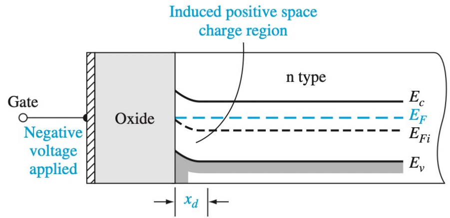


Figure: Energy-band diagram for a moderate negative gate bias (depletion mode)

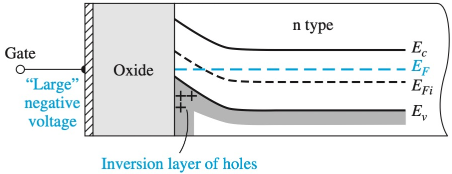


Figure: Energy-band diagram for a large negative gate bias (inversion mode)

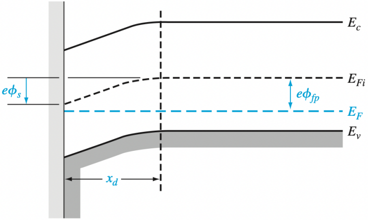
Depletion Layer Thickness

- **Surface potential** ϕ_s: the difference (in V) between E_{Fi} measured in the semiconductor and E_{Fi} measured at the surface
- **Potential difference** ϕ_{fp}: the difference (in V) between E_{Fi} and E_F

$$\phi_{fp} = V_t \ln\left(\frac{N_a}{n_i}\right)$$

- **Space charge width** x_d:

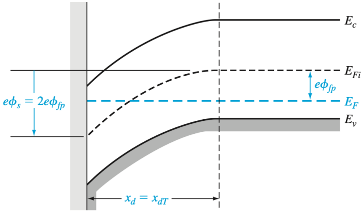
$$x_d = \left(\frac{2\epsilon_s\phi_s}{eN_a}\right)^{1/2}$$



Depletion Layer Thickness

- **Threshold inversion point**: for p-type semiconductor, the electron concentration at the surface equals to the hole concentration in the semiconductor
- **Maximum space charge width** x_{dT}:

$$x_{dT} = \left(\frac{4\epsilon_s \phi_{fp}}{eN_a}\right)^{1/2}$$



Quiz

- Could you write the formulas for PMOS (N-type semiconductor)?
  - ϕ_{fn}:
  - x_d:
  - x_{dT}:

Work Function Difference

- Modified metal work function ϕ_m'
- Modified electron affinity χ'
- Potential drop across the oxide for zero applied gate voltage V_{ox0}
- Surface potential ϕ_{s0}

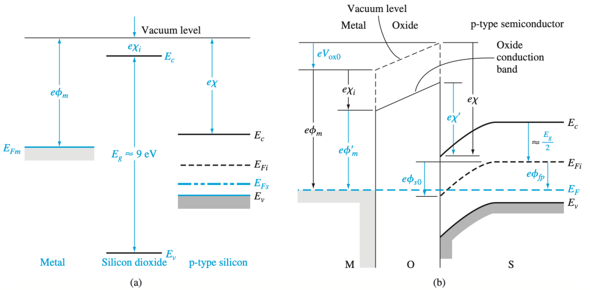


Figure 10.13 | (a) Energy levels in a MOS system prior to contact and (b) energy-band diagram through the MOS structure in thermal equilibrium after contact.

Work Function Difference

- NMOS: $\phi_{ms} = \phi_m^{'} - \left(\chi^{'} + \frac{E_g}{2e} + \phi_{fp}\right)$
- PMOS: $\phi_{ms} = \phi_m^{'} - \left(\chi^{'} + \frac{E_g}{2e} - \phi_{fn}\right)$
- When n^+ polysilicon is used as metal (NMOS):
  $\phi_{ms} = \left[\chi^{'} - \left(\chi^{'} + \frac{E_g}{2e} + \phi_{fp}\right)\right] = -\left(\frac{E_g}{2e} + \phi_{fp}\right)$
- When p^+ polysilicon is used as metal (NMOS):
  $\phi_{ms} = \left[\left(\chi^{'} + \frac{E_g}{2e}\right) - \left(\chi^{'} + \frac{E_g}{2e} + \phi_{fp}\right)\right] = \left(\frac{E_g}{2e} - \phi_{fp}\right)$

Flat-Band Voltage

- **Flat-band voltage** V_{FB}: the applied gate voltage such that there is no band bending in the semiconductor
- **Fixed charge density in the oxide** Q'_{ss}
- **Charge density on the metal** Q'_m

$$V_{FB} = \phi_{ms} - \frac{Q'_{ss}}{C_{ox}}$$

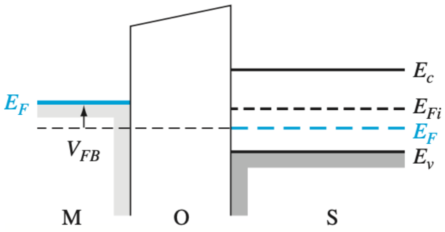


Figure: Energy-band diagram of a MOS capacitor at flat band

Threshold Voltage

- **Threshold voltage** V_T: the gate voltage needed at the threshold inversion point
- **Charge density on the metal at the inversion point** Q'_{mT}
- **Maximum charge density in depletion region** $Q'_{SD}(\max)$: $|Q'_{SD}(\max)| = eN_a x_{dT}$
- NMOS:

$$V_{TN} = \frac{|Q'_{SD}(\max)|}{C_{ox}} - \frac{Q'_{ss}}{C_{ox}} + \phi_{ms} + 2\phi_{fp}$$

$$V_{TN} = (|Q'_{SD}(\max)| - Q'_{ss}) \left(\frac{t_{ox}}{\epsilon_{os}}\right) + \phi_{ms} + 2\phi_{fp}$$

$$V_{TN} = \frac{|Q'_{SD}(\max)|}{C_{ox}} + V_{FB} + 2\phi_{fp}$$

Threshold Voltage

- PMOS: $|Q'_{SD}(\max)| = eN_d x_{dT}$
- PMOS:

$$V_{TP} = -\frac{|Q'_{SD}(\max)|}{C_{ox}} - \frac{Q'_{ss}}{C_{ox}} + \phi_{ms} - 2\phi_{fn}$$

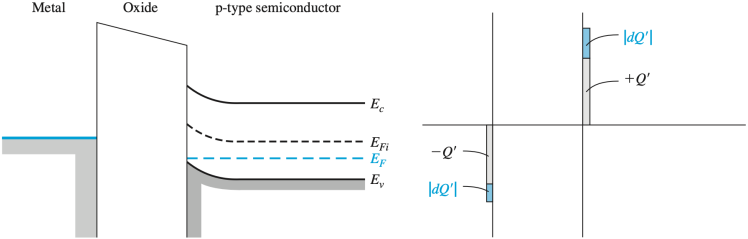
$$V_{TP} = (-|Q'_{SD}(\max)| - Q'_{ss})\left(\frac{t_{ox}}{\epsilon_{os}}\right) + \phi_{ms} - 2\phi_{fn}$$

$$V_{TP} = -\frac{|Q'_{SD}(\max)|}{C_{ox}} + V_{FB} - 2\phi_{fn}$$

Capacitance-Voltage Characteristics

- In accumulation mode:

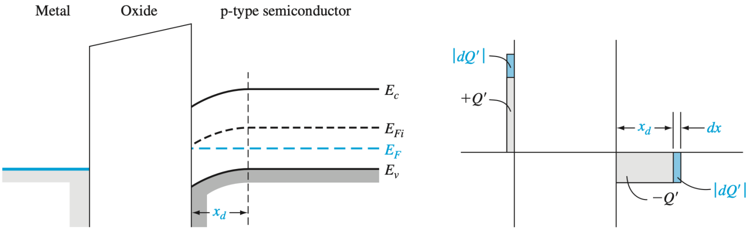
$$C'(\text{acc}) = C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$



Capacitance-Voltage Characteristics

- In depletion mode:

$$C'(\text{depl}) = \frac{\epsilon_{ox}}{t_{ox} + \left(\frac{\epsilon_{ox}}{\epsilon_s}\right) x_d}$$



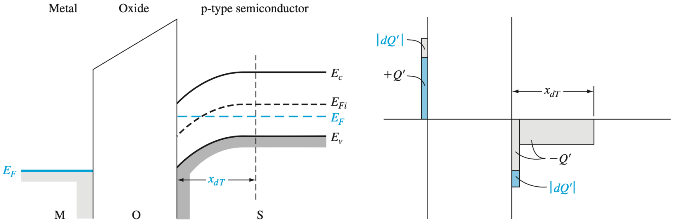
Capacitance-Voltage Characteristics

- In inversion mode:

$$C'(\text{inv}) = C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

- The minimum capacitance (at threshold inversion point):

$$C'(\text{min}) = \frac{\epsilon_{ox}}{t_{ox} + \left(\frac{\epsilon_{ox}}{\epsilon_s}\right) x_{dT}}$$



Capacitance-Voltage Characteristics

- The flat-band capacitance (between the accumulation mode and the depletion mode):

$$C'(\text{FB}) = \frac{\epsilon_{ox}}{t_{ox} + \left(\frac{\epsilon_{ox}}{\epsilon_s}\right)\sqrt{\left(\frac{kT}{e}\right)\left(\frac{\epsilon_s}{eN_a}\right)}}$$

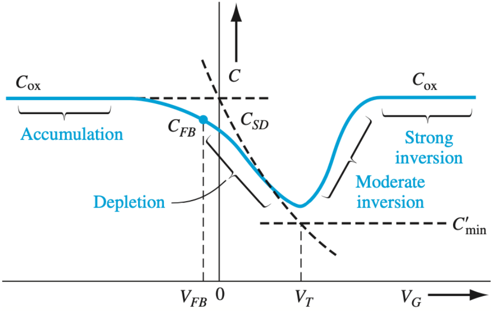


Figure: The low frequency capacitance of NMOS vs the gate voltage

N-channel MOSFET Structure

- **Enhancement mode**: the semiconductor substrate is not inverted directly under the oxide with zero gate voltage
- **Depletion mode**: a channel region exists under the oxide with zero gate voltage

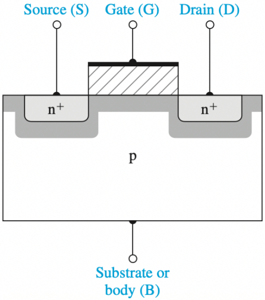


Figure: NMOS enhancement mode

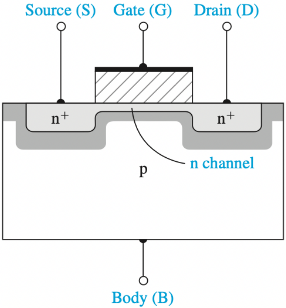


Figure: NMOS depletion mode

P-channel MOSFET Sturcture

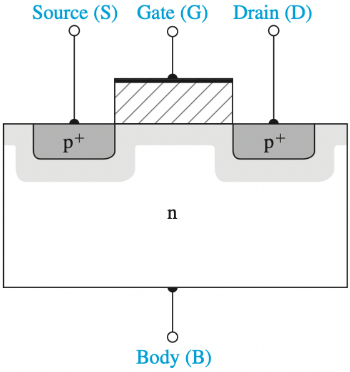


Figure: PMOS enhancement mode

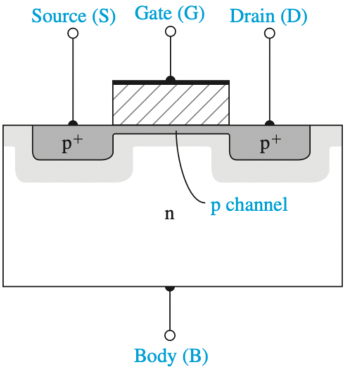
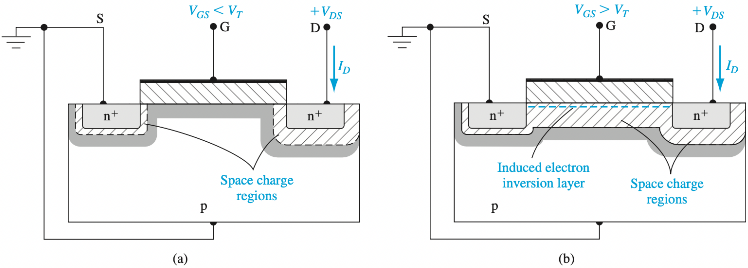


Figure: PMOS depletion mode

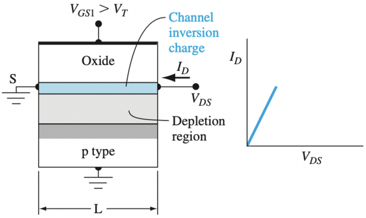
Current-Voltage Relationship

- For NMOS in enhancement mode, when V_{DS} is close to 0
- $V_{GS} < V_T$: no inversion layer, no current
- $V_{GS} > V_T$: inversion layer created, current flow from drain to source

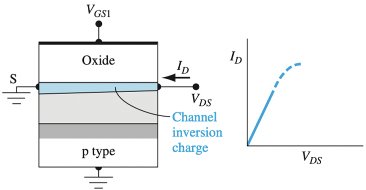


C-V Relationship with Different V_{DS}

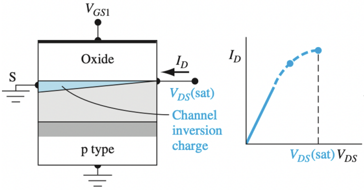
- When V_{DS} increases, the inversion charge density around the drain decreases. When $V_{DS} = V_{DS}(\text{sat})$, it reaches "pinch off"



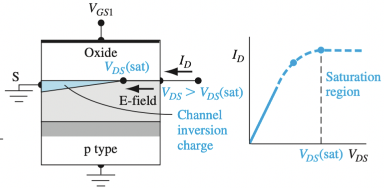
(a) A small V_{DS} value



(a) A larger V_{DS} value



(a) A value when $V_{DS} = V_{DS}(sat)$ "Pinch-off"



(a) A value when $V_{DS} > V_{DS}(sat)$

Current-Voltage Relationship

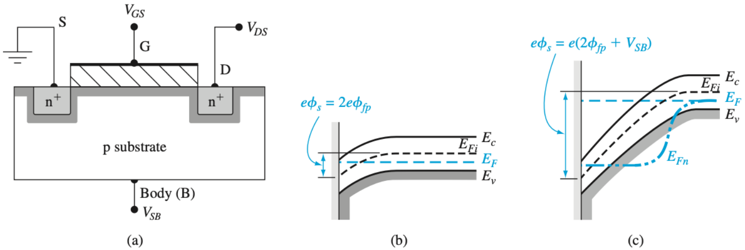
- For NMOS
  - $V_{GS} < V_T$:
$$I_{DS} = 0$$
  - $V_{GS} > V_T$ and $V_D < V_{GS} - V_T$:
$$I_{DS} = \frac{W\mu_n C_{ox}}{2L}[2(V_{GS} - V_T)V_{DS} - V_{DS}^2]$$
  - $V_{GS} > V_T$ and $V_D \geq V_{GS} - V_T$:
$$I_{DS} = \frac{W\mu_n C_{ox}}{2L}(V_{GS} - V_T)^2$$

Transconductance

- **Transconductance**: the change in drain current with respect to the corresponding change in gate voltage

$$
\begin{aligned}
g_m &= \frac{\partial I_D}{\partial V_{GS}} \\
&= \begin{cases} \mu_n C_{ox} \frac{W}{L} V_{DS} & 0 < V_{DS} < V_{GS} - V_T \\ \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T) & V_{DS} > V_{GS} - V_T \end{cases}
\end{aligned}
$$

Substrate Bias Effects



- When $V_{SB} = 0$: $Q'_{SD}(\max) = -\sqrt{2e\epsilon_s N_a(2\phi_{fp})}$
- When $V_{SB} > 0$: $Q'_{SD} = -\sqrt{2e\epsilon_s N_a(2\phi_{fp} + V_{SB})}$

Substrate Bias Effects

- The change in threshold voltage $\Delta V_T = V_T(V_{SB} > 0) - V_T(V_{SB} = 0)$:

$$
\begin{aligned}
\Delta V_T &= -\frac{\Delta Q'_{SD}}{C_{ox}} \\
&= \frac{\sqrt{2e\epsilon_s N_a}}{C_{ox}} \left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right] \\
&= \gamma \left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right]
\end{aligned}
$$

where $\gamma = \frac{\sqrt{2e\epsilon_s N_a}}{C_{ox}}$ is defined as the body-effect coefficient.

Conclusion

- The two-terminal MOS structure
  - Energy-band diagrams
  - Depletion layer thickness
  - Work function difference
  - Flat-band voltage
  - Threshold voltage
  - MOSFET structure
  - Capacitance-voltage characteristic
  - Current-voltage relationship
  - Transconductance
  - Substrate bias effects