
VE320 – Summer 2021

Semiconductor Physics

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**Chapter 10 Fundamentals of Metal-Oxide-Semiconductor
Field Effect Transistors**



Outline

10.1 The two-terminal MOS structure

10.2 Capacitance-voltage characteristics

10.3 Non-ideal effects

10.4 The basic MOSFET operation



Outline

10.1 The two-terminal MOS structure

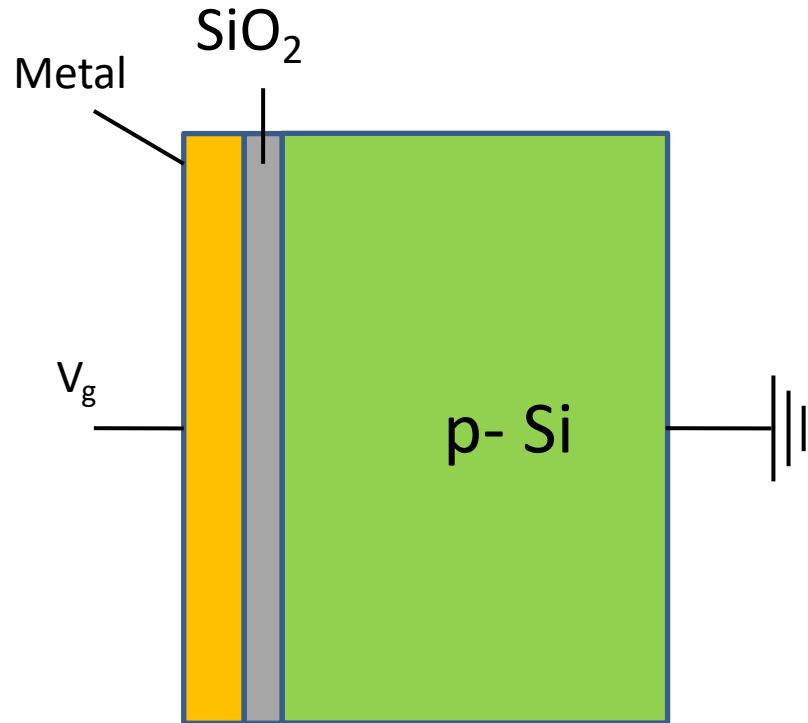
10.2 Capacitance-voltage characteristics

10.3 Non-ideal effects

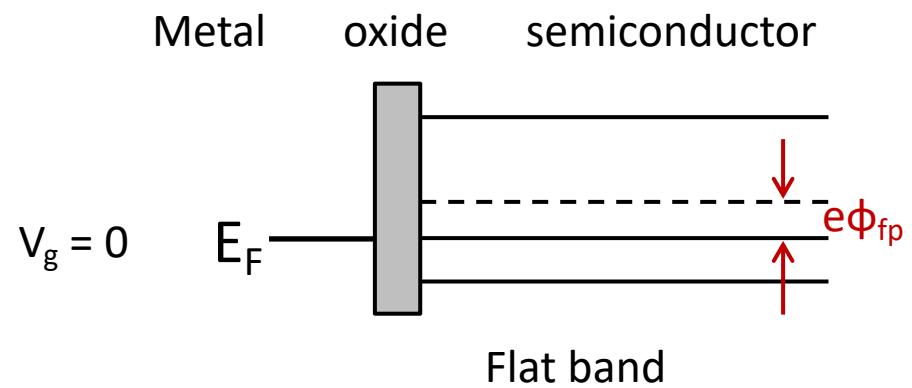
10.4 The basic MOSFET operation



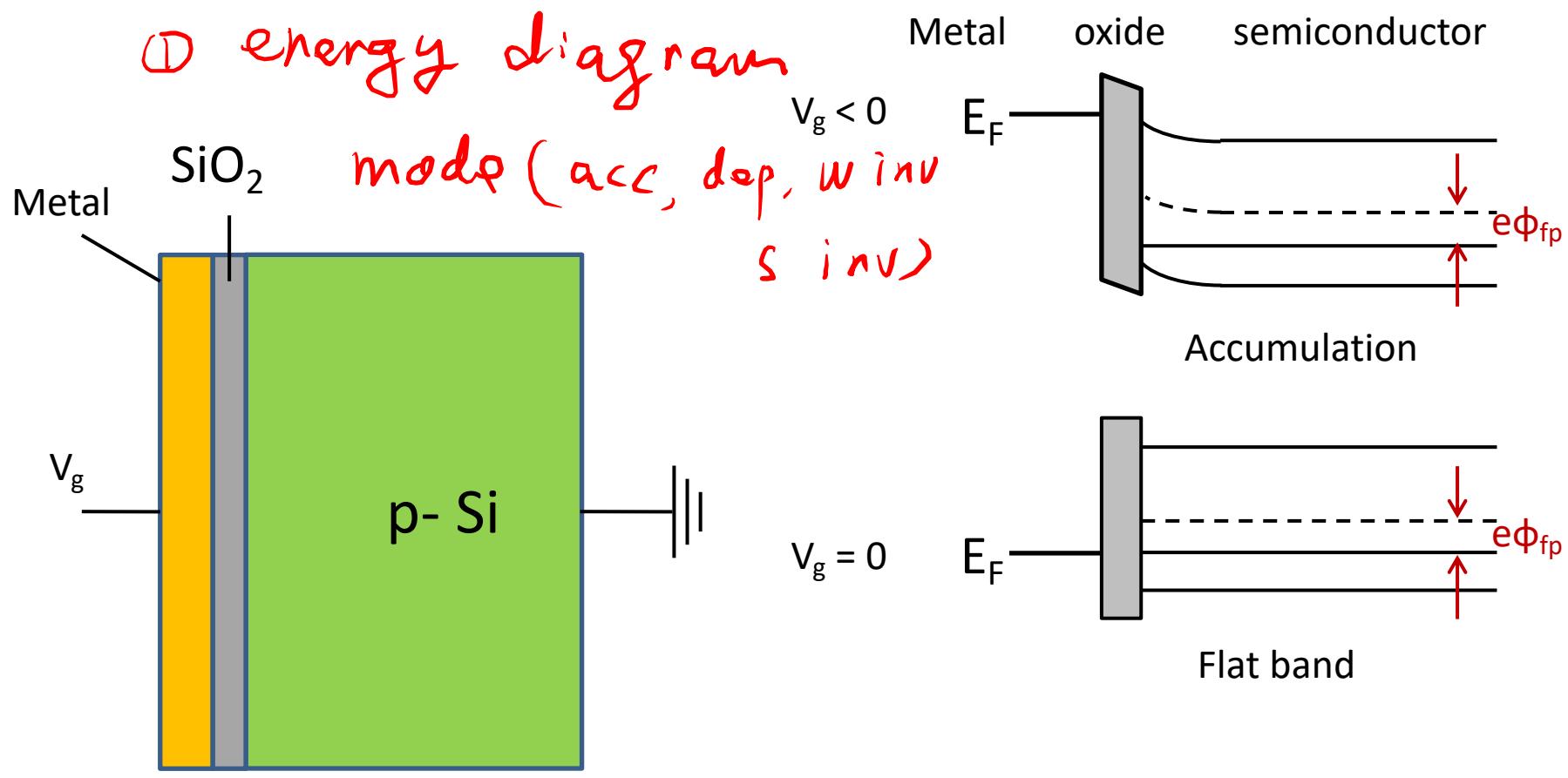
10.1 The two-terminal MOS structure



Metal-insulator-semiconductor (MIS)

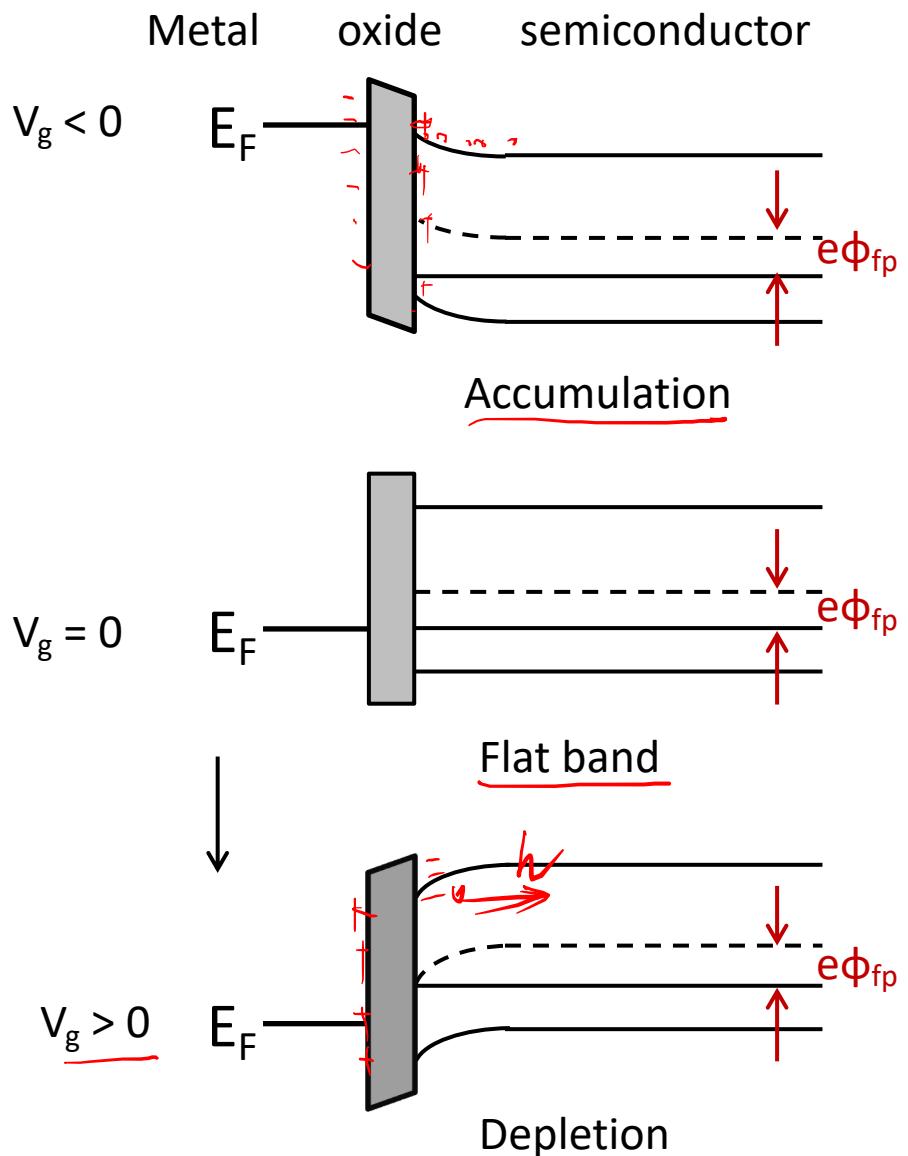
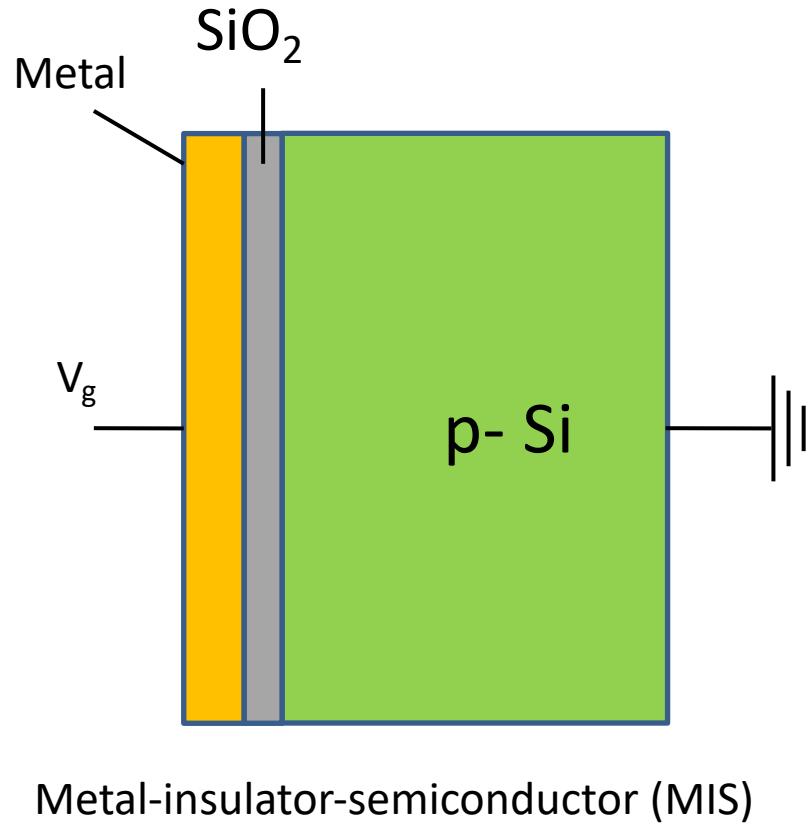


10.1 The two-terminal MOS structure

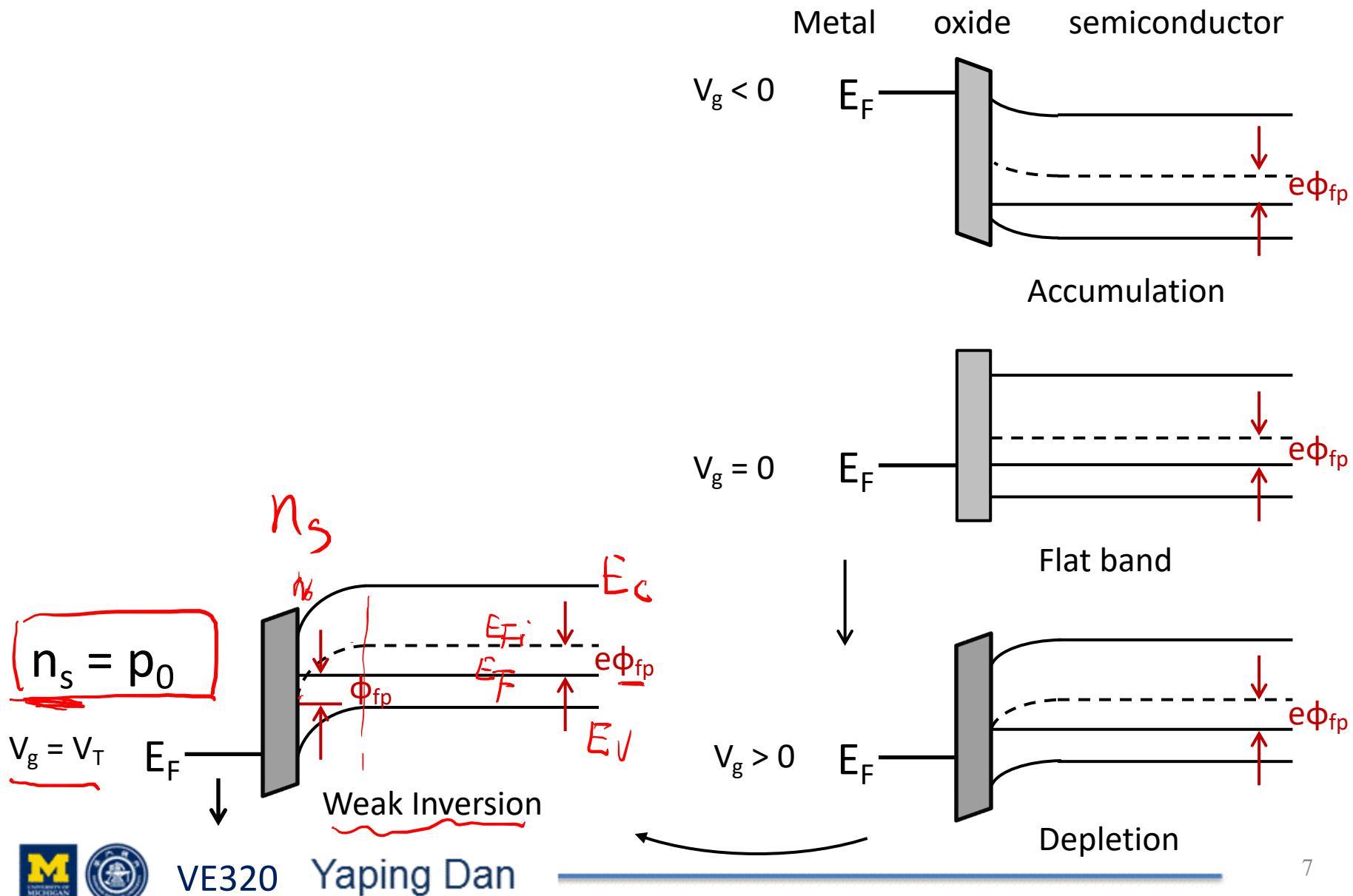


Metal-insulator-semiconductor (MIS)

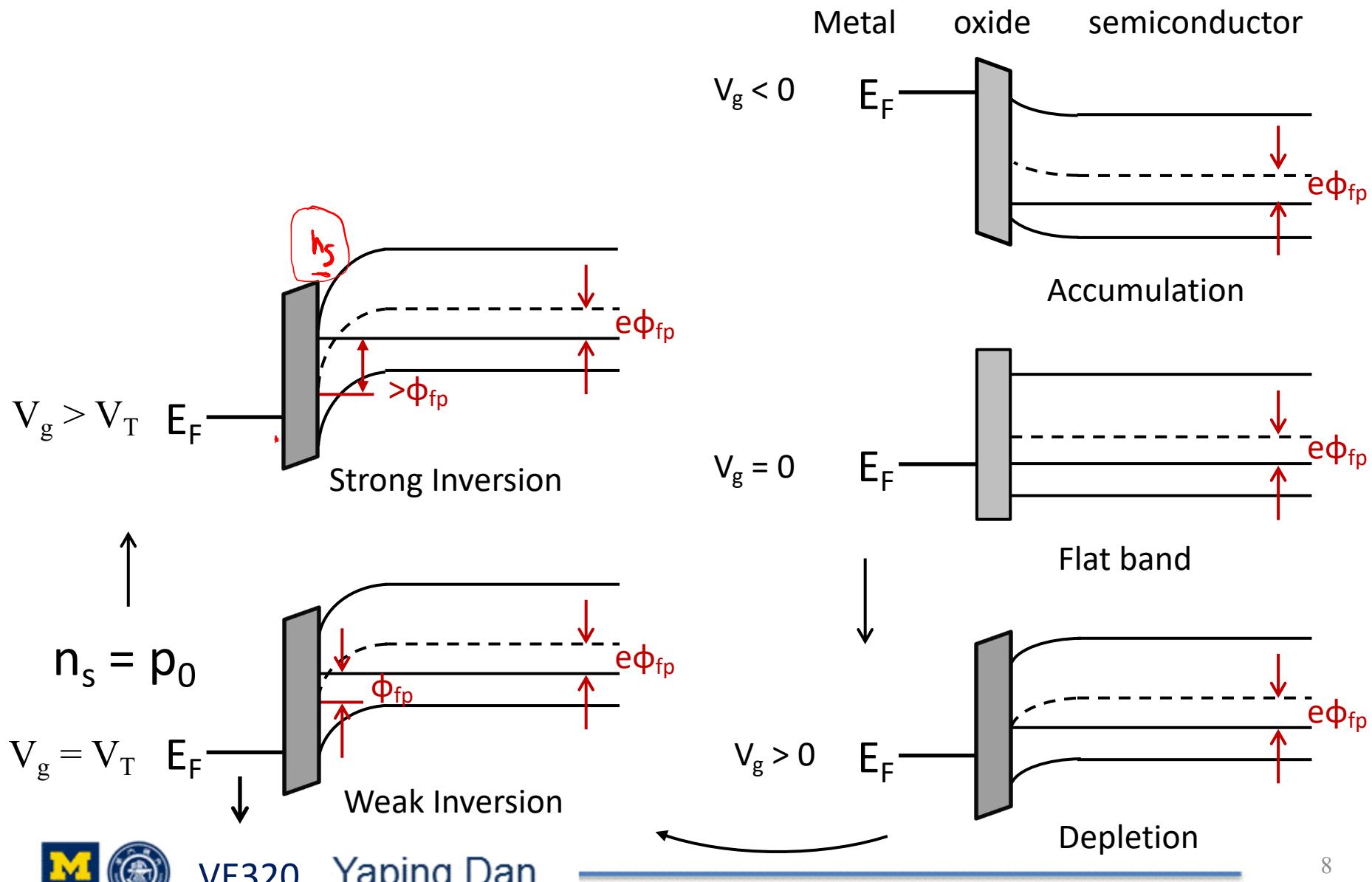
10.1 The two-terminal MOS structure



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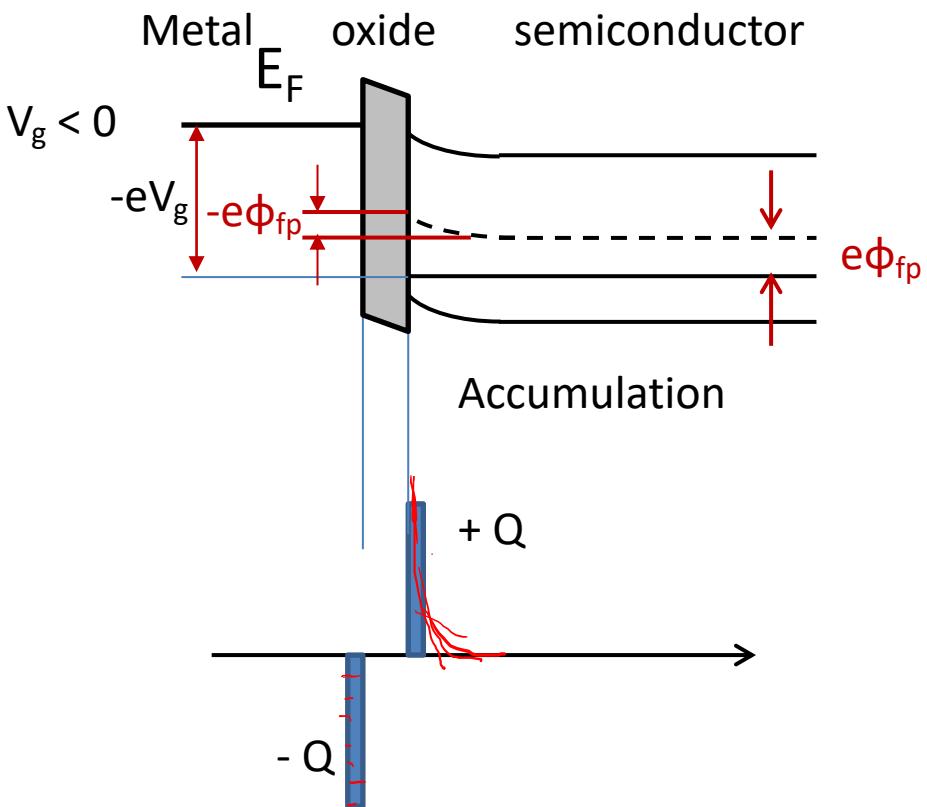


10.1 The two-terminal MOS structure



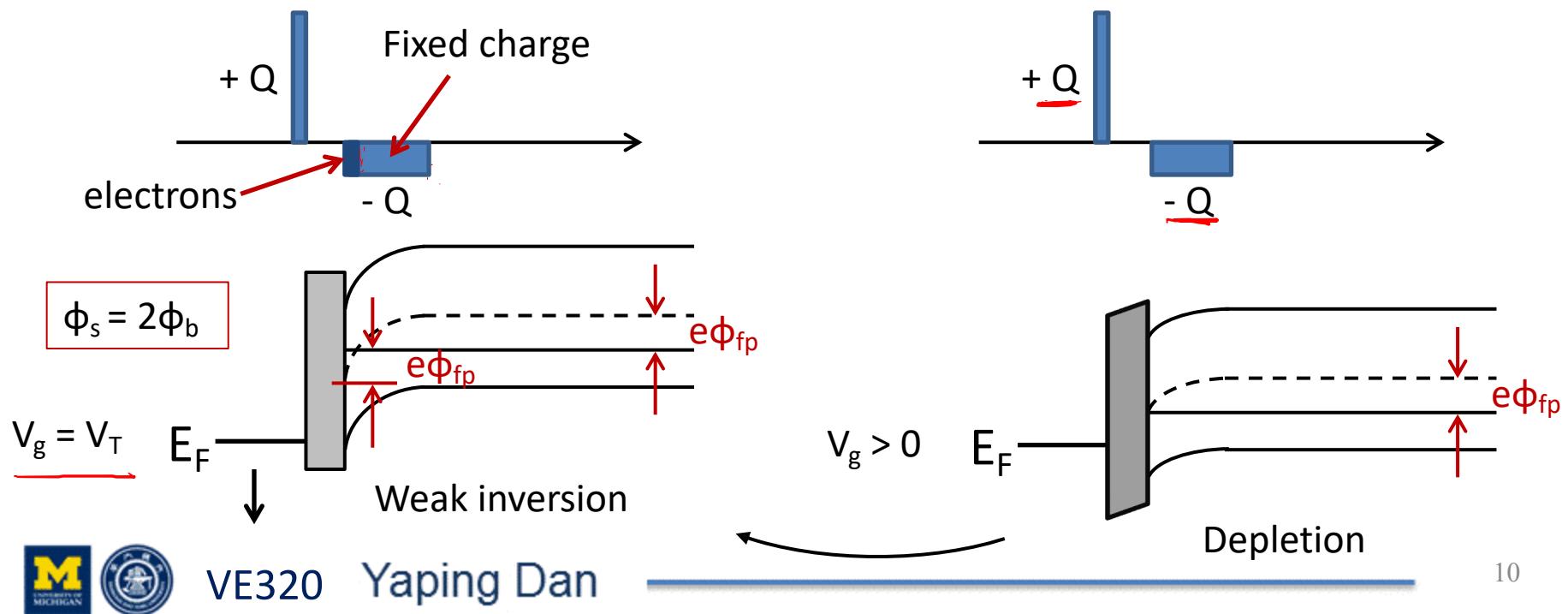
10.1 The two-terminal MOS structure

② Charge distribution



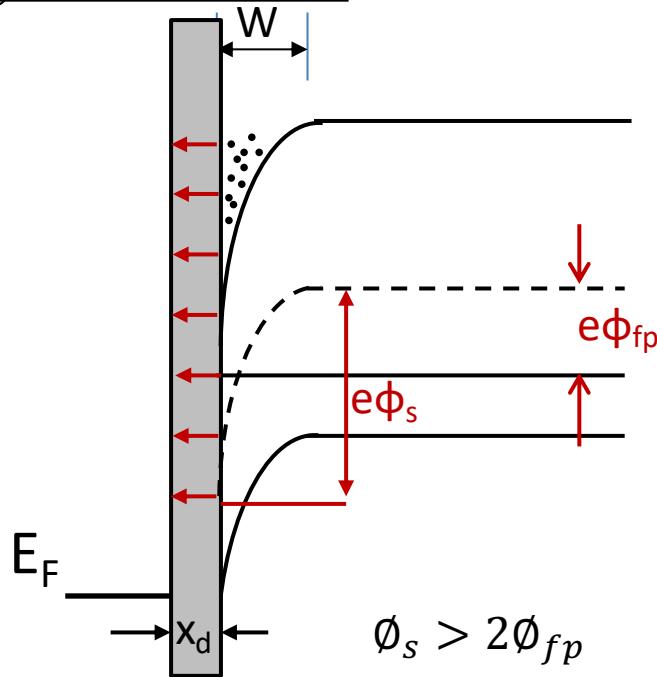
10.1 The two-terminal MOS structure

Charge distribution



10.1 The two-terminal MOS structure

Charge distribution



$$\Delta Q_f = \sigma n_s \delta$$

Fixed charge

+ Q

electrons

n_s

σn_s

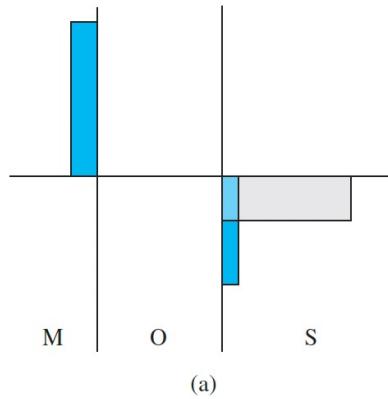
ϕ_s

- Q

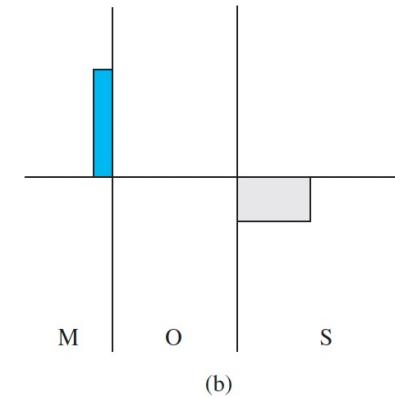
Check your understanding

Example Problem #1

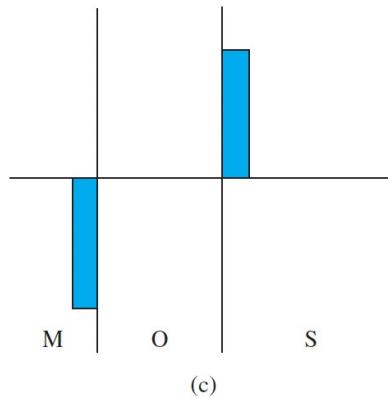
The dc charge distributions of four ideal MOS capacitors are shown in Figure P10.1. For each case: (a) Is the semiconductor n or p type? (b) Is the device biased in the accumulation, depletion, or inversion mode? (c) Draw the energy-band diagram in the semiconductor region.



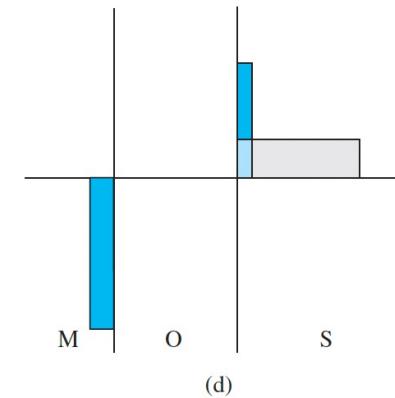
(a)



(b)



(c)

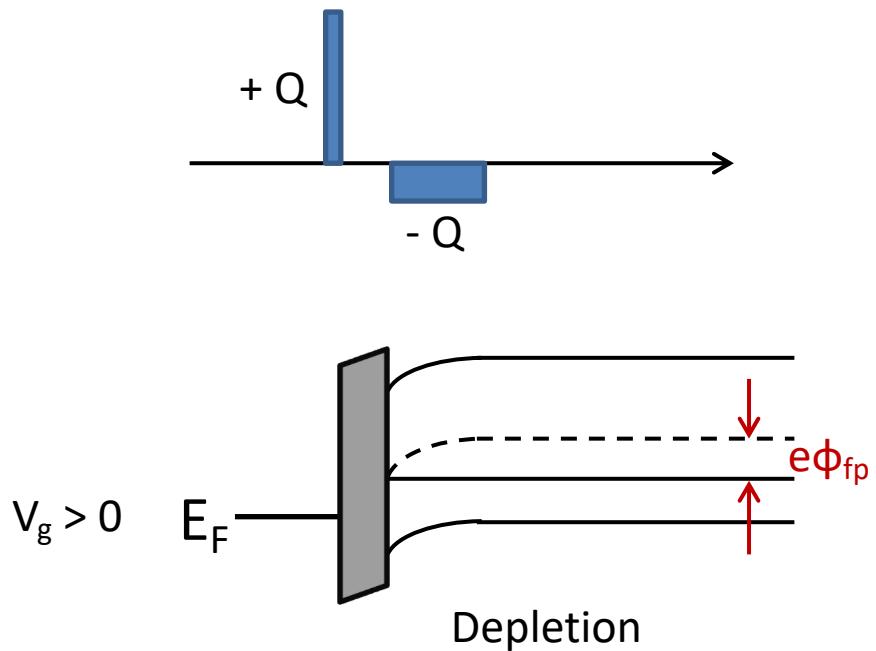


(d)

10.1 The two-terminal MOS structure

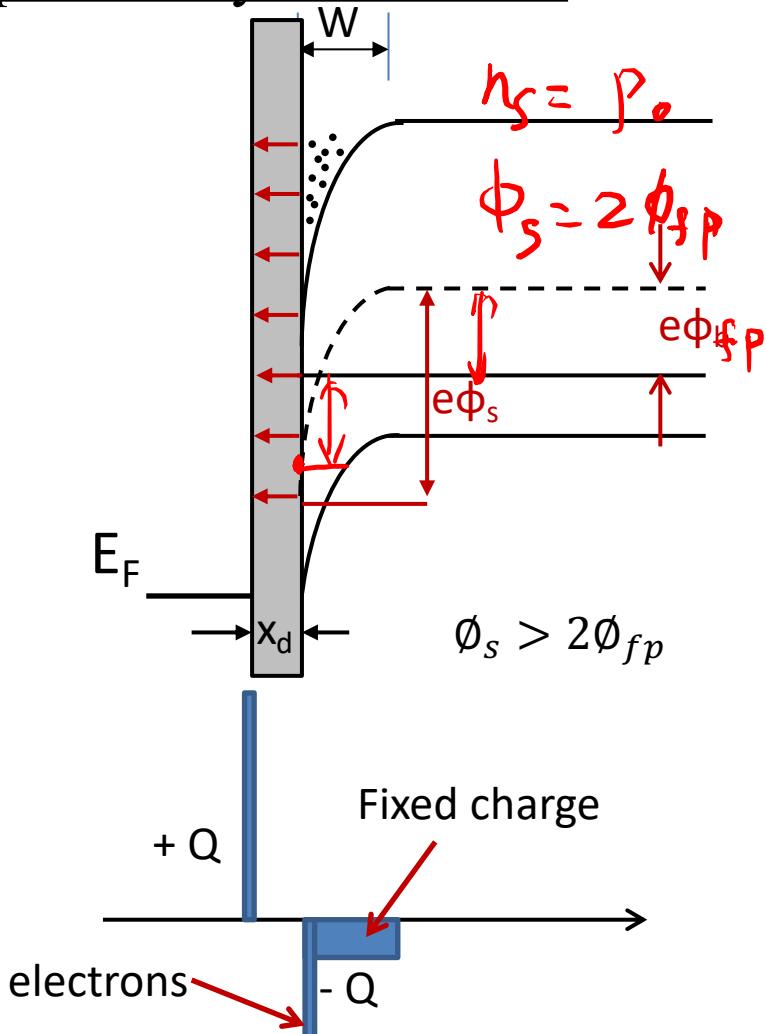
③ Depletion layer thickness

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



10.1 The two-terminal MOS structure

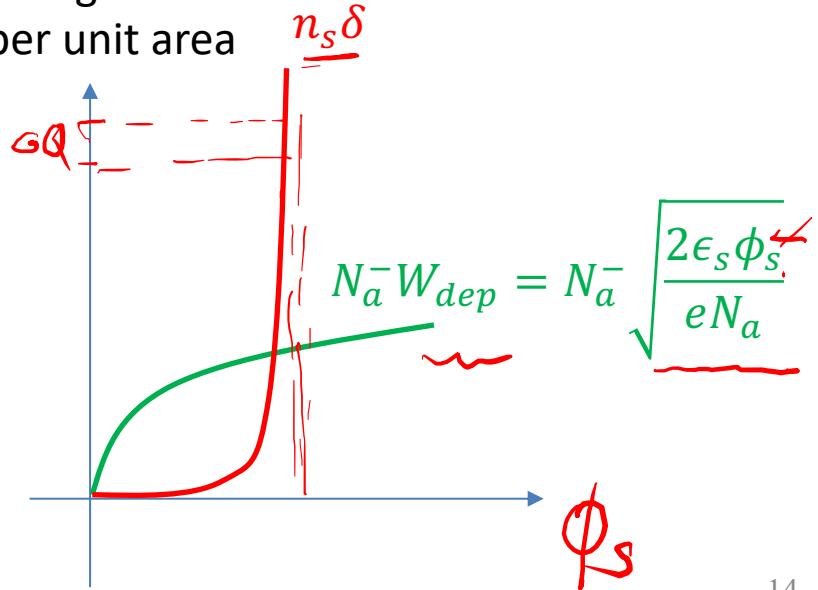
Depletion layer thickness



Maximum depletion layer

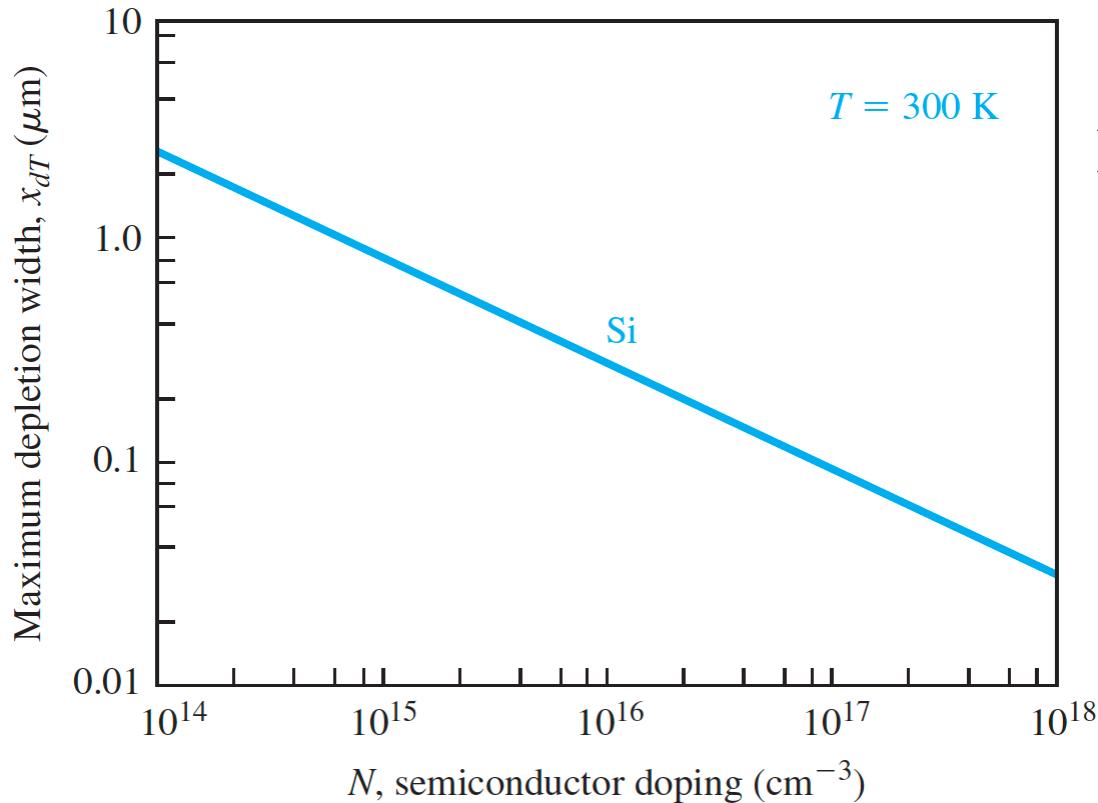
$$x_{dT} = \left(\frac{4\epsilon_s \phi_{fp}}{eN_a} \right)^{1/2}$$

Charges per unit area



10.1 The two-terminal MOS structure

Depletion layer thickness



Maximum depletion layer

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

Outline

10.1 The two-terminal MOS structure

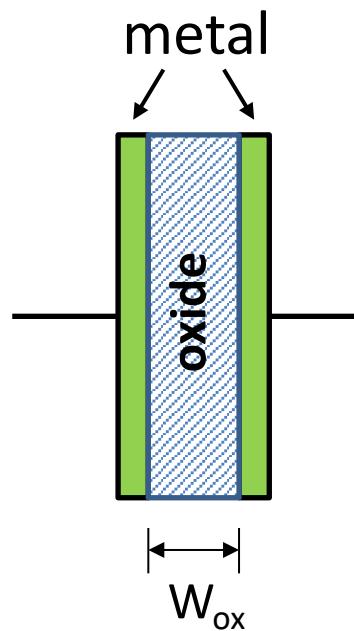
10.2 Capacitance-voltage characteristics

10.3 Non-ideal effects

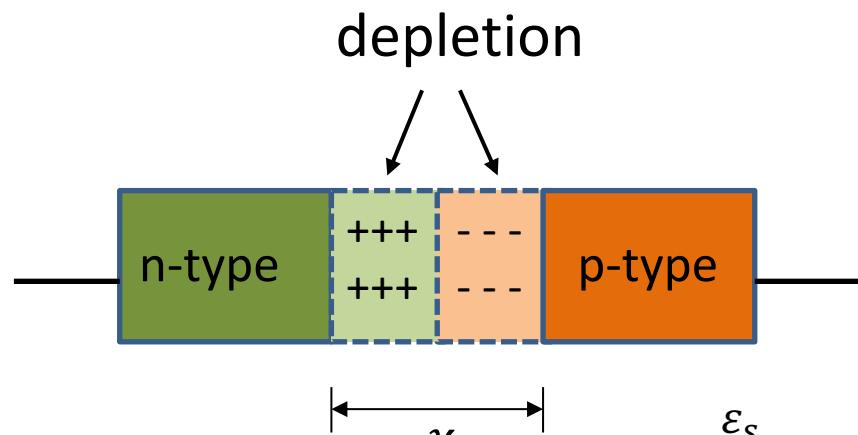
10.4 The basic MOSFET operation



10.2 The capacitance-voltage characteristics



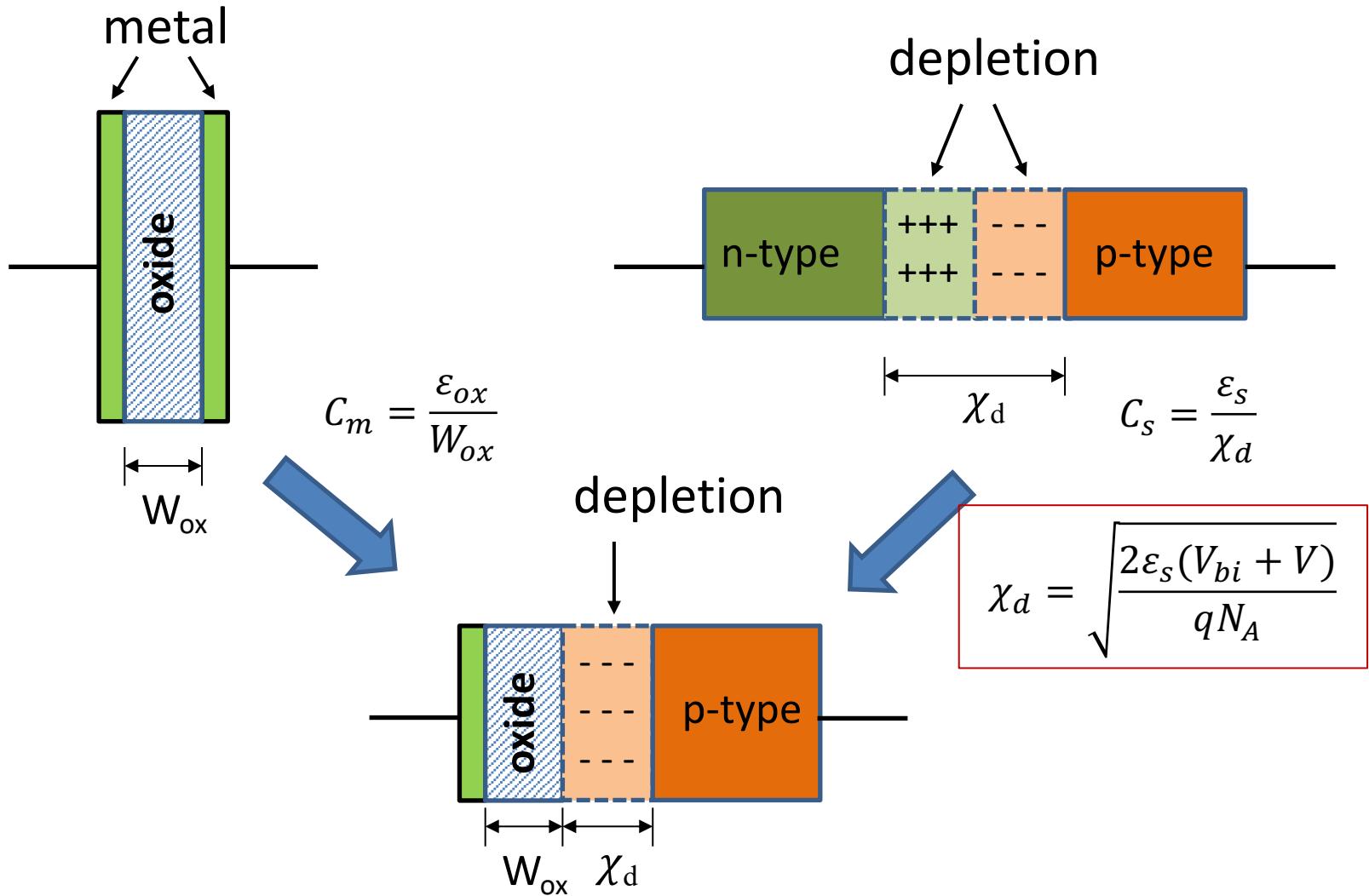
$$C_m = \frac{\epsilon_{ox}}{W_{ox}}$$



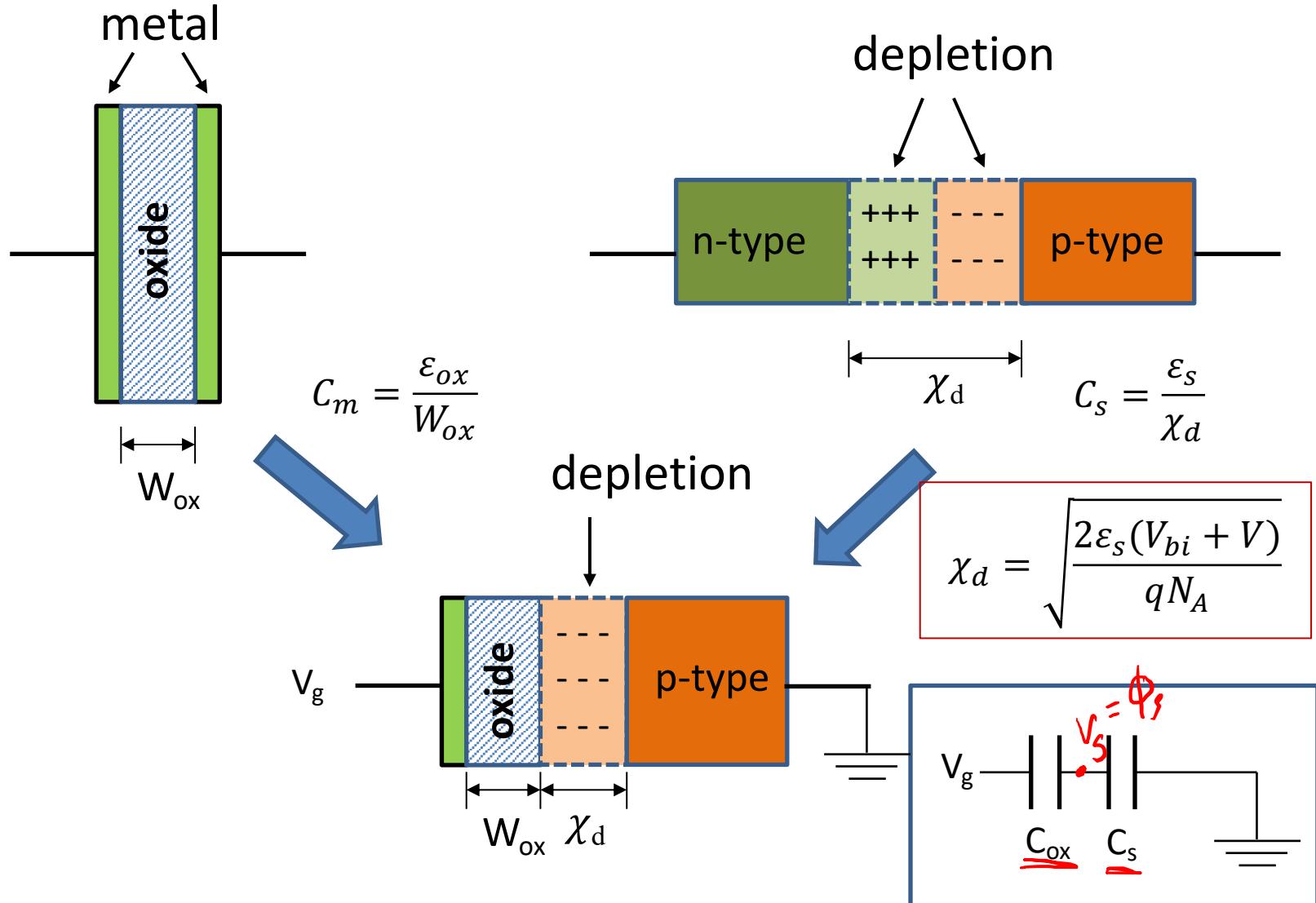
$$C_s = \frac{\epsilon_s}{\chi_d}$$

$$\chi_d = \sqrt{\frac{2\epsilon_s(V_{bi} + V)}{qN_A}}$$

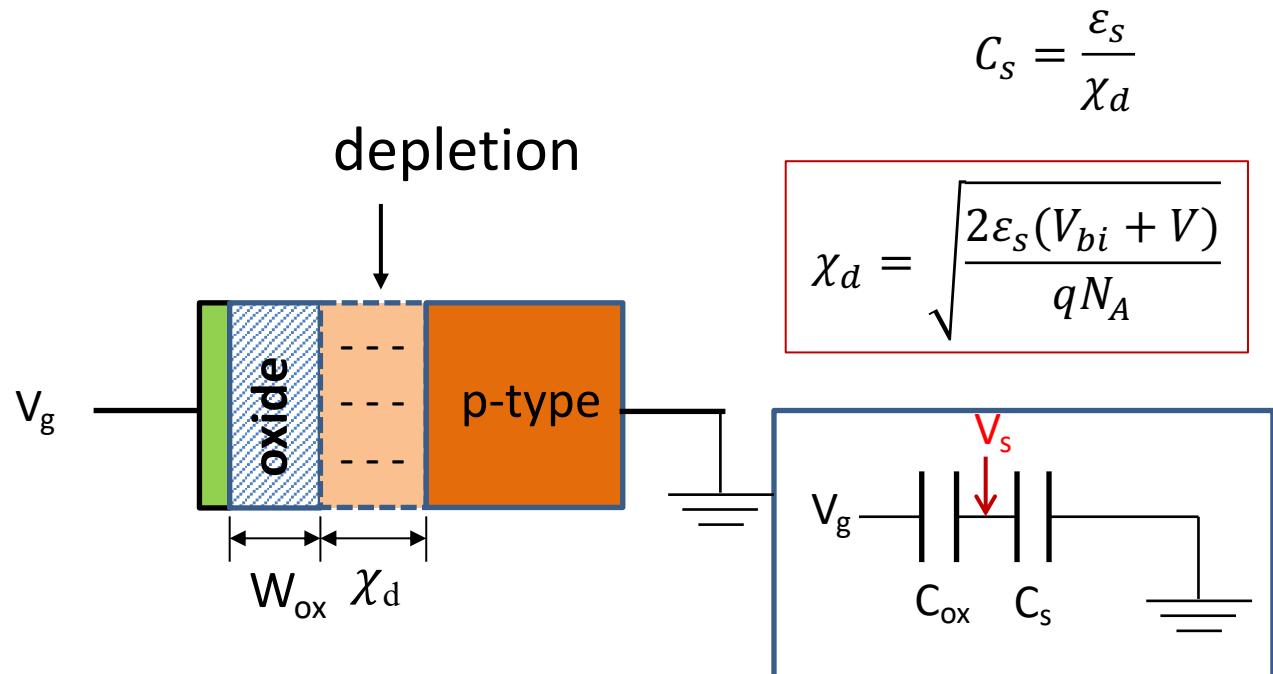
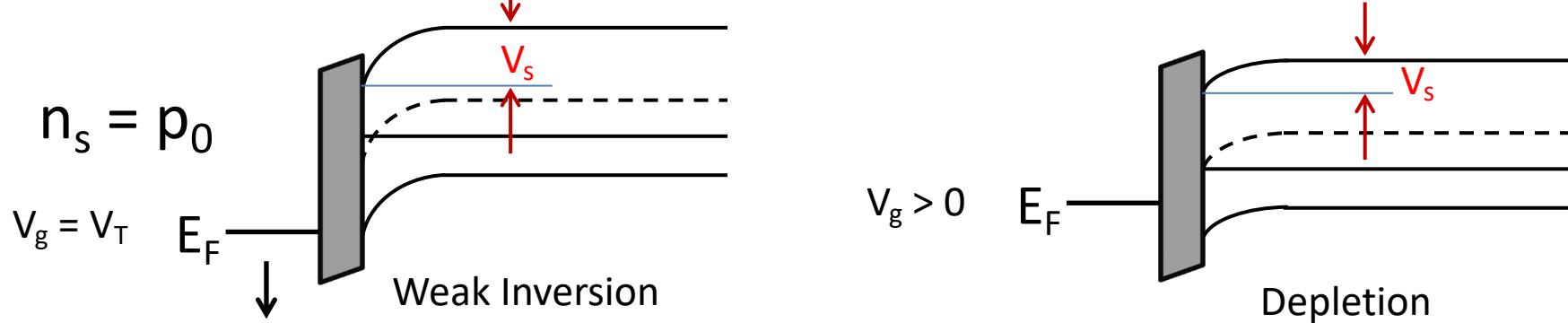
10.2 The capacitance-voltage characteristics



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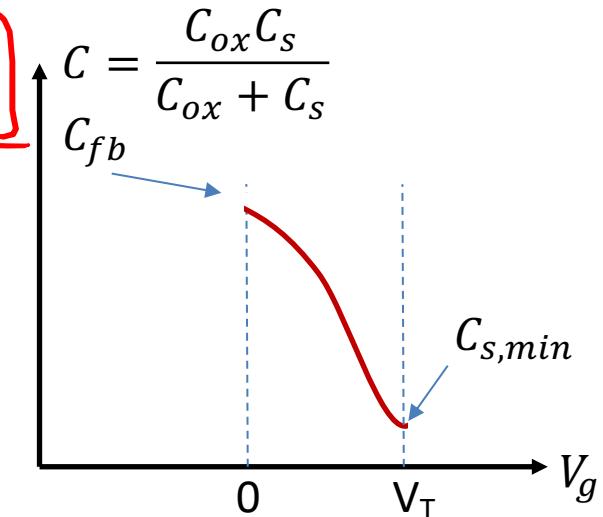
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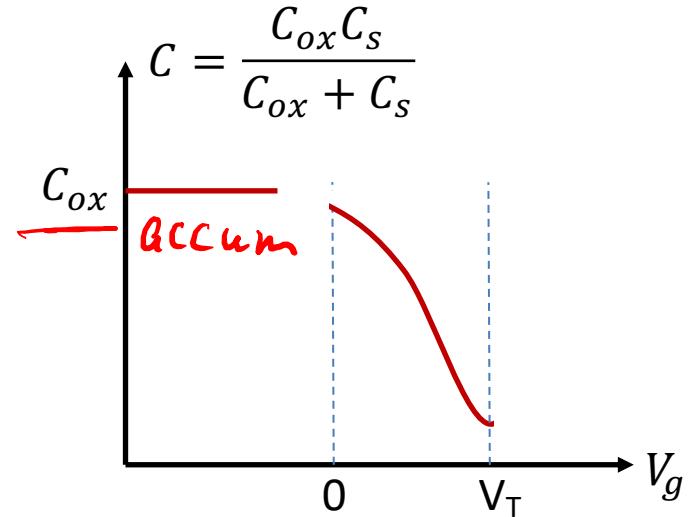
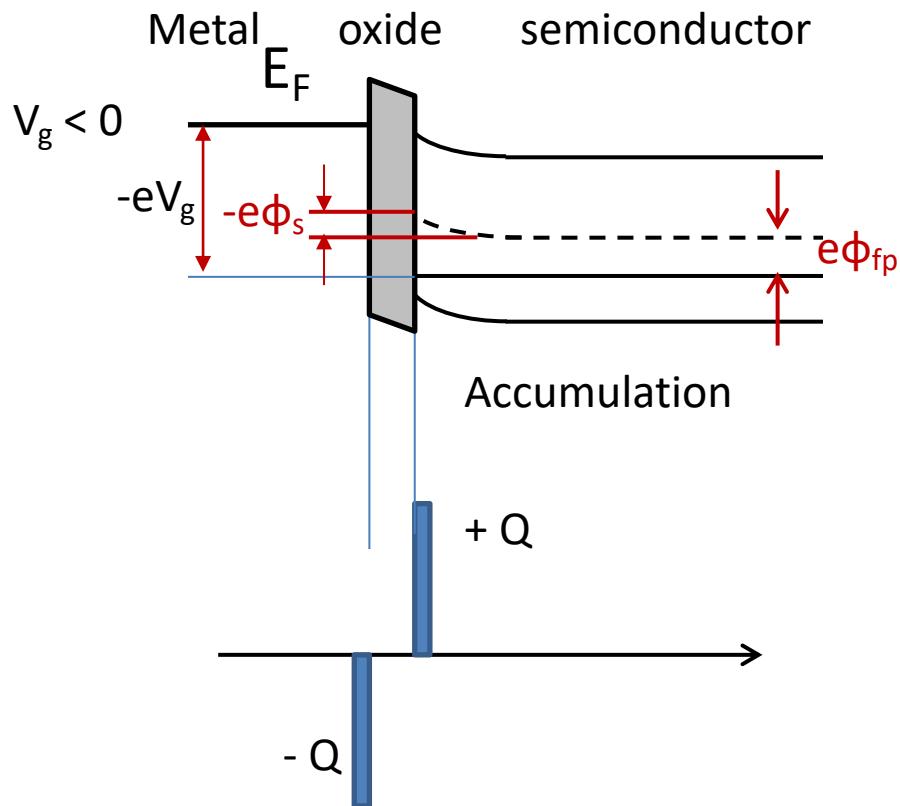
$$A C_s^3 + B C_s^2 + C C_s + D = 0$$

$$\left\{ \begin{array}{l} V_s = \frac{C_g \cdot C_{ox}}{C_{ox} + C_s} \\ C_s = \frac{\epsilon_s}{\sqrt{\frac{2 \epsilon_s V_s}{8 N_A}}} \end{array} \right.$$



10.2 The capacitance-voltage characteristics

Accumulation



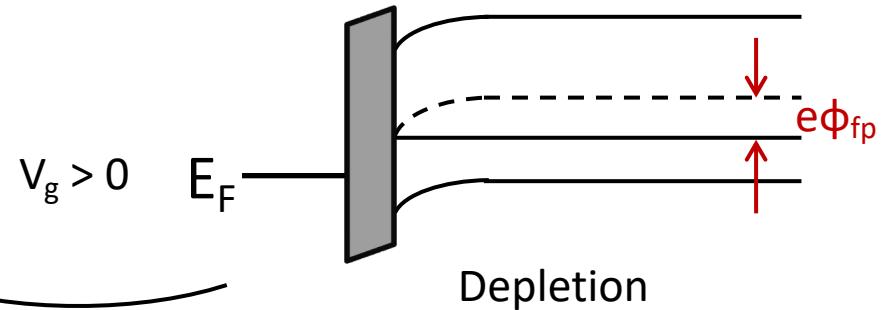
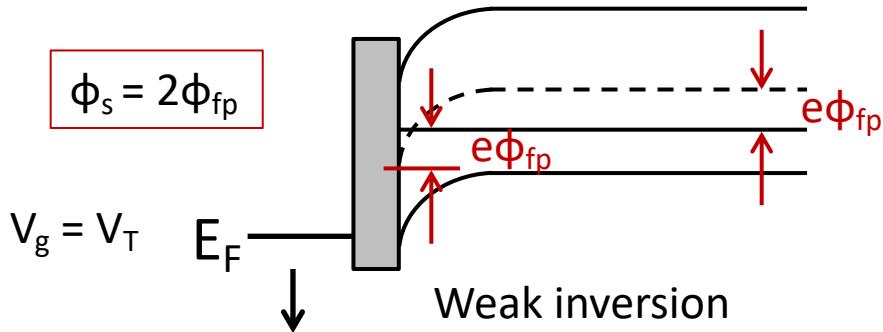
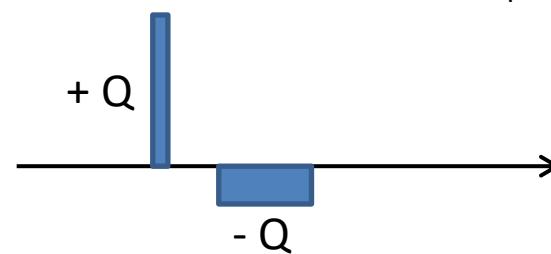
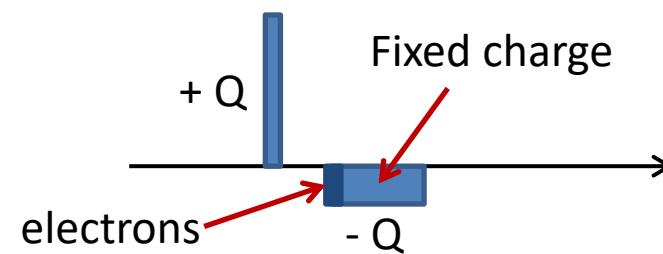
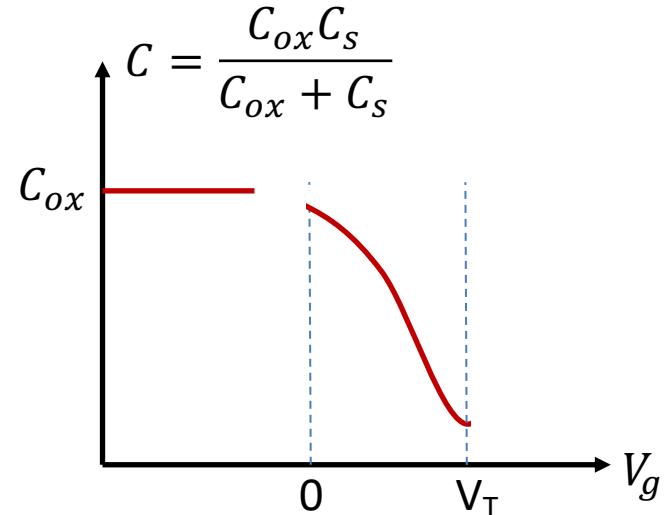
$$C_s \rightarrow \infty$$

$$C = \frac{C_s C_{ox}}{C_s + C_{ox}} \approx C_{ox}$$

10.2 The capacitance-voltage characteristics

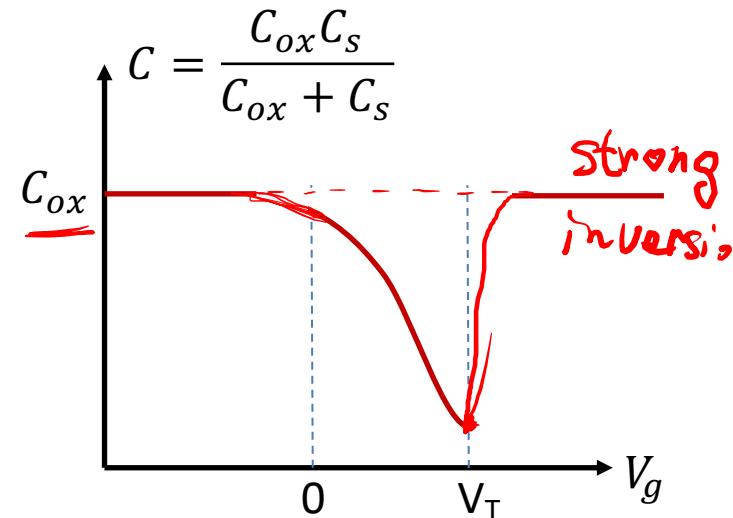
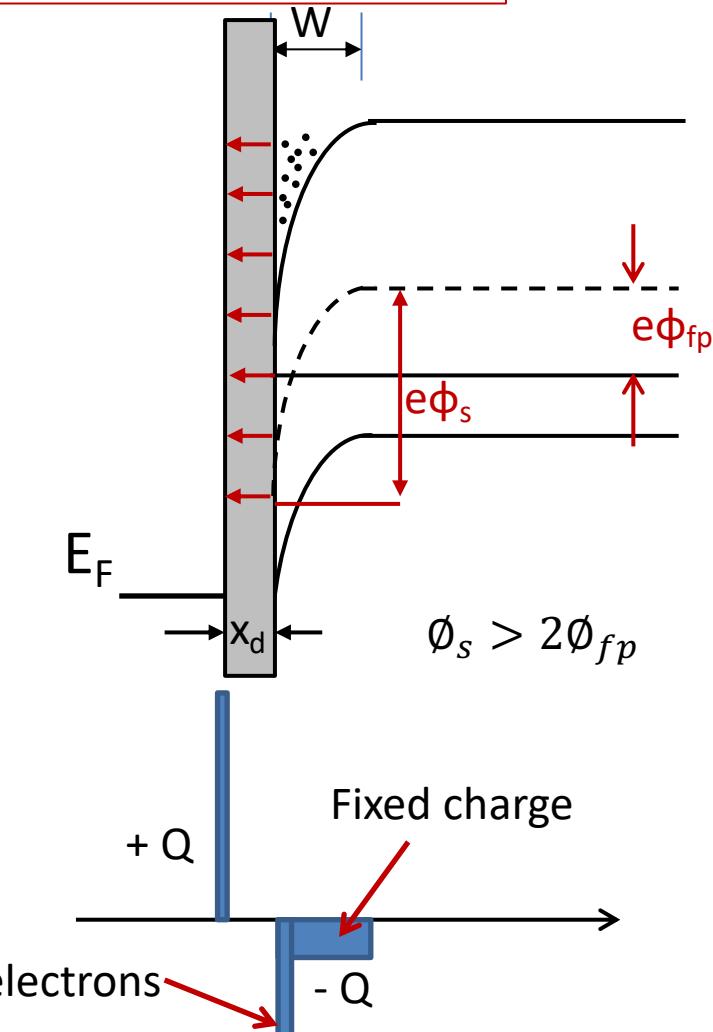
Depletion and weak inversion

$$C_s = \frac{\epsilon_s}{\sqrt{\frac{2\epsilon_s(V_s)}{qN_A}}}$$



10.2 The capacitance-voltage characteristics

Strong inversion

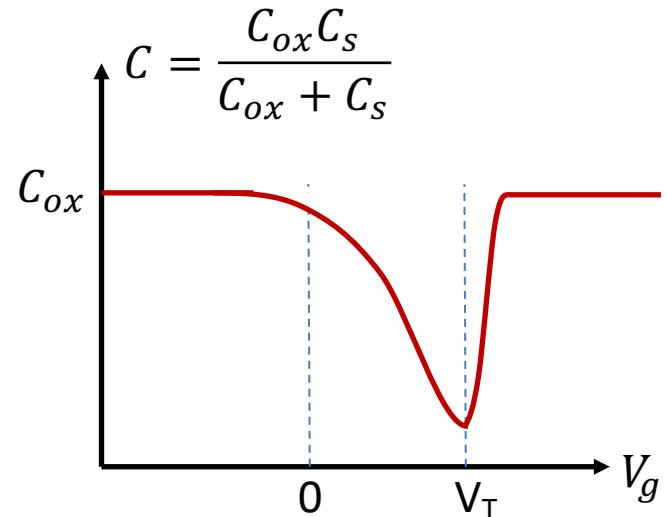
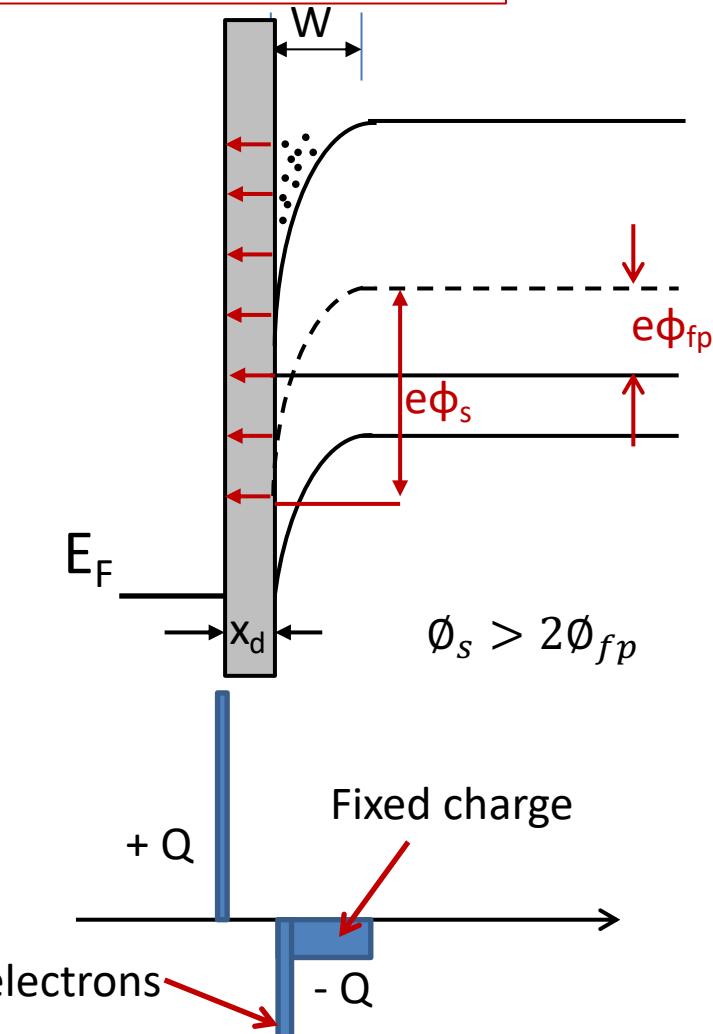


$$C_s \rightarrow \infty$$

$$C = \frac{C_s C_{ox}}{C_s + C_{ox}} \approx C_{ox}$$

10.2 The capacitance-voltage characteristics

Strong inversion



$$C_s \rightarrow \infty$$

$$C = \frac{C_s C_{ox}}{C_s + C_{ox}} \approx C_{ox}$$

Check your understanding

Problem Example #2

Consider a p-type silicon substrate at $T = 300 \text{ K}$ doped to $N_a = 10^{16} \text{ cm}^{-3}$.

The oxide is silicon dioxide with a thickness of $t_{ox} = 18 \text{ nm} = 180 \text{ \AA}$, and the gate is aluminum.

Calculate C_{ox} , C'_{min} , and C'_{FB} for a MOS capacitor.

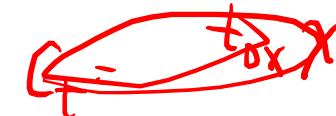
$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-14}}{18 \times 10^{-7}} = 1.92 \times 10^{-7} \text{ F/cm}^2$$

$$V_g = \begin{array}{c} \downarrow \\ | + | - | \end{array} \quad C_{ox} S = \frac{1}{\epsilon_{ox} t_{ox}}$$

$$\cancel{X_{dT}} X_{dT} = \left(\frac{4 \epsilon_s \phi_{fp}}{e N_a} \right)^{1/2}$$

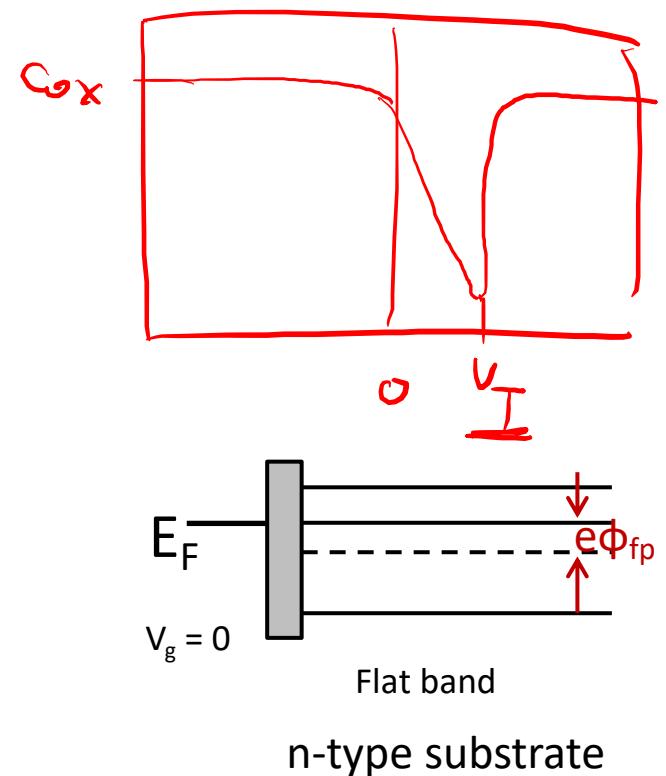
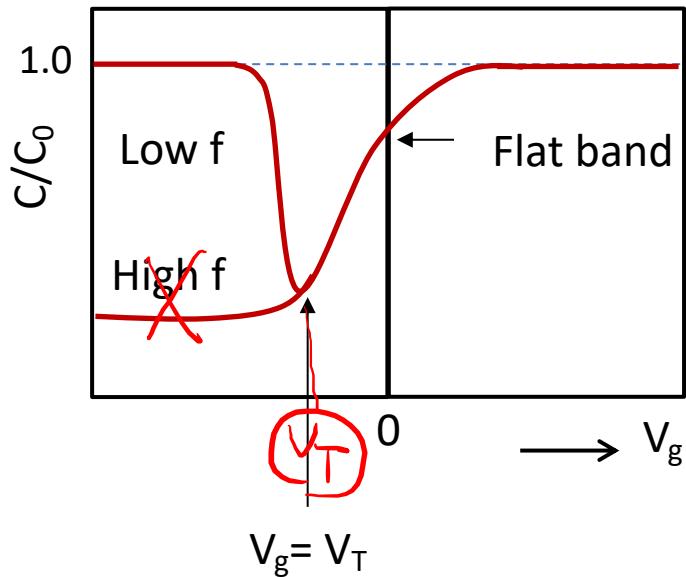
$$\frac{1}{C_t} = \frac{1}{C_{ox}} + \frac{1}{C_{min}} = \frac{\epsilon_{ox}}{t_{ox}} + \frac{\epsilon_s}{X_{dT}}$$

$$C_{min} = \frac{\epsilon_s}{X_{dT}}$$



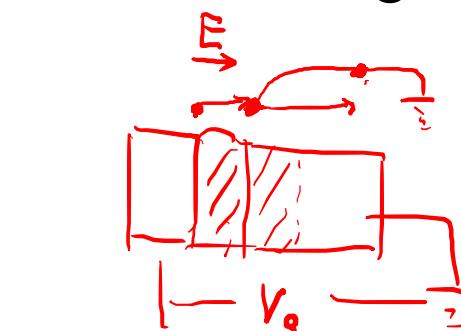
10.2 The capacitance-voltage characteristics

n-type semiconductor



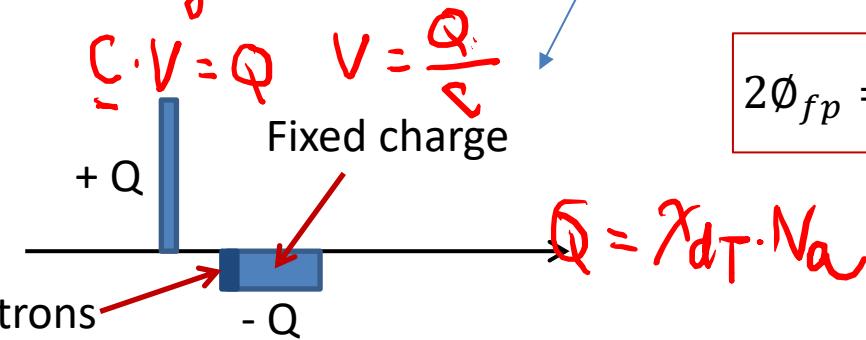
10.2 The capacitance-voltage characteristics

Threshold voltage



$$V_T = V_g = \frac{E \cdot t_{ox} + \phi_s}{t_{ox}} \quad \text{---}$$

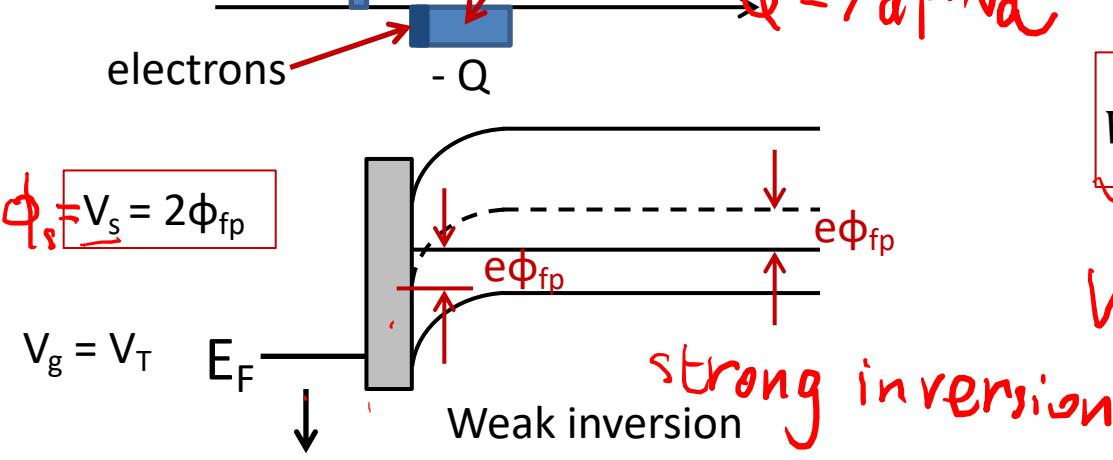
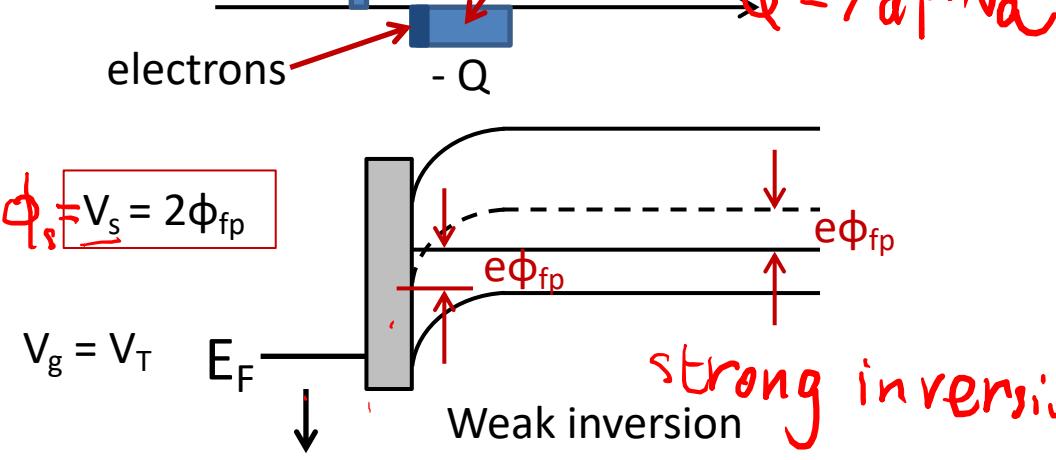
$$C_s = \frac{\epsilon_s}{\sqrt{\frac{2\epsilon_s(V_s)}{qN_A}}} = \frac{\epsilon_s}{\sqrt{\frac{2\epsilon_s(2\phi_{fp})}{qN_A}}}$$



$$C \cdot V = Q \quad V = \frac{Q}{C}$$

Fixed charge

$$2\phi_{fp} = \frac{V_T C_{ox}}{C_{ox} + C_s} \Rightarrow V_T = 2\phi_{fp} + 2\phi_{fp} \frac{C_s}{C_{ox}}$$

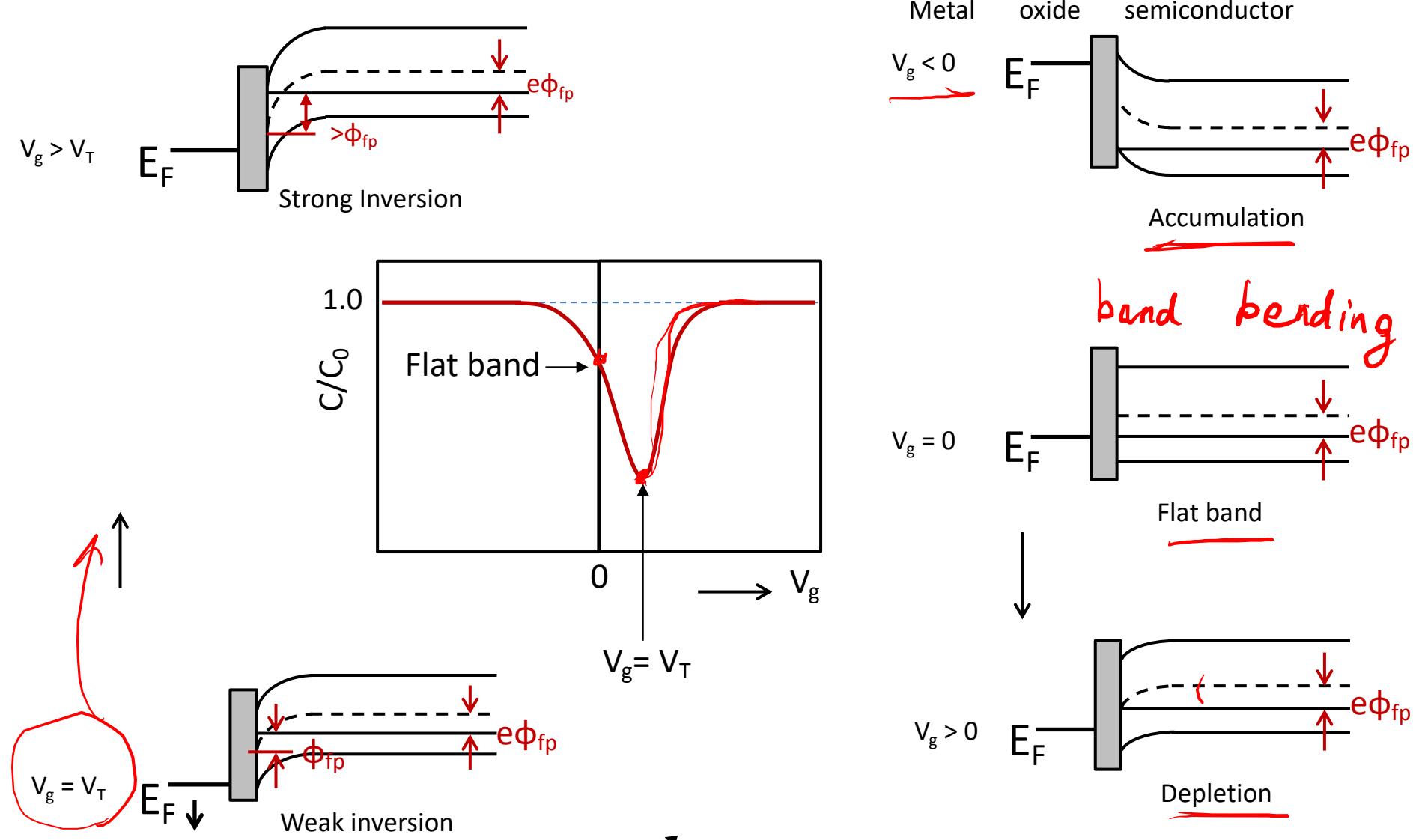


$$V_T = 2\phi_{fp} + \frac{2\sqrt{e\epsilon_s N_A \phi_{fp}}}{C_{ox}}$$

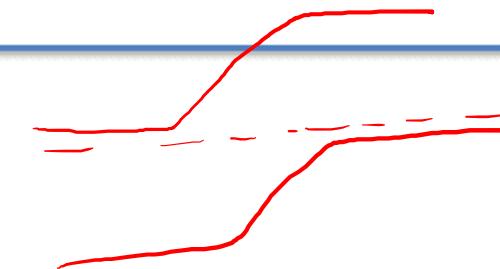
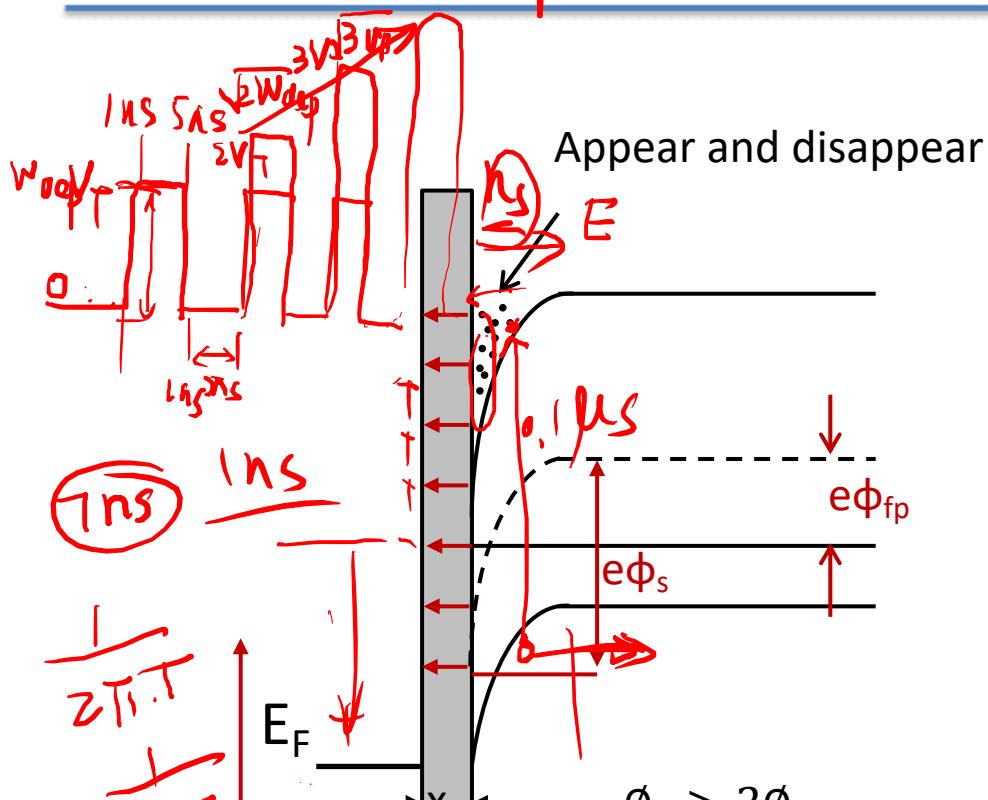
$$V_T = 2\phi_{fp} + \frac{Na \cdot \chi_{dT}}{C_{ox}}$$

$$\chi_{dT} = \sqrt{\frac{4\epsilon_s \cdot \phi_{fp}}{eN_A}}$$

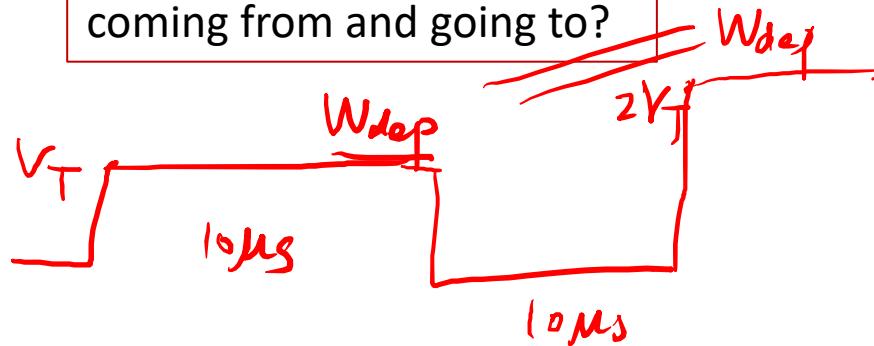
10.2 The capacitance-voltage characteristics: summary



Question: W_{dop}

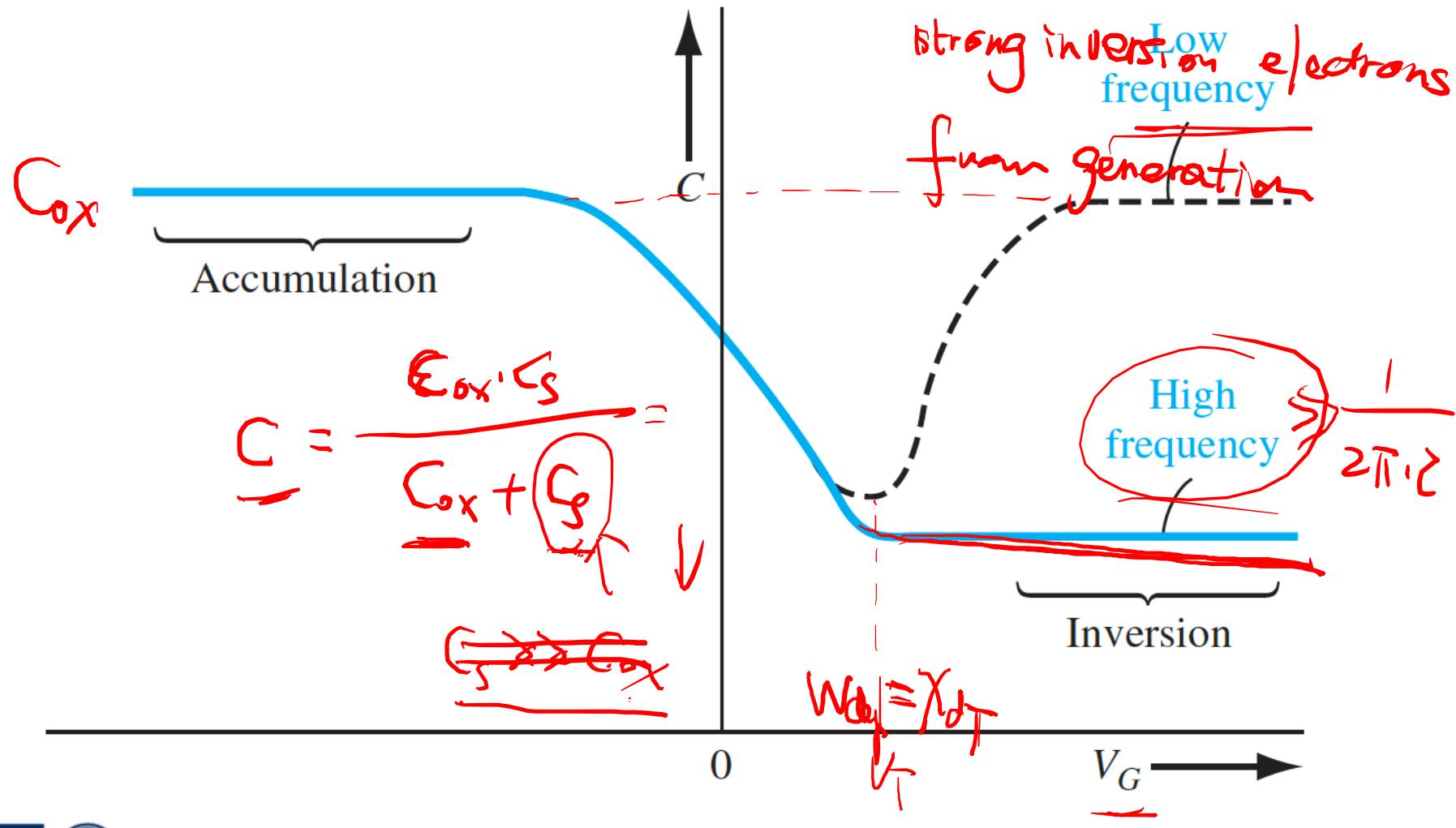


Where are the electrons coming from and going to?



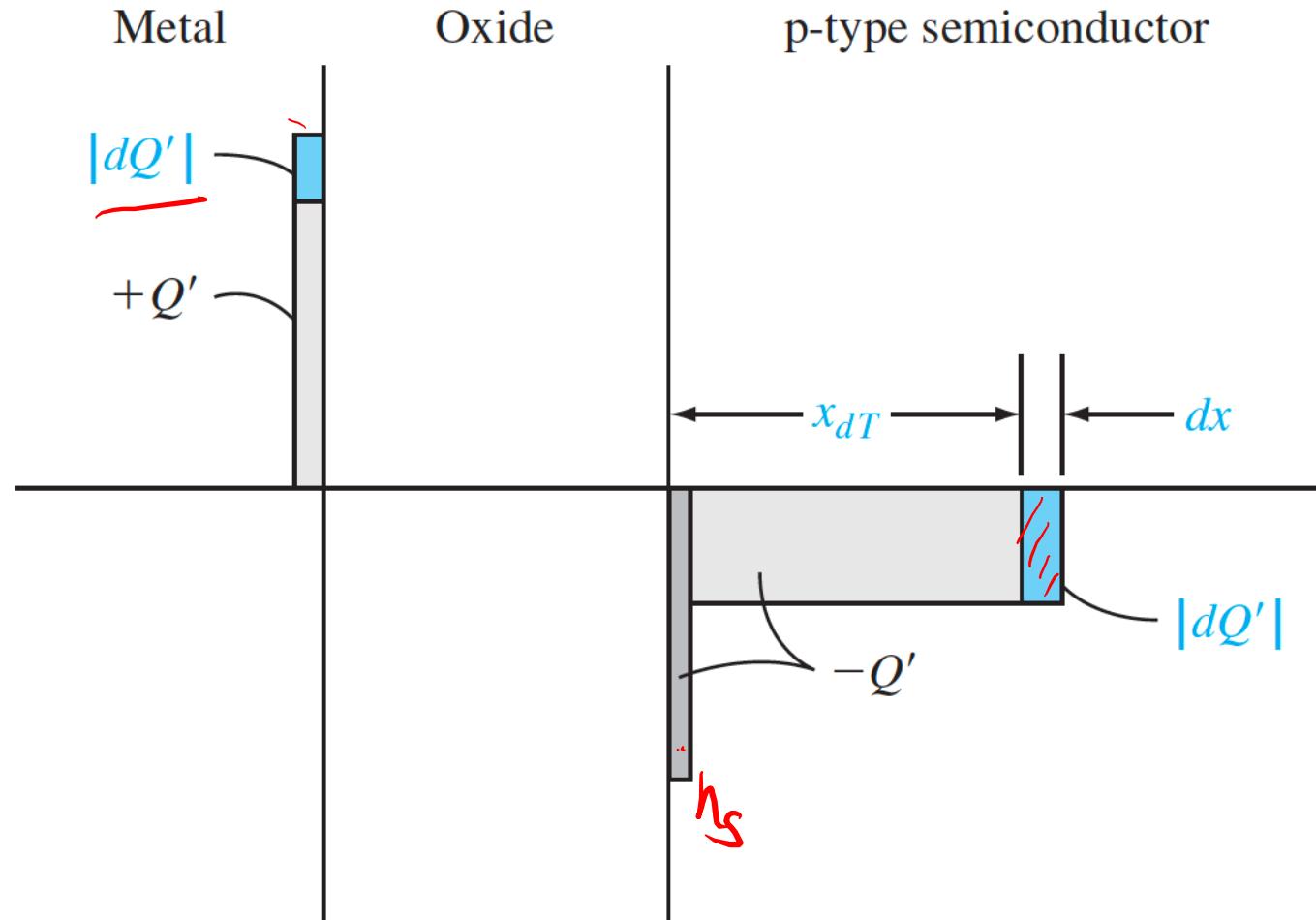
10.2 The capacitance-voltage characteristics

Frequency dependence



10.2 The capacitance-voltage characteristics

Frequency dependence



Outline

10.1 The two-terminal MOS structure

10.2 Capacitance-voltage characteristics

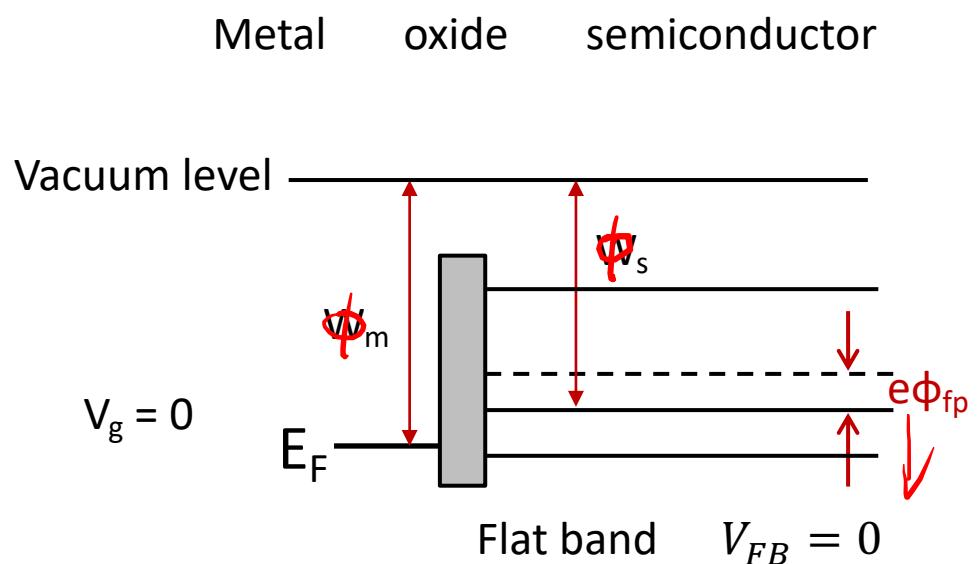
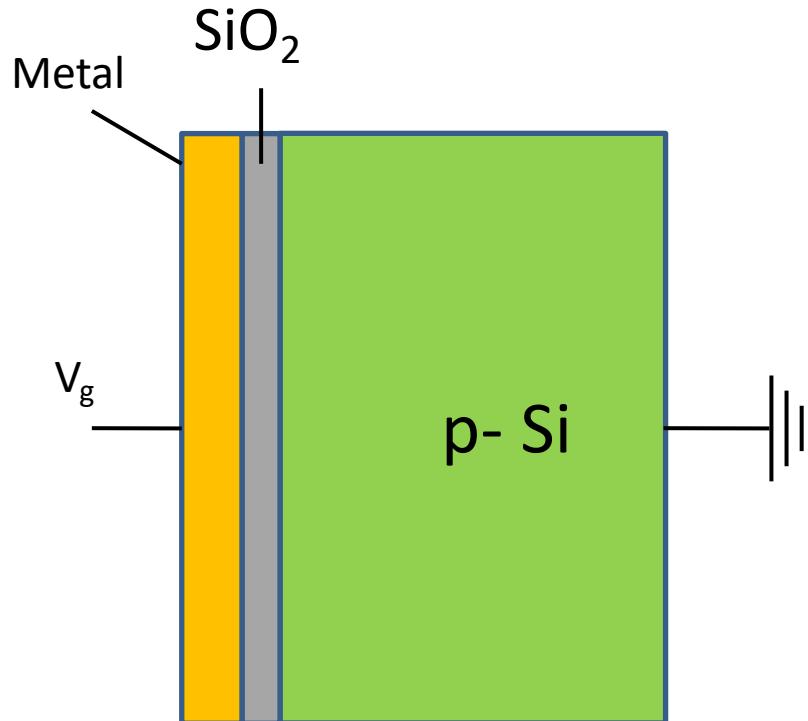
10.3 Non-ideal effects

10.4 The basic MOSFET operation



10.3 Non-ideal effects

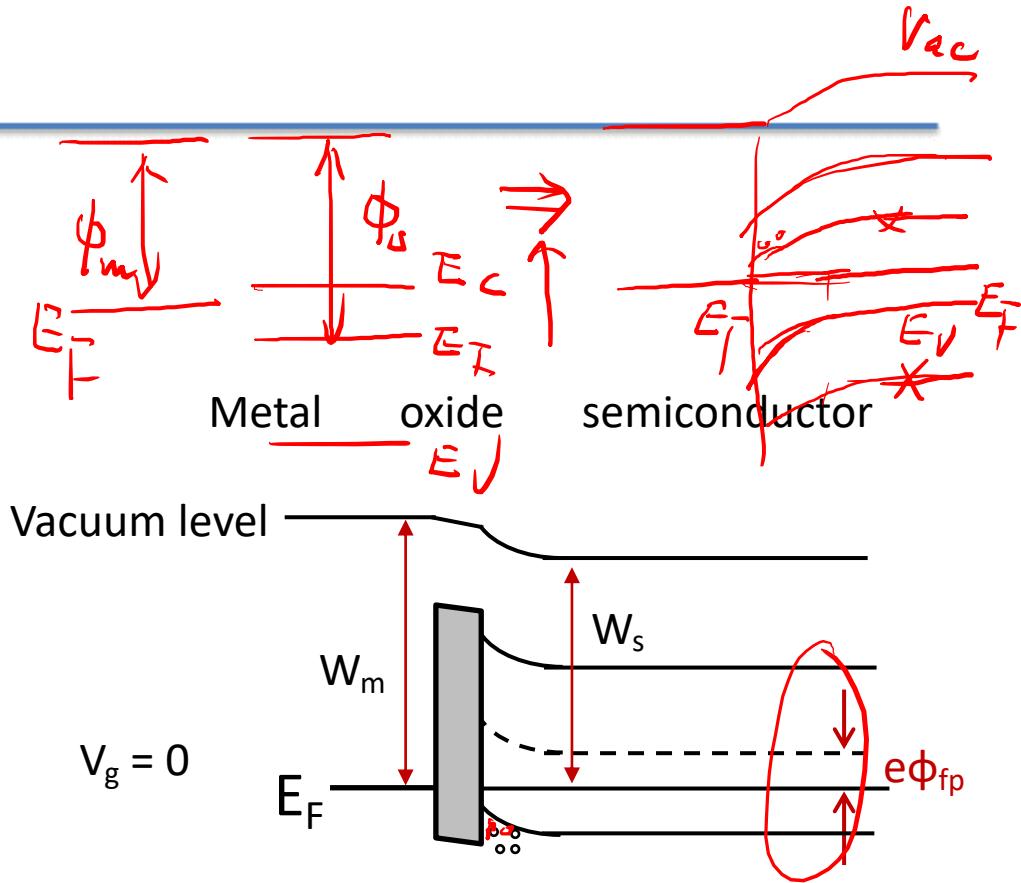
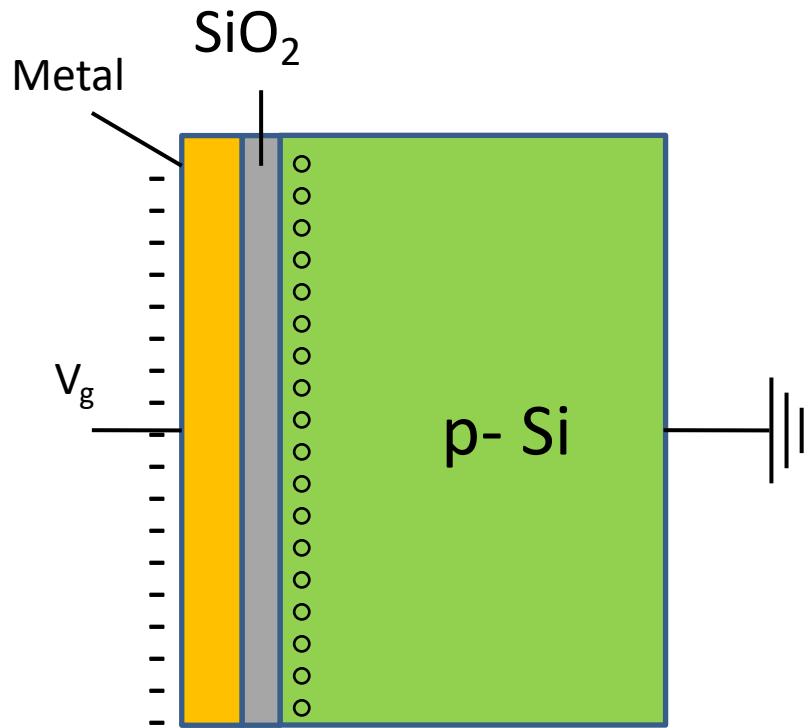
Work function difference



Metal-insulator-semiconductor (MIS)

10.3 Non-ideal effects

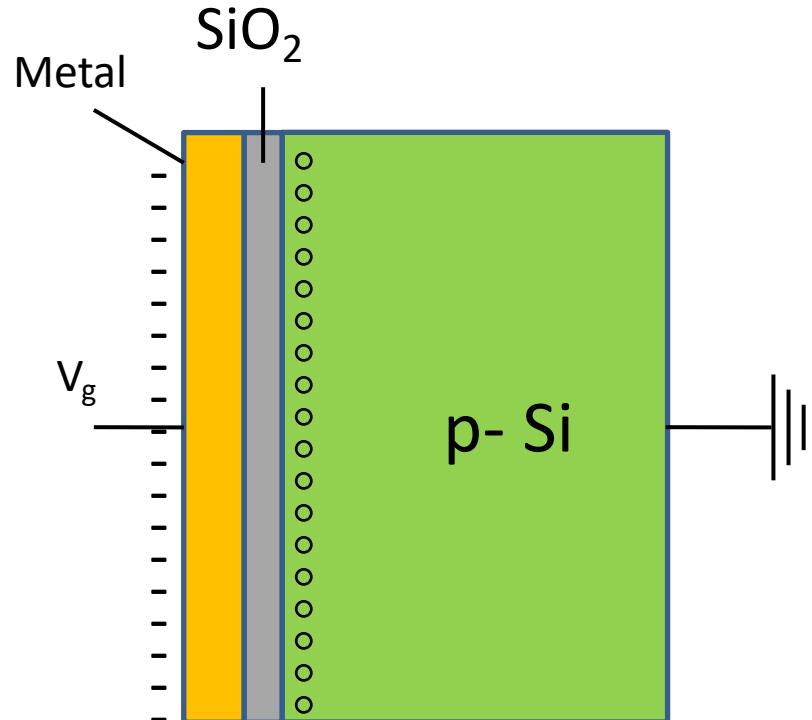
Work function difference



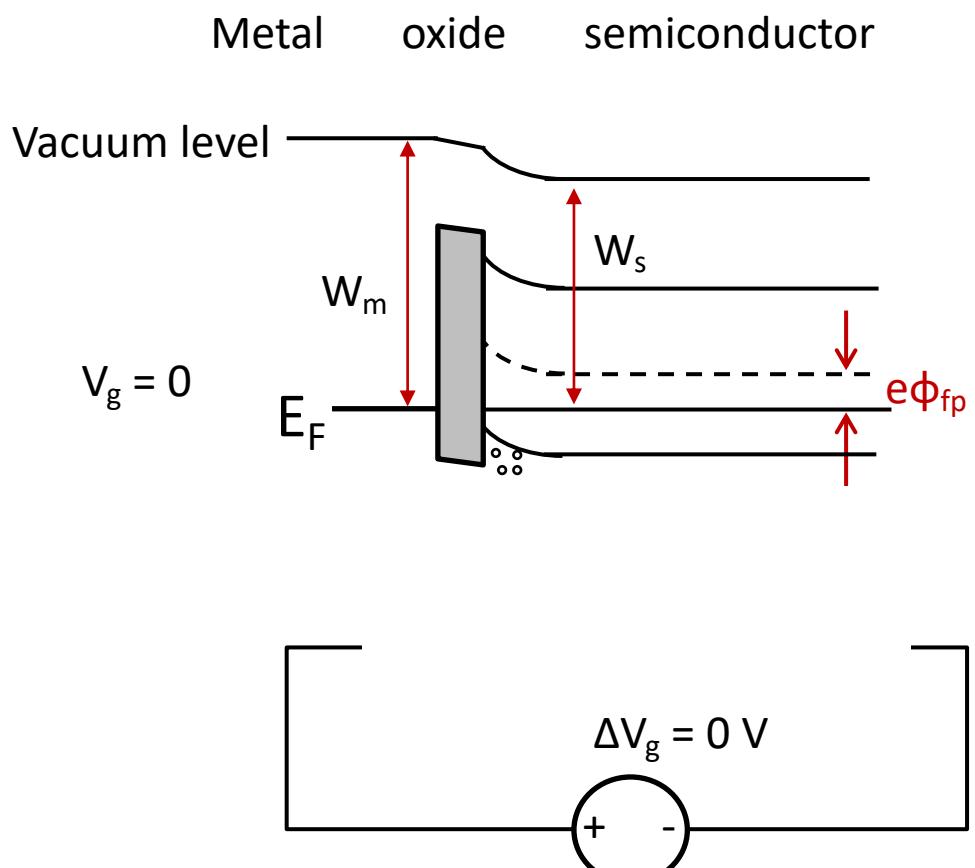
Metal-insulator-semiconductor (MIS)

10.3 Non-ideal effects

Work function difference



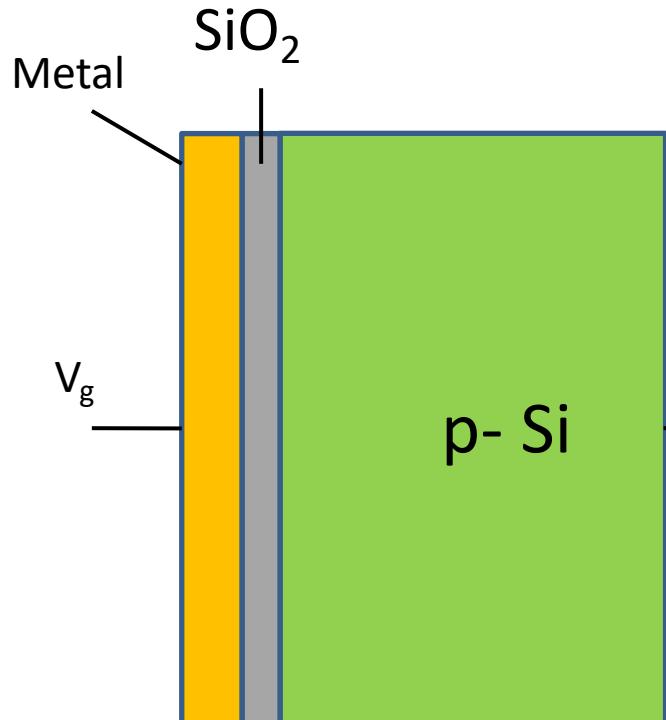
Metal-insulator-semiconductor (MIS)



10.3 Non-ideal effects

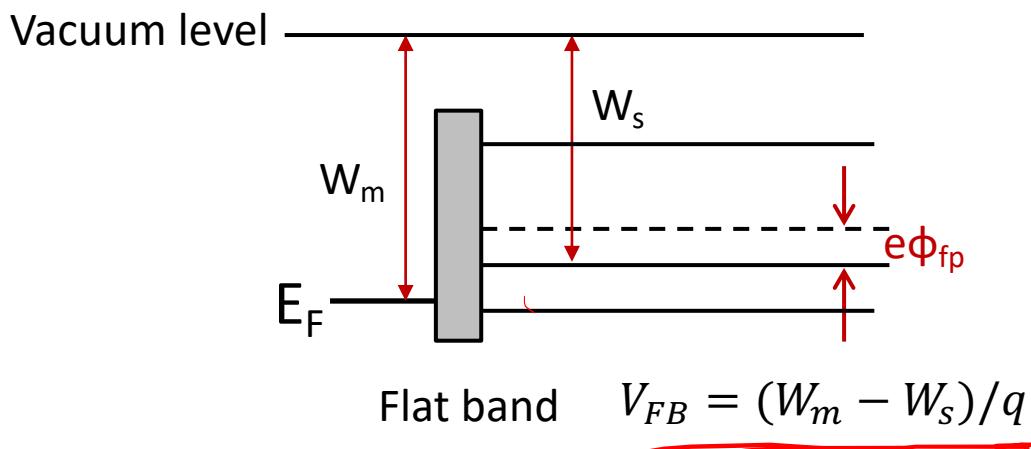
$$\sqrt{\frac{4\epsilon\phi_{FI}}{2N_0}}$$

Work function difference



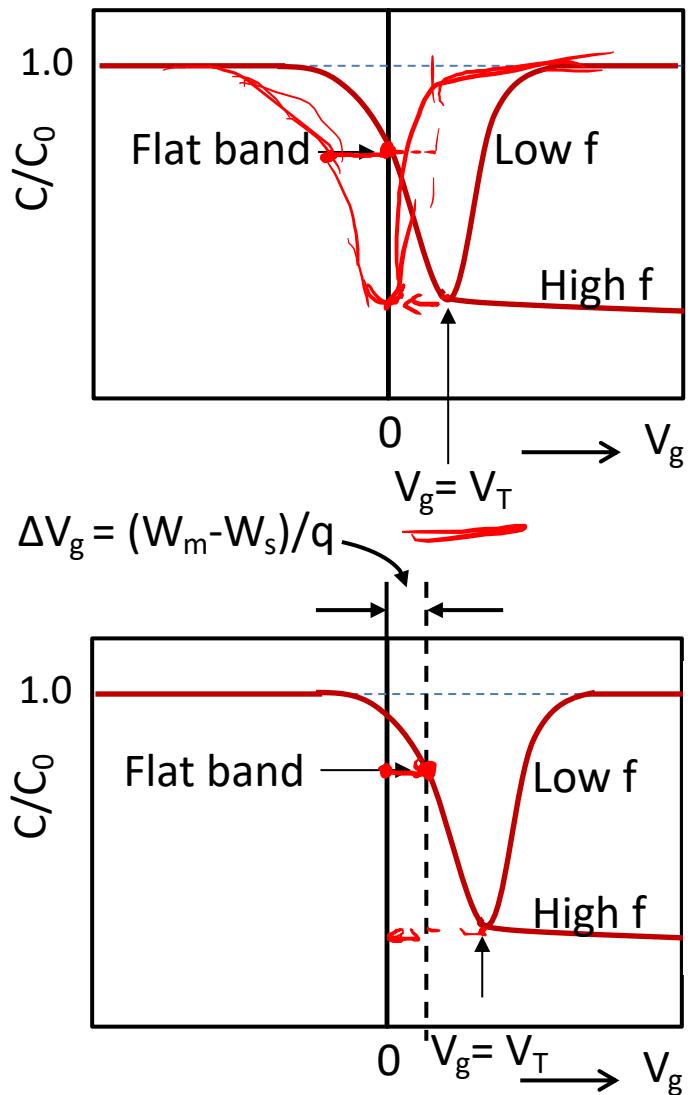
Metal-insulator-semiconductor (MIS)

$$V_T = 2\phi_{fp} + \frac{N_a \cdot \chi_{dT}}{C_{ox}} + \frac{\phi_m - \phi_s}{\gamma}$$

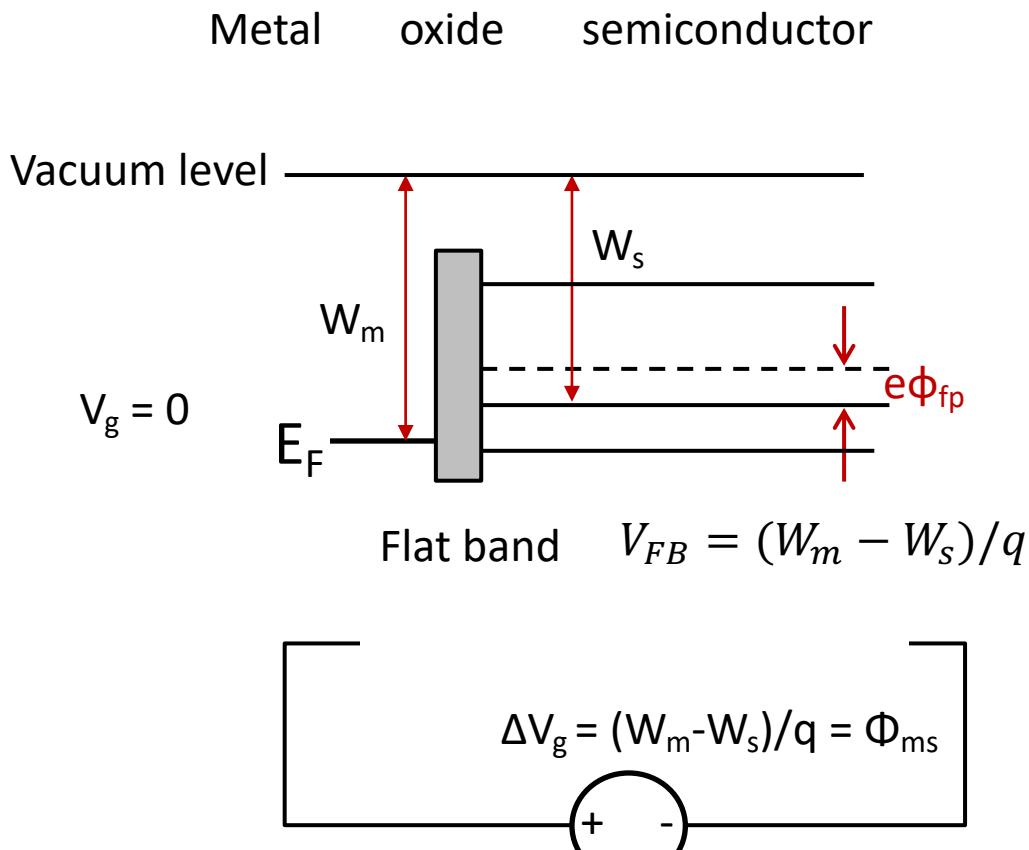


$$\Delta V_g = (W_m - W_s)/q = \Phi_{ms}$$

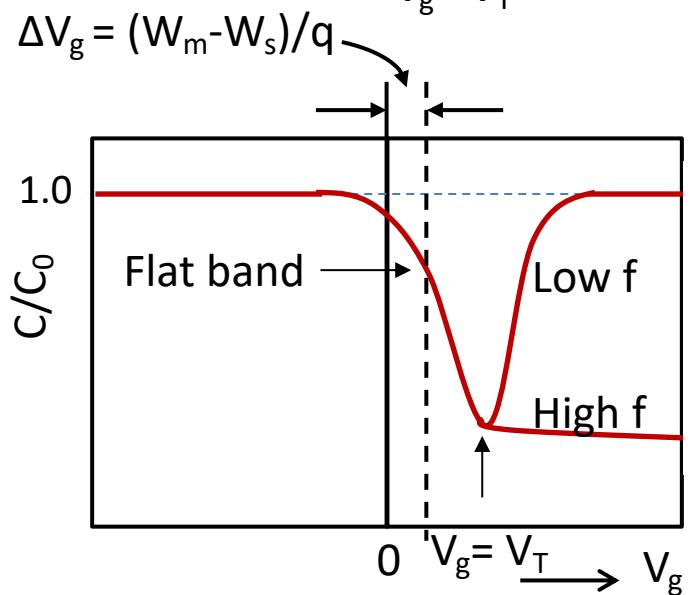
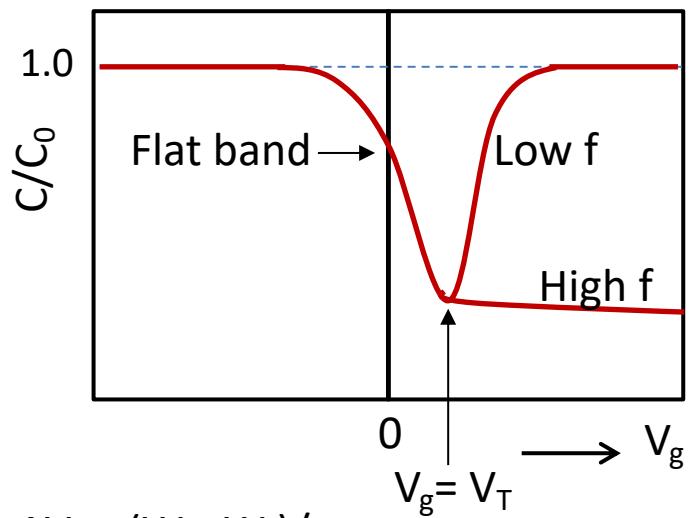
10.3 Non-ideal effects



Work function difference



10.3 Non-ideal effects



Work function difference

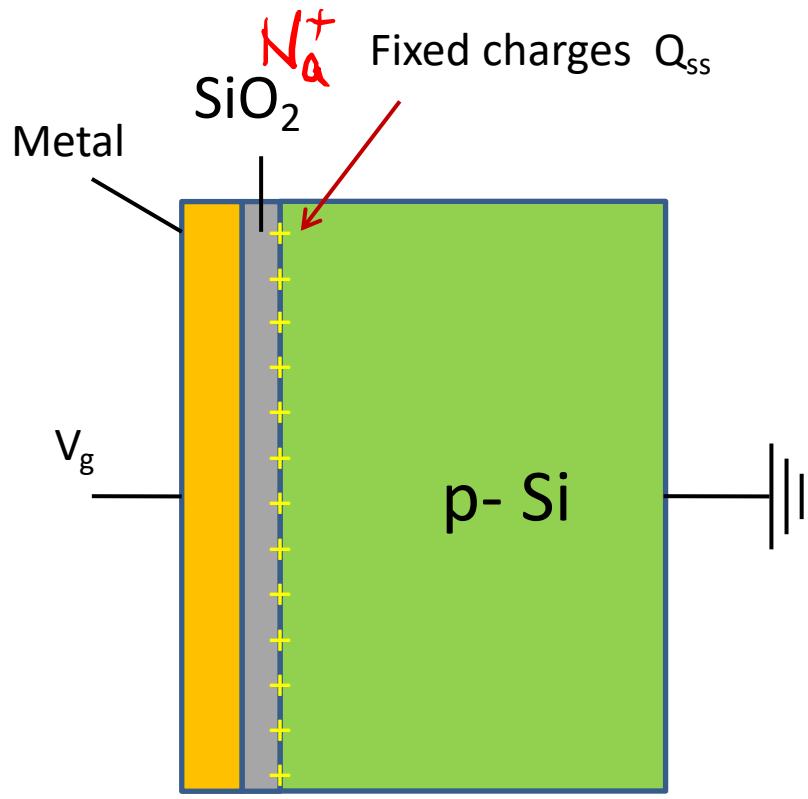
$$V_T = 2\phi_{fp} + t_{ox} \sqrt{\frac{4eN_a\epsilon_{Si}\phi_{fp}}{\epsilon_{ox}^2}} = 2\phi_b + \frac{|Q_{SD}|}{C_{ox}}$$

$$\begin{aligned} V_T &= 2\phi_{fp} + t_{ox} \sqrt{\frac{4eN_a\epsilon_{Si}\phi_{fp}}{\epsilon_{ox}^2}} + V_{FB} \\ &= 2\phi_{fp} + \frac{|Q_{SD}|}{C_{ox}} + \phi_{ms} \end{aligned}$$

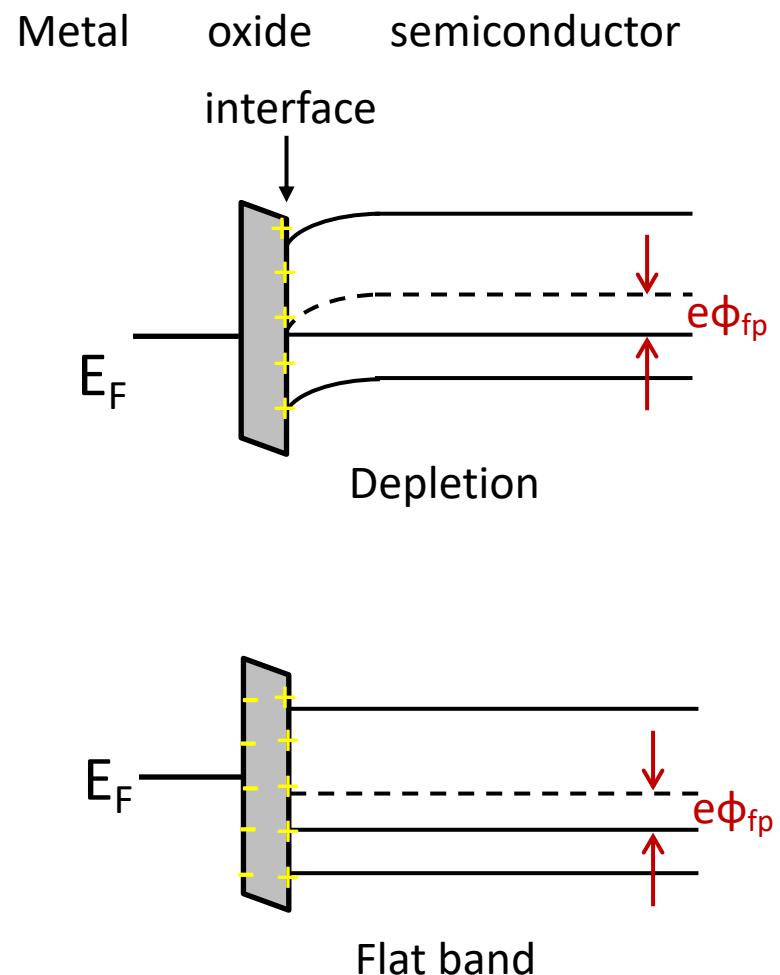
$\phi_m - \phi_s$

10.3 Non-ideal effects

Fixed charges



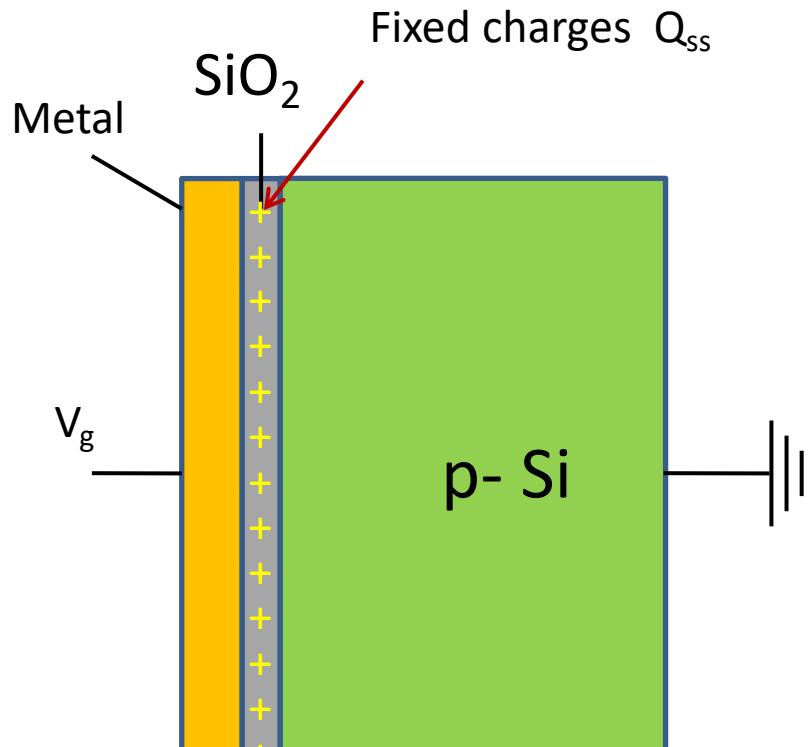
Metal-insulator-semiconductor (MIS)



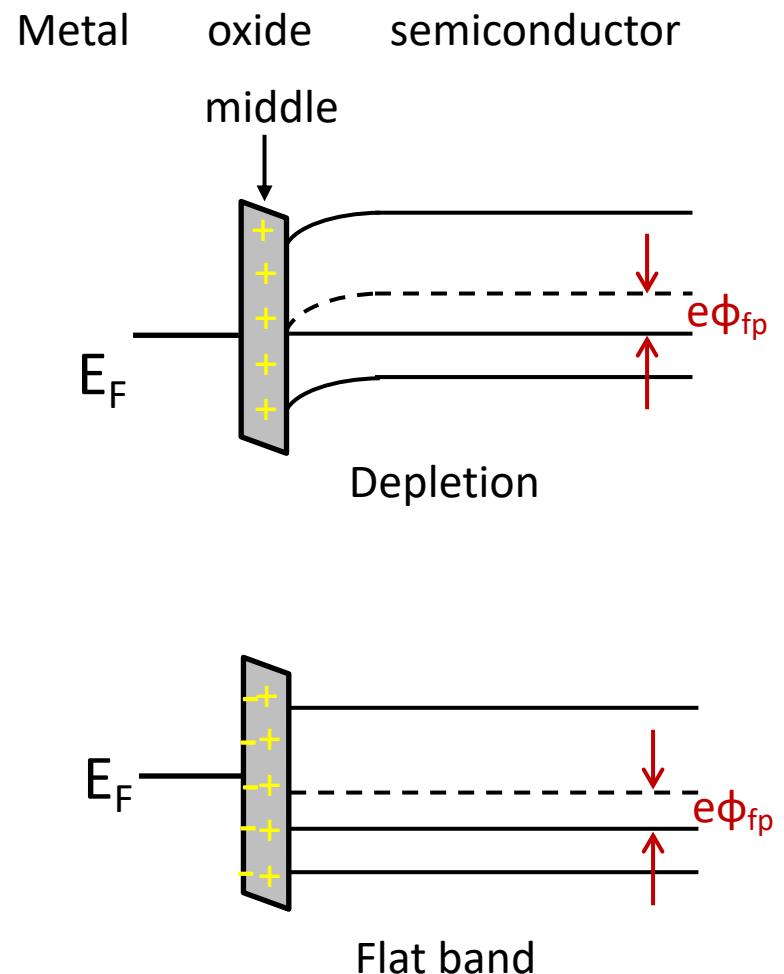
$$V_g = V_{FB} = -Q_{ss}/C$$

10.3 Non-ideal effects

Fixed charges



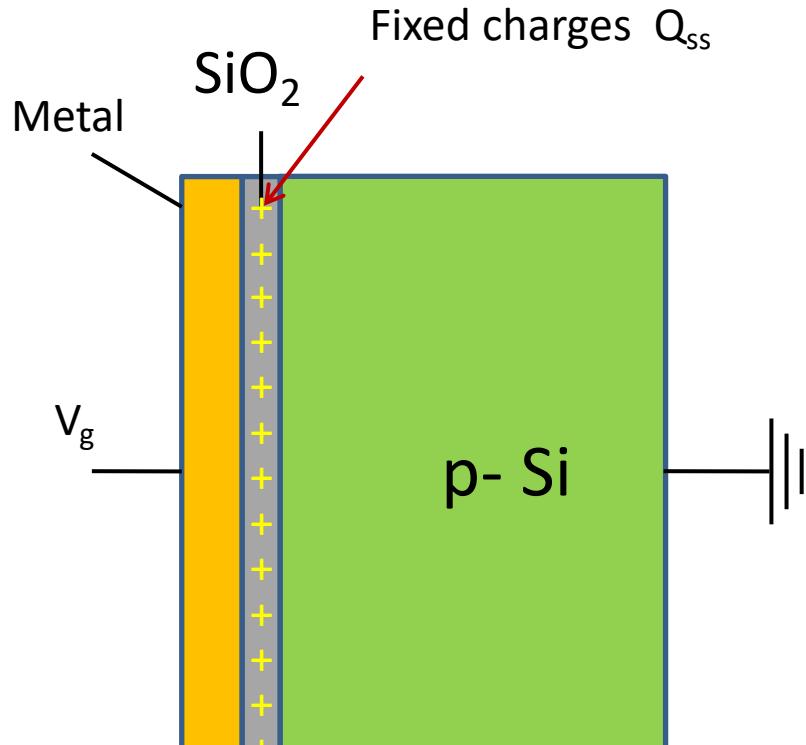
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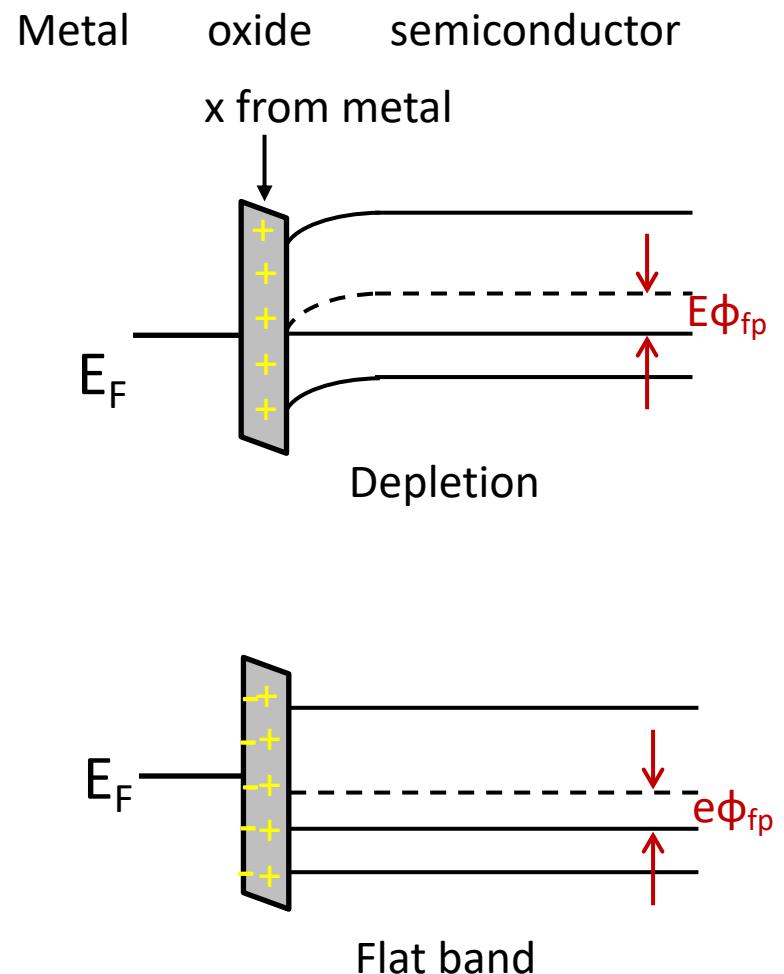
$$V_g = V_{FB} = -Q_{ss}/2C$$

10.3 Non-ideal effects

Fixed charges



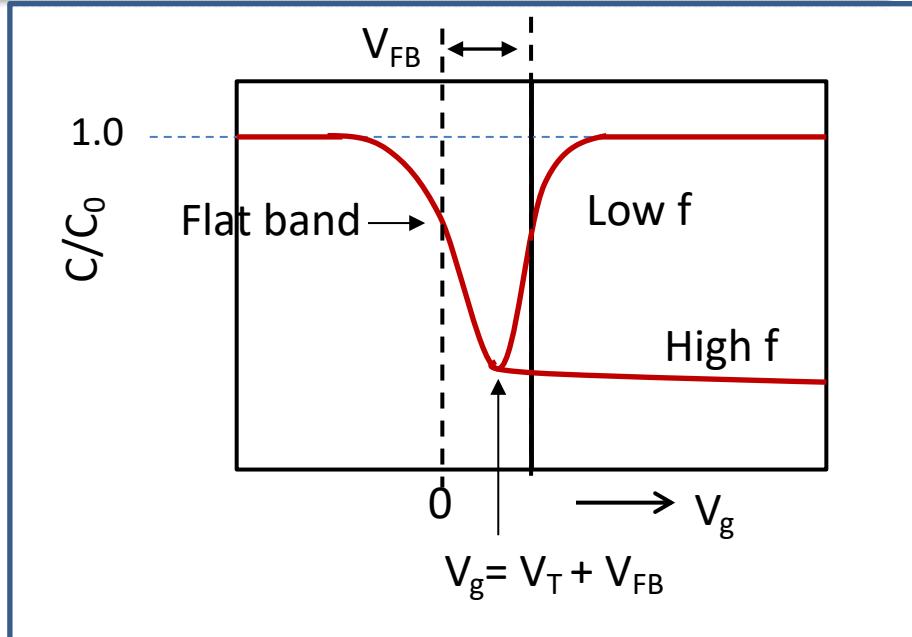
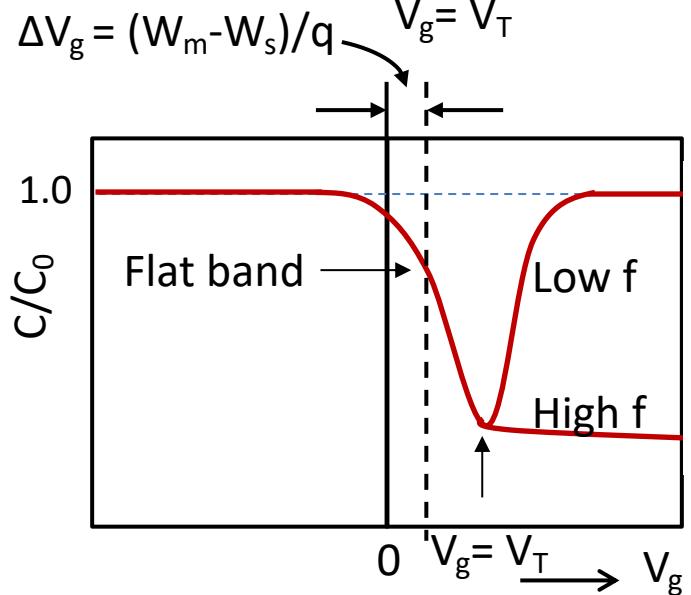
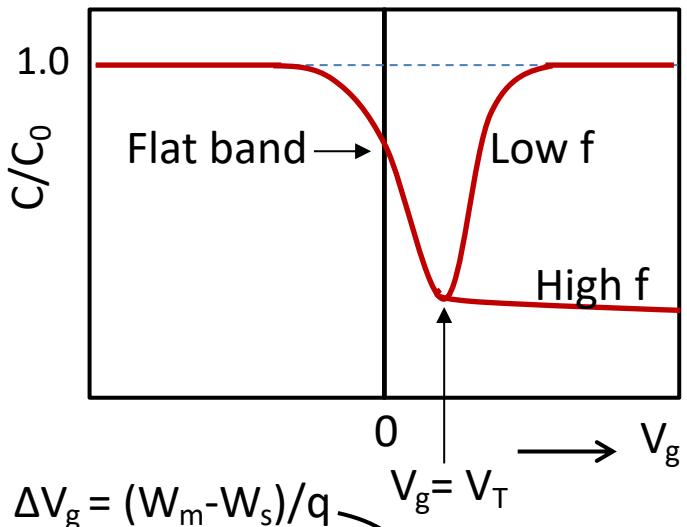
Metal-insulator-semiconductor (MIS)



$$V_g = V_{FB} = -\frac{Q_{ss}}{C} \cdot \frac{x}{d}$$

10.3 Non-ideal effects

Fixed charges

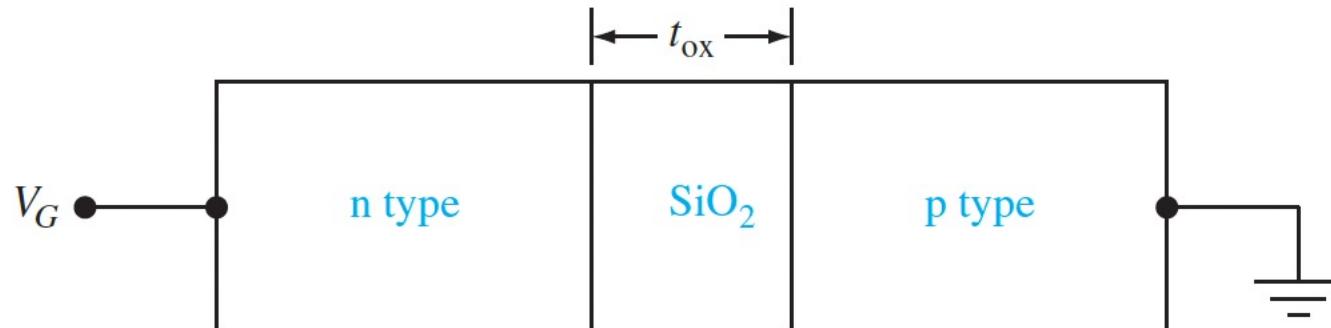


$$\begin{aligned}
 V_T &= 2\phi_{fp} + t_{ox} \sqrt{\frac{4eN_a\epsilon_{Si}\phi_{fp}}{\epsilon_{ox}^2}} + V_{FB} \\
 &= 2\phi_{fp} + \frac{|Q_{SD}|}{C_{ox}} + \phi_{ms} - \frac{Q_{ss}}{C_{ox}}
 \end{aligned}$$

Check your understanding

Problem Example #3

Consider an SOS capacitor as shown in Figure P10.29. Assume the SiO_2 is ideal (no trapped charge) and has a thickness of $t_{\text{ox}} = \underline{\underline{500 \text{ \AA}}}$. The doping concentrations are $N_d = 10^{16} \text{ cm}^{-3}$ and $N_a = 10^{16} \text{ cm}^{-3}$. (a) Sketch the energy-band diagram through the device for (i) flat band, (ii) $V_G = +3 \text{ V}$, and (iii) $V_G = -3 \text{ V}$. (b) Calculate the flat-band voltage. (c) Estimate the voltage across the oxide for (i) $V_G = +3 \text{ V}$ and (ii) $V_G = -3 \text{ V}$. (d) Sketch the high-frequency $C-V$ characteristic curve.



Check your understanding

Problem Example #3



Check your understanding

Problem Example #3



Check your understanding

Problem Example #3



Check your understanding

Problem Example #4

Objective: Calculate the threshold voltage of a MOS system using an aluminum gate.

Consider a p-type silicon substrate at $T = 300$ K doped to $N_a = 10^{15}$ cm $^{-3}$. Let $Q'_{ss} = 10^{10}$ cm $^{-2}$, $t_{ox} = 12$ nm = 120 Å, and assume the oxide is silicon dioxide.



Check your understanding

Problem Example #4



Outline

10.1 The two-terminal MOS structure

10.2 Capacitance-voltage characteristics

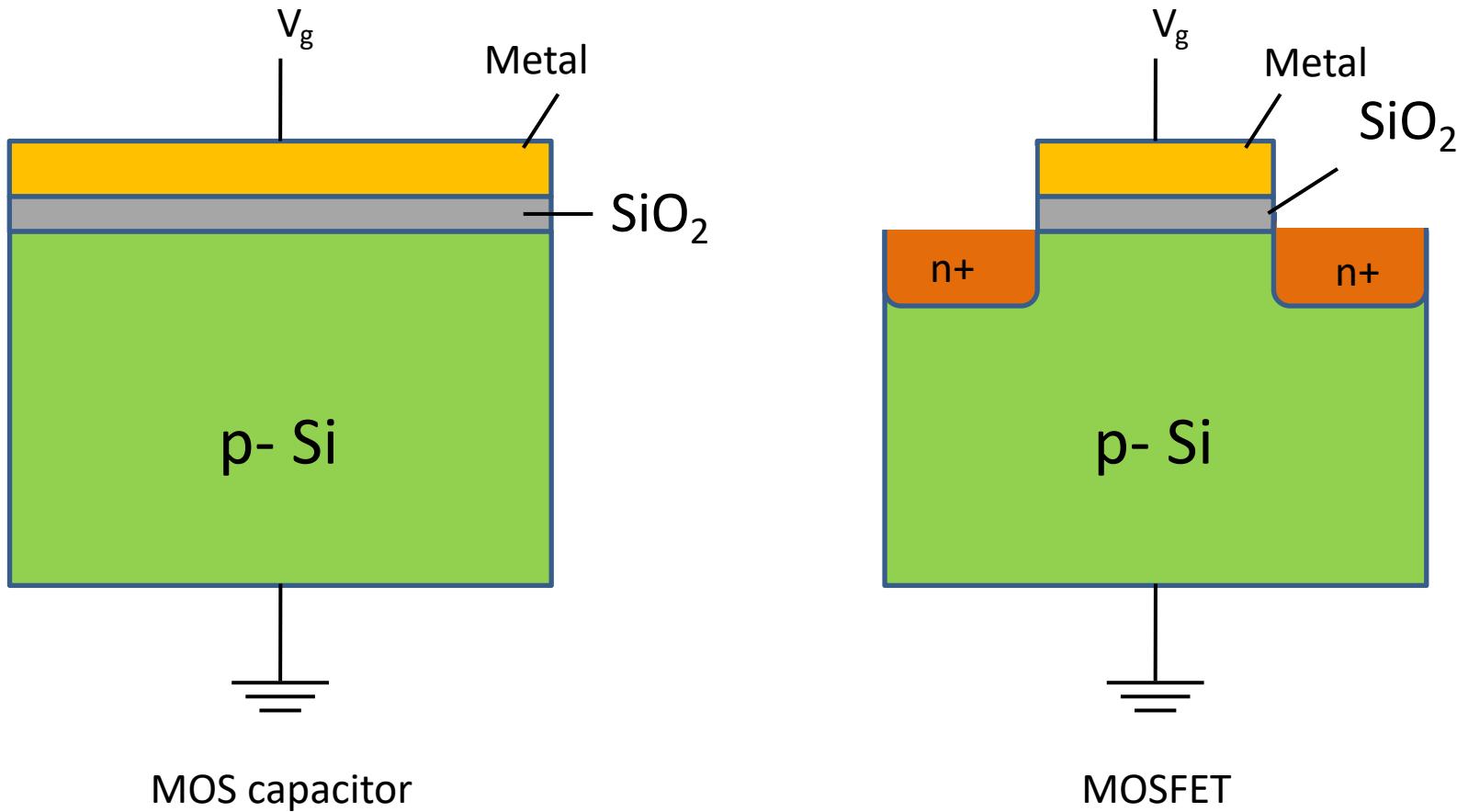
10.3 Non-ideal effects

10.4 The basic MOSFET operation



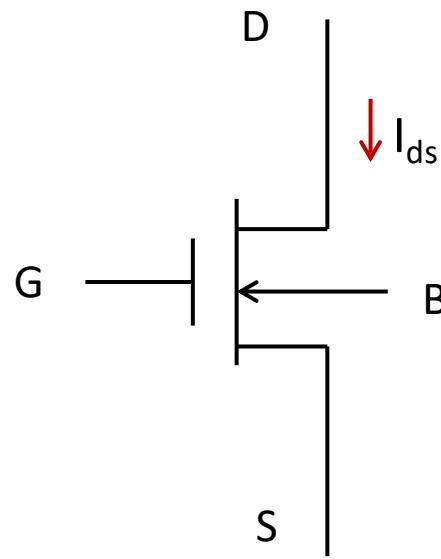
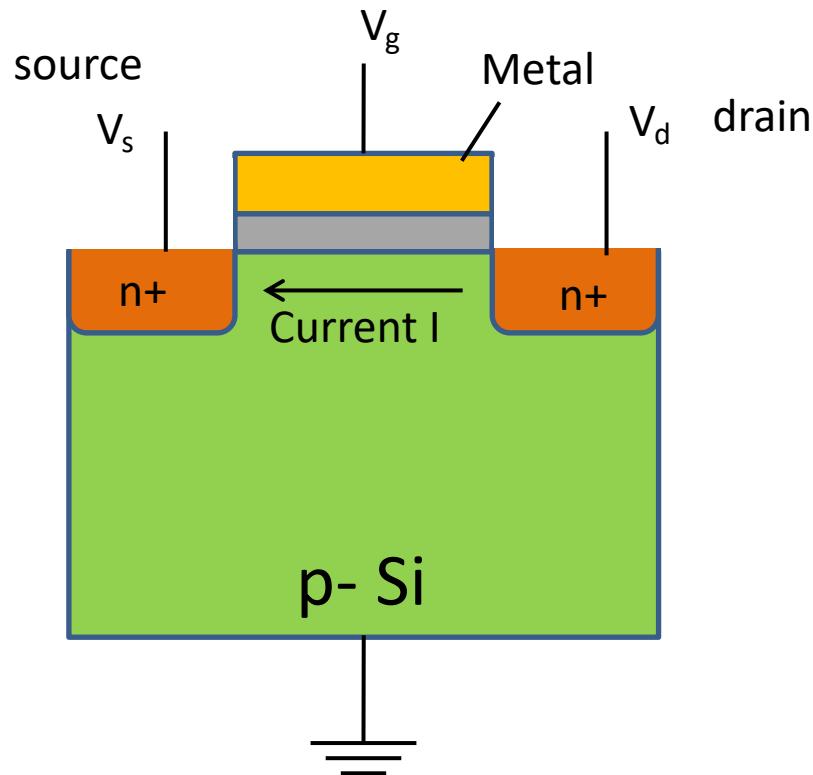
10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: MOSFET



10.4 The basic MOSFET operation

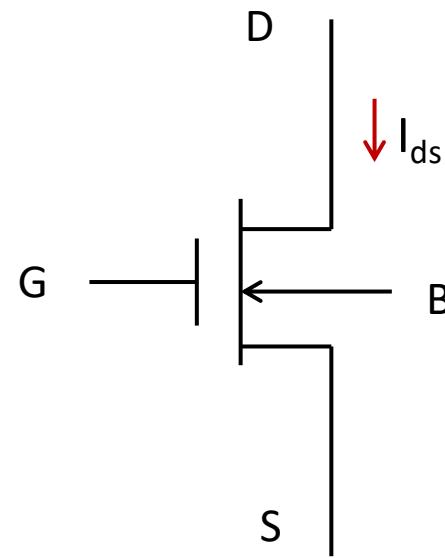
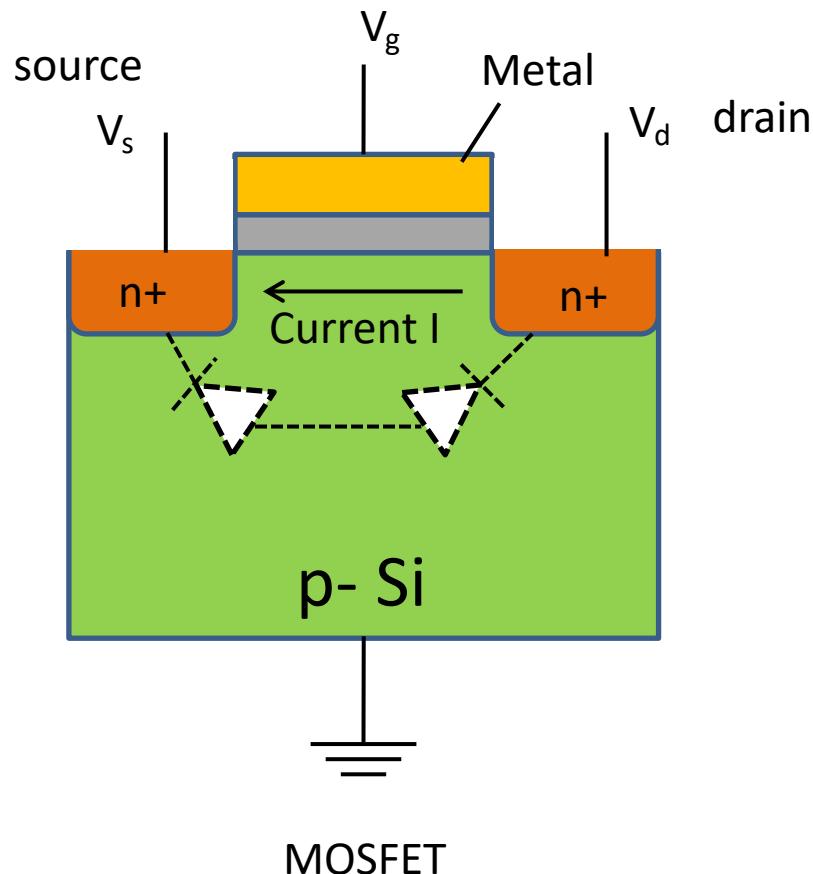
Metal-Oxide-Semiconductor field effect transistor: MOSFET



Metal-oxide-semiconductor (MOS)

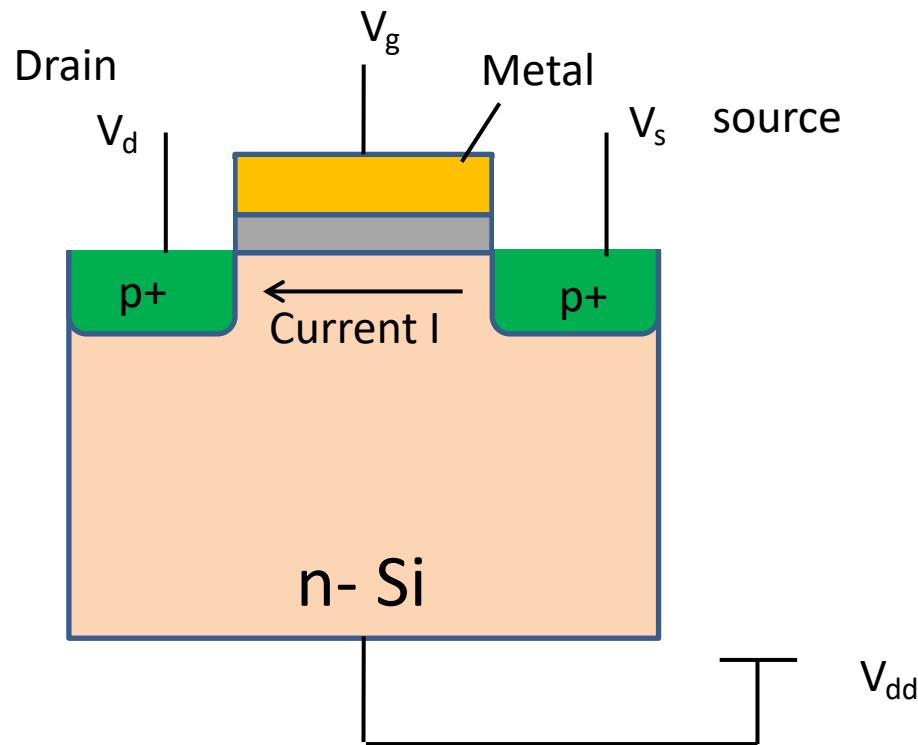
10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: MOSFET

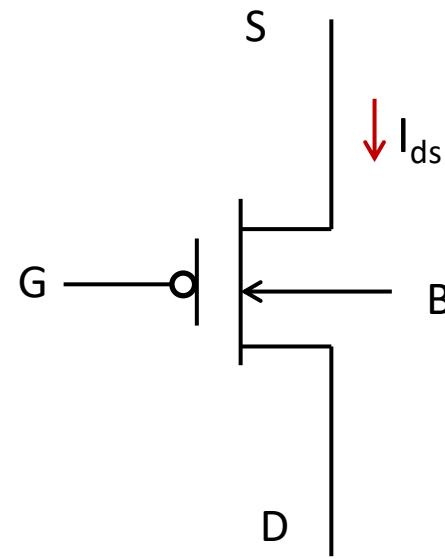


10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: p-type MOSFET

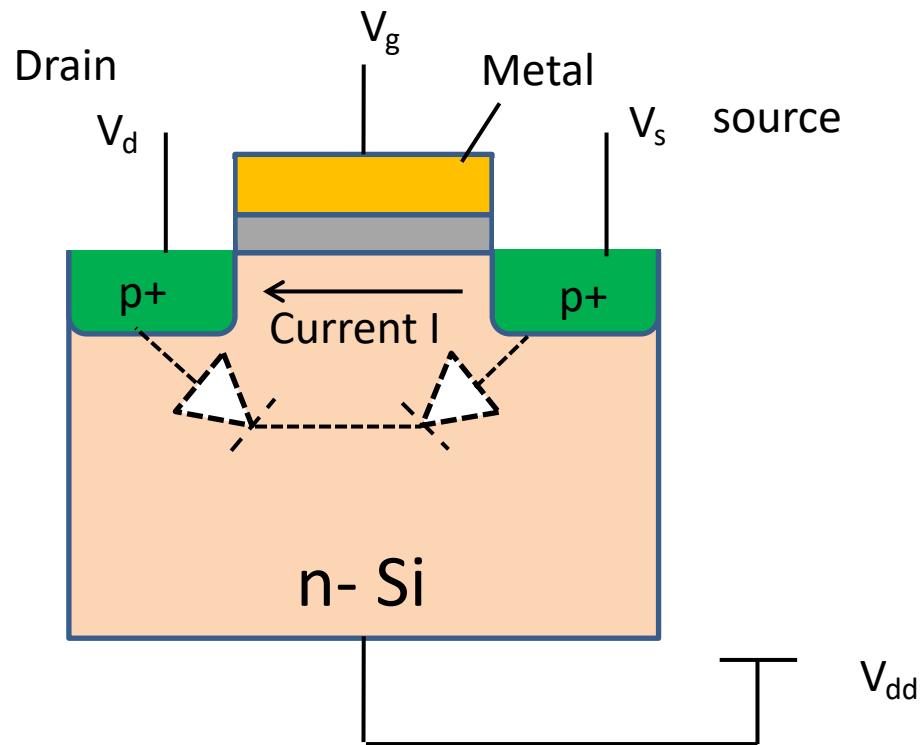


P-type MOSFET

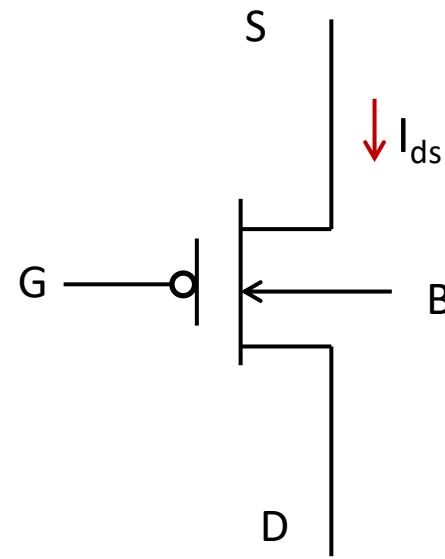


10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: P MOSFET

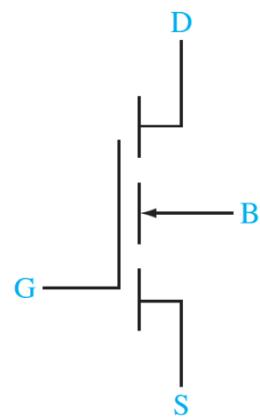
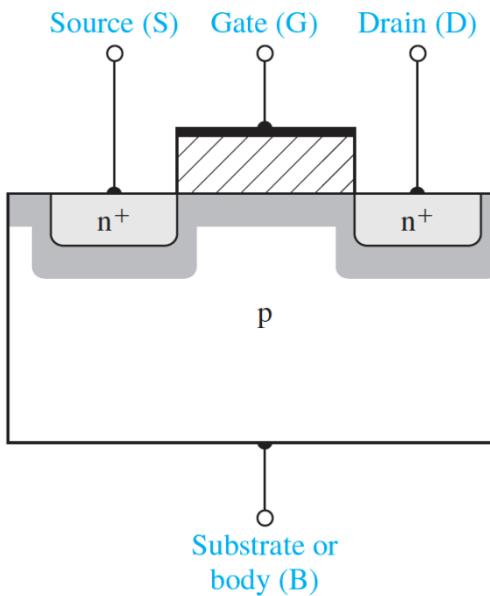


P-type MOSFET

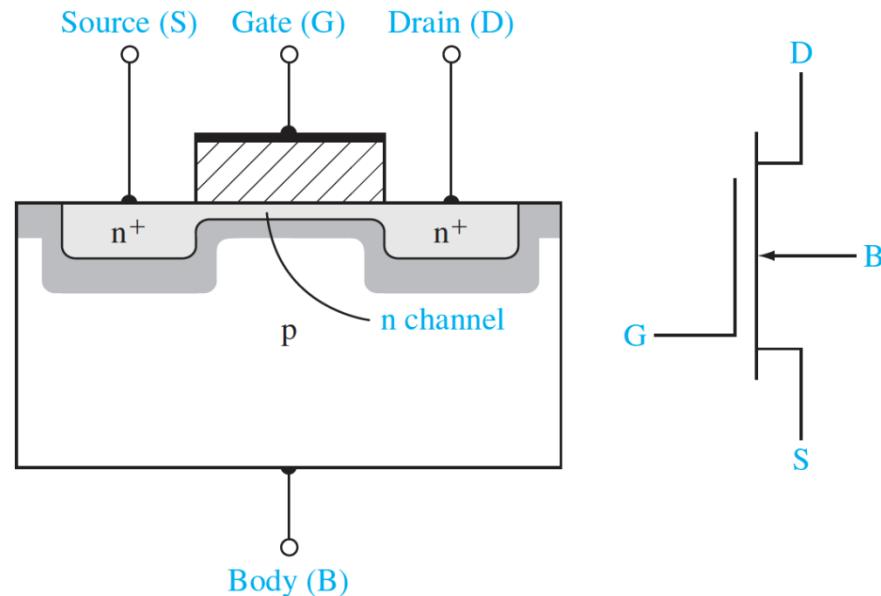


10.4 The basic MOSFET operation

MOSFET structures



NMOS Enhancement mode

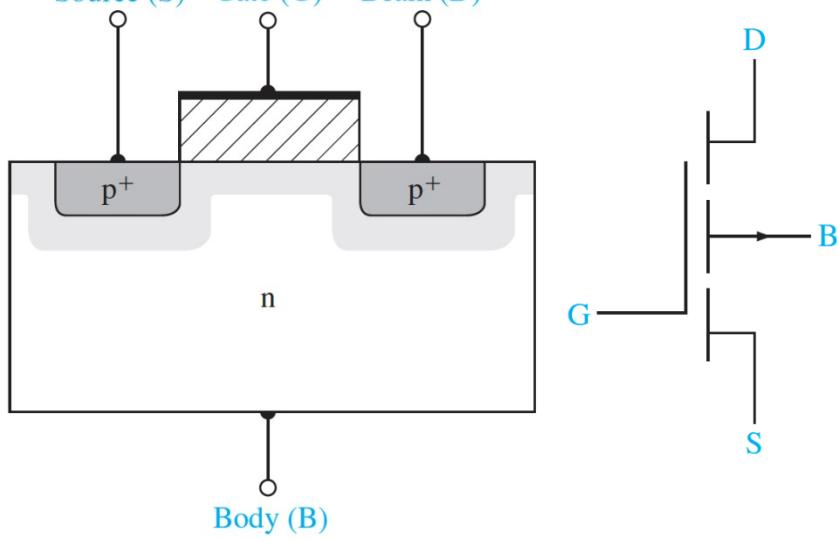


NMOS Depletion mode

10.4 The basic MOSFET operation

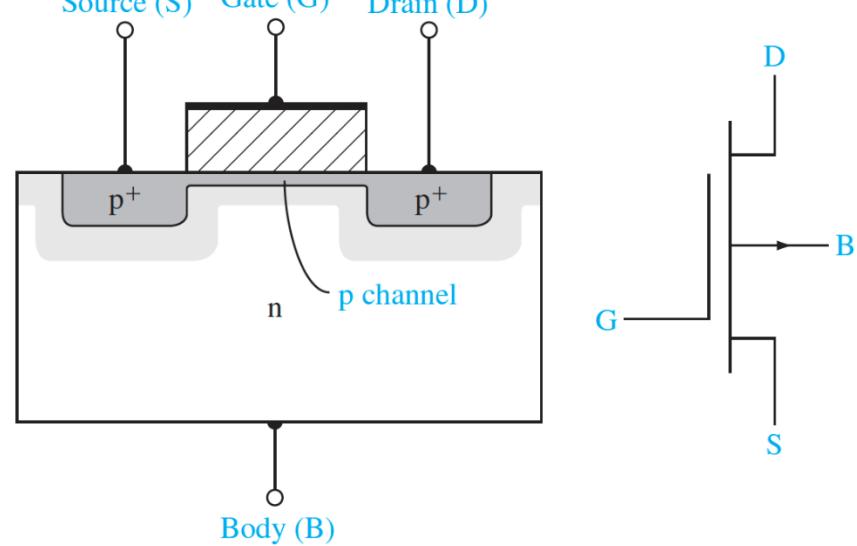
MOSFET structures

Source (S) Gate (G) Drain (D)



PMOS Enhancement mode

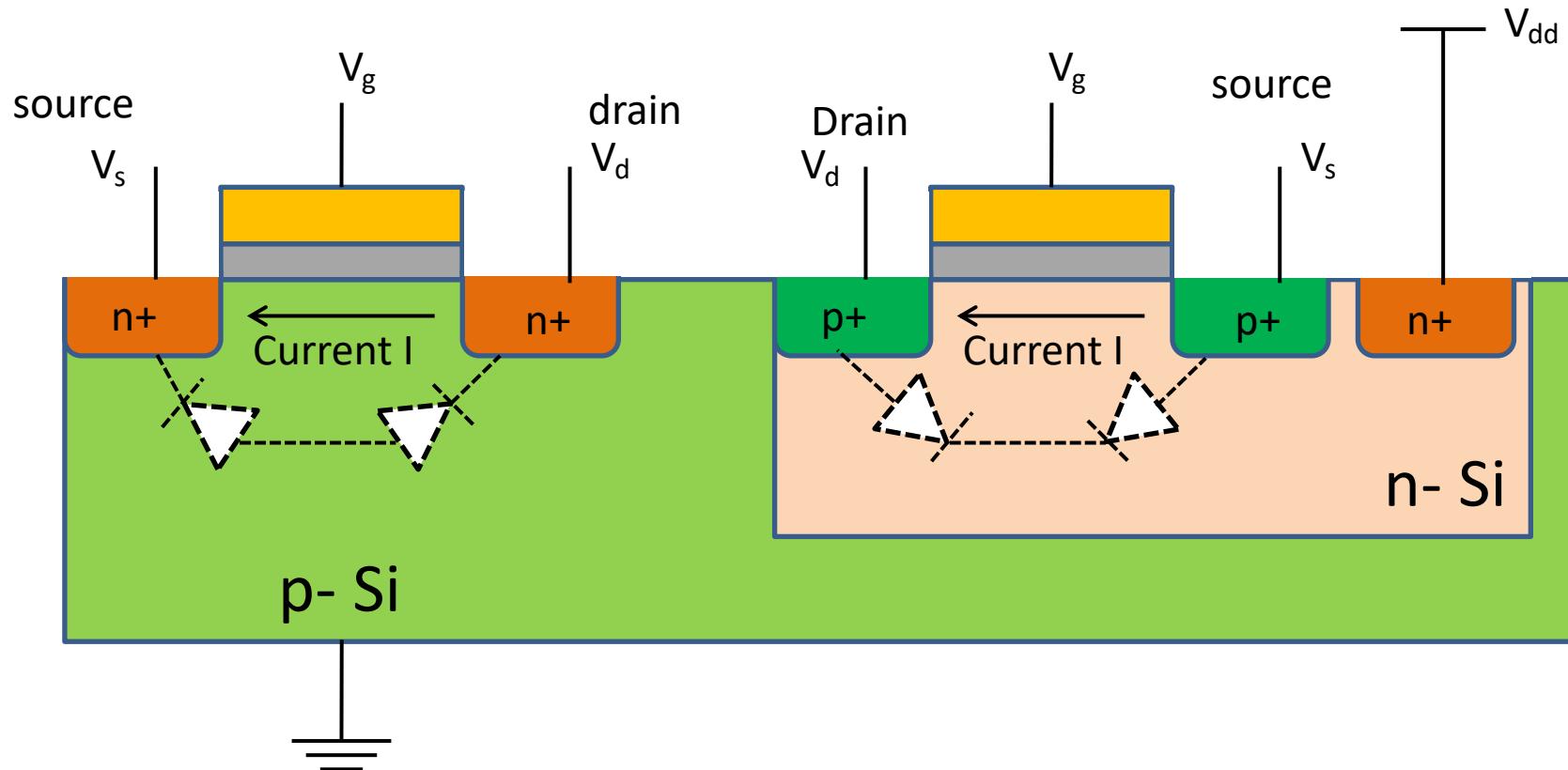
Source (S) Gate (G) Drain (D)



PMOS Depletion mode

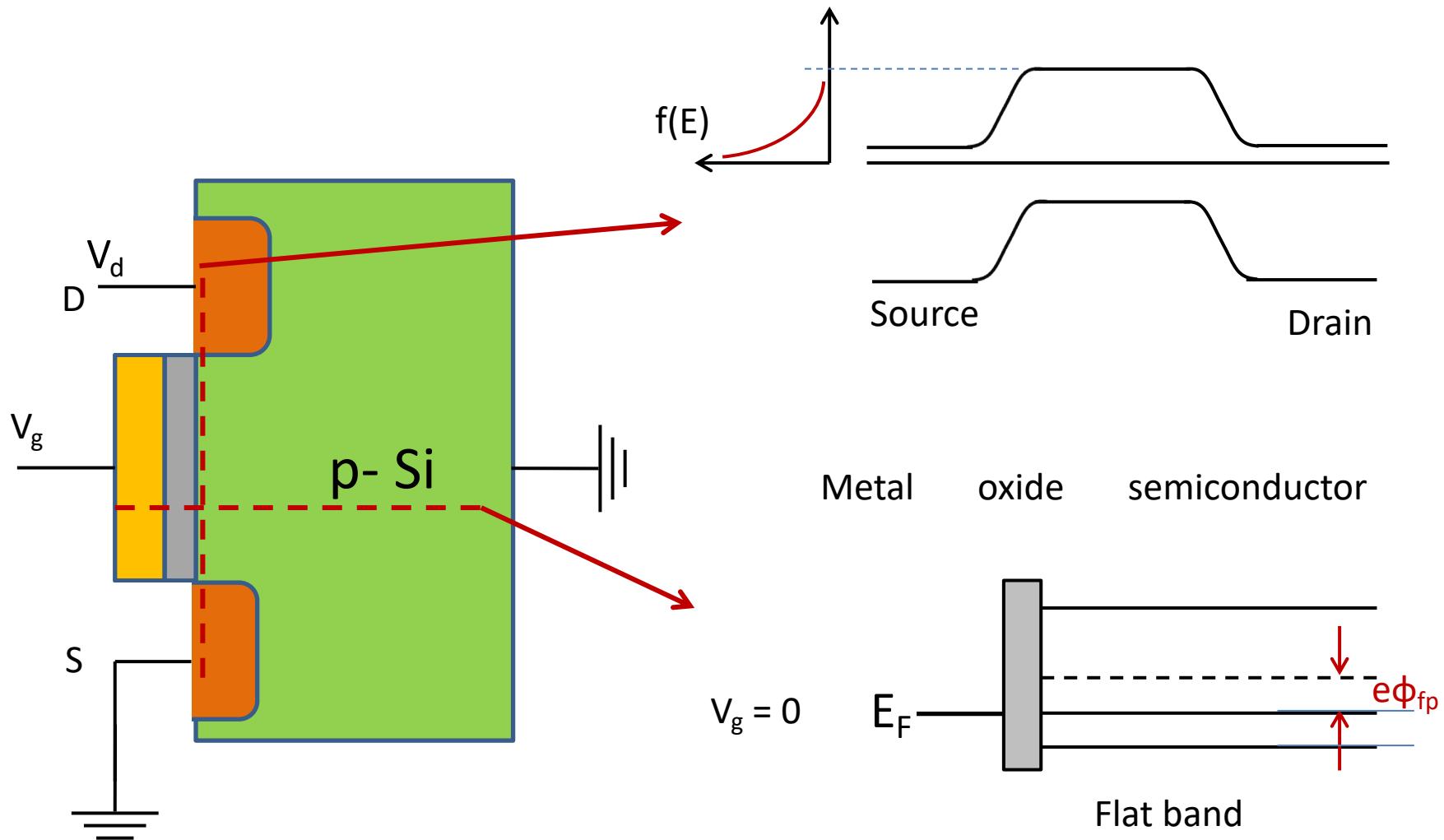
10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: CMOS

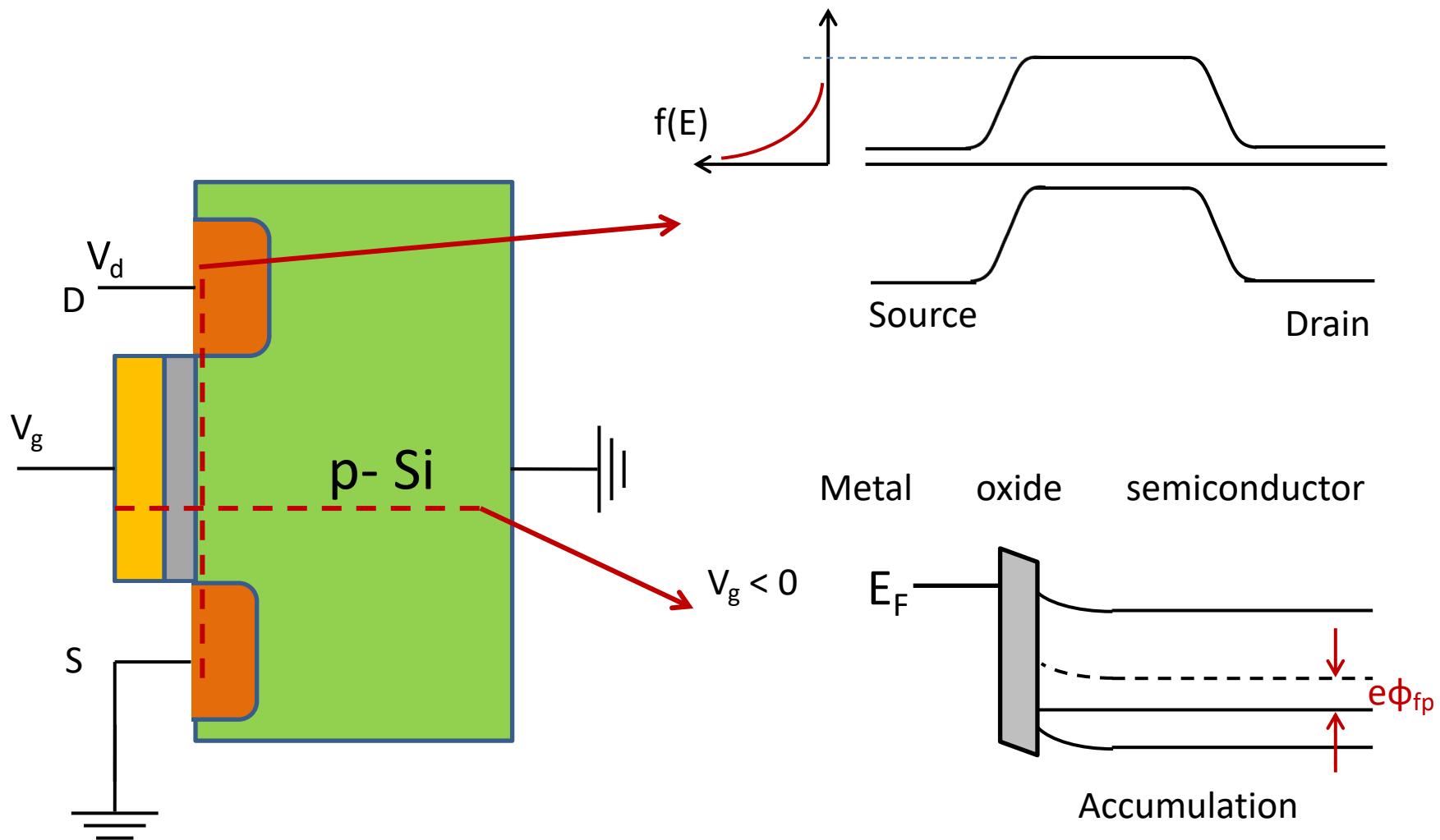


Complementary Metal-oxide-semiconductor (CMOS) field effect transistors

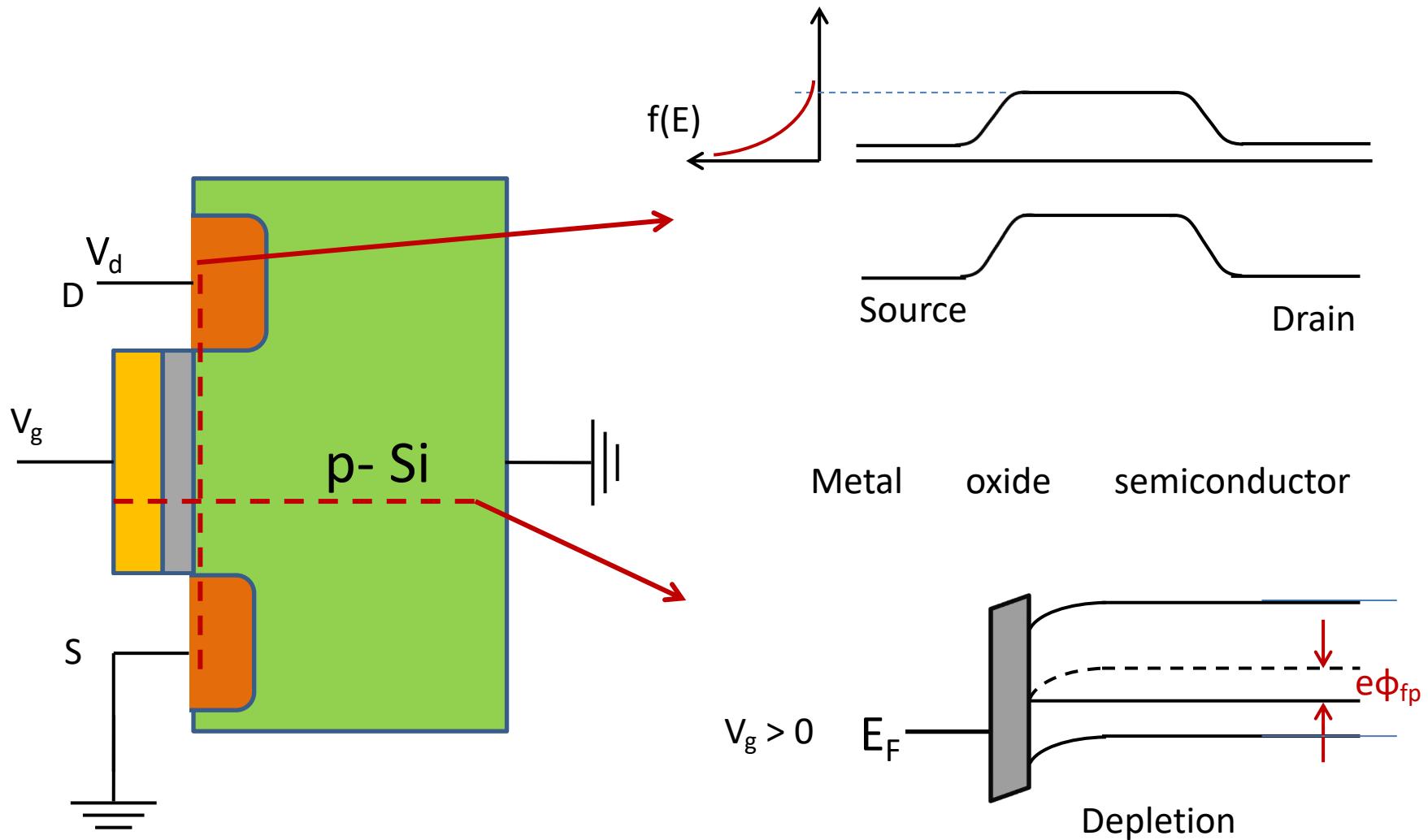
10.4 The basic MOSFET operation



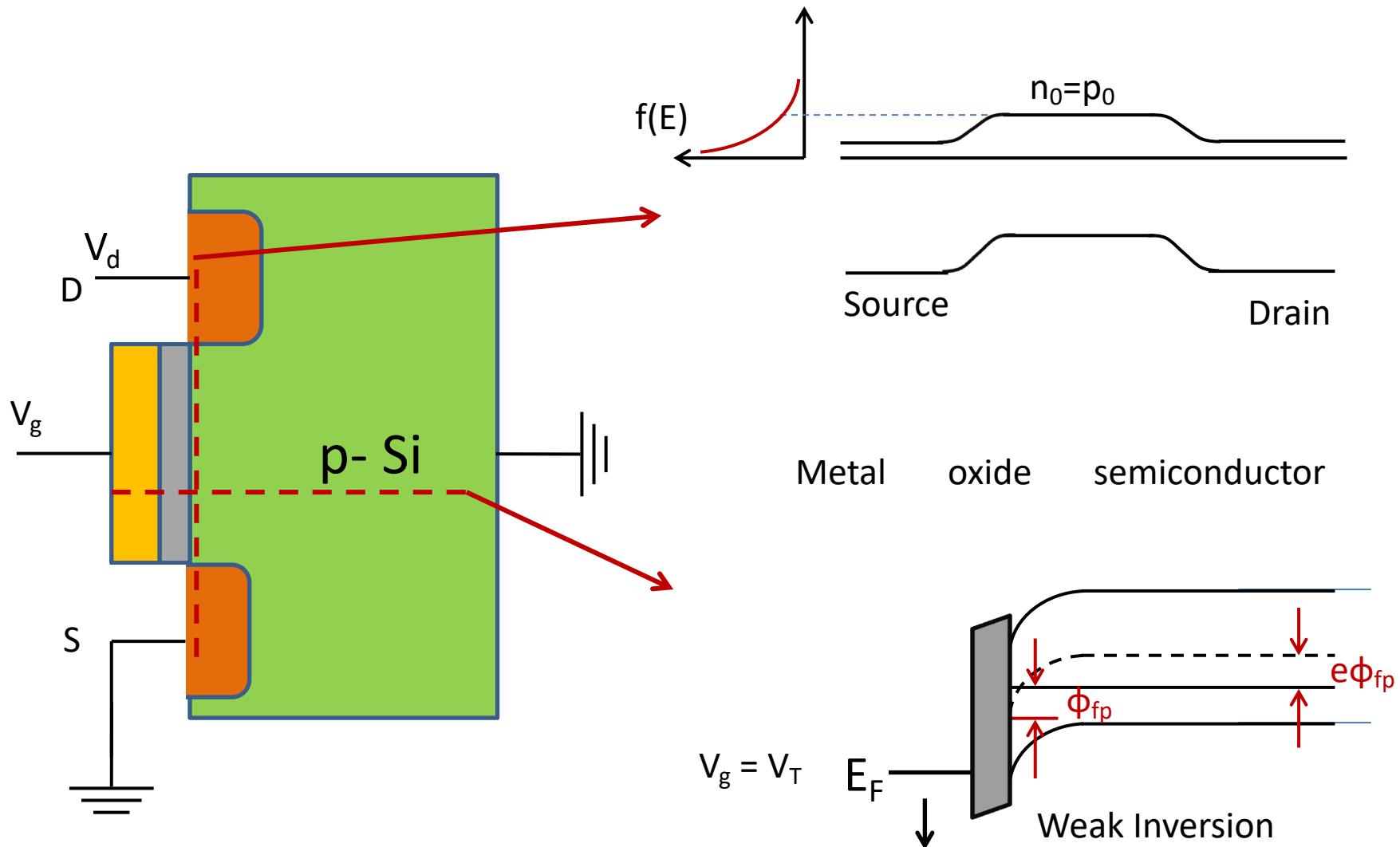
10.4 The basic MOSFET operation



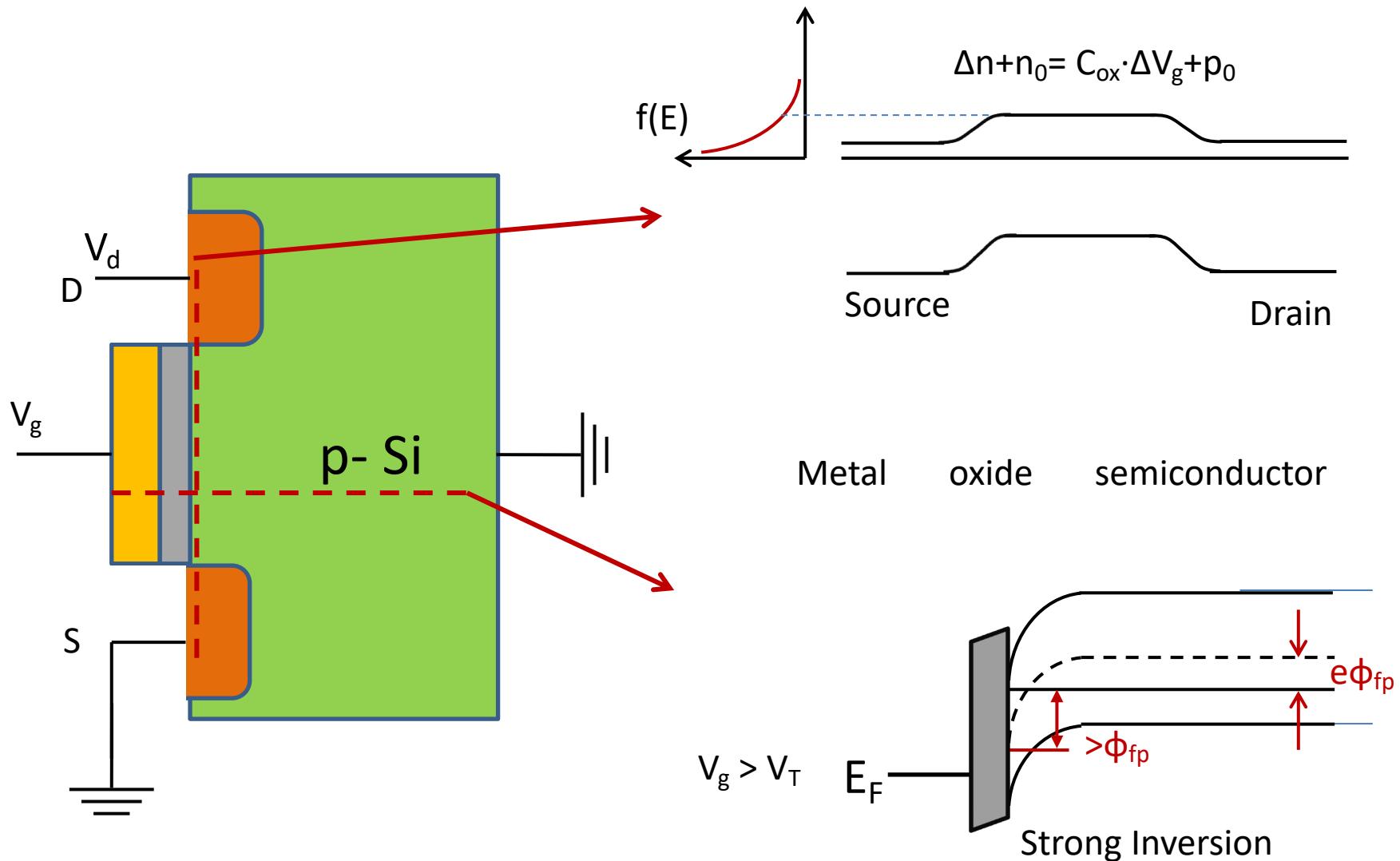
10.4 The basic MOSFET operation



10.4 The basic MOSFET operation



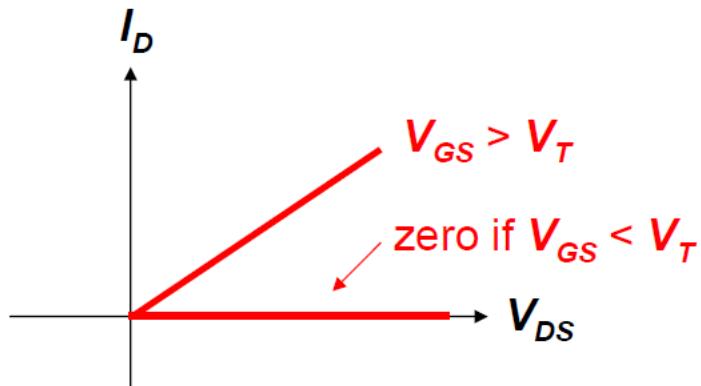
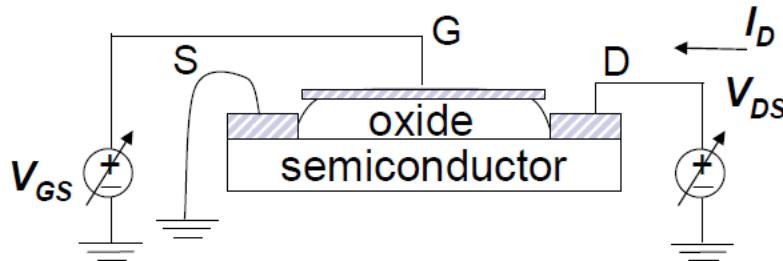
10.4 The basic MOSFET operation



10.4 The basic MOSFET operation

NMOSFET I_D vs. V_{DS} Characteristics

Next consider I_D (flowing into D) versus V_{DS} , as V_{GS} is varied:



Above threshold ($V_{GS} > V_T$):
“inversion layer” of electrons appears, so conduction between **S** and **D** is possible

Below “threshold” ($V_{GS} < V_T$):
no charge \rightarrow no conduction

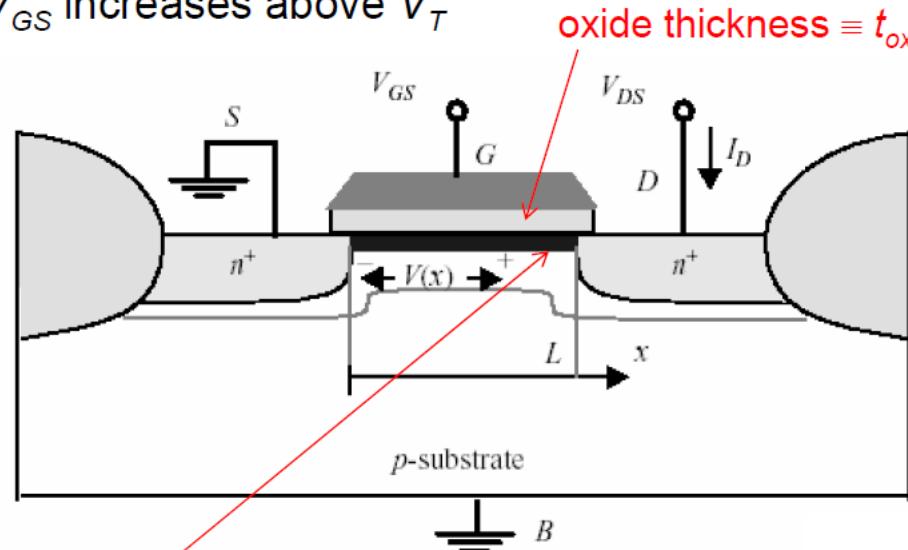
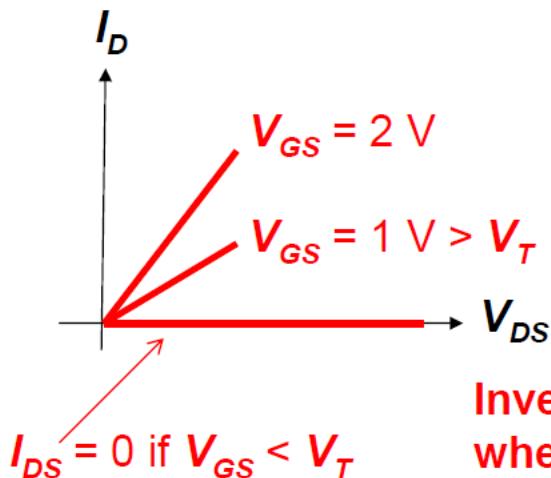
10.4 The basic MOSFET operation

Current-voltage characteristics

The MOSFET as a Controlled Resistor

- The MOSFET behaves as a resistor when V_{DS} is low:
 - Drain current I_D increases linearly with V_{DS}
 - Resistance R_{DS} between SOURCE & DRAIN depends on V_{GS}
 - R_{DS} is lowered as V_{GS} increases above V_T

NMOSFET Example:



$$\text{Inversion charge density } Q(x) = -C_{ox}[V_{GS} - V_T - V(x)]$$

where $C_{ox} \equiv \epsilon_{ox} / t_{ox}$

10.4 The basic MOSFET operation

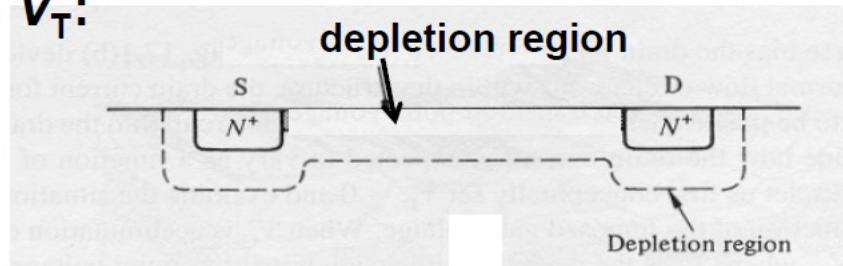
Derivation of I_{ds} vs V_{ds} and V_{gs}



10.4 The basic MOSFET operation

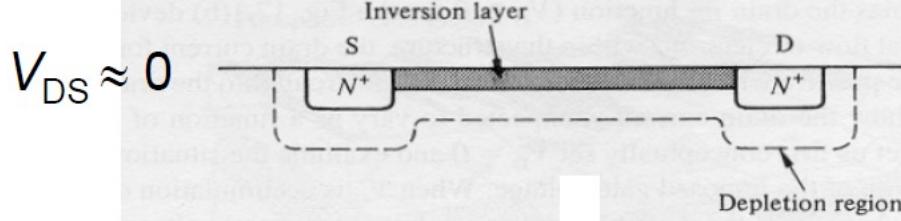
Charge in an N-Channel MOSFET

$V_{GS} < V_T$:

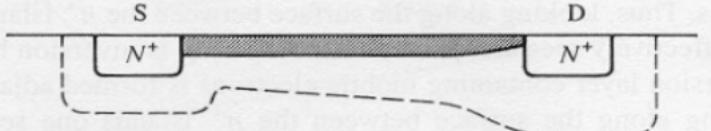


(no inversion layer at surface)

$V_{GS} > V_T$:



$V_{DS} \approx 0$
(small)



$$\begin{aligned}I_D &= WQ_{inv}v \\&= WQ_{inv}\mu_n E \\&= WQ_{inv}\mu_n \left(\frac{V_{DS}}{L} \right)\end{aligned}$$

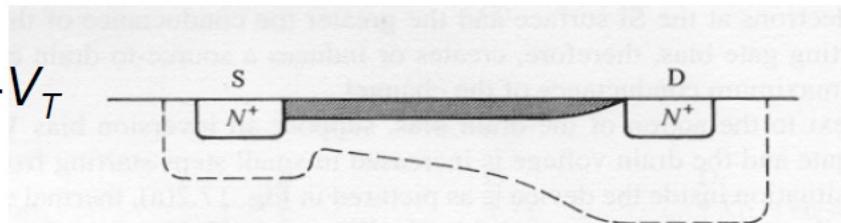
Average electron velocity v is proportional to lateral electric field E

10.4 The basic MOSFET operation

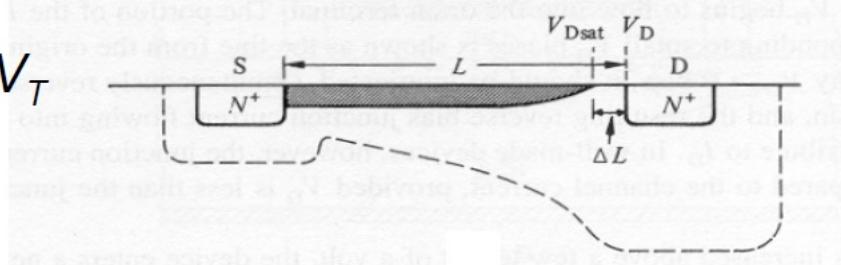
What Happens at Larger V_{DS} ?

$V_{GS} > V_T$:

$$V_{DS} = V_{GS} - V_T$$



$$V_{DS} > V_{GS} - V_T$$



Inversion-layer
is “pinched-off”
at the drain end

As V_{DS} increases above $V_{GS} - V_T \equiv V_{DSAT}$,

the length of the “pinch-off” region ΔL increases:

- “extra” voltage ($V_{DS} - V_{DSat}$) is dropped across the distance ΔL
 - the voltage dropped across the inversion-layer “resistor” remains V_{DSat}
- ⇒ the drain current I_D saturates

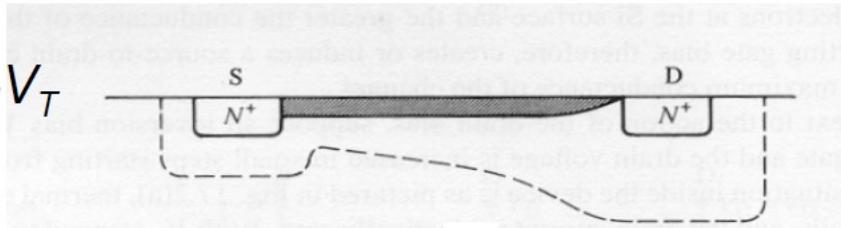
Note: Electrons are swept into the drain by the E -field when they enter the pinch-off region.

10.4 The basic MOSFET operation

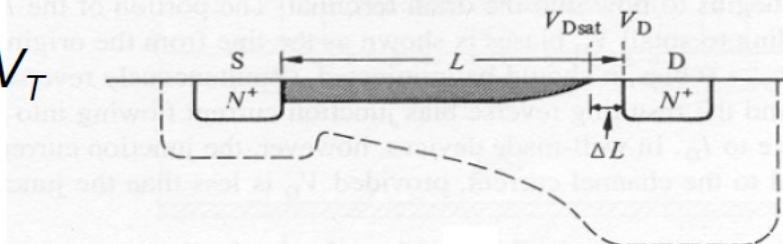
What Happens at Larger V_{DS} ?

$V_{GS} > V_T$:

$$V_{DS} = V_{GS} - V_T$$



$$V_{DS} > V_{GS} - V_T$$

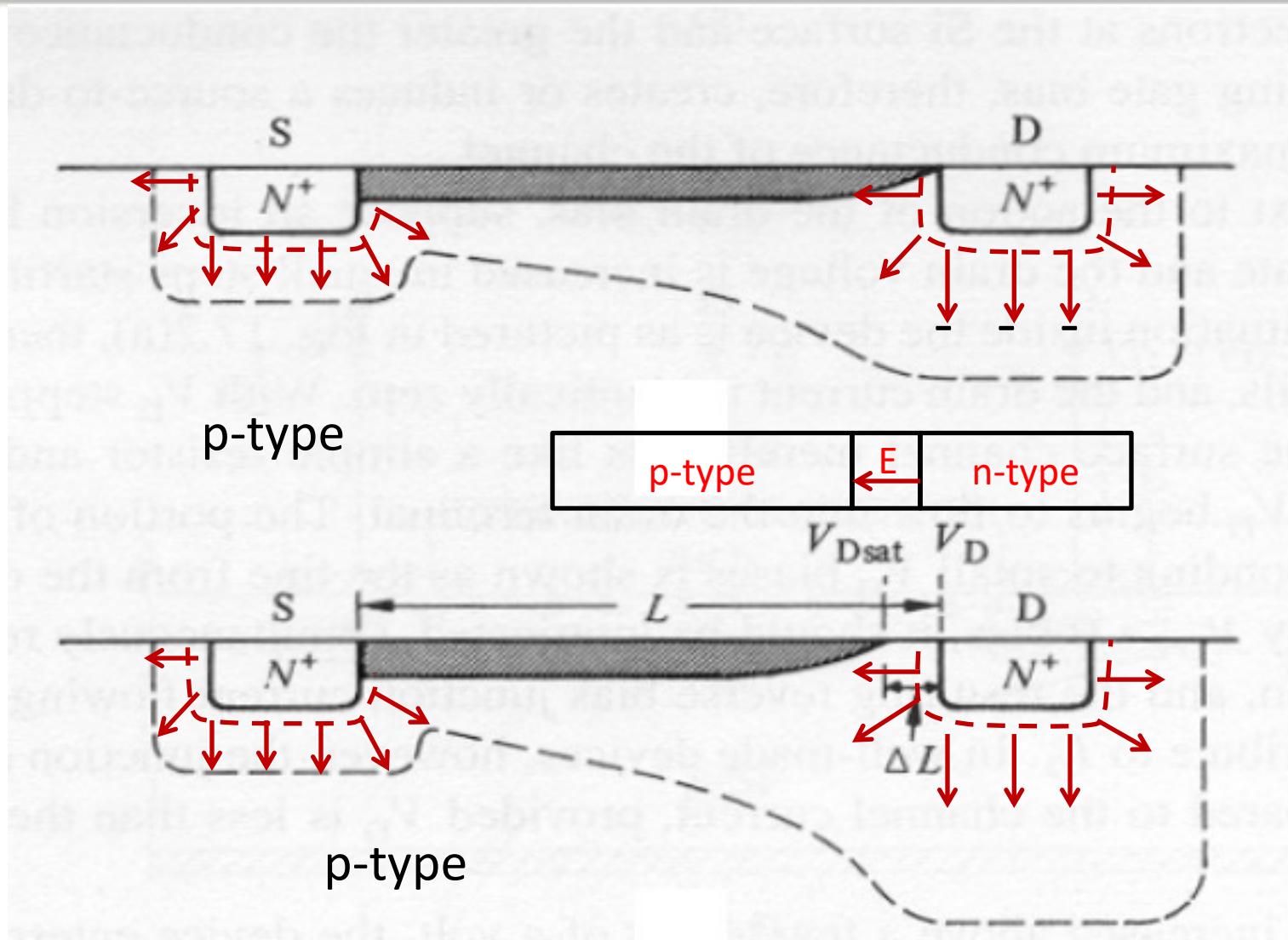


As V_{DS} increases above $V_{GS} - V_T \equiv V_{DSAT}$,

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

I_D will not increase after
 $V_{DS} \geq V_{GS} - V_T$

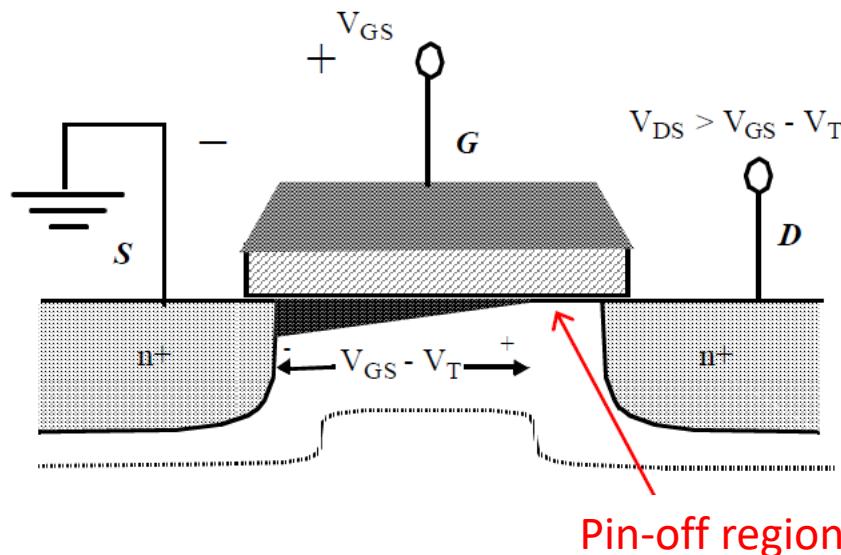
10.4 The basic MOSFET operation



10.4 The basic MOSFET operation

Summary of I_D vs. V_{DS}

- As V_{DS} increases, the inversion-layer charge density at the drain end of the channel is reduced; therefore, I_D does not increase linearly with V_{DS} .
- When V_{DS} reaches $V_{GS} - V_T$, the channel is “pinched off” at the drain end, and I_D saturates (i.e. it does not increase with further increases in V_{DS}).



$$I_{DSAT} = \mu_n C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2$$

10.4 The basic MOSFET operation

I_D vs. V_{DS} Characteristics

The MOSFET I_D - V_{DS} curve consists of two regions:

1) Resistive or “Triode” Region: $0 < V_{DS} < V_{GS} - V_T$

$$I_D = k'_n \frac{W}{L} \left[V_{GS} - V_T - \frac{V_{DS}}{2} \right] V_{DS}$$

where $k'_n = \mu_n C_{ox}$

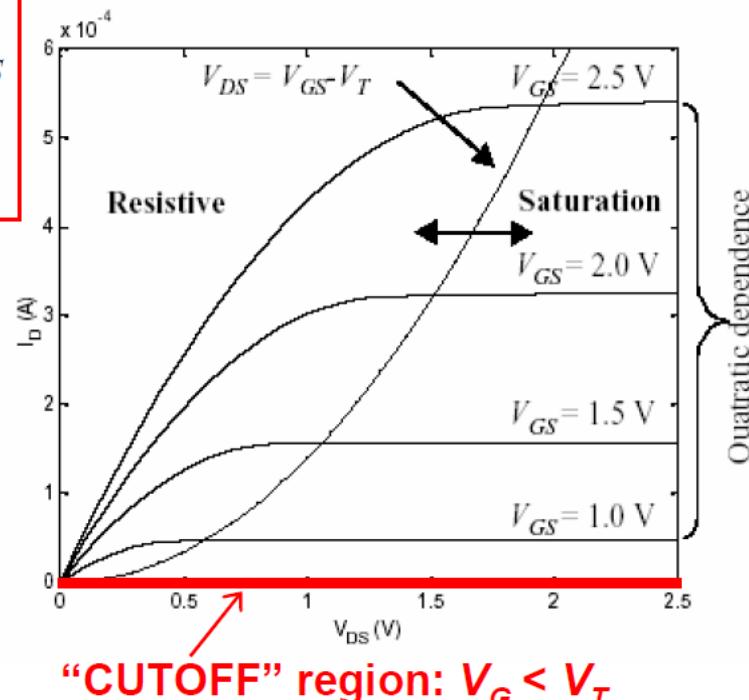
process transconductance parameter

2) Saturation Region:

$$V_{DS} > V_{GS} - V_T$$

$$I_{DSAT} = \frac{k'_n}{2} \frac{W}{L} (V_{GS} - V_T)^2$$

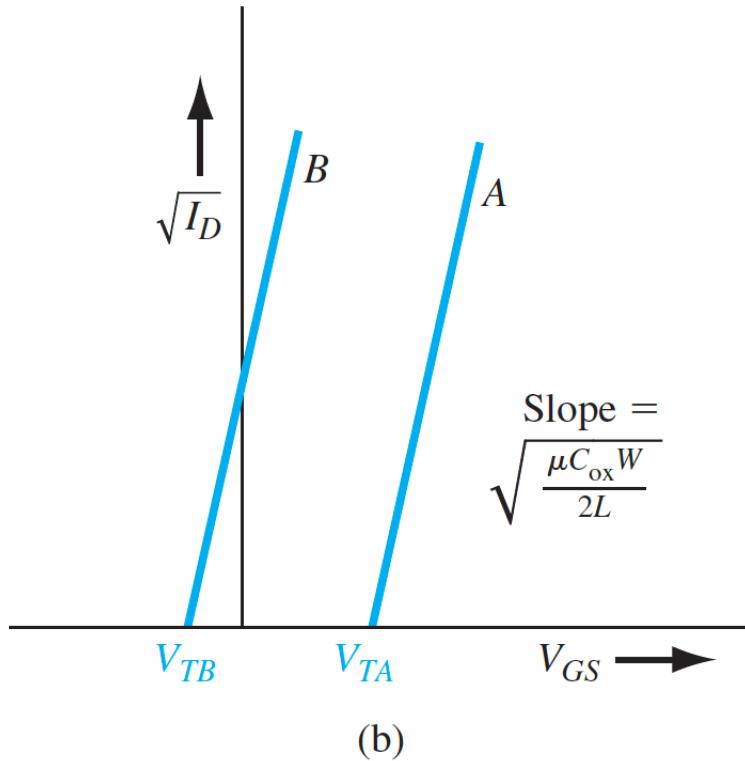
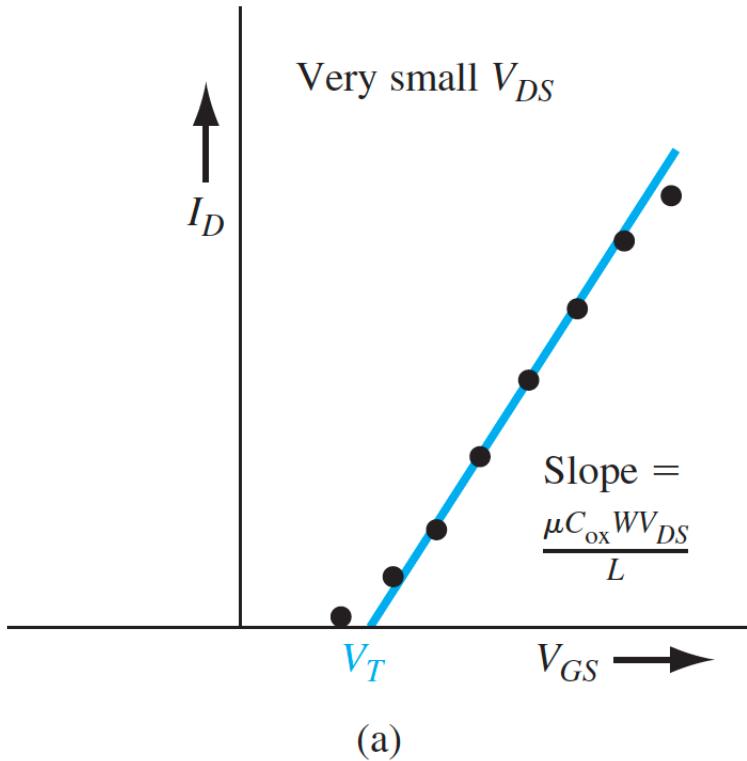
where $k'_n = \mu_n C_{ox}$



10.4 The basic MOSFET operation

$$I_D = \frac{W\mu_n C_{\text{ox}}}{L} (V_{GS} - V_T)V_{DS}$$

$$\sqrt{I_D(\text{sat})} = \sqrt{\frac{W\mu_n C_{\text{ox}}}{2L}}(V_{GS} - V_T)$$



Check your understanding

Problem example 5

Objective: Design the width of a MOSFET such that a specified current is induced for a given applied bias.

Consider an ideal n-channel MOSFET with parameters $L = 1.25 \mu\text{m}$, $\mu_n = 650 \text{ cm}^2/\text{V}\cdot\text{s}$, $C_{\text{ox}} = 6.9 \times 10^{-8} \text{ F/cm}^2$, and $V_T = 0.65 \text{ V}$. Design the channel width W such that $I_D(\text{sat}) = 4 \text{ mA}$ for $V_{GS} = 5 \text{ V}$.



Check your understanding

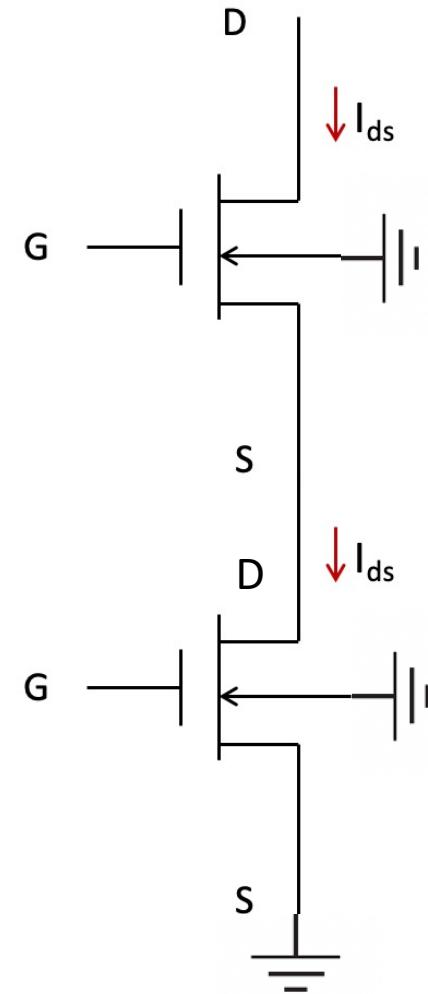
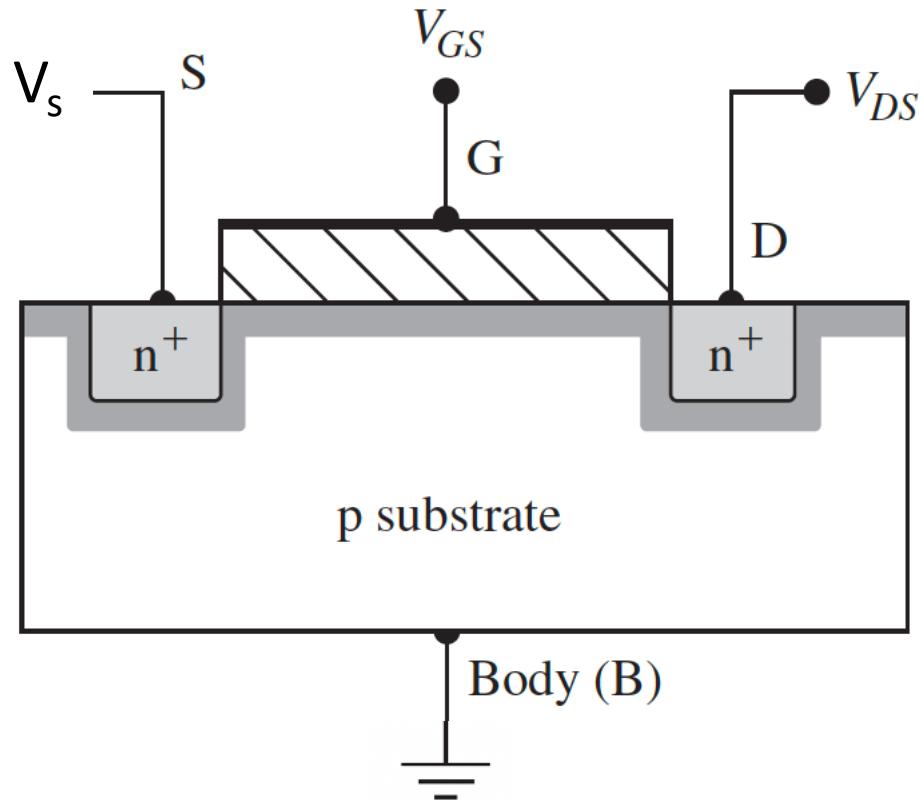
Problem example 5



VE320 Yaping Dan

10.4 The basic MOSFET operation

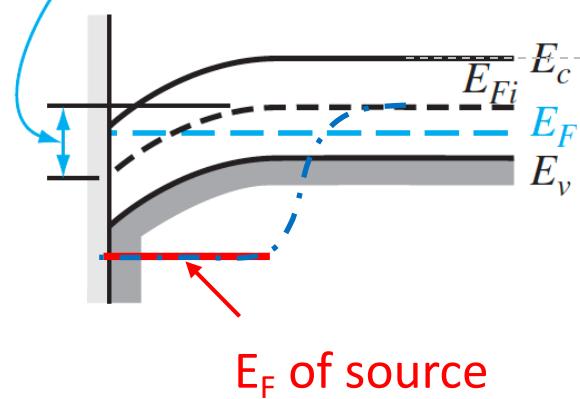
Substrate bias effect



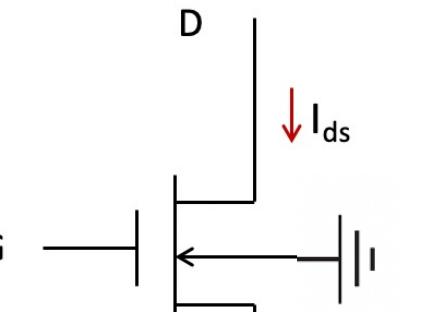
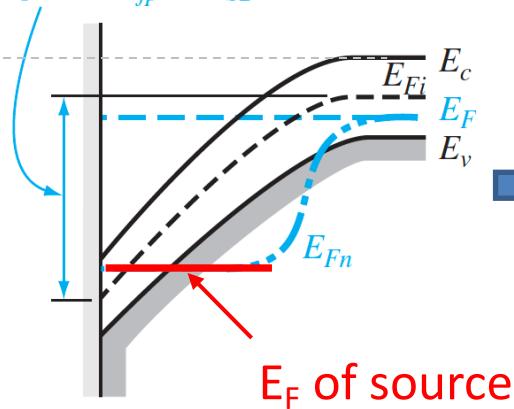
10.4 The basic MOSFET operation

Substrate bias effect

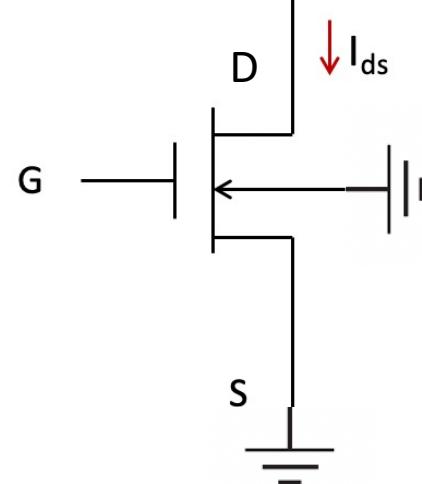
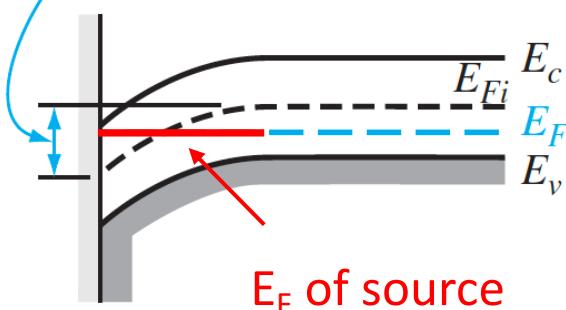
$$e\phi_s = 2e\phi_{fp}$$



$$e\phi_s = e(2\phi_{fp} + V_{SB})$$



$$e\phi_s = 2e\phi_{fp}$$



10.4 The basic MOSFET operation

Substrate bias effect

When $V_{SB} = 0$, we had

When $V_{SB} > 0$, the space charge width increases and we now have

The change in the space charge density is then



10.4 The basic MOSFET operation

Substrate bias effect

$$\Delta V_T = -\frac{\Delta Q'_{SD}}{C_{ox}} = \frac{\sqrt{2e\epsilon_s N_a}}{C_{ox}} [\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}]$$

$$\gamma = \frac{\sqrt{2e\epsilon_s N_a}}{C_{ox}}$$

$$\Delta V_T = \gamma [\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}]$$



Check your understanding

Problem example 6

Objective: Calculate the body-effect coefficient and the change in the threshold voltage due to an applied source-to-body voltage.

Consider an n-channel silicon MOSFET at $T = 300$ K. Assume the substrate is doped to $N_a = 3 \times 10^{16} \text{ cm}^{-3}$ and assume the oxide is silicon dioxide with a thickness of $t_{ox} = 20 \text{ nm} = 200 \text{ \AA}$. Let $V_{SB} = 1 \text{ V}$.



Check your understanding

Problem example 7

