VE320 – Summer 2024

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

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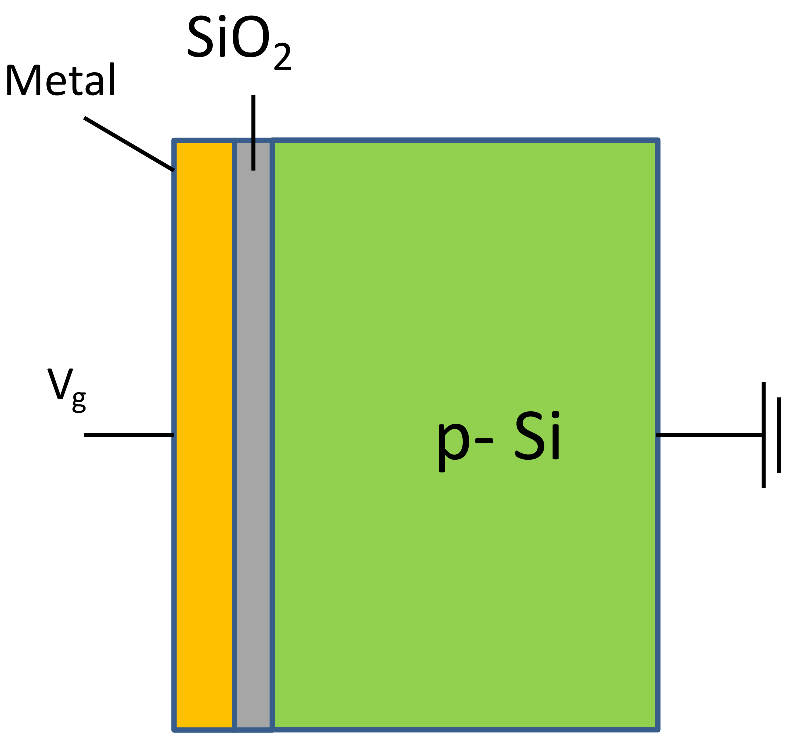
10.2 Capacitance-voltage characteristics

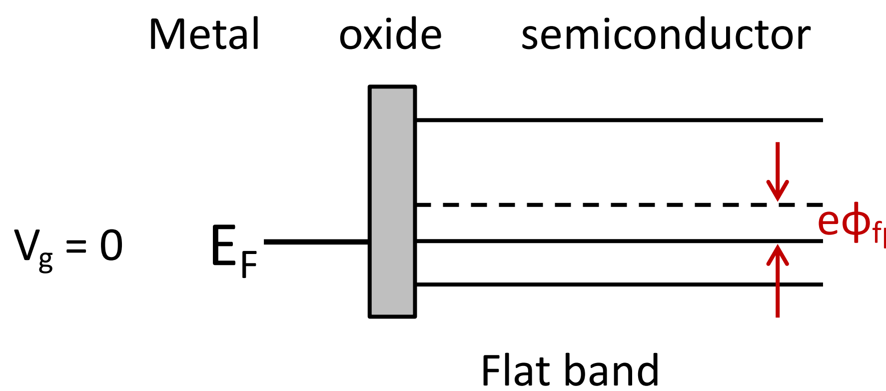
10.3 Non-ideal effects

10.4 The basic MOSFET operation

10.1 The two-terminal MOS structure



Metal-insulator-semiconductor (MIS)



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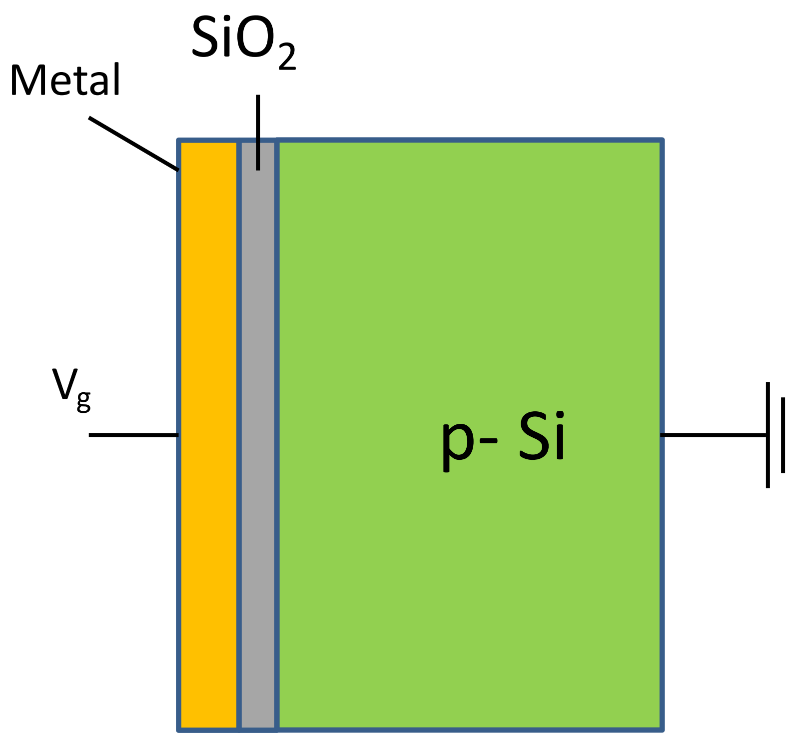

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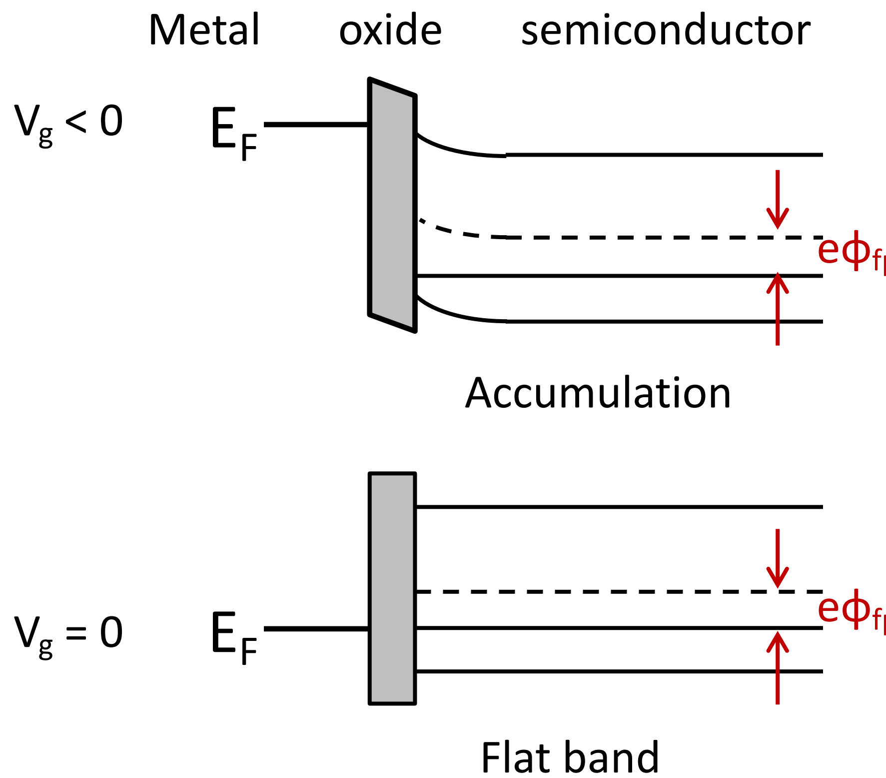

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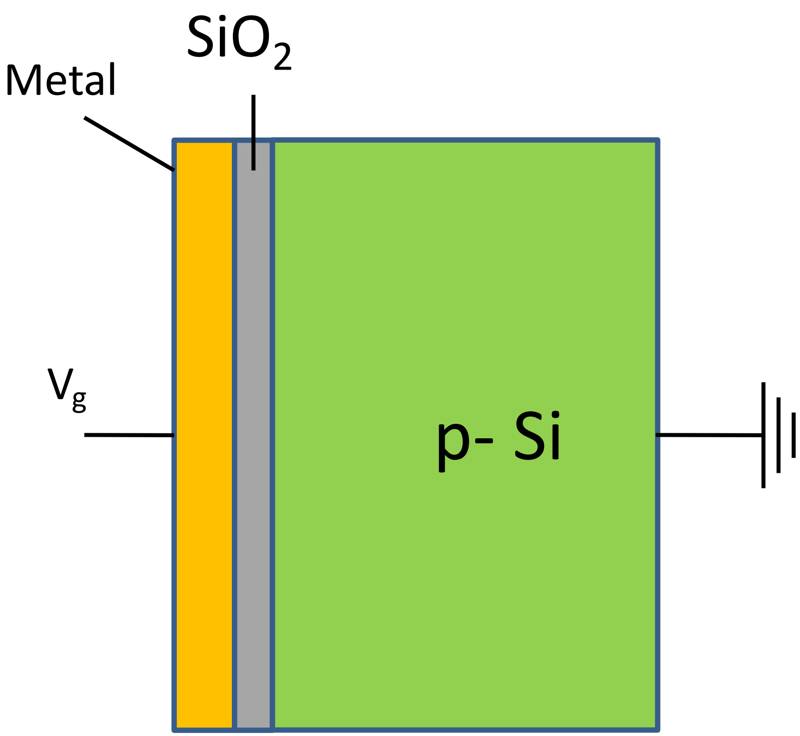

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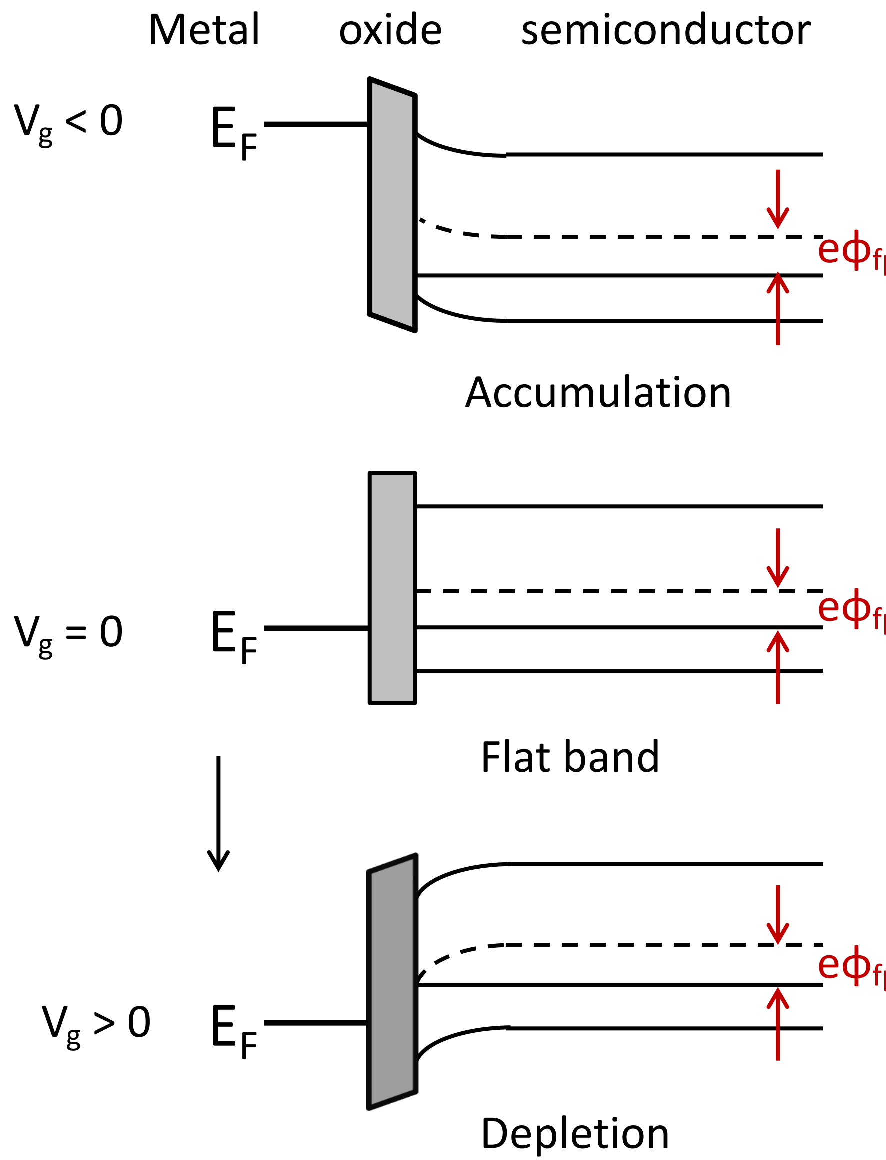

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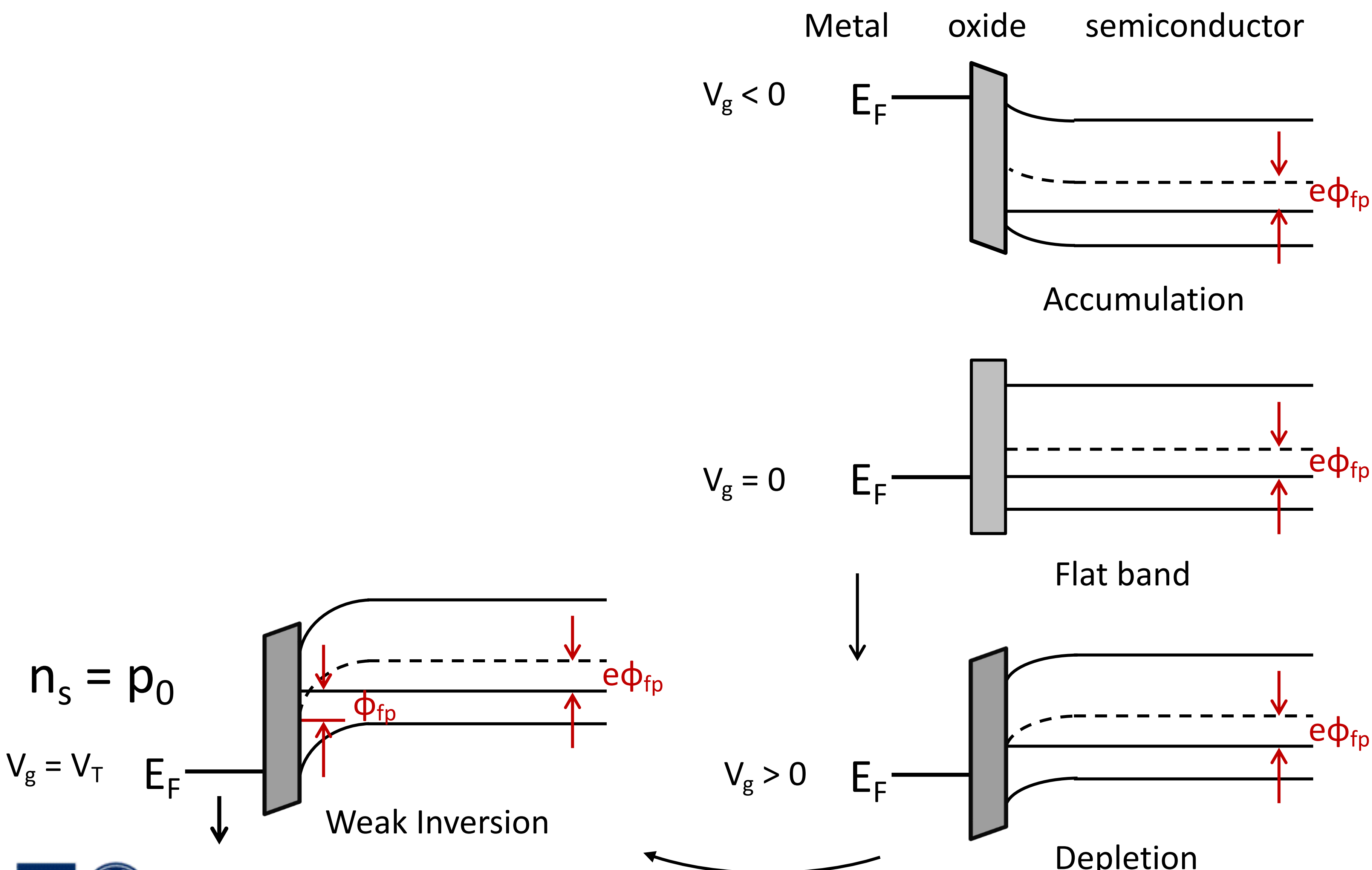

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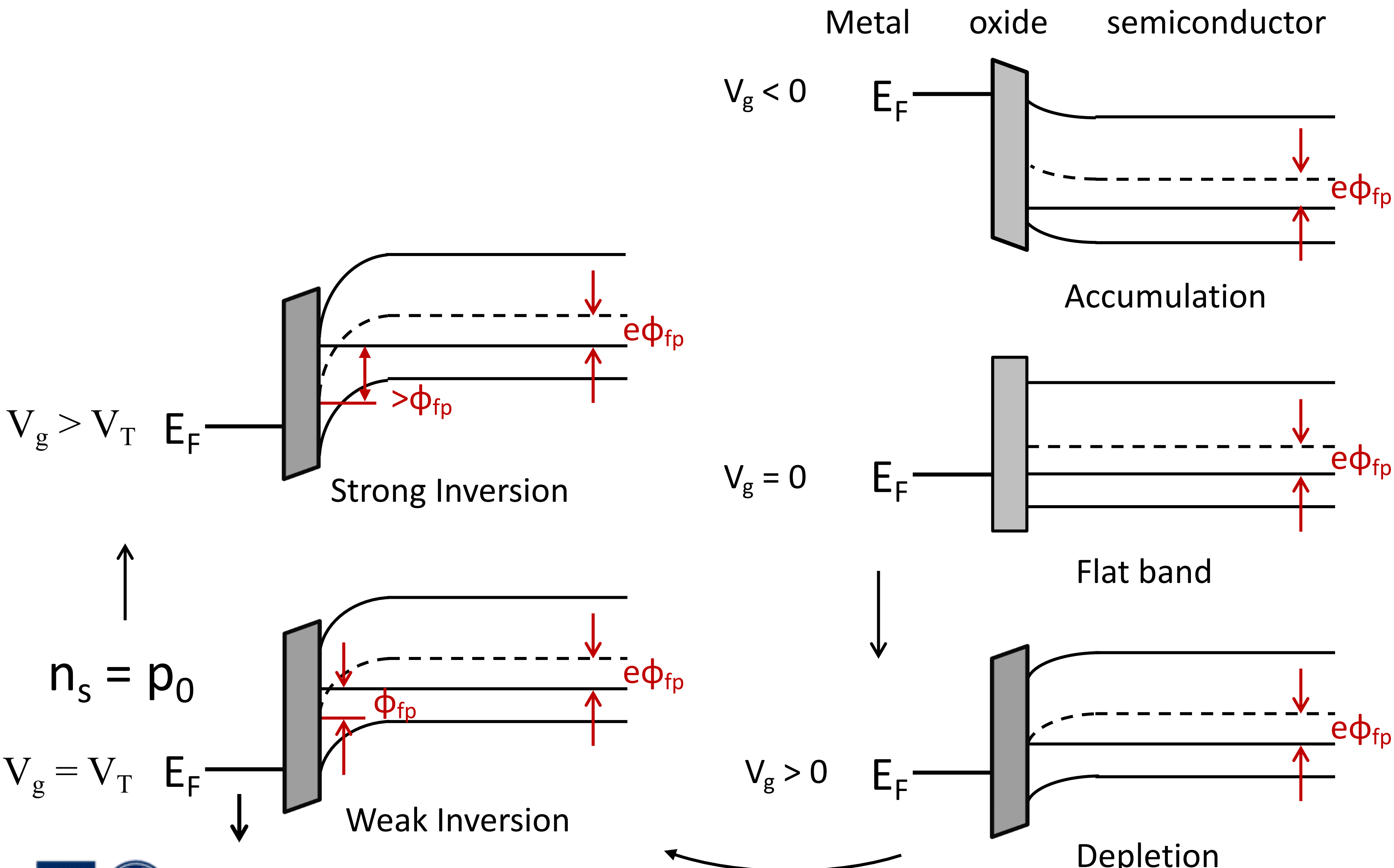
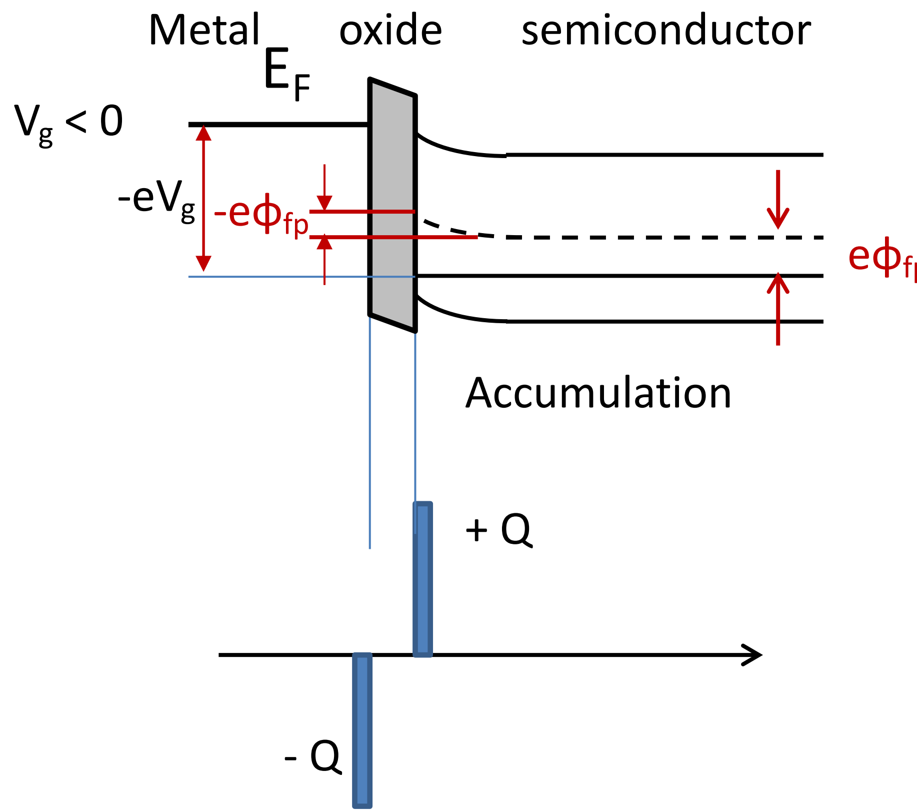


10.1 The two-terminal MOS structure

Charge distribution



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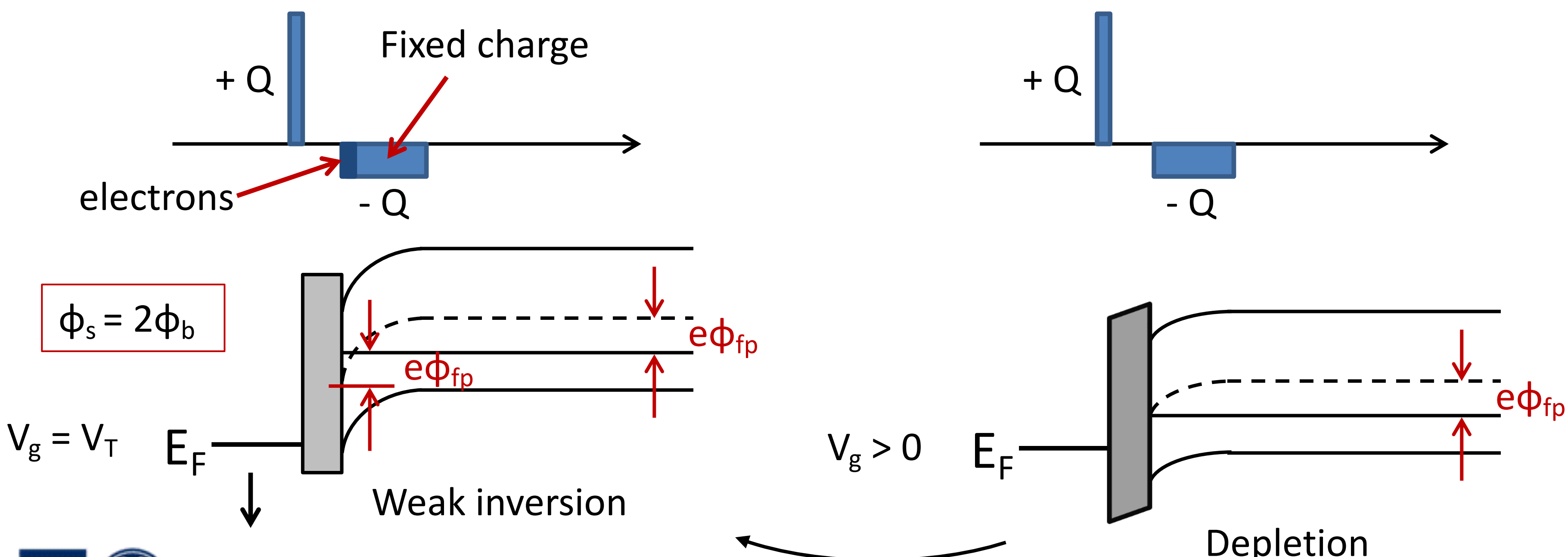

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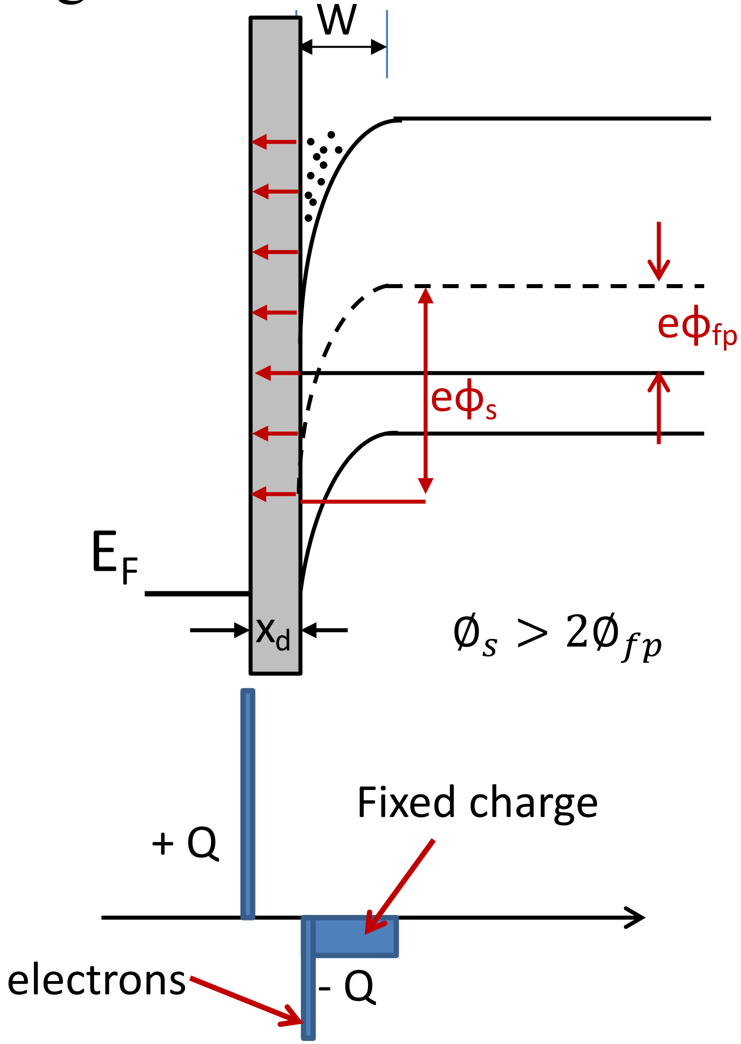
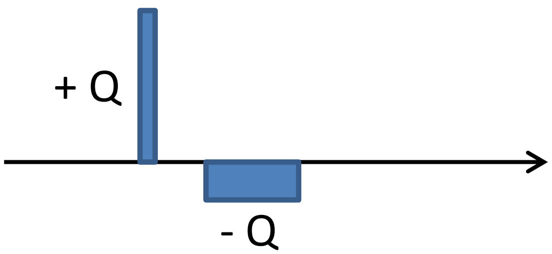
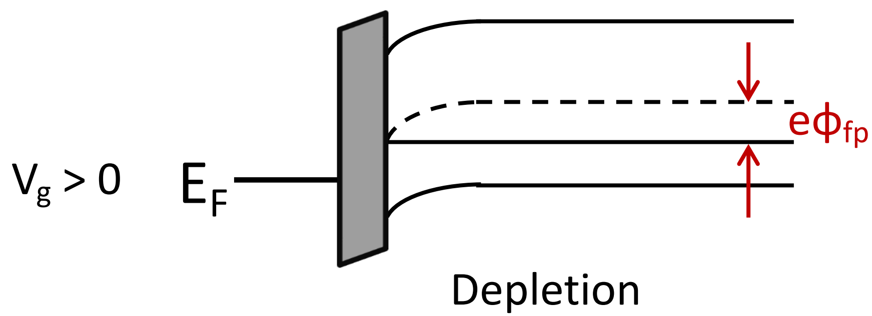


10.1 The two-terminal MOS structure

Depletion layer thickness



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



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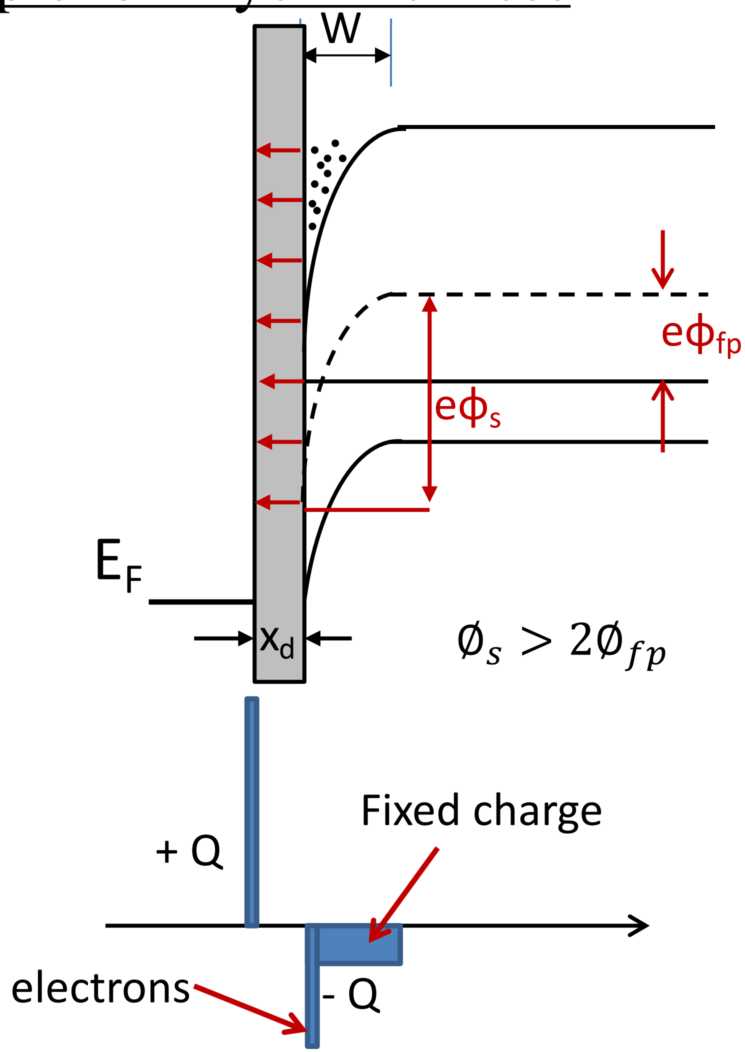
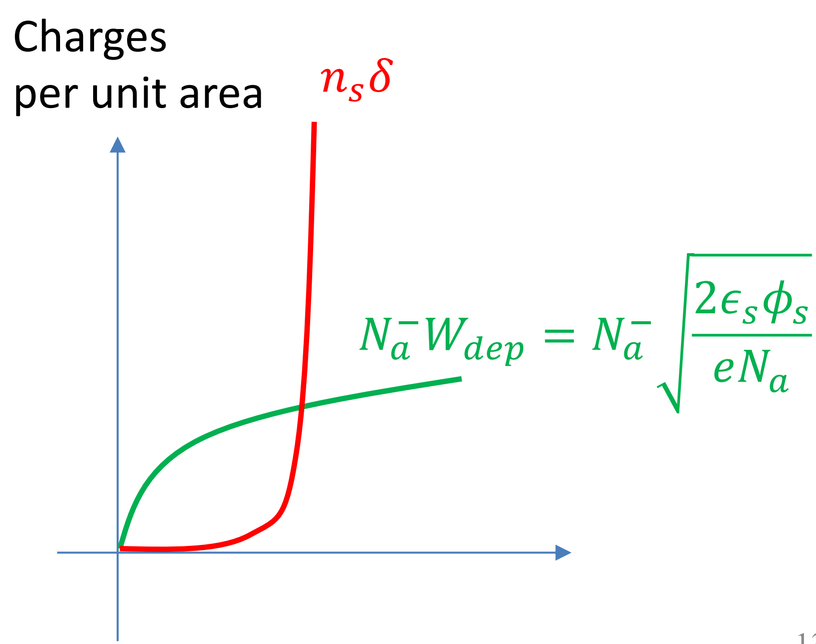


Maximum depletion layer

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



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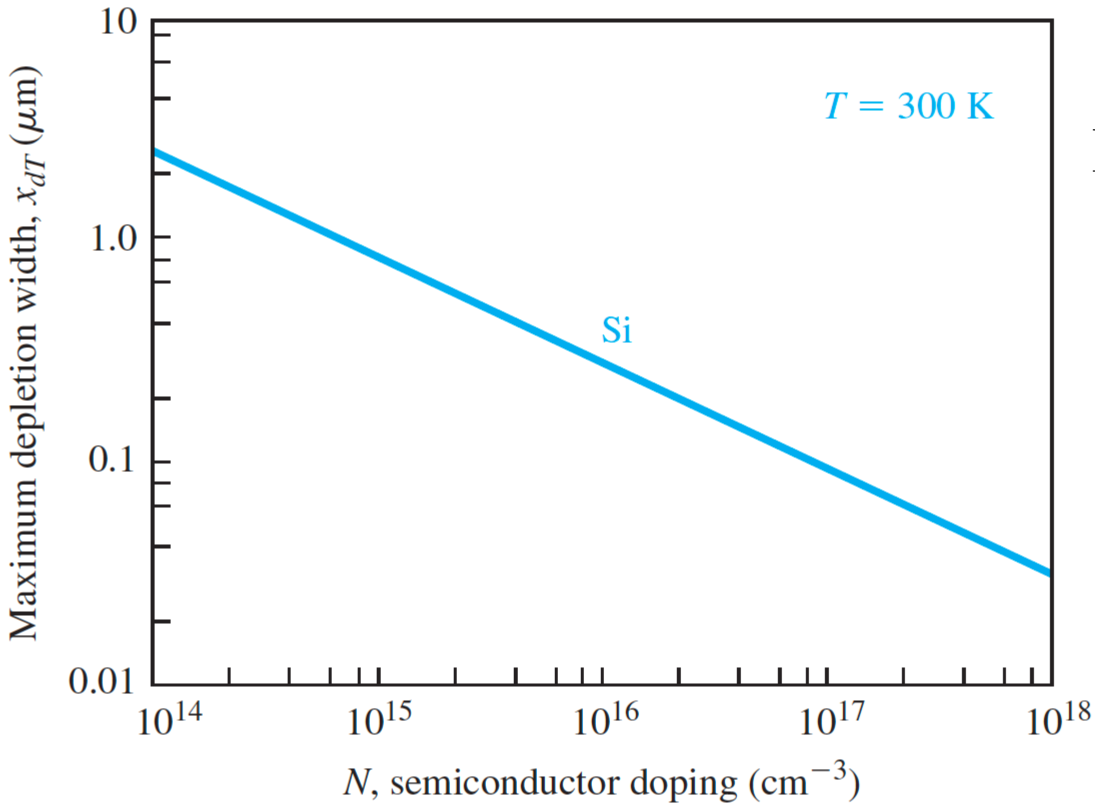

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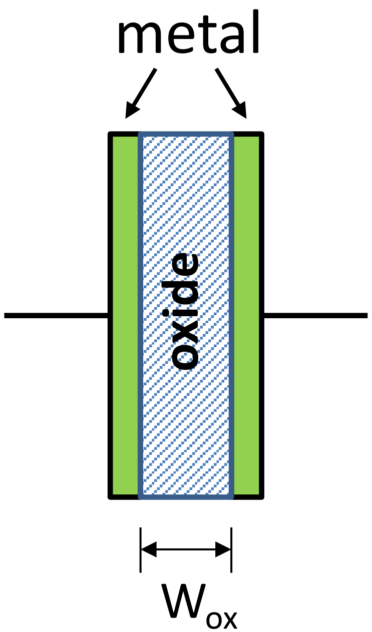
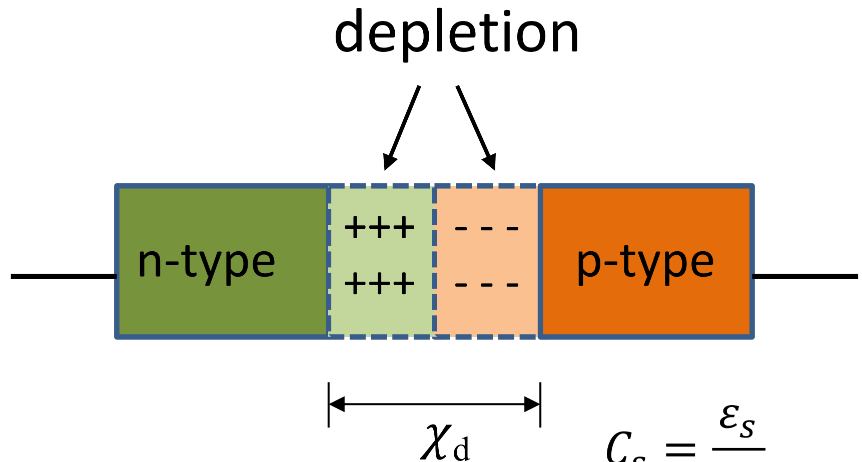
10.2 The capacitance-voltage characteristics



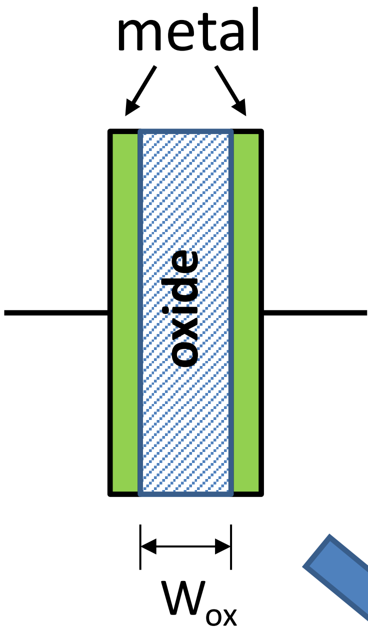
$$C_m = \frac{\varepsilon_{ox}}{W_{ox}}$$



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

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

10.2 The capacitance-voltage characteristics



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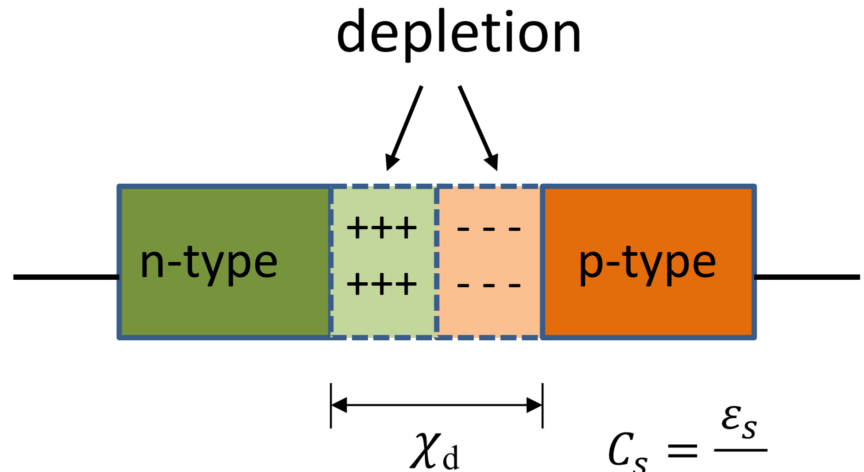

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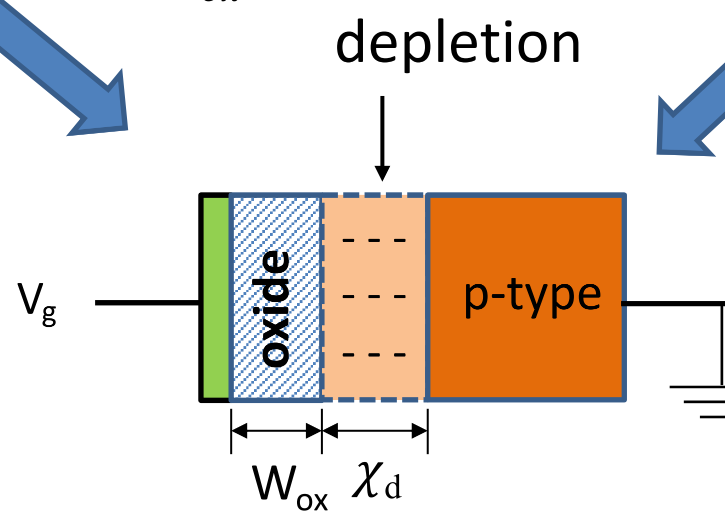
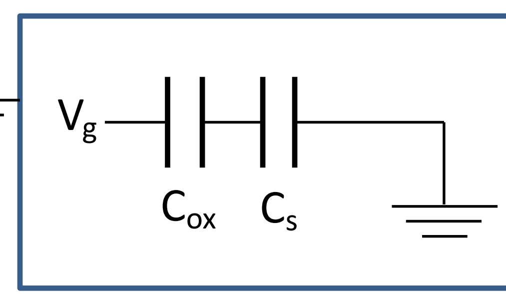


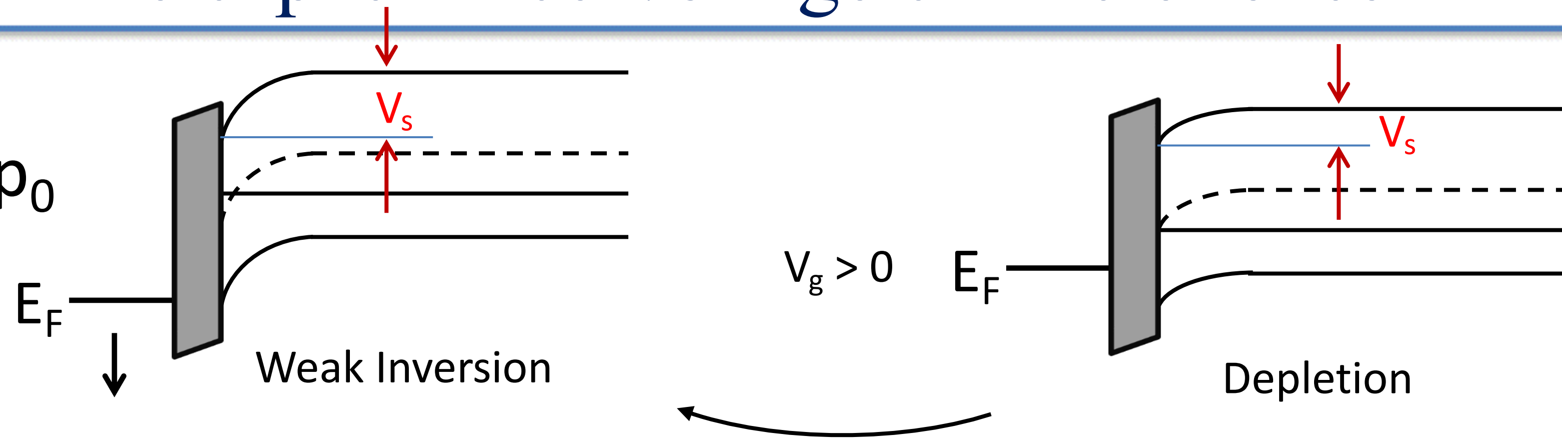
$$\boxed{\chi_d = \sqrt{\frac{2\varepsilon_s (V_{bi} + V)}{qN_A}}}$$



10.2 The capacitance-voltage characteristics

$n_s = p_0$

$V_g = V_T$



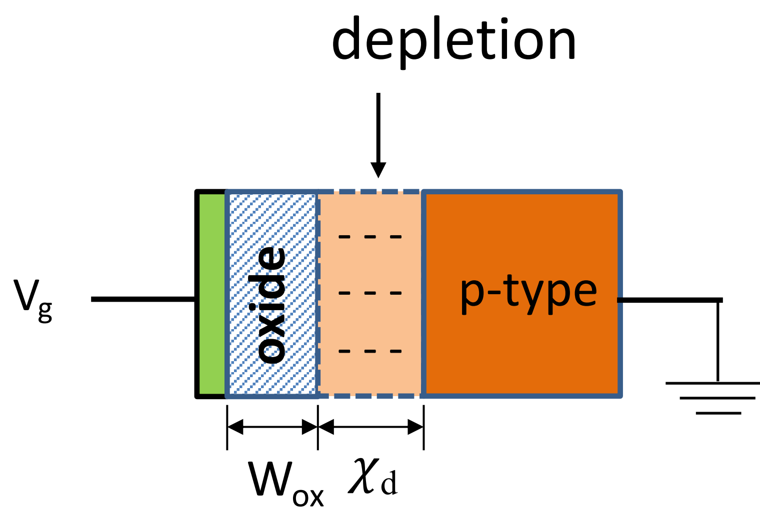
$$C_s = \frac{\varepsilon_s}{\chi_d}$$

Net charge is zero!

$$(V_g - V_s)C_{ox} = V_s C_s$$

$$V_g C_{ox} = V_s C_{ox} + V_s C_s$$

$$V_s = \frac{V_g C_{ox}}{C_{ox} + C_s}$$



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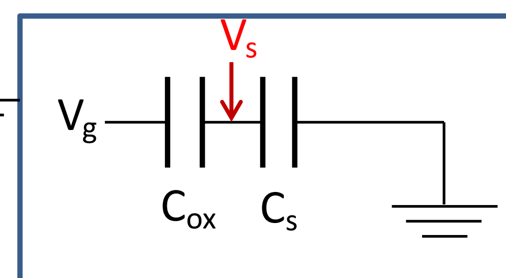


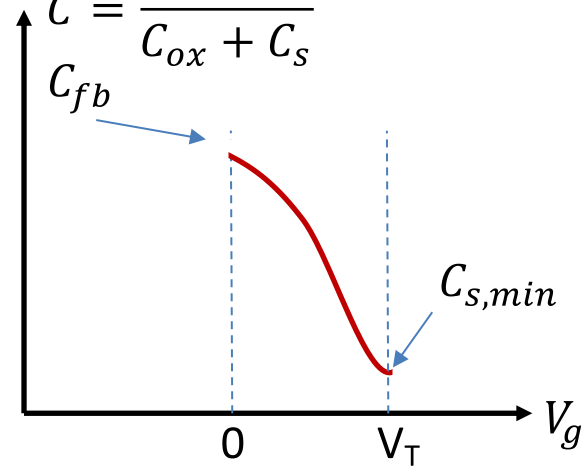
10.2 The capacitance-voltage characteristics

$$\begin{cases} \boxed{V_s = \dfrac{V_g C_{ox}}{C_{ox} + C_s}} \\[2ex] \boxed{C_s = \dfrac{\varepsilon_s}{\sqrt{\dfrac{2\varepsilon_s(V_s)}{qN_A}}}} \end{cases}$$

$$C_{min} = \frac{C_{ox} C_{s,min}}{C_{ox} + C_{s,min}}$$

$$C_{s,min} = \frac{\varepsilon_s}{\sqrt{\dfrac{4\varepsilon_s \phi_{fp}}{qN_a}}}$$

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



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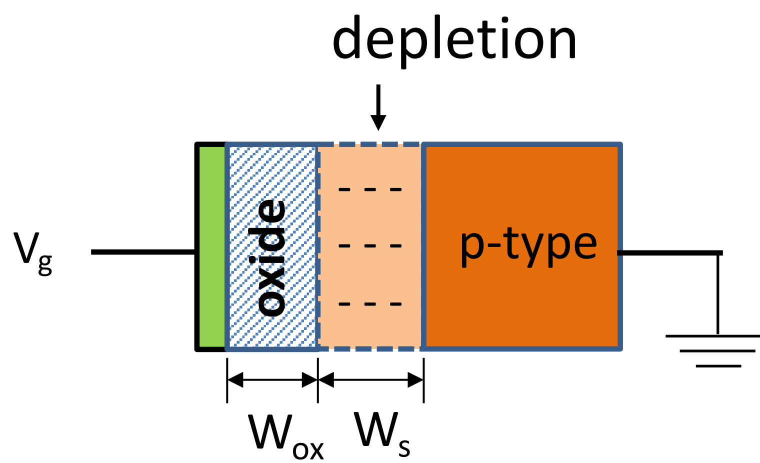
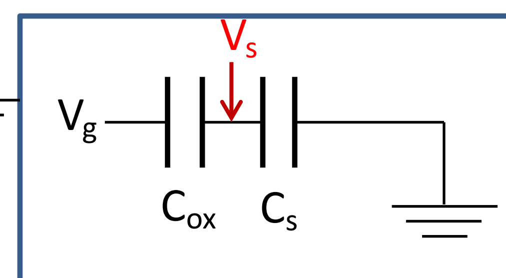
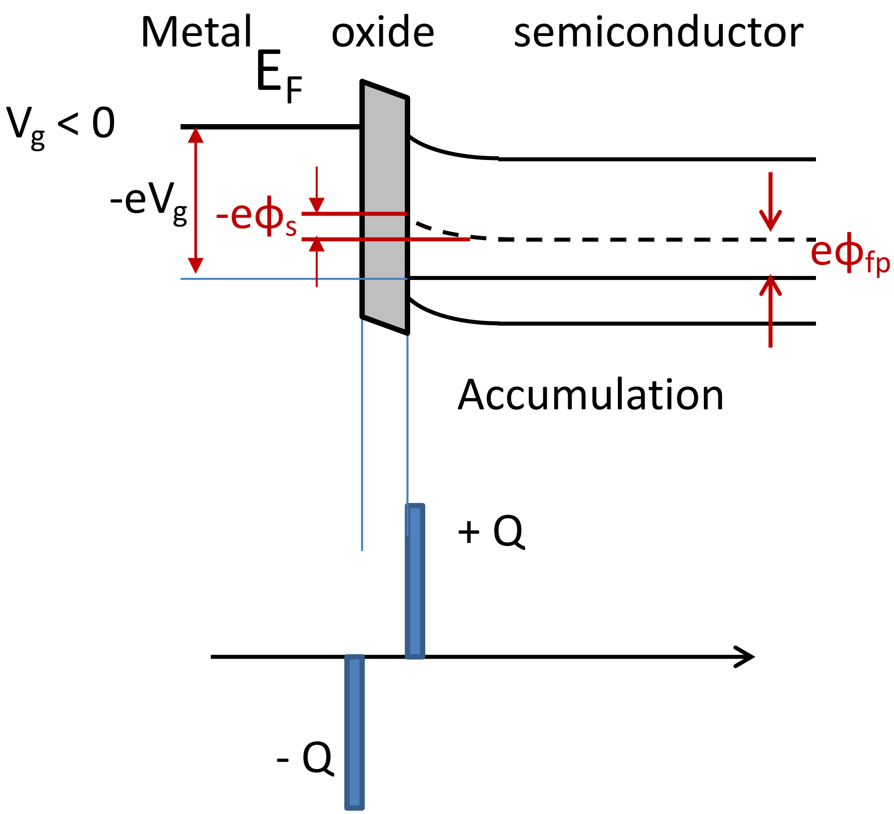


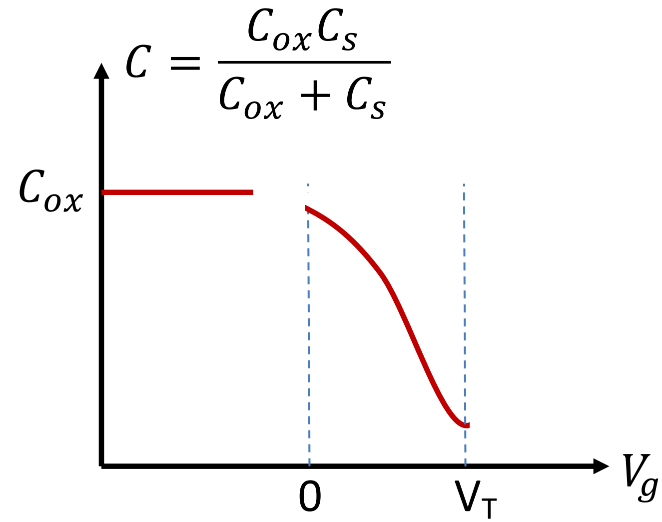
$$\boxed{W_s = \sqrt{\frac{2\varepsilon_s(V_s)}{qN_A}}}$$



10.2 The capacitance-voltage characteristics

Accumulation





$$C_s \to \infty$$

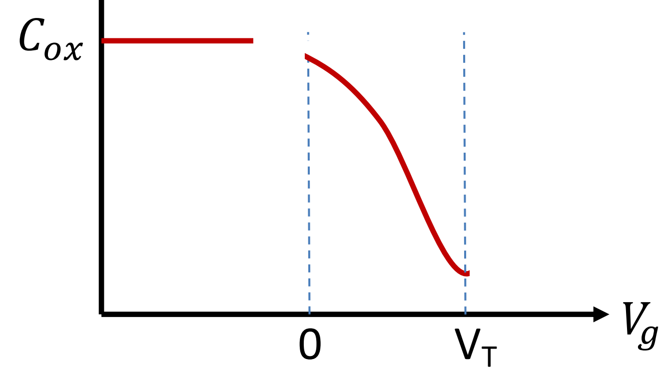
$$C = \frac{C_s C_{ox}}{C_s + C_{ox}} \approx C_{ox}$$

10.2 The capacitance-voltage characteristics

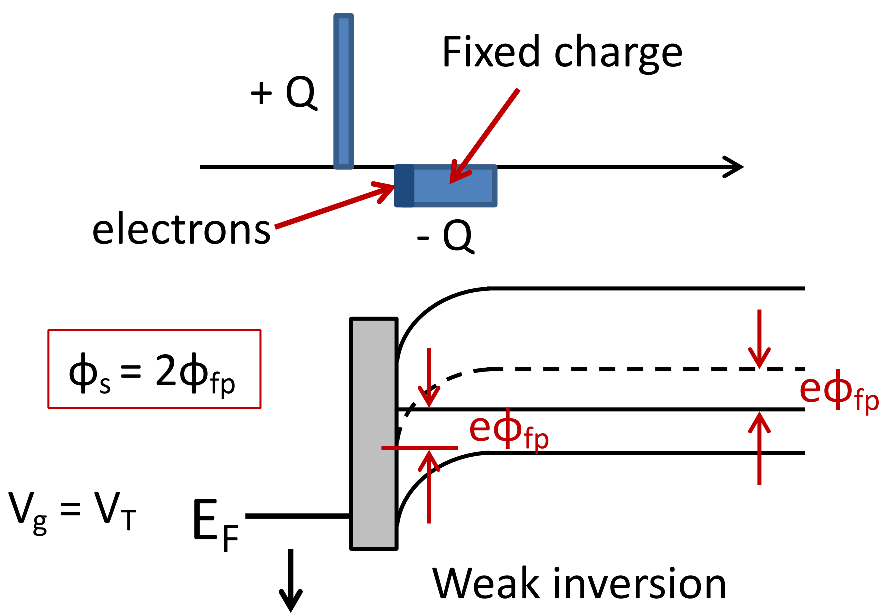
Depletion and weak inversion

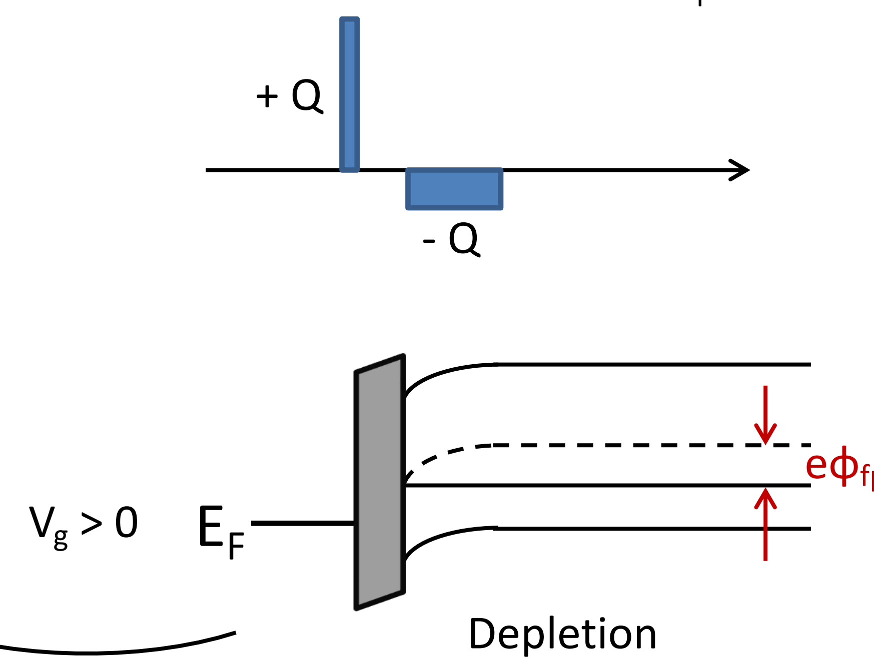
$$C_s = \frac{\varepsilon_s}{\sqrt{\frac{2\varepsilon_s (V_s)}{qN_A}}}$$

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



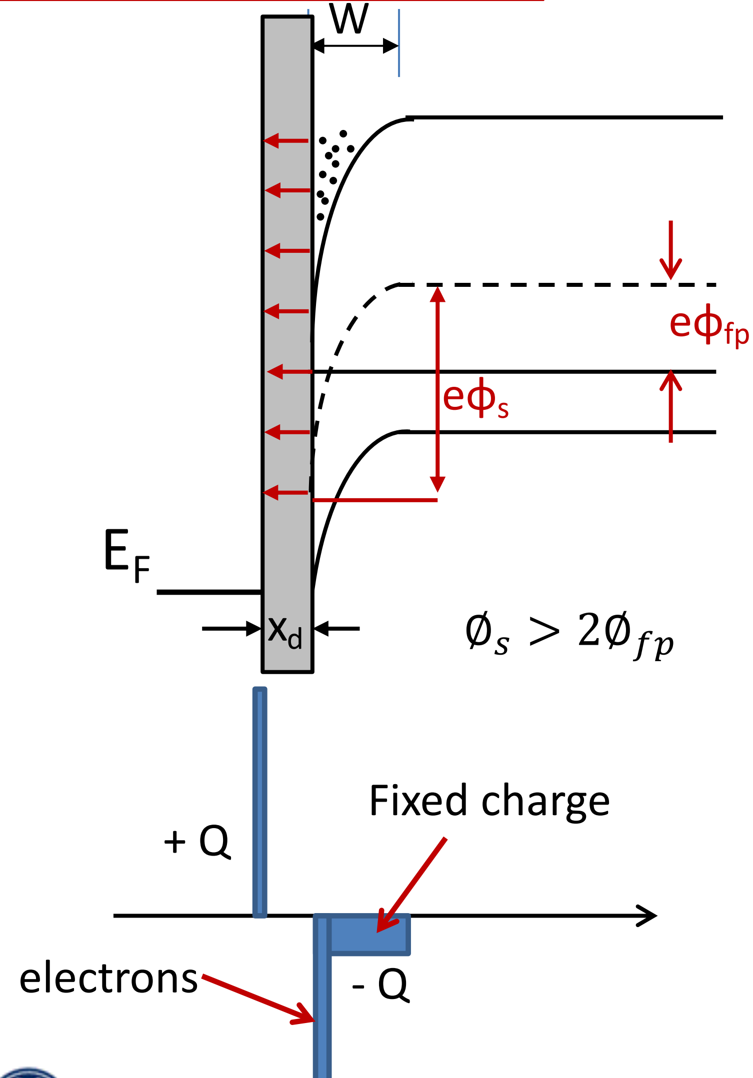
$\phi_s = 2\phi_{fp}$



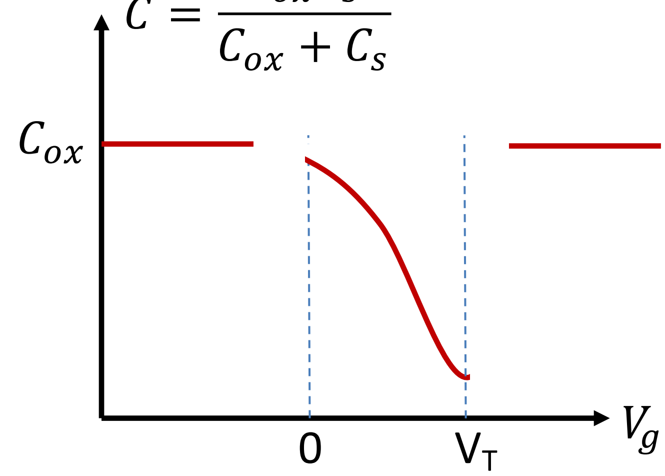


10.2 The capacitance-voltage characteristics

Strong inversion



$$\phi_s > 2\phi_{fp}$$



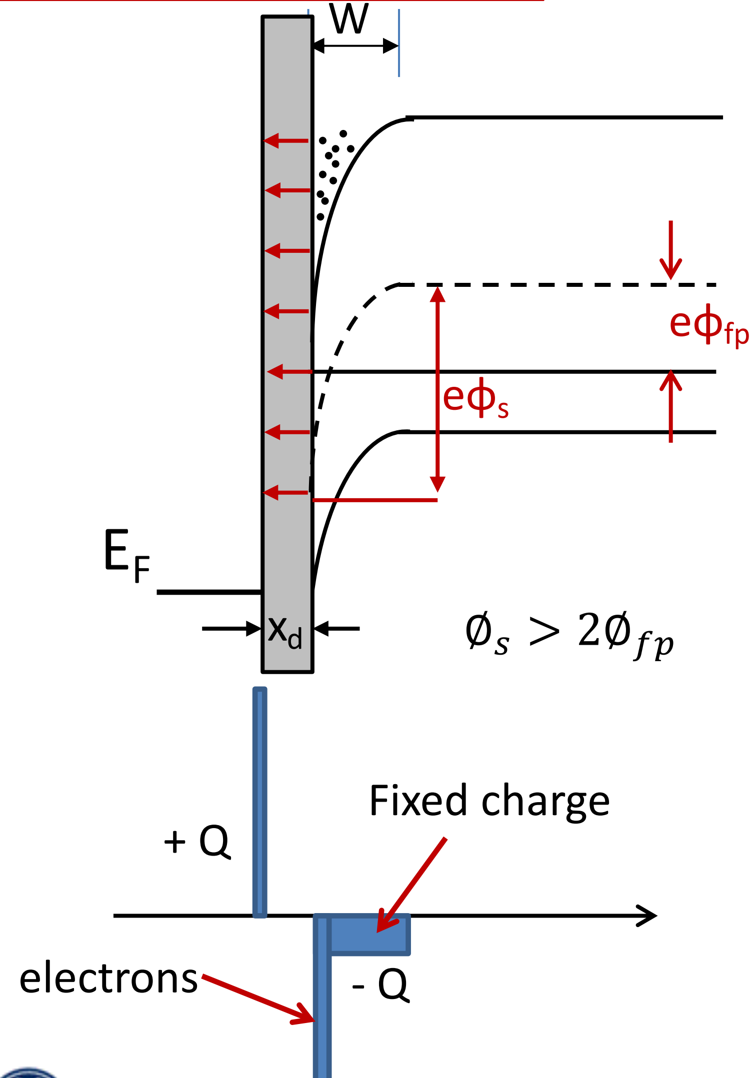
$$C = \frac{C_{ox}C_s}{C_{ox} + C_s}$$

$$C_s \rightarrow \infty$$

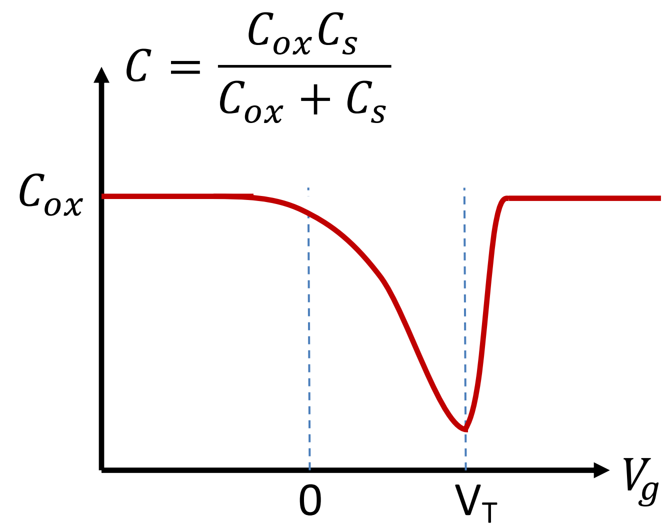
$$C = \frac{C_s C_{ox}}{C_s + C_{ox}} \approx C_{ox}$$

10.2 The capacitance-voltage characteristics

Strong inversion



$\emptyset_s > 2\emptyset_{fp}$

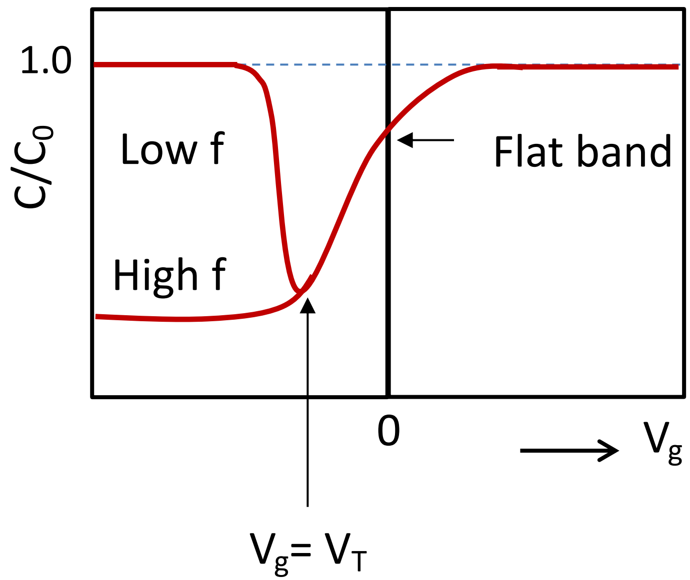


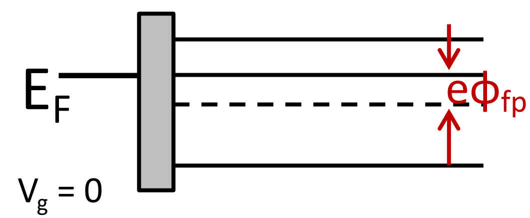
$C_s \rightarrow \infty$

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

10.2 The capacitance-voltage characteristics

n-type semiconductor





n-type substrate

10.2 The capacitance-voltage characteristics

Problem Example

Consider a p-type silicon substrate at $T = 300$ K doped to $N_a = 10^{16}$ cm^{-3}. The oxide is silicon dioxide with a thickness of $t_{ox} = 18$ nm $= 180$ Å, and the gate is aluminum.

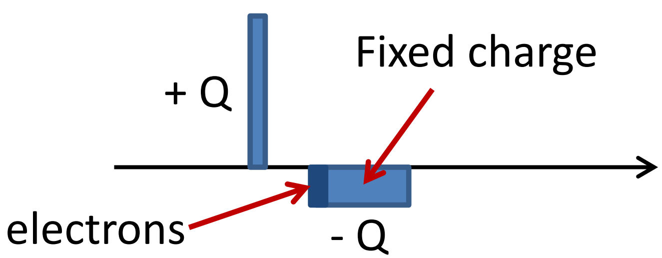
Calculate Cox, Cmin’ for a MOS capacitor.

10.2 The capacitance-voltage characteristics

Threshold voltage

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

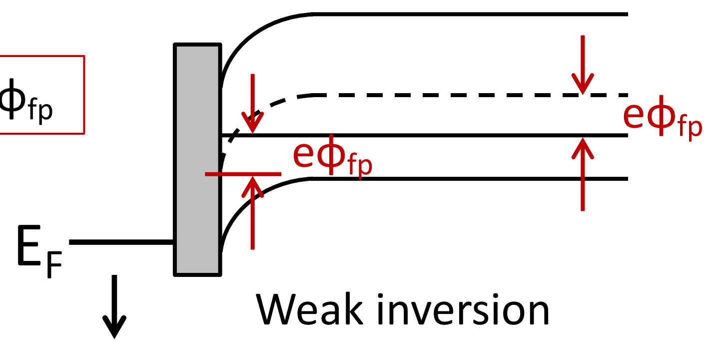
$$2\phi_{fp} = \frac{V_T C_{ox}}{C_{ox} + C_s} \Rightarrow V_T = 2\phi_{fp} + 2\phi_{fp}\frac{C_s}{C_{ox}}$$



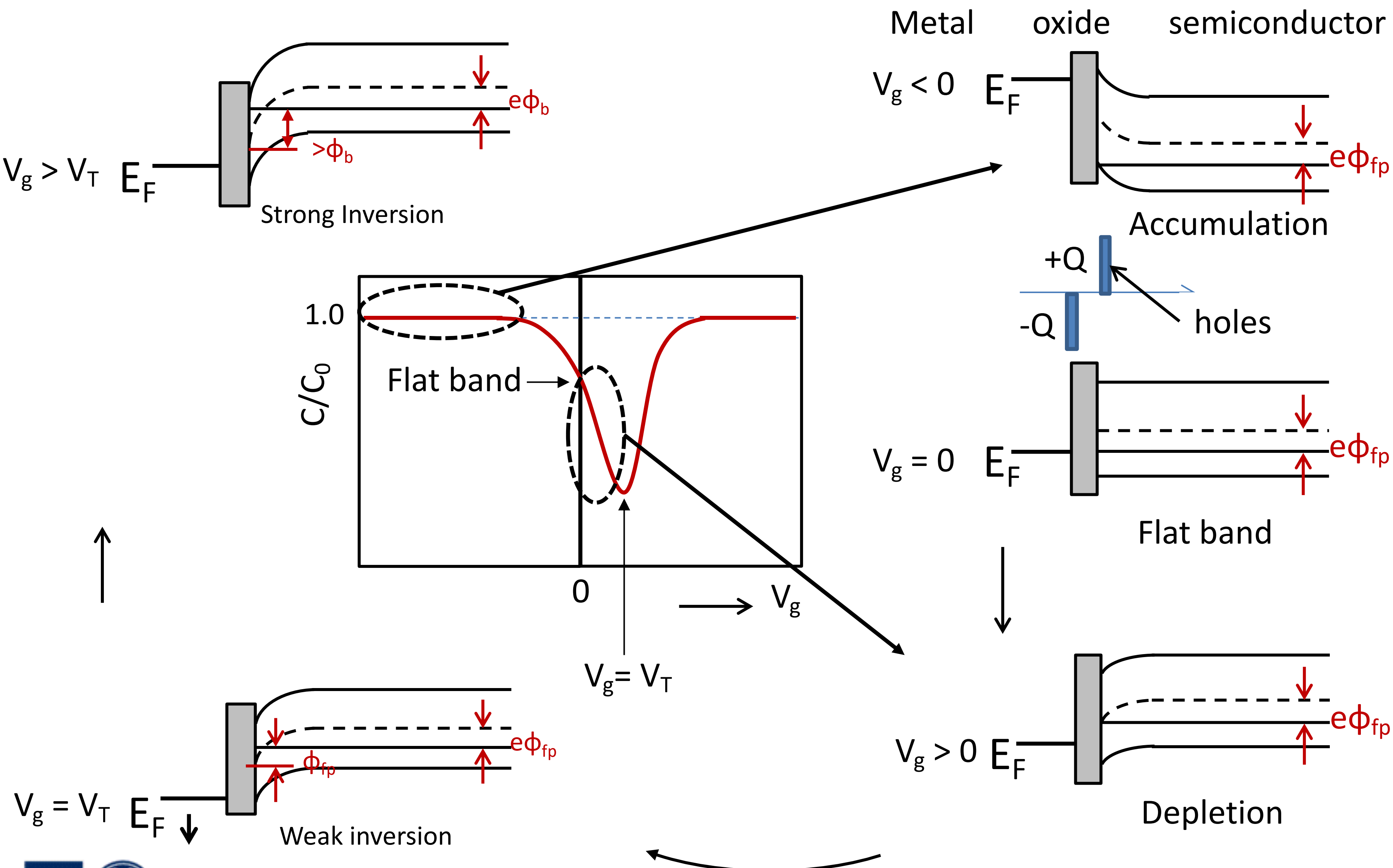
$V_s = 2\phi_{fp}$

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

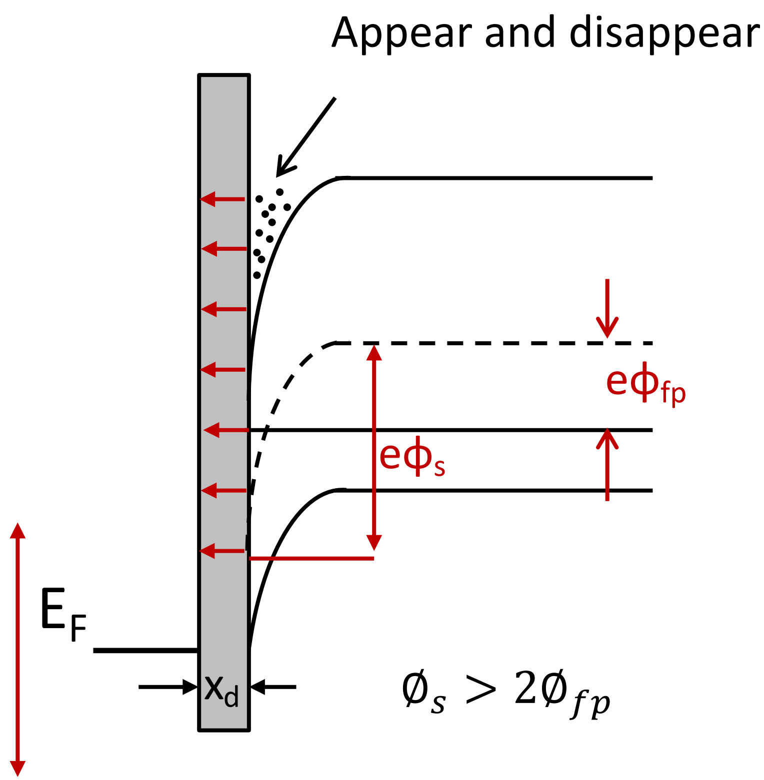
$V_g = V_T$



10.2 The capacitance-voltage characteristics: summary



Question:

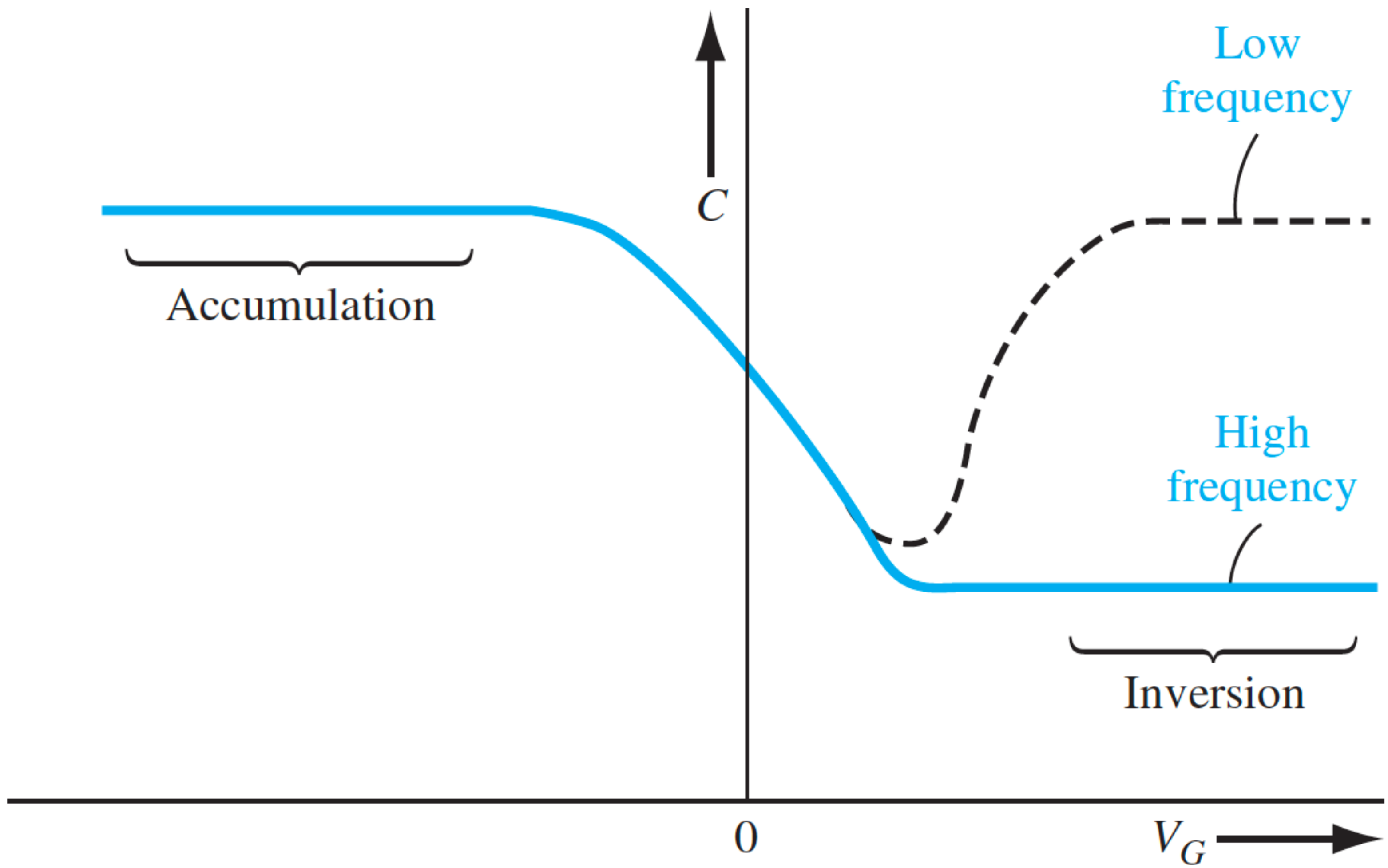


$$\emptyset_s > 2\emptyset_{fp}$$

Where are the electrons coming from and going to?

10.2 The capacitance-voltage characteristics

Frequency dependence



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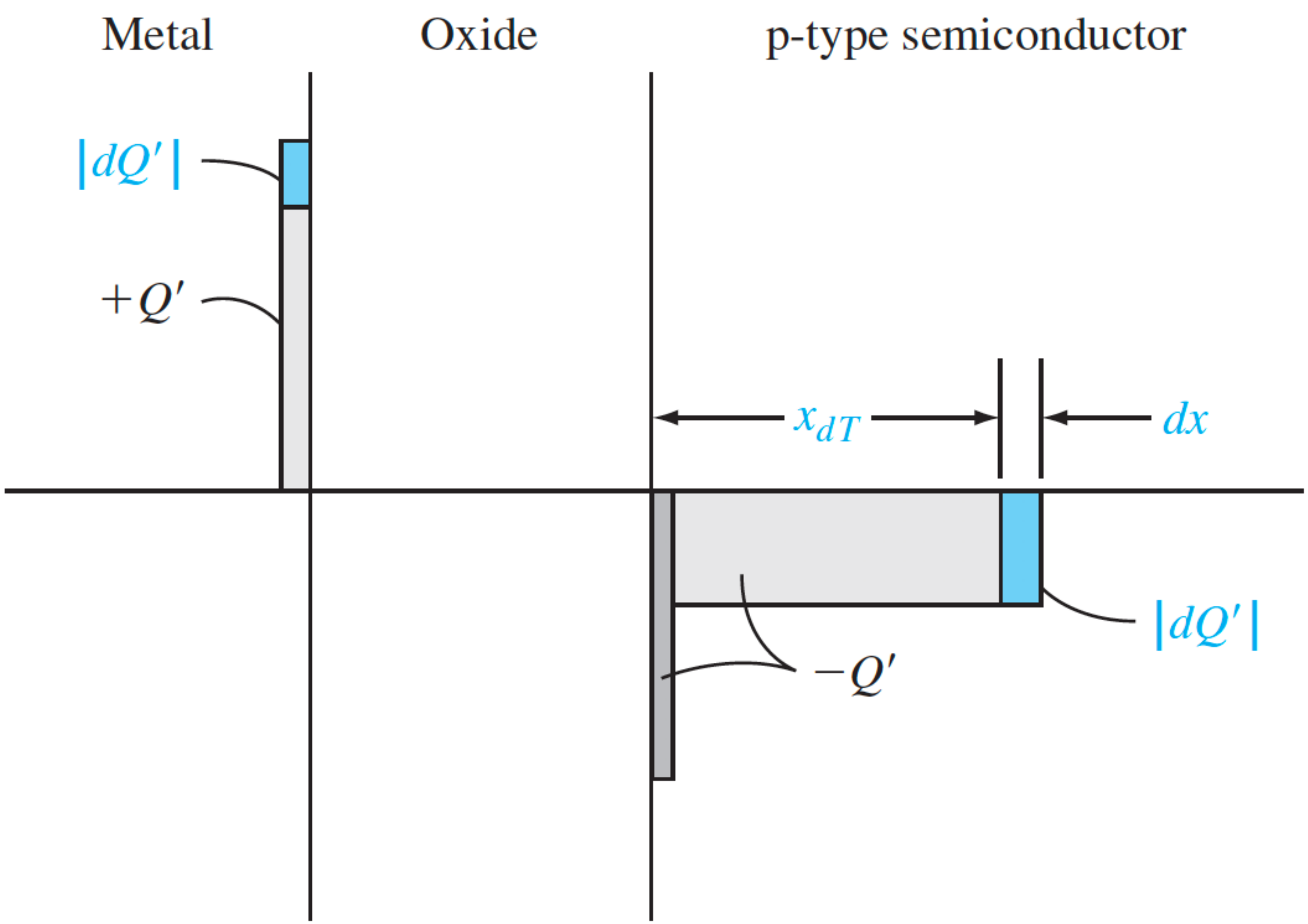
Frequency dependence



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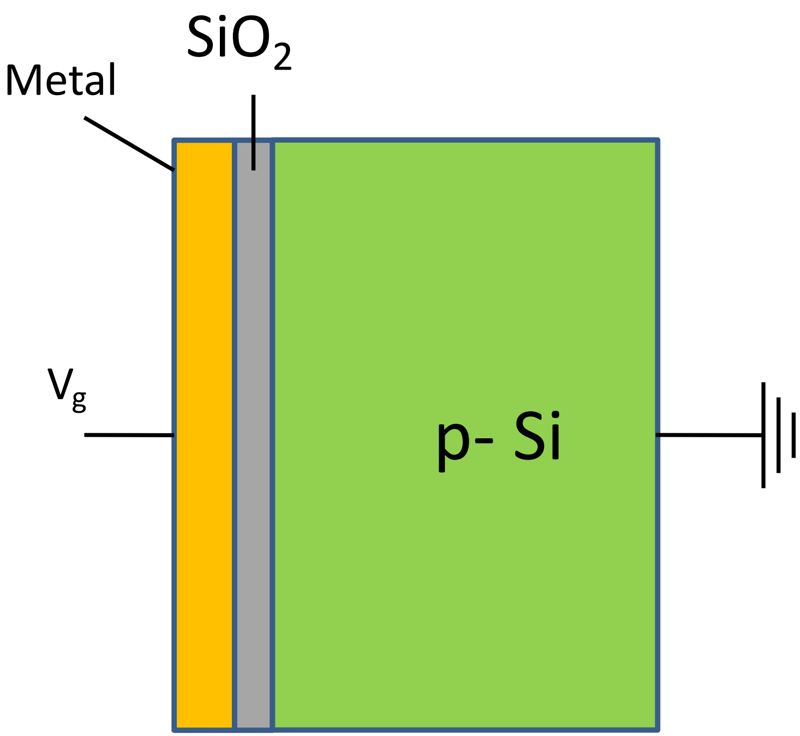
10.3 Non-ideal effects

<u>Work function difference</u>



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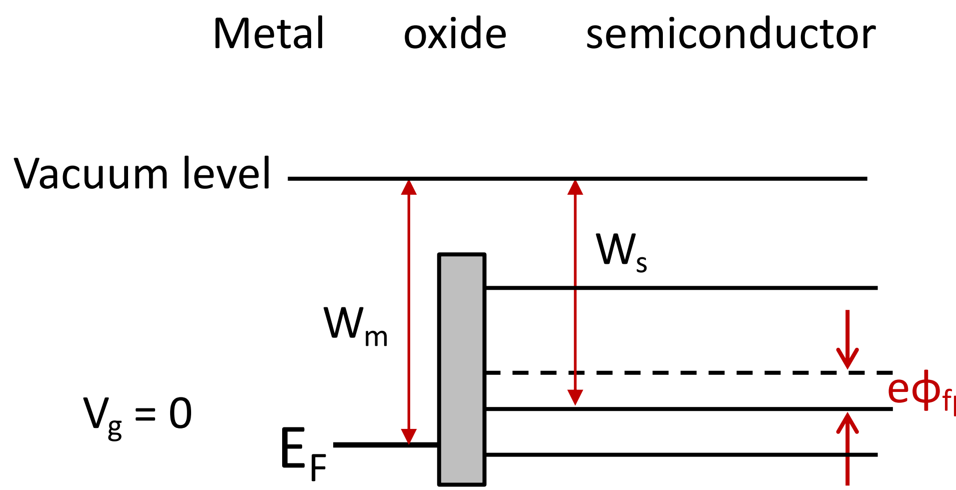
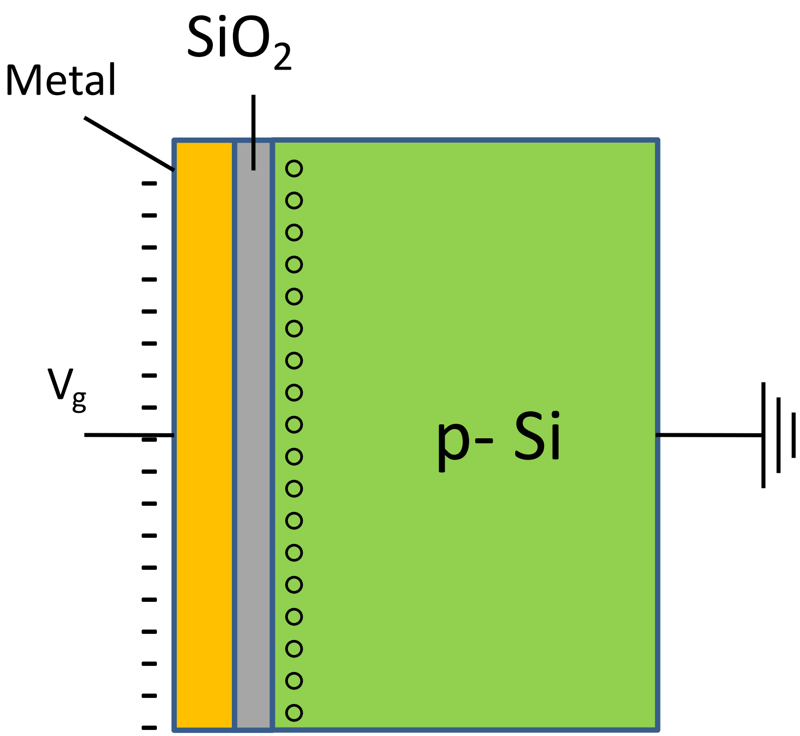


$V_{FB} = 0$

10.3 Non-ideal effects

Work function difference



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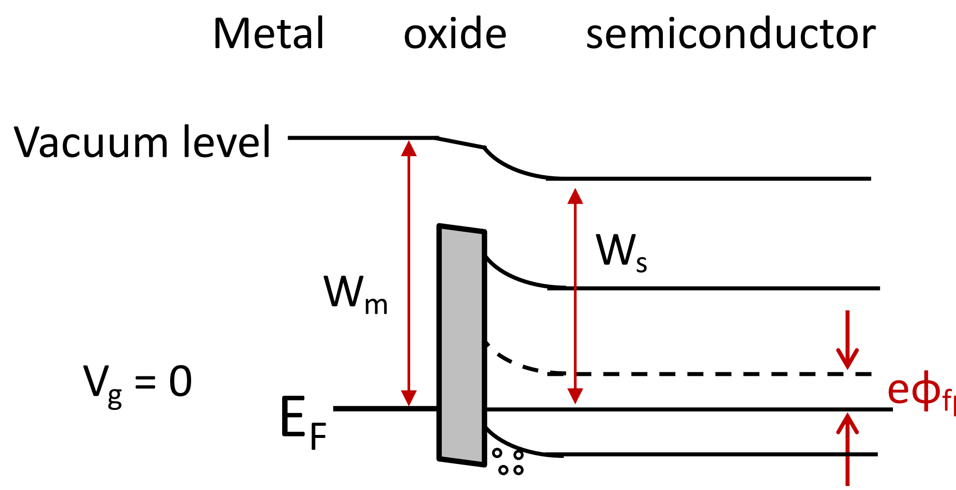

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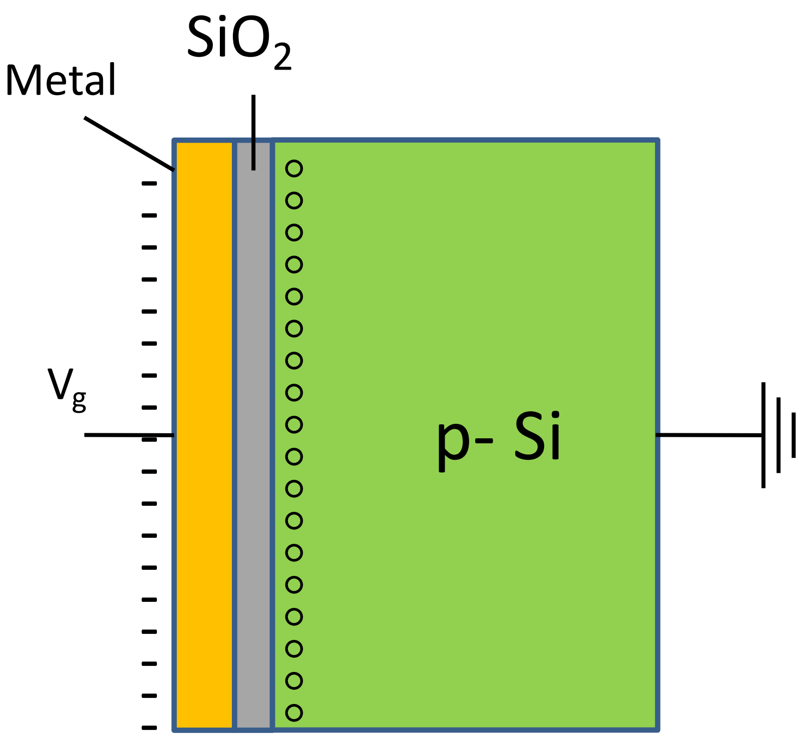

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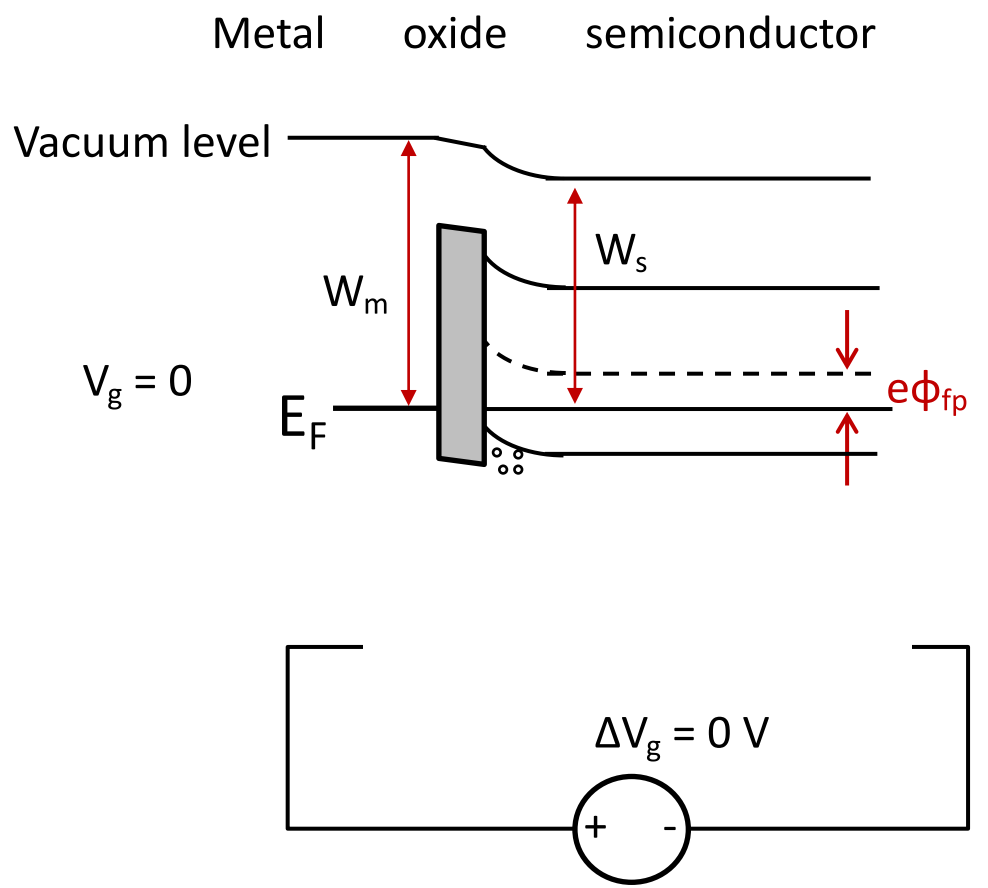

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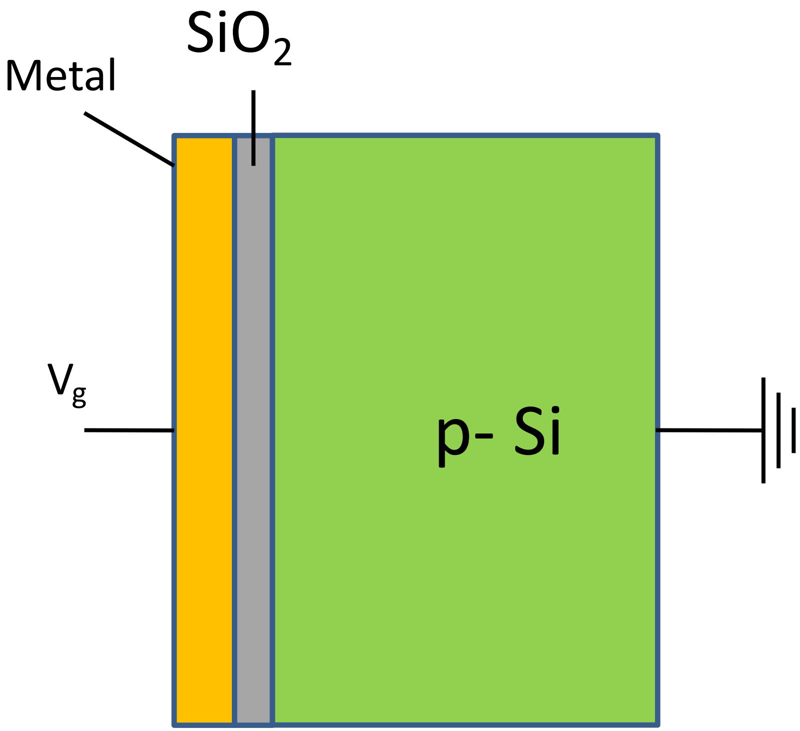
Work function difference



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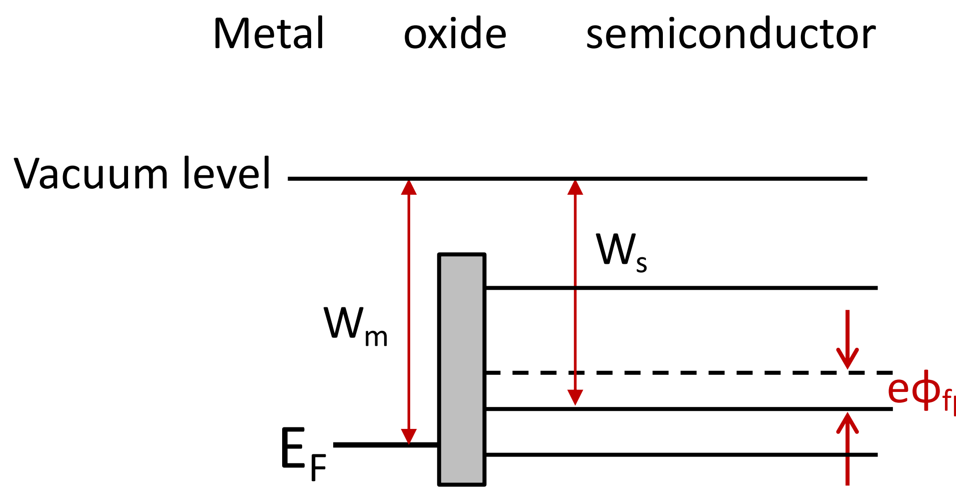
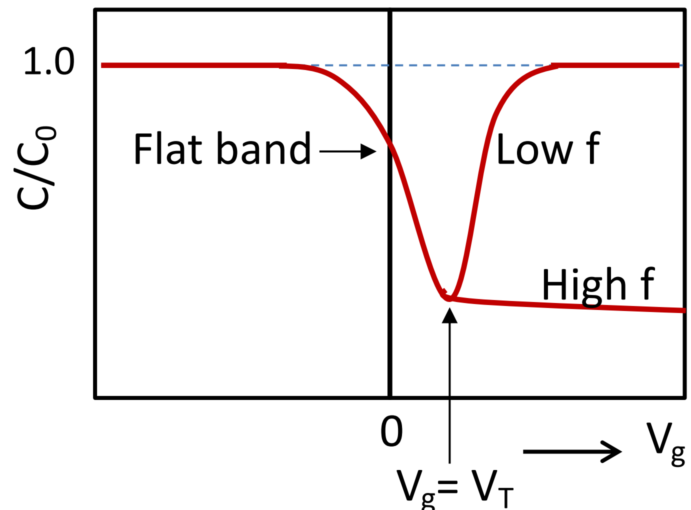


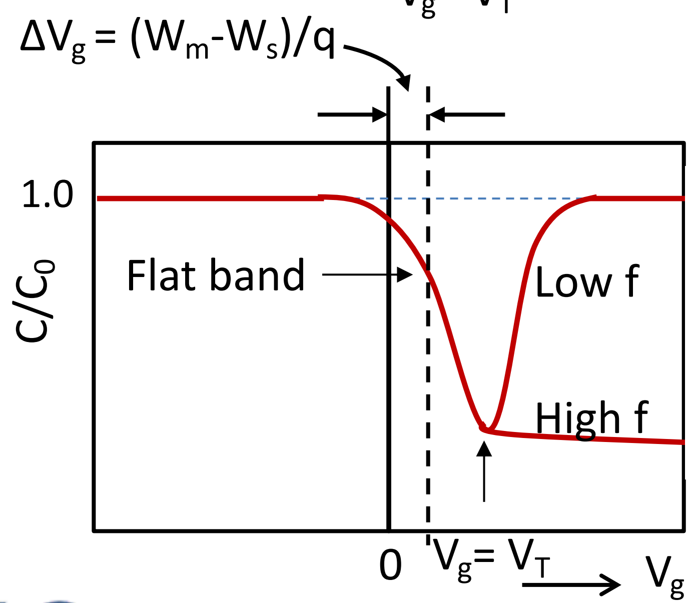
Flat band $V_{FB} = (W_m - W_s)/q$

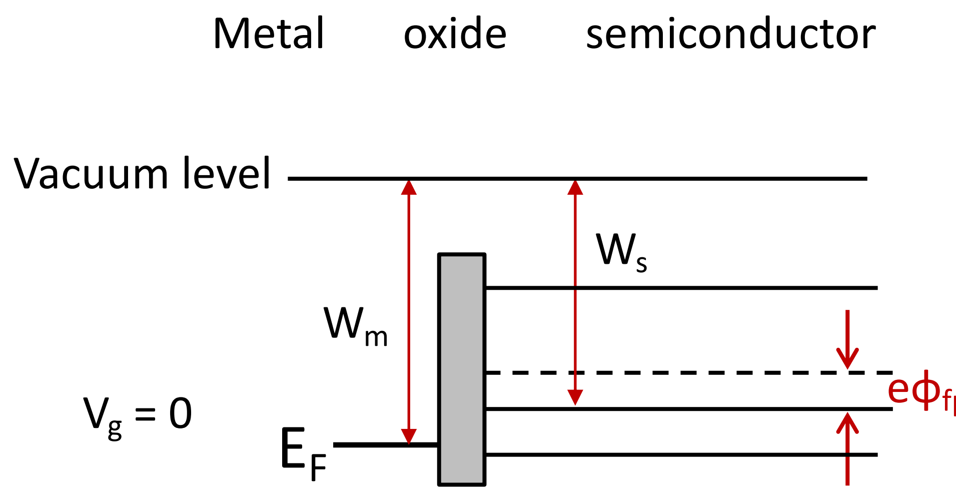
$\Delta V_g = (W_m - W_s)/q = \Phi_{ms}$

10.3 Non-ideal effects

Work function difference







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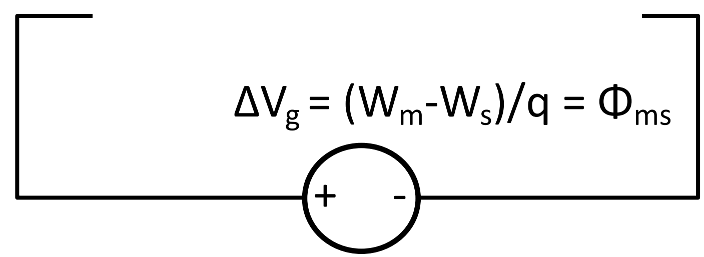
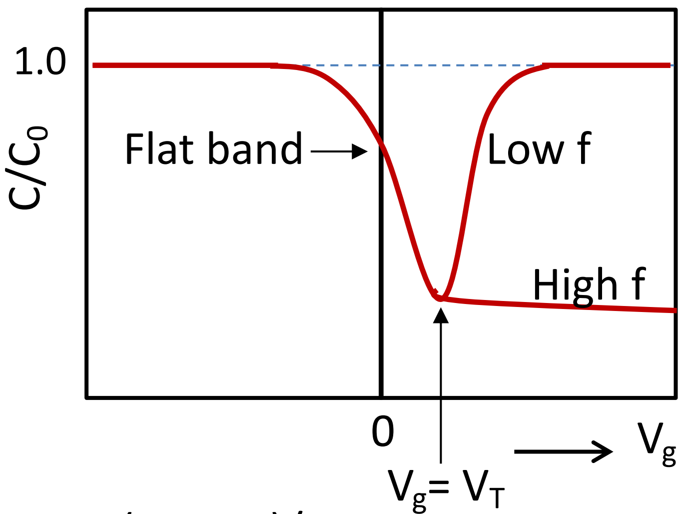
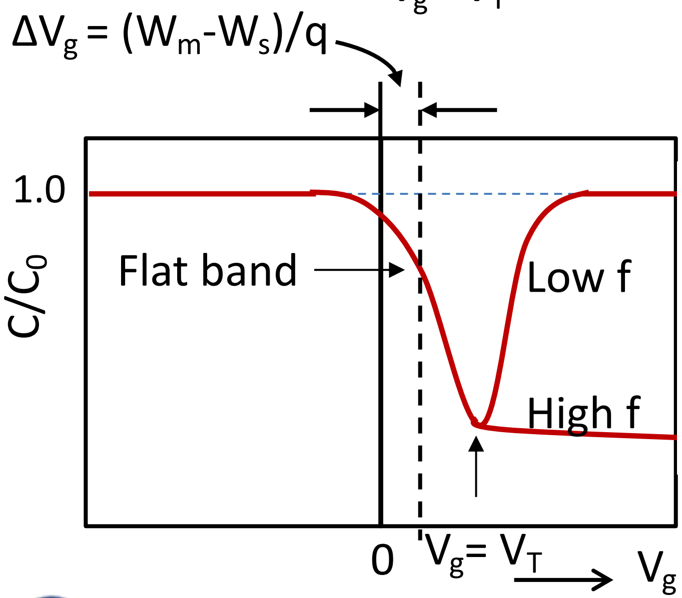


10.3 Non-ideal effects

Work function difference



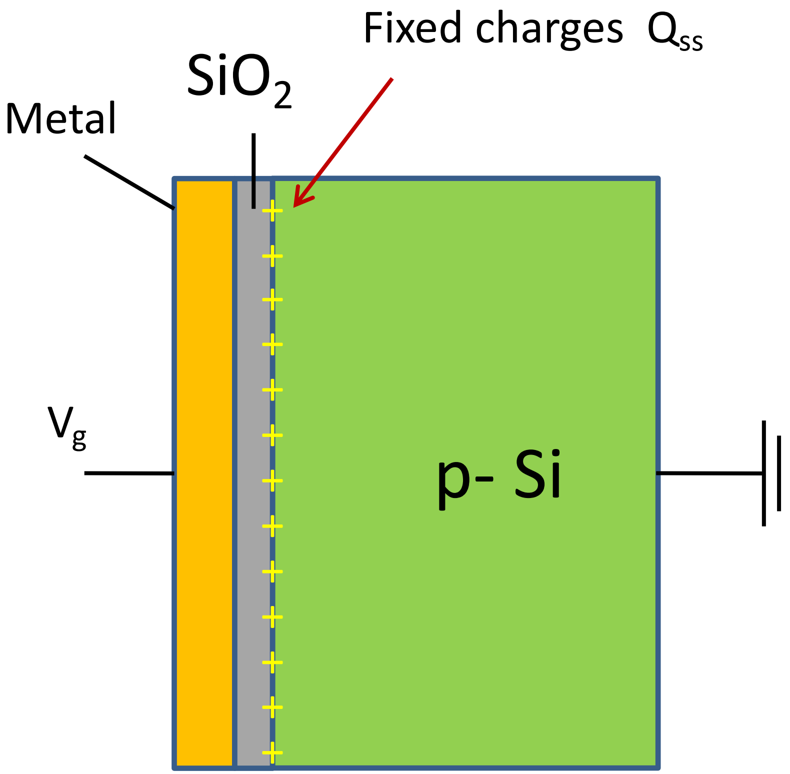
$$V_T = 2\phi_{fp} + t_{ox}\sqrt{\frac{4eN_a\varepsilon_{Si}\phi_{fp}}{\varepsilon_{ox}^2}} = 2\phi_b + \frac{|Q_{SD}|}{C_{ox}}$$



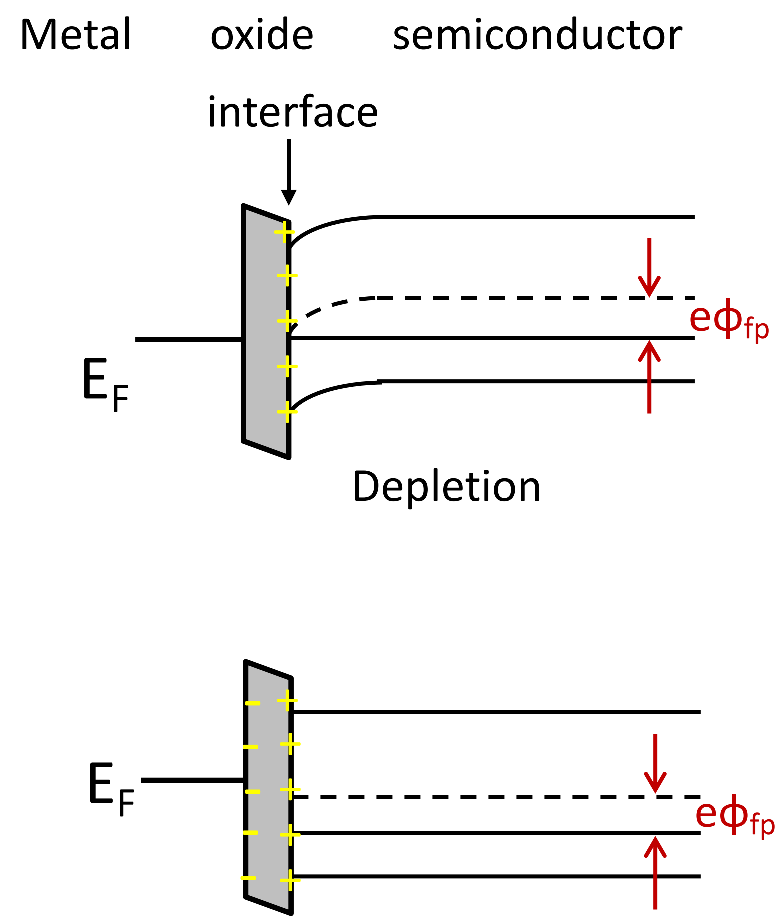
$$V_T = 2\phi_{fp} + t_{ox}\sqrt{\frac{4eN_a\varepsilon_{Si}\phi_{fp}}{\varepsilon_{ox}^2}} + V_{FB}$$
$$= 2\phi_{fp} + \frac{|Q_{SD}|}{C_{ox}} + \phi_{ms}$$

10.3 Non-ideal effects

Fixed charges



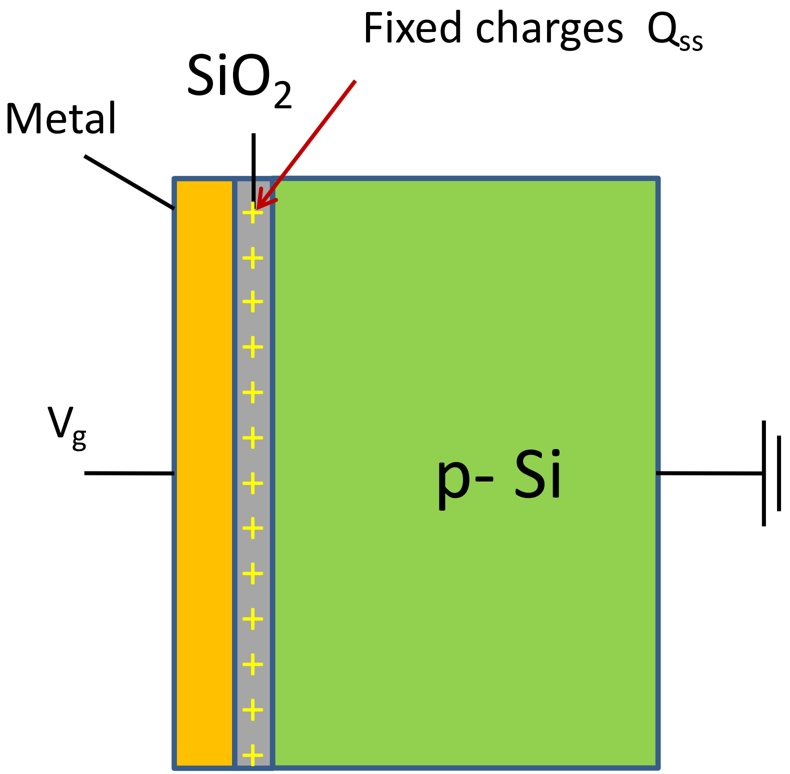
Metal-insulator-semiconductor (MIS)



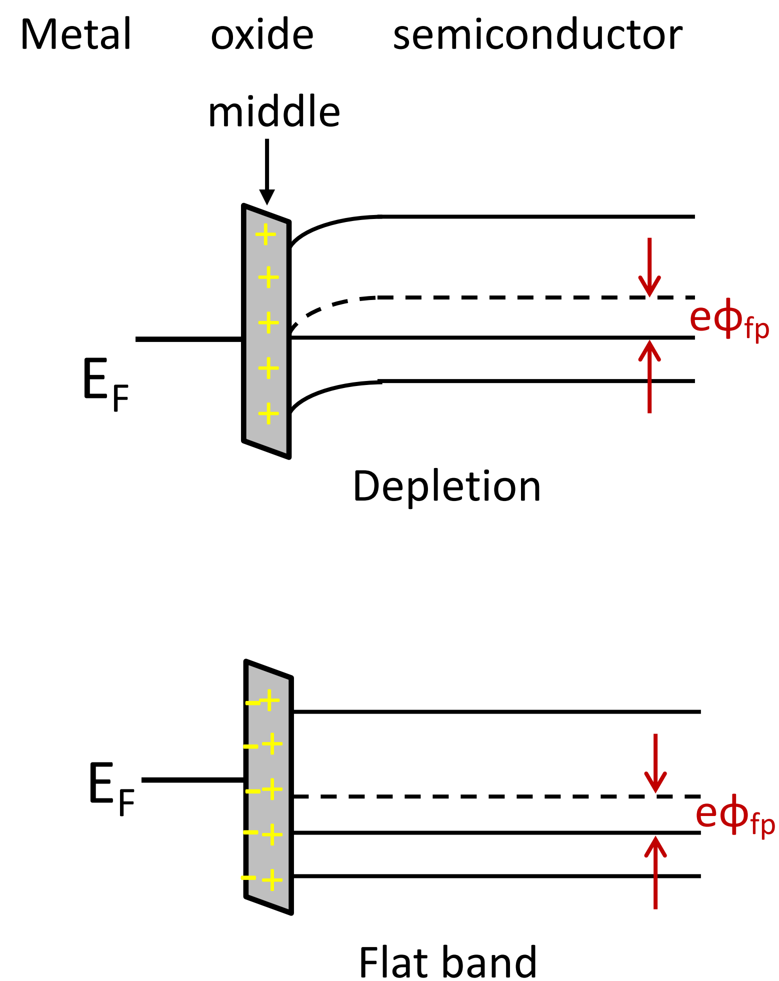
$$V_g = V_{FB} = -Q_{ss}/C$$

10.3 Non-ideal effects

Fixed charges



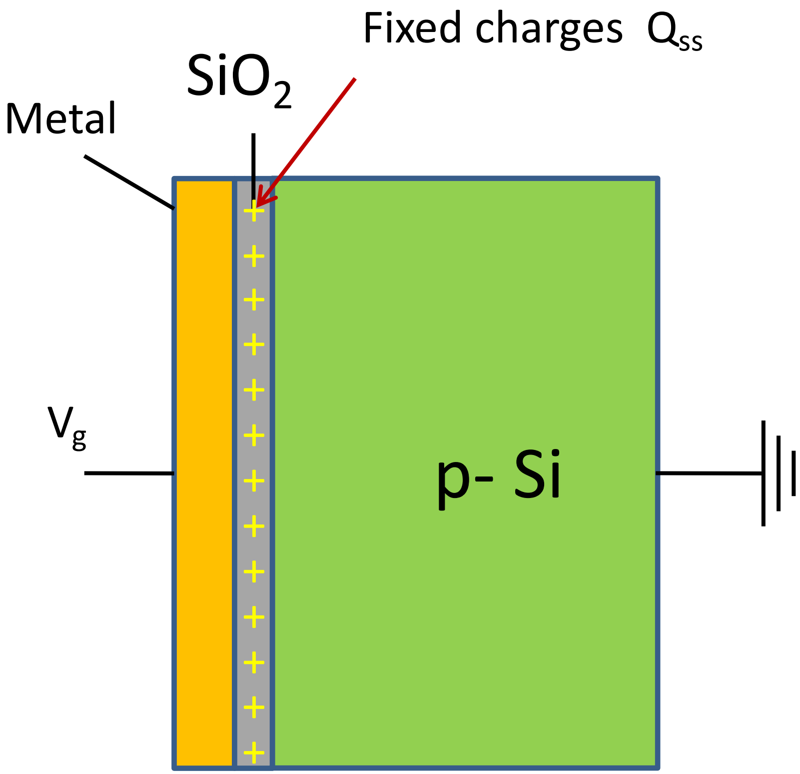
Metal-insulator-semiconductor (MIS)



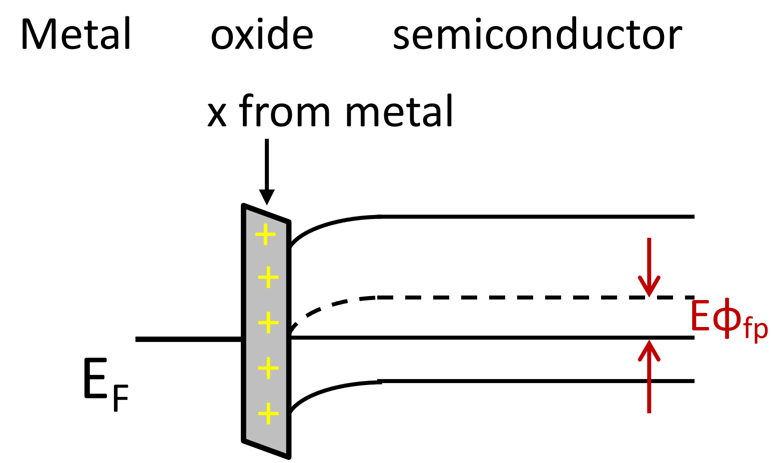
$$V_g = V_{FB} = -Q_{ss}/2C$$

10.3 Non-ideal effects

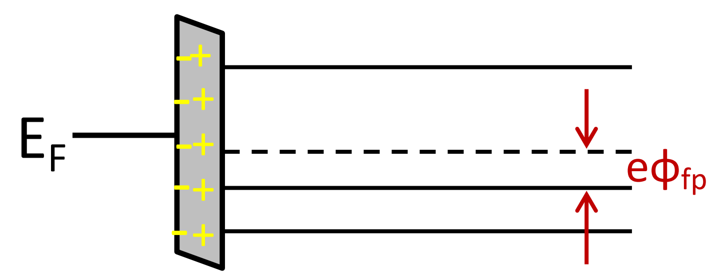
Fixed charges



Metal-insulator-semiconductor (MIS)



Depletion

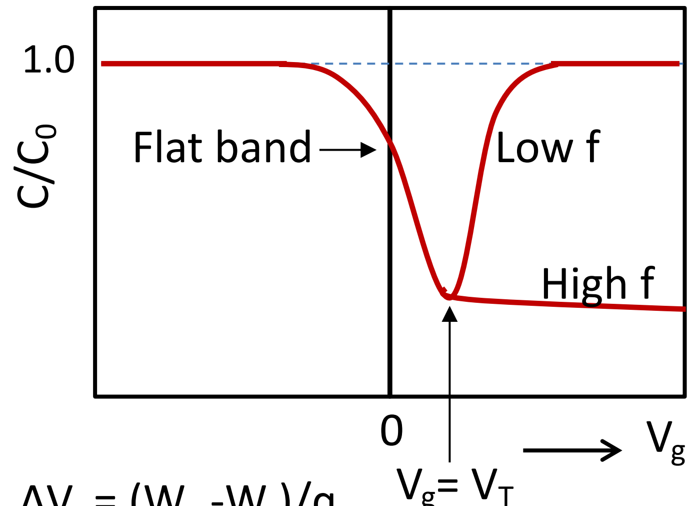


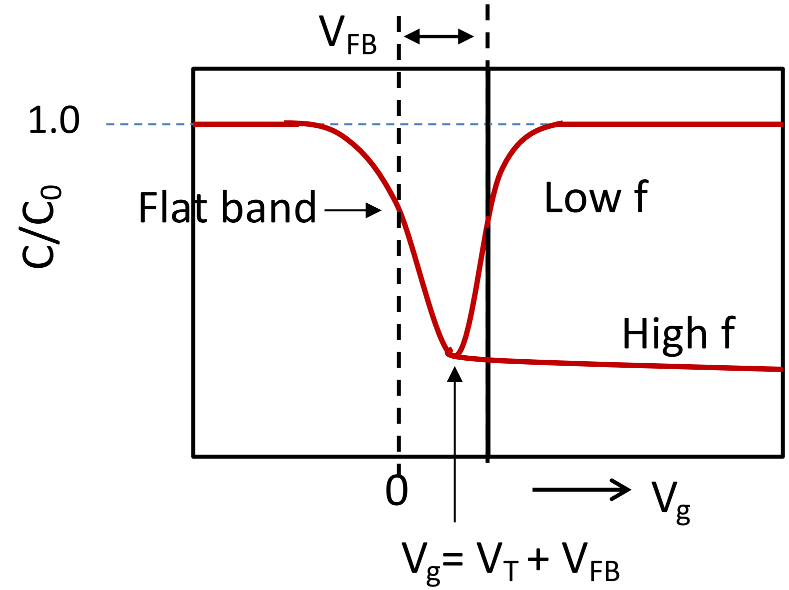
Flat band

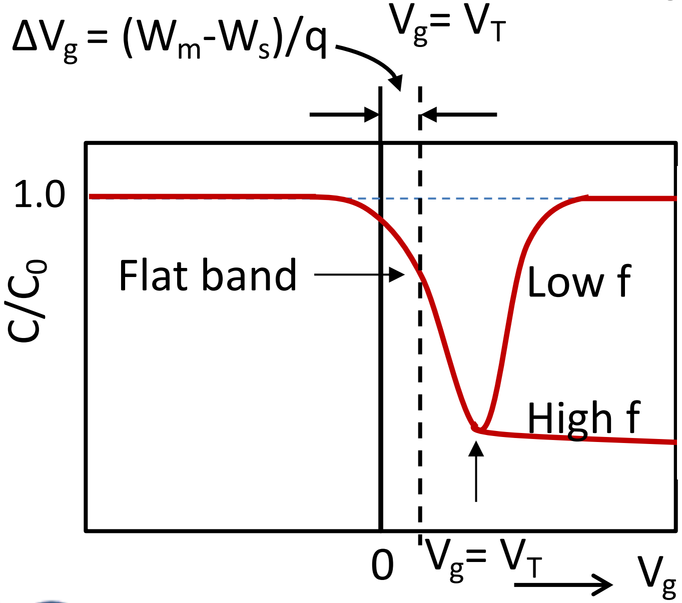
$$V_g = V_{FB} = -\frac{Q_{SS}}{C} \cdot \frac{x}{d}$$

10.3 Non-ideal effects

Fixed charges







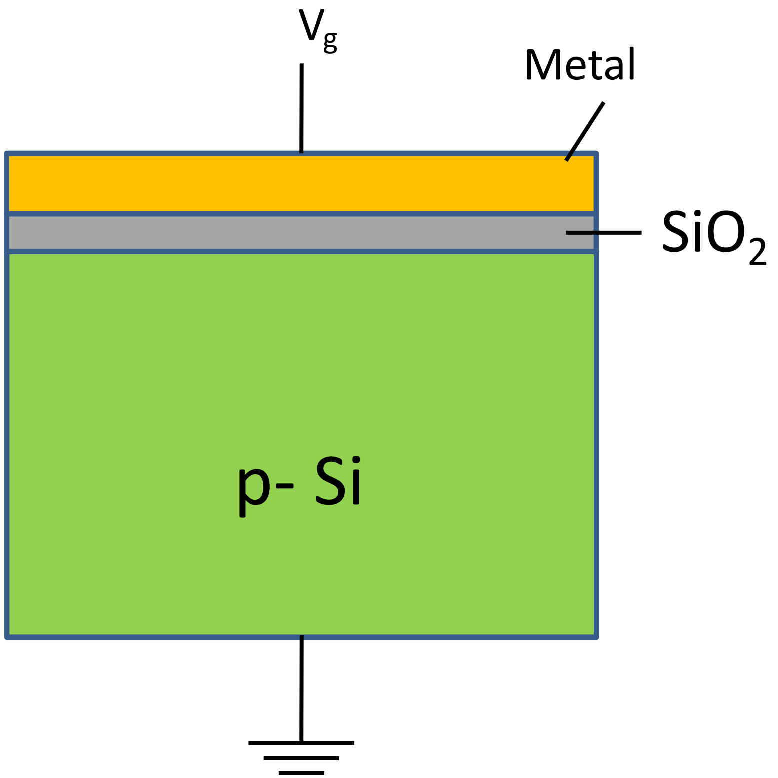
$$V_T = 2\phi_{fp} + t_{ox}\sqrt{\frac{4eN_a\varepsilon_{Si}\phi_{fp}}{\varepsilon_{ox}^2}} + V_{FB}$$

$$= 2\phi_{fp} + \frac{|Q_{SD}|}{C_{ox}} + \phi_{ms} - \frac{Q_{ss}}{C_{ox}}$$

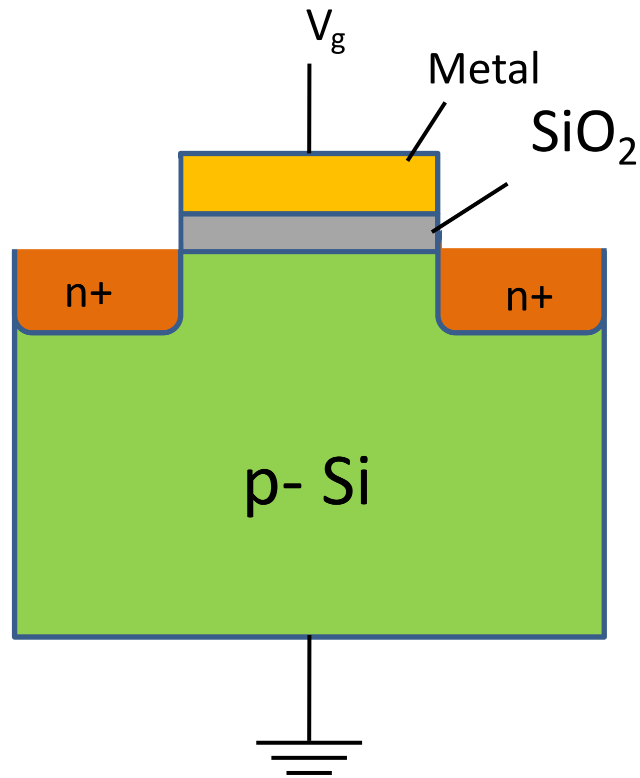
Outline

10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: MOSFET



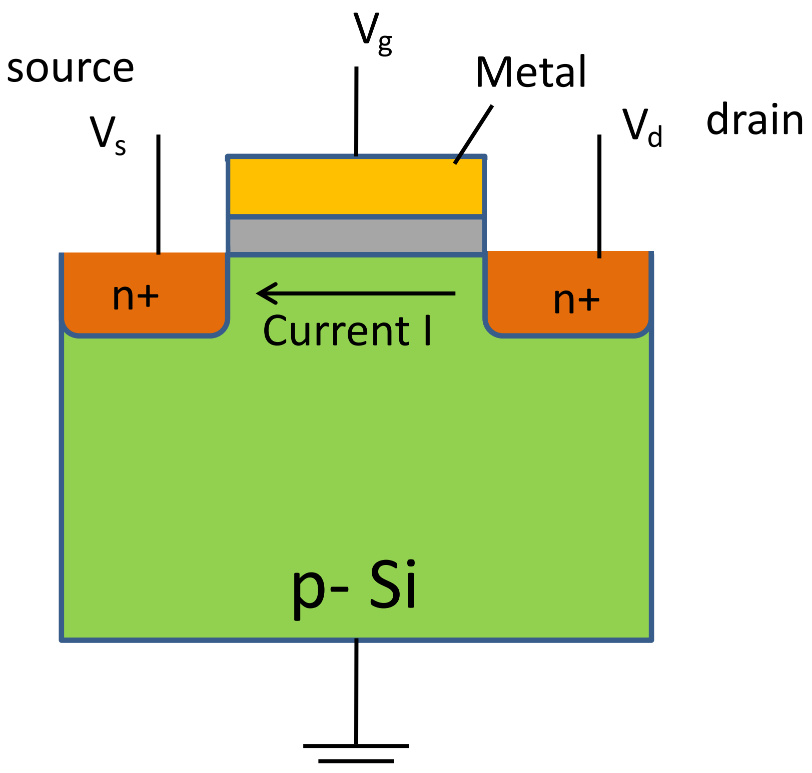
MOS capacitor



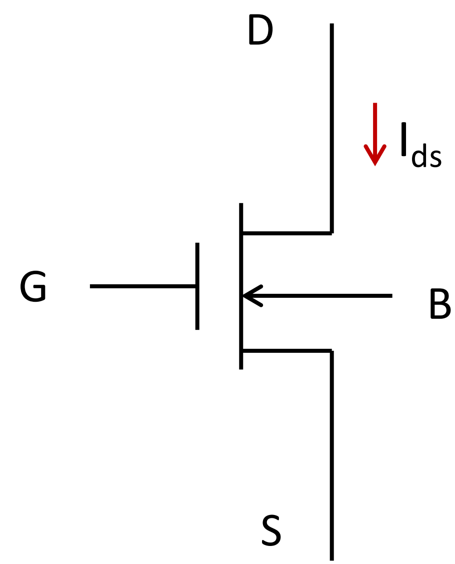
MOSFET

10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: MOSFET

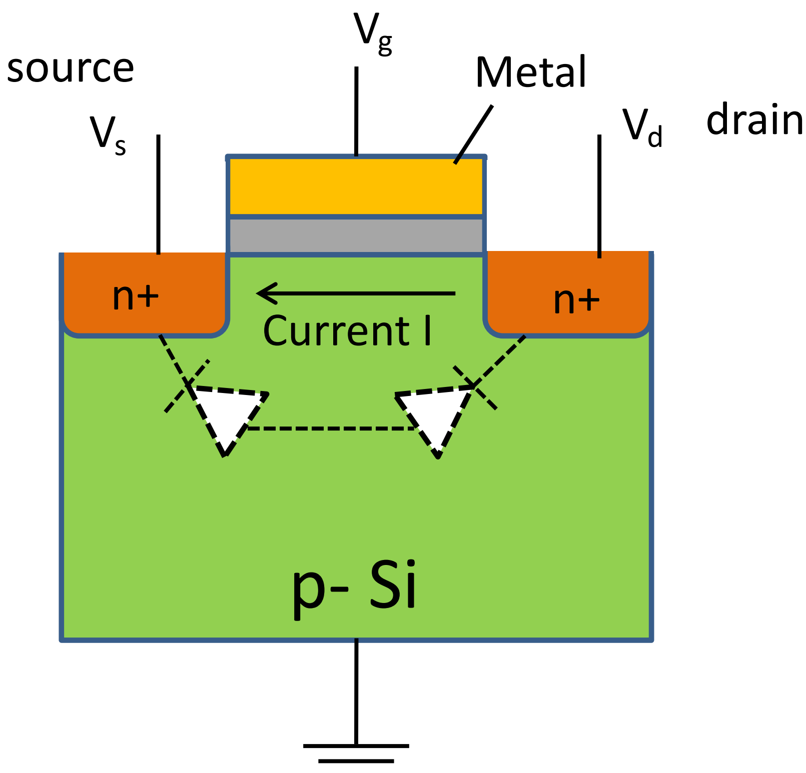


Metal-oxide-semiconductor (MOS)

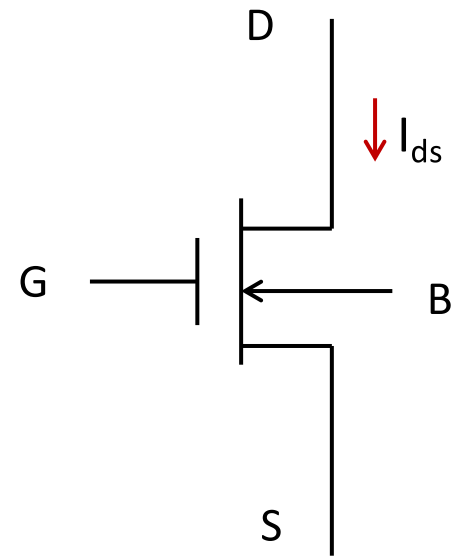


10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: MOSFET

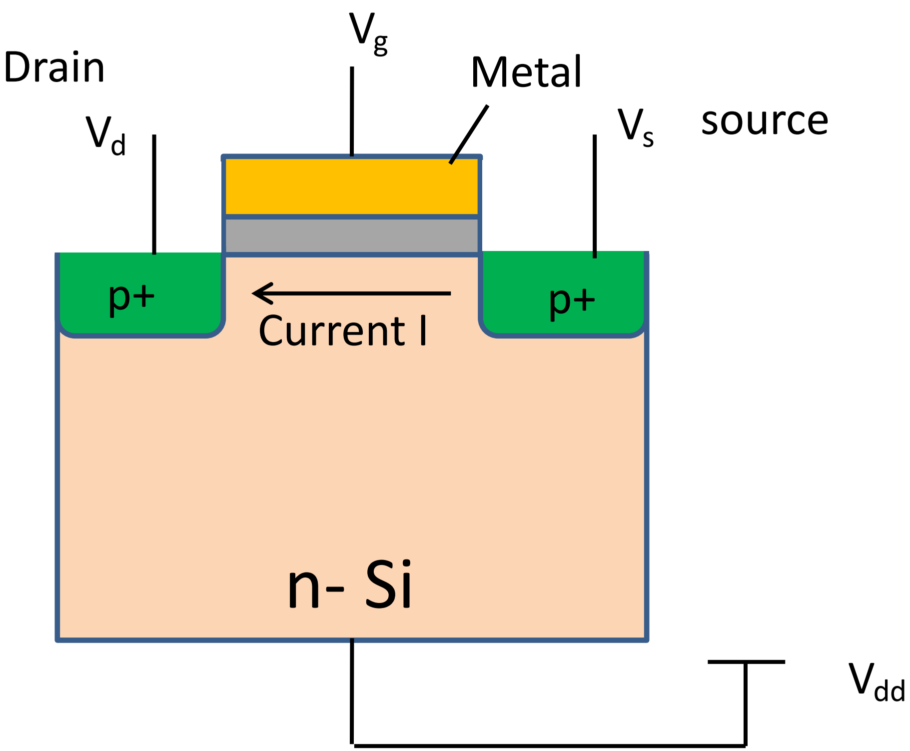


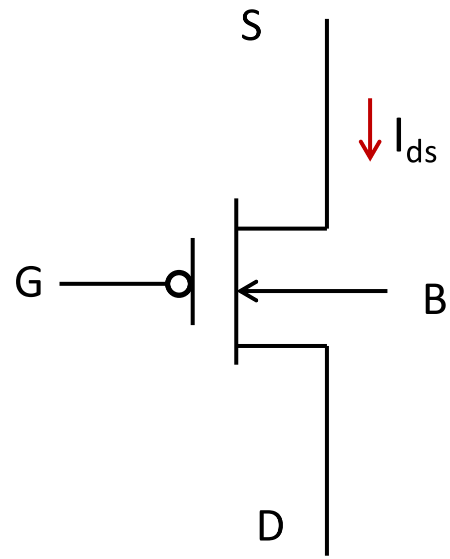
MOSFET



10.4 The basic MOSFET operation

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

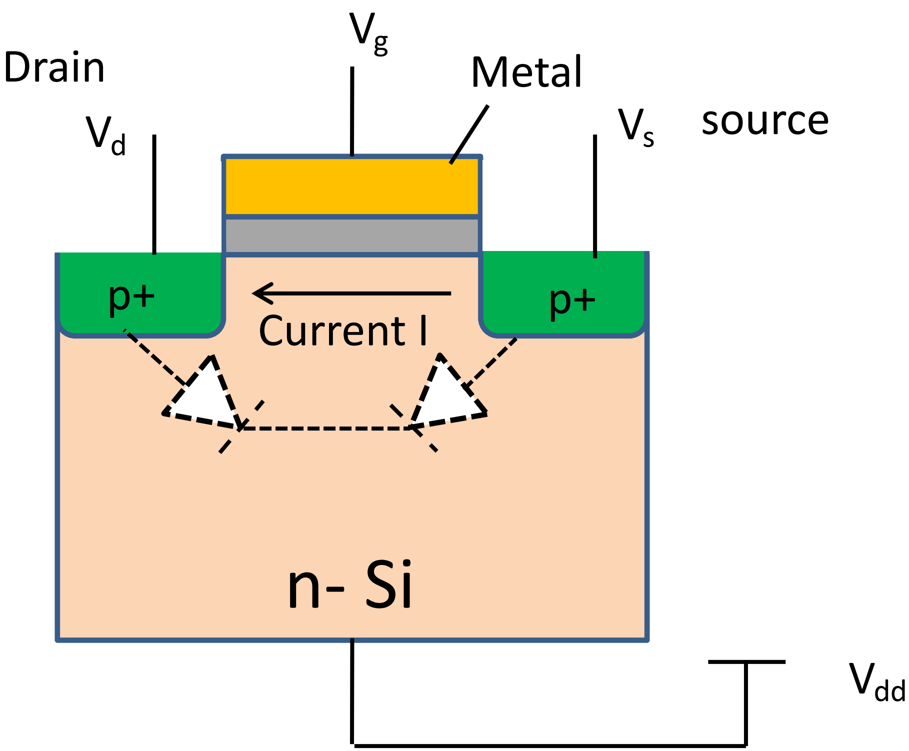


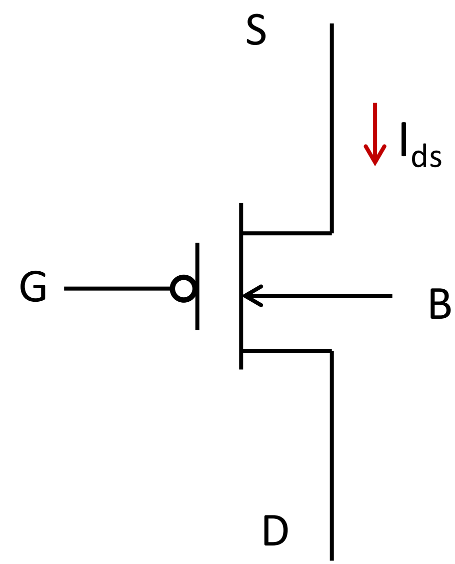


P-type MOSFET

10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: P MOSFET

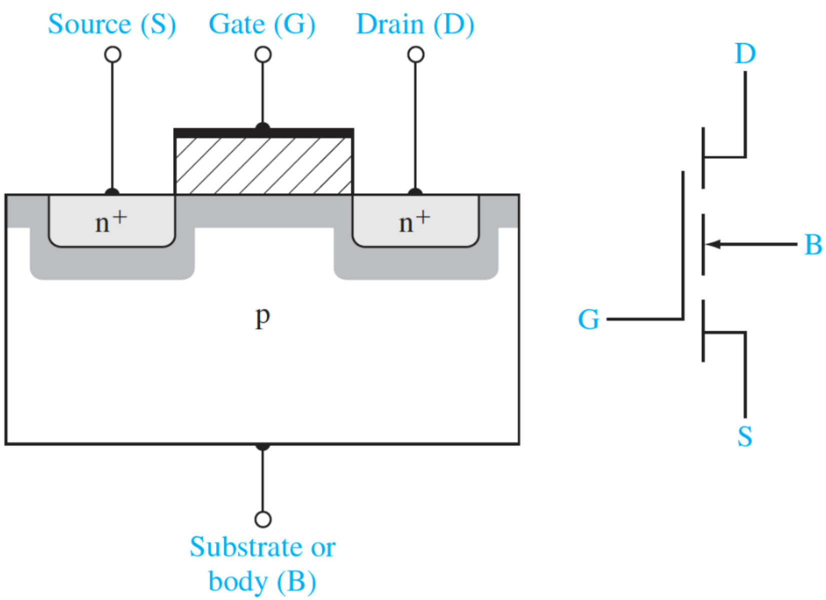




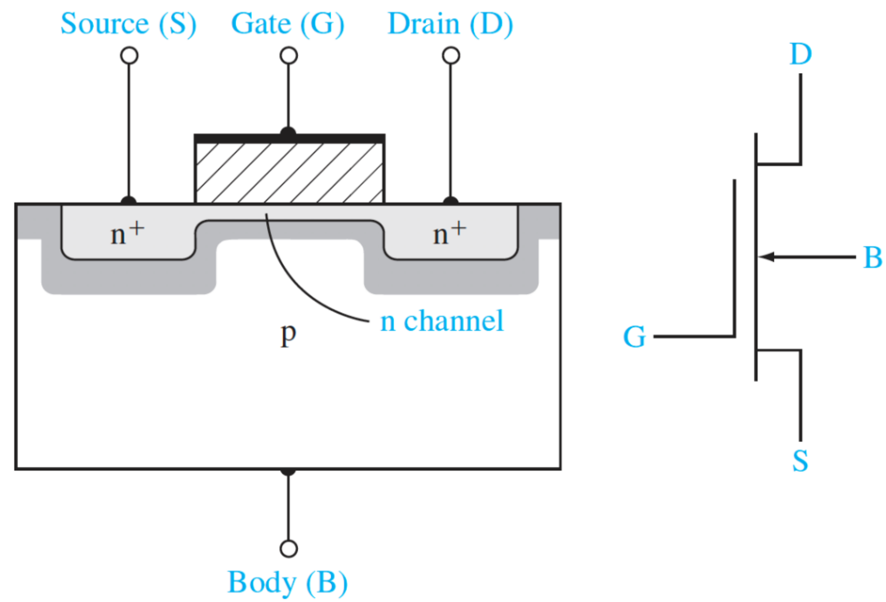
P-type MOSFET

10.4 The basic MOSFET operation

MOSFET structures



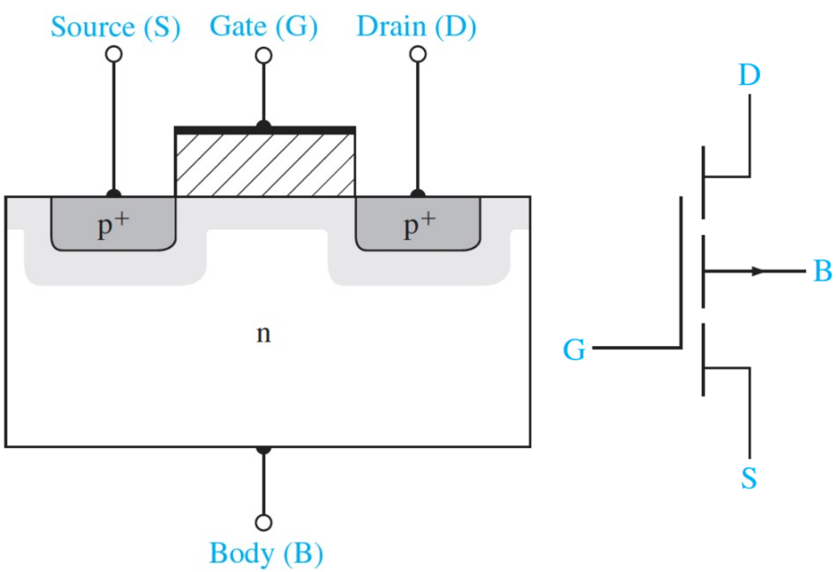
NMOS Enhancement mode



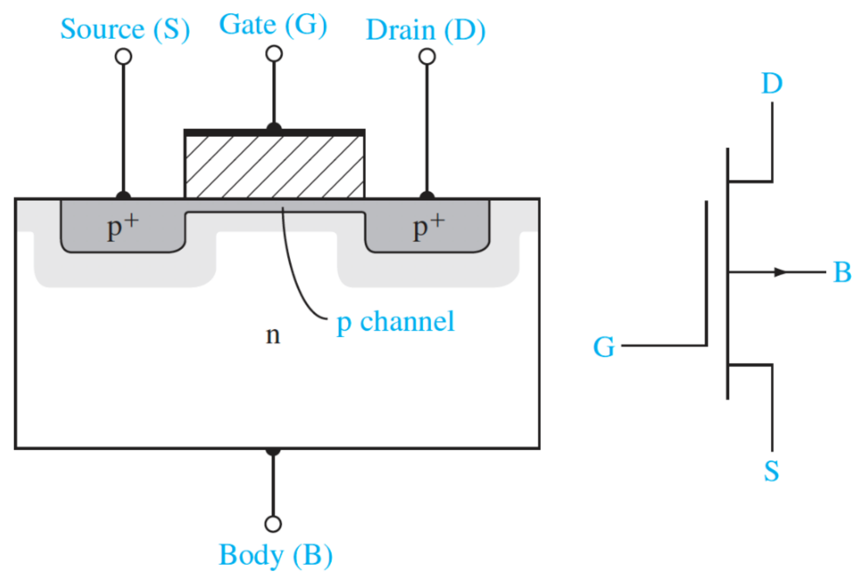
NMOS Depletion mode

10.4 The basic MOSFET operation

MOSFET structures



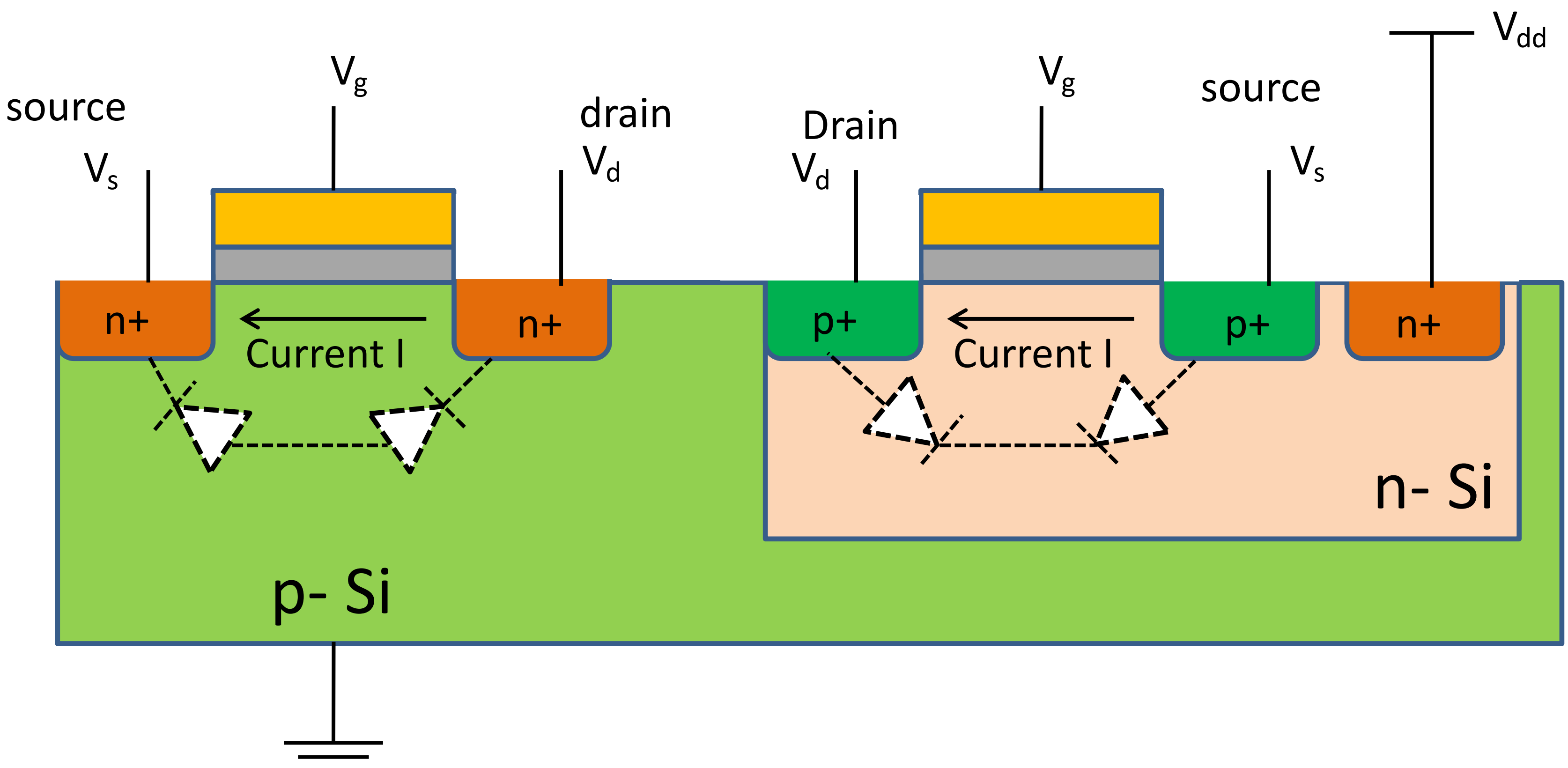
PMOS Enhancement mode



PMOS Depletion mode

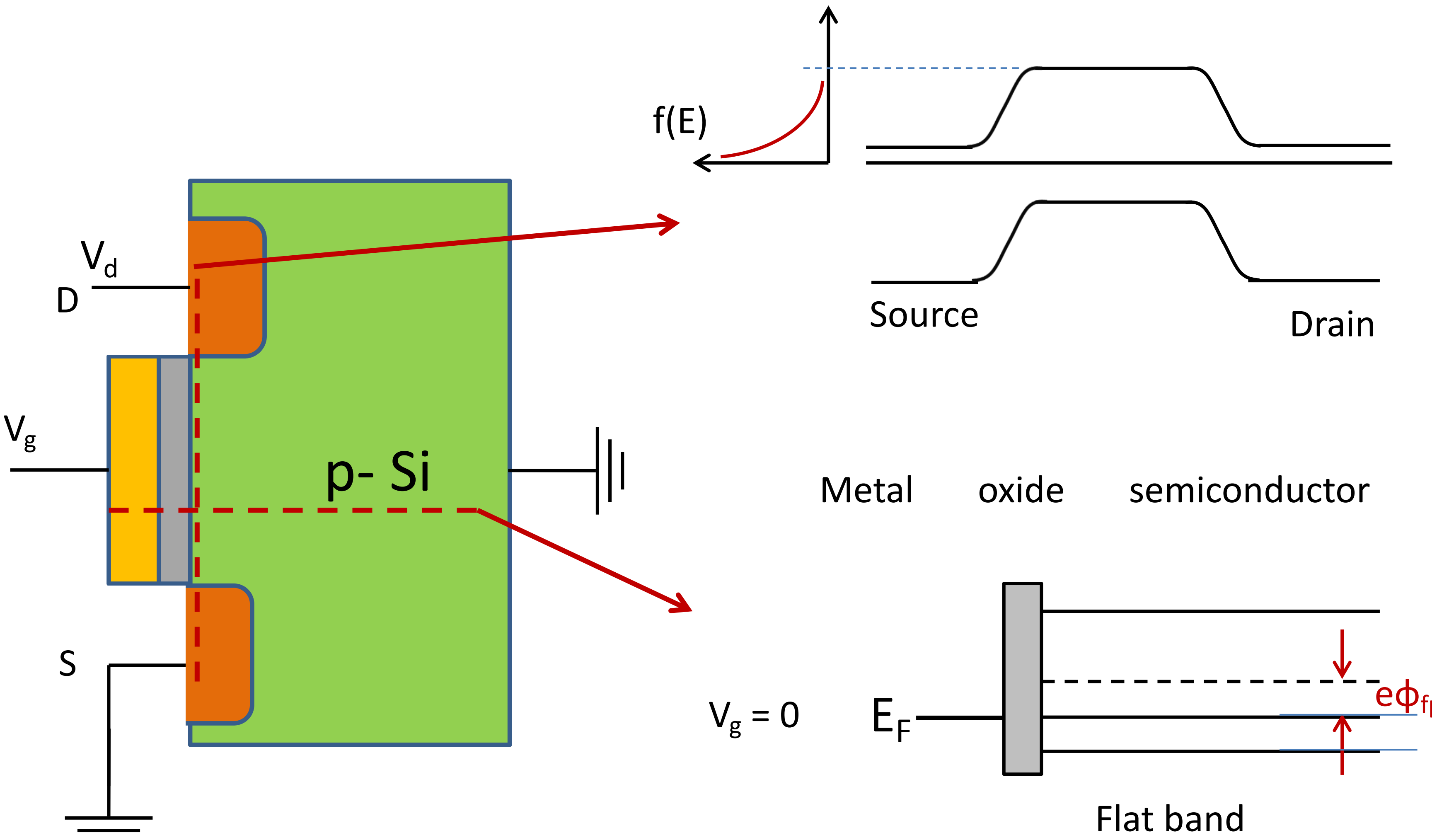
10.4 The basic MOSFET operation

Metal-Oxide-Semiconductor field effect transistor: CMOS

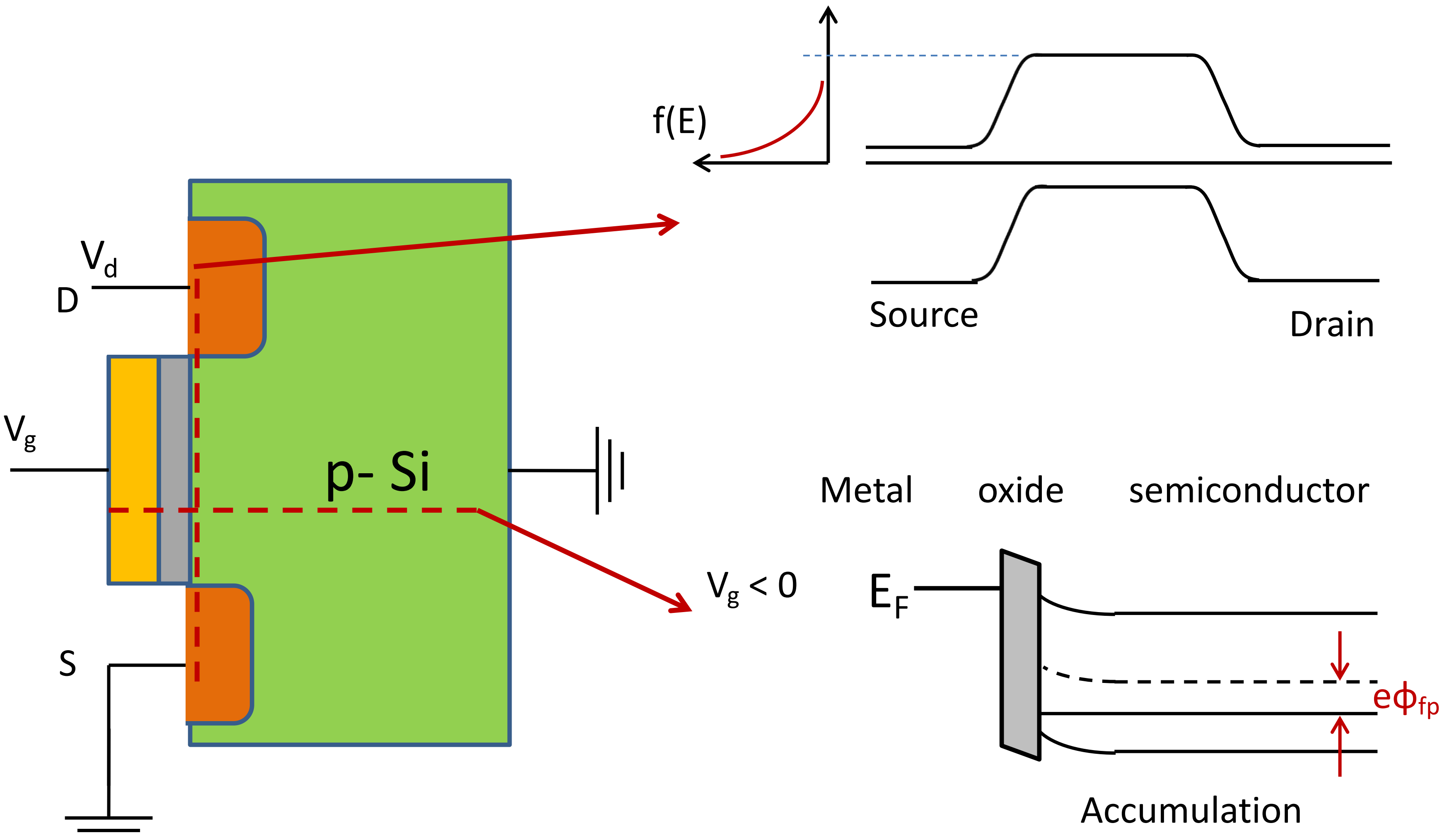


Complementary Metal-oxide-semiconductor (CMOS) field effect transistors

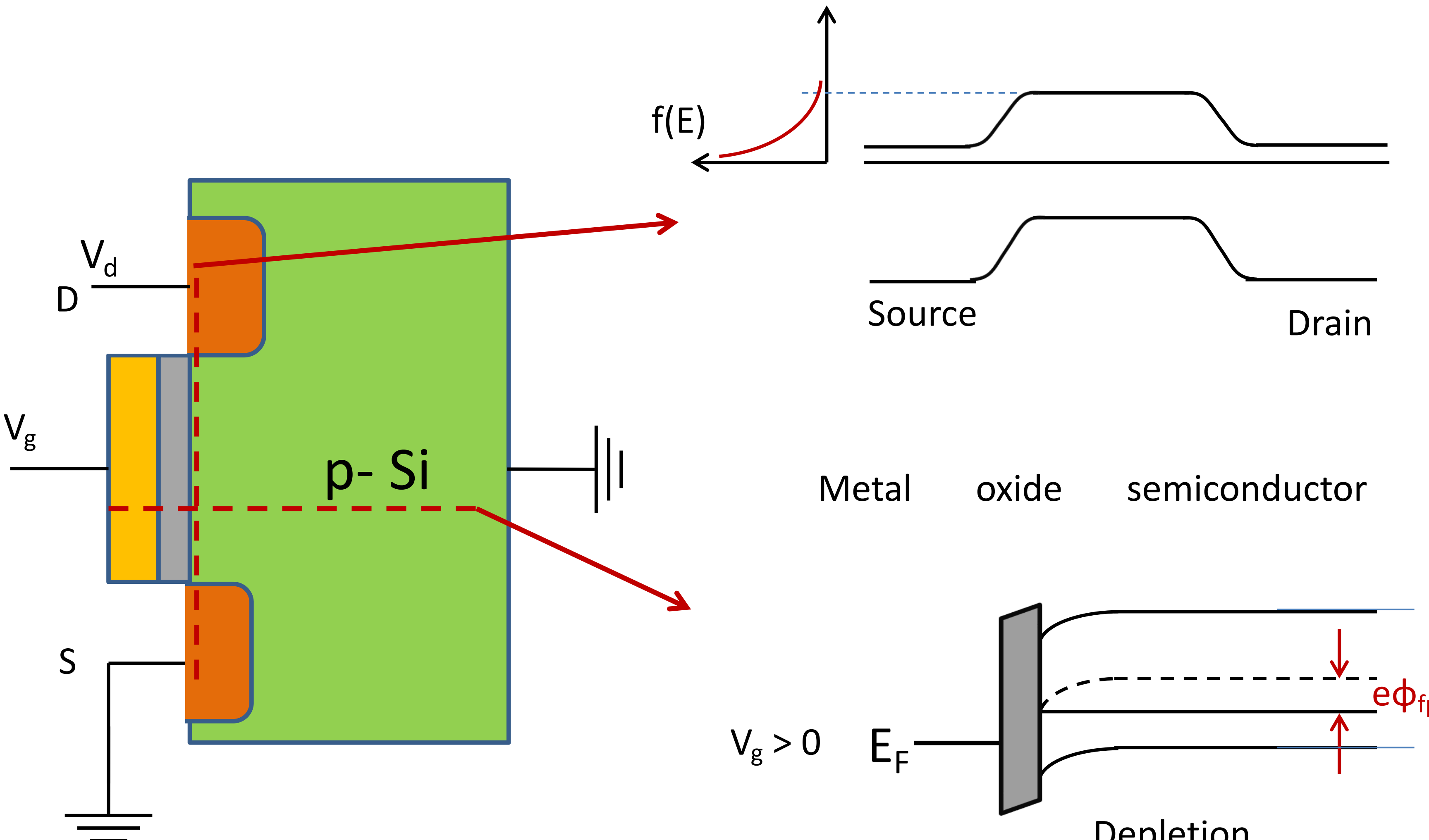
10.4 The basic MOSFET operation



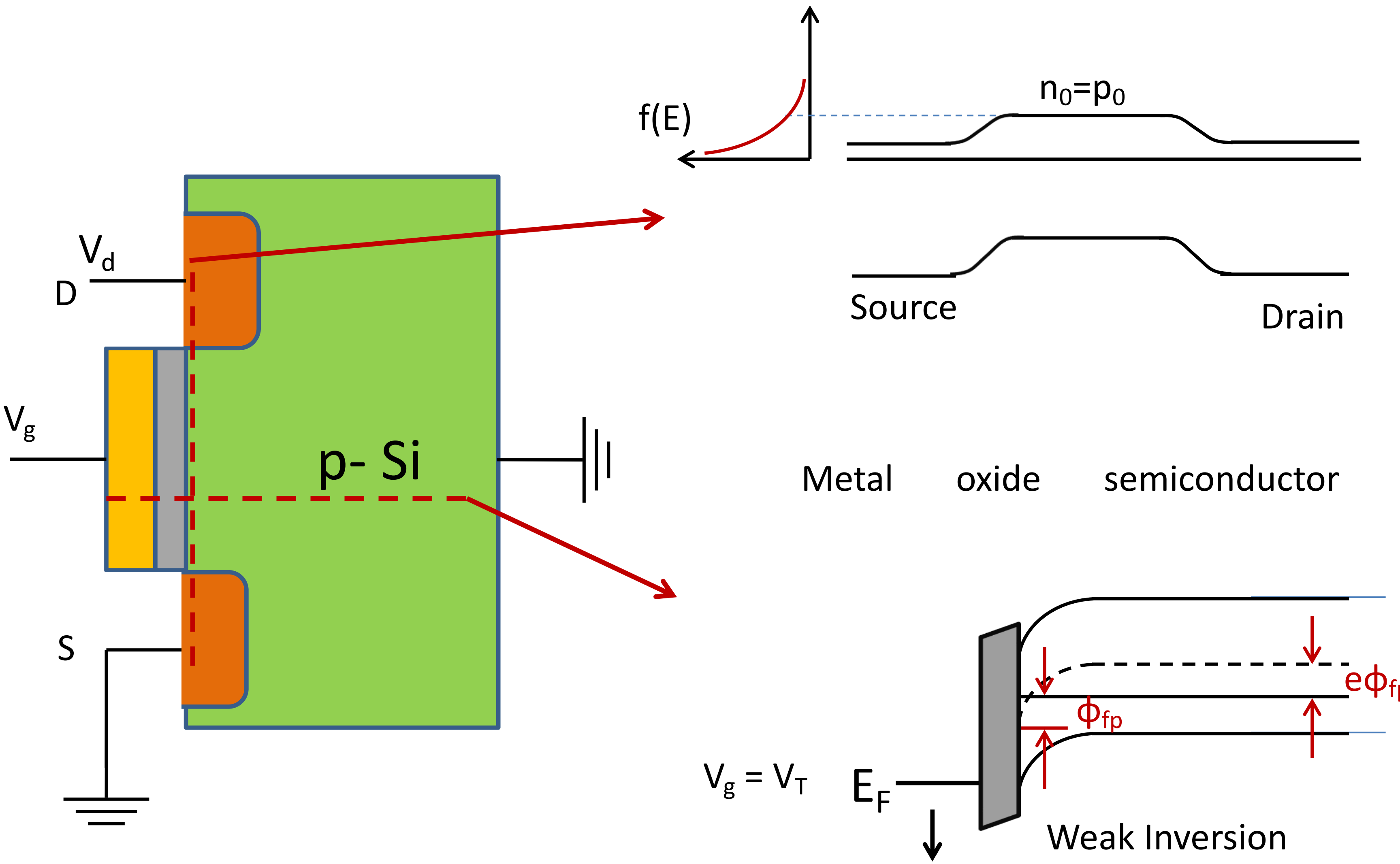
10.4 The basic MOSFET operation



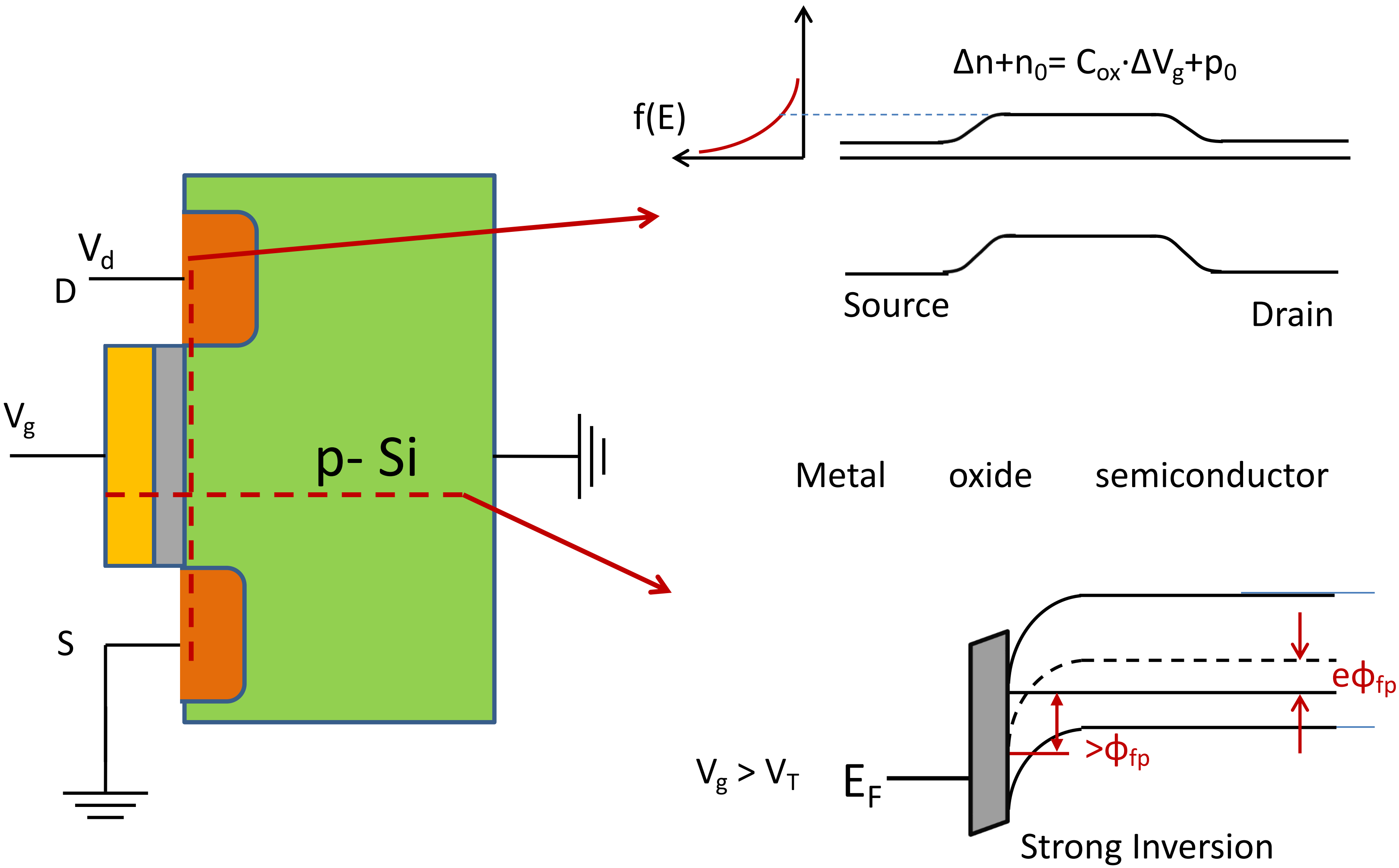
10.4 The basic MOSFET operation



10.4 The basic MOSFET operation

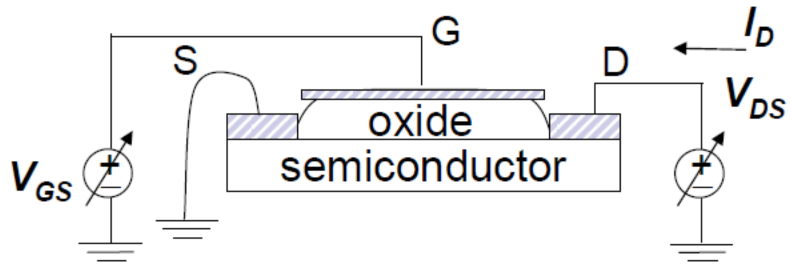


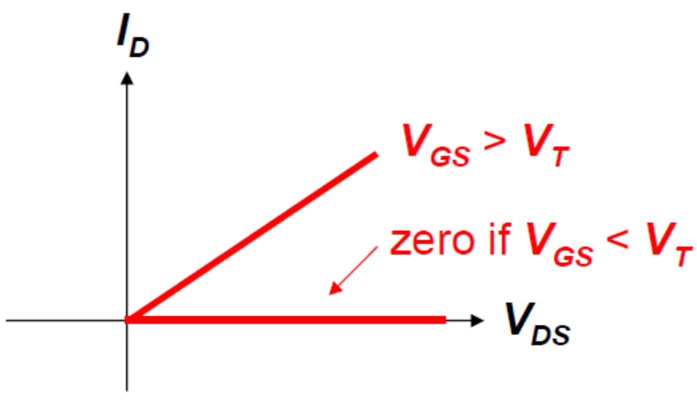
10.4 The basic MOSFET operation



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 → no conduction

10.4 The basic MOSFET operation

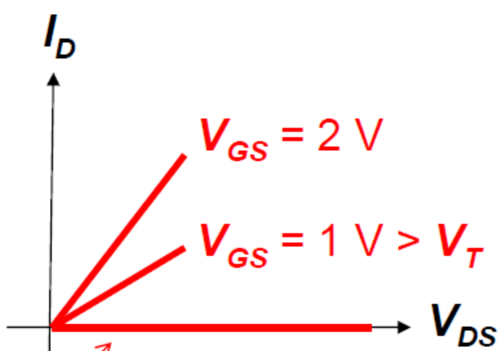
<u>Current-voltage characteristics</u>

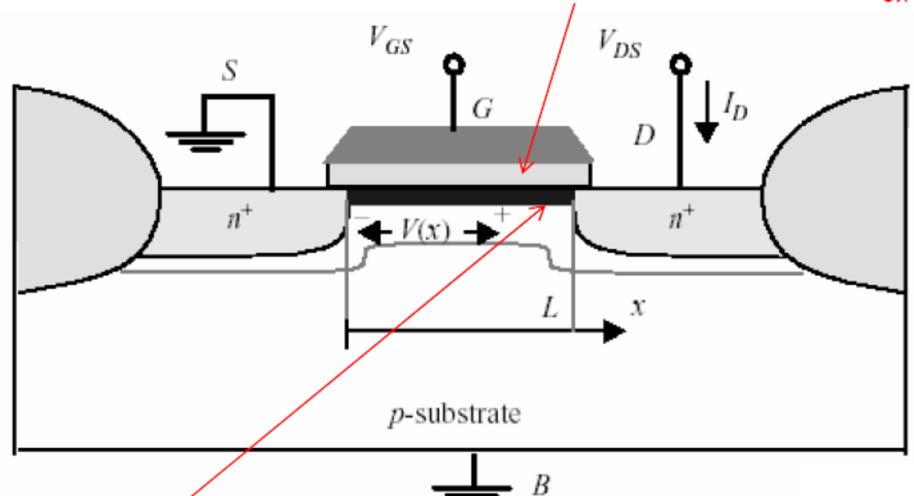
The MOSFET as a Controlled Resistor

- 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

oxide thickness $\equiv t_{ox}$

<u>NMOSFET Example</u>:





I_{DS} = 0 if $V_{GS} < V_T$

Inversion charge density $Q_i(x) = -C_{ox}[V_{GS}-V_T-V(x)]$
where $C_{ox} \equiv \varepsilon_{ox} / t_{ox}$

10.4 The basic MOSFET operation

$$J_{DS} = qn\mu_n E = qn\mu_n \frac{V_{DS}}{L}$$

$$I_{DS} = J_{DS}A_c = J_{DS}\delta W$$

$$I_{DS} = J_{DS}A_c = qn\mu_n \frac{V_{DS}}{L}\delta W = qn\delta\mu_n \frac{W}{L}V_{DS}$$

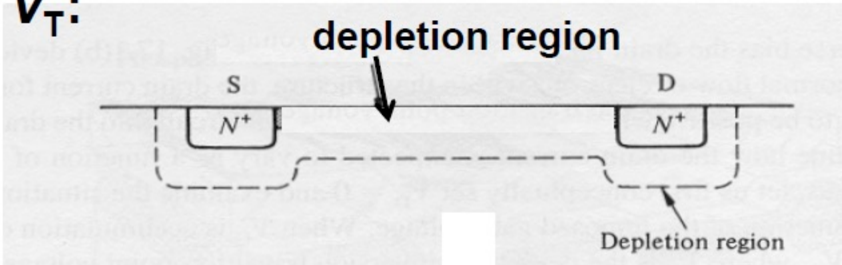
$$qn\delta = -Q_i(x) = C_{ox}[V_{GS} - V_T - V(x)]$$

$$I_{DS} = C_{ox}[V_{GS} - V_T - \frac{1}{2}V_{DS}]\mu_n \frac{W}{L}V_{DS}$$

10.4 The basic MOSFET operation

Charge in an N-Channel MOSFET

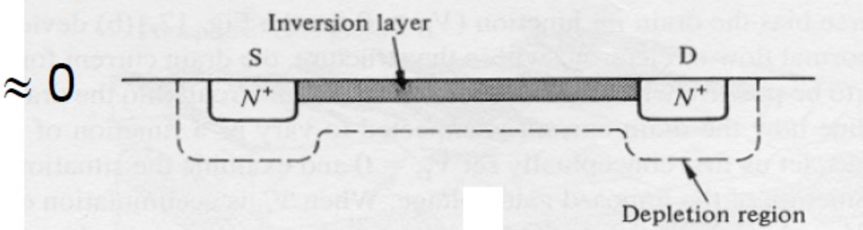
$V_{GS} < V_T$:



(no inversion layer at surface)

$V_{GS} > V_T$:

$V_{DS} \approx 0$

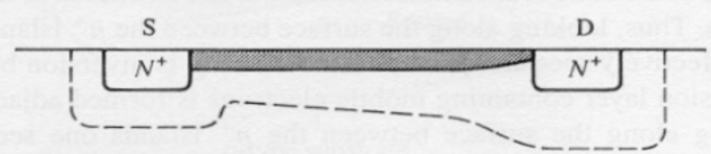


$$I_D = WQ_{inv}v$$

$$= WQ_{inv}\mu_n E$$

$$= WQ_{inv}\mu_n \left(\frac{V_{DS}}{L}\right)$$

$V_{DS} > 0$ (small)



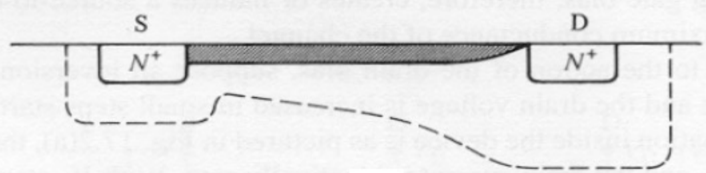
Average electron velocity ***v*** is proportional to lateral electric field ***E***

10.4 The basic MOSFET operation

What Happens at Larger V_{DS}?

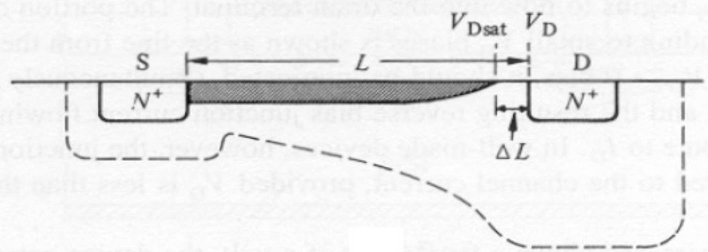
$V_{GS} > V_T$:

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



Inversion-layer is "pinched-off" at the drain end

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



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}

$\Rightarrow$ the drain current I_D saturates

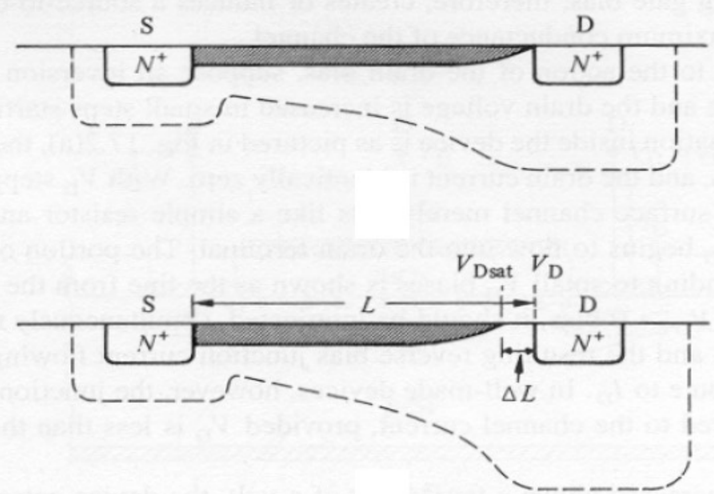
Note: Electrons are swept into the drain by the *E*-field when they enter the pinch-off region.

What Happens at Larger V_{DS}?

$V_{GS} > V_T$:

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

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



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

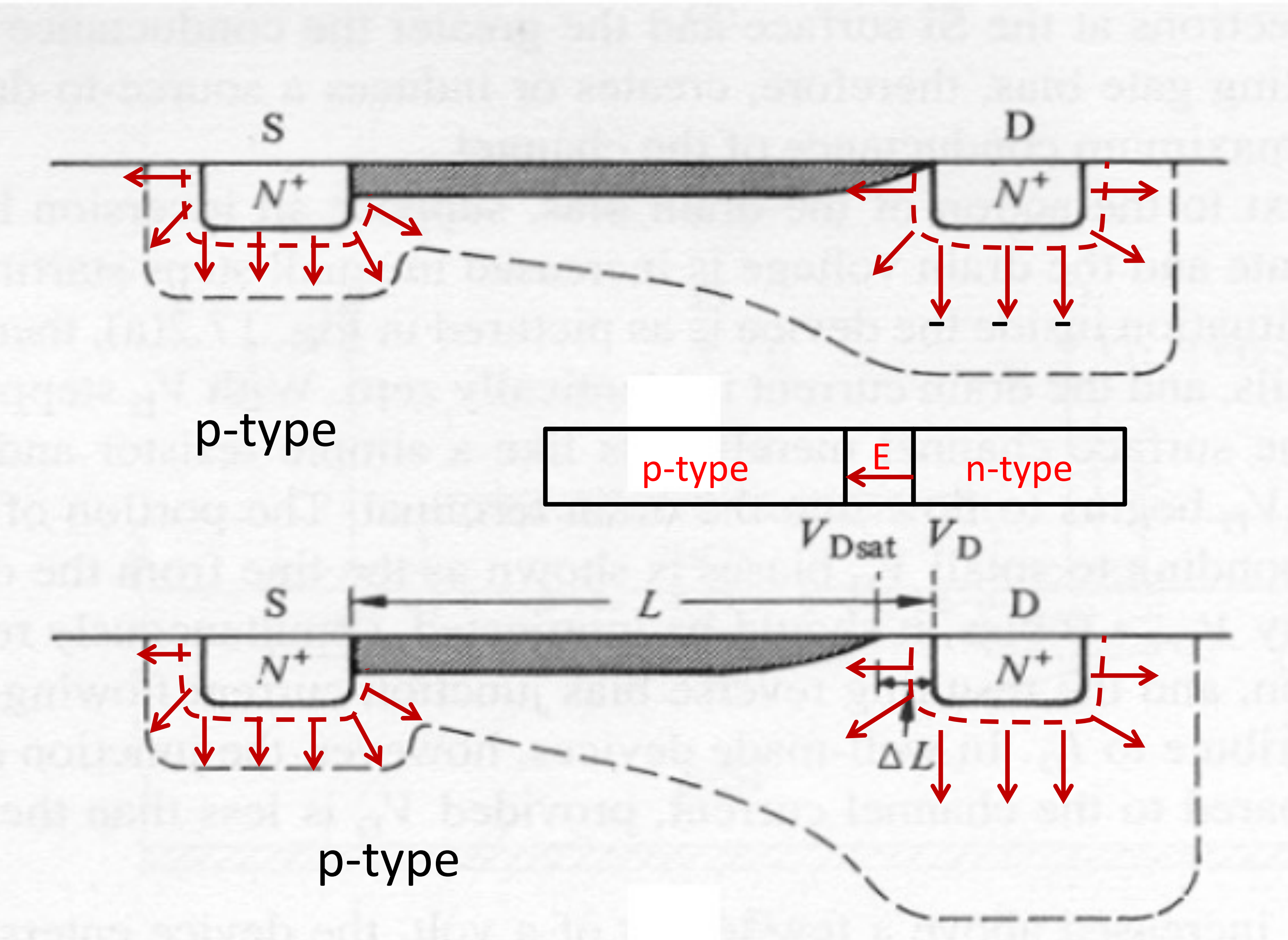
As V_{DS} increases above $V_{GS} - V_T \equiv V_{DSAT}$,

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

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

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

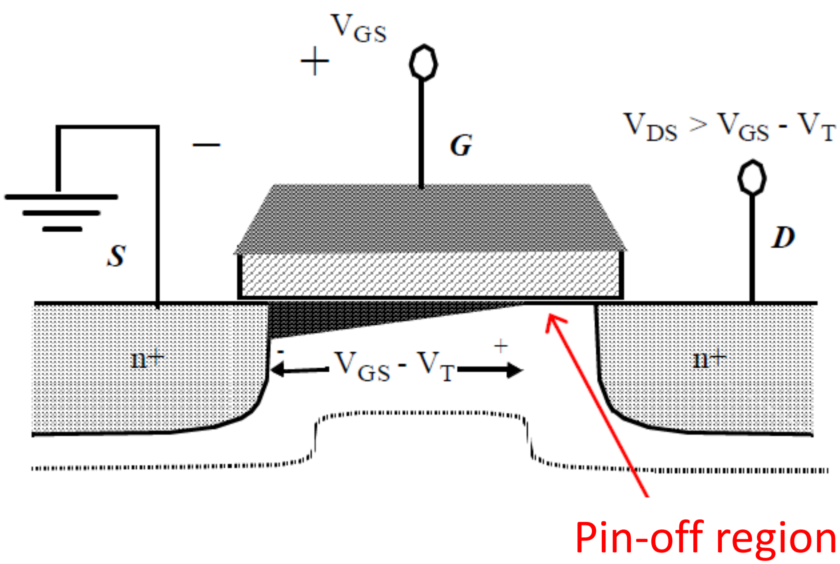
10.4 The basic MOSFET operation



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}).



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

I_D vs. V_{DS} Characteristics

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

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

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

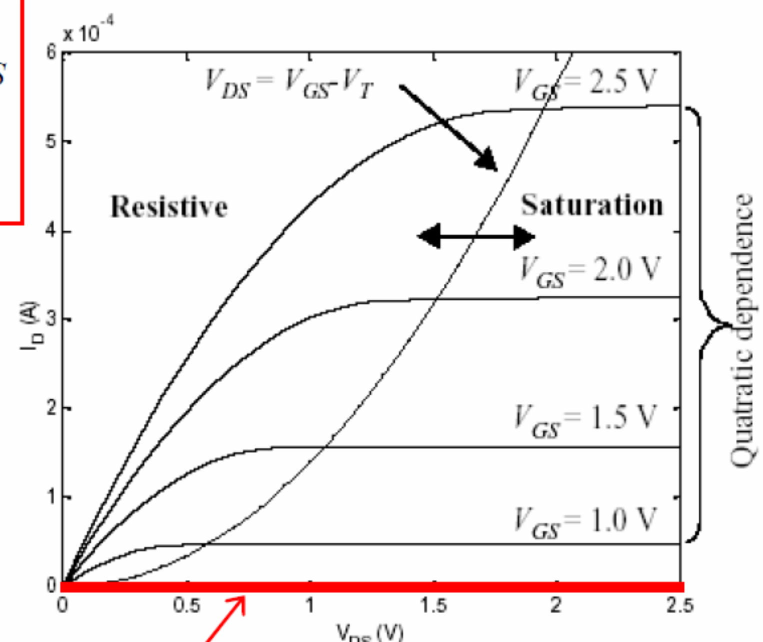
where $k_n' = \mu_n C_{ox}$

process transconductance parameter

2) Saturation Region:
$V_{DS} > V_{GS} - V_T$

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

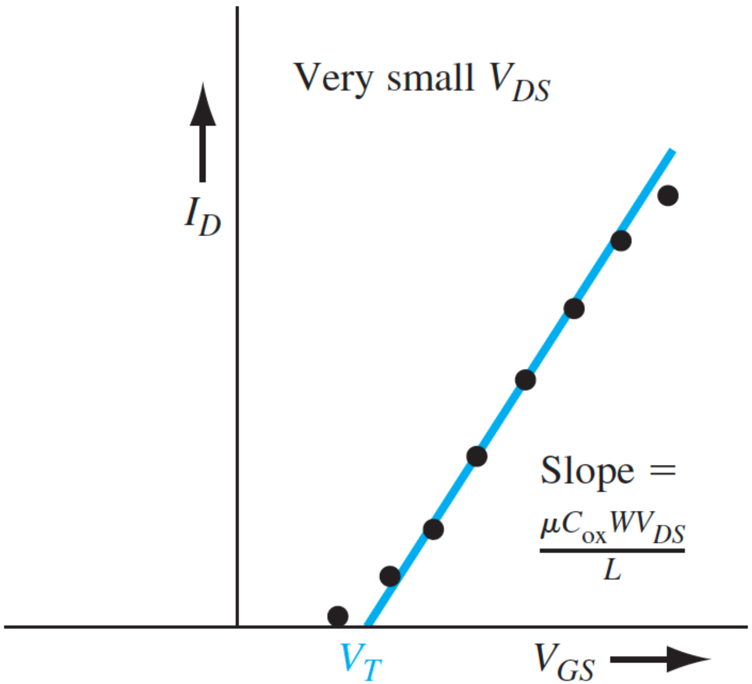
where $k_n' = \mu_n C_{ox}$



"CUTOFF" region: $V_G < V_T$

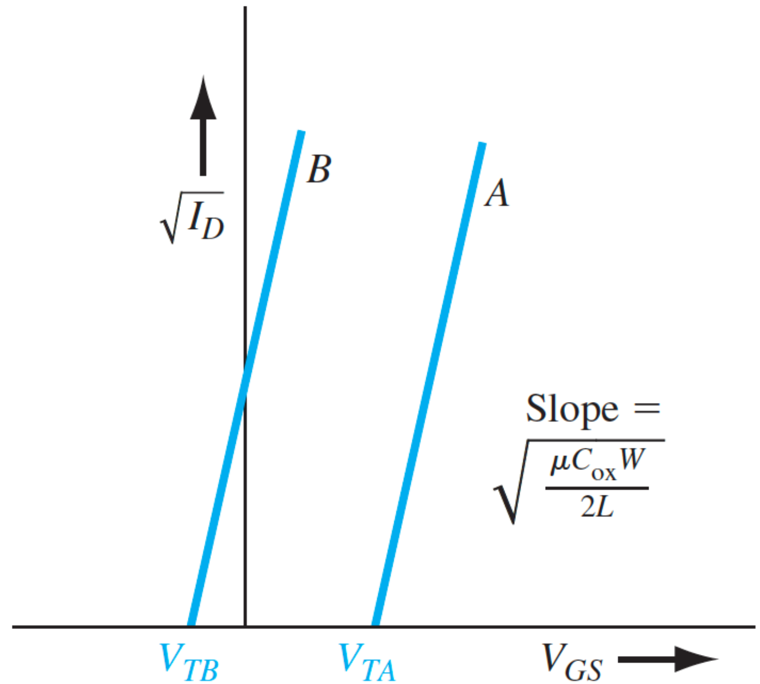
10.4 The basic MOSFET operation

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



(a)

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



(b)

10.4 The basic MOSFET operation

Transconductance: $$g_m = \frac{\partial I_D}{\partial V_{GS}}$$

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

$$g_{mL} = \frac{\partial I_D}{\partial V_{GS}} = \frac{W\mu_n C_{\mathrm{ox}}}{L} \cdot V_{DS}$$

$0 < V_{DS} < V_{GS} - V_T$

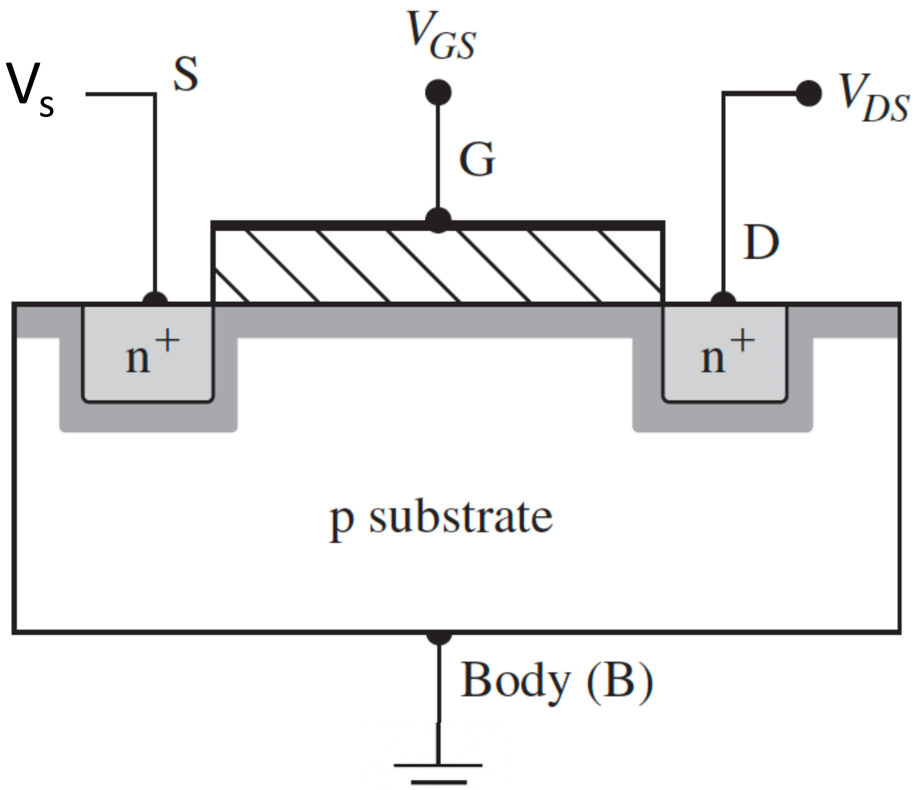
$$I_{DSAT} = \frac{k_n'}{2}\frac{W}{L}\left(V_{GS} - V_T\right)^2$$

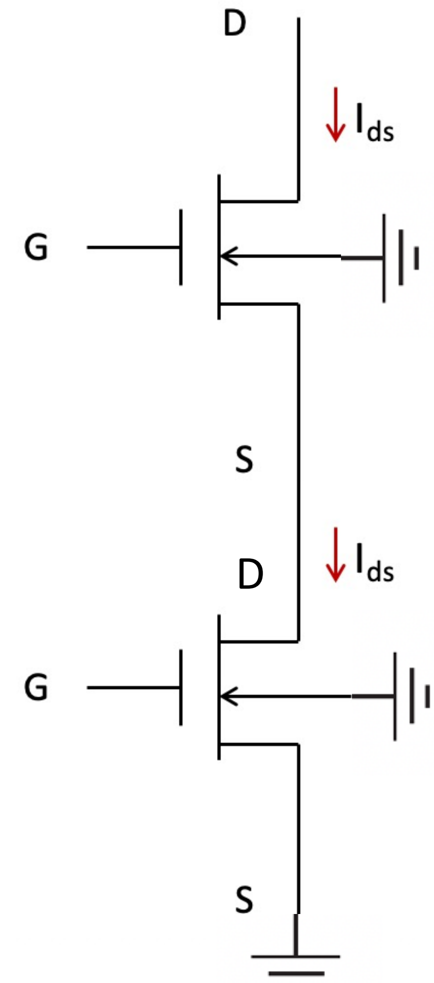
$$g_{ms} = \frac{\partial I_D(\mathrm{sat})}{\partial V_{GS}} = \frac{W\mu_n C_{\mathrm{ox}}}{L}(V_{GS} - V_T)$$

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

10.4 The basic MOSFET operation

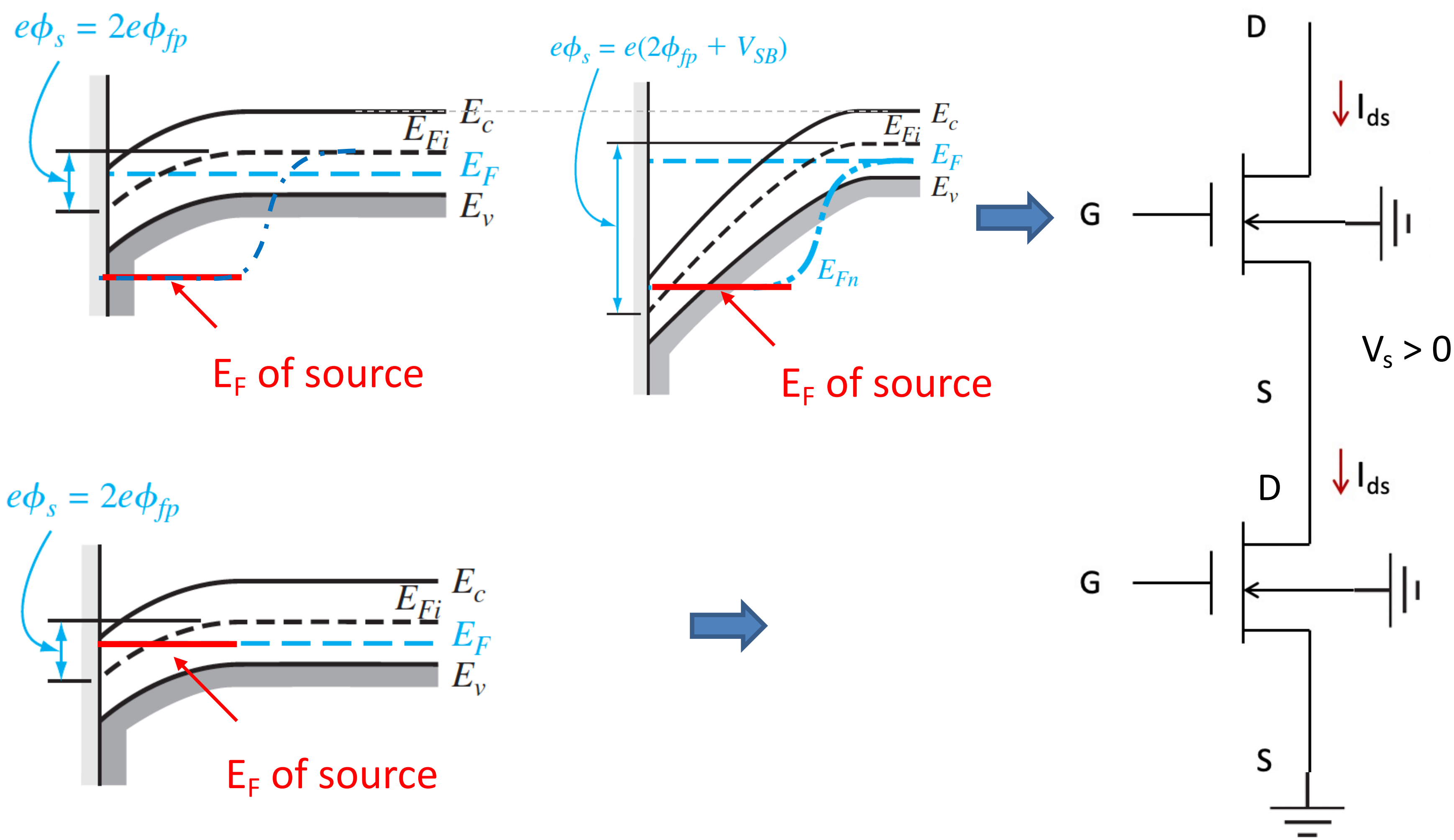
Substrate bias effect





10.4 The basic MOSFET operation

Substrate bias effect



10.4 The basic MOSFET operation

Substrate bias effect

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

$$Q'_{SD}\,(\max) = -eN_a x_{dT} = -\sqrt{2e\epsilon_s N_a (2\phi_{fp})}$$

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

$$Q'_{SD} = -eN_a x_d = -\sqrt{2e\epsilon_s N_a (2\phi_{fp} + V_{SB})}$$

The change in the space charge density is then

$$\Delta Q'_{SD} = -\sqrt{2e\epsilon_s N_a}\left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right]$$

10.4 The basic MOSFET operation

Substrate bias effect

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

$$\gamma = \frac{\sqrt{2e\epsilon_s N_a}}{C_{ox}} \qquad \Delta V_T = \gamma\left[\sqrt{2\phi_{fp} + V_{SB}} - \sqrt{2\phi_{fp}}\right]$$