VE 320 Fall 2021

Introduction to Semiconductor Devices

Instructor: Rui Yang （杨睿）

Office: JI Building 434

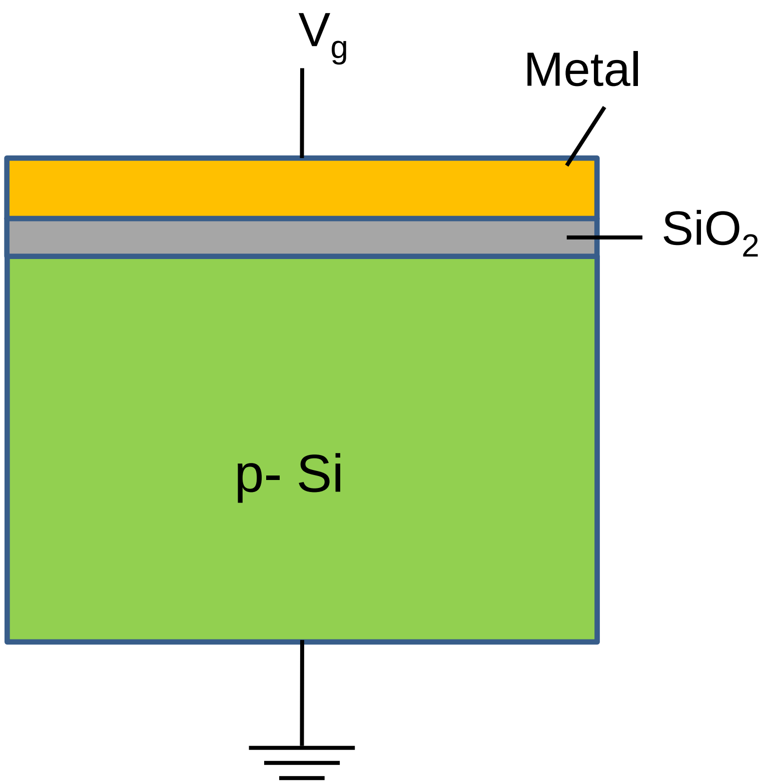
rui.yang@sjtu.edu.cn

Lecture 12

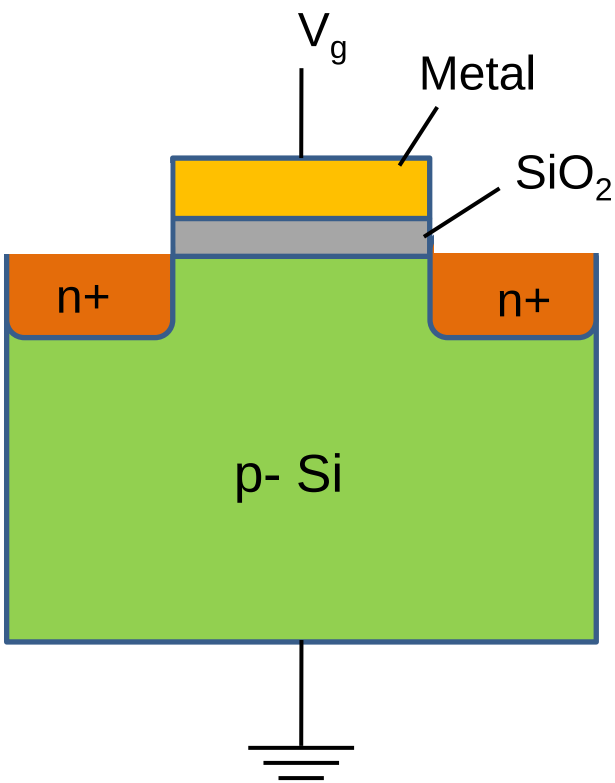
MOSFET
(Chapter 10 & 11)

MOS capacitor and MOSFET

Metal-Oxide-Semiconductor field effect transistor: MOSFET



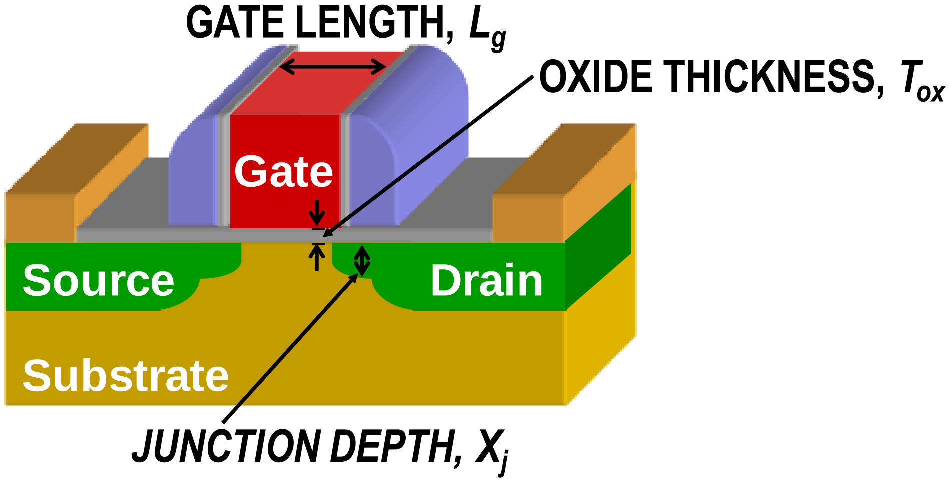
MOS capacitor

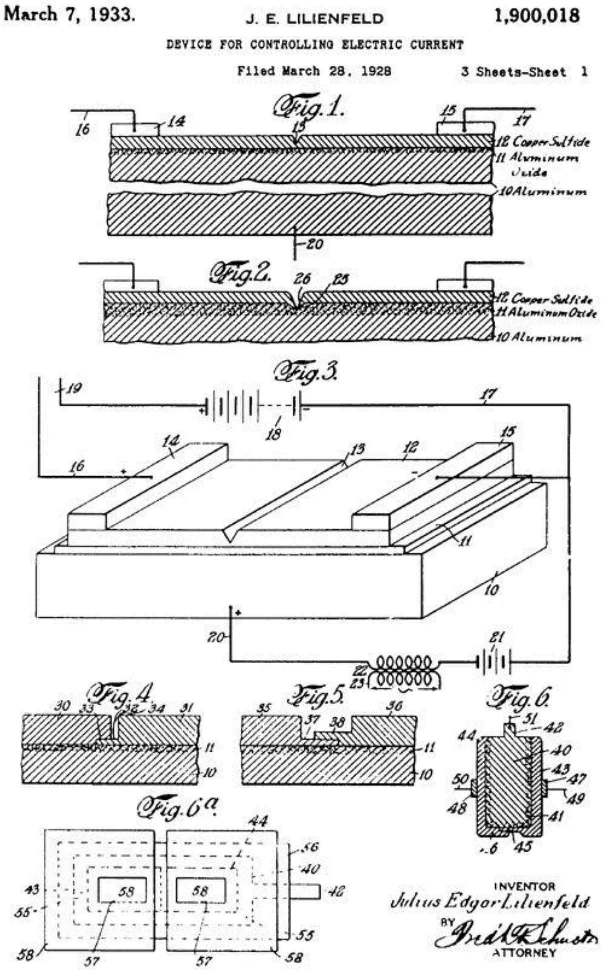


MOSFET

MOS capacitor and MOSFET

Metal-Oxide-Semiconductor field effect transistor: MOSFET



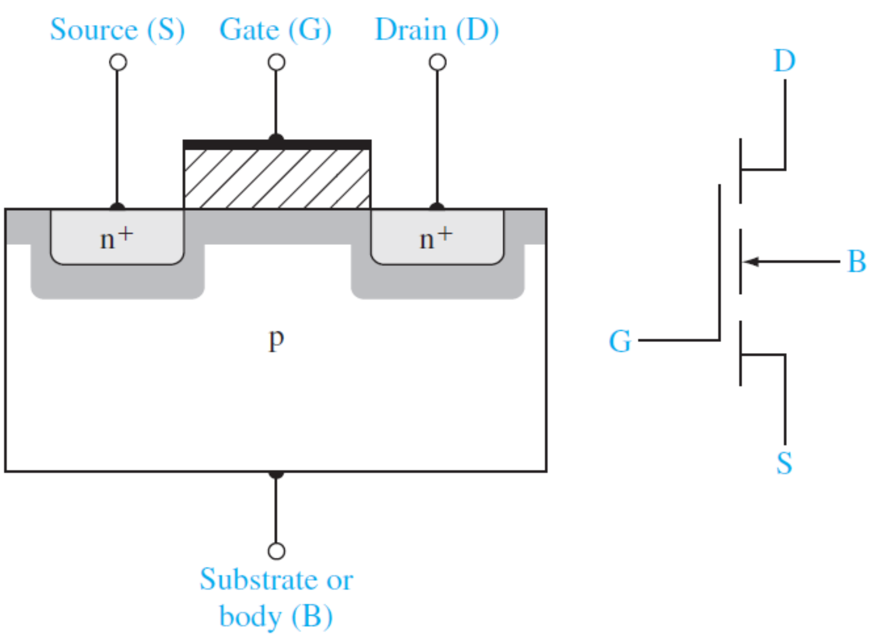


- First MOSFET patents: Julius Lilienfeld (early 1930s)
- This invalidated most of Bardeen, Brattain and Shockley's transistor patent claims in the late 1940s!
- But the MOSFET did not work in practice until the 1960s. Why?

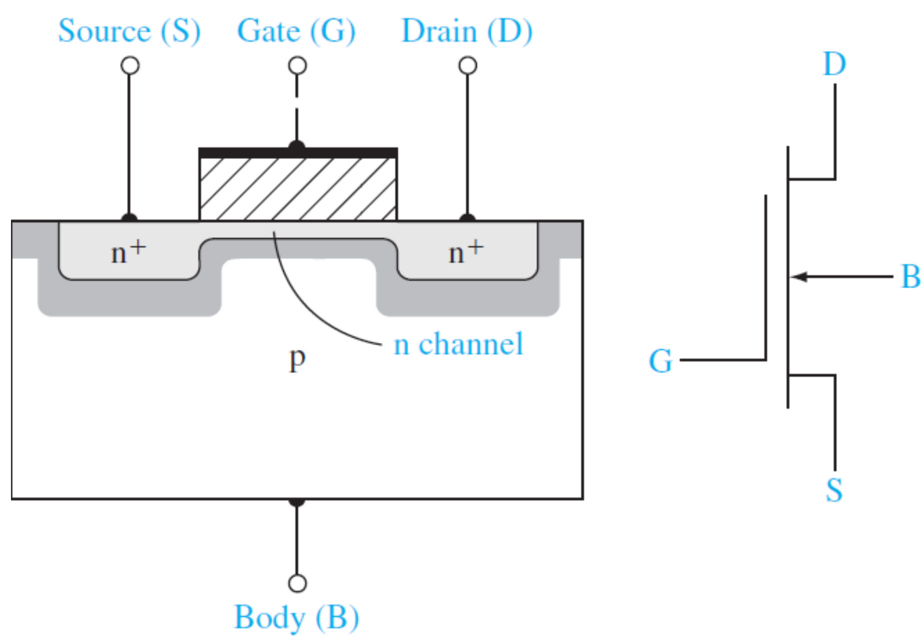
MOSFET

Different types of MOSFETs:

n-channel enhancement mode MOSFET



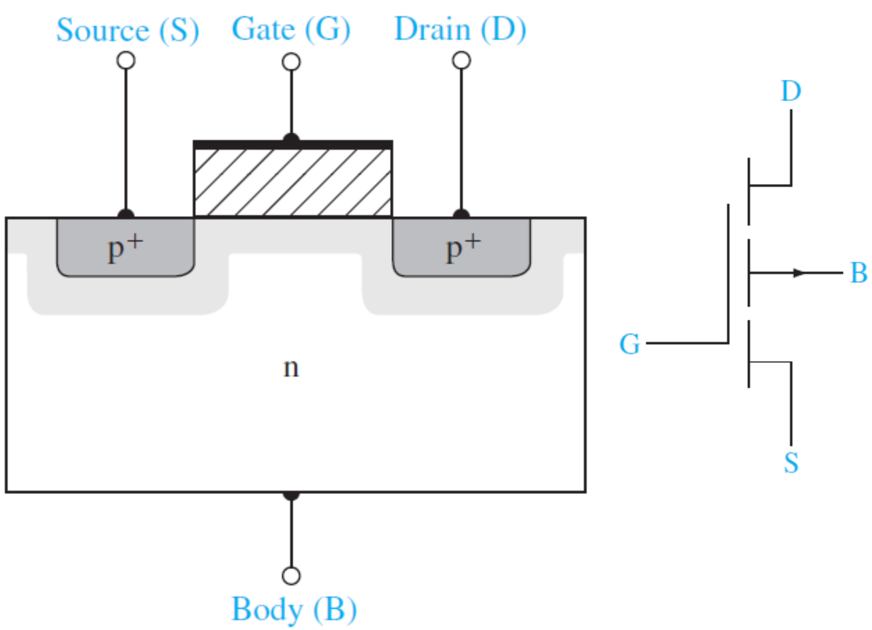
n-channel depletion mode MOSFET



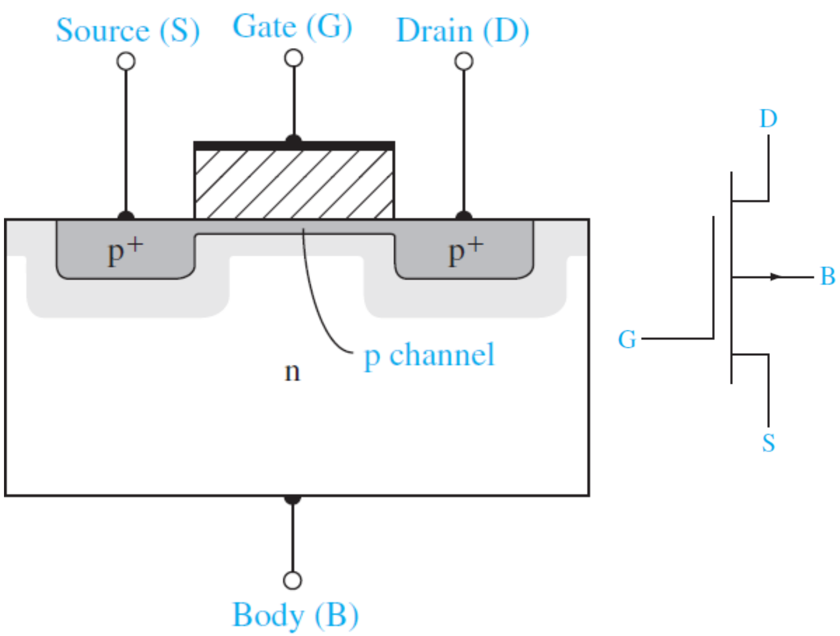
MOSFET

Different types of MOSFETs:

p-channel enhancement mode MOSFET

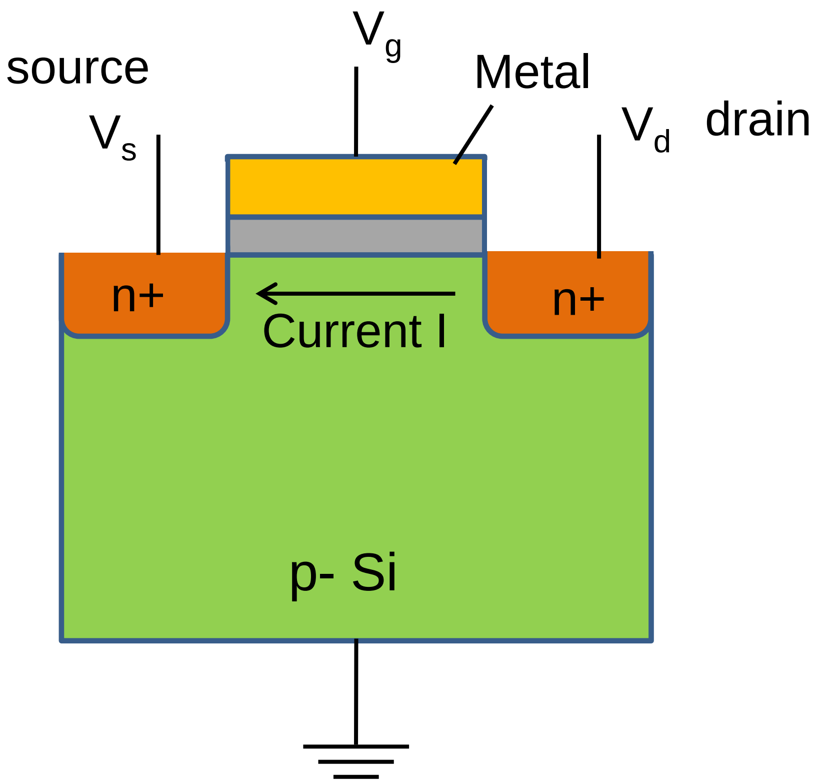


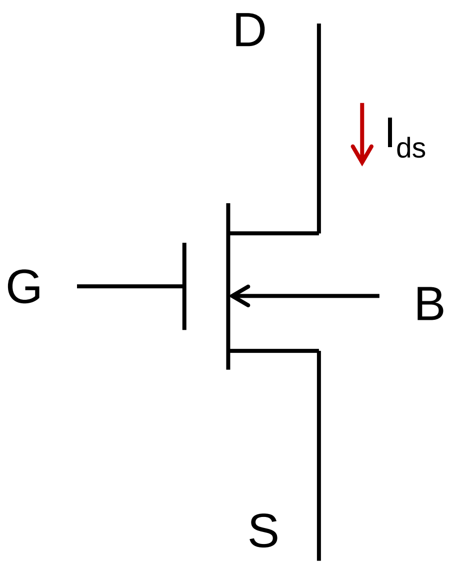
p-channel depletion mode MOSFET



MOSFET structure and band bending

Metal-Oxide-Semiconductor field effect transistor: MOSFET

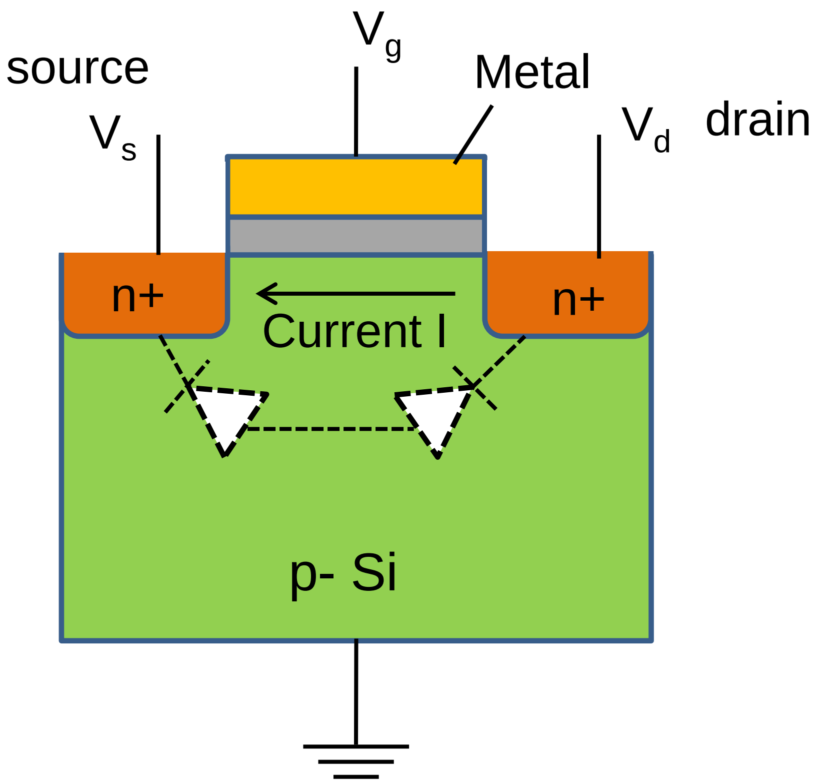




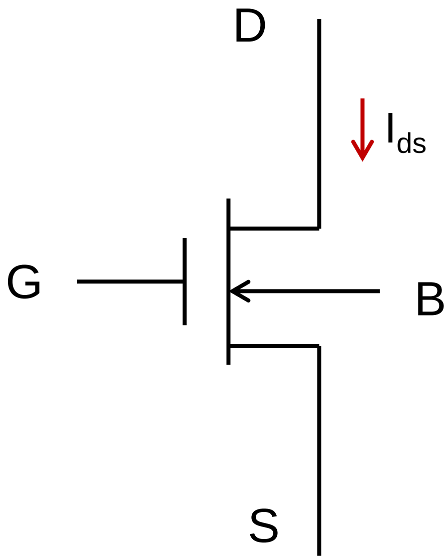
Metal-oxide-semiconductor (MOS)

MOSFET structure and band bending

Metal-Oxide-Semiconductor field effect transistor: MOSFET



MOSFET



MOSFET structure and band bending

V_{GS}<V_T

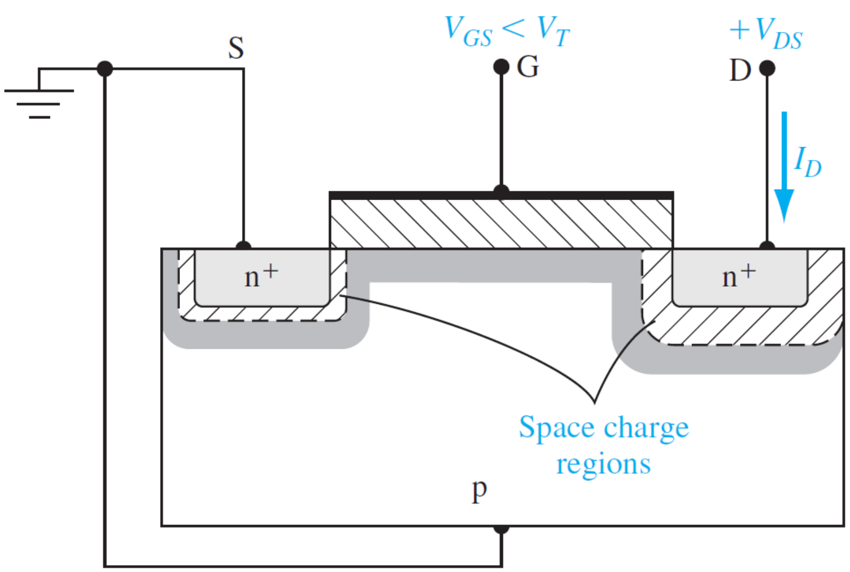
Nearly zero current

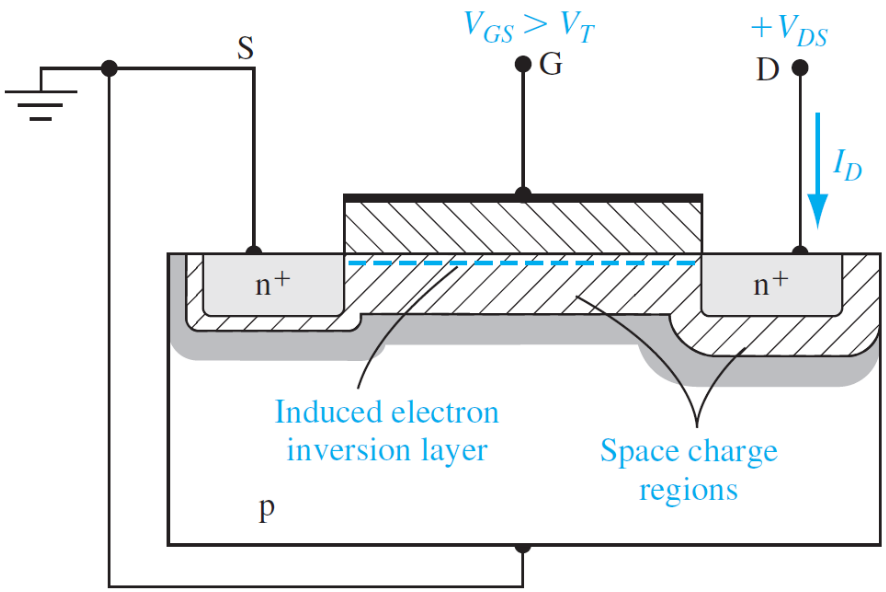
V_{GS}>V_T, small V_{DS}

Like a resistor: ideally (good contact)

$$I_D = g_d V_{DS}$$

$$g_d = \frac{W}{L} \cdot \mu_n |Q'_n|$$





MOSFET structure and band bending

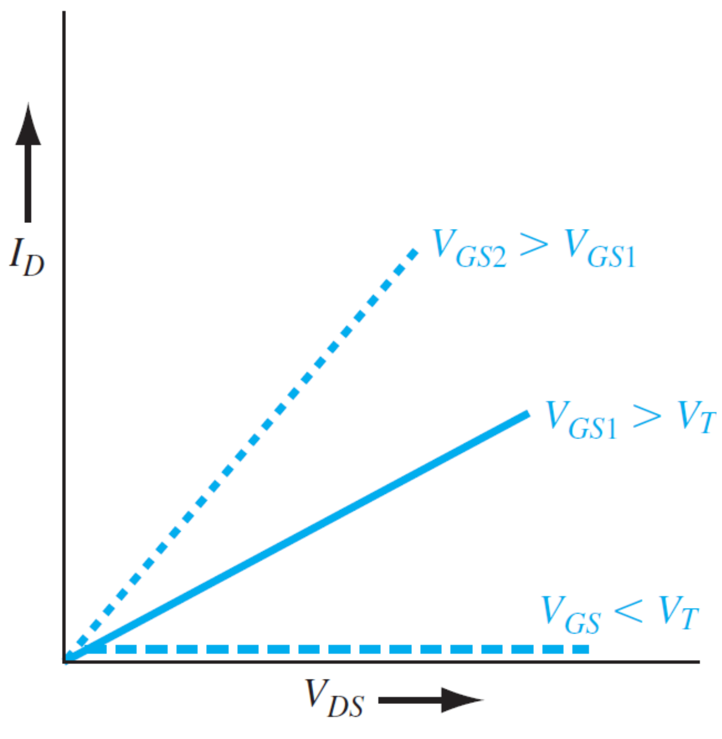
μ_n: mobility of the electrons in the inversion layer
$|Q_n'|$: magnitude of the inversion layer charge per unit area

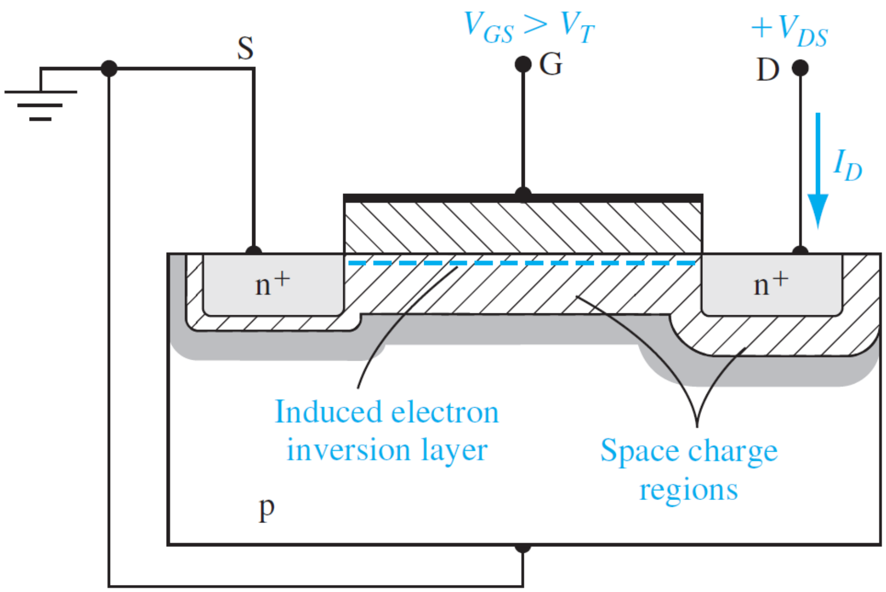
V_{GS}>V_T, small V_{DS}

Like a resistor: ideally (good contact)

$$I_D = g_d V_{DS}$$

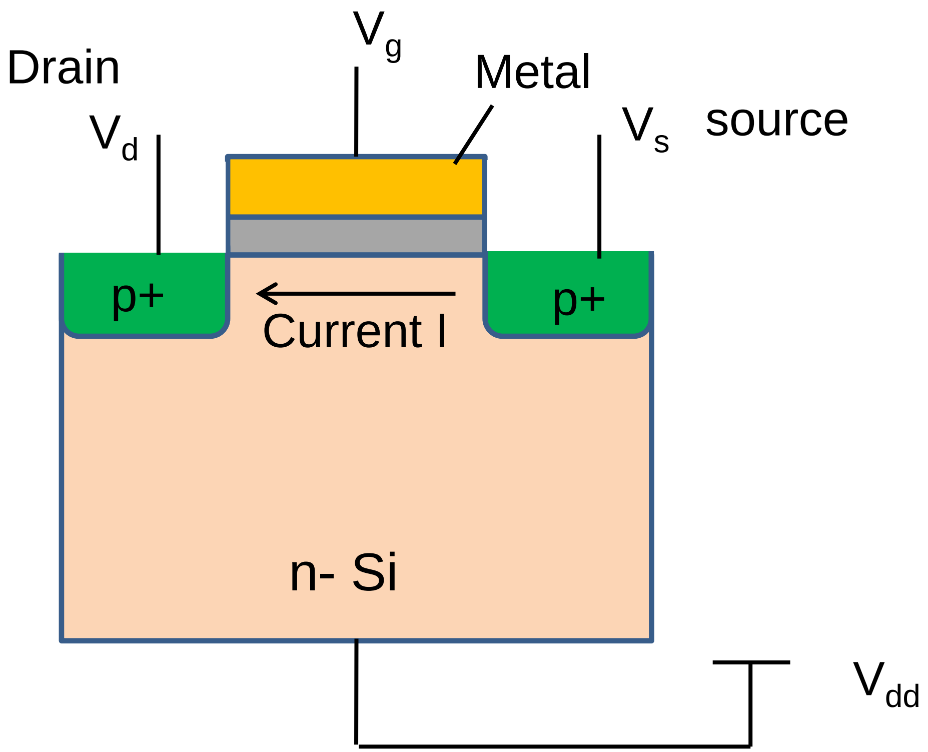
$$g_d = \frac{W}{L} \cdot \mu_n |Q_n'|$$

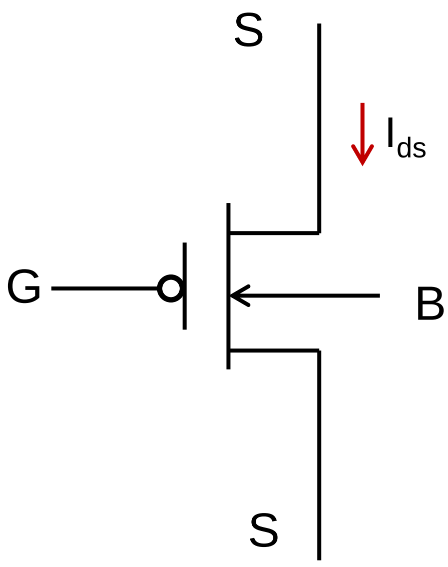




MOSFET structure and band bending

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

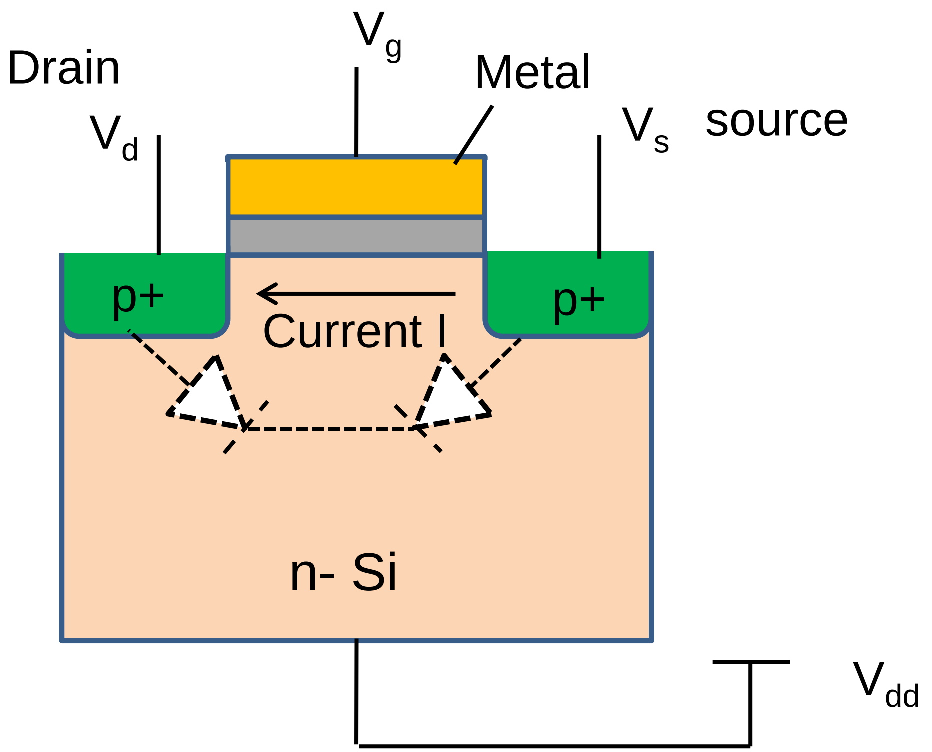




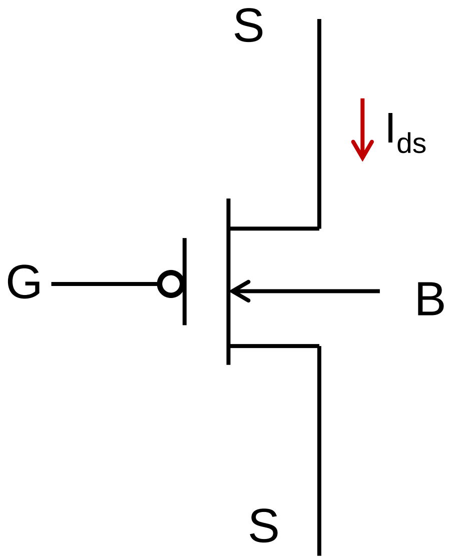
P-type MOSFET

MOSFET structure and band bending

Metal-Oxide-Semiconductor field effect transistor: P MOSFET

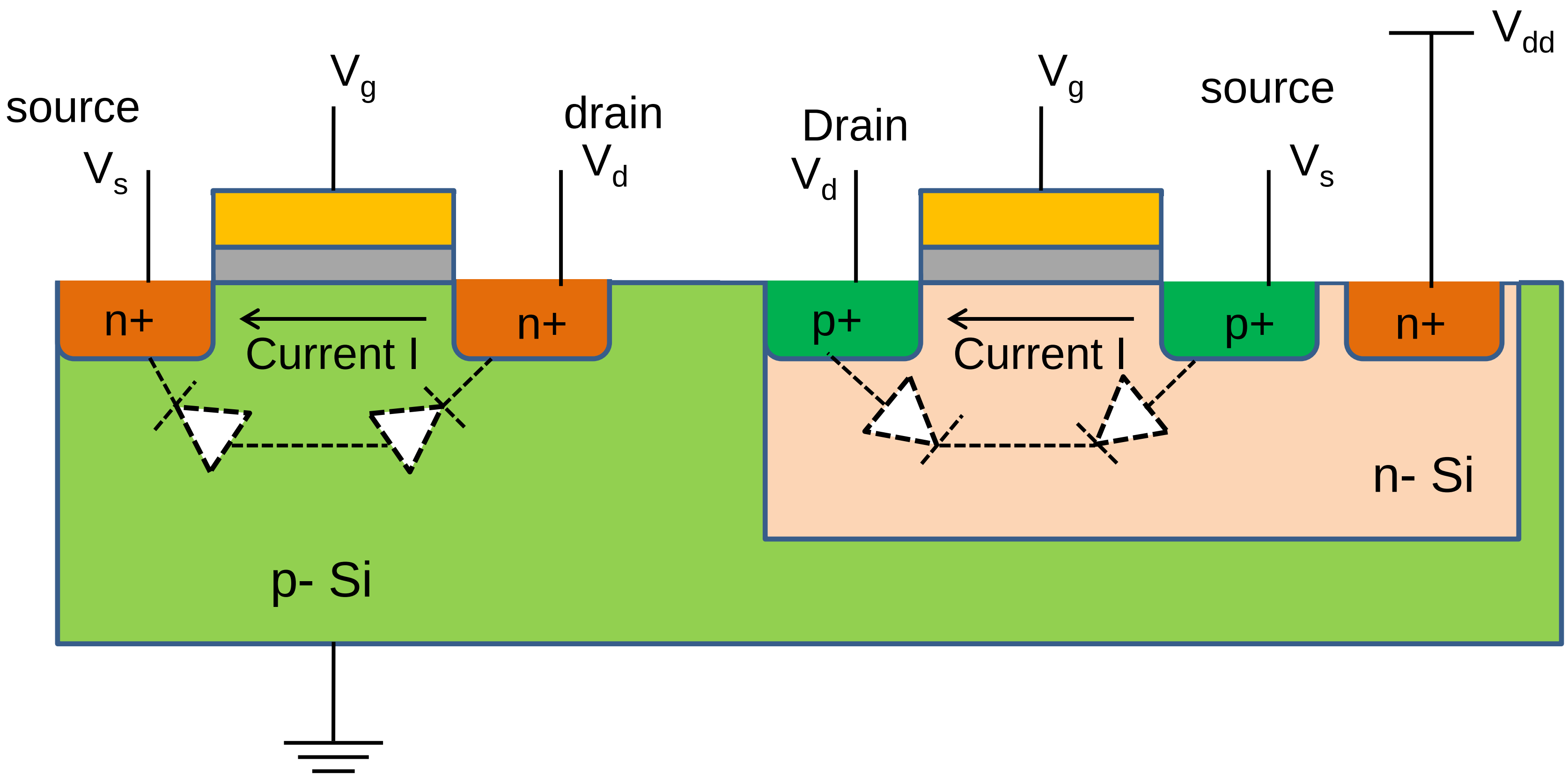


P-type MOSFET



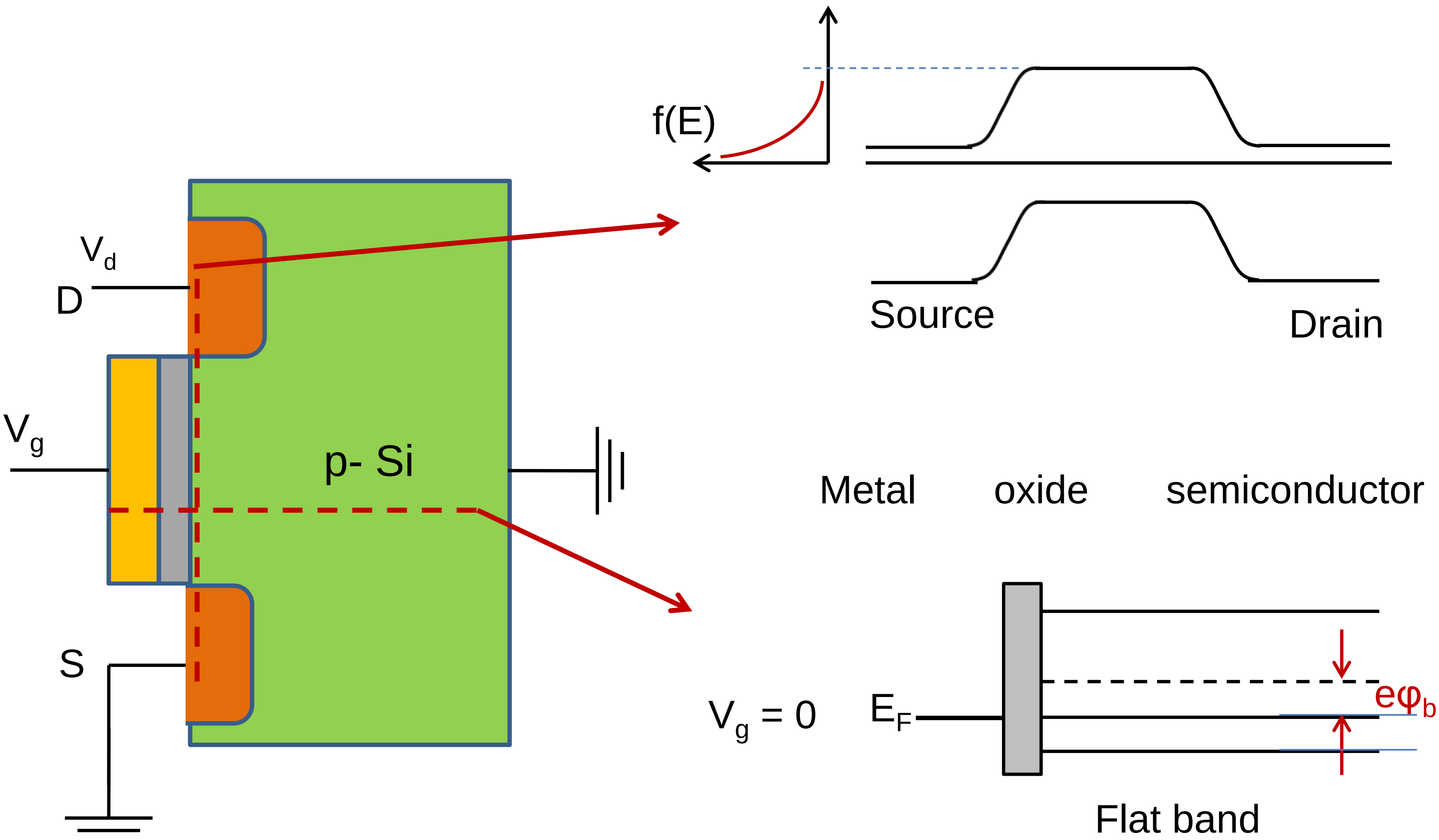
MOSFET structure and band bending

Metal-Oxide-Semiconductor field effect transistor: MOSFET

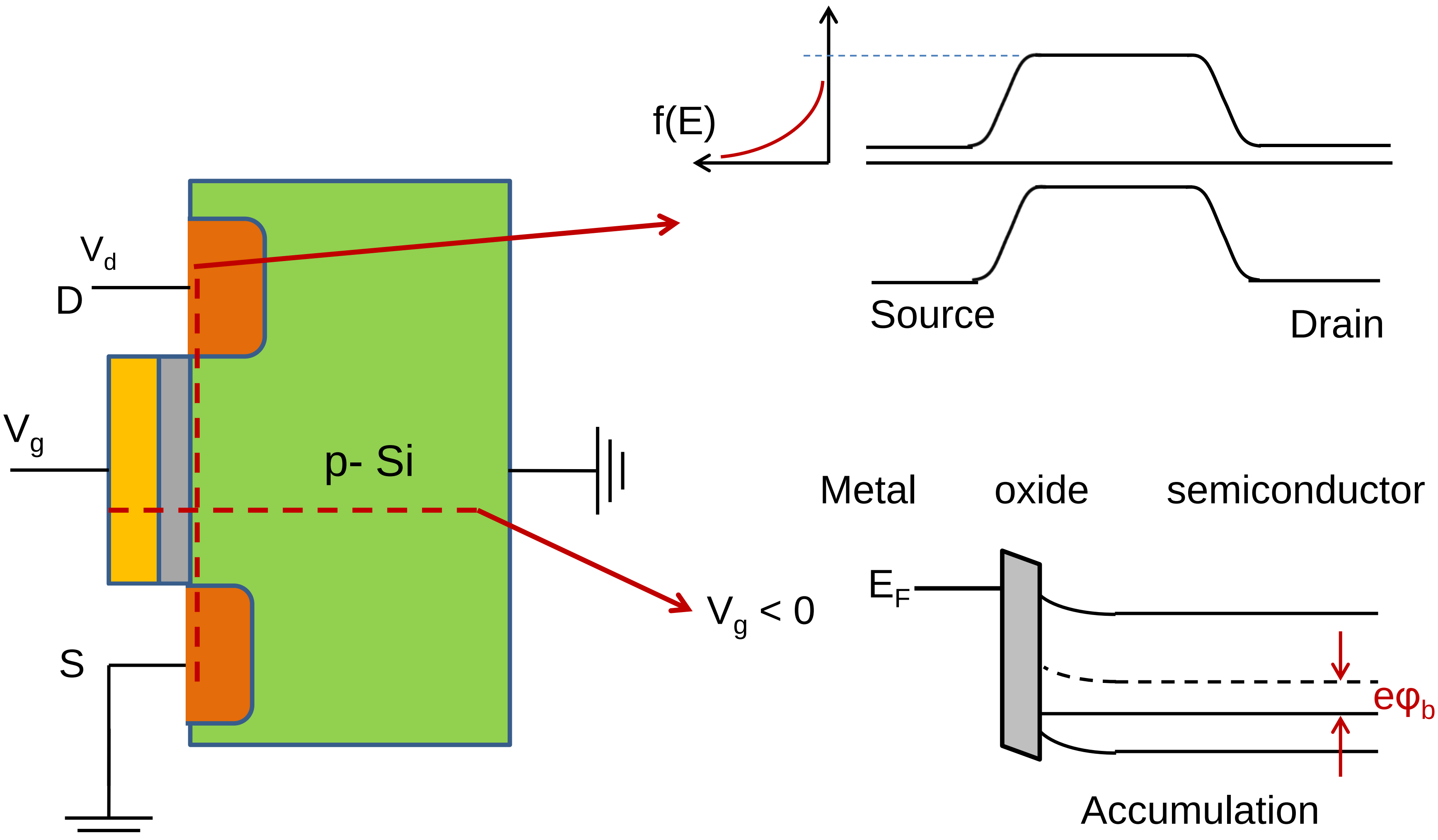


Complementary Metal-oxide-semiconductor (CMOS) field effect transistors

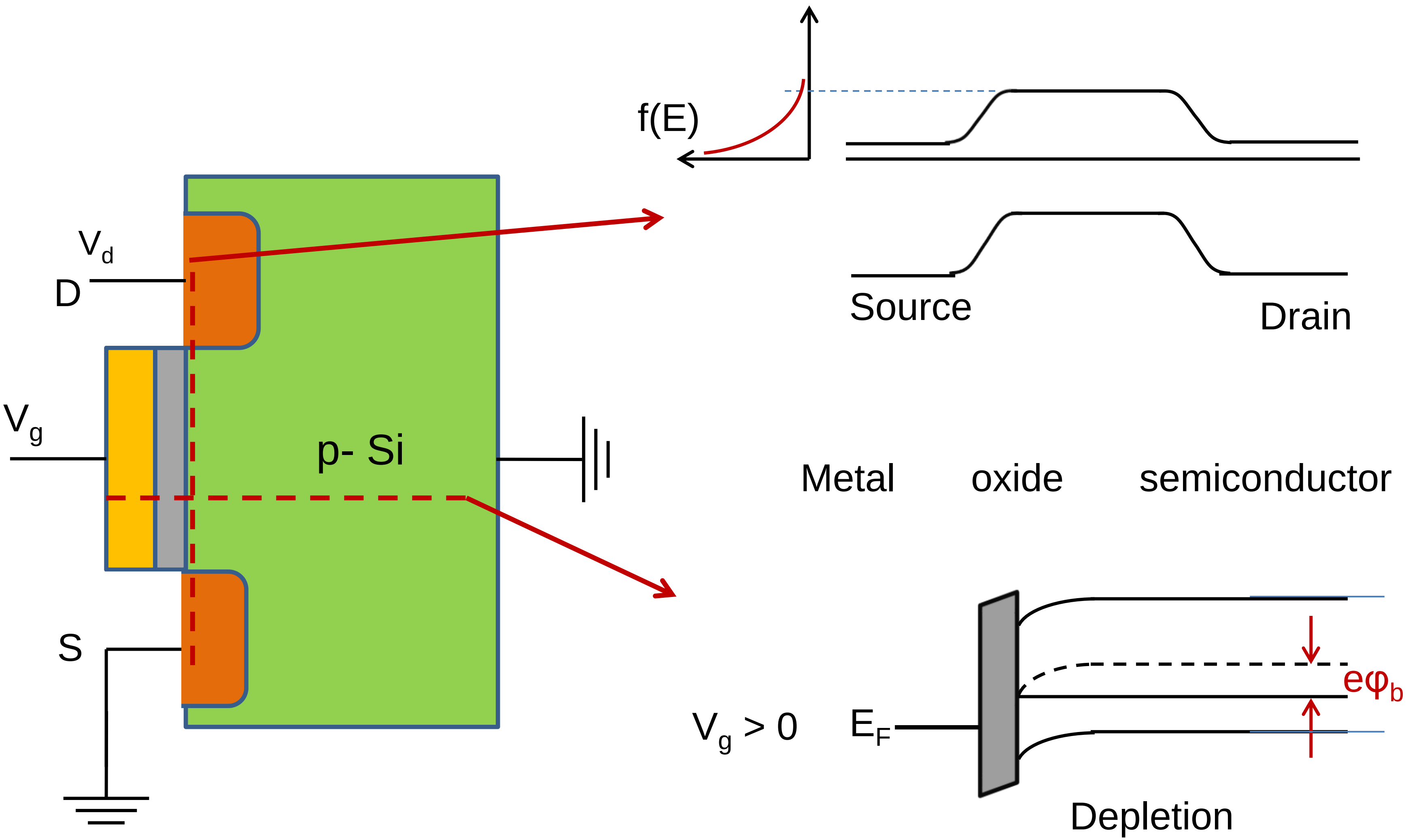
MOSFET structure and band bending



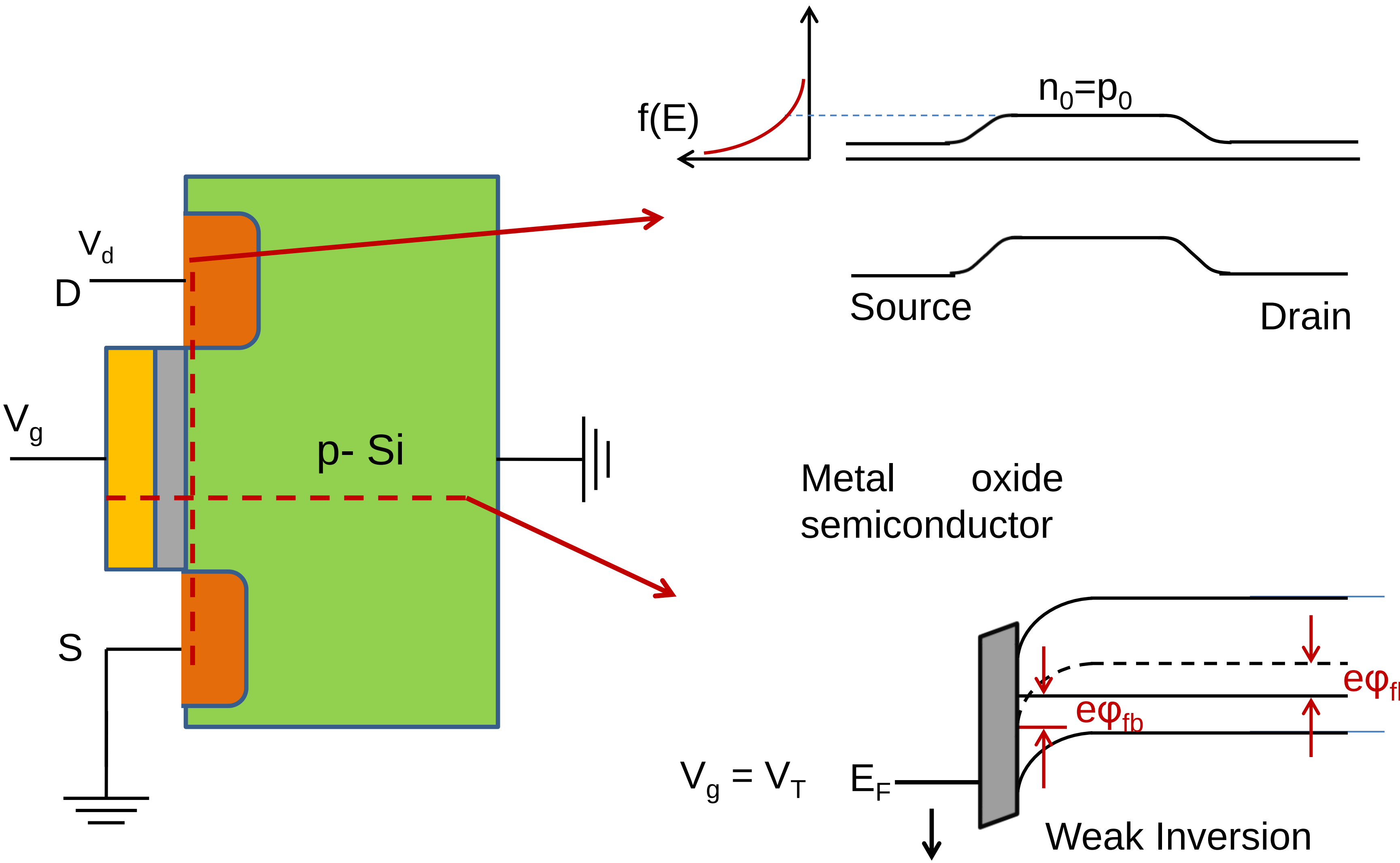
MOSFET structure and band bending



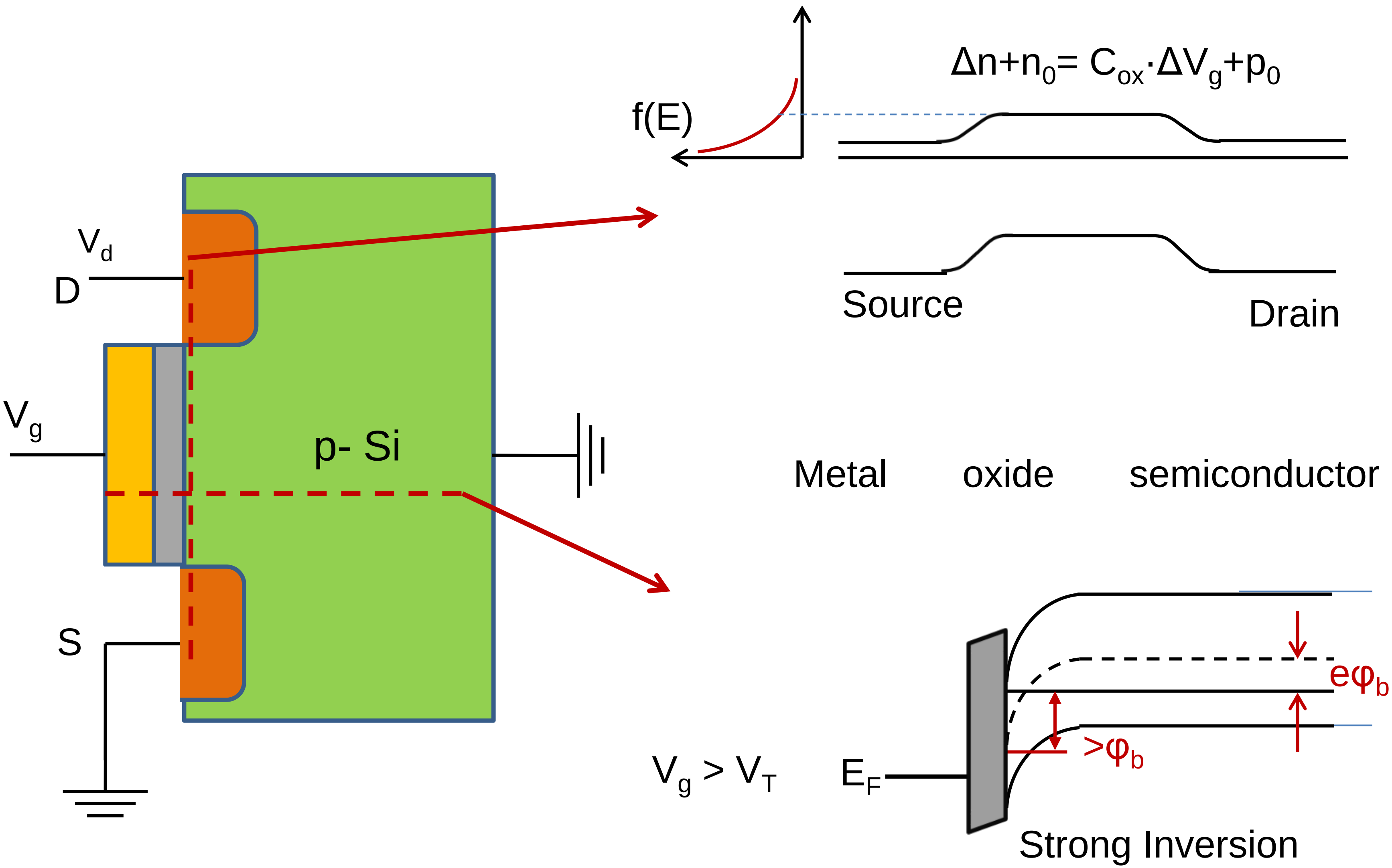
MOSFET structure and band bending



MOSFET structure and band bending



MOSFET structure and band bending

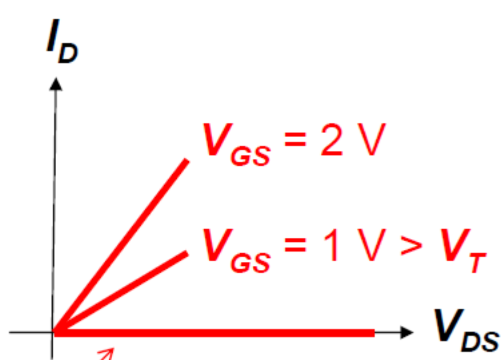


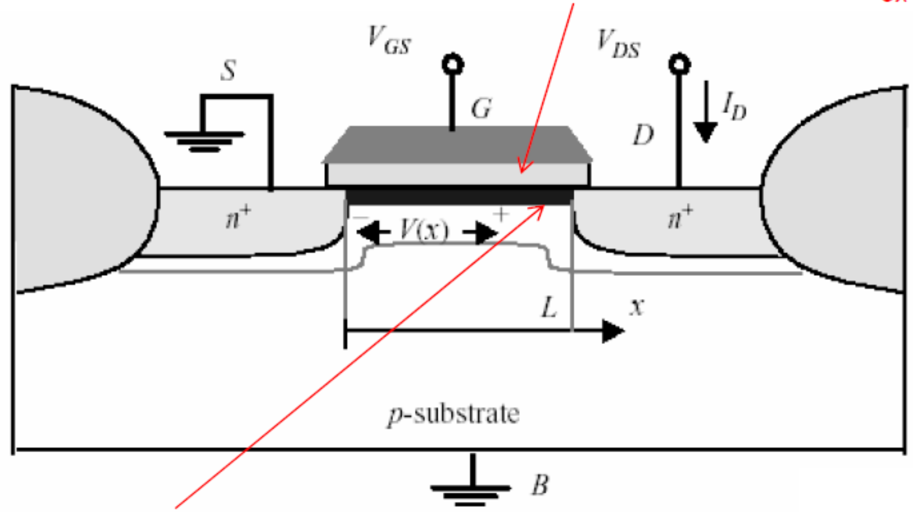
The MOSFET as a Controlled Resistor

- 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 $\equiv t_{ox}$

NMOSFET Example:





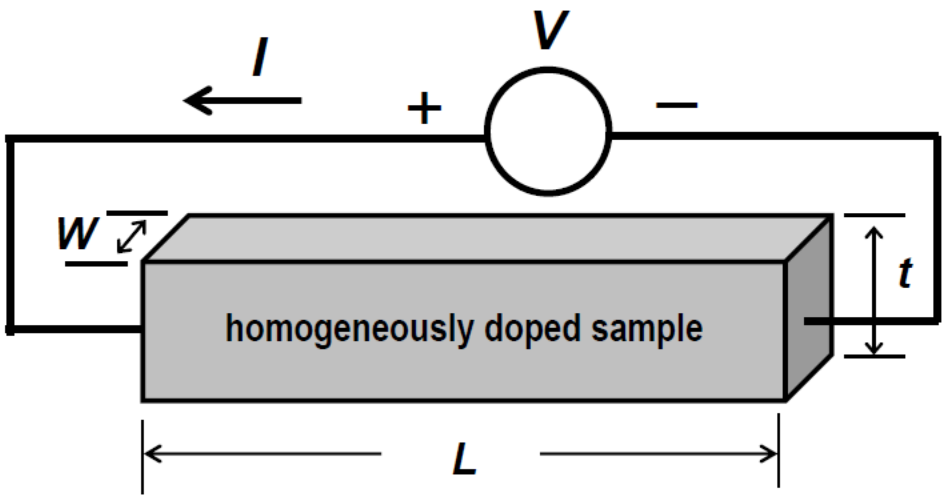
I_{DS} = 0 if $V_{GS} < V_T$

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

MOSFET: current-voltage characteristics

Sheet Resistance Revisited

Consider a sample of n-type semiconductor:



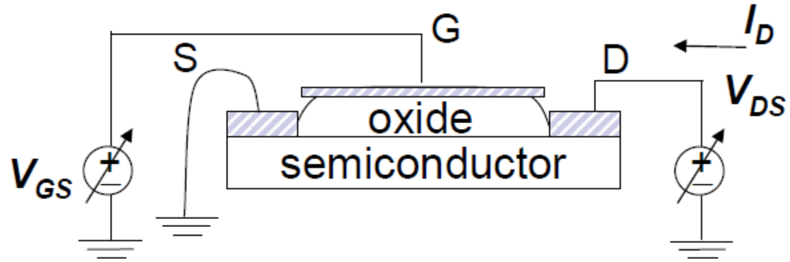
$$R_s = \frac{\rho}{t} = \frac{1}{\sigma t} = \frac{1}{q\mu_n n t} = \frac{1}{\mu_n Q_n}$$

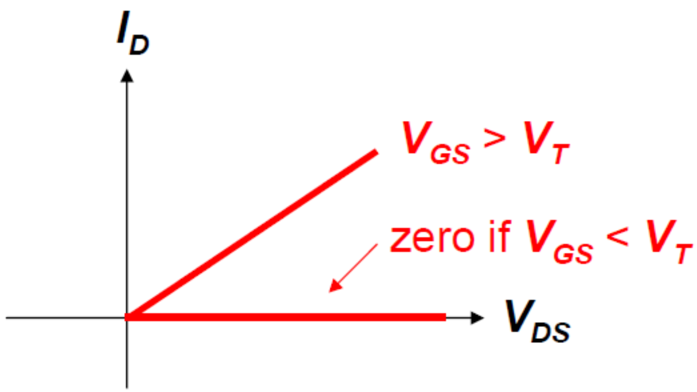
where Q_n is the charge per unit area

MOSFET: current-voltage characteristics

NMOSFET I_D vs. V_{DS} Characteristics

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

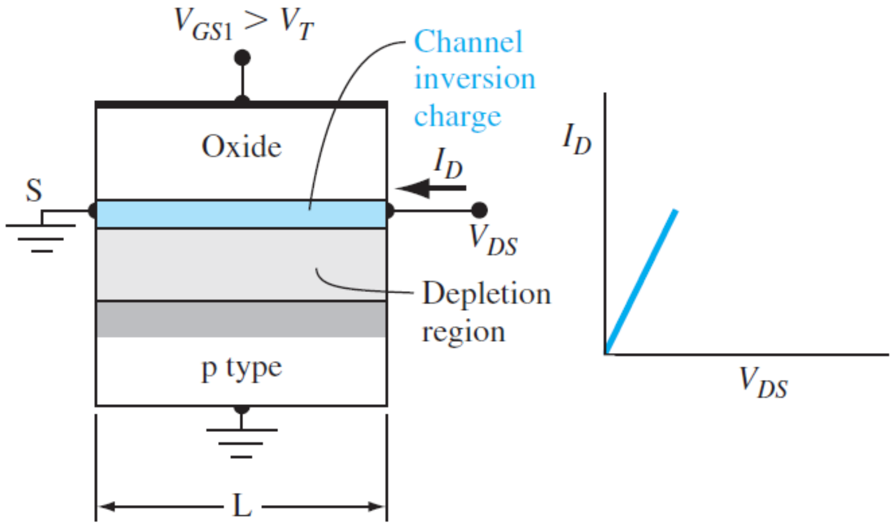


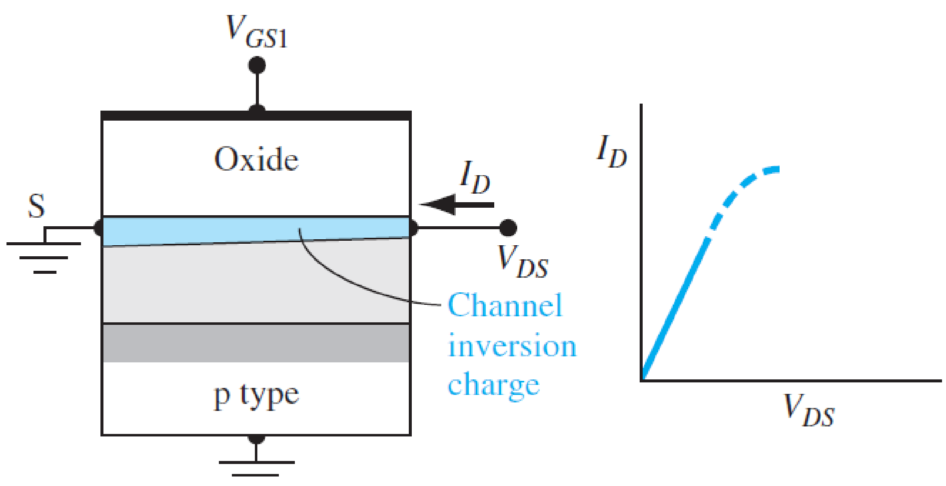


Above threshold ($V_{GS} > V_T$):
"inversion layer" of electrons appears, so conduction between **S** and **D** is possible

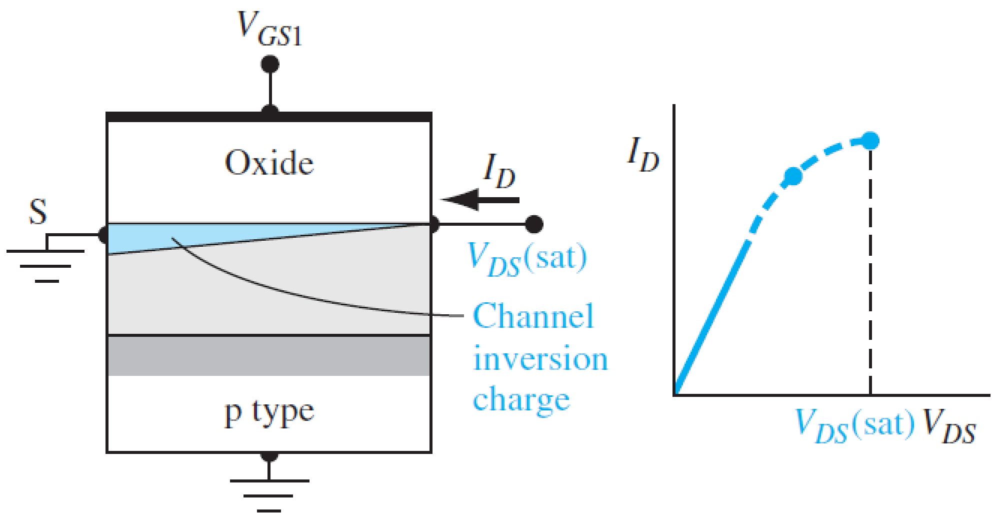
Below "threshold" ($V_{GS} < V_T$):
no charge → no conduction

MOSFET: current-voltage characteristics

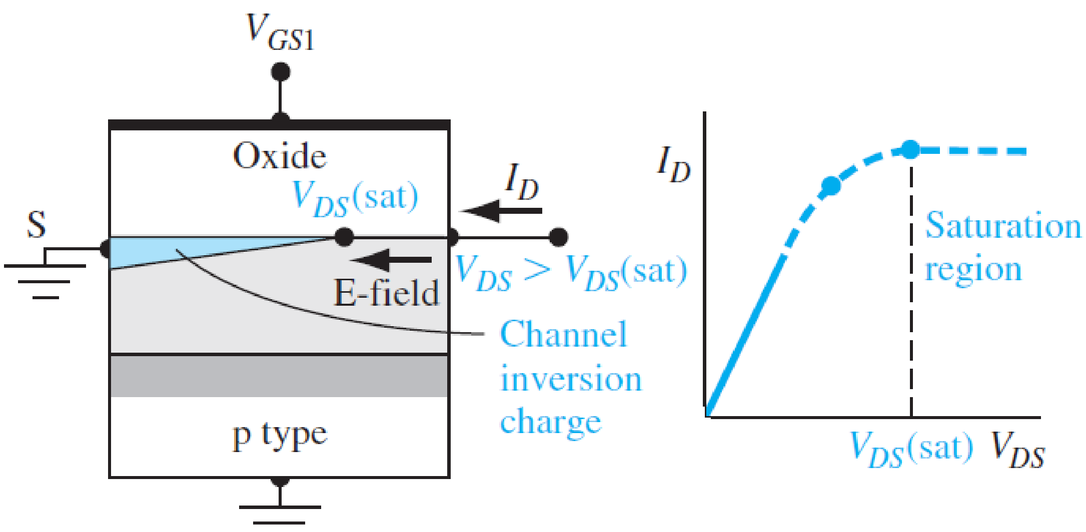




MOSFET: current-voltage characteristics



$$V_{DS}(\text{sat}) = V_{GS} - V_T$$

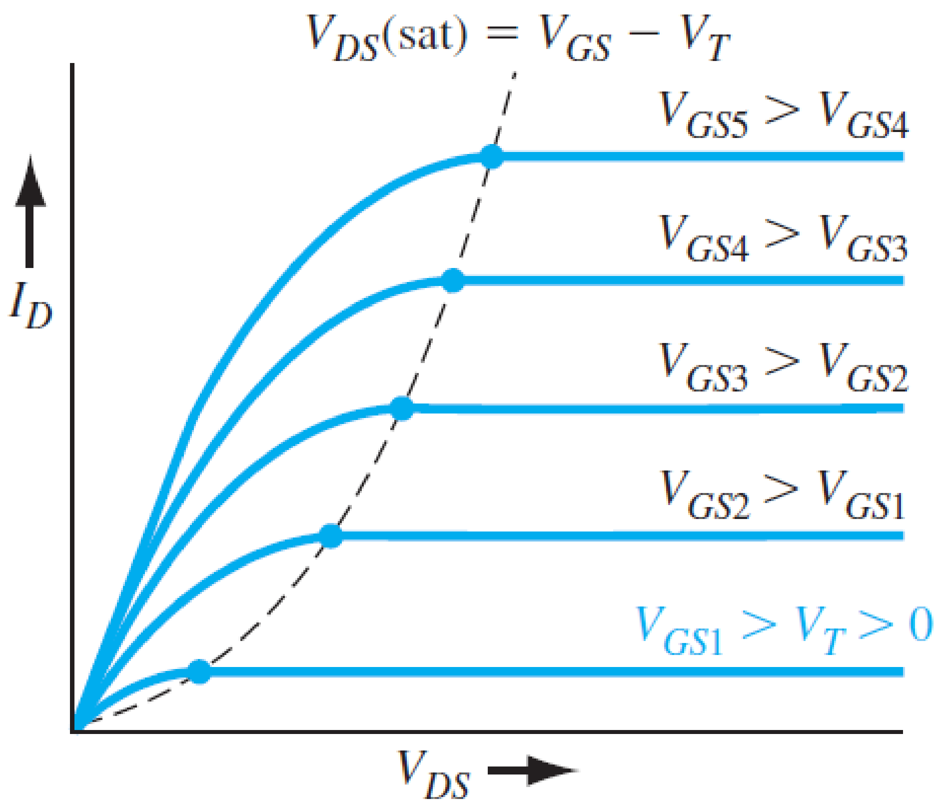


$V_{DS} > V_{DS}(\text{sat})$

The region of the I_D versus V_{DS} characteristic is referred to as the *saturation region*

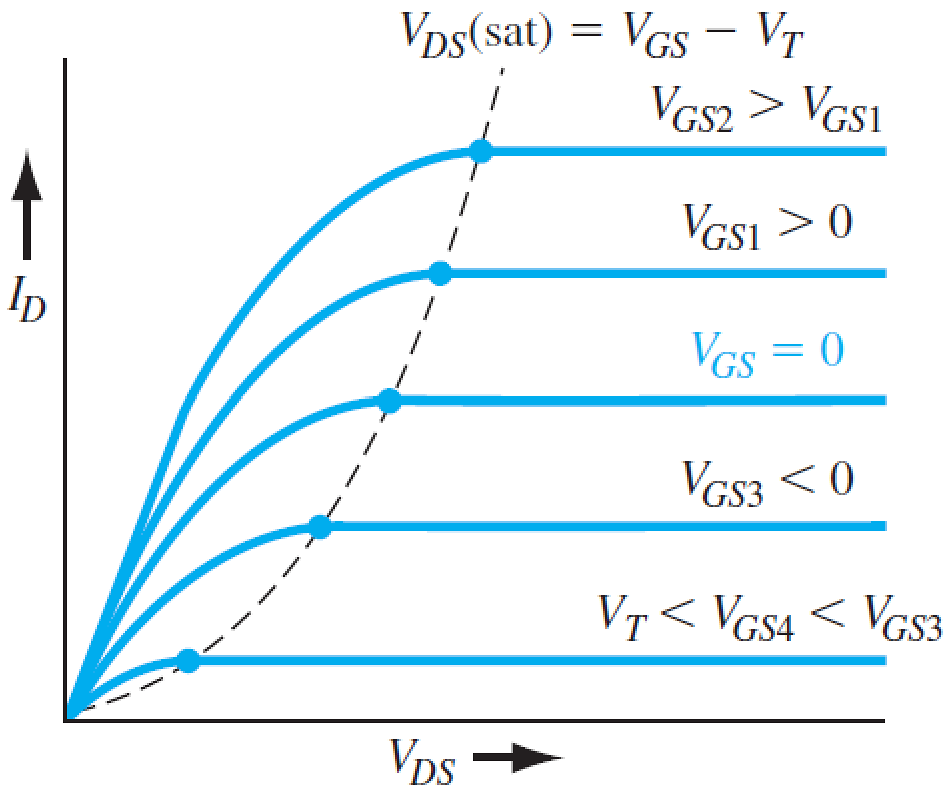
MOSFET: current-voltage characteristics

n-channel enhancement mode



MOSFET: current-voltage characteristics

n-channel depletion mode



MOSFET: current-voltage characteristics

Before saturation

MOSFET as a Controlled Resistor (cont'd)

$$I_D = \frac{V_{DS}}{R_{DS}}$$

$$R_{DS} = R_s(L/W) = \frac{L/W}{\mu_n Q_i} = \frac{L/W}{\mu_n C_{ox}(V_{GS} - V_T - \frac{V_{DS}}{2})}$$

average value of $V(x)$

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

We can make R_{DS} low by

- applying a large "gate drive" ($V_{GS} - V_T$)
- making W large and/or L small

MOSFET: current-voltage characteristics

Before saturation

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

$k_n' = \mu_n C_{ox}$ is called the process conduction parameter for the n-channel MOSFET, unit: A /V^2

$$I_D = K_n\left[2(V_{GS} - V_T)V_{DS} - V_{DS}^2\right]$$

$$K_n = (W\mu_n C_{ox})/2L = (k_n'/2) \cdot (W/L)$$

is called the conduction parameter for the n-channel MOSFET, unit: A /V^2

MOSFET: current-voltage characteristics

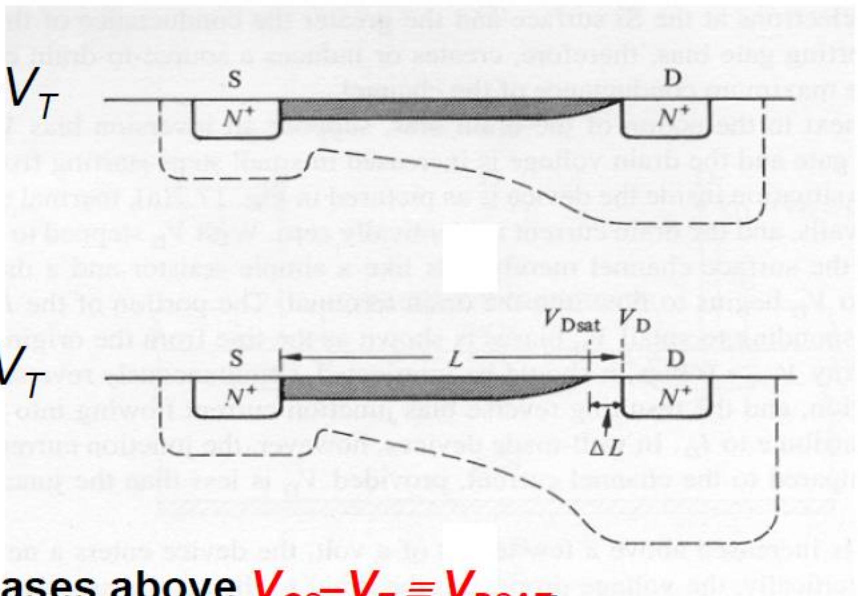
What Happens at Larger V_{DS}?

$V_{GS} > V_T$:

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

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

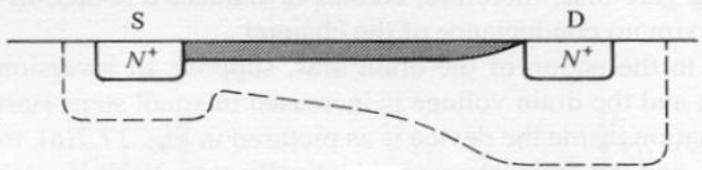
Note: Electrons are swept into the drain by the *E*-field when they enter the pinch-off region.

MOSFET: current-voltage characteristics

What Happens at Larger V_{DS}?

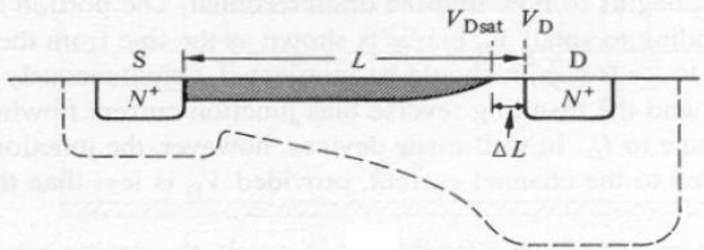
$V_{GS} > V_T$:

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



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 $V_{ds} \geq V_{gs} - V_T$

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

MOSFET: current-voltage characteristics

- When $V_{DS} > V_{GS} - V_T$ the un-inverted (drain depletion) region increases, as does the pinch-off region
- Any increase in V_{DS}:
  - Reduces the amount of inversion charge, but…
  - Increases the lateral field (charge velocity)
- The two effects cancel each other out, so at high V_{DS} the drain current is no longer a function of V_{DS}! The current saturates to a value only dependent on V_{GS} (i.e. charge).
- Putting in $V_{DS} = V_{GS} – V_T$ (the pinch-off, i.e. saturation condition) in the previous equation:

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

Why is this desirable?

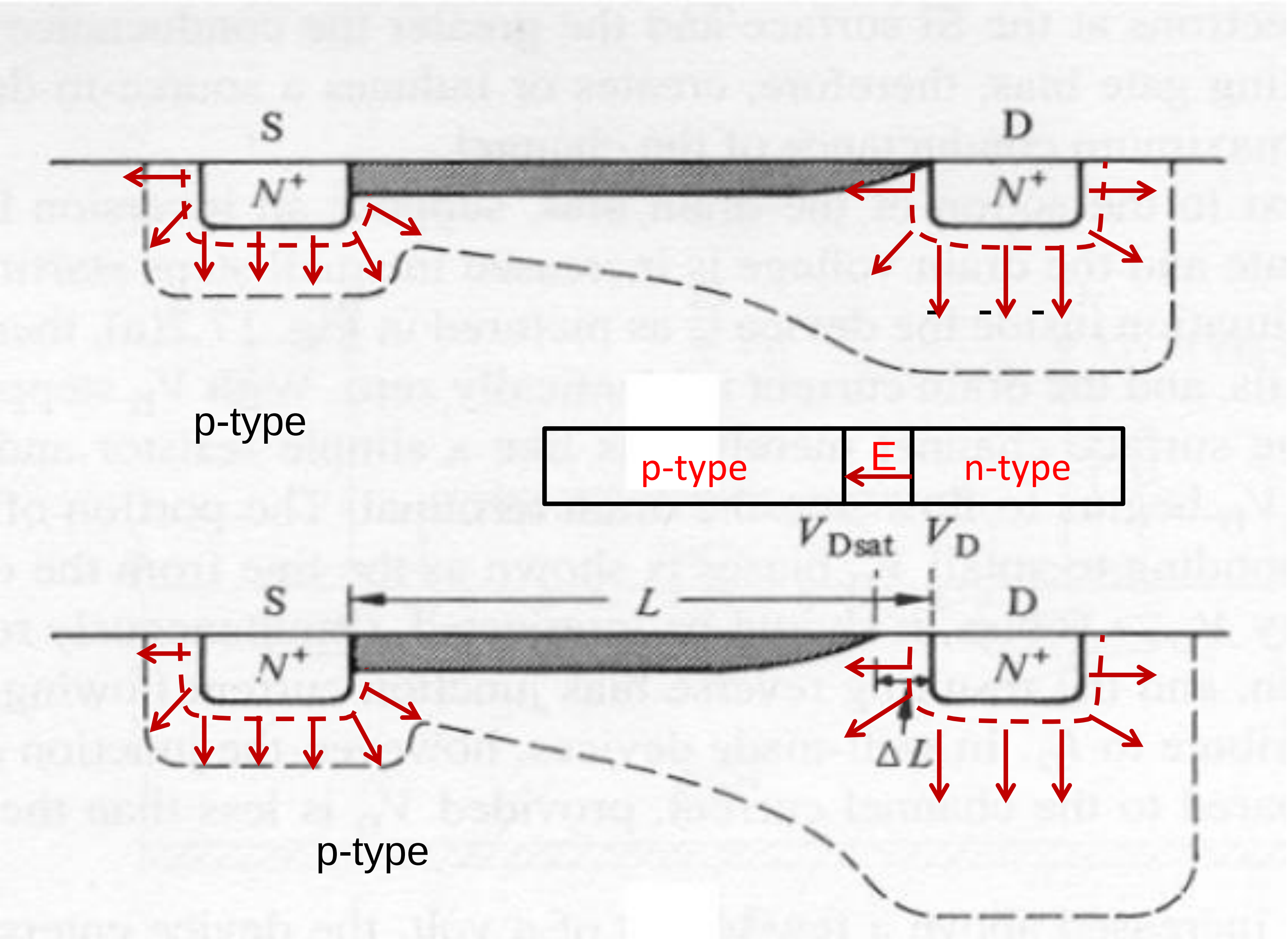
MOSFET: current-voltage characteristics

- When $V_{DS} > V_{GS} - V_T$ the un-inverted (drain depletion) region increases, as does the pinch-off region
- Any increase in V_{DS}:
  - Reduces the amount of inversion charge, but…
  - Increases the lateral field (charge velocity)
- The two effects cancel each other out, so at high V_{DS} the drain current is no longer a function of V_{DS}! The current saturates to a value only dependent on V_{GS} (i.e. charge).
- Putting in $V_{DS} = V_{GS} – V_T$ (the pinch-off, i.e. saturation condition) in the previous equation:

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

Why is this desirable?
Voltage gain, dV_{DS}/dI_D, because small changes in I_D cause large swings in V_{DS}

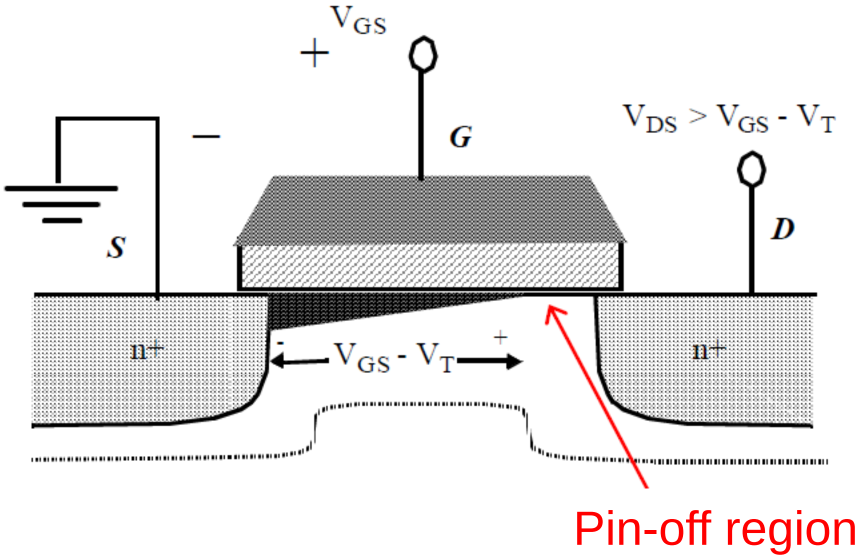
Why electrons can pass through the “pinch-off” region



MOSFET: current-voltage characteristics

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}).



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

MOSFET: current-voltage characteristics

I_D vs. V_{DS} Characteristics

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

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

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

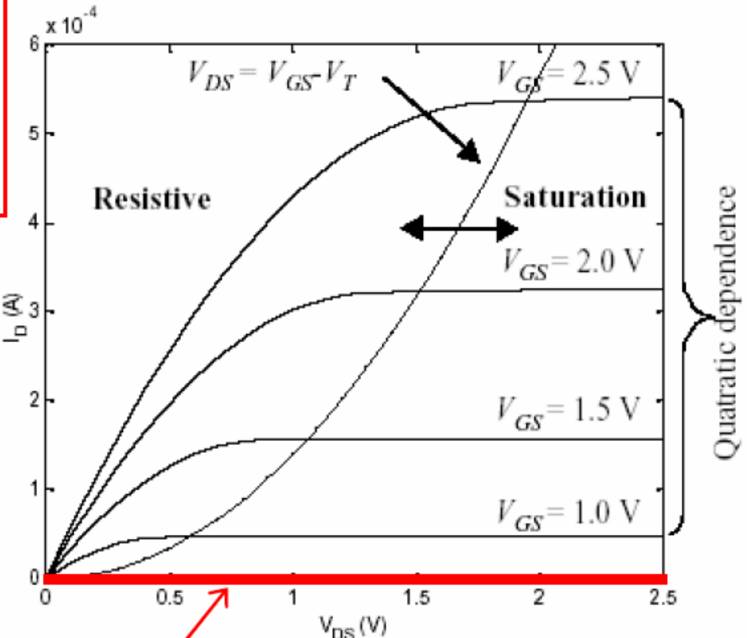
where $k_n' = \mu_n C_{ox}$

process transconductance parameter

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

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

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



"CUTOFF" region: $V_G < V_T$

$$I_D = K_n(V_{GS} - V_T)^2$$

MOSFET: current-voltage characteristics

Transconductance (transistor gain): the change in drain current with respect to the corresponding change in gate voltage

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

n-channel MOSFET operating in the nonsaturation region

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

The transconductance increases linearly with V_{DS} but is independent of V_{GS} in the nonsaturation region

n-channel MOSFET operating in the saturation region

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

The transconductance increases linearly with V_{GS} but is independent of V_{DS} in the saturation region

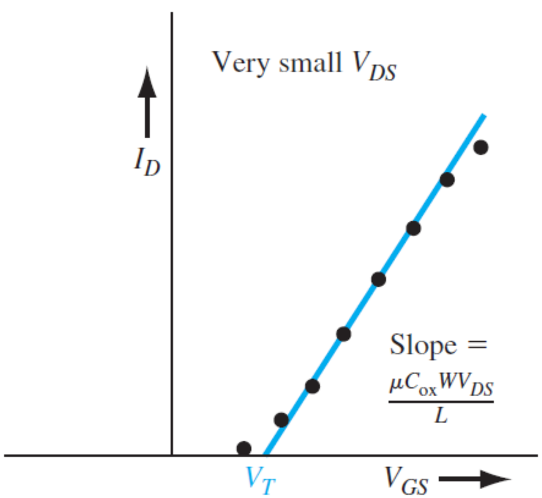
The transconductance is a function of the geometry of the device as well as of carrier mobility and threshold voltage

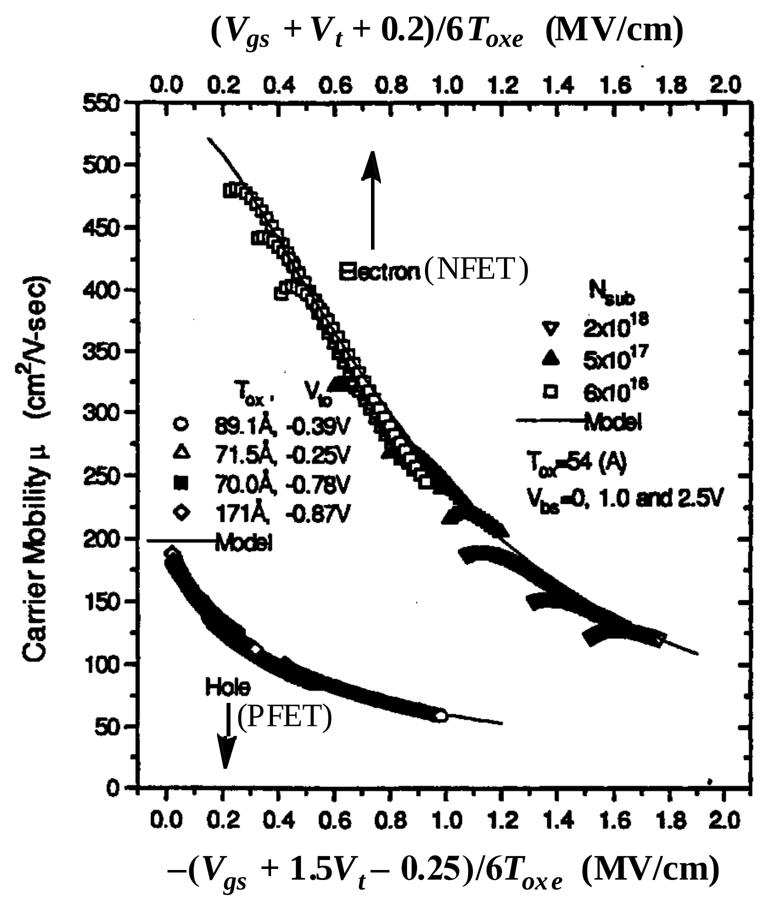
MOSFET: current-voltage characteristics

- What is the "effective mobility" μ_{eff} in the MOSFET channel?
- Can we look it up in the bulk-silicon charts?
- Scattering mechanisms affecting mobility in channel:
  - Charged impurity (Coulomb) scattering
  - Lattice vibration (phonon) scattering
  - Surface roughness scattering

At small V_{DS}:

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



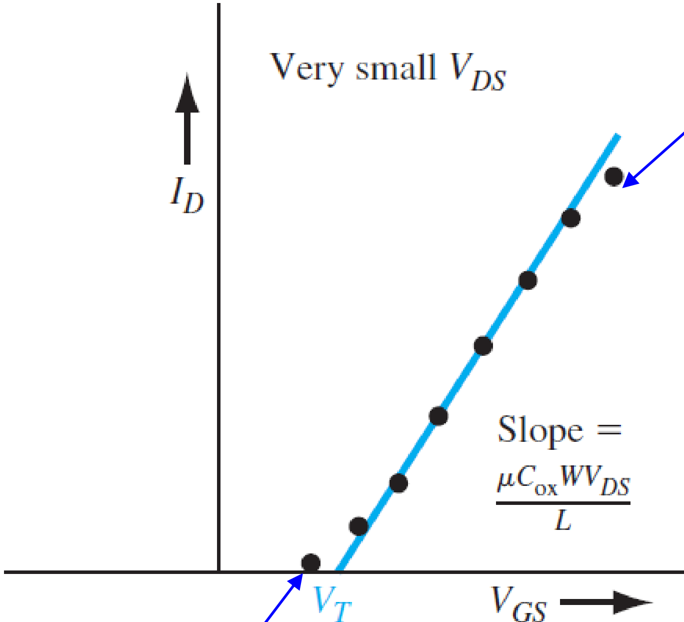


MOSFET: current-voltage characteristics

- What is the "effective mobility" μ_{eff} in the MOSFET channel?

At small V_{DS}:

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



Mobility changes with gate voltage, here, mobility decreases at large V_{GS}

Extrapolation to zero current: threshold voltage
Slope: proportional to mobility

Subthreshold

MOSFET: current-voltage characteristics

P- channel device:

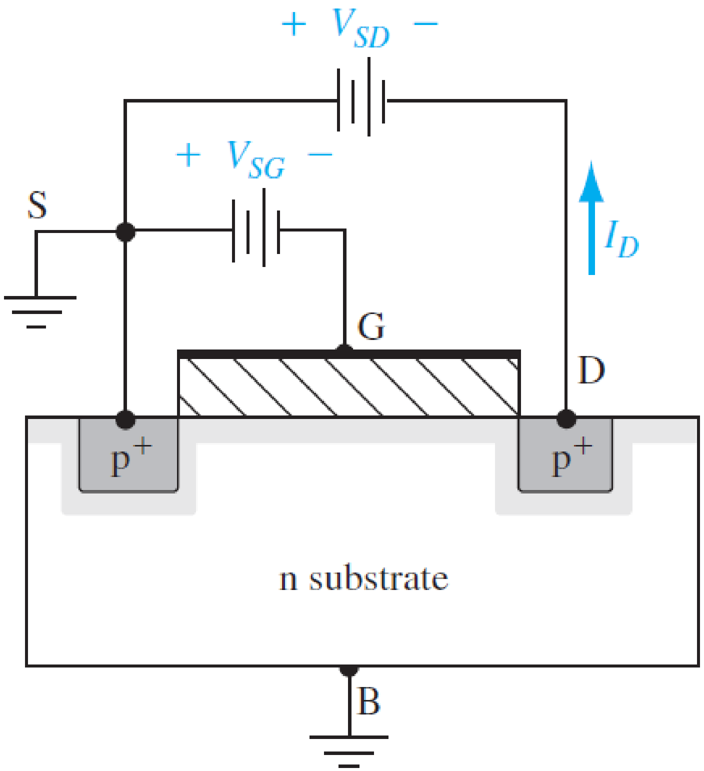
Enhancement mode

At small V_{DS}: (nonsaturation region)

$$I_D = \frac{W\mu_p C_{ox}}{2L}\left[2(V_{SG} + V_T)V_{SD} - V_{SD}^2\right]$$

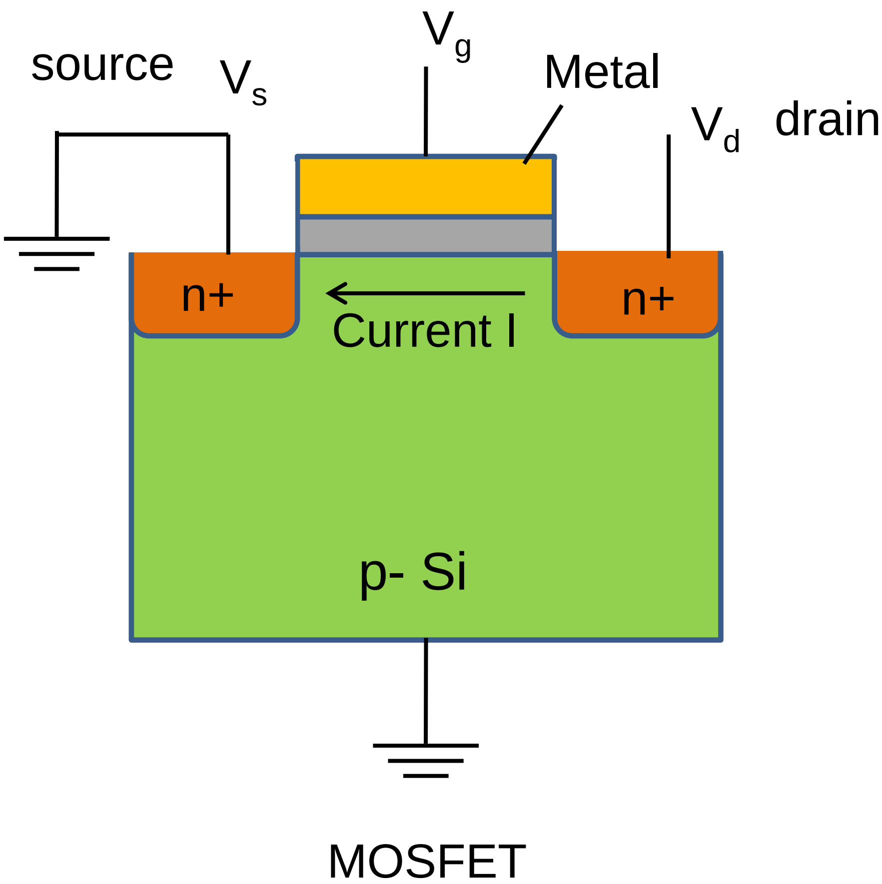
At large V_{DS}: (saturation region)

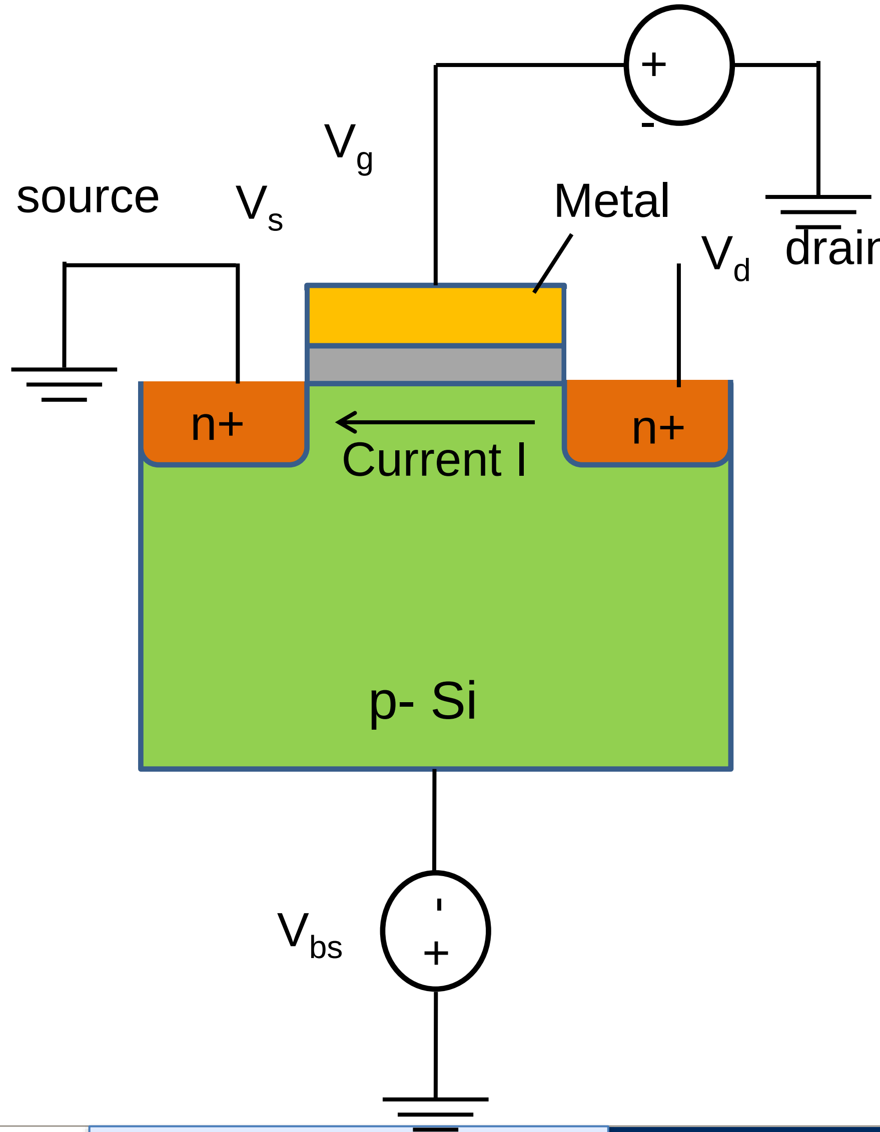
$$I_D(\text{sat}) = \frac{W\mu_p C_{ox}}{2L}(V_{SG} + V_T)^2$$



MOSFET: body effect

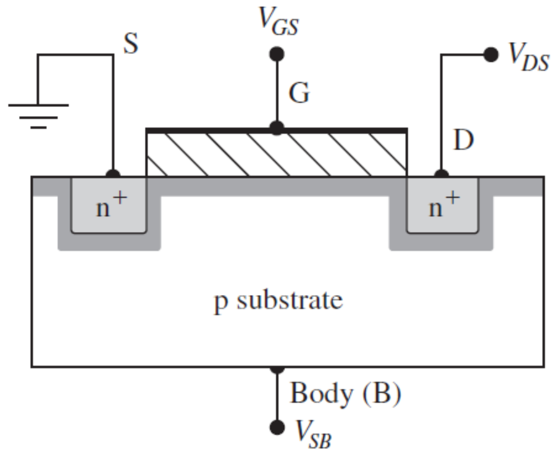
Substrate bias:





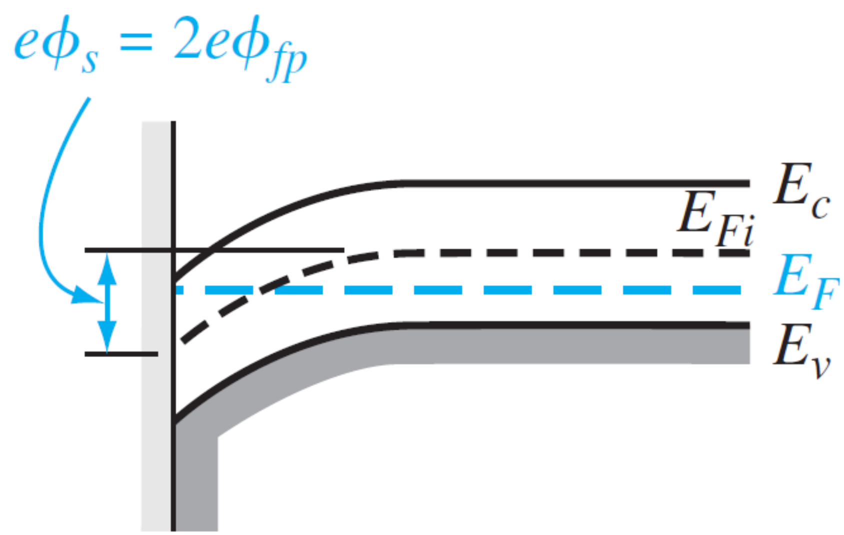
MOSFET: body effect

Substrate bias:



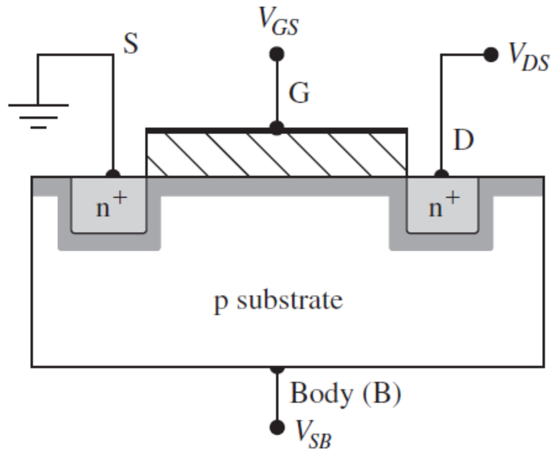
V_{SB} can not be negative

V_{SB}=0, at inversion point

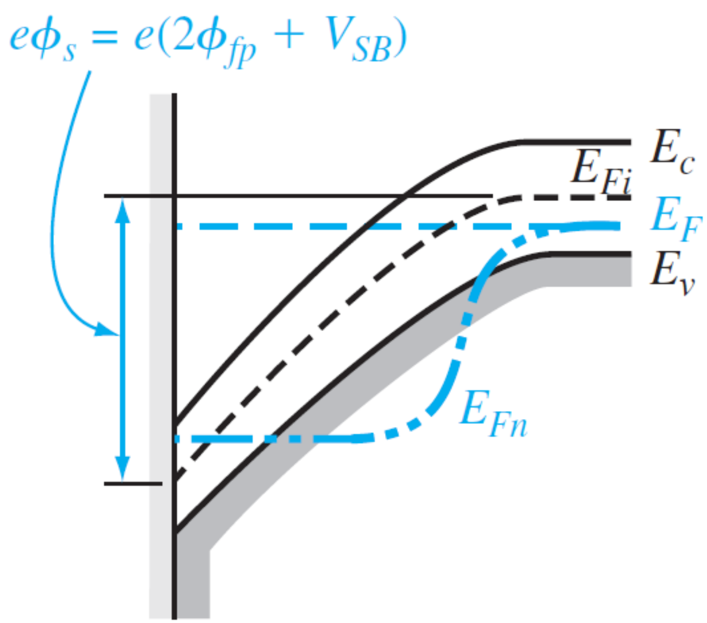


MOSFET: body effect

Substrate bias:



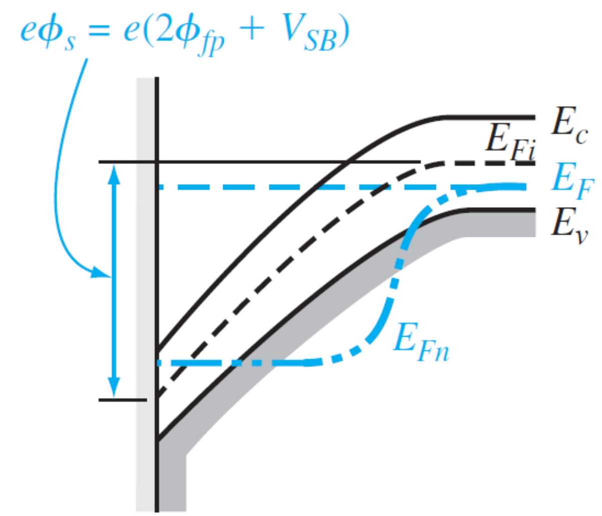
V_{SB}>0, at inversion point



MOSFET: body effect

Substrate bias:

V_{SB}>0:
The newly created electrons have higher potential energy than the electrons in the source, so will move laterally and flow out of the source terminal.



Inversion condition $\phi_s = 2\phi_{fp} + V_{SB}$

Space charge width increase
Threshold voltage increases

$$Q'_{SD}\,(\max) = -eN_a x_{dT} = -\sqrt{2e\epsilon_s N_a(2\phi_{fp})}$$ For V_{SB}=0

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

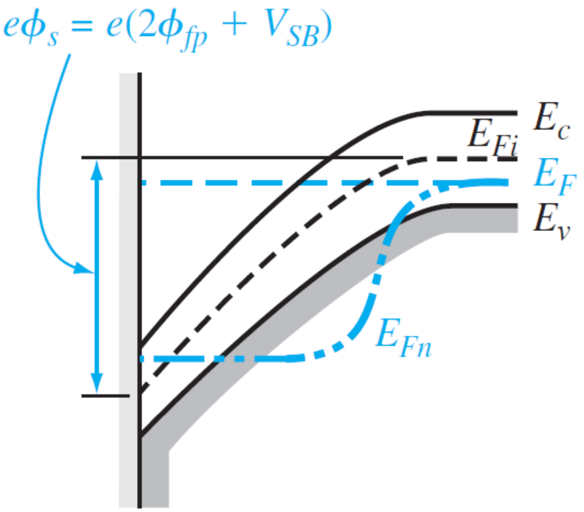
The change in the space charge density

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

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

MOSFET: body effect

Substrate bias:



The increase in threshold voltage

$$\Delta V_T = V_T(V_{SB} > 0) - V_T(V_{SB} = 0)$$

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

Define body-effect coefficient

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

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

MOSFET: body effect

Body-effect coefficient $\gamma = \frac{\sqrt{2e\epsilon_s N_a}}{C_{ox}}$

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