VE 320 Fall 2021

Introduction to Semiconductor Devices

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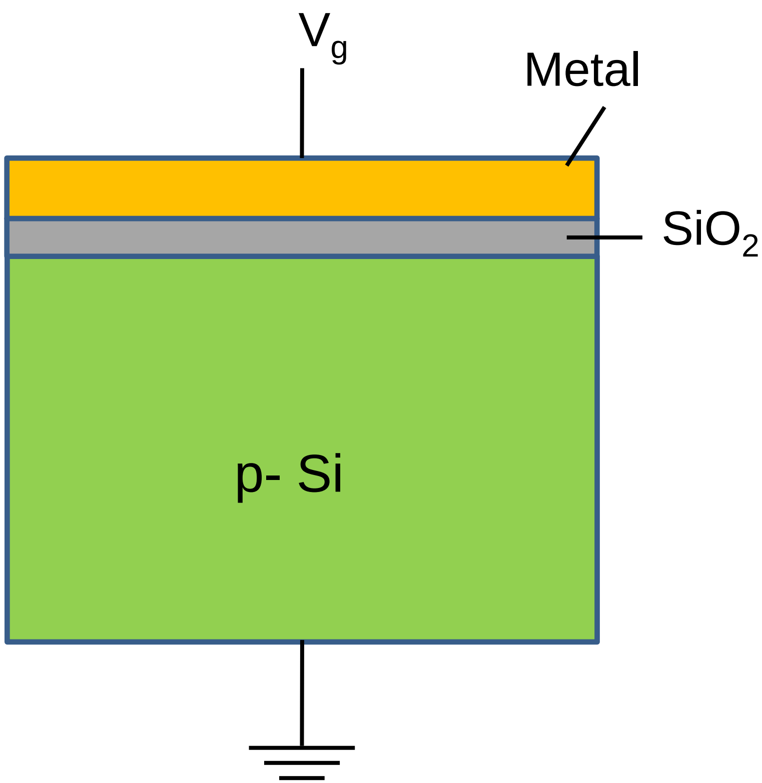
Lecture 11

MOS Capacitor
(Chapter 10)

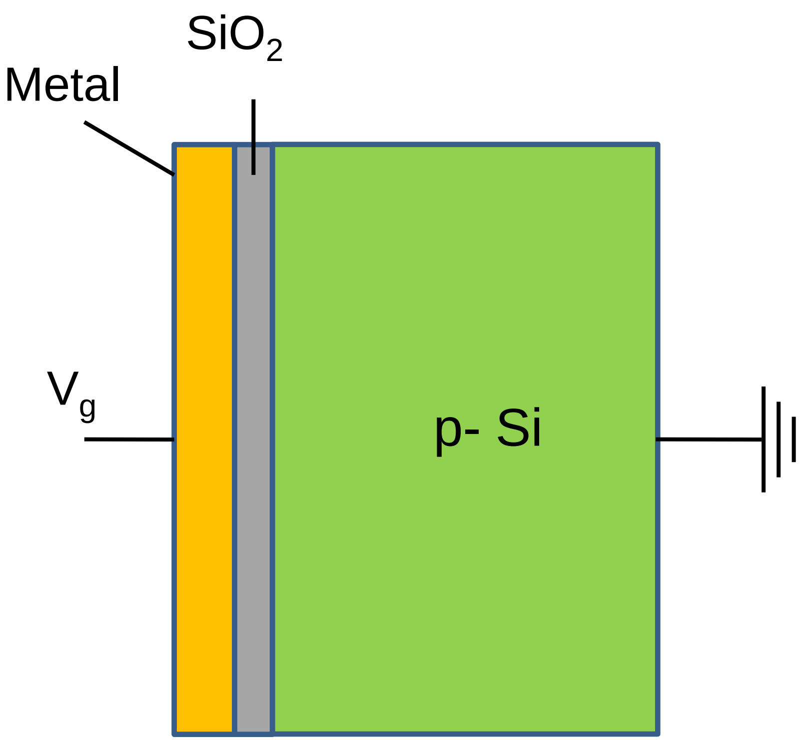
MOS structure and band bending



Metal-oxide-semiconductor (MOS)

MOS structure and band bending

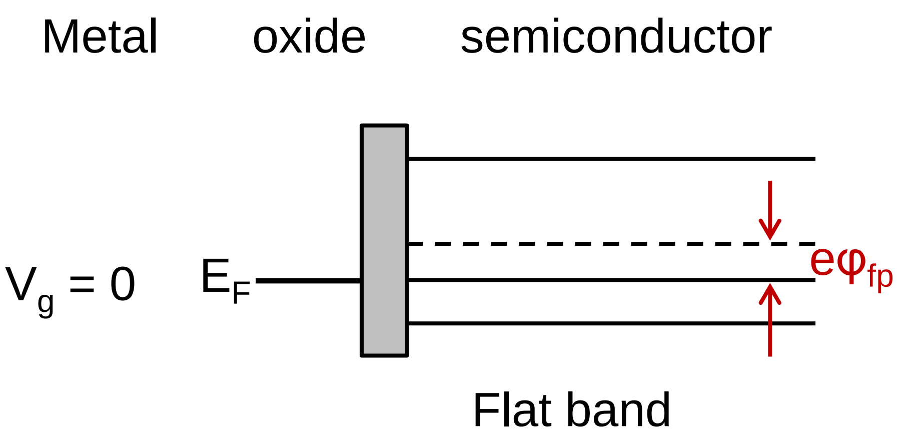
MOS capacitor



Metal-insulator-semiconductor (MIS)

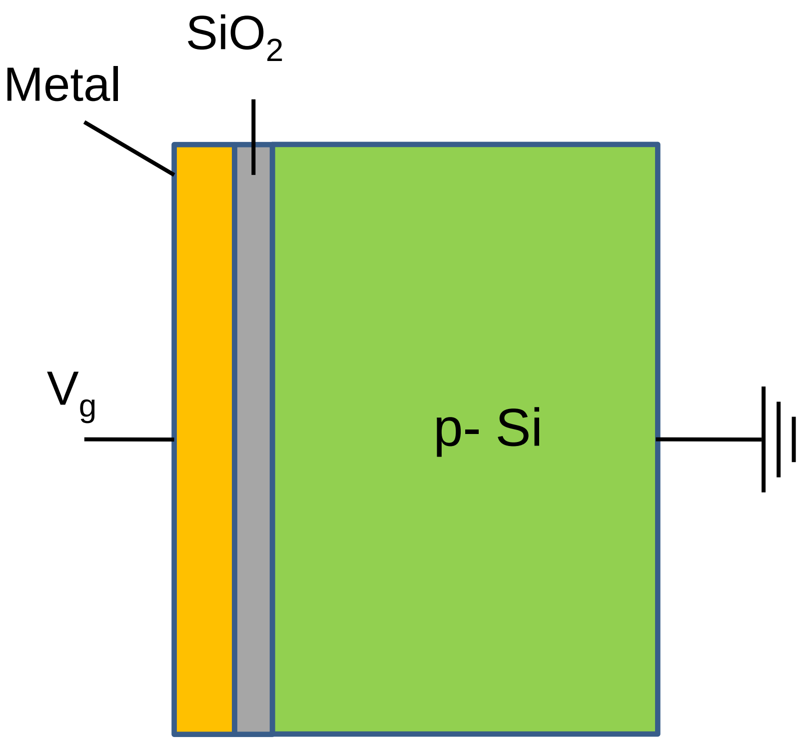
Ideal case:

1. Metal and semiconductor have the same work function $\Phi_m = \Phi_s$
2. No interface states or surface states



MOS structure and band bending

MOS capacitor

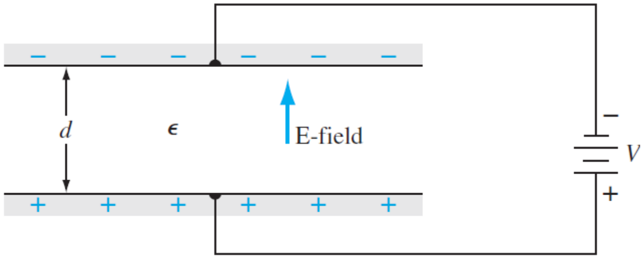


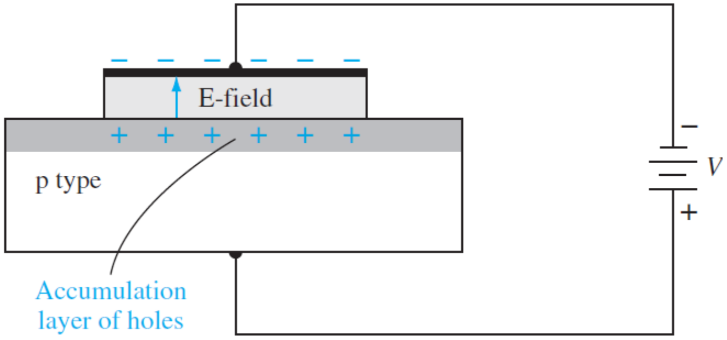
Metal-insulator-semiconductor (MIS)

Ideal case:

1. Metal and semiconductor have the same work function $\Phi_m=\Phi_s$
2. No interface states or surface states

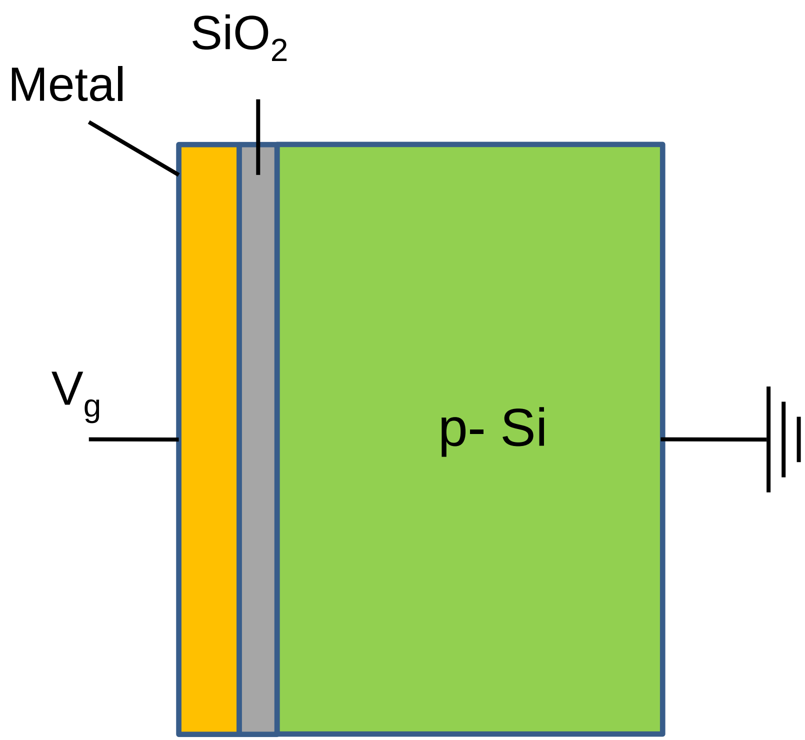
Apply voltage: parallel-plate capacitor



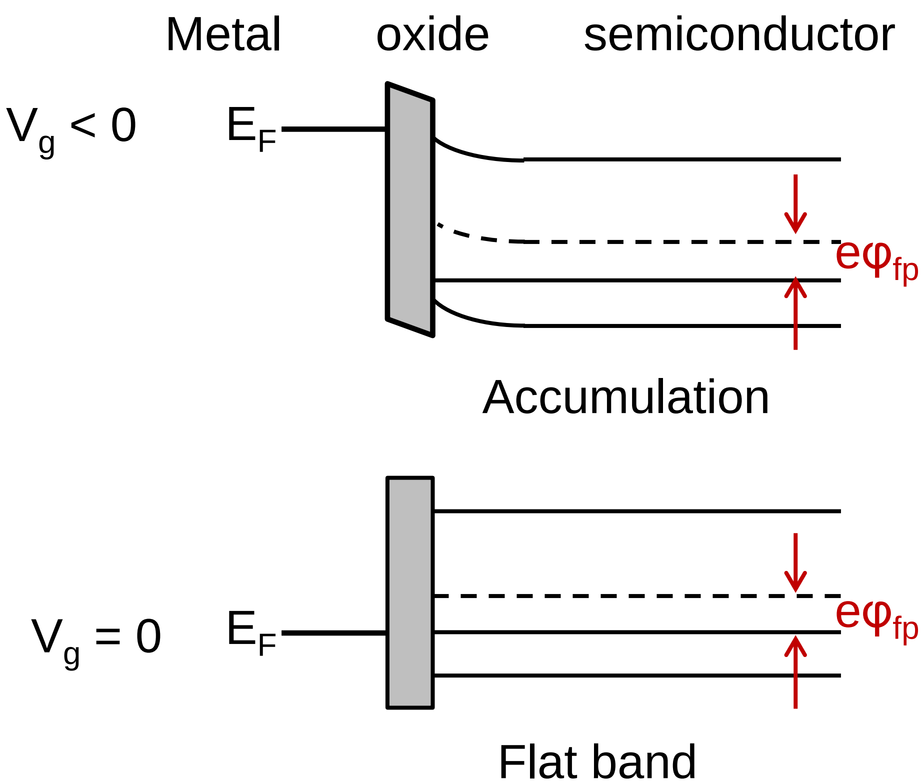


MOS structure and band bending

MOS capacitor



Metal-insulator-semiconductor (MIS)



MOS structure and band bending

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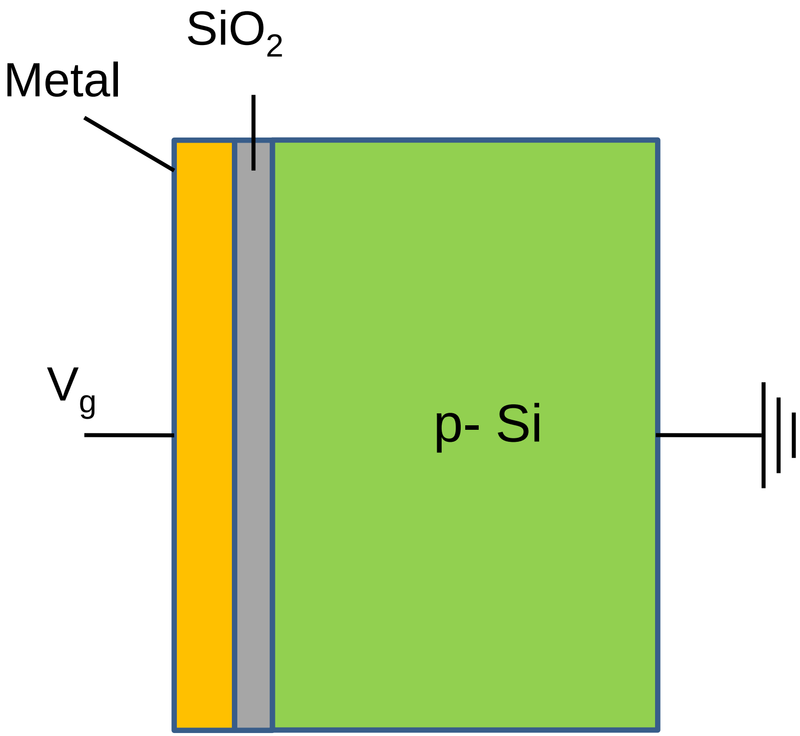

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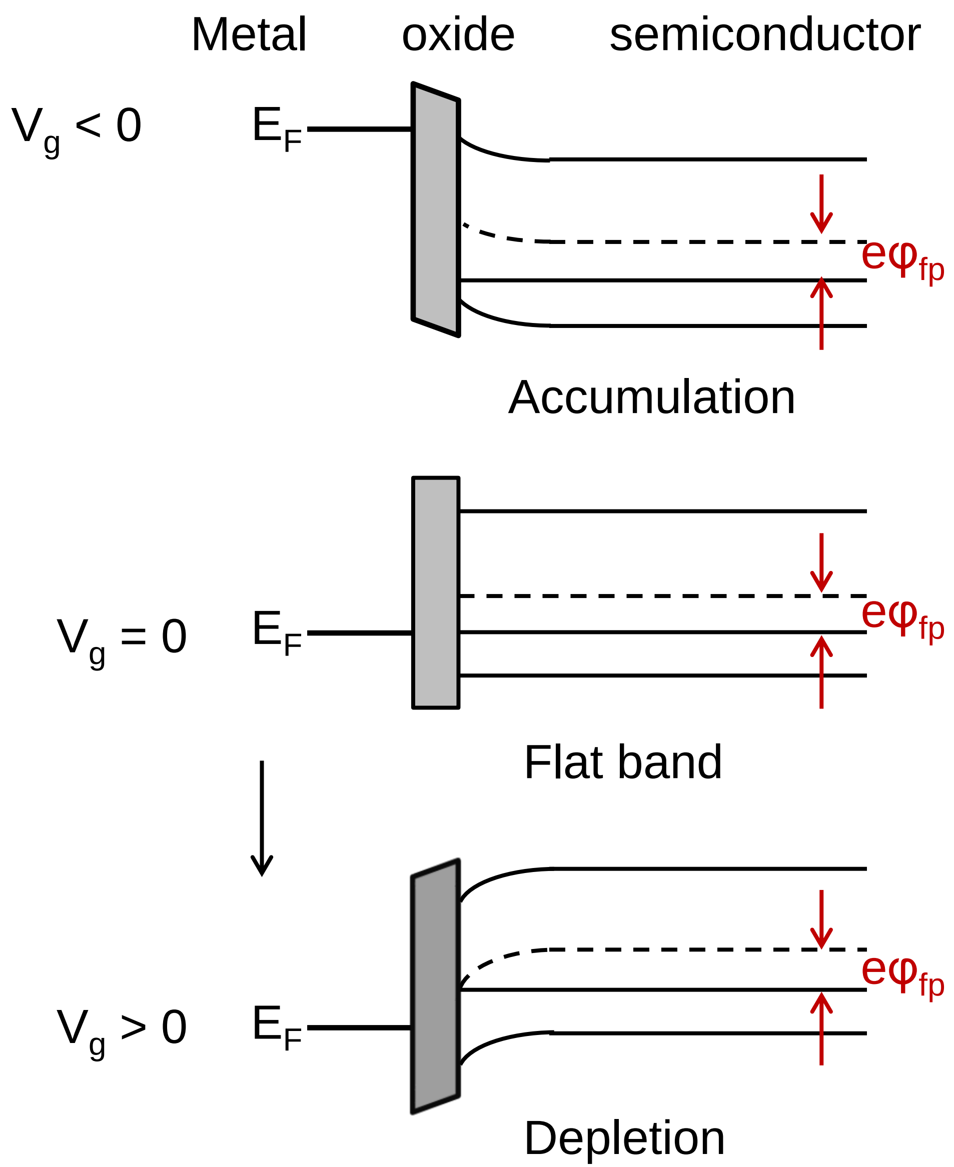
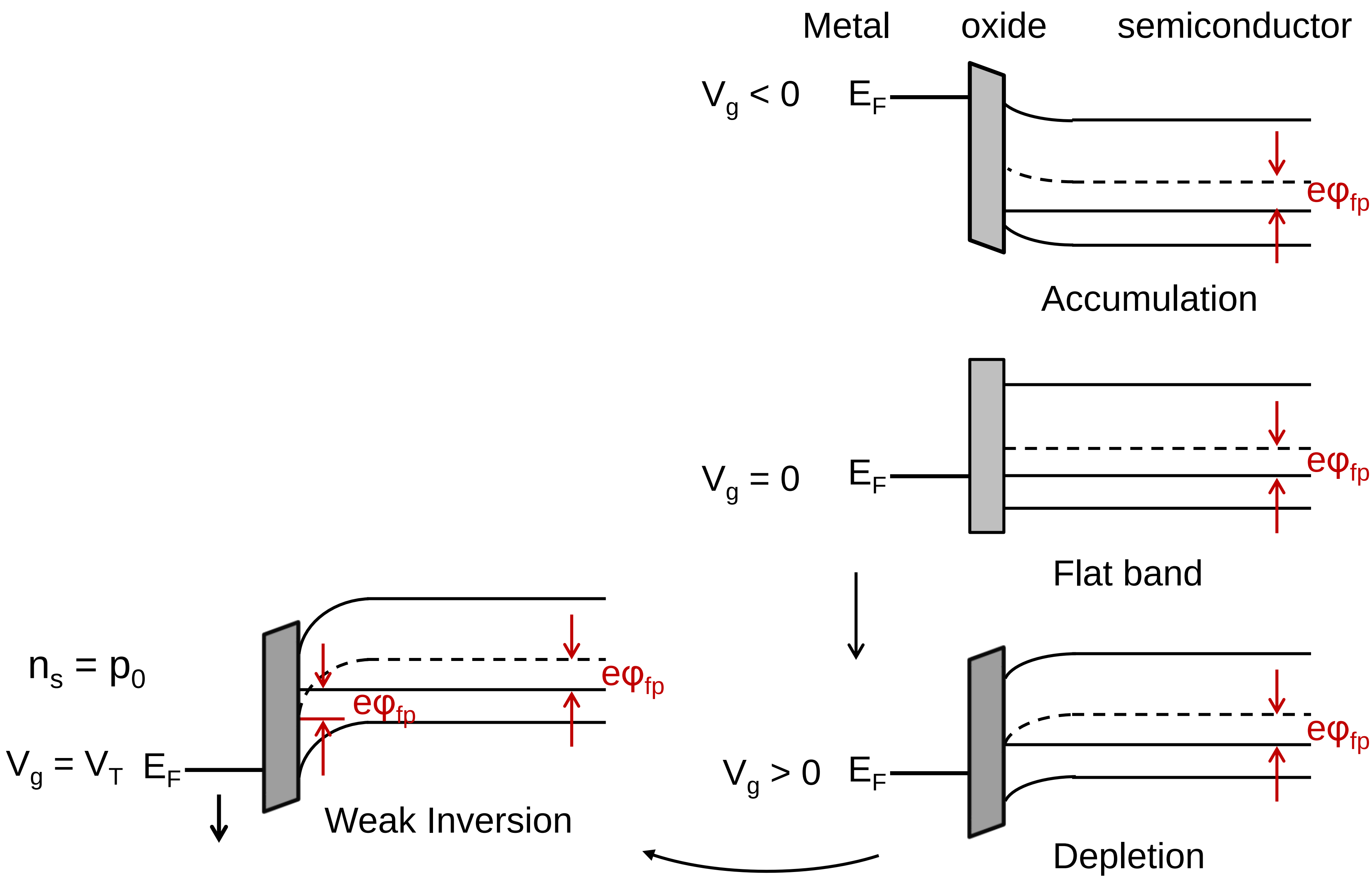
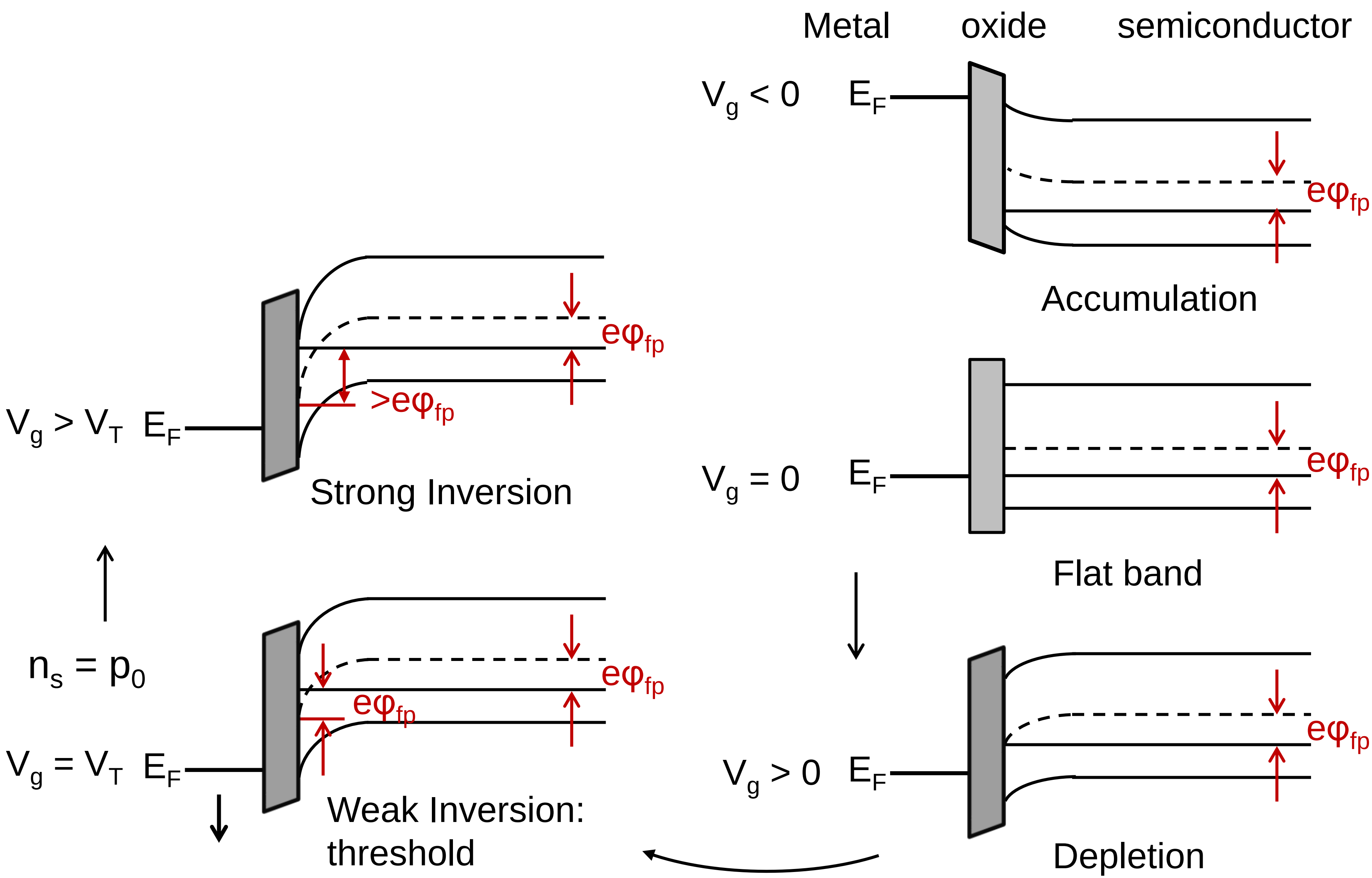


MOS structure and band bending

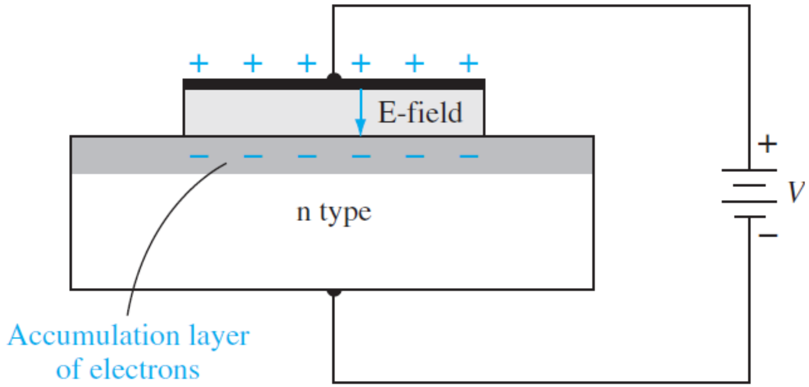


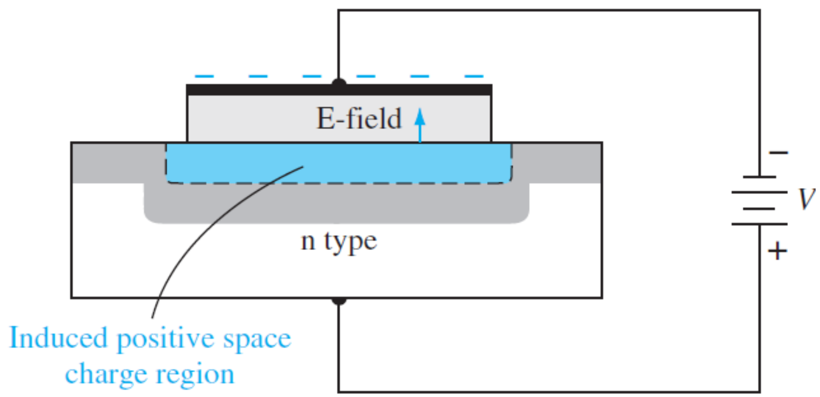
MOS structure and band bending



MOS structure and band bending

Similarly, if the substrate is n-type Si:





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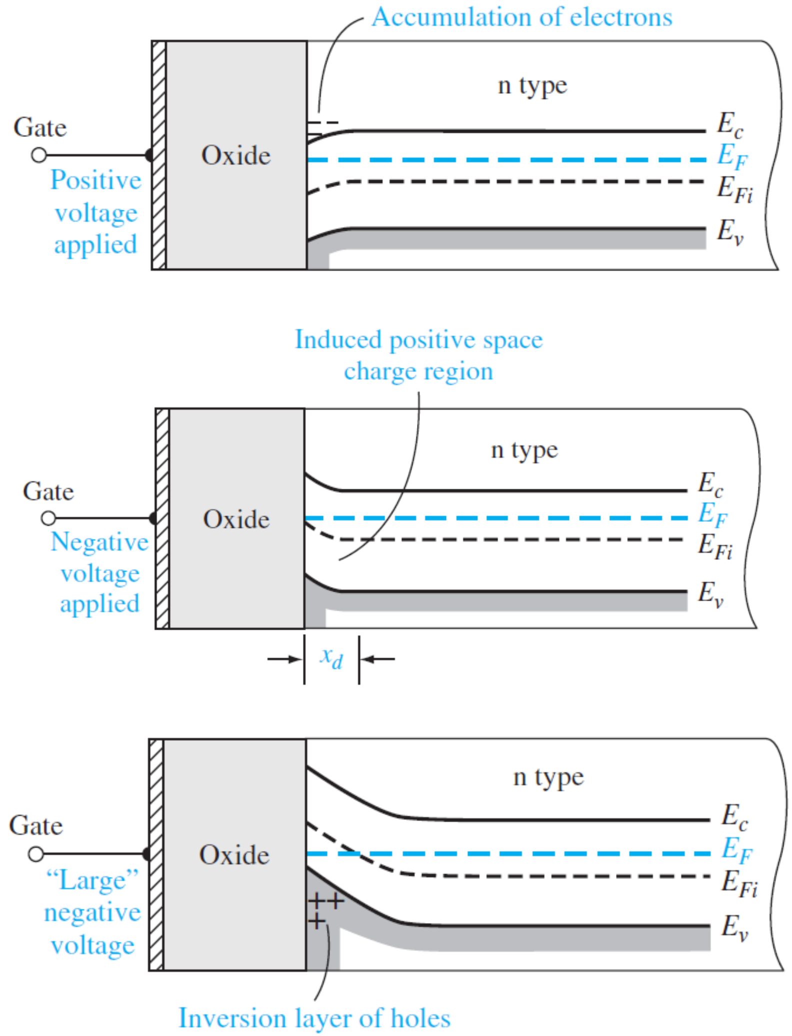
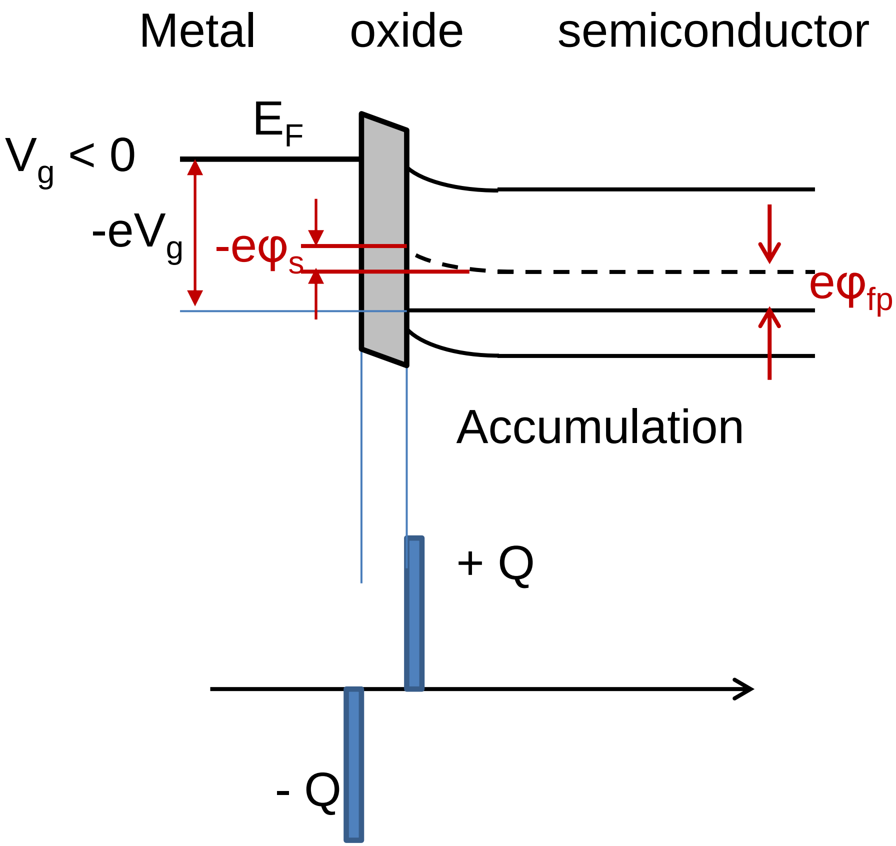


Charge Distribution

Accumulation



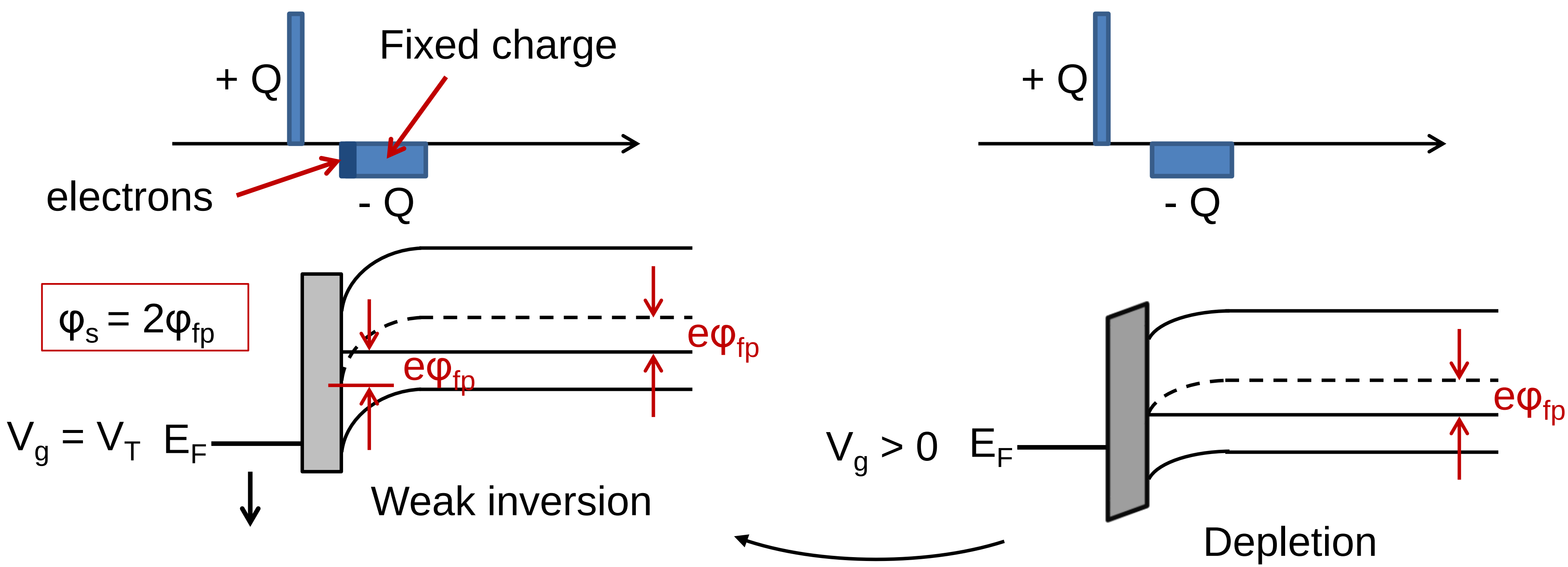
Charge Distribution

Depletion and weak inversion

Threshold inversion point:

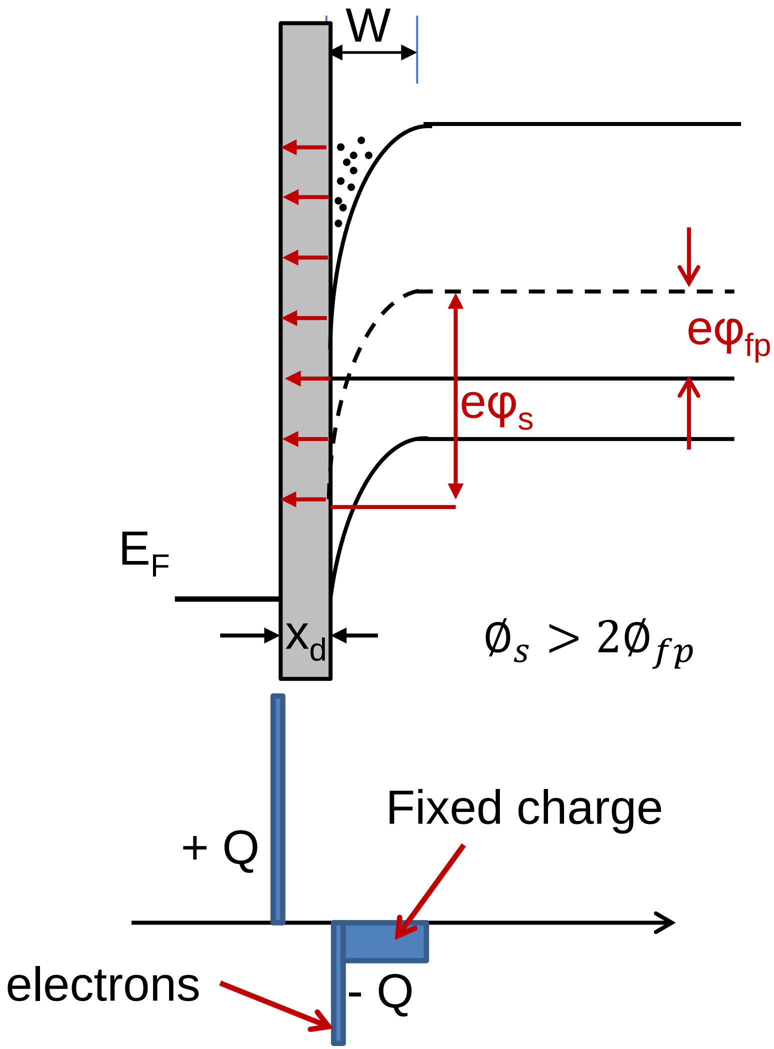
Electron concentration at the surface is the same as the hole concentration in the bulk

V_T: threshold voltage



MOS structure and band bending

Strong inversion



Charge density:

$$n = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

At the surface:

$$n_s = n_i \exp\left[\frac{e(\phi_{fp} + \Delta\phi_s)}{kT}\right] = n_i \exp\left[\frac{\phi_{fp} + \Delta\phi_s}{V_t}\right]$$

$$n_s = n_i \exp\left(\frac{\phi_{fp}}{V_t}\right) \cdot \exp\left(\frac{\Delta\phi_s}{V_t}\right)$$

$\Delta\Phi_s$ is the surface potential greater than $2\Phi_{fp}$

Write $n_{st} = n_i \exp\left(\frac{\phi_{fp}}{V_t}\right)$

is the surface charge density at the threshold inversion point

$$n_s = n_{st} \exp\left(\frac{\Delta\phi_s}{V_t}\right)$$

MOS structure and band bending

Width of the space charge region (p-type substrate)

Distance between E_{Fi} and E_F

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

Surface potential (difference between E_{Fi} measured in bulk and measured at the surface): φ_s, or the amount of band bending

Space charge width: similar to one-sided pn junction (assume abrupt depletion)

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

Maximum space charge width at the inversion transition point:

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

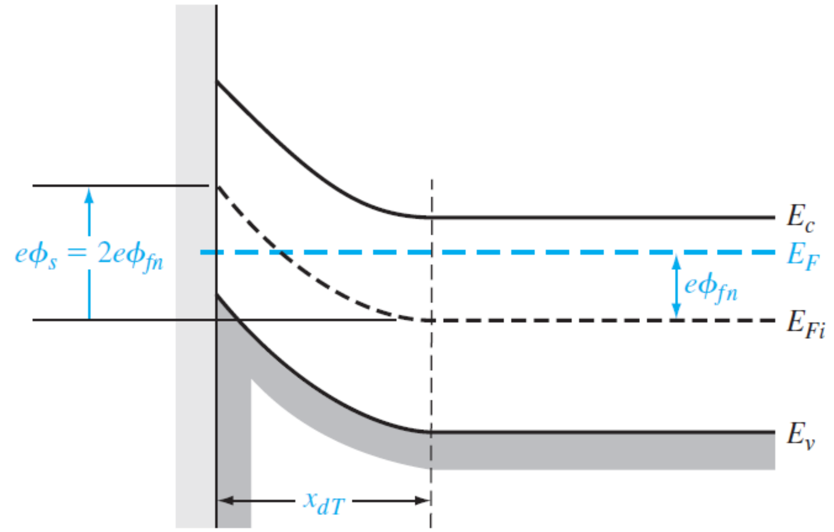
MOS structure and band bending

Width of the space charge region (n-type substrate)

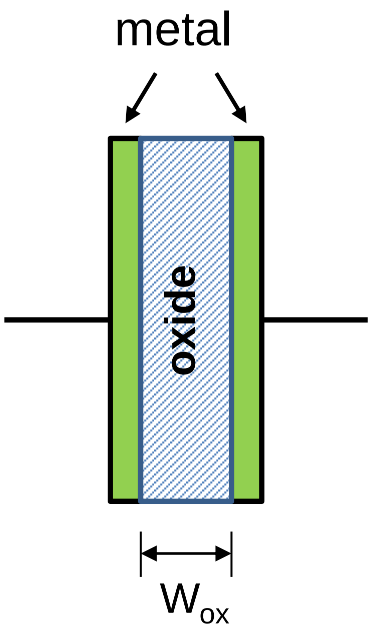
$$\phi_{fn} = V_t \ln\left(\frac{N_d}{n_i}\right)$$

Maximum space charge width at the inversion transition point:

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



MOS capacitor



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

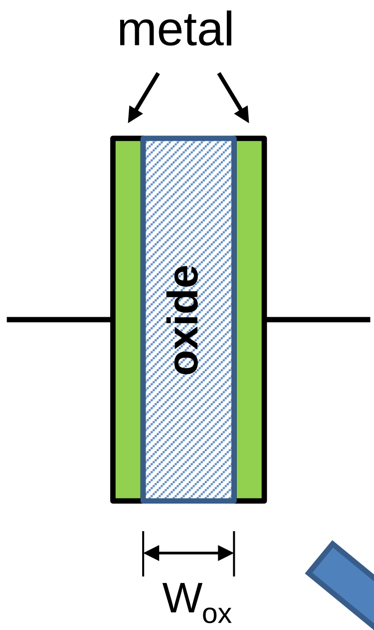
In accumulation:

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

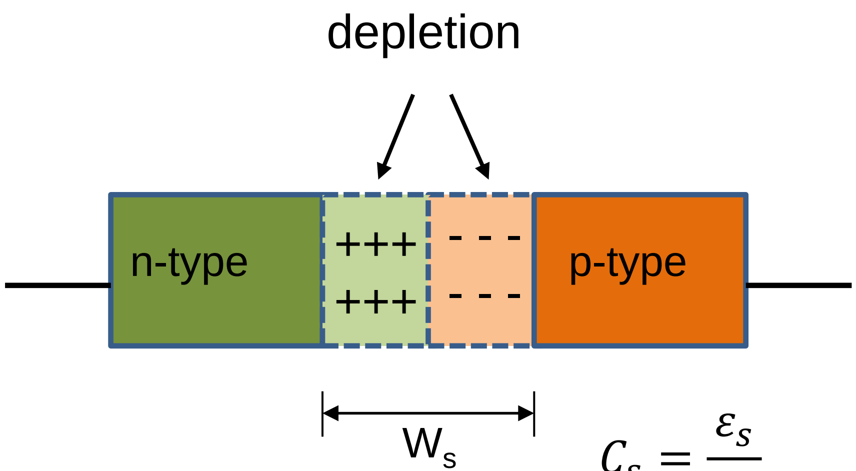
Capacitance per unit area

MOS capacitor

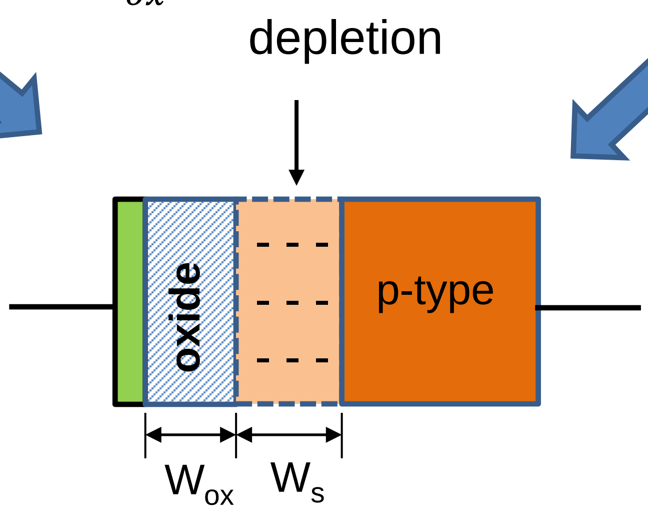
With depletion:



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

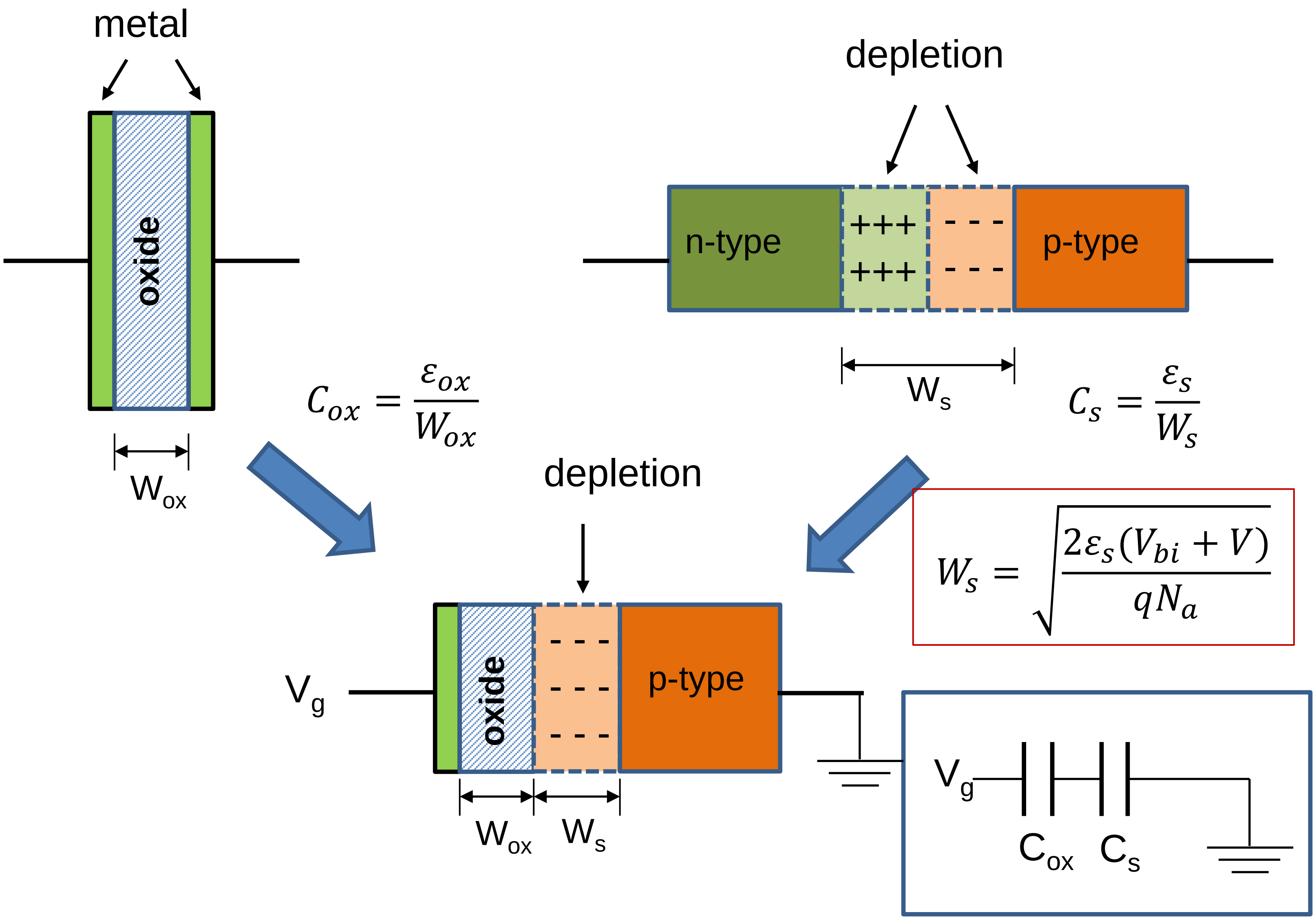


$$C_s = \frac{\varepsilon_s}{W_s}$$



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

MOS capacitor



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

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

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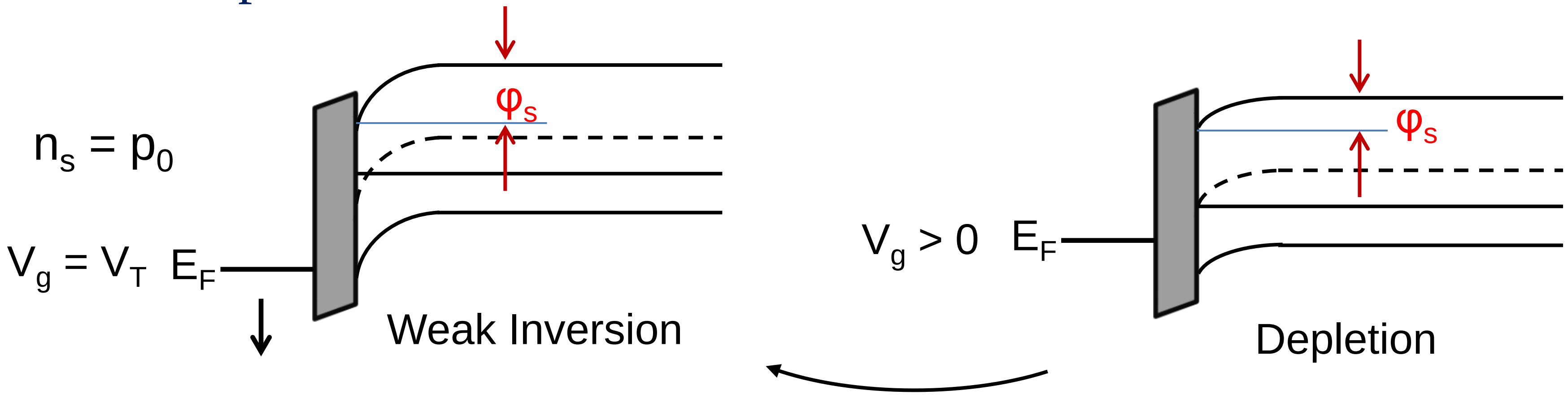
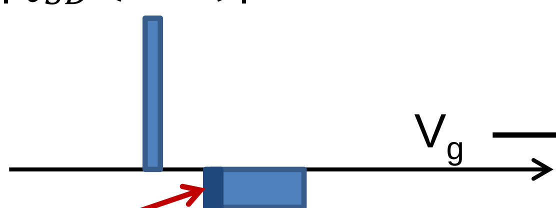
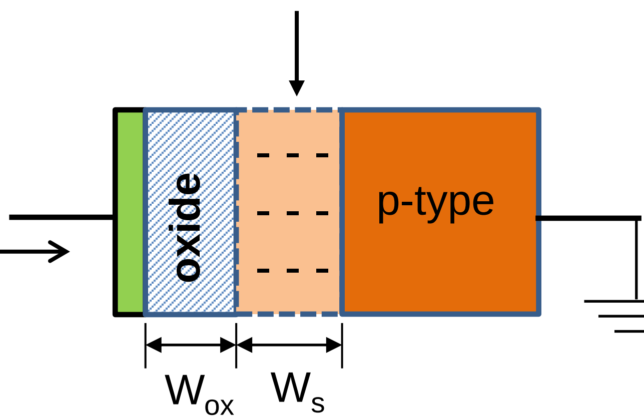
MOS capacitor



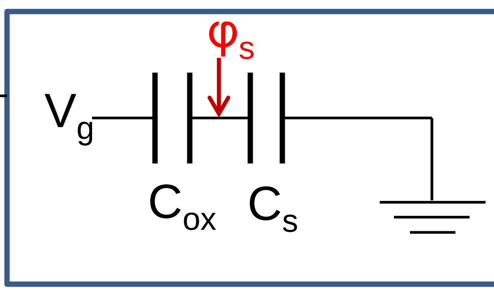
$$C_s = \frac{\varepsilon_s}{W_s}$$

Net charge is zero!





$$W_s = \sqrt{\frac{2\varepsilon_s(\varphi_s)}{eN_a}}$$

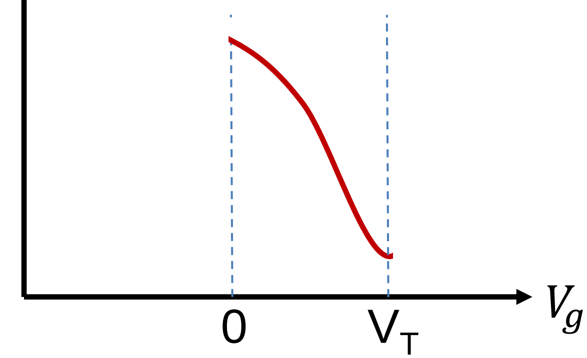


MOS capacitor

$$\boxed{\varphi_s = \frac{V_g C_{ox}}{C_{ox} + C_s}}$$

$$\boxed{C_s = \frac{\varepsilon_s}{\sqrt{\frac{2\varepsilon_s(\varphi_s)}{eN_a}}}}$$

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



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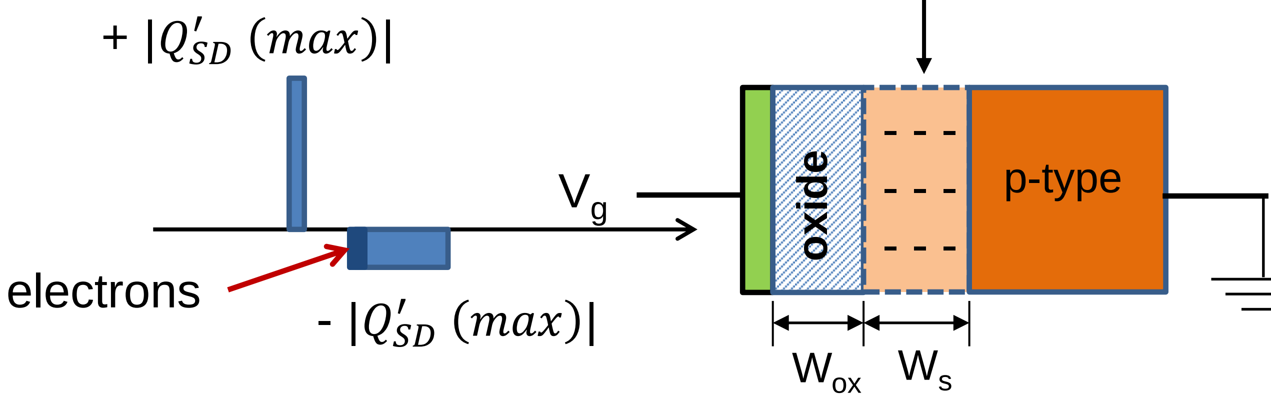
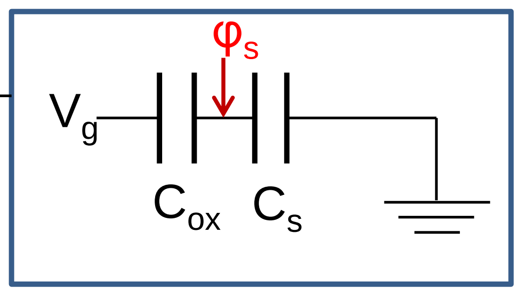
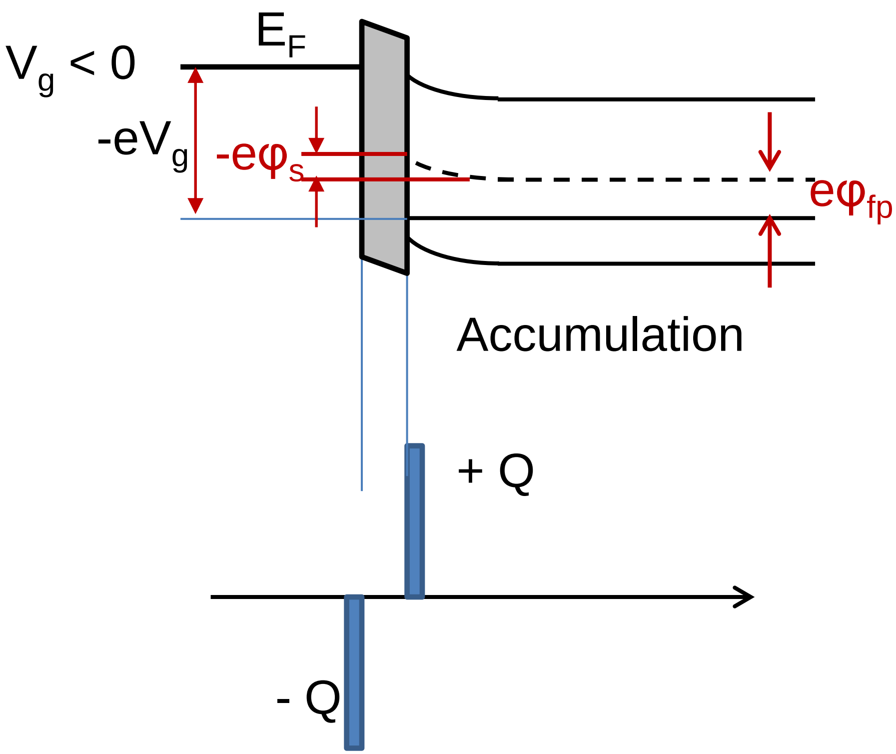


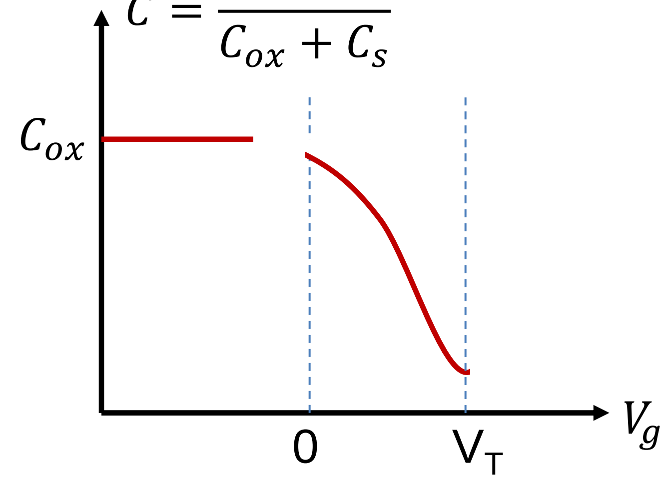
$$\boxed{x_d = W_s = \sqrt{\frac{2\varepsilon_s(\varphi_s)}{eN_a}}}$$



Previously…Charge Distribution

Accumulation





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

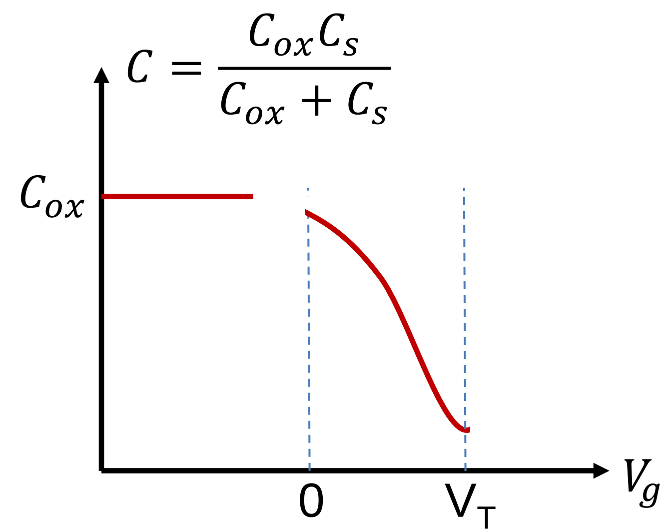
$$C_s \to \infty$$

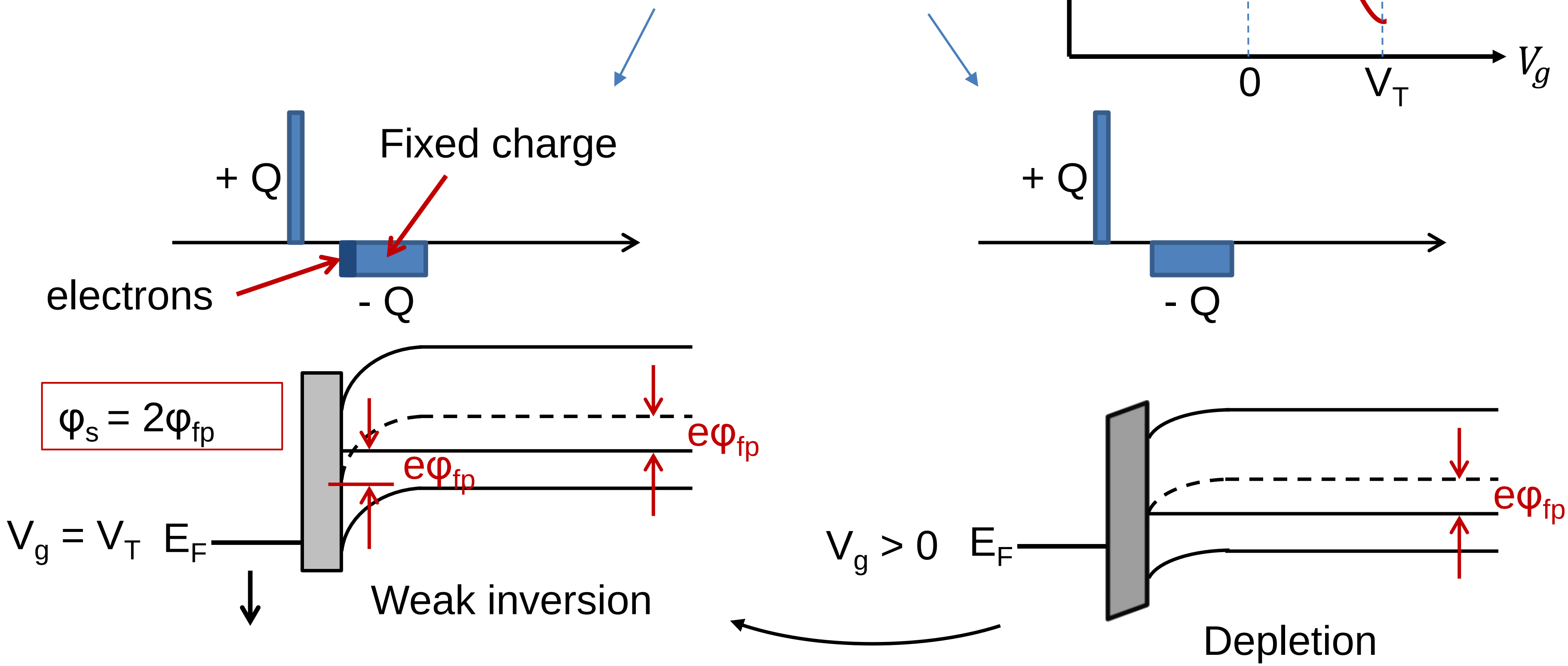
$$C = \frac{C_s C_{ox}}{C_s + C_{ox}} \approx C_{ox}$$

Previously…Charge Distribution

Depletion and weak inversion

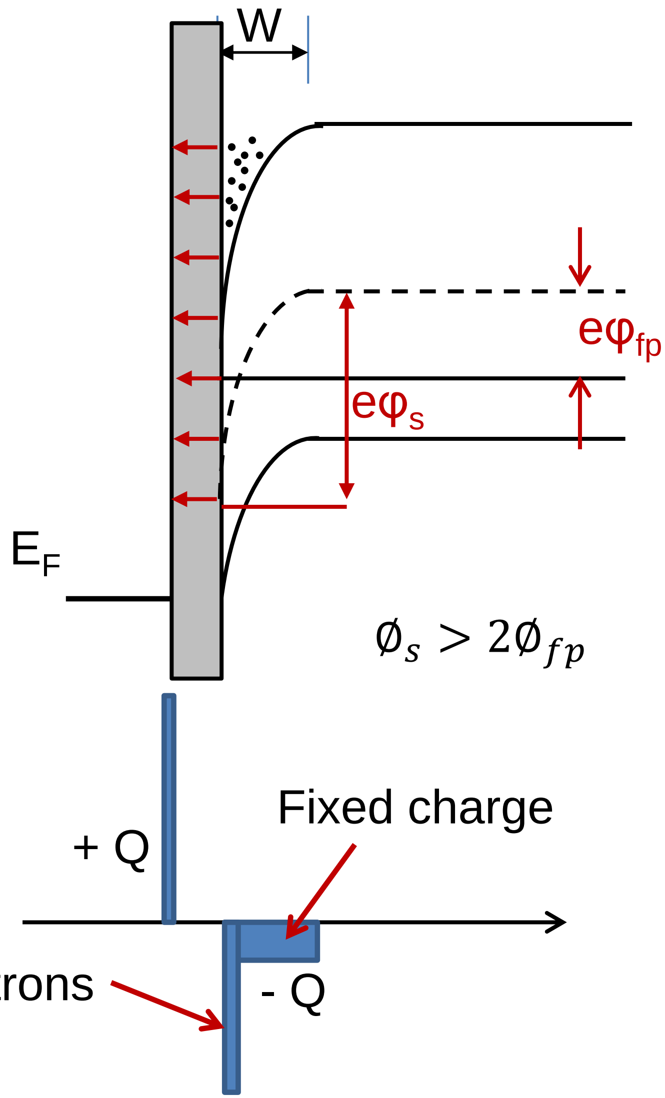
$$C_s = \frac{\varepsilon_s}{\sqrt{\frac{2\varepsilon_s(\varphi_s)}{eN_a}}}$$



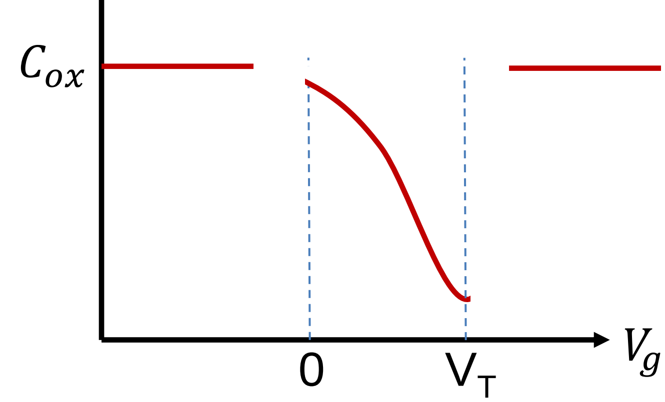


Previously…Charge Distribution

Strong inversion



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

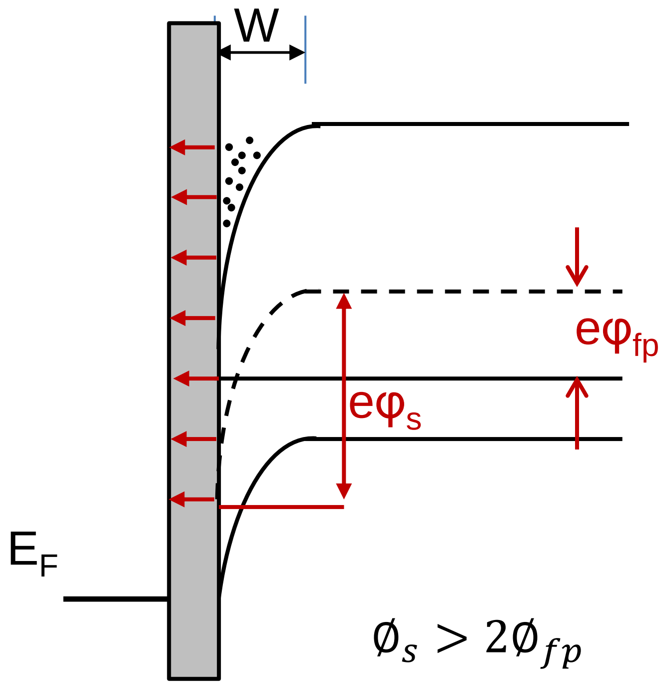


$C_s \rightarrow \infty$

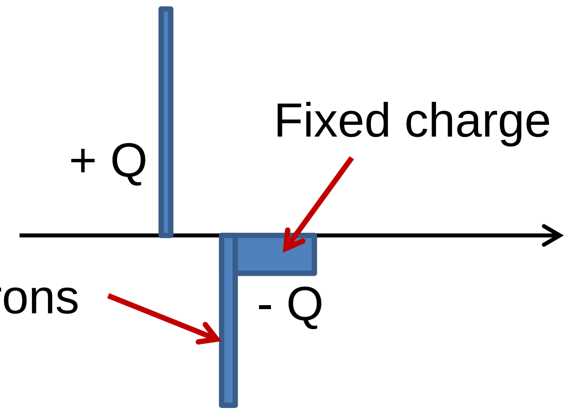
$$C = \frac{C_s C_{ox}}{C_s + C_{ox}} \approx C_{ox}$$

Capacitance vs Voltage (CV) curve

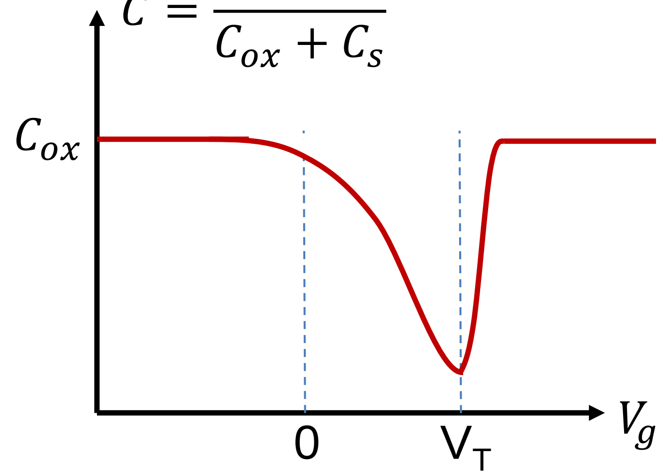
Strong inversion



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



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

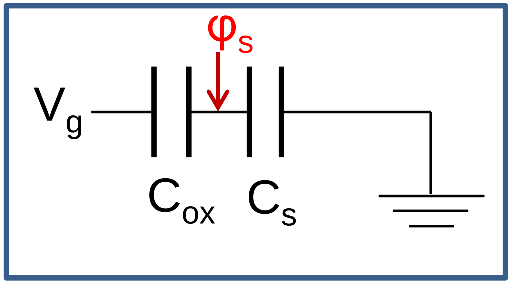


$$C_s \rightarrow \infty$$

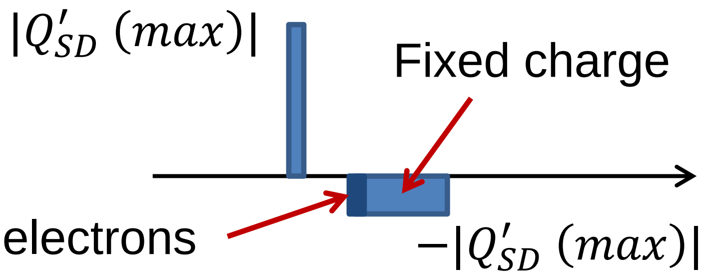
$$C = \frac{C_s C_{ox}}{C_s + C_{ox}} \approx C_{ox}$$

Threshold Voltage (V_T)

Ideal case:
Metal and p-type semiconductor have the same work function $\Phi_m=\Phi_s$



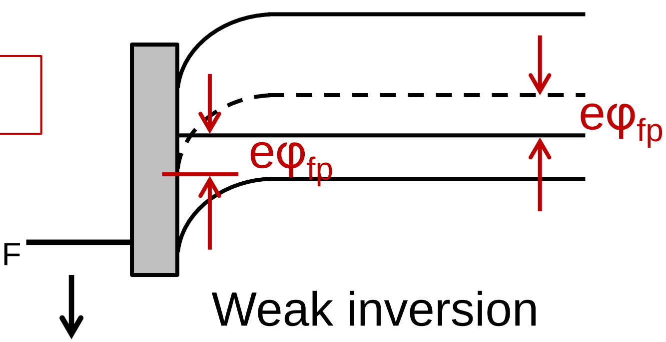
$$C_s = \frac{\varepsilon_s}{\sqrt{\frac{2\varepsilon_s(\varphi_s)}{eN_a}}} = \frac{\varepsilon_s}{\sqrt{\frac{2\varepsilon_s(2\varphi_{fp})}{eN_a}}}$$



$$|Q'_{SD}\,(max)| = (V_T - 2\varphi_{fp})\, C_{ox}$$

$$V_T = 2\varphi_{fp} + \frac{|Q'_{SD}\,(max)|}{C_{ox}}$$

$\varphi_s = 2\varphi_{fp}$



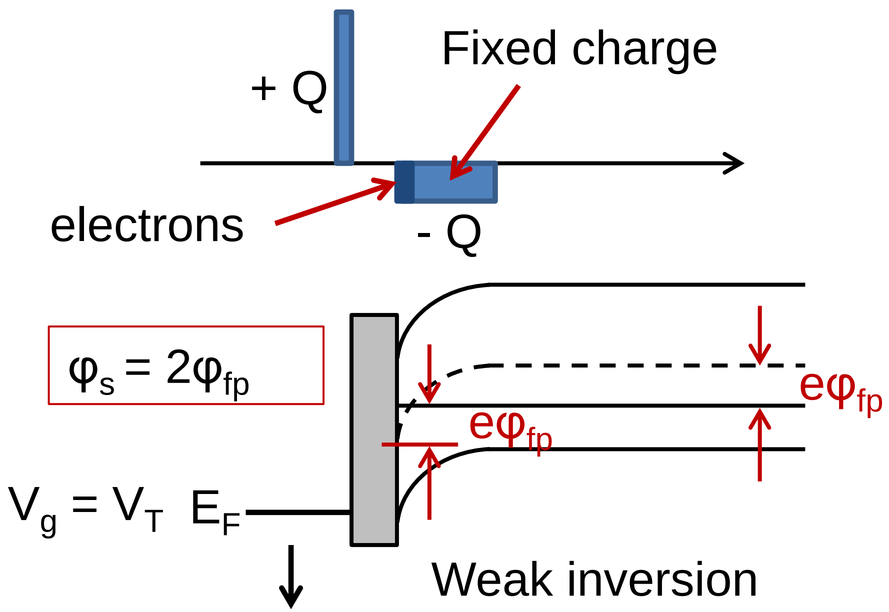
$$V_T = 2\varphi_{fp} + \frac{2\sqrt{e\varepsilon_s N_a \varphi_{fp}}}{C_{ox}}$$

Threshold Voltage (V_T)

If metal and semiconductor have different work function: $\Phi_m \neq \Phi_s$

$$C_s = \frac{\varepsilon_s}{\sqrt{\frac{2\varepsilon_s(\varphi_s)}{eN_a}}} = \frac{\varepsilon_s}{\sqrt{\frac{2\varepsilon_s(2\varphi_{fp})}{eN_a}}}$$

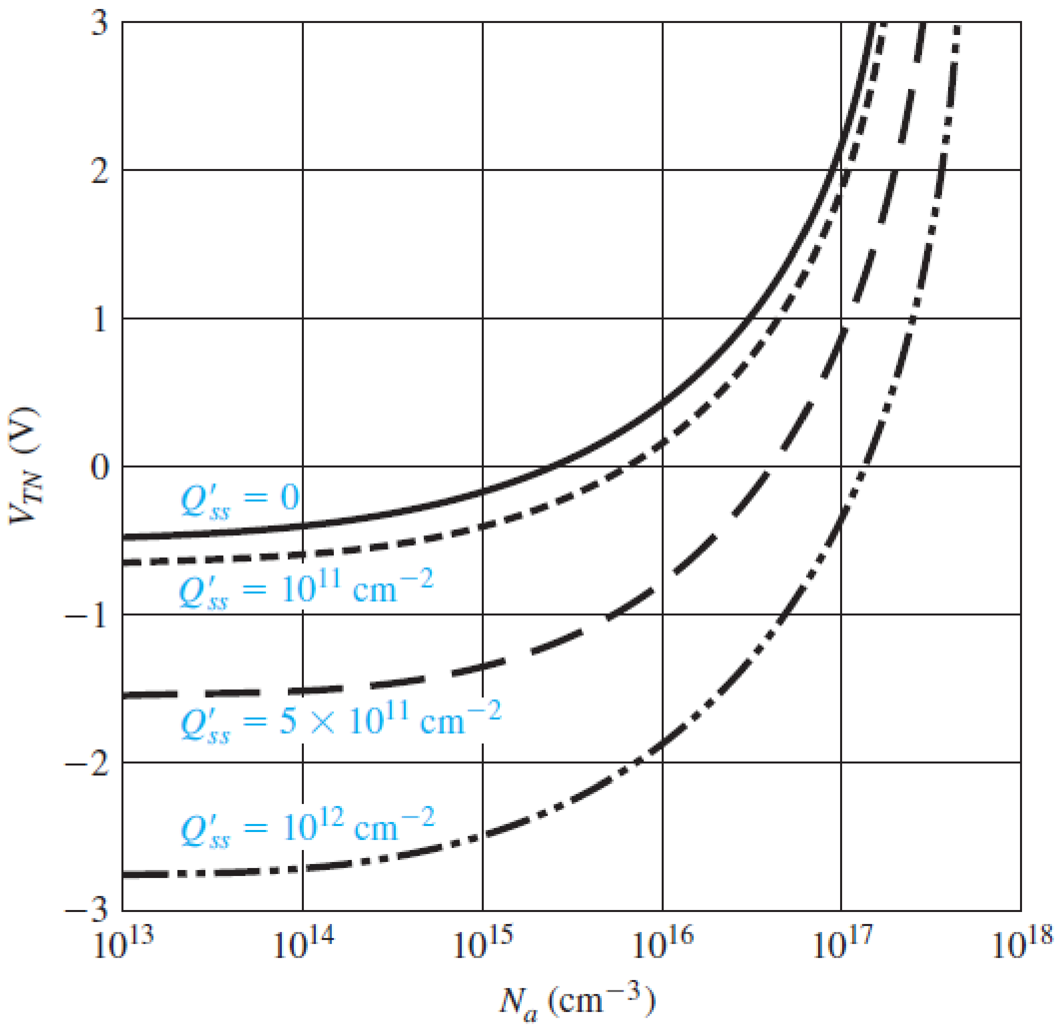
$$|Q'_{SD}\,(max)| = (V_T - 2\varphi_{fp})\,C_{ox}$$



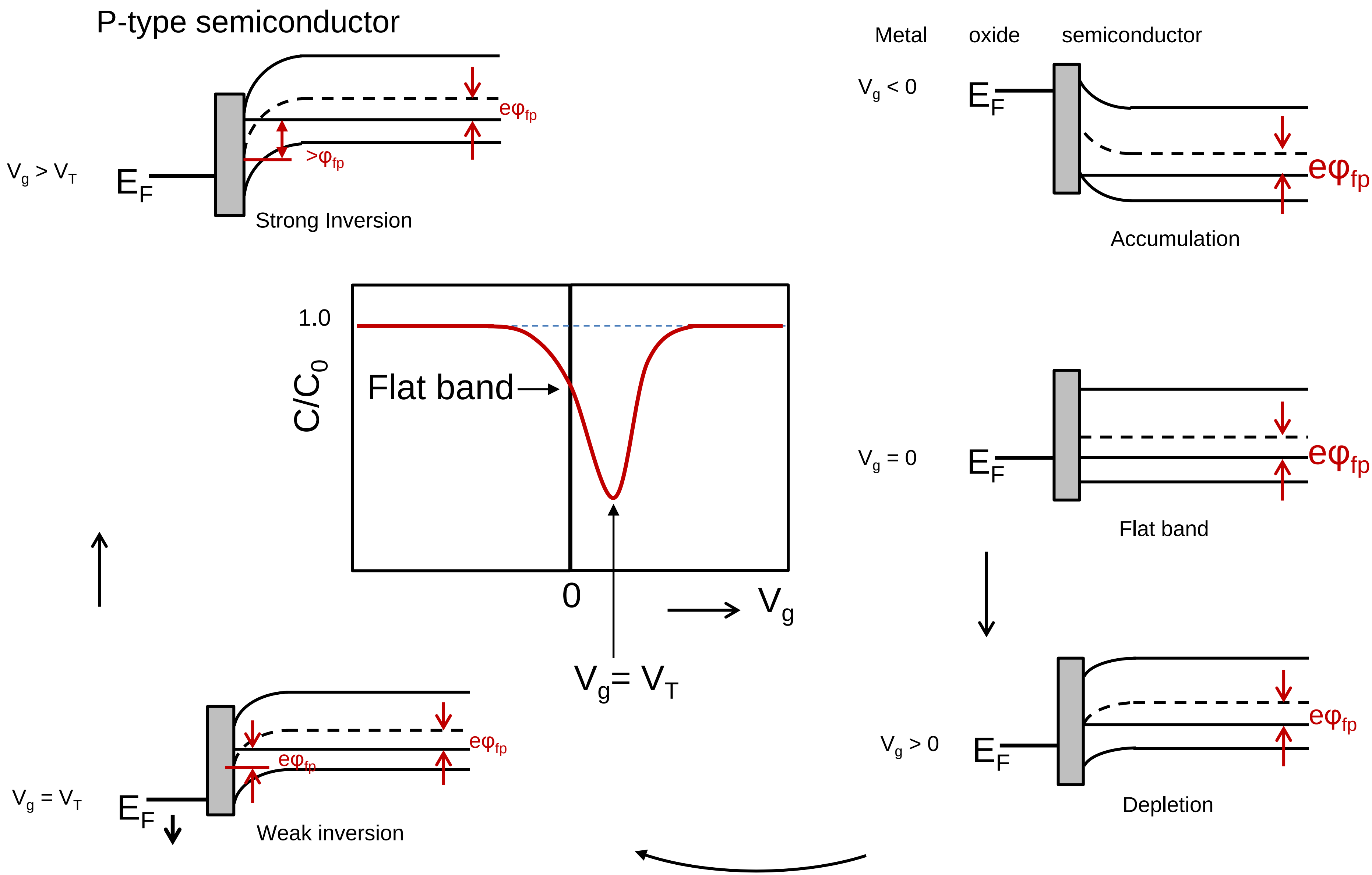
$$V_{TN} = \frac{|Q'_{SD}(\max)|}{C_{ox}} + V_{FB} + 2\phi_{fp}$$

V_{FB}: flat band voltage, will be discussed later

Threshold Voltage (V_T)

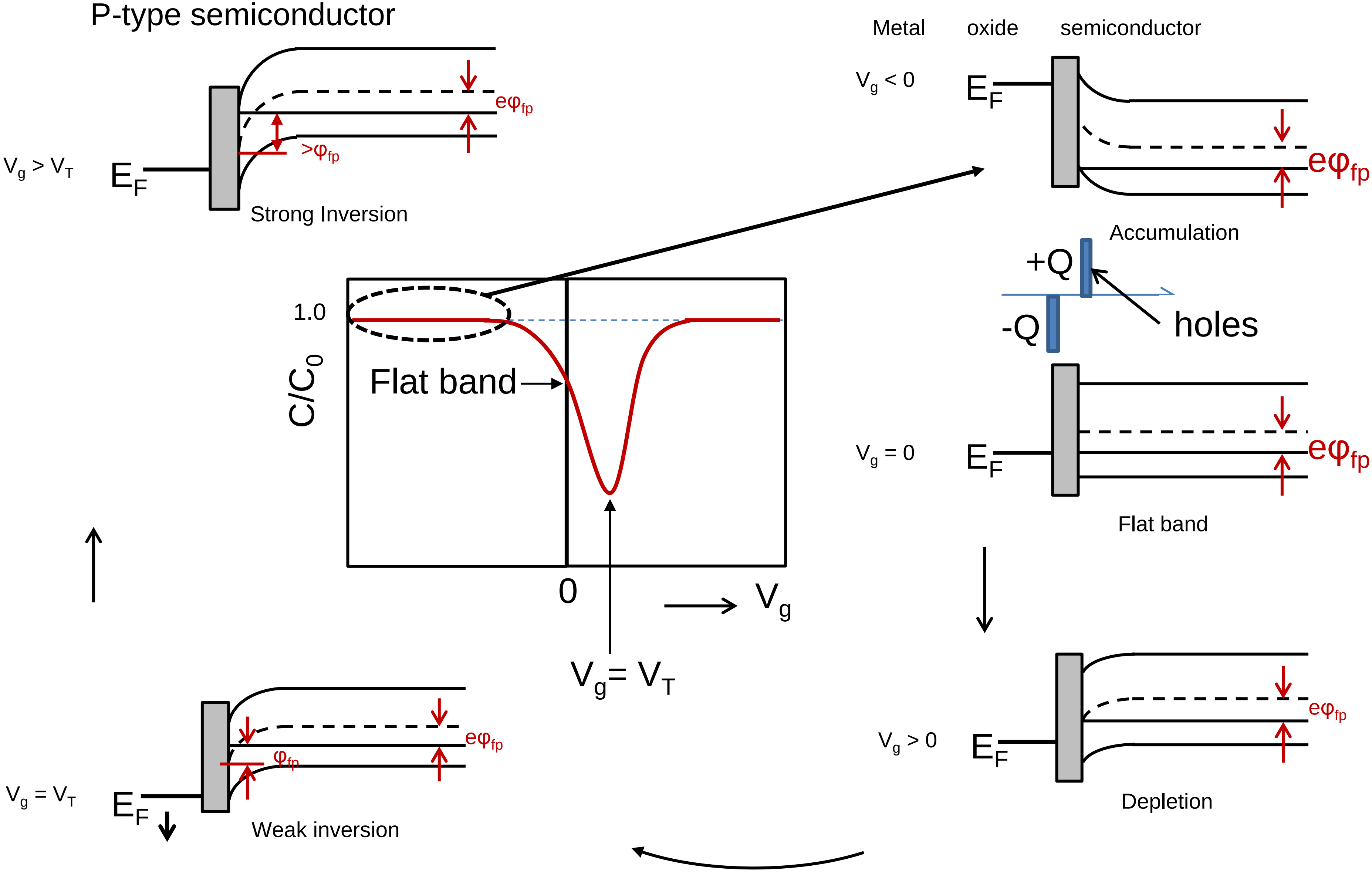


Summary: C-V characteristics

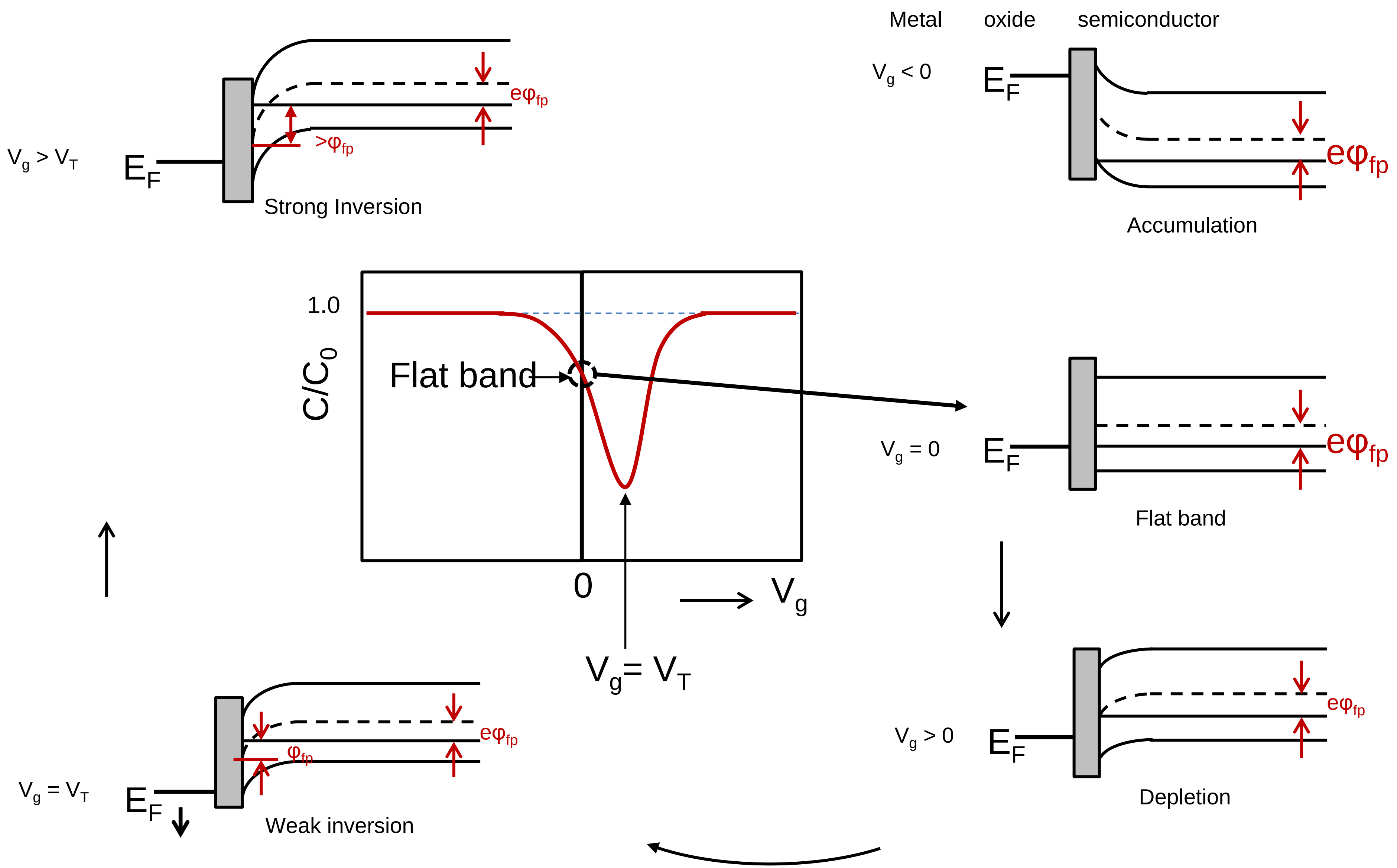


Summary: C-V characteristics

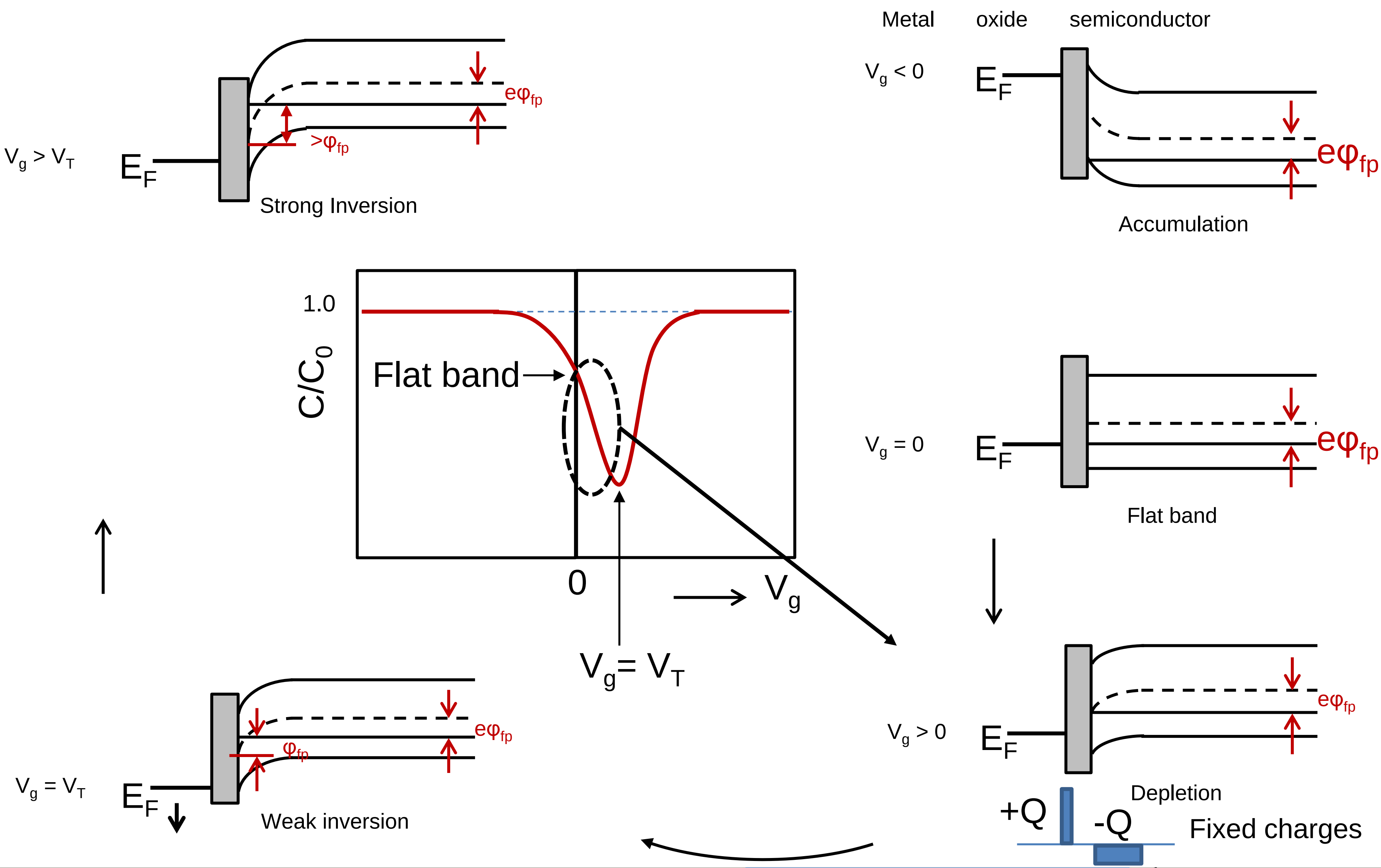
P-type semiconductor



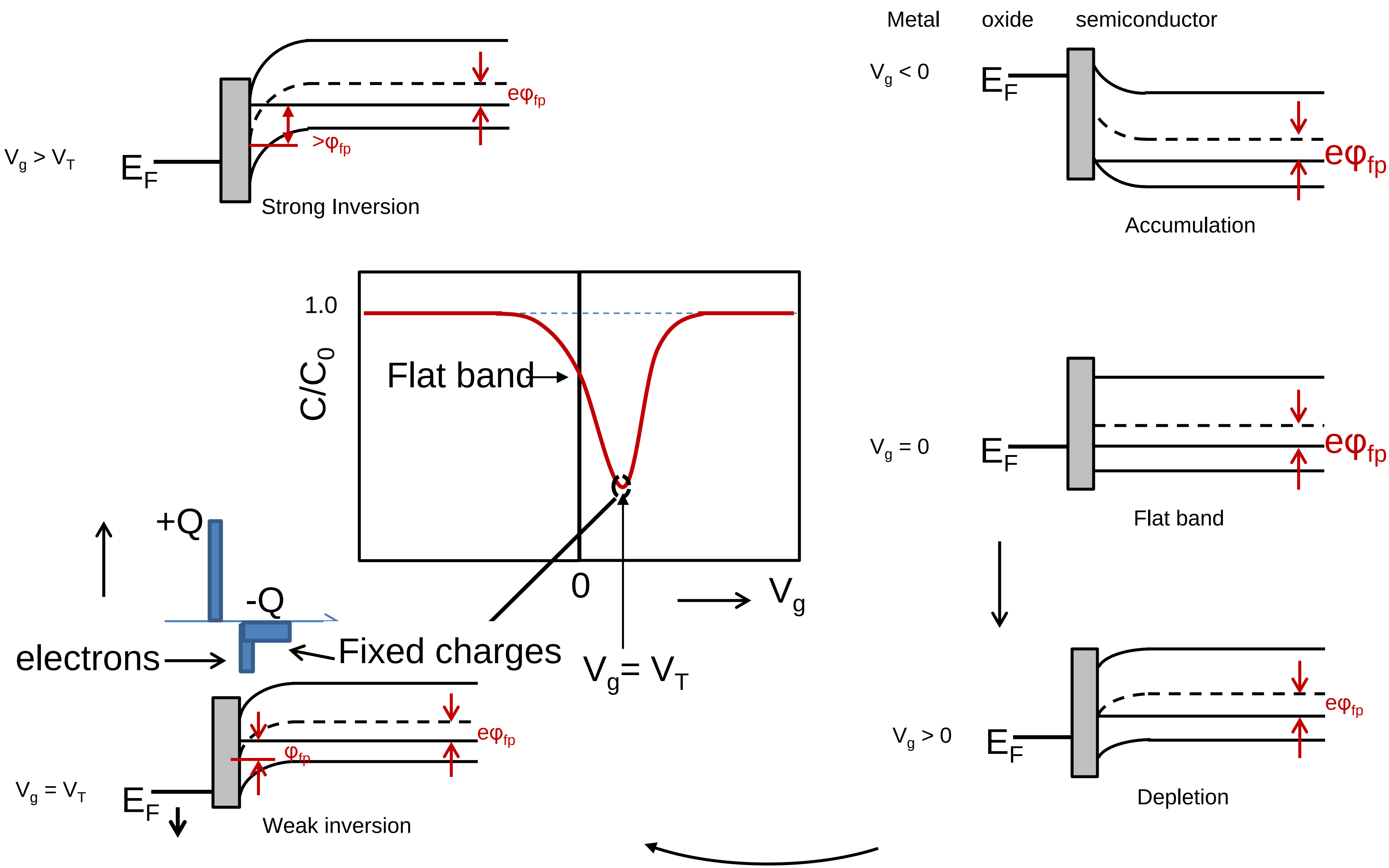
Summary: C-V characteristics



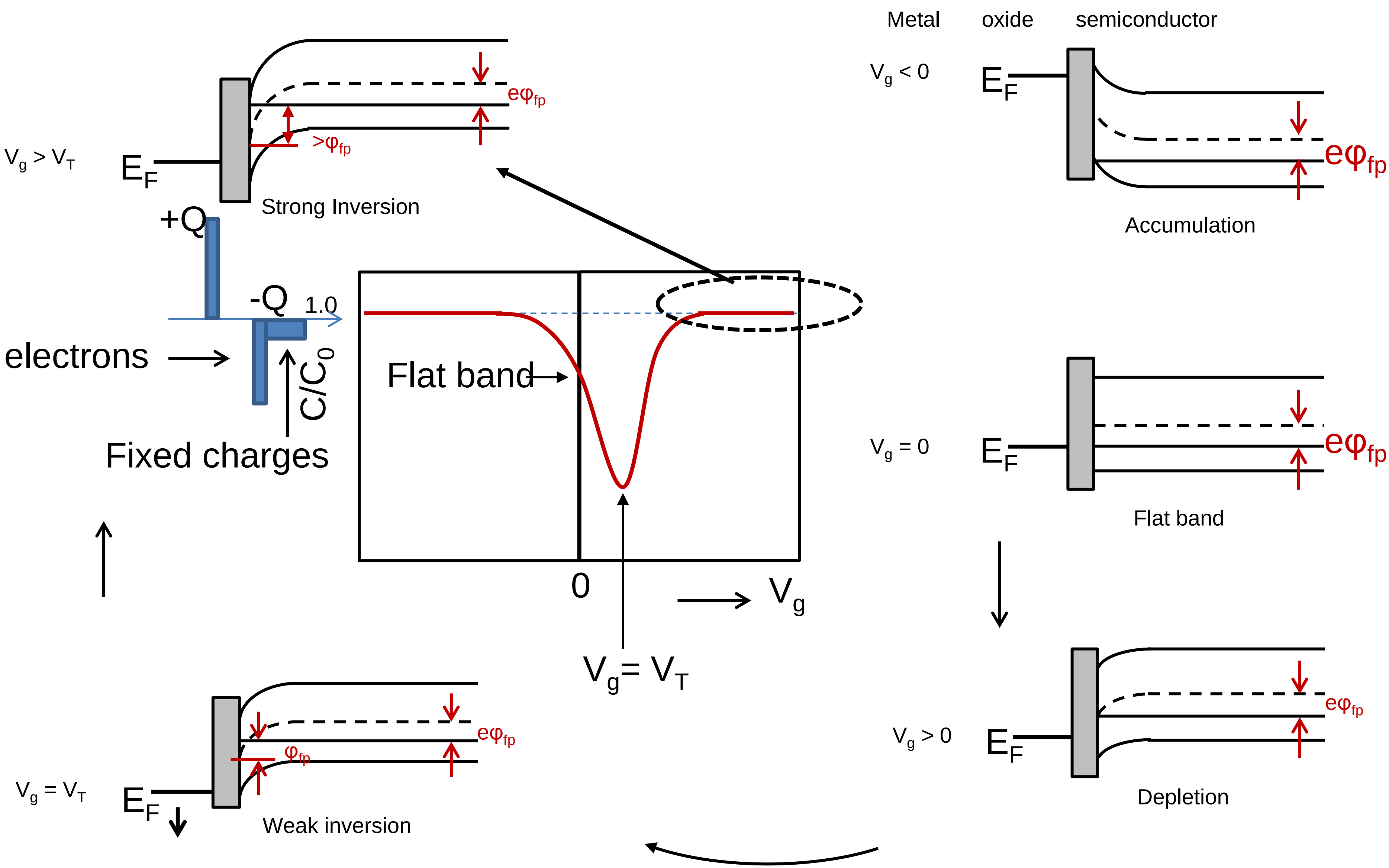
Summary: C-V characteristics



Summary: C-V characteristics

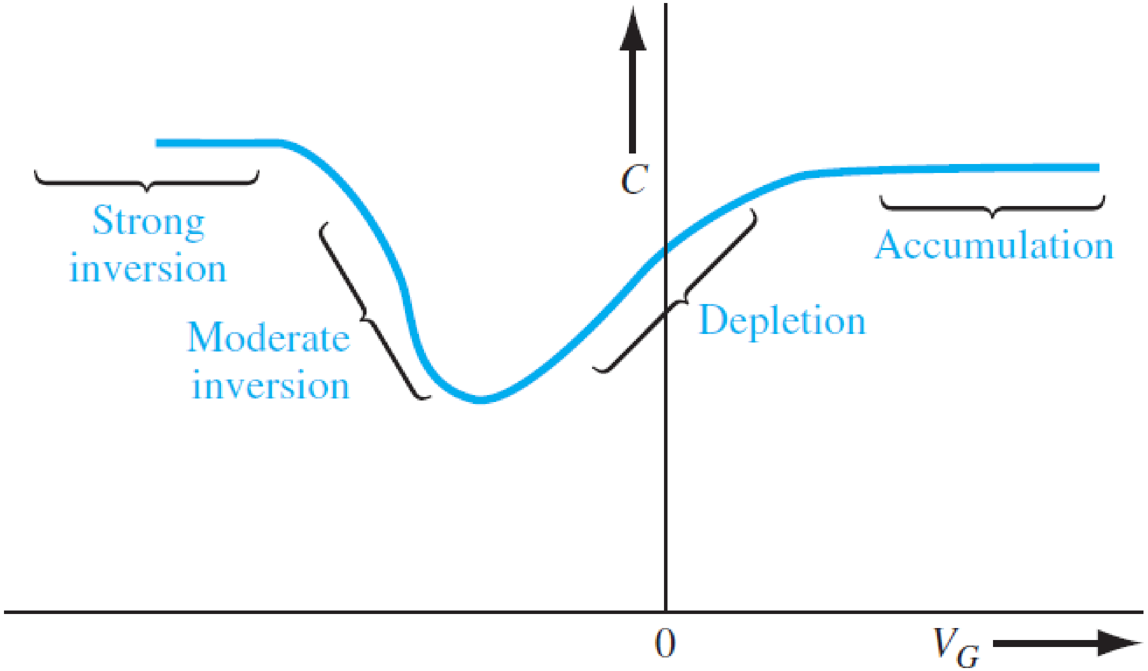


Summary: C-V characteristics

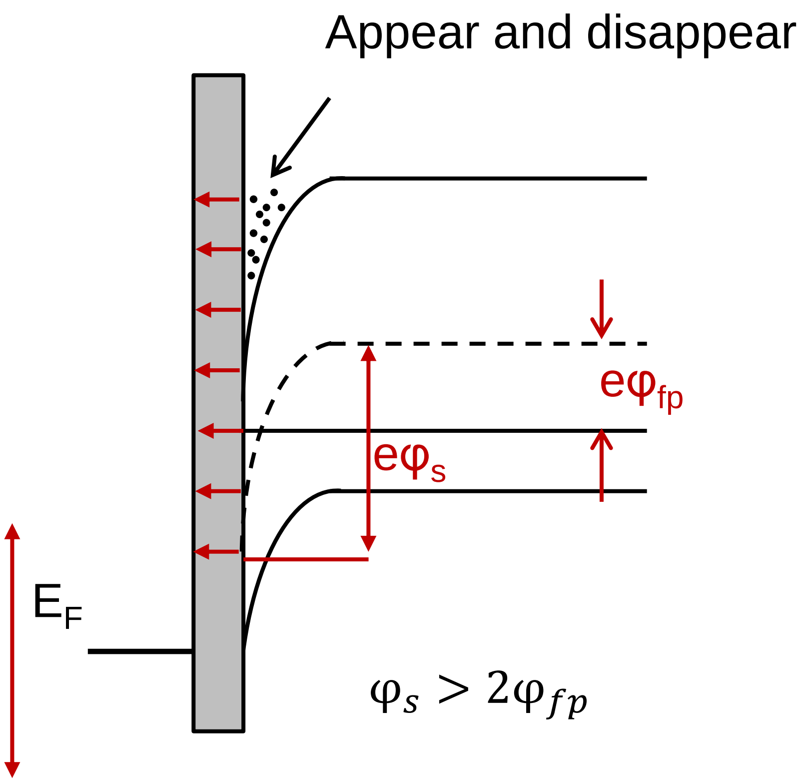


Capacitance vs Voltage (CV) curve

n-type semiconductor

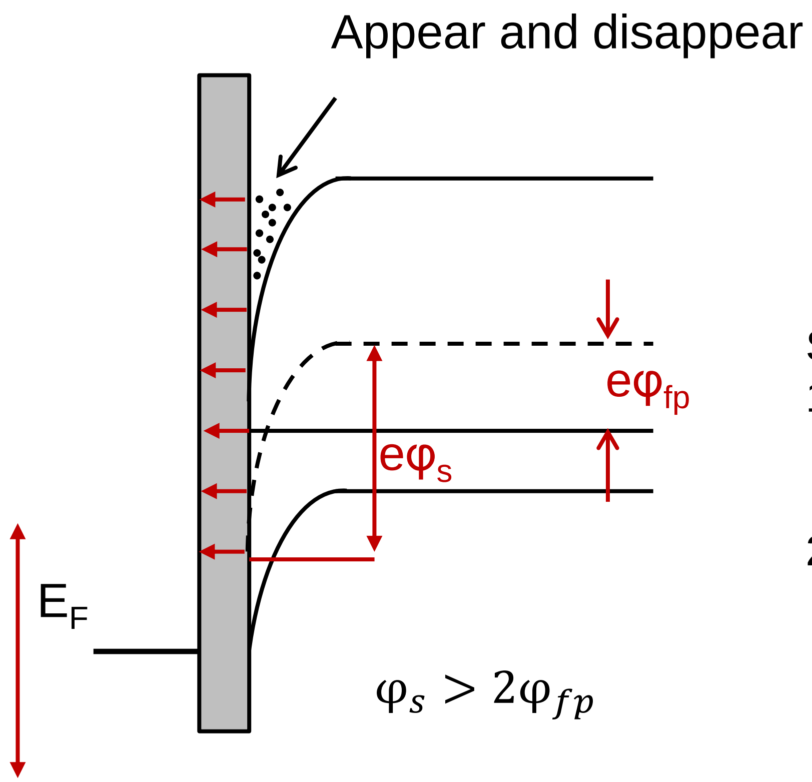


Question:



Where are the electrons coming from and going to?

Question:

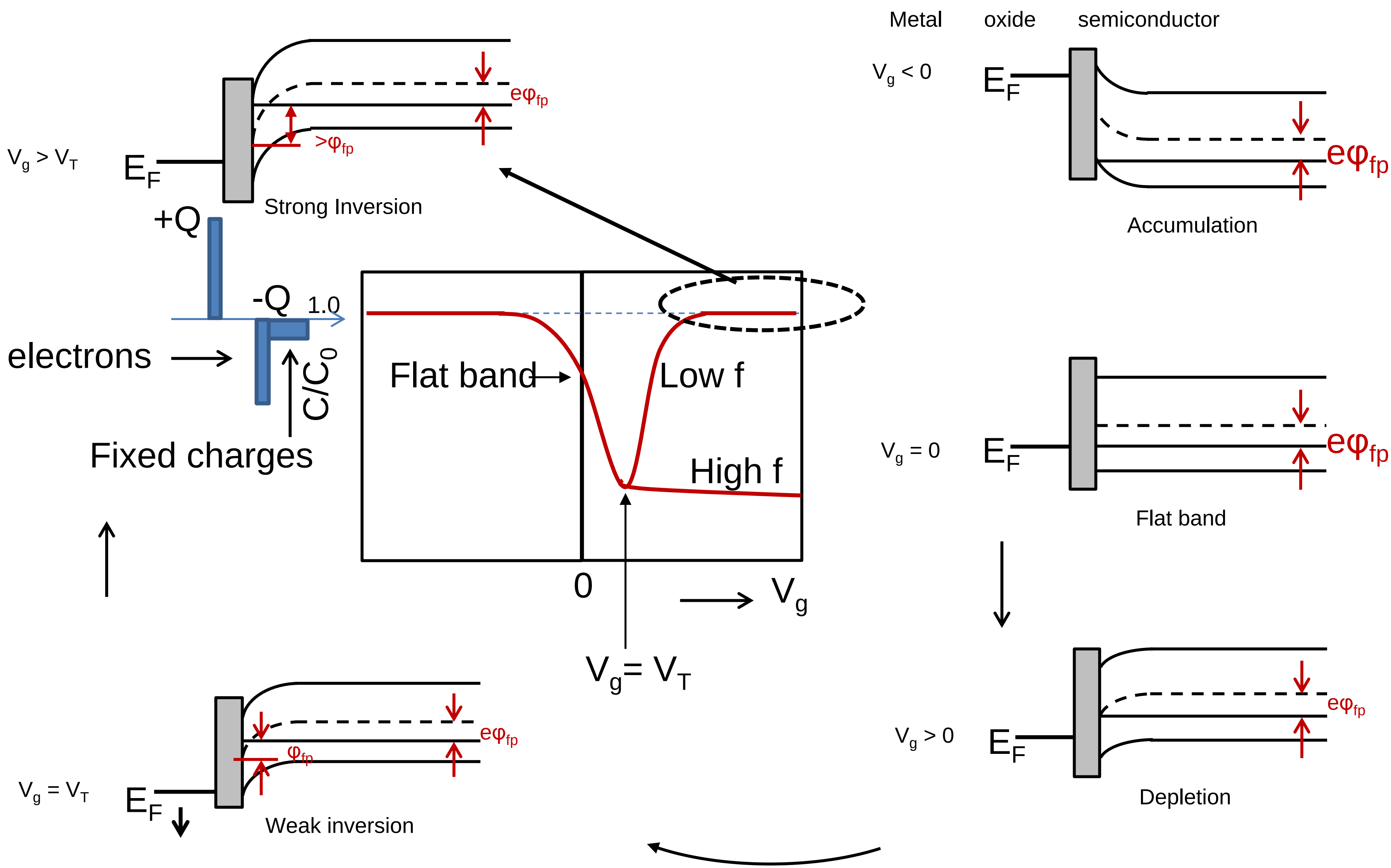


Where are the electrons coming from and going to?

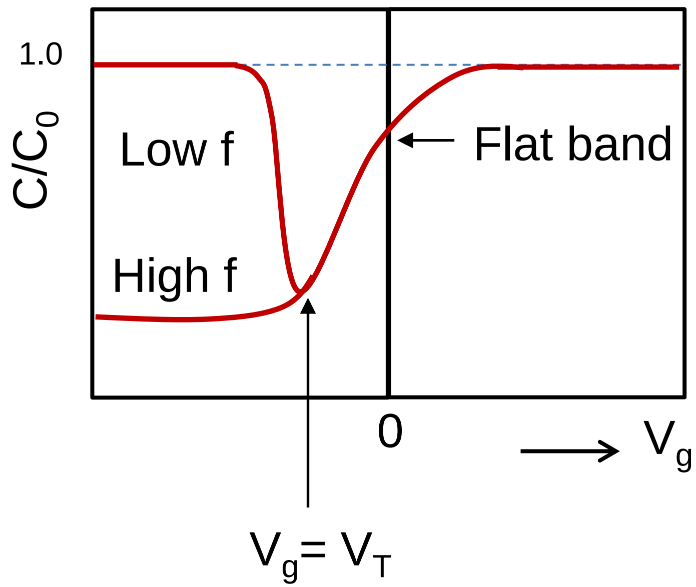
Source:

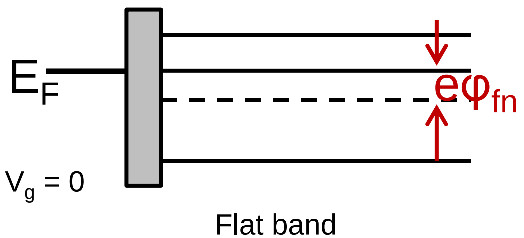
1. diffusion of minority carrier electrons from the p-type substrate across the space charge region
2. thermal generation of electron–hole pairs within the space charge region

C-V characteristics: frequency dependent, p-type substrate



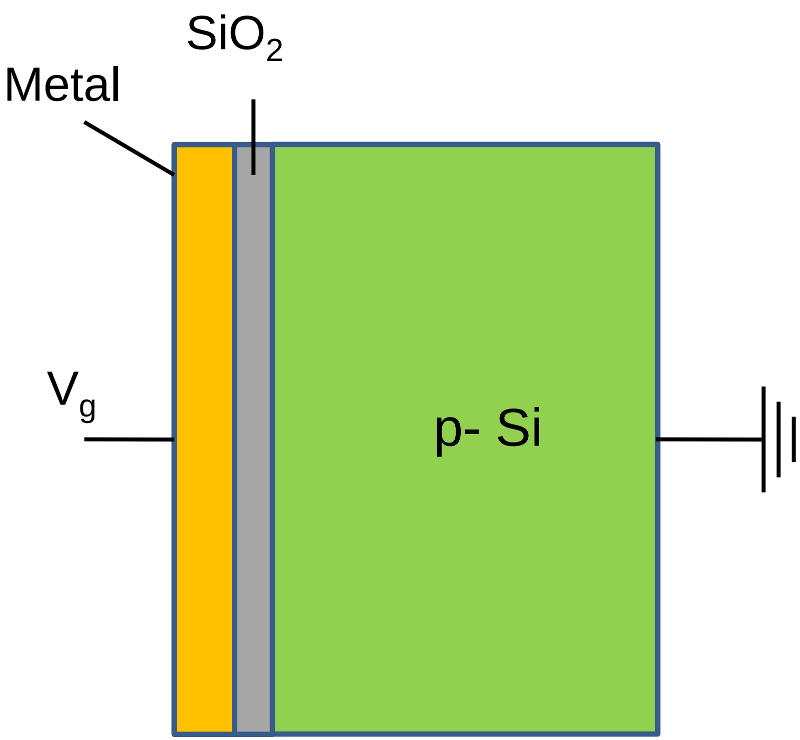
C-V characteristics: n-type substrate



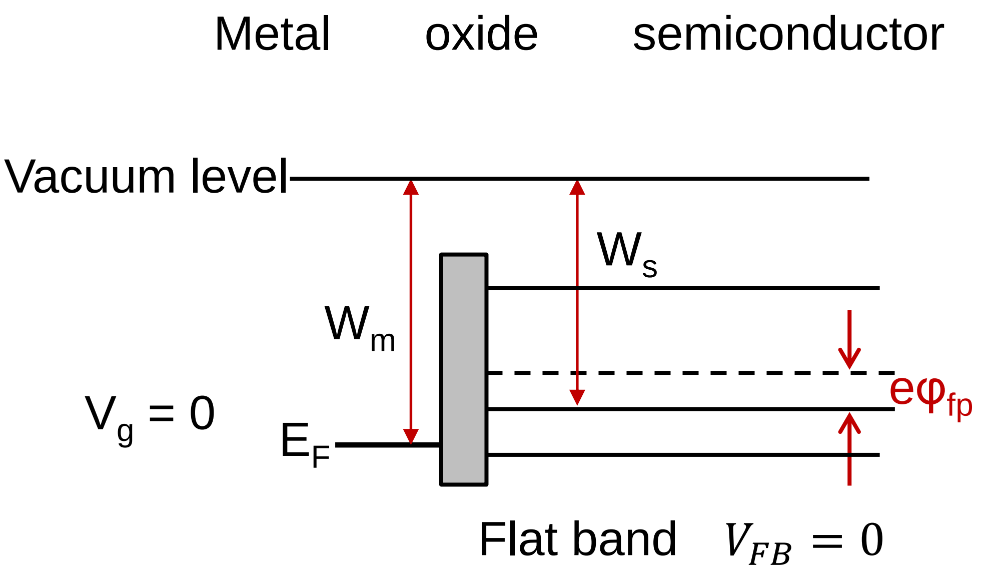


n-type substrate

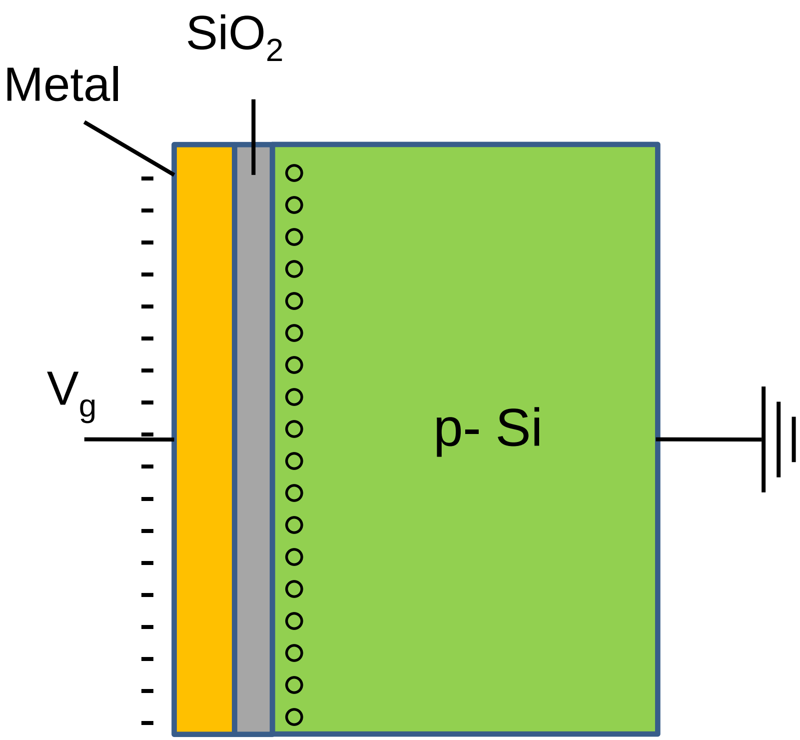
MIS structure: work function

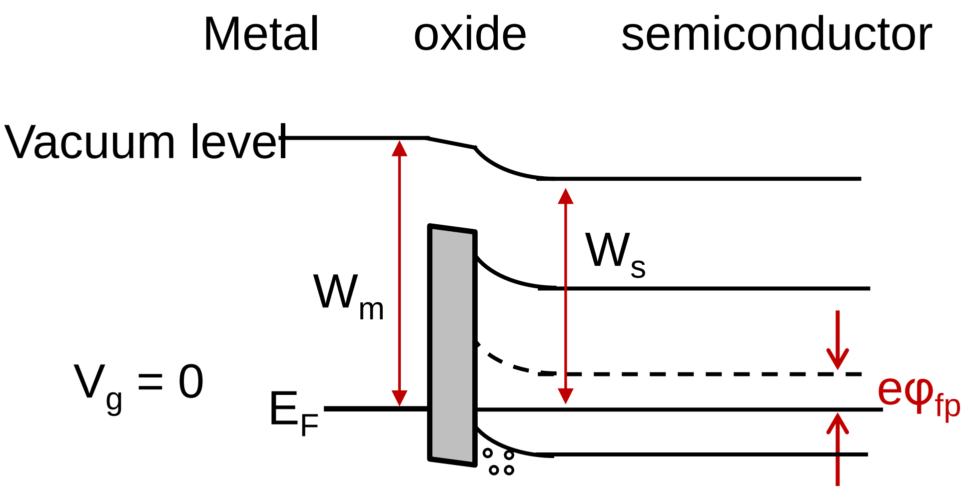


Metal-insulator-semiconductor (MIS)



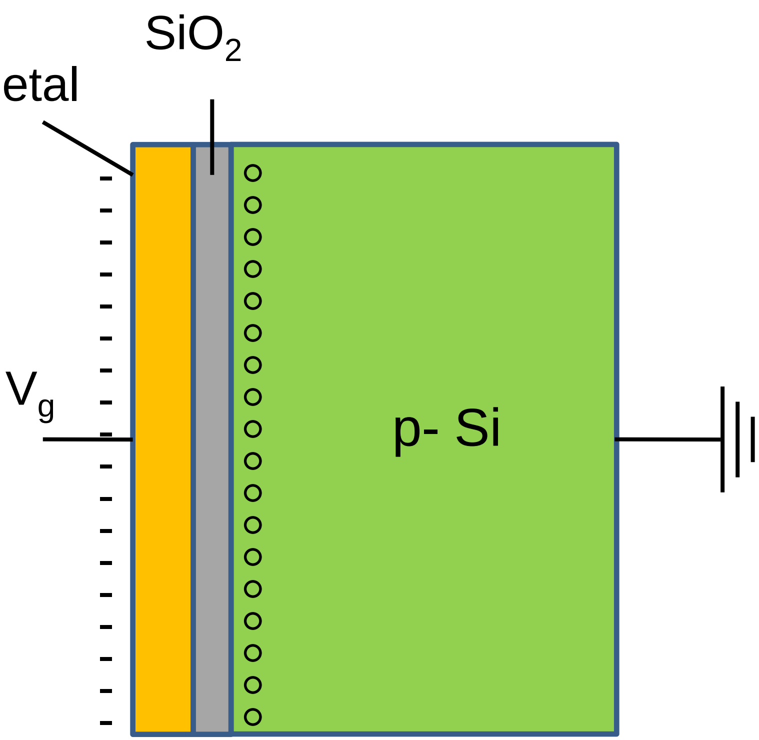
MIS structure: work function



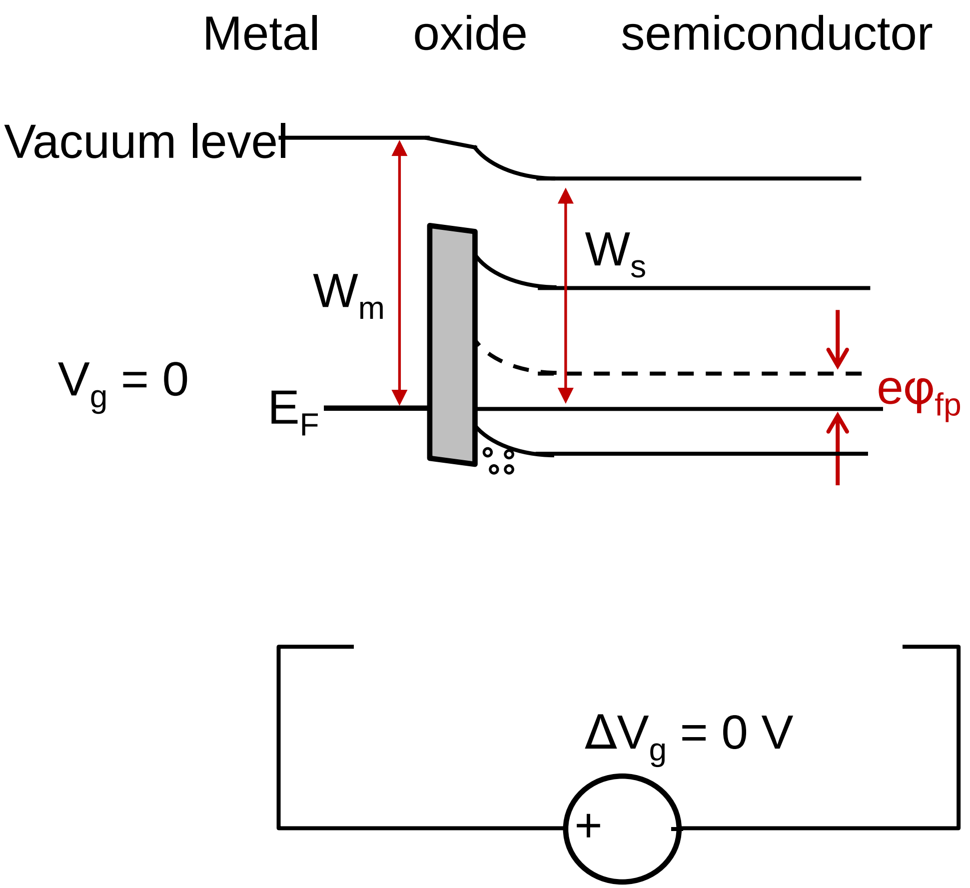


Metal-insulator-semiconductor (MIS)

MIS structure: work function

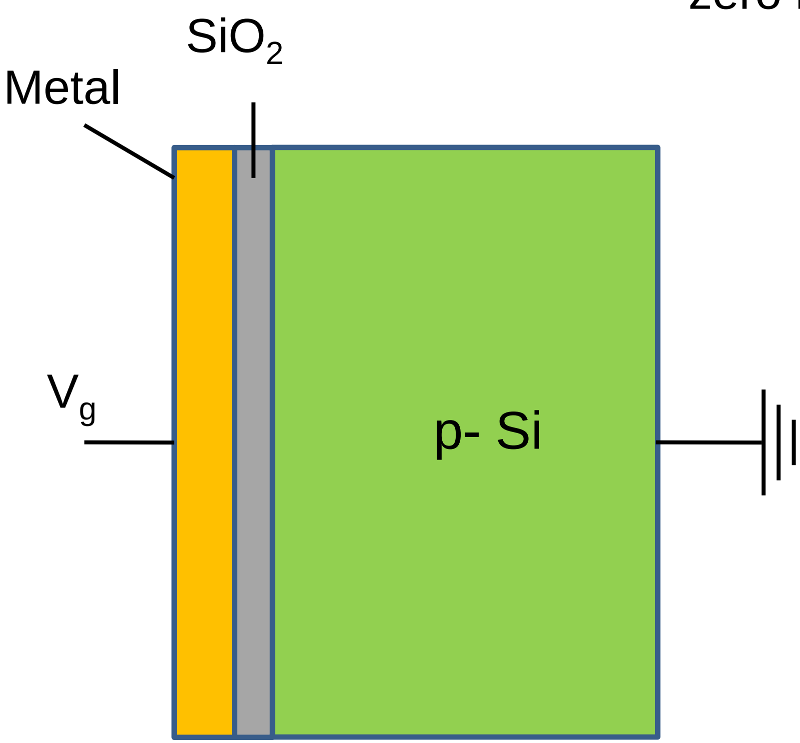


Metal-insulator-semiconductor (MIS)

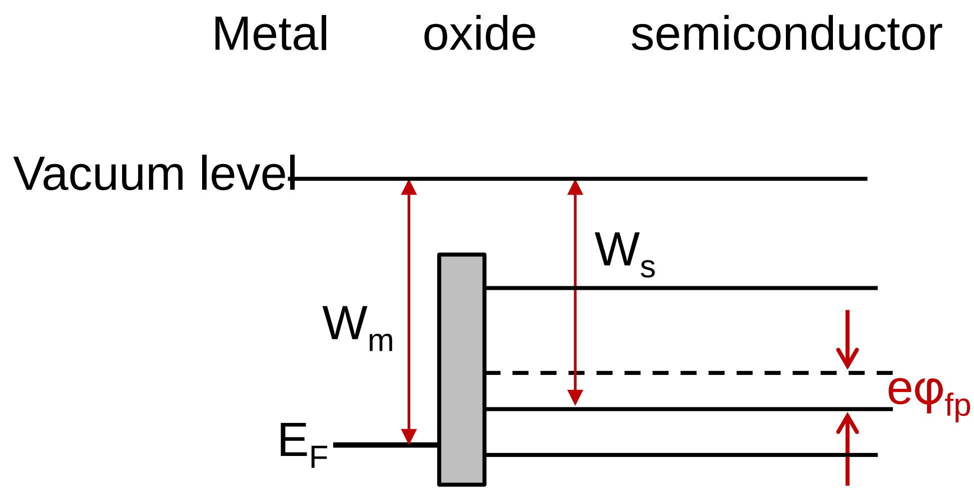


MIS structure: work function

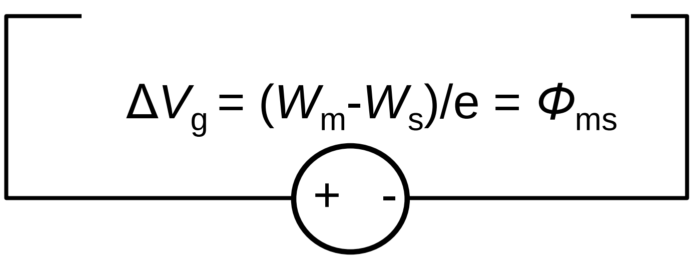
Flat band voltage: applied gate voltage such that there is no band bending in the semiconductor, and zero net space charge in this region



Metal-insulator-semiconductor (MIS)

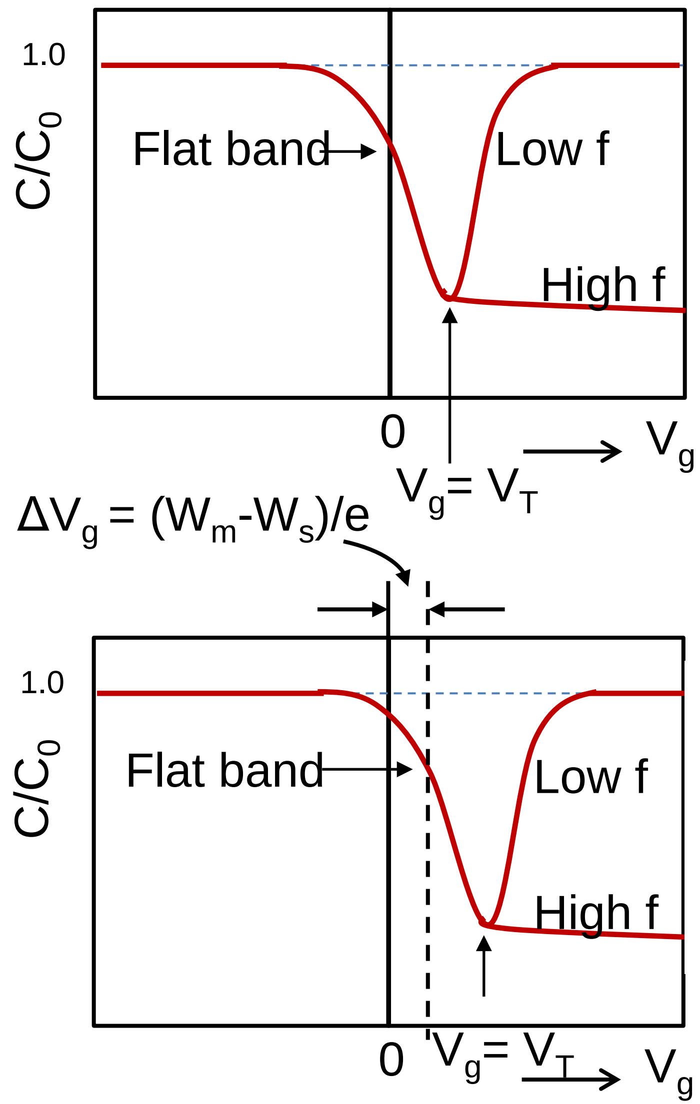


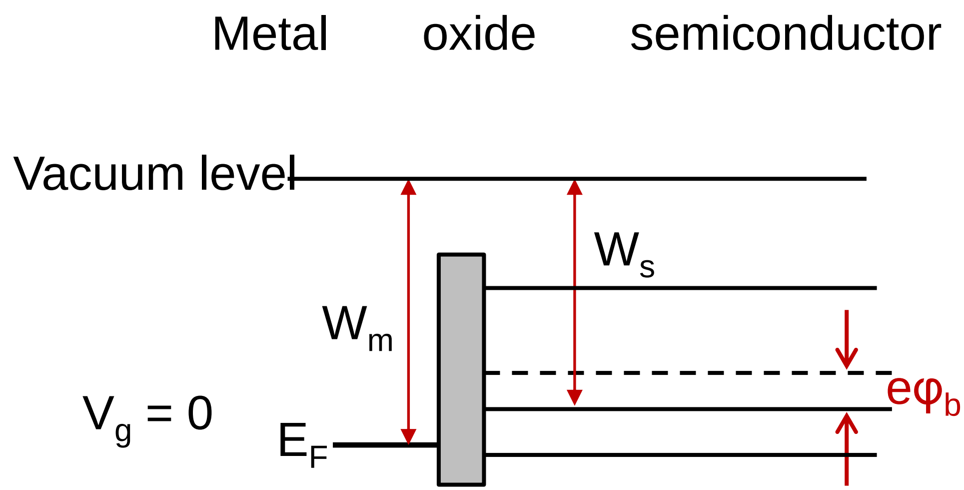
Flat band $V_{FB} = (W_m - W_s)/e$



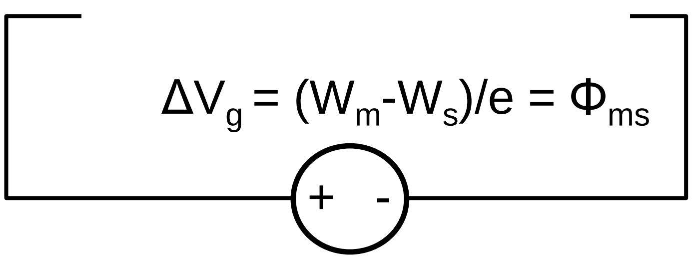
$\Delta V_g = (W_m - W_s)/e = \Phi_{ms}$

MIS structure: work function

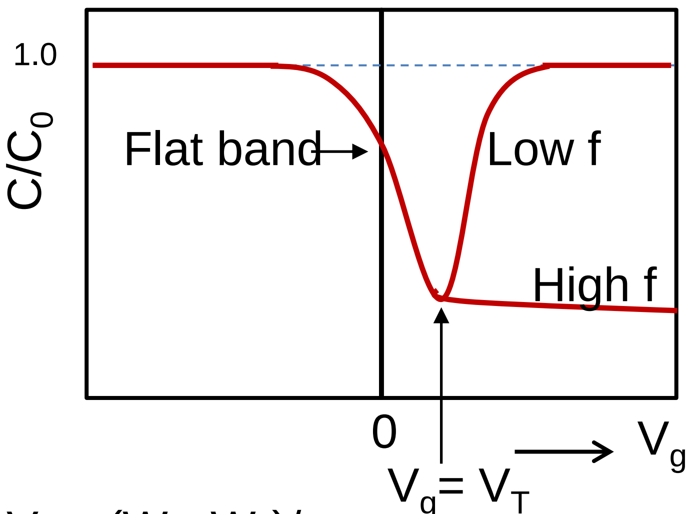




Flat band $V_{FB} = (W_m - W_s)/e$

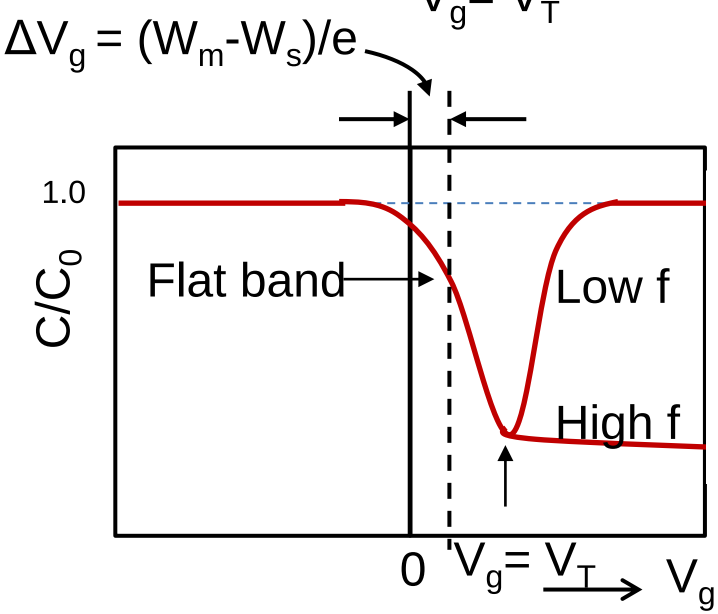


MIS structure: work function



Same work function

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

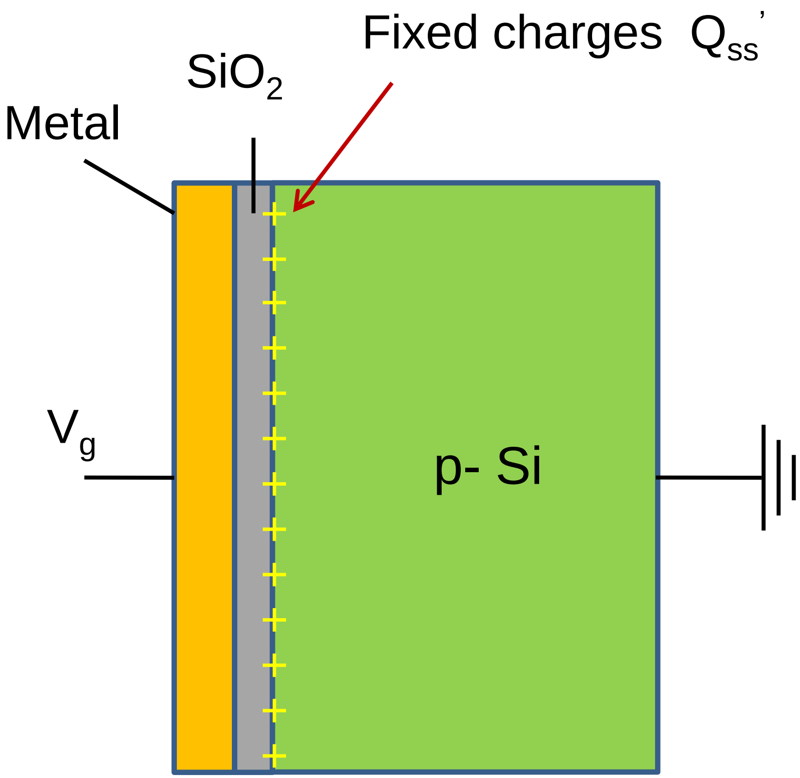


Different work function

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

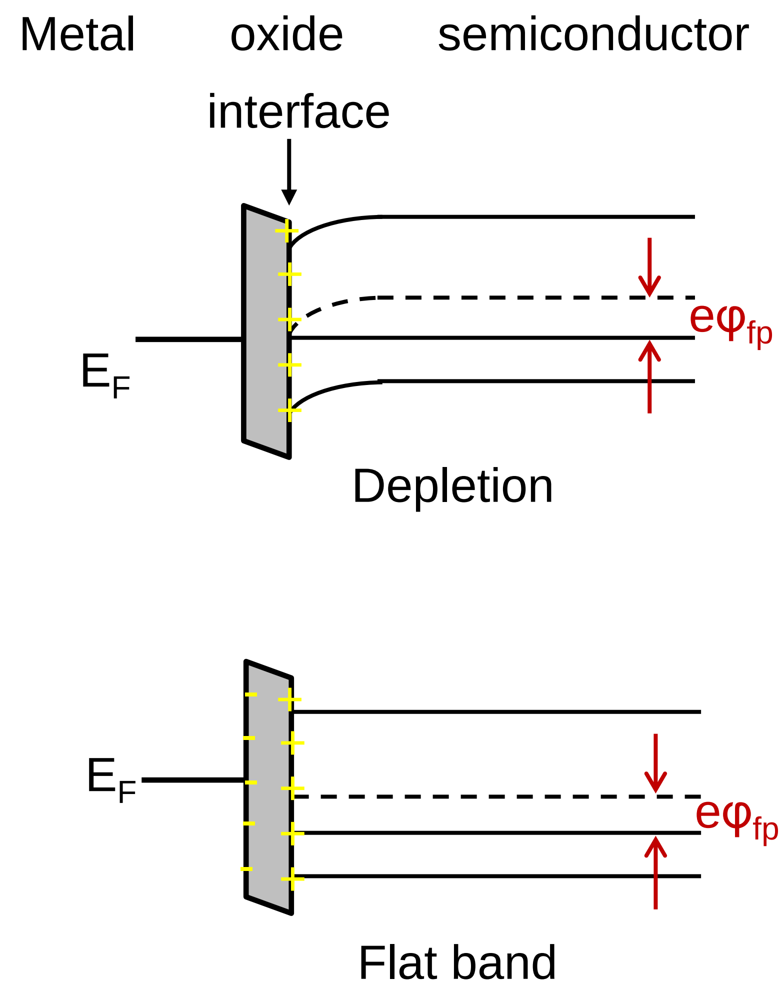
$$= 2\phi_{fp} + \frac{|Q_{SD}|}{C_{ox}} + \phi_{ms}$$

MIS structure: fixed charges



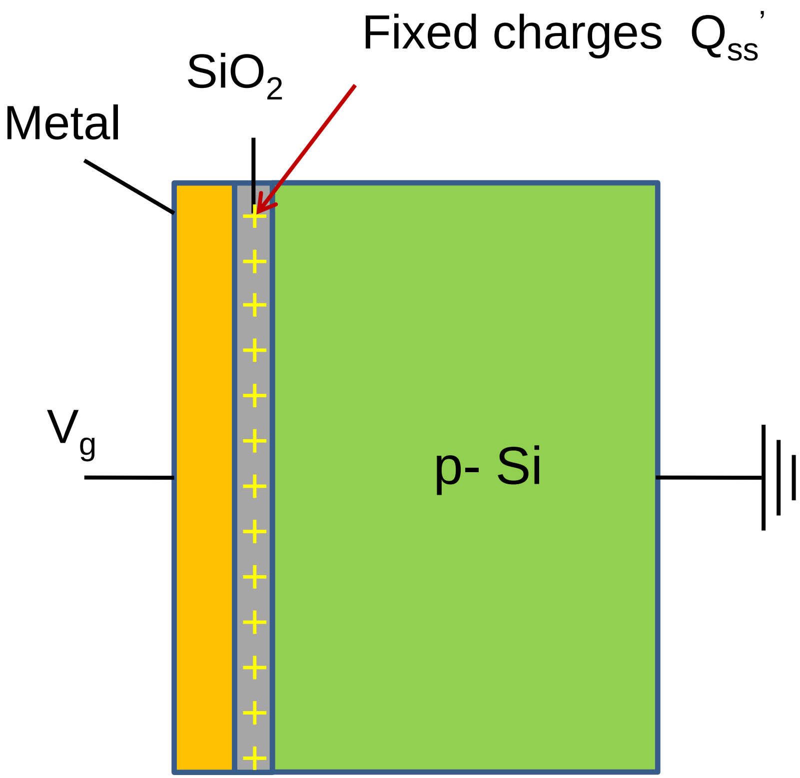
Metal-insulator-semiconductor (MIS)

Same work function



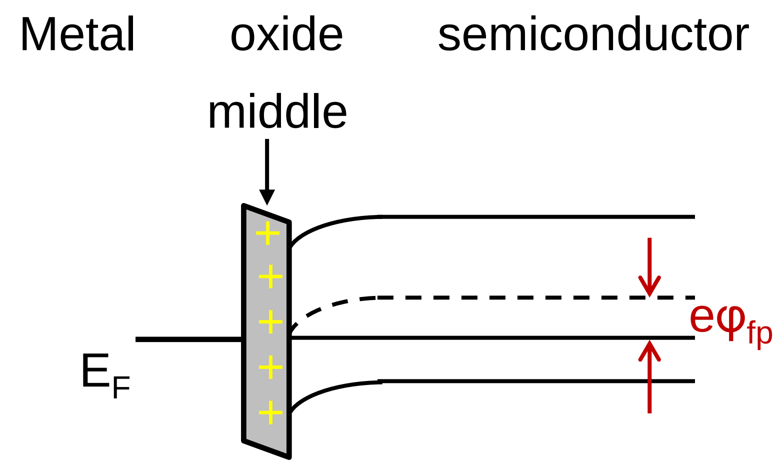
$$V_g = V_{FB} = -Q_{ss}'/C$$

MIS structure: fixed charges

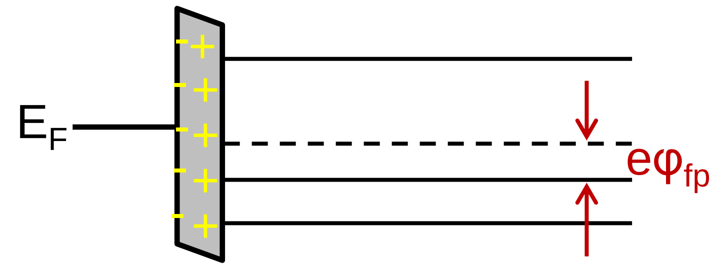


Metal-insulator-semiconductor (MIS)

Same work function



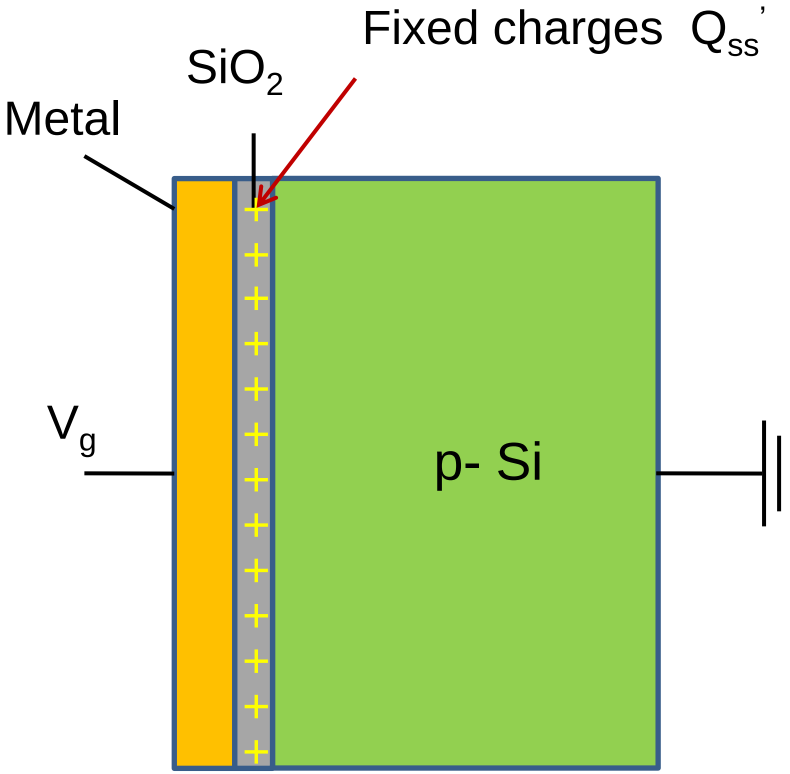
Depletion



Flat band

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

MIS structure: fixed charges

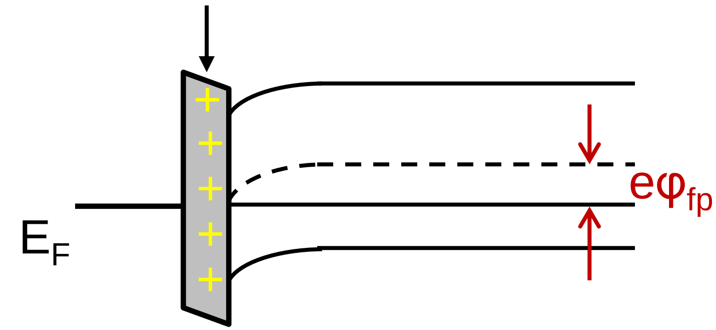


Metal-insulator-semiconductor (MIS)

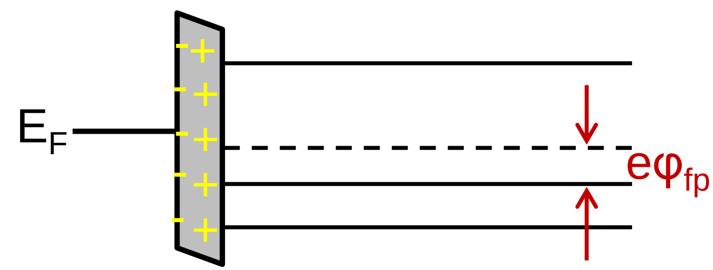
Same work function

Metal oxide semiconductor

x from metal



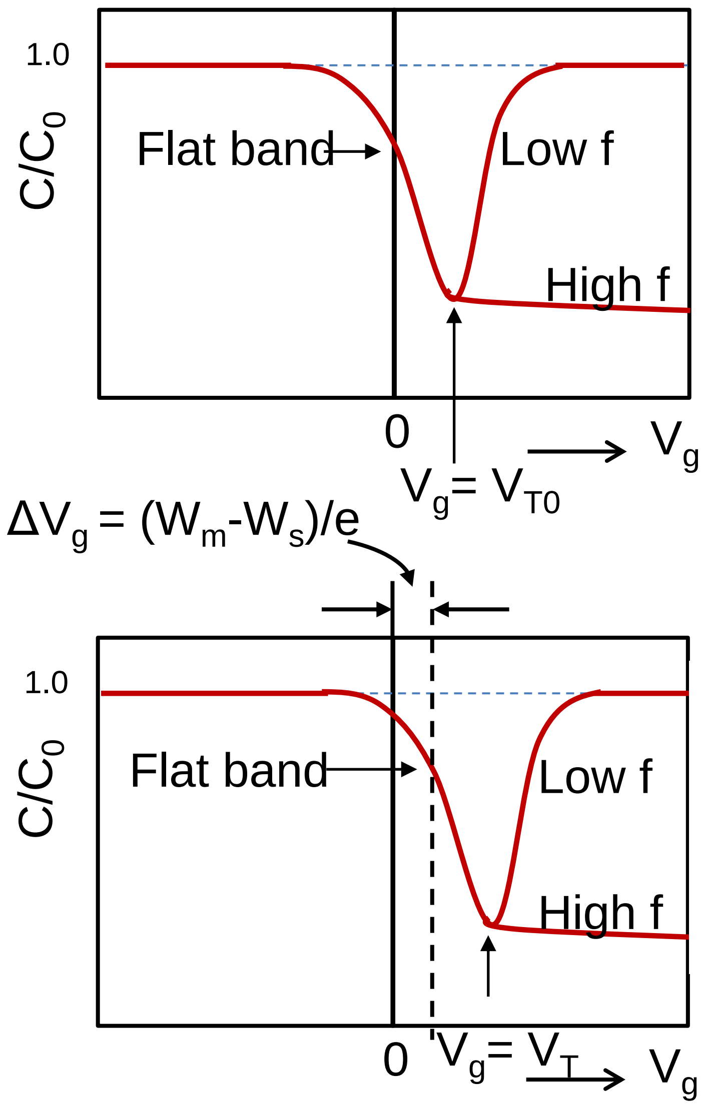
Depletion



Flat band

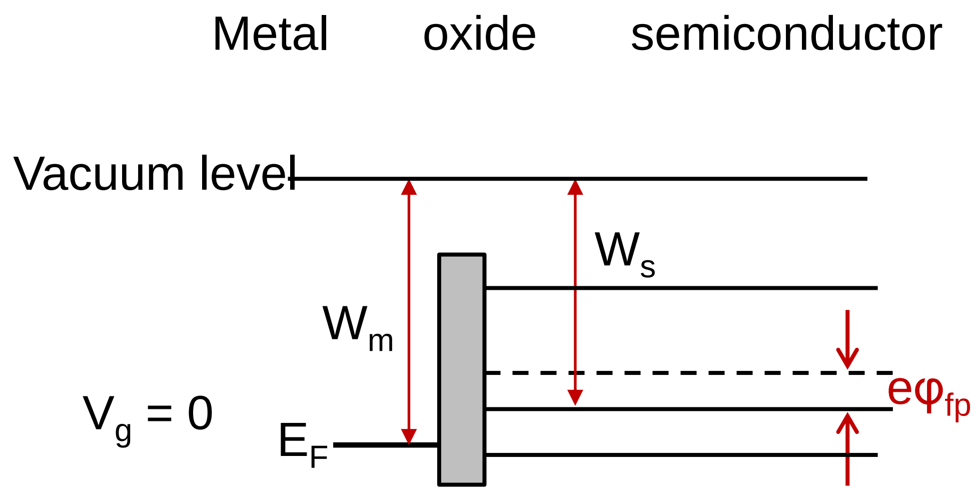
$$V_g = V_{FB} = -\frac{Q_{ss}'}{C} \cdot \frac{x}{d}$$

MIS structure: work function



Different work function

Consider the trapped charge per unit area in the oxide Q_{ss}'



Flat band

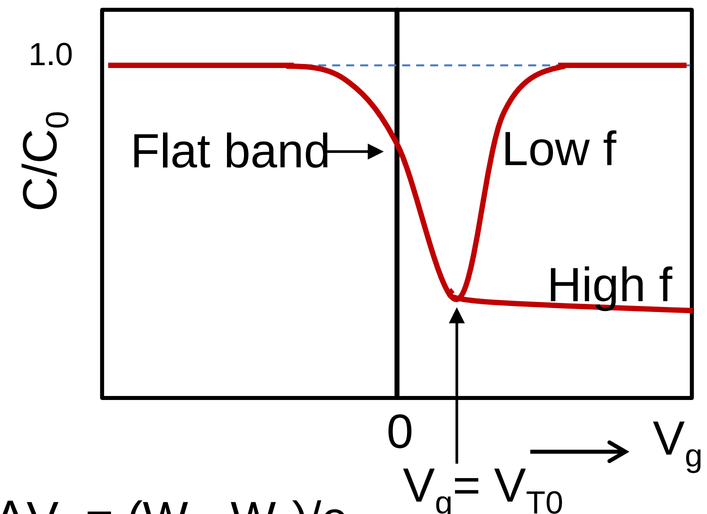
$$V_{FB} = \phi_{ms} - \frac{Q'_{ss}}{C_{ox}}$$

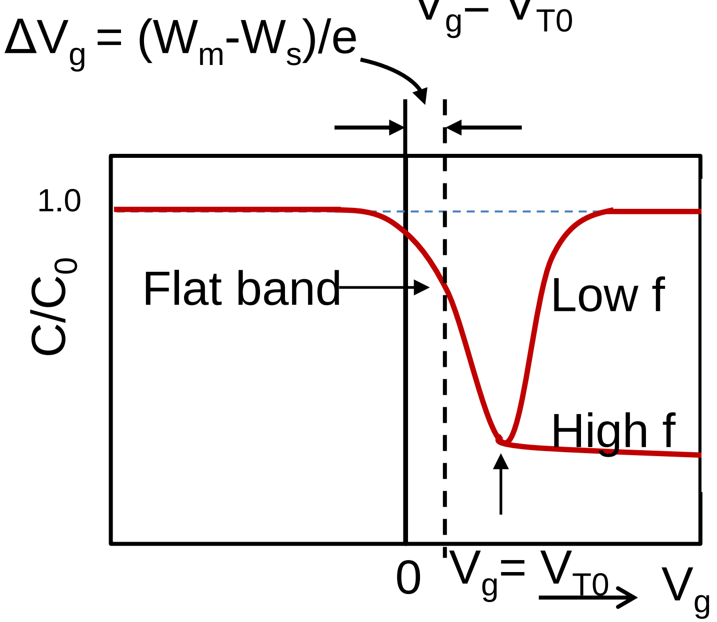
$$V_{FB} = \frac{W_m - W_s}{e} - \frac{Q'_{ss}}{C_{ox}}$$

The flat-band voltage shifts to more negative voltages for a positive fixed oxide charge

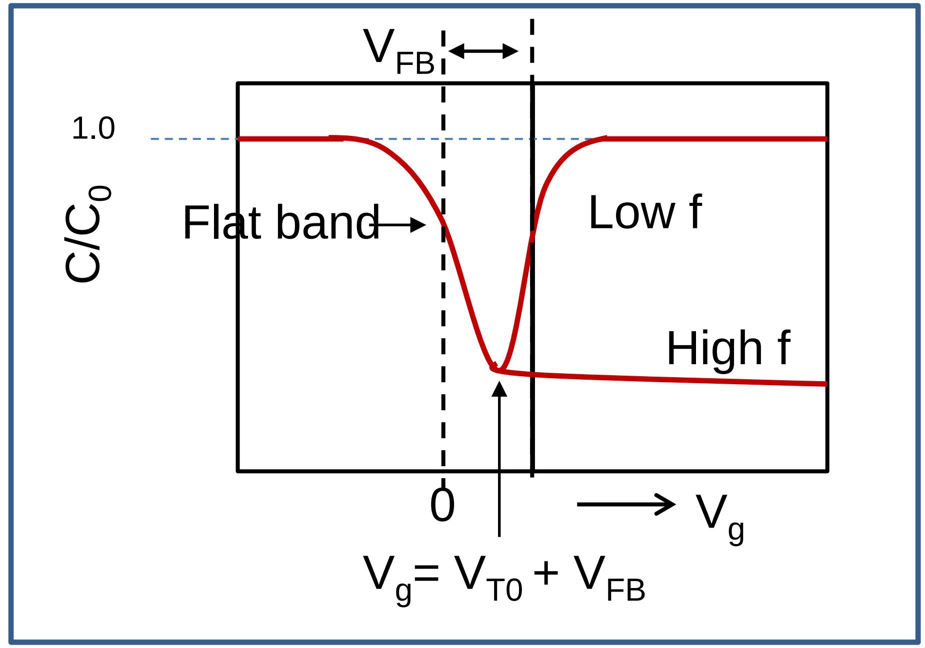
MIS structure: fixed charges

Same work function





Different work function

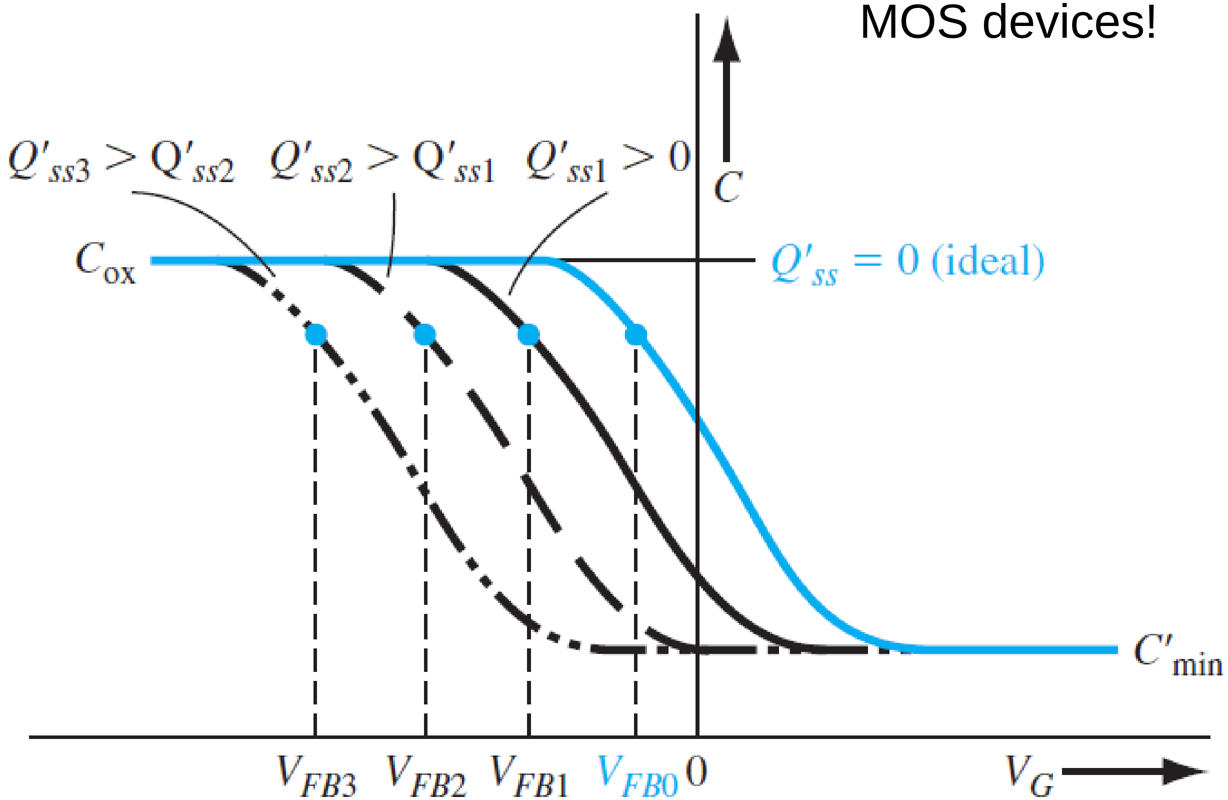


Different work function, with oxide charges

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

MIS structure: fixed charges

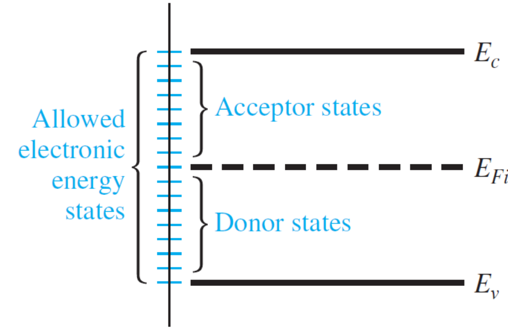
High frequency

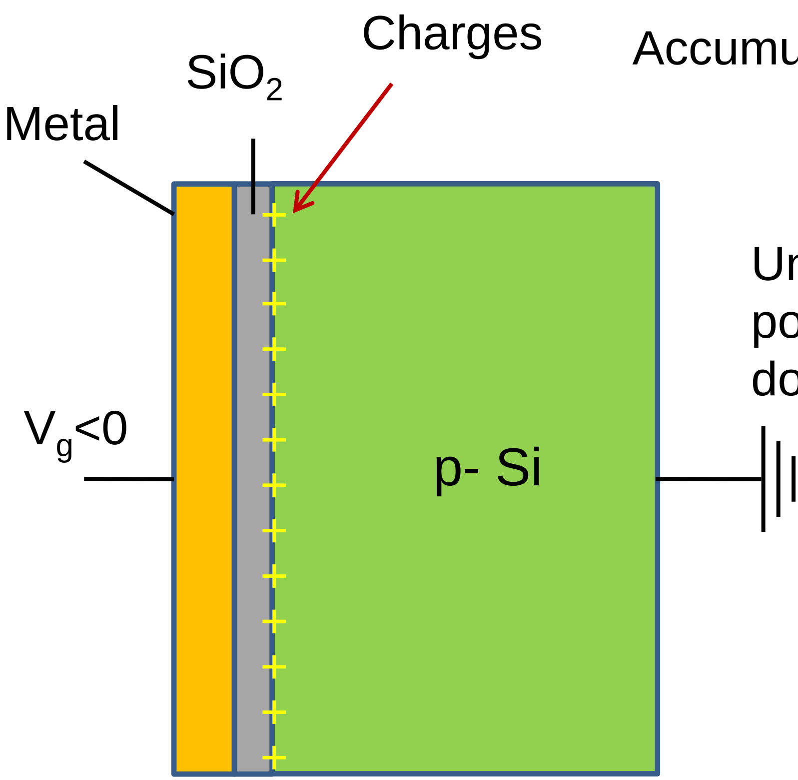


Can be used to characterize the fixed oxide charge in MOS devices!

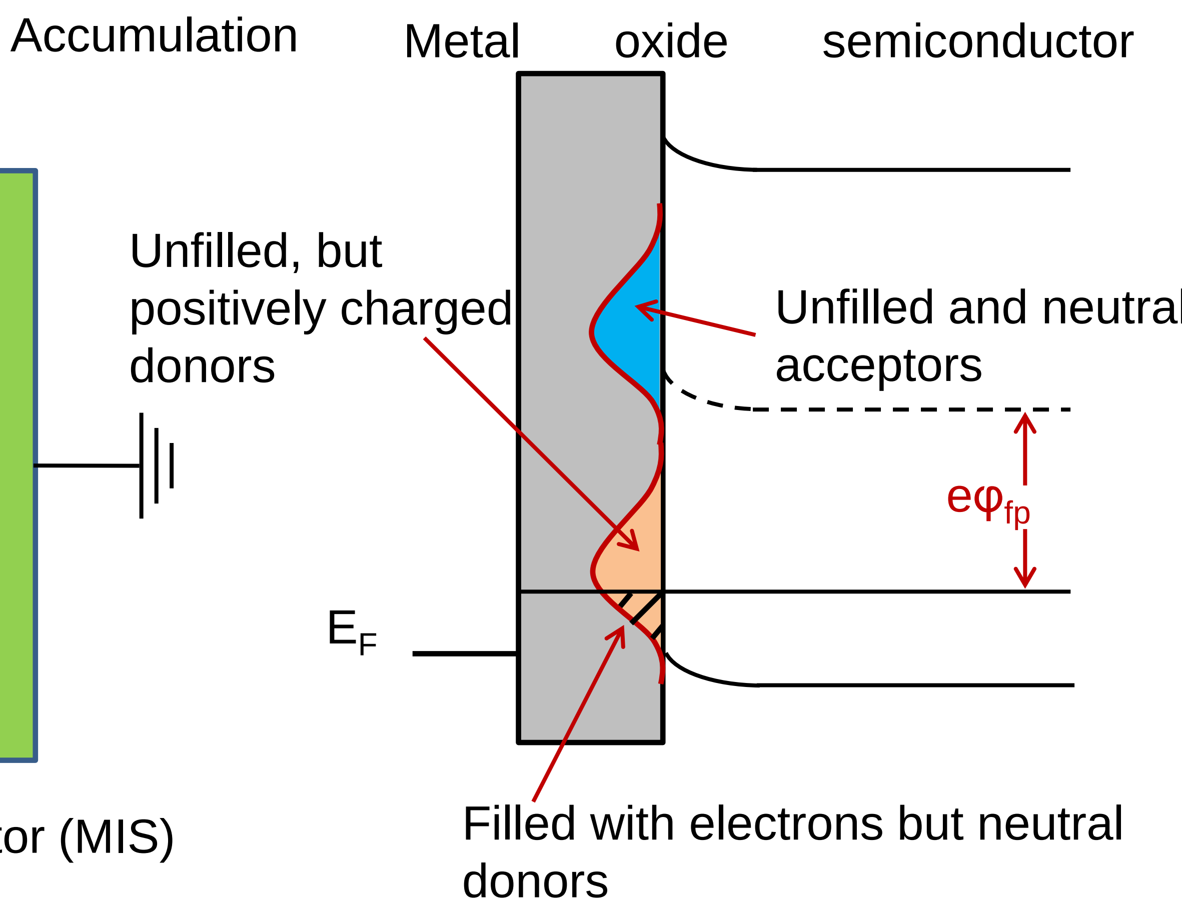
MIS structure: surface states

An acceptor state is neutral if the Fermi level is below the state and becomes negatively charged if the Fermi level is above the state.
A donor state is neutral if the Fermi level is above the state and becomes positively charged if the Fermi level is below the state.





Metal-insulator-semiconductor (MIS)



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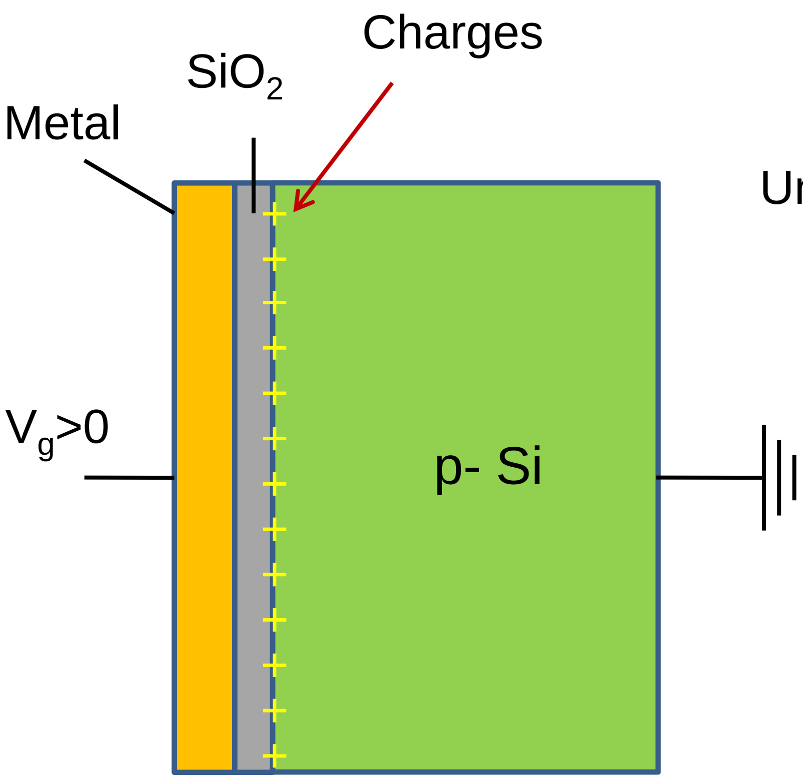
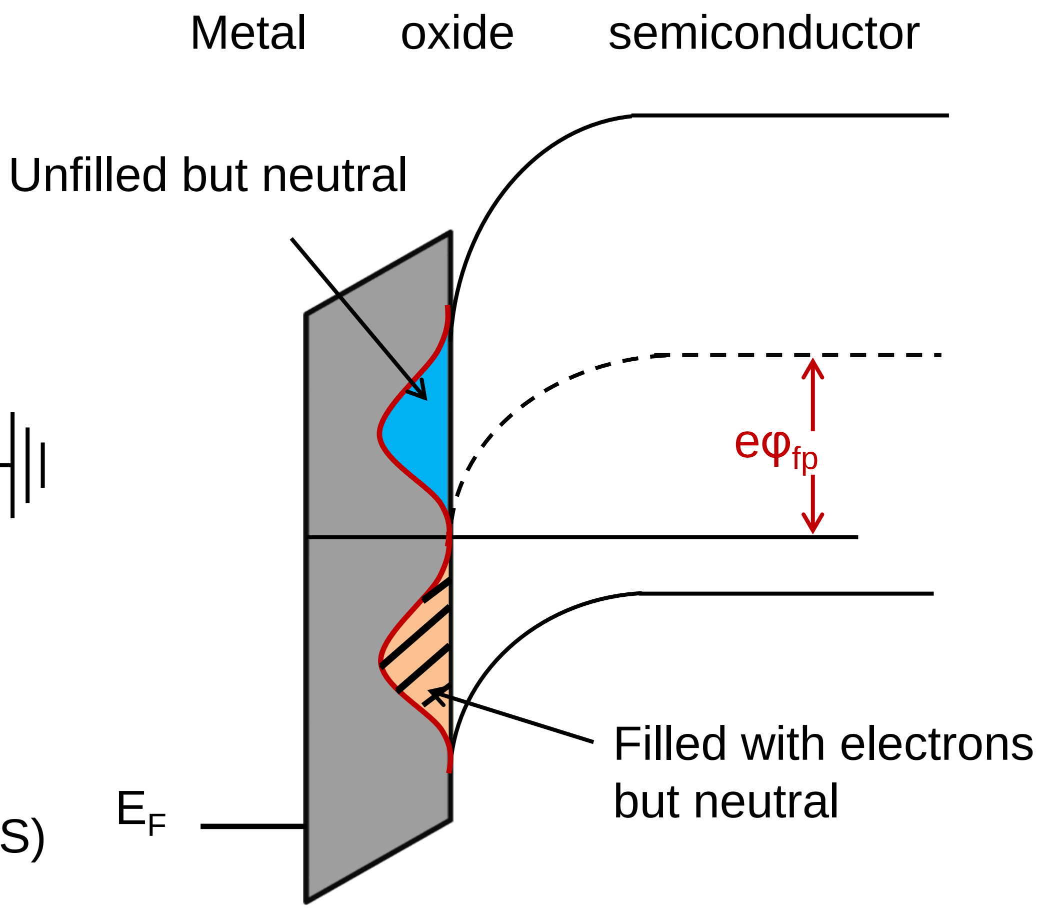
MIS structure: surface states

Midgap: all interface states are neutral

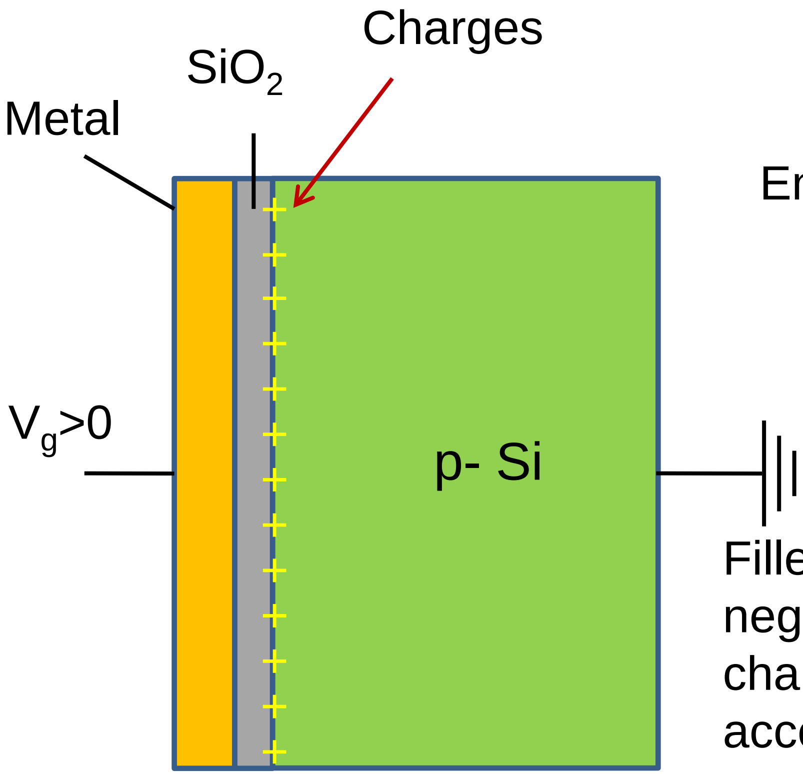


Metal-insulator-semiconductor (MIS)

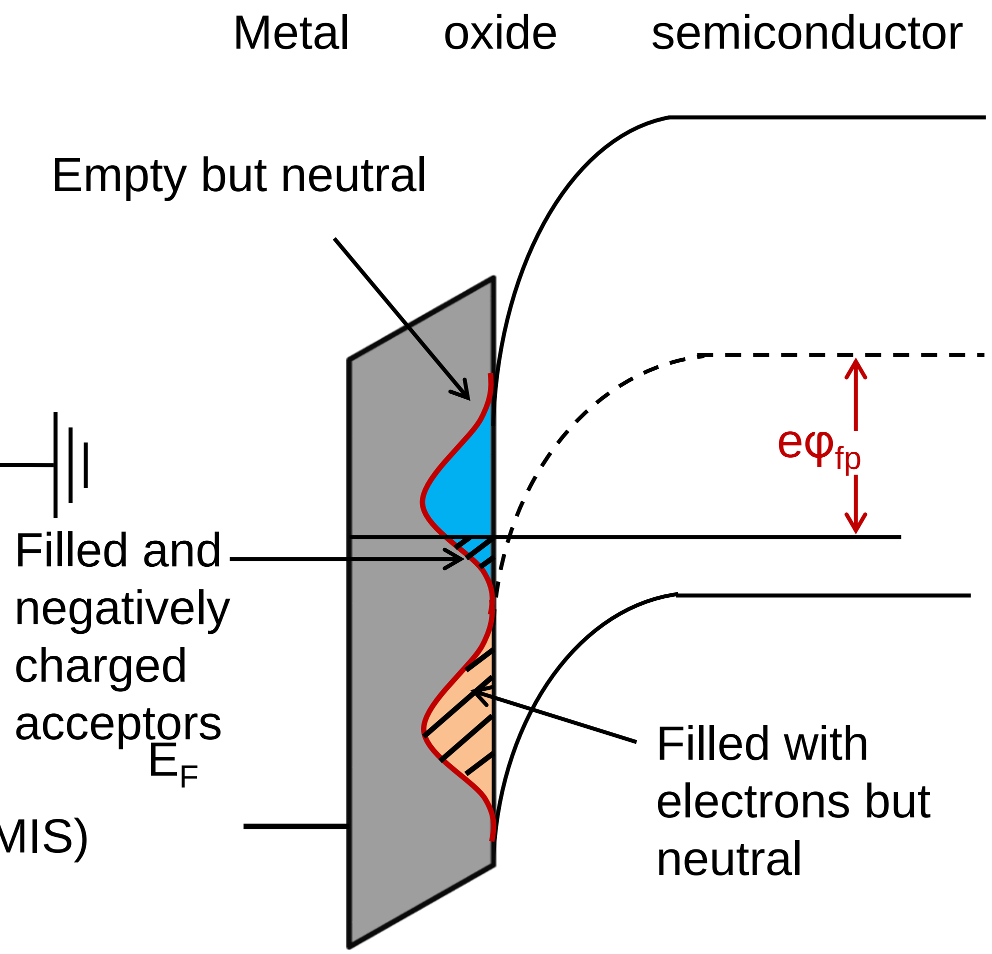


MIS structure: surface states

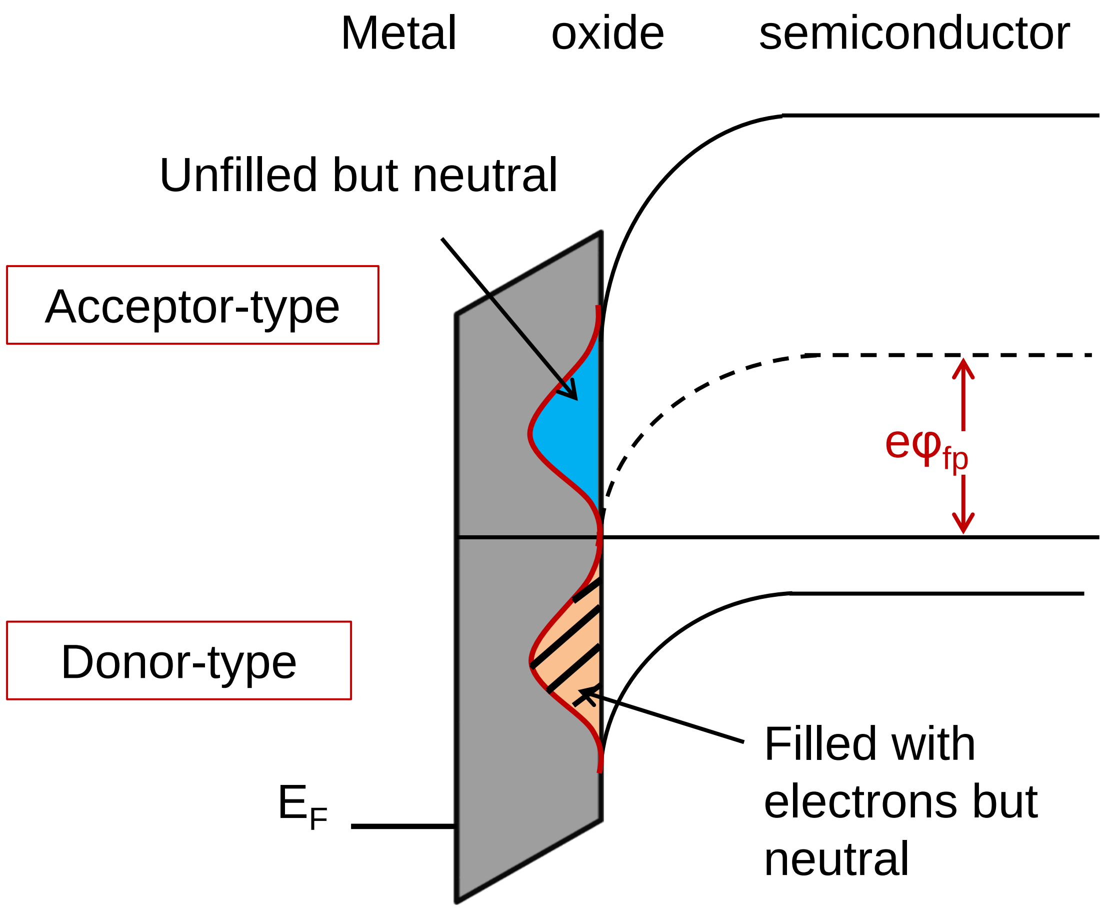
Inversion



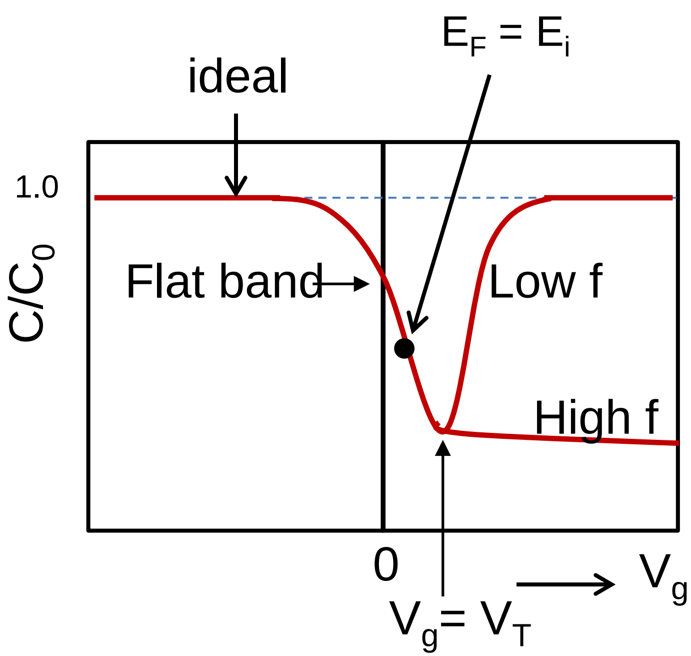
Metal-insulator-semiconductor (MIS)

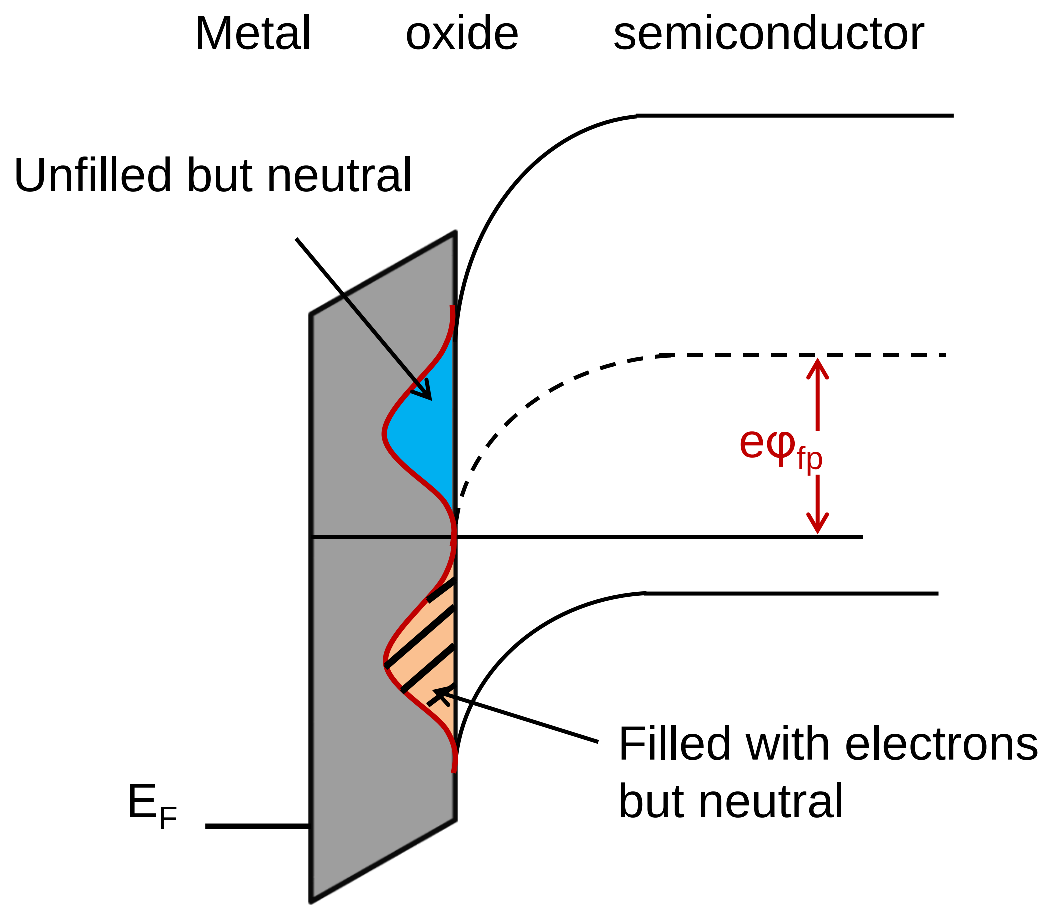


MIS structure: surface states

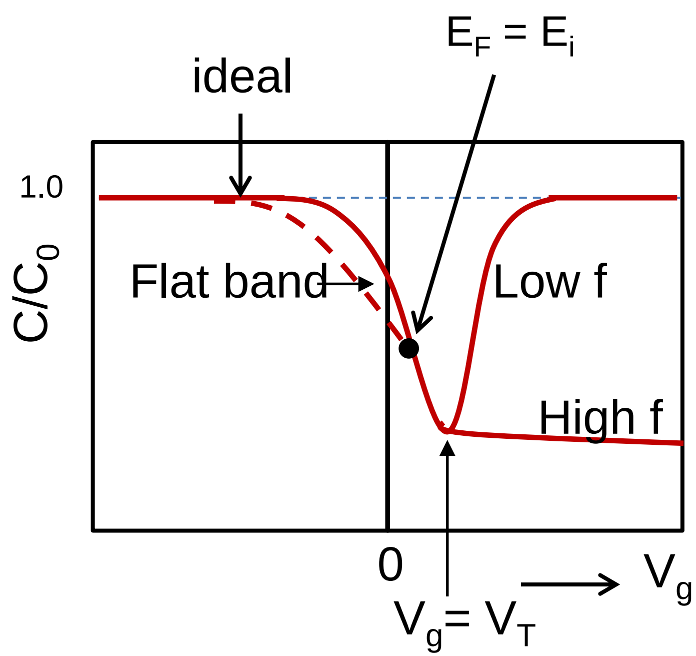


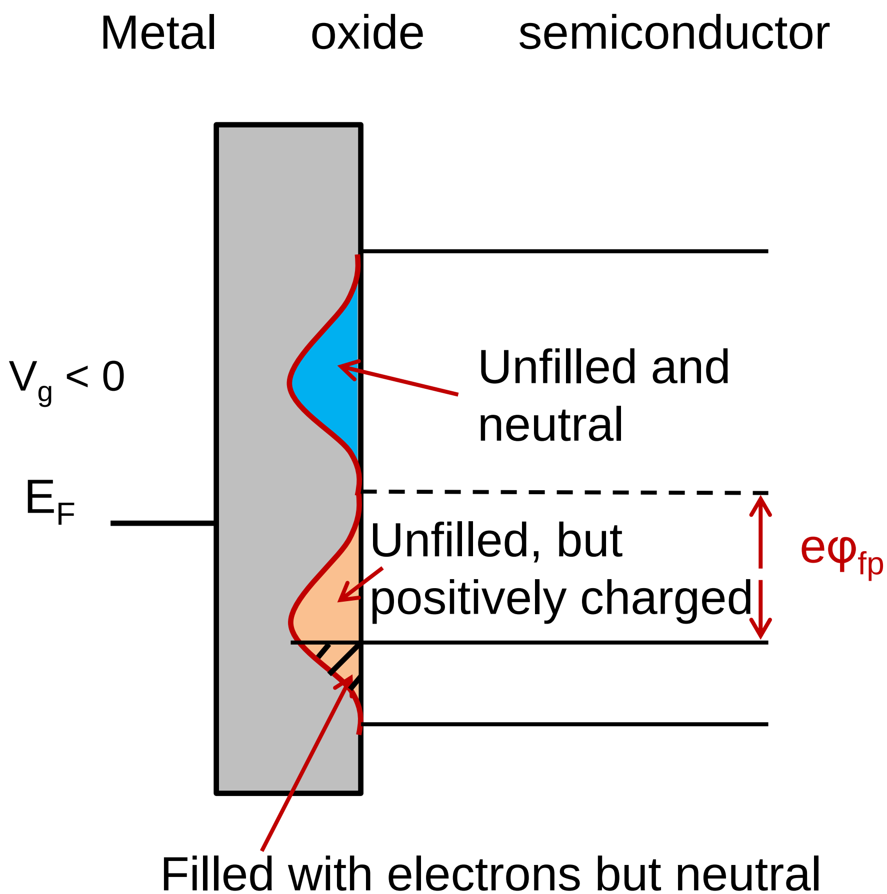
MIS structure: surface states



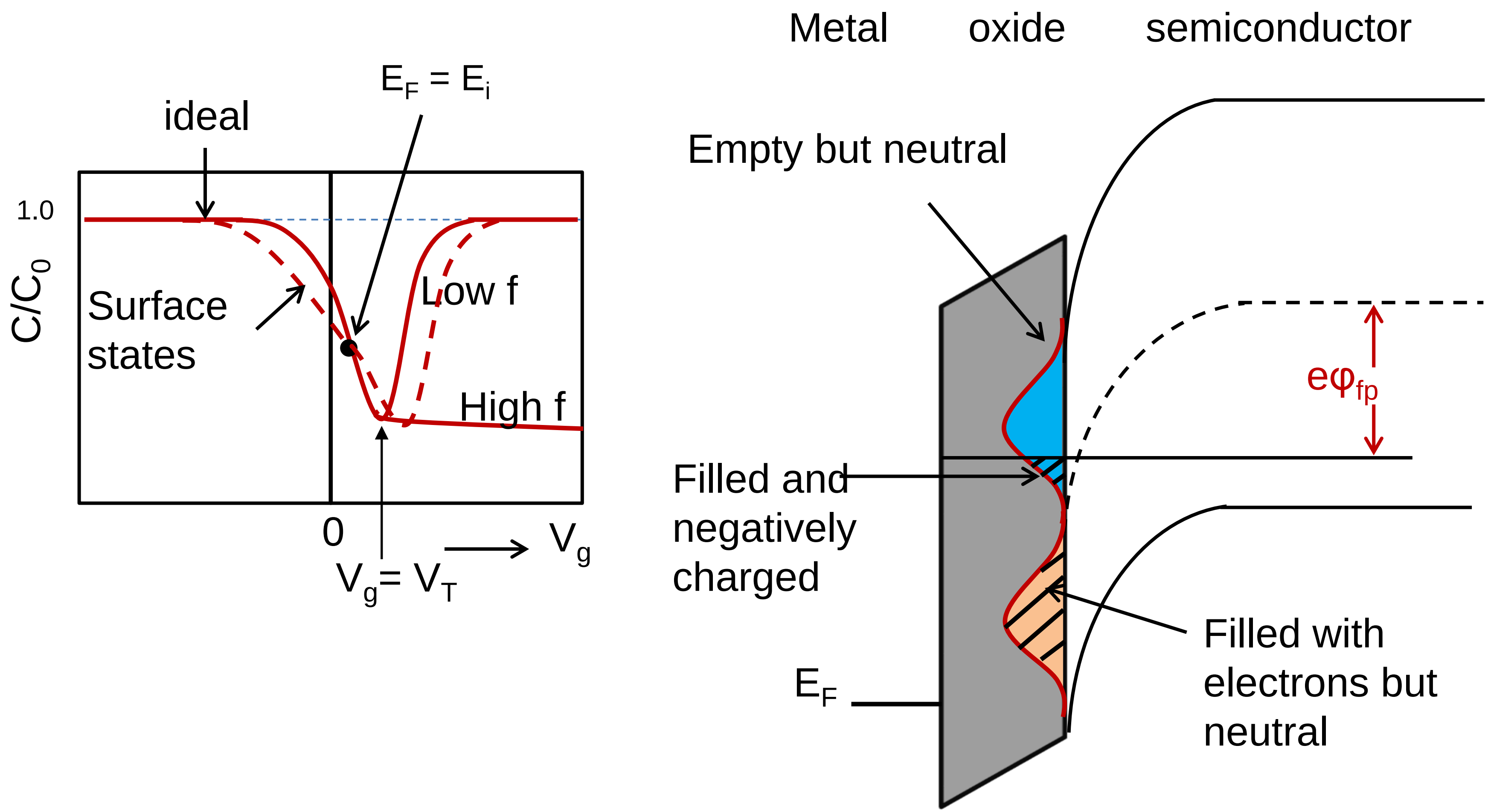


MIS structure: surface states



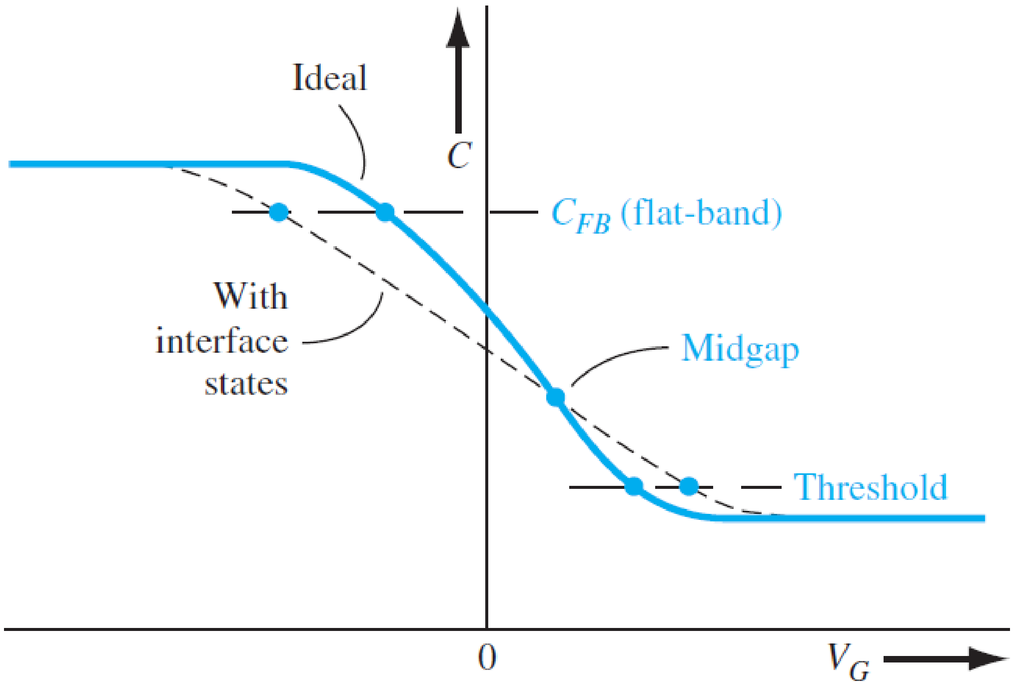


MIS structure: surface states



MIS structure: surface states

“Smeared out” C-V curves



Can be used to measure the interface states in MOS devices