EE-557
Semiconductor devices I

MOSFETs

Génie Electrique et Electronique
Master Program
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Outline of the lecture

Metal-Oxide-Semiconductors Field Effect Transistors (MOSFETs)

References:

- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)

Key questions

- What happens if a **voltage is applied** to the metal with respect to the semiconductor in a MOS structure?

- How much voltage needs to be applied to bring the MOS structure to the onset of inversion?

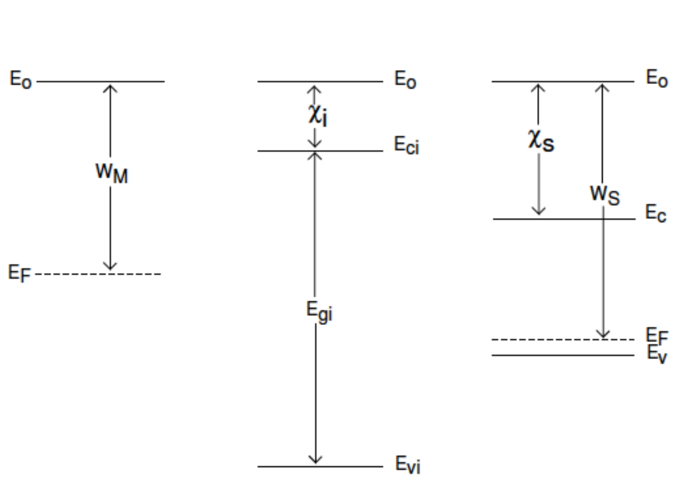
- How does the inversion charge evolve with voltage?

- **How sharply** does the inversion layer ”turn on” and ”off” with the gate voltage?

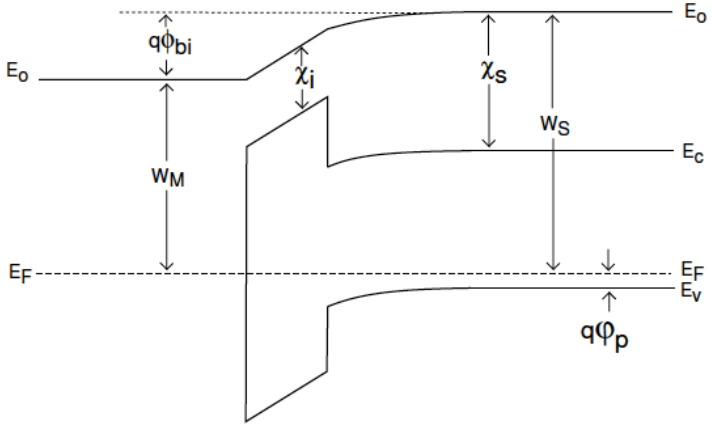
Metal-Oxide-Semiconductor Structure

Ideal MOS structure under zero bias

Depletion ($W_S > W_M$ in the case of a p-type semiconductor)

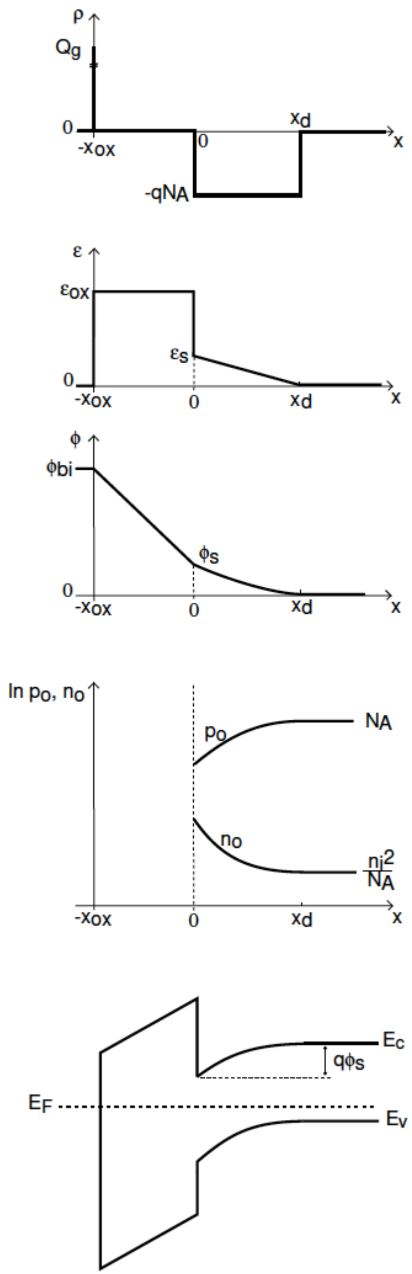


a) metal, insulator and semiconductor far apart



b) metal, insulator and semiconductor in intimate contact

$$q\phi_{bi} = W_S - W_M$$



Integrated semiconductor charge:

$$Q_s \simeq -qN_A x_d$$

Field at semiconductor surface:

$$\mathcal{E}_s \simeq \frac{qN_A x_d}{\epsilon_s}$$

Field in insulator:

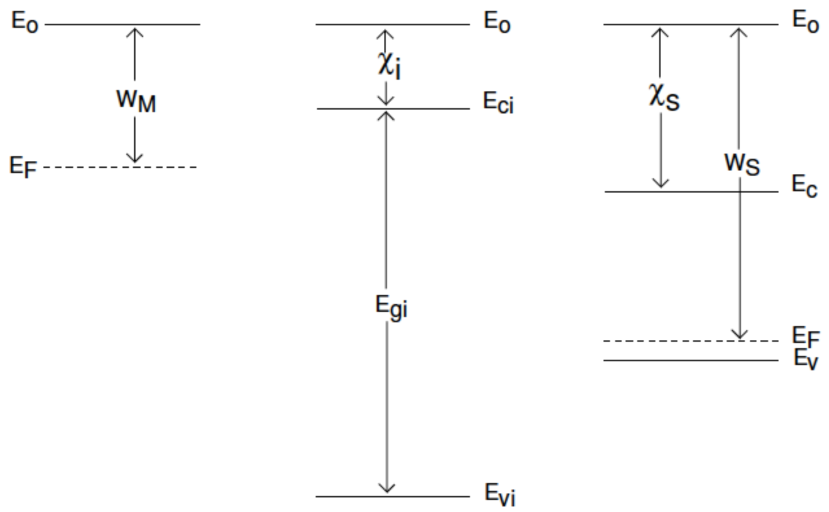
$$\mathcal{E}_{ox} \simeq \frac{qN_A x_d}{\epsilon_{ox}}$$

Surface potential:

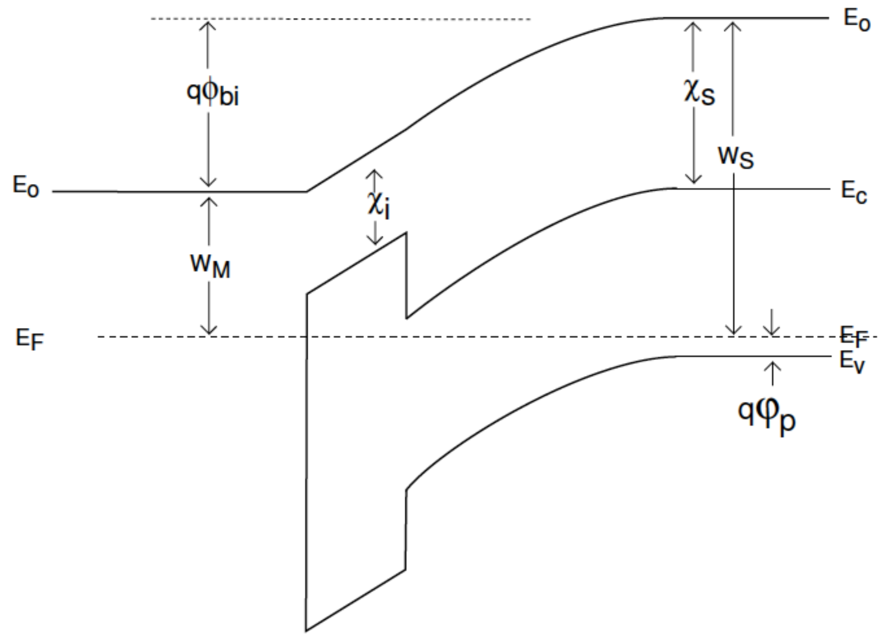
$$\phi_s \simeq \frac{qN_A x_d^2}{2\epsilon_s}$$

Ideal MOS structure under zero bias

Inversion ($W_S >> W_M$ in the case of a p-type semiconductor)



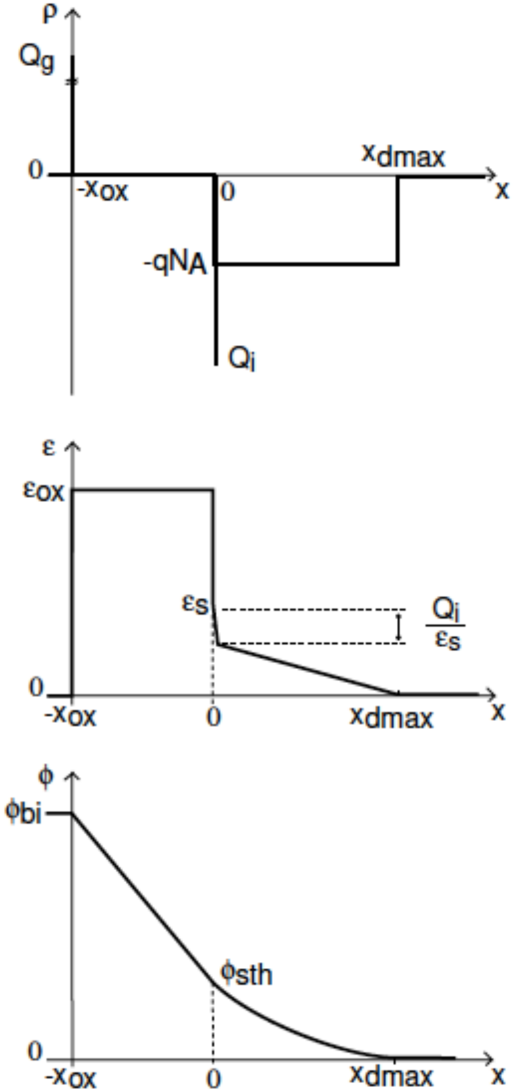
a) metal, insulator and semiconductor far apart

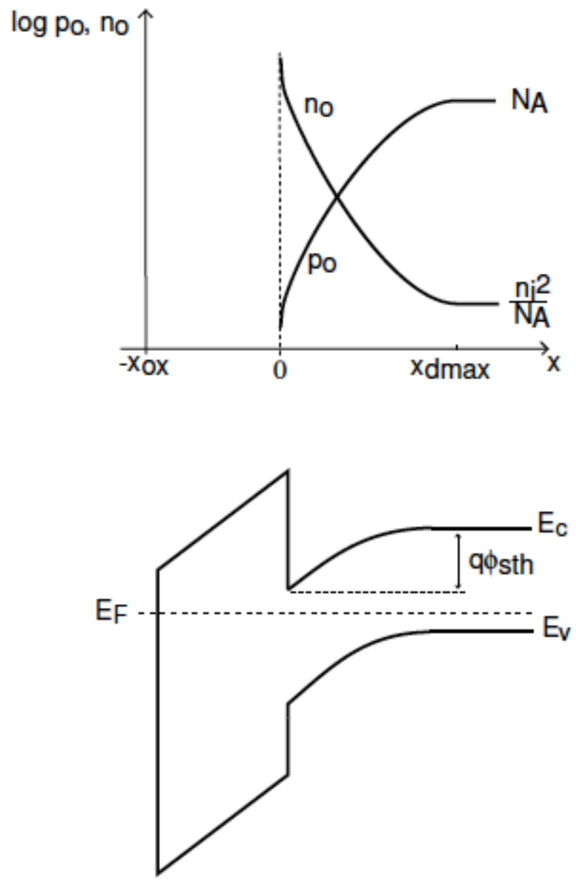


b) metal, insulator and semiconductor in intimate contact

Ideal MOS structure under zero bias

Inversion





$$Q_s = Q_d + Q_i$$

Ideal MOS structure under zero bias

Do **sheet-charge approximation**: inversion layer much thinner than any other vertical dimensions of the problem.

Two consequences:

1. ϕ_s depends on Q_d but is independent of Q_i (ϕ does not change while crossing a sheet of charge):

$$Q_d = -qN_A x_d \simeq -\sqrt{2\epsilon_s q N_A \phi_s}$$

2. ϕ_s in inversion rather insensitive to actual value of W_M:

$$\phi_s \simeq \phi_{sth}$$

ϕ_{sth} is *surface potential at threshold*

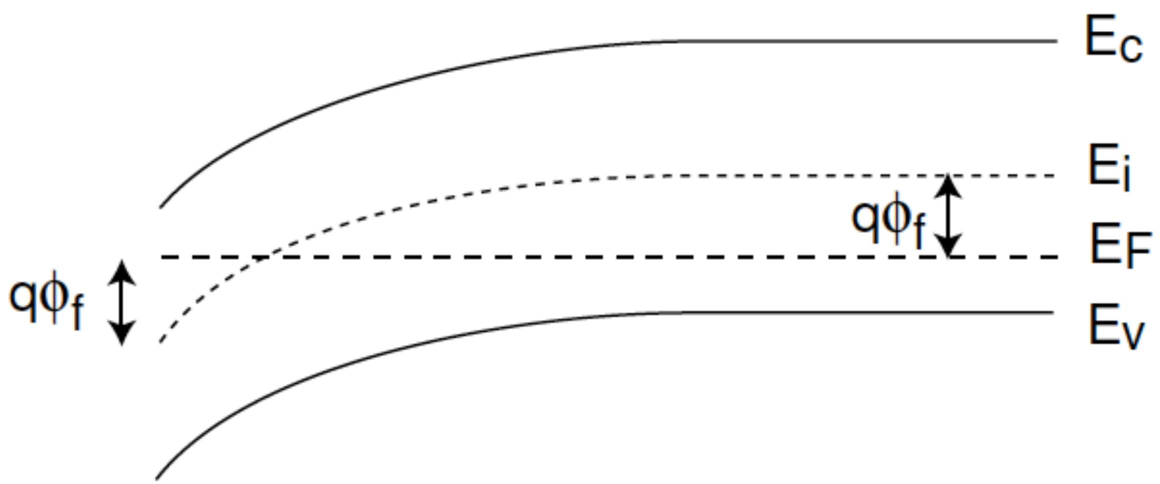
Ideal MOS structure under zero bias

Rough estimate of ϕ_{sth}: value that brings surface right at edge of inversion, that is, $n_o(0)= N_A$:

$$n_o(x=0)|_{threshold} = \frac{n_i^2}{N_A} \exp \frac{q\phi_{sth}}{kT} = N_A$$

Then:

$$\boxed{\phi_{sth} = 2\frac{kT}{q} \ln \frac{N_A}{n_i} \equiv 2\phi_f}$$



Threshold: when the semiconductor type changes at the surface from p-type to n-type

Ideal MOS structure under zero bias

Within the **sheet-charge approximation**, electrostatic problem is easy to solve:
In inversion, ϕ_s independent of W_M thus x_d independent of W_M:

$$x_d \simeq x_{dmax} = \sqrt{\frac{2\epsilon_s \phi_{sth}}{qN_A}}$$

Total depletion region charge:

$$Q_d \simeq Q_{dmax} = -qN_A x_{dmax} = -\sqrt{2\epsilon_s q N_A \phi_{sth}}$$

From fundamental electrostatics relation in inversion:

$$\phi_{bi} = \phi_s - \frac{Q_s}{C_{ox}} = \phi_{sth} - \frac{Q_i + Q_{dmax}}{C_{ox}}$$

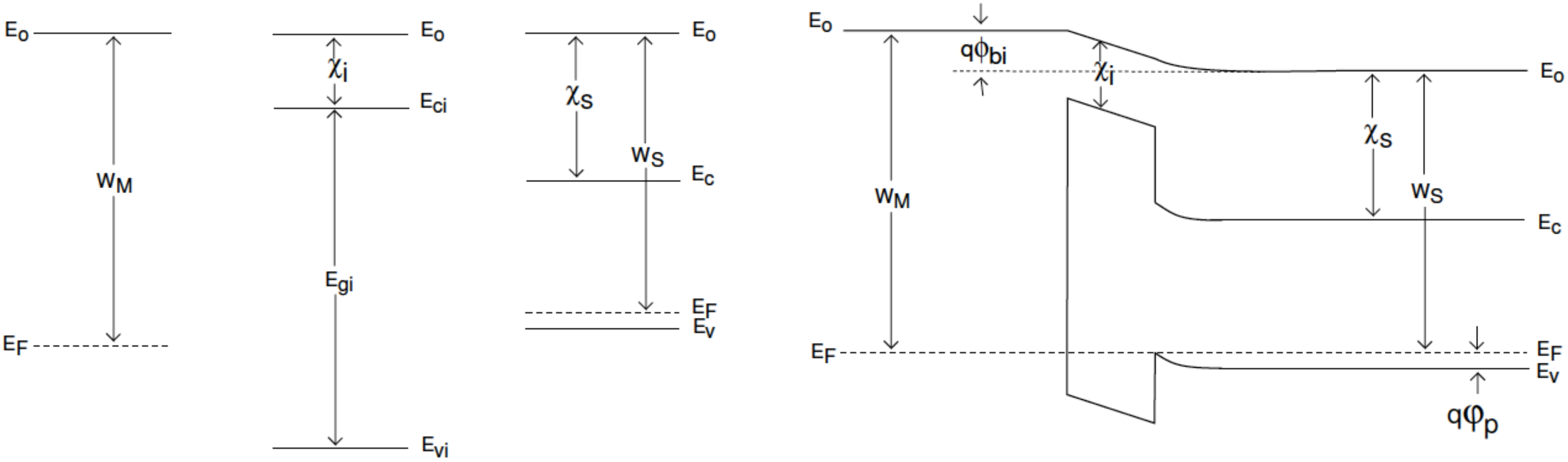
Derive expression for Q_i in inversion:

$$Q_i = -C_{ox}(\phi_{bi} - \phi_{sth}) - Q_{dmax}$$

Metal-Oxide-Semiconductor Structure

Ideal MOS structure under zero bias

Accumulation ($W_S < W_M$)



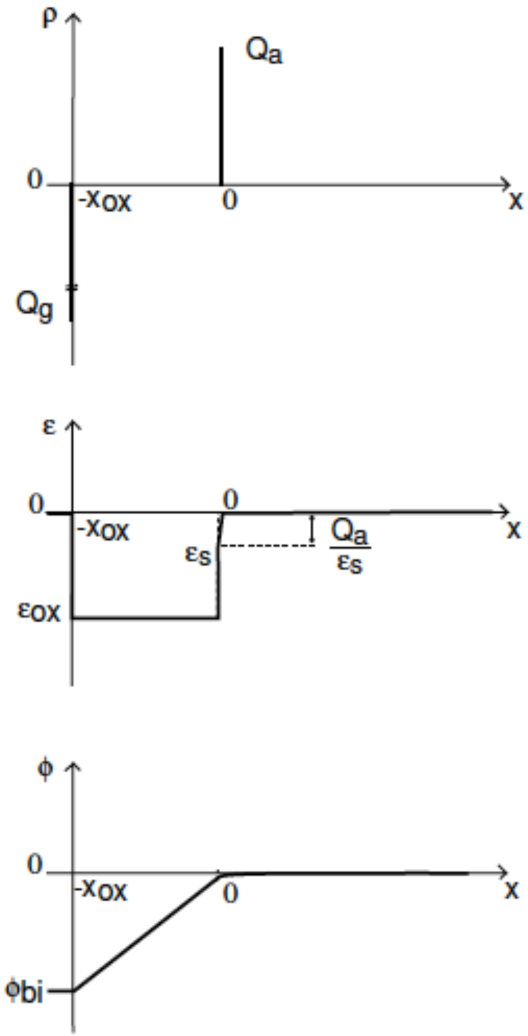
a) metal, insulator and semiconductor far apart

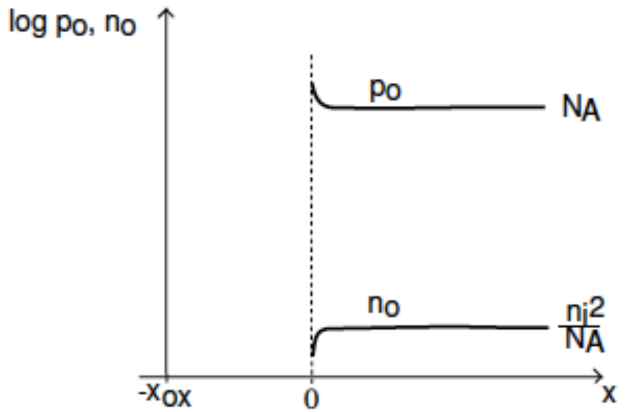
b) metal, insulator and semiconductor in intimate contact

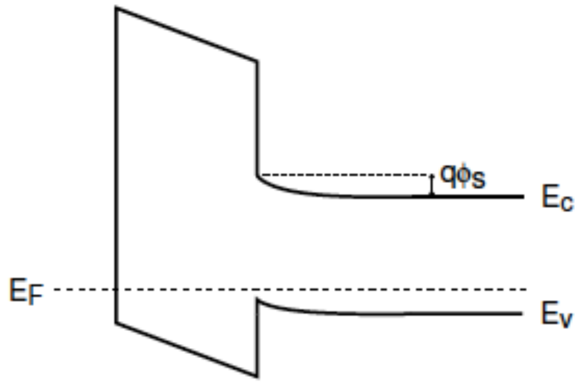
Metal-Oxide-Semiconductor Structure

Ideal MOS structure under zero bias

Accumulation







$$Q_s = Q_a$$

Ideal MOS structure under zero bias

Sheet-charge approximation again:

$$\phi_s \simeq 0$$

Use fundamental electrostatics equation again:

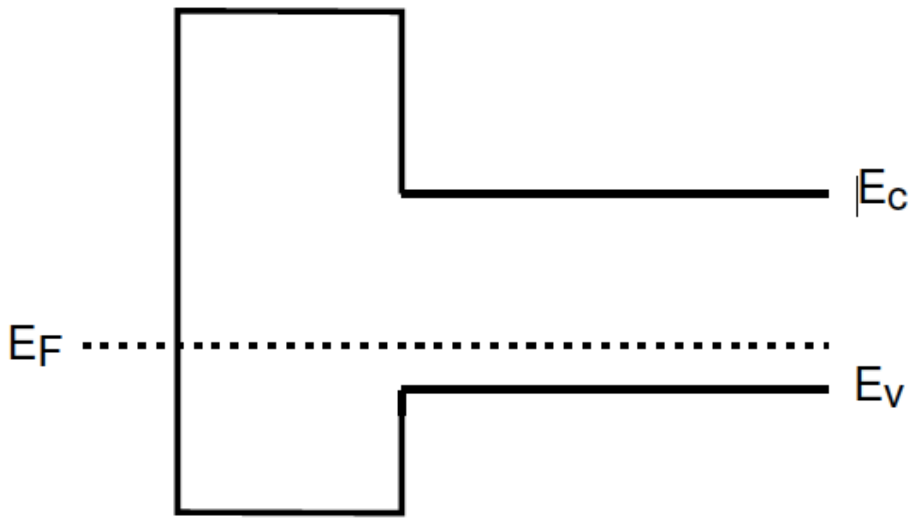
$$Q_a \simeq -C_{ox}\phi_{bi}$$

Metal-Oxide-Semiconductor Structure

Ideal MOS structure under zero bias

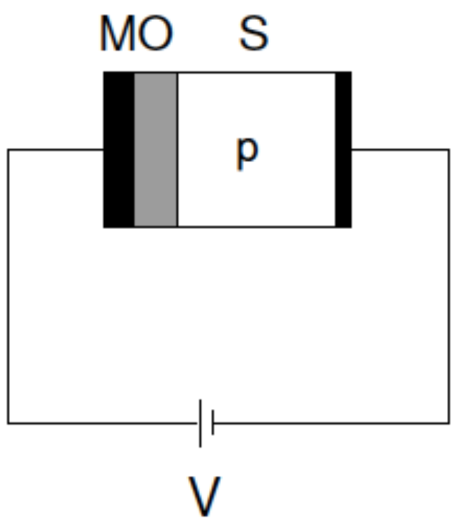
Flat-band

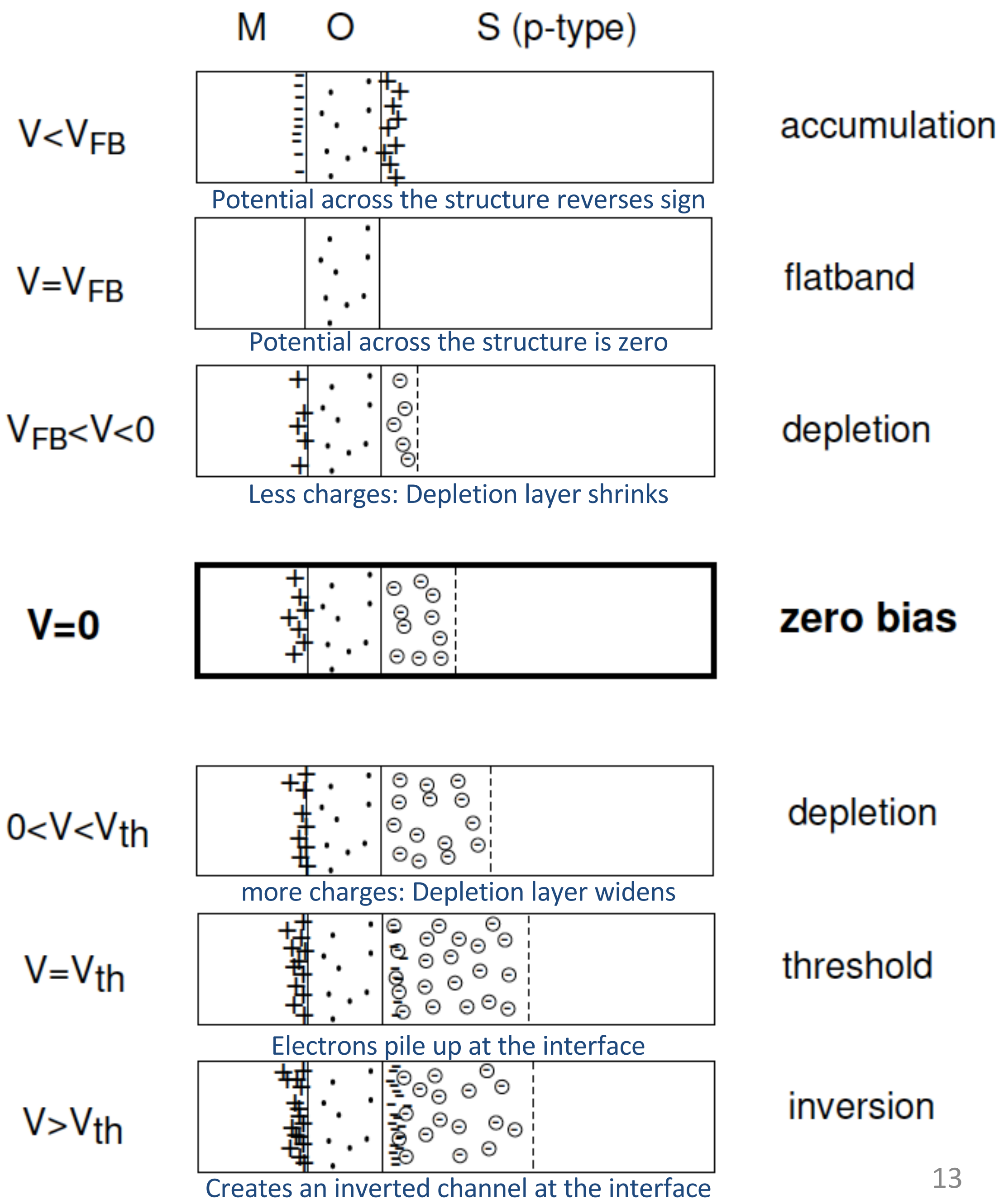
If $\phi_{bi}=0$: $Q_s=0$, $E_s=0$, $E_{ox}=0$, $\phi_s=0$ $\Rightarrow$ **Perfect charge neutrality everywhere**.



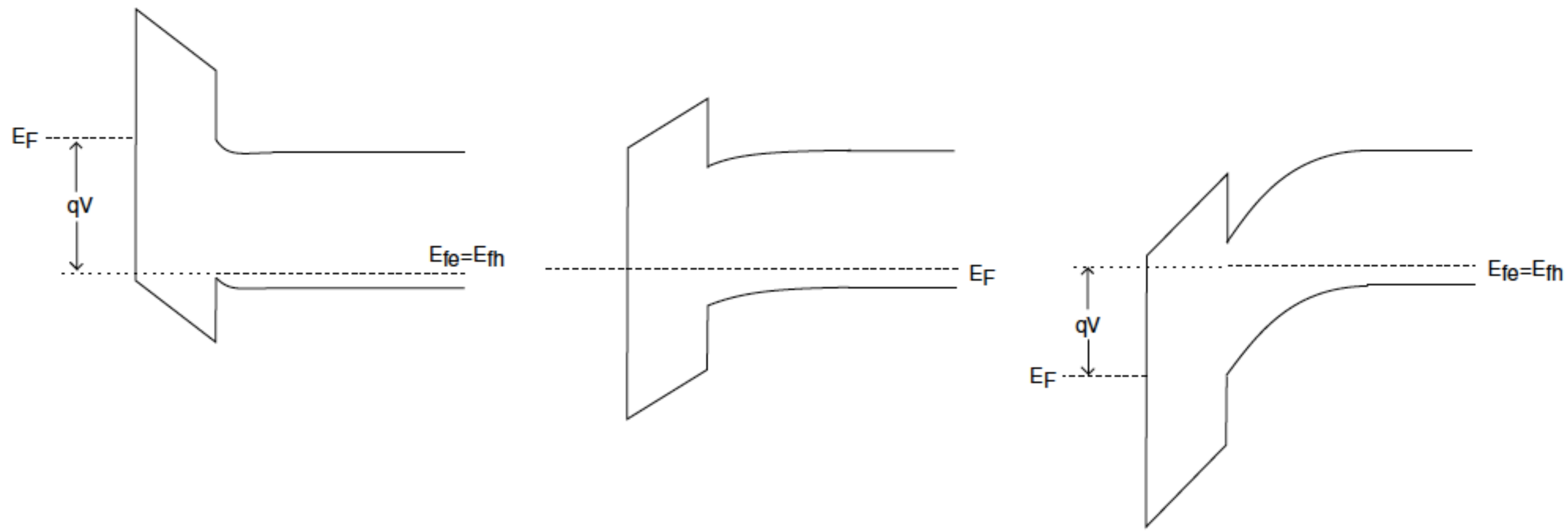
Ideal MOS structure under bias

Apply voltage V to metal with respect to semiconductor:





Ideal MOS structure under bias



a) accumulation (V<0) b) zero bias (depletion) c) inversion (V>0)

MOS structure can **swing all the way from accumulation to inversion**.

Semiconductor remains in quasi-equilibrium (no carrier flow, no carrier injection)

$$E_{fe} = E_{fh} = E_F$$

Electrostatics identical to zero bias but potential difference across structure changed:

$$\boxed{\phi_{bi} \longrightarrow \phi_{bi} + V}$$

Ideal MOS structure under bias

Total potential build-up across structure:

$$\phi_{bi} + V = \phi_s - \frac{Q_s}{C_{ox}}$$

Several important results:

Flat-band voltage: $\phi_s = 0,\ Q_s = 0$: $\boxed{V_{FB} = -\phi_{bi}}$

Threshold voltage for inversion: $Q_i = 0,\ Q_d = Q_{dmax},\ \phi_s = \phi_{sth}$:

$$V_{th} = -\phi_{bi} + \phi_{sth} - \frac{Q_{dmax}}{C_{ox}} = V_{FB} + \phi_{sth} + \gamma\sqrt{\phi_{sth}}$$

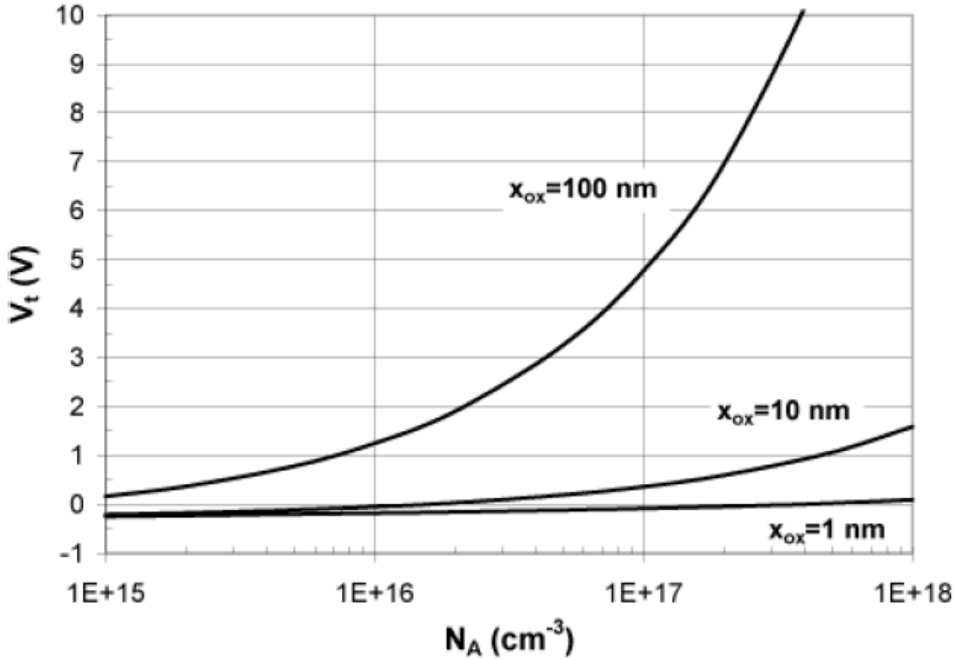
Ideal MOS structure under bias

$$V_{th} = -\phi_{bi} + \phi_{sth} - \frac{Q_{dmax}}{C_{ox}} = V_{FB} + \phi_{sth} + \gamma\sqrt{\phi_{sth}}$$

In inversion ($V > V_{th}$): $$\boxed{Q_i = -C_{ox}(V - V_{th}) \qquad \text{for } V \geq V_{th}}$$

Once reached inversion, the **inversion charge increases linearly with the applied voltage in excess of V_{th}**.

V_t plays key role in MOSFET operation.



Key dependencies:

$$N_A \uparrow \rightarrow V_t \uparrow$$

$$x_{ox} \uparrow \rightarrow V_t \uparrow$$

Exercise

Consider an MOS structure made out of a W gate (WM = 4.54 eV), a 4.5 nm SiO_2 insulator, and a p-type doped Si substrate with Na = 6 x 10^{17} cm-3.

1.Estimate the electric field in the oxide and the surface potential at zero bias.

2. Now let's use of a poly-Si gate (W_M= 4.04 eV). Calculate Qs and its extent into the semiconductor for V = -0.5 V.

3. Compute V_T and Qi for V = 2 V

Dynamics of the MOS structure

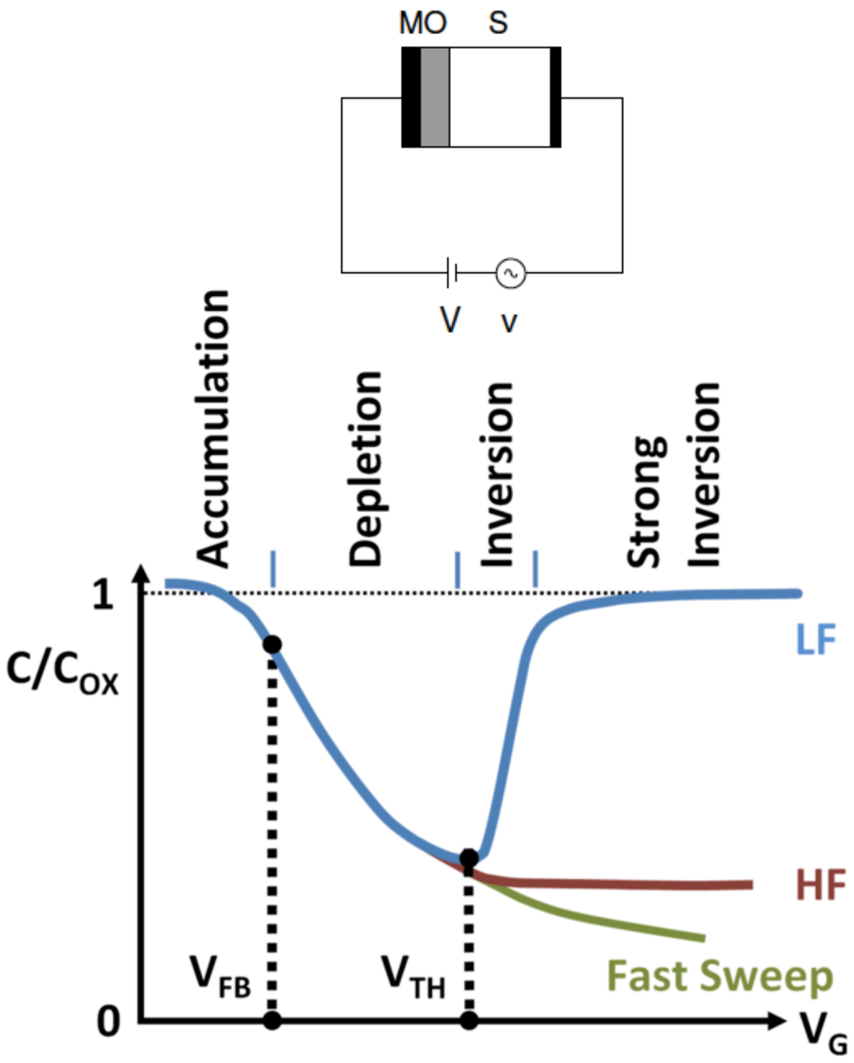
- MOS structure looks and behaves like capacitor
- C-V characteristics summarize complex behavior of MOS
- **C-V characteristics**: powerful diagnostic tool of wide applicability

Three key issues to study:

- impact of bias voltage
- impact of frequency of small-signal
- Dynamic behavior under fast changing conditions

Dynamics of the MOS structure

Qualitative discussion first:



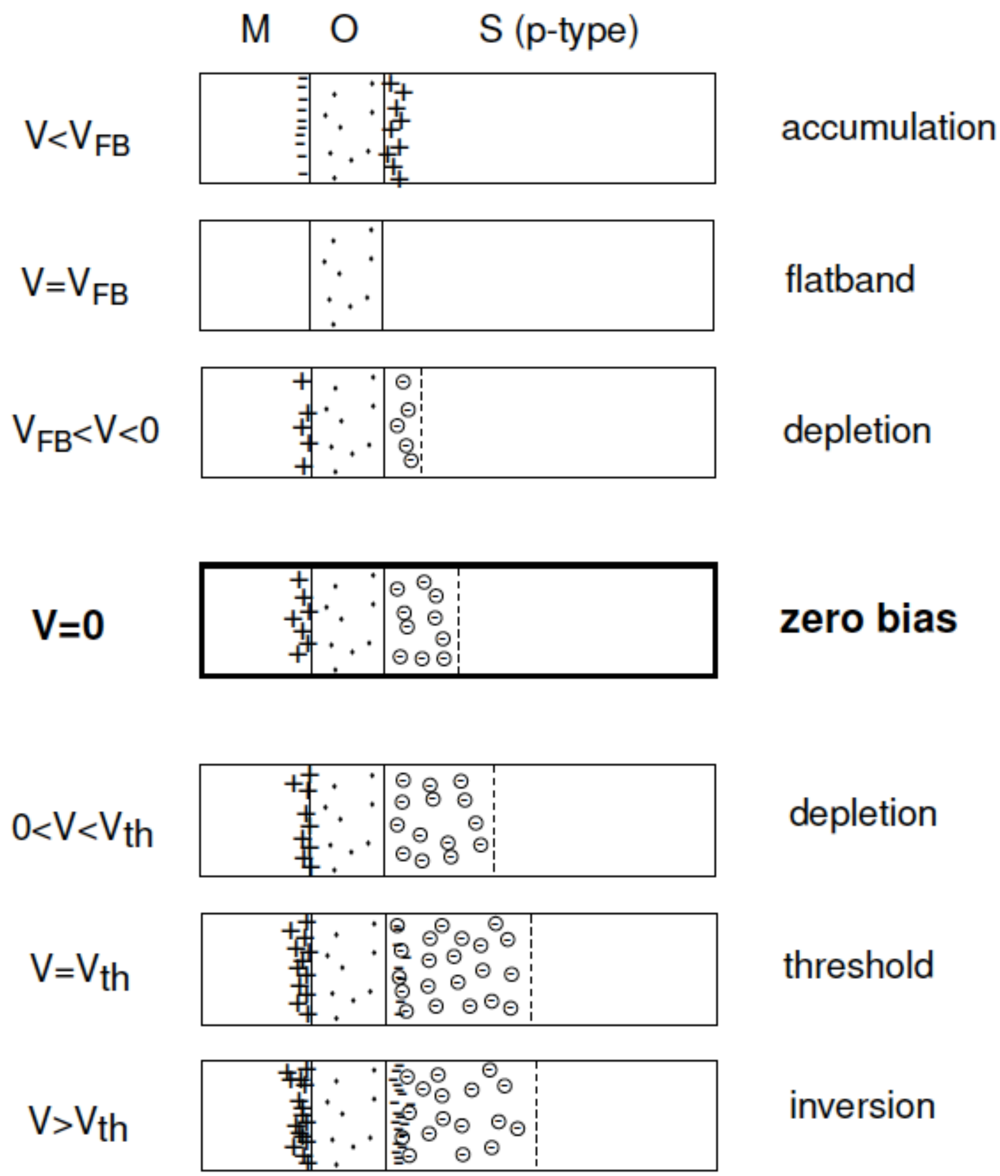


Image from: http://en.citizendium.org/wiki/MOS_capacitor

MOS structure under bias

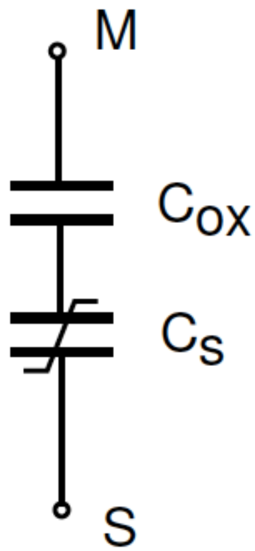
Dynamics of the MOS structure

General definition of capacitance:

$$C = \frac{dQ_g}{dV} = -\frac{dQ_s}{dV}$$

After some algebra:

$$C = \frac{1}{\frac{1}{C_{ox}} + \frac{1}{C_s}}$$



where C_s is defined as:

$$C_s = -\frac{dQ_s}{d\phi_s}$$

Note: $C_s > 0$.

Qs is defined as the charge in the depletion region:

$$Q_s \simeq -qN_A x_d$$ where $$x_d \simeq \frac{\epsilon_s}{C_{ox}}\left(\sqrt{1+\frac{4\phi_{bi}}{\gamma^2}}-1\right)$$ $$\gamma = \frac{1}{C_{ox}}\sqrt{2\epsilon_s q N_A}$$

Quasi-static C-V characteristics

If frequency of AC voltage signal is low enough:
quasi-static conditions: use Poisson-Boltzmann formulation:

Accumulation

$$\boxed{C_s \simeq \frac{q}{2kT} C_{ox}(V_{FB} - V)}$$

For **|V| sufficiently larger than |V_{FB}|**, **C_s becomes large**, and independent of V :

$$\boxed{C \simeq C_{ox}}$$

Quasi-static C-V characteristics

Depletion

Semiconductor capacitance

$$\boxed{C_s \simeq \frac{C_{ox}}{\sqrt{1+4\frac{V-V_{FB}}{\gamma^2}}-1}}$$

Total capacitance

$$\boxed{C \simeq \frac{C_{ox}}{\sqrt{1+4\frac{V-V_{FB}}{\gamma^2}}}}$$

Square-root dependence on V.

Quasi-static C-V characteristics

Inversion

$$C_s \simeq \frac{q}{2kT} C_{ox} (V - V_{th})$$

For V sufficiently larger than V_{th}, C_s is large and:

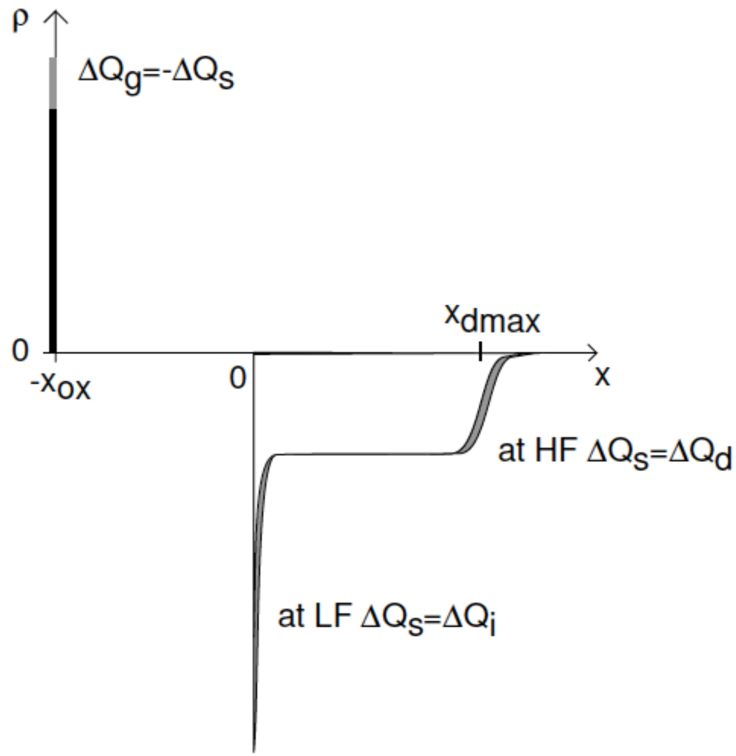
$$\boxed{C \simeq C_{ox}}$$

Independent of V

Quasi-static C-V characteristics

For **high-frequency AC signals**, inversion layer can't keep up with the frequency: since it is formed by minority carriers. So the time constants are in the order of **µs-ms**

C-V characteristics modified in inversion.
Evolution of ΔQ in inversion for LF and HF:



At low-frequency:

$$\Delta Q_s \simeq \Delta Q_i$$

At high-frequency:

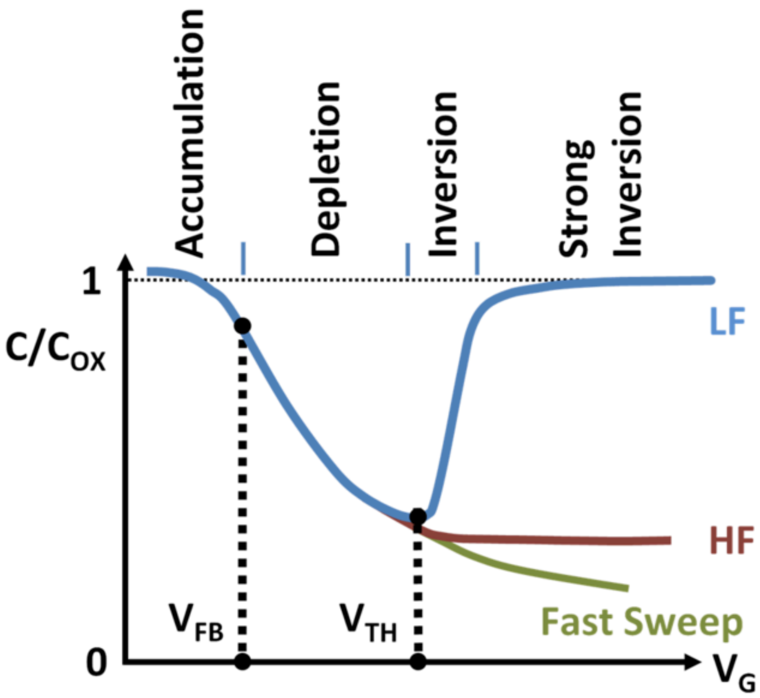
$$\Delta Q_s \simeq \Delta Q_d$$

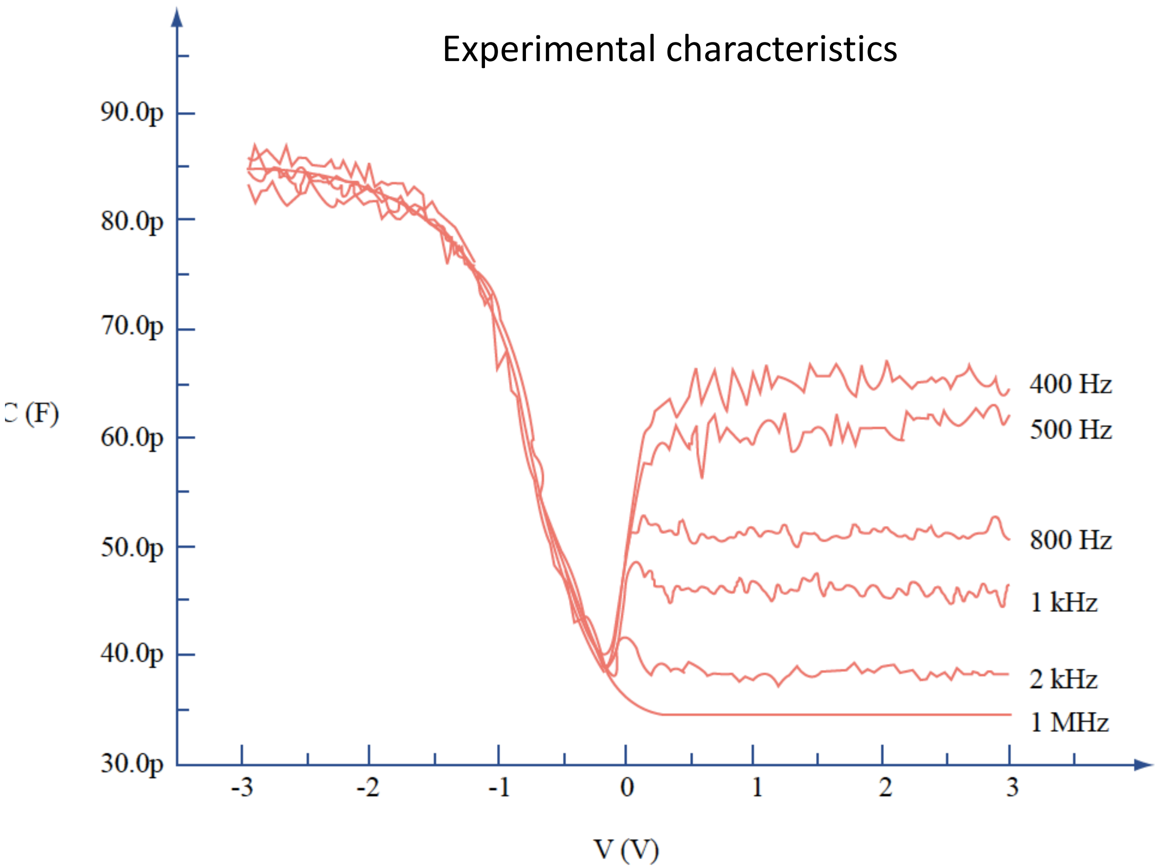
Since $x_d \sim x_{dmax}$,

$$C_{s,HF} \simeq C_{s,dep}(V_{th}) \simeq \frac{\gamma C_{ox}}{2\sqrt{2\phi_f}} \equiv C_{sth}$$

Quasi-static C-V characteristics

C-V characteristics:





Key conclusions

In inversion, $\phi_s \sim \phi_{sth}$, roughly independent of metal.

In accumulation, $\phi_s \sim 0$, roughly independent of metal.

At Si/SiO_2 interface, semiconductor can **swing all the way from accumulation to inversion** by the application of a voltage.

To first order, surface potential in inversion and accumulation does not change with V.

Flatband voltage: voltage that produces flatband:

$$V_{FB} = -\phi_{bi}$$

Threshold voltage: voltage beyond which an inversion layer of electrons is formed:

$$V_{th} = V_{FB} + 2\phi_f + \gamma\sqrt{2\phi_f}$$

Beyond threshold, absolute inversion **charge increases linearly with voltage**:

$$Q_i = -C_{ox}(V - V_{th})$$

Key conclusions

In **sub-threshold regime**, inversion charge drops exponentially with V below threshold:

$$Q_e \propto \exp \frac{q\phi_s}{kT} \propto \exp \frac{q(V - V_{th})}{nkT}$$

Inverse sub-threshold slope:

$$S = n\frac{kT}{q}\ln 10 \geq 60\ mV/dec \ \text{ at 300 K}$$

Typical inverse sub-threshold slope of well designed MOSFETs at300K: S ~80−100 mV/dec.

MOS capacitance: series of oxide capacitance and semiconductor capacitance:

$$\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_s}$$

For low-frequency excitation: $C(acc) \simeq C(inv) \simeq C_{ox}$