Lecture 23 - The Si surface and the Metal-Oxide-Semiconductor Structure *(cont.)*

April 4, 2007

Contents:

1. Ideal MOS structure under bias *(cont.)*
2. Dynamics of the MOS structure

Reading assignment:

del Alamo, Ch. 8, §8.3 (8.3.5), §8.4 (8.4.1, 8.4.2)

Key questions

- How sharply does the inversion layer "turn on" and "off" with the gate voltage?
- How do the capacitance-voltage characteristics of the MOS structure look like?
- How do the C-V characteristics of a MOS structure depend on the frequency of the small signal?

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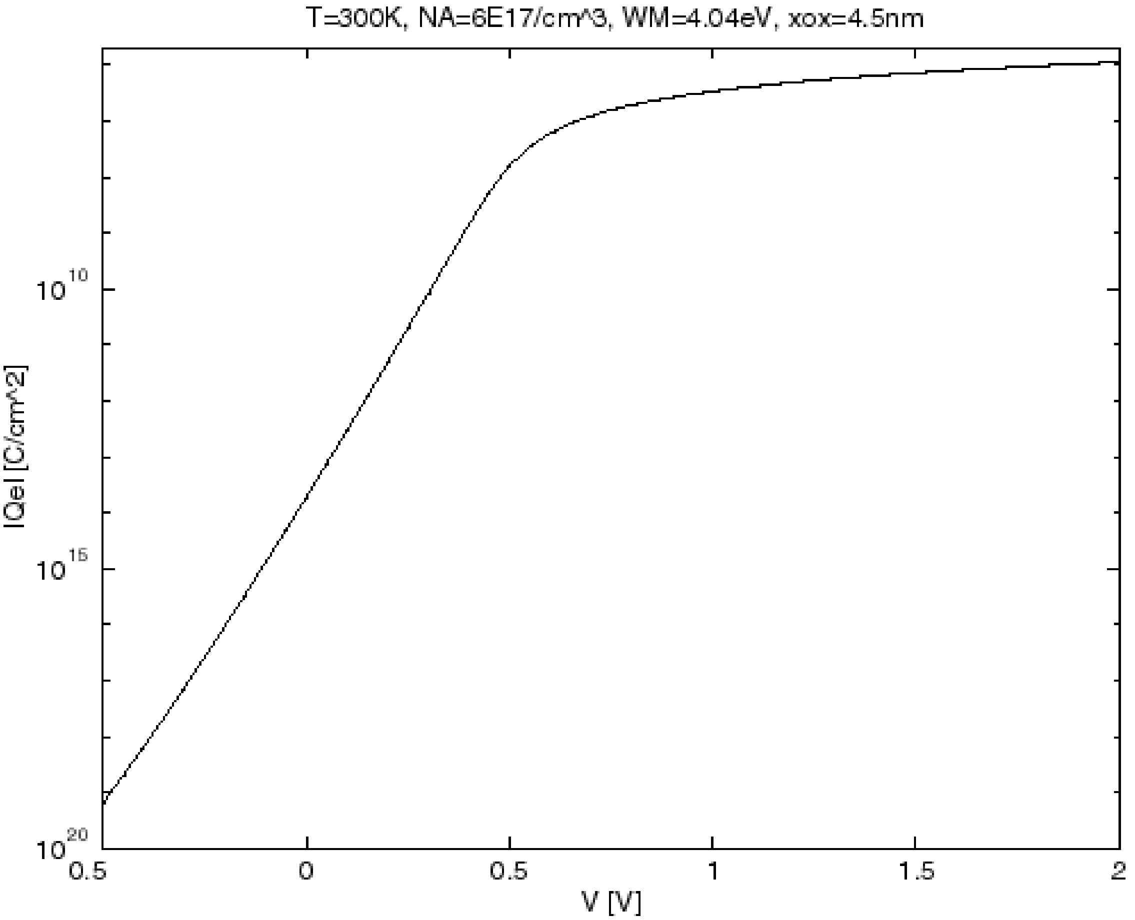
1. MOS structure under bias *(cont.)*

□ Subthreshold regime

In MOSFETs interested in current with the device nominally OFF, that is, for $V < V_{th}$: SUBTHRESHOLD CURRENT

MOS structure in *depletion* but finite electron concentration at surface:



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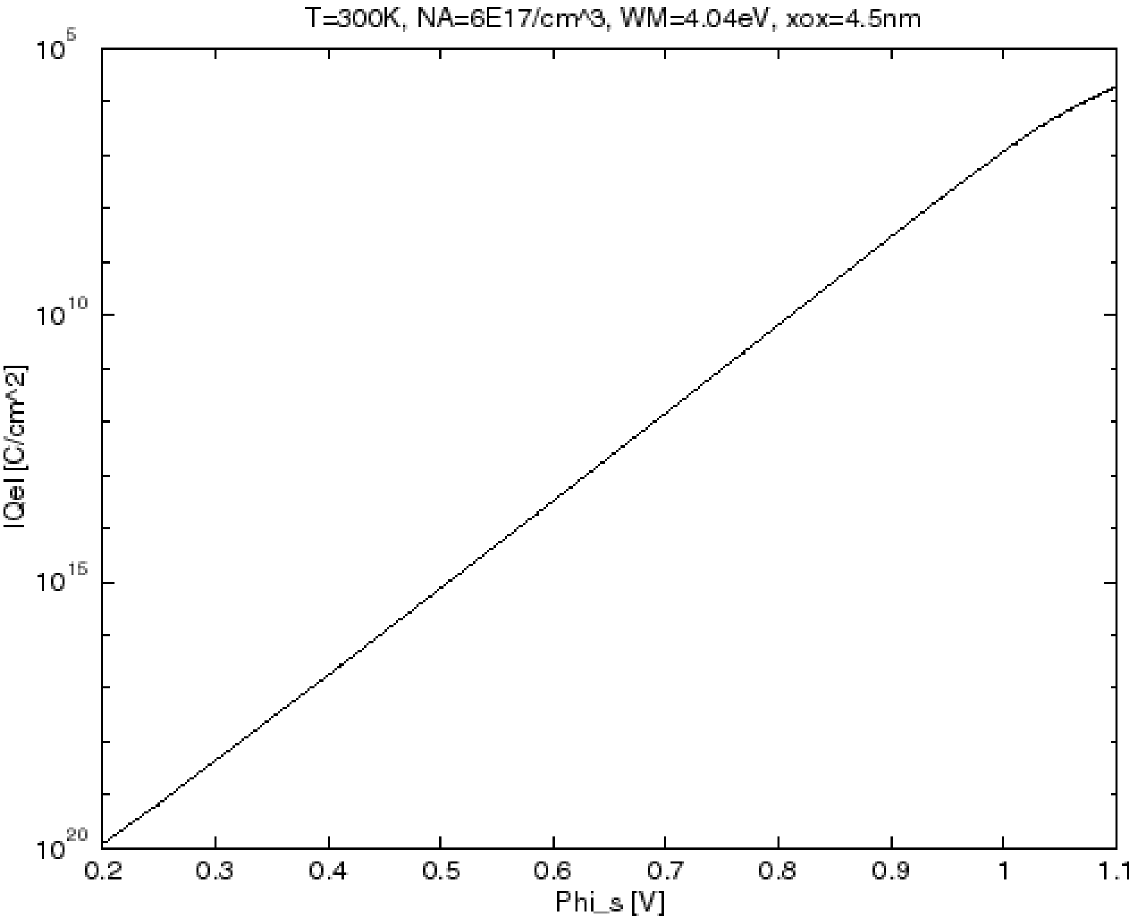
Compute Q_e in depletion:

$$Q_e \simeq -\frac{kT}{q}\frac{n_i^2}{N_A^2}\sqrt{\frac{q\epsilon_s N_A}{2\phi_s}}\exp\frac{q\phi_s}{kT}$$

This key dependence seen in exact solution:



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Express Q_e in terms ov V by expanding ϕ_s around ϕ_{sth}:

$$Q_e \simeq -\frac{kT}{q}\sqrt{\frac{q\epsilon_s N_A}{4\phi_f}}\exp\frac{q(V-V_{th})}{nkT}$$

with:

$$n = \frac{dV}{d\phi_s}|_{th} \simeq 1 + \frac{\gamma}{2\sqrt{2\phi_f}}$$

Note:

$$n > 1$$

Key characteristic of subthreshold regime is *inverse subthreshold slope*:

$$S = n\frac{kT}{q}\ln 10$$

At best, if $n = 1$, $S = 60\ mV/dec$ at room temperature.
Typically, $S = 80 - 100\ mV/dec$.

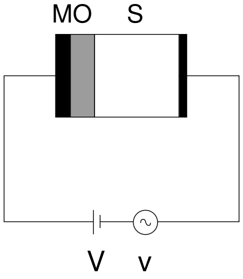
2. Dynamics of the MOS structure

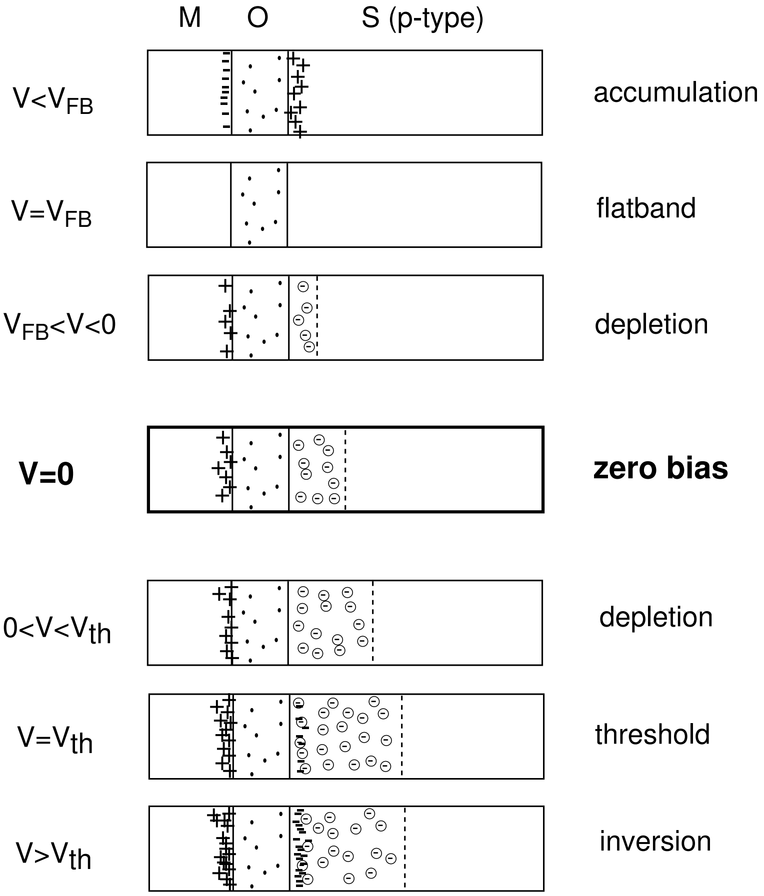
- MOS structure looks and behaves like capacitor
- C-V characteristics summarize complex behavior of MOS
- C-V characteristics: powerful diagnostic tool of wide applicability

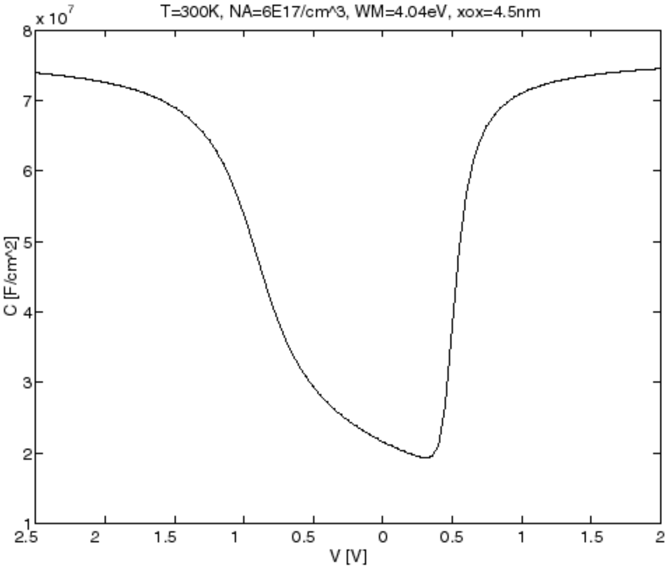
Three key issues to study:

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

☐ Qualitative discussion first:







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□ General definition of capacitance:

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

After some algebra:

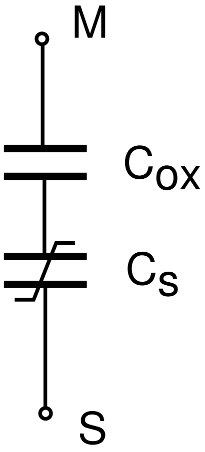
$$C = \frac{1}{\frac{1}{C_{ox}} + \frac{1}{C_s}}$$

where C_s is defined as:

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

Note: $C_s > 0$.

Simple physical interpretation:



□ Quasi-static C-V characteristics

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

$$Q_s = -\sqrt{2\epsilon_s kTN_A}F(\phi_s)$$

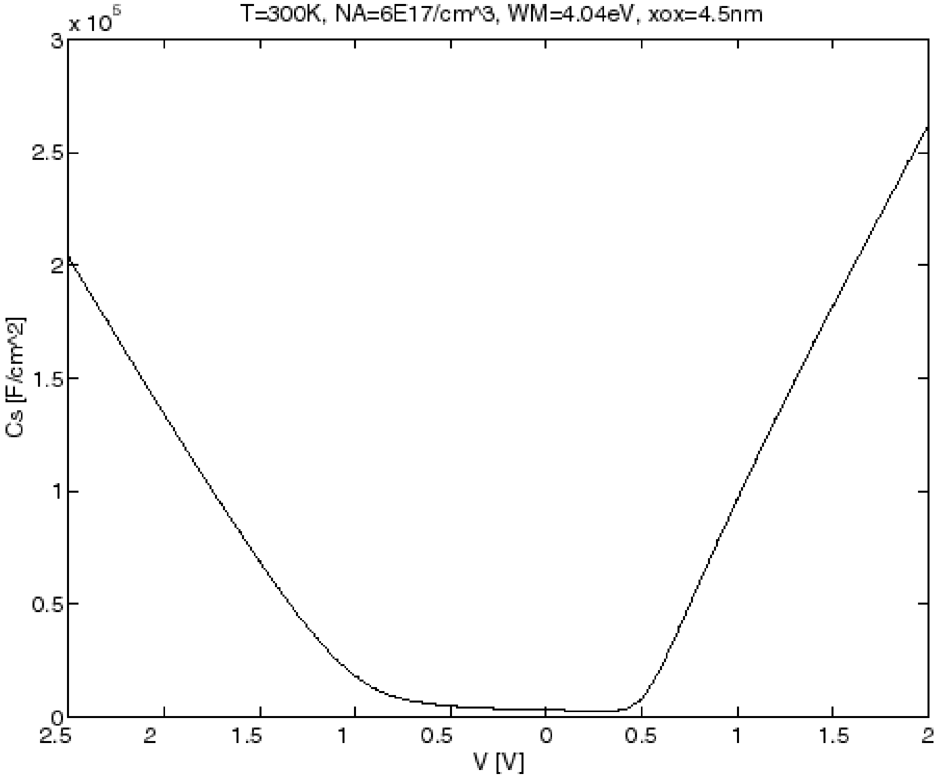
Then:

$$C_s = -\frac{dQ_s}{d\phi_s} = \sqrt{2\epsilon_s kTN_A}\,\frac{dF(\phi_s)}{d\phi_s}$$

This yields:

$$C_s = \frac{\epsilon_s}{\sqrt{2}L_D}\frac{1}{F(\phi_s)}[(-\exp\frac{-q\phi_s}{kT}+1)+\frac{n_i^2}{N_A^2}(\exp\frac{q\phi_s}{kT}-1)]$$

Results of calculations for typical MOS structure:



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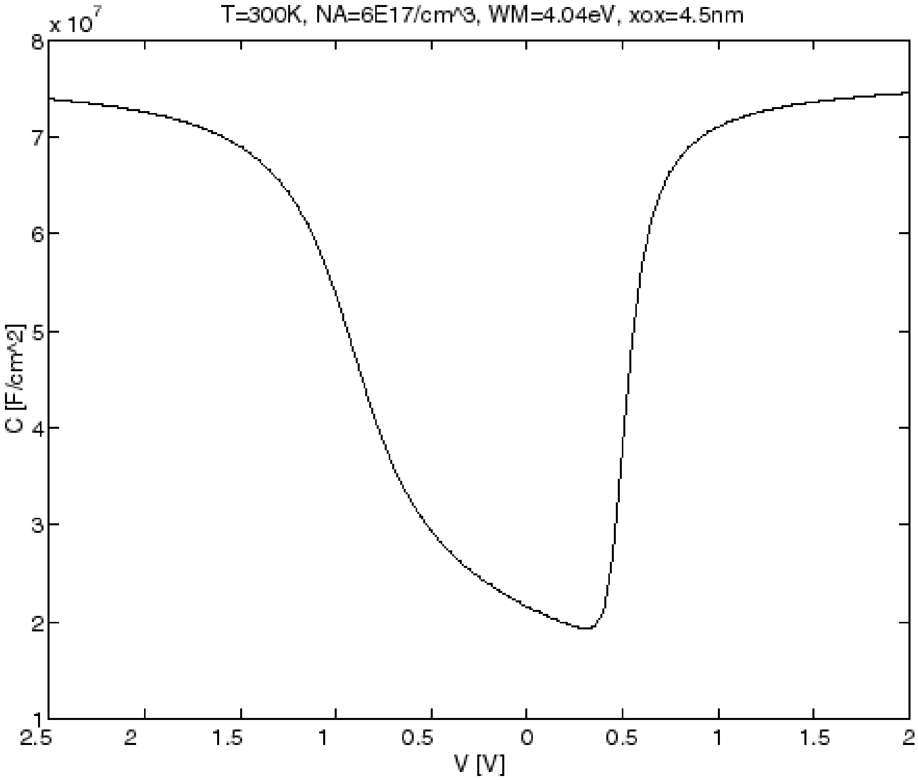

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□ ANALYTICAL APPROXIMATIONS TO C

- *Accumulation*

$$F(\phi_s) \simeq -\exp\frac{-q\phi_s}{2kT}$$

Then:

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

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

$$C \simeq C_{ox}$$

Independent of V.

- *Depletion*

$$F(\phi_s) \simeq \sqrt{\frac{q\phi_s}{kT}}$$

Which yields:

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

Overall capacitance:

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

Square-root dependence on V.

- *Inversion*

$$F(\phi) \simeq \frac{n_i}{N_A} \exp \frac{q\phi}{2kT}$$

This results in:

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

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

$$C \simeq C_{ox}$$

Independent of V.

□ High-frequency C-V characteristics

Time constants associated with charge modulation in semiconductor:

- *Accumulation*: hole concentration modulated in accumulation layer (majority carriers)

$$\tau \sim max(\tau_d,\ RC)$$

- *Depletion*: hole concentration modulated at edge of depletion layer (majority carriers)

$$\tau \sim max(\tau_d,\ RC)$$

- *Inversion*: electron concentration modulated in inversion layer (minority carriers)

$$\tau \sim \tau_g$$

with $\tau_g \equiv$ generation lifetime.

For high-frequency AC signals, inversion layer can't keep up: C-V characteristics modified in inversion.

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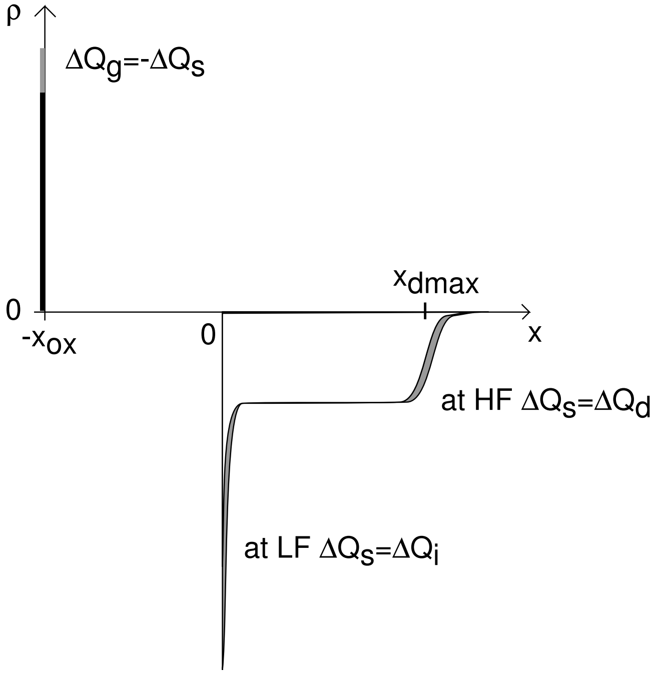
Evolution of ΔQ in inversion for LF and HF:



At low-frequency:

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

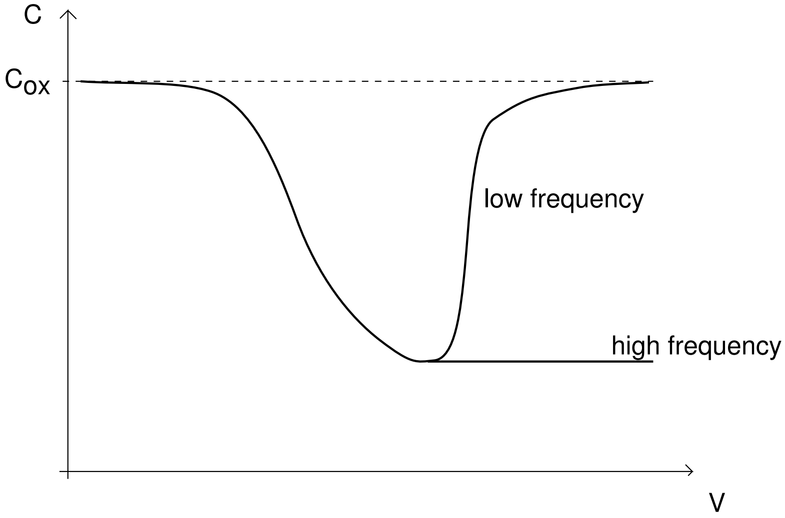
At high-frequency:

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

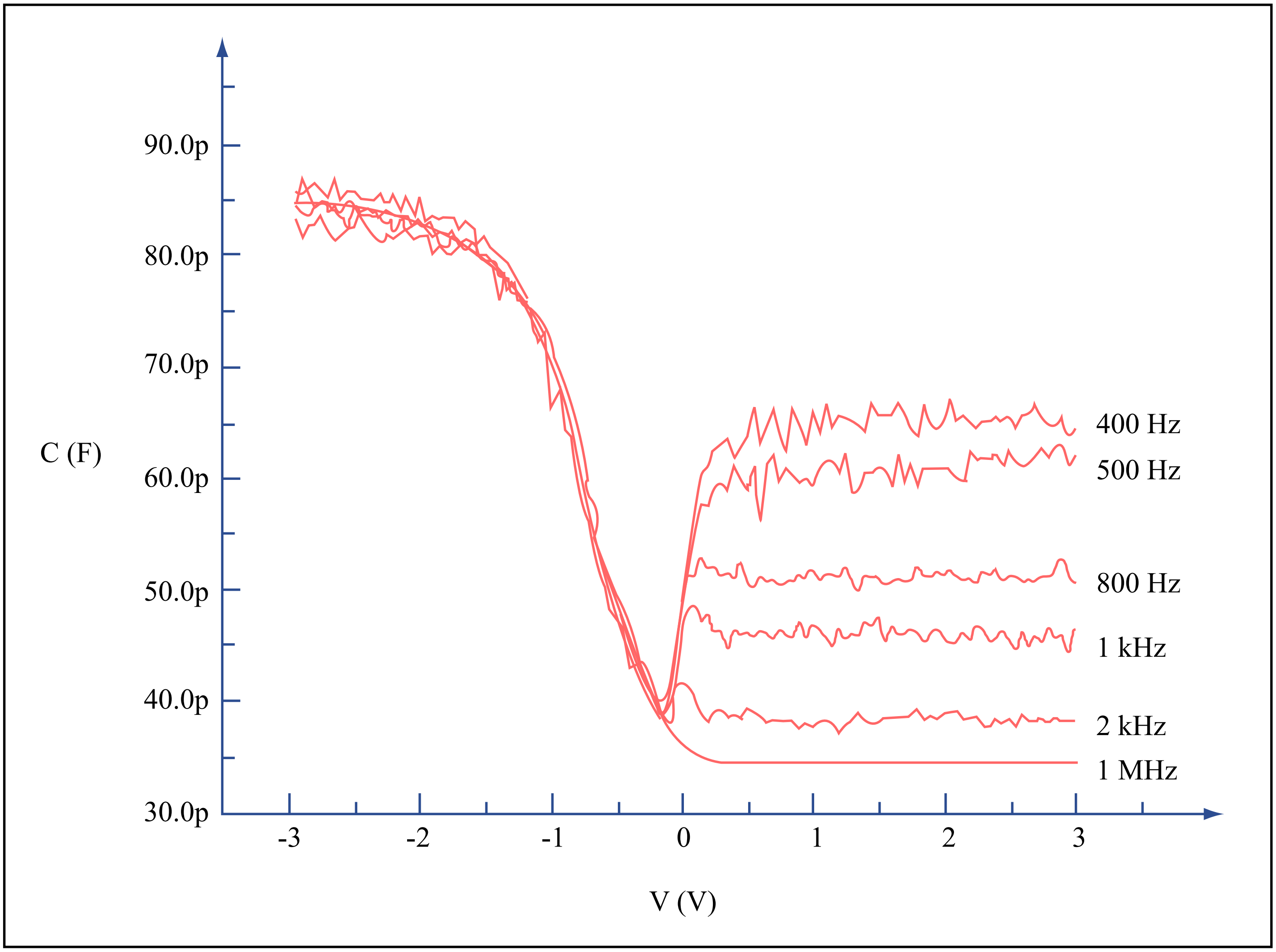
Since $x_d \simeq x_{dmax}$,

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

C-V characteristics:



Experimental high-frequency C-V characteristics:



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Key conclusions

- In *subthreshold 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 subthreshold slope*:

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

- Typical inverse subthreshold slope of well designed MOSFETs at 300 K: $S \sim 80-100\ mV/dec$.

- MOS capacitance: series of oxide capacitance and semiconductor capacitance:

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

- For low-frequency excitation:

$$C(acc) \simeq C(inv) \simeq C_{ox}$$

Self study

- General derivation of C-V characteristics from Poisson-Boltzmann formulation.
- Algebra behind analytical approximations for capacitance-voltage characteristics in accumulation, depletion and inversion.

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