Lecture 22 - The Si surface and the Metal-Oxide-Semiconductor Structure *(cont.)*

April 2, 2007

Contents:

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

Reading assignment:

del Alamo, Ch. 8, §8.3 (8.3.2-8.3.4)

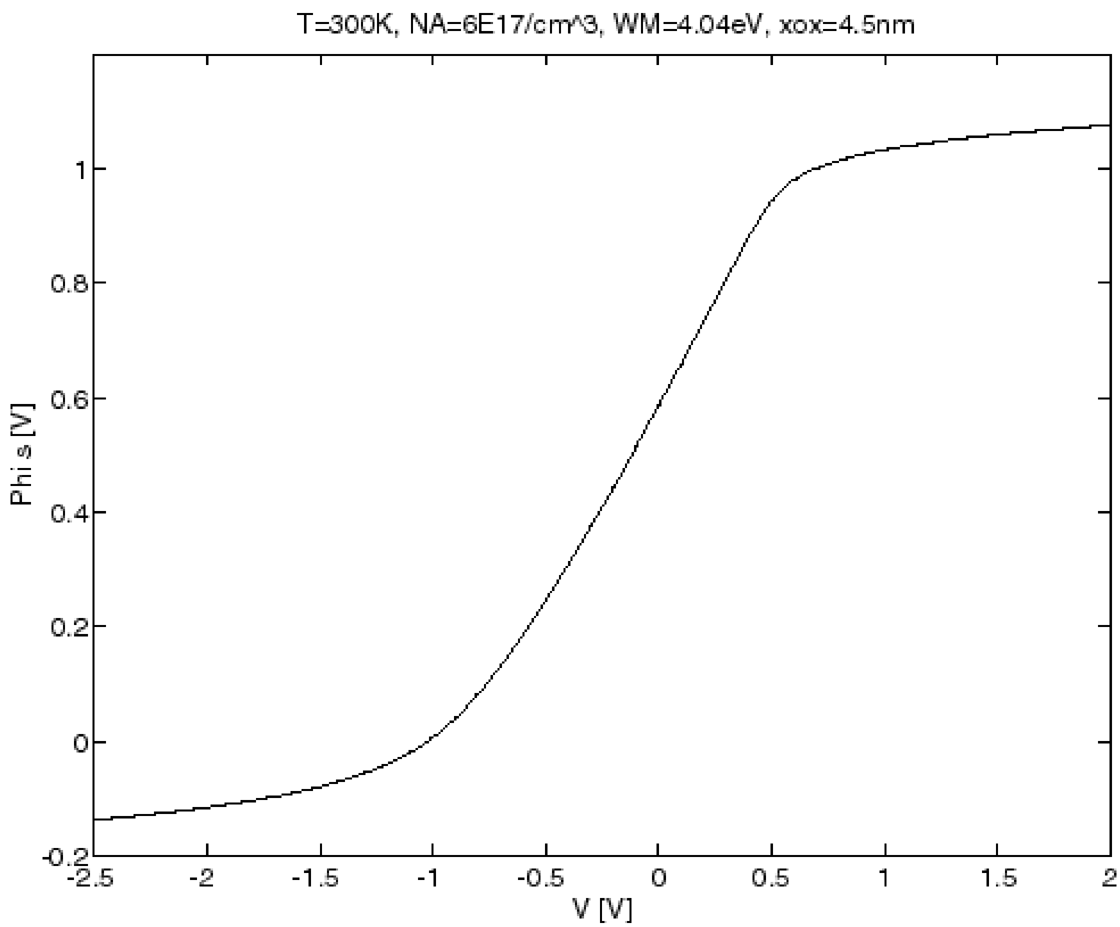
Key questions

- What are the key simplifications that one can make to the Poisson-Boltzmann formulation in order to develop simple first-order models for the various regimes of operation of the MOS structure?
- How thick are the inversion and accumulations layers?

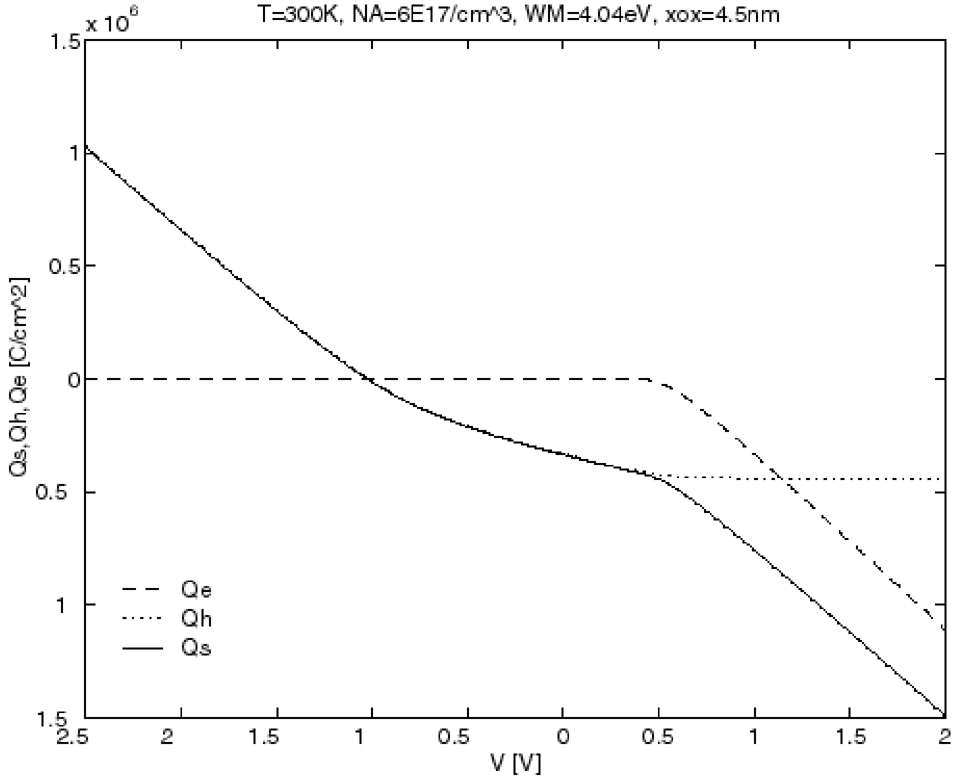
1. Ideal MOS structure outside equilibrium *(cont.)*

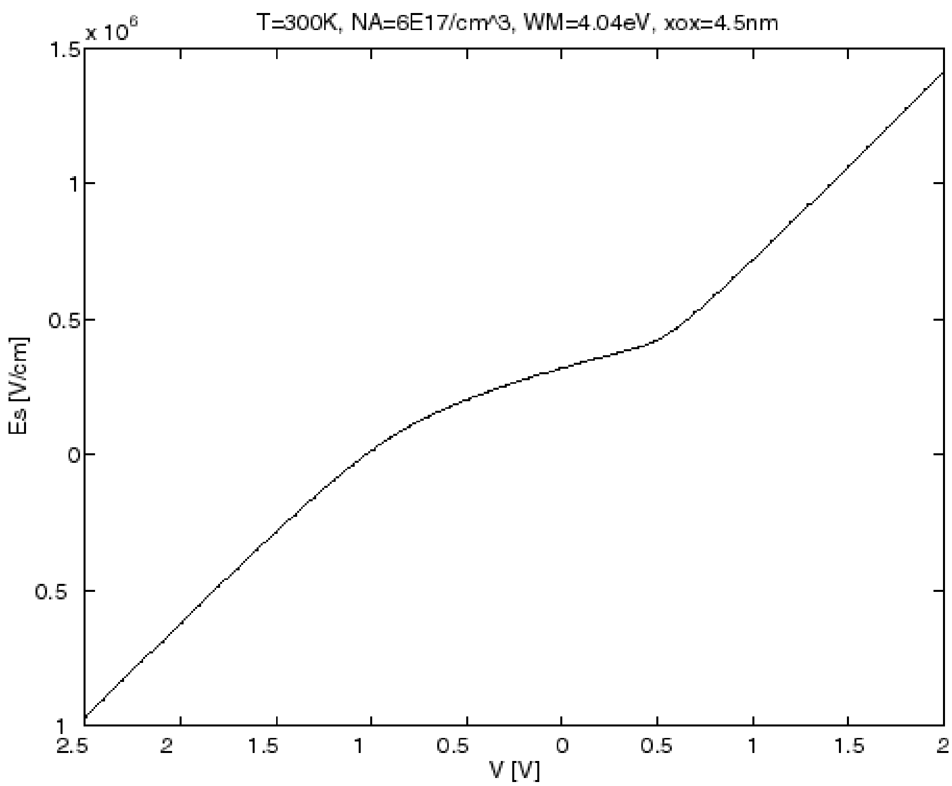
□ Next few viewgraphs: results of calculations for:

- $W_M = 4.04\ eV$ (n^+ polySi gate)
- $x_{ox} = 4.5\ nm$
- $N_A = 6 \times 10^{17}\ cm^{-3}$
- $T = 300\ K$

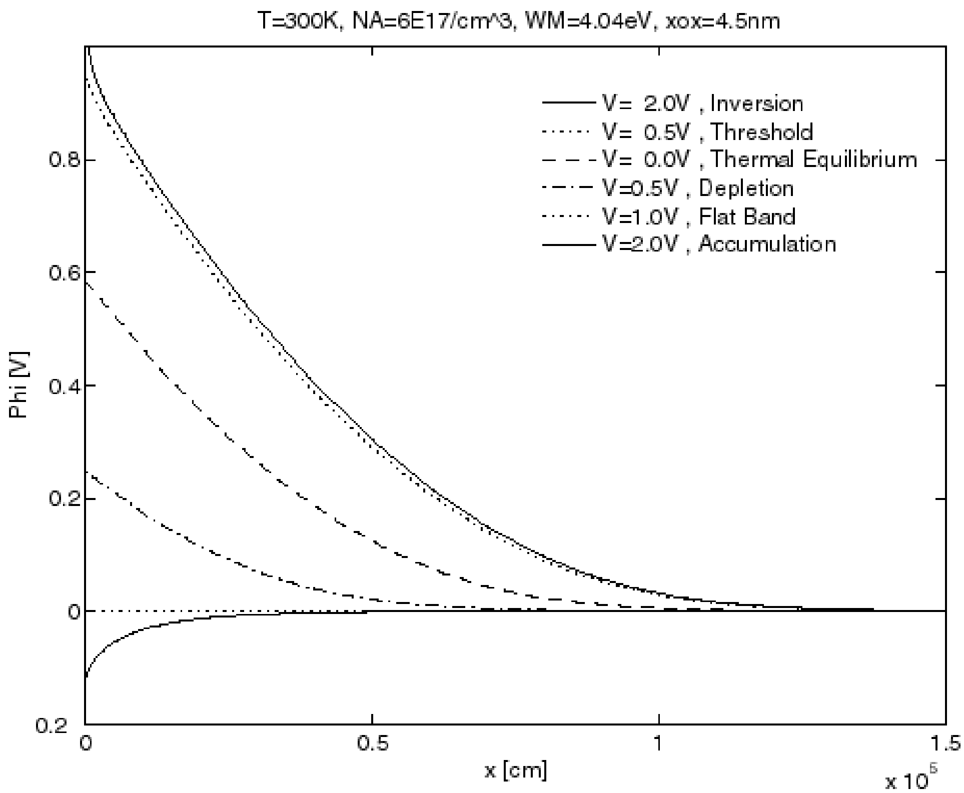


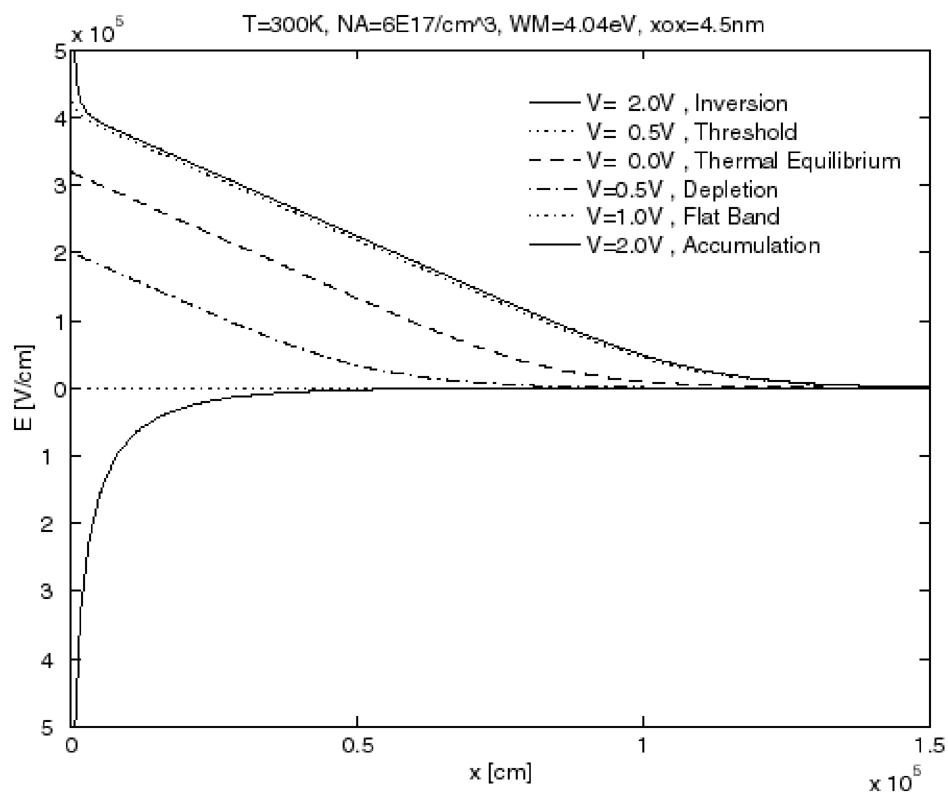
Courtesy of S. Mertens, MIT. Used with permission.



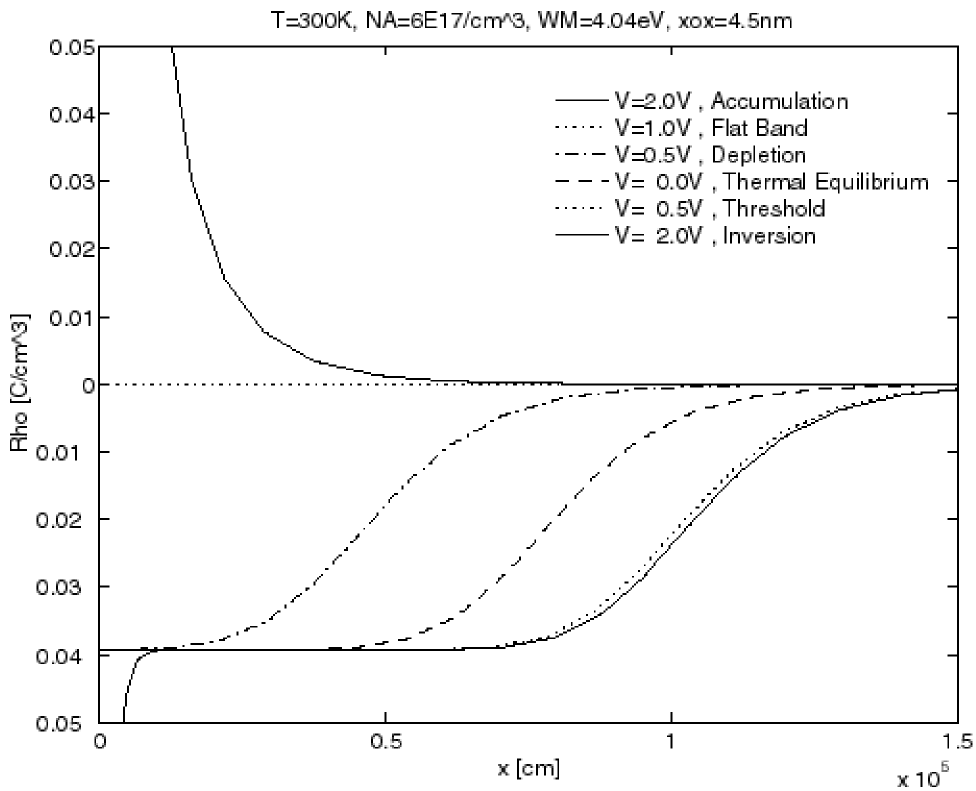


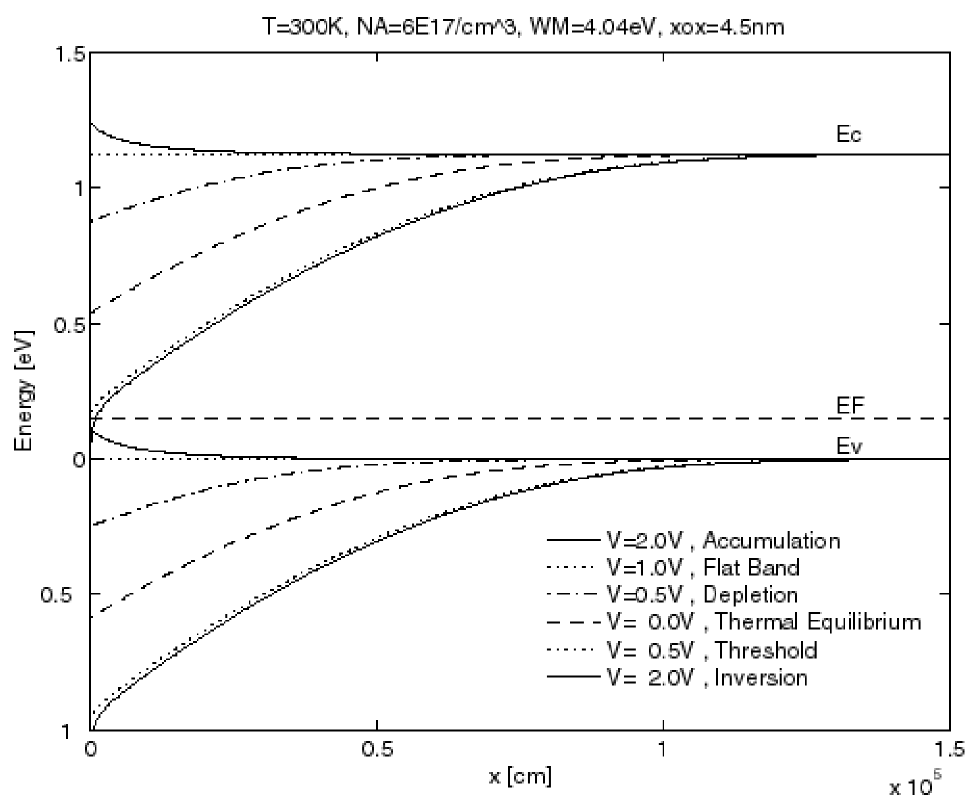
Courtesy of S. Mertens, MIT. Used with permission.



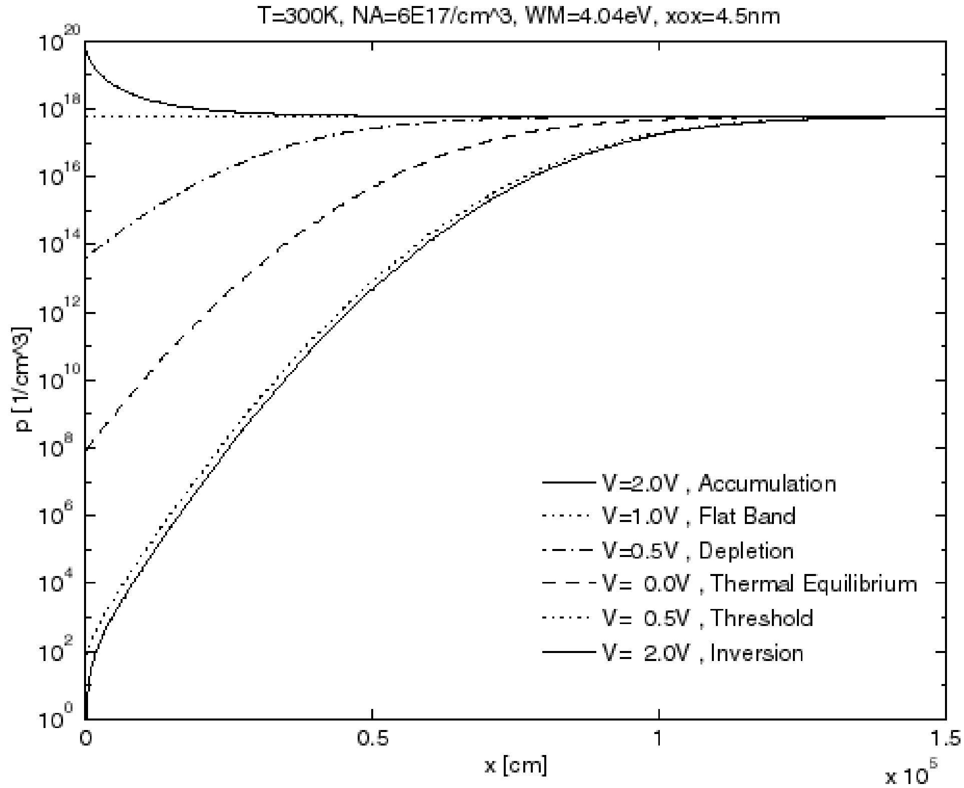


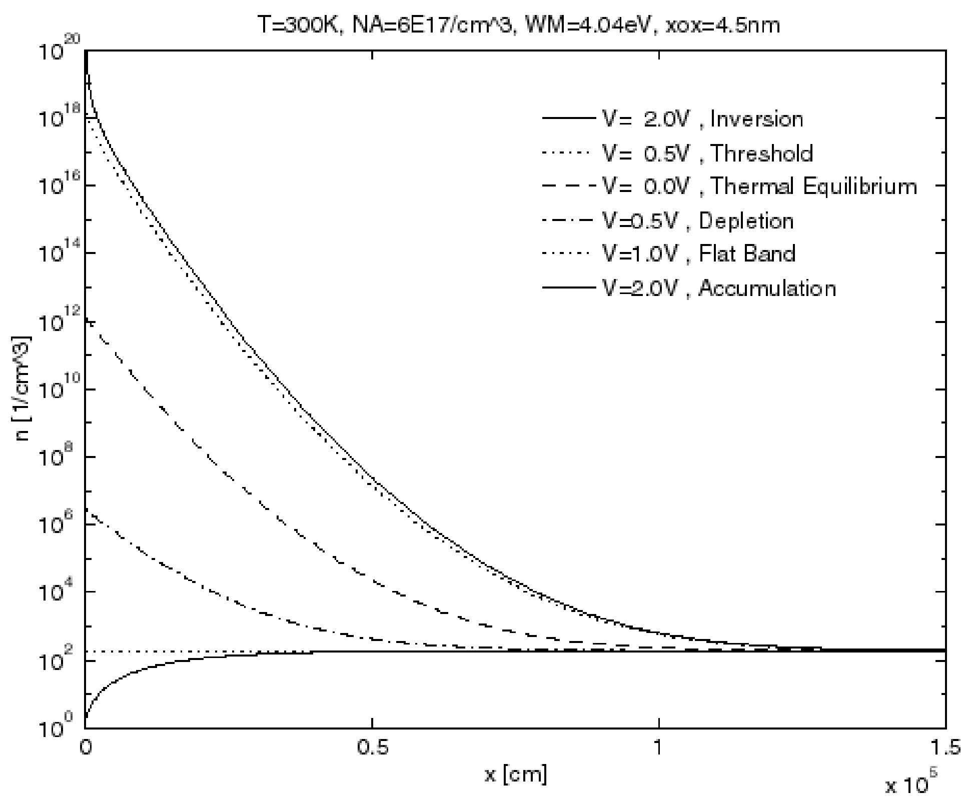
Courtesy of S. Mertens, MIT. Used with permission.





Courtesy of S. Mertens, MIT. Used with permission.

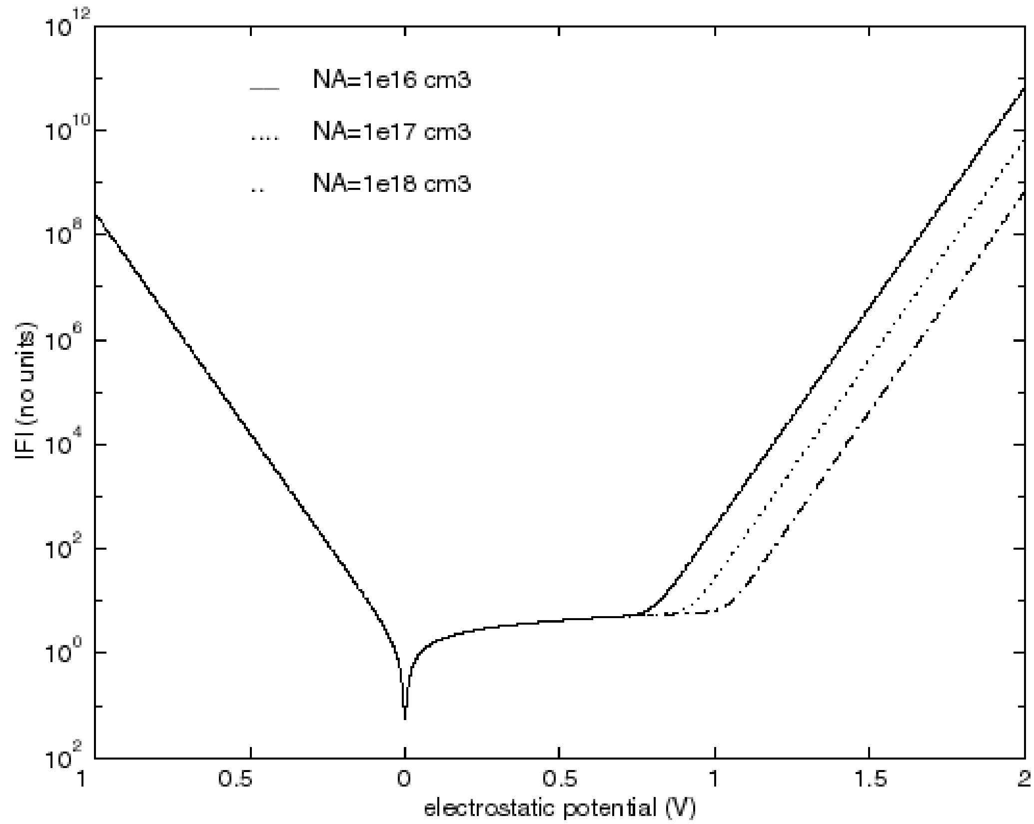




Courtesy of S. Mertens, MIT. Used with permission.

□ Properties of $F(\phi)$ function:

$$F(\phi) = \frac{\phi}{|\phi|}[(\exp\frac{-q\phi}{kT} + \frac{q\phi}{kT} - 1) + \frac{n_i^2}{N_A^2}(\exp\frac{q\phi}{kT} - \frac{q\phi}{kT} - 1)]^{1/2}$$



Courtesy of S. Mertens, MIT. Used with permission.

- For $\phi = 0$, $F(0) = 0$.
- For $\phi = 0$, $\frac{d^2F}{d\phi^2}|_0 = 0$.
- For $\phi < 0$, $F(\phi) < 0$. For $\phi > 0$, $F(\phi) > 0$.
- For all ϕ, $\frac{dF}{d\phi} > 0$.

- Last three terms multiplied by small prefactor:

$$\frac{n_i^2}{N_A^2} \sim 10^{-10} - 10^{-14}$$

- For $\phi < 0$ and $|\phi|$ more than a few $\frac{kT}{q}$:

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

- For $\phi > 0$ and ϕ more than a few $\frac{kT}{q}$, but not too large:

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

- For $\phi > 0$ and sufficiently large:

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

□ Approximations for **depletion**

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

Yields:

$$x_d = \sqrt{\frac{2\epsilon_s \phi_s}{qN_A}}$$

Relationship between ϕ and V:

$$\phi_s = \frac{\gamma^2}{4}[\sqrt{1 + 4\frac{V - V_{FB}}{\gamma^2}} - 1]^2$$

Depletion charge:

$$Q_s = -\frac{1}{2}\gamma^2 C_{ox}[\sqrt{1 + 4\frac{V - V_{FB}}{\gamma^2}} - 1]$$

□ Approximations for **Accumulation**

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

Results in accumulation region thickness:

$$x_{acc} \simeq \sqrt{2}L_D$$

Relationship between V and ϕ_s:

$$\phi_s \simeq -\frac{2kT}{q}\ln[\sqrt{\frac{q}{kT}}\frac{1}{\gamma}(V_{FB} - V)]$$

Accumulation charge:

$$Q_h = Q_s \simeq \sqrt{2\epsilon_s kTN_A}\exp\frac{-q\phi_s}{2kT}$$

In terms of V:

$$Q_h \simeq C_{ox}(V_{FB} - V)$$

□ Approximations for **Inversion**

Piecewise description of $F(\phi)$:

$$F(\phi) \simeq \sqrt{\frac{q\phi}{kT}} \qquad \text{for } \phi < 2\phi_f$$

$$F(\phi) \simeq \sqrt{\frac{q2\phi_f}{kT} + \exp\frac{q(\phi - 2\phi_f)}{kT} - 1} \qquad \text{for } \phi > 2\phi_f$$

Results in inversion region thickness:

$$x_{inv} \simeq \sqrt{2}L_D$$

Depletion region thickness:

$$x_d = x_{inv} + \sqrt{\frac{2\epsilon_s 2\phi_f}{qN_A}} \simeq x_{dmax}$$

Relationship between ϕ_s and V:

$$\phi_s \simeq 2\phi_f + \frac{kT}{q}\ln[\frac{q}{kT}\frac{1}{\gamma^2}(V - V_{FB} - 2\phi_f)^2 - \frac{q2\phi_f}{kT} + 1]$$

Electron charge in inversion layer:

$$Q_e \simeq -\sqrt{2\epsilon_s kTN_A}[\sqrt{\frac{q2\phi_f}{kT} + \exp\frac{q(\phi_s - 2\phi_f)}{kT} - 1} - \sqrt{\frac{q2\phi_f}{kT}}]$$

In terms of V:

$$Q_e \simeq -C_{ox}(V - V_{th})$$

with:

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

Assumed threshold surface potential $\phi_{sth} = 2\phi_f$. Empirically, often:

$$\phi_{sth} \simeq 2\phi_f + m\frac{kT}{q}$$

with m around 5.

Key conclusions

- Charge control relationship for inversion charge:

$$Q_e \simeq -C_{ox}(V - V_{th})$$

- Charge control relationship for accumulation charge:

$$Q_h \simeq C_{ox}(V_{FB} - V)$$

- Inversion and accumulation layer thickness of order of Debye length.
- Better choice for surface potential at threshold:

$$\phi_{sth} \simeq 2\phi_f + m\frac{kT}{q}$$

  with m around 5.

Self study

- Derivation of analytical approximations for electrostatics in depletion, accumulation and inversion from Poisson-Boltzmann formulation.