Fundamentals of Nanotransistors

Unit 2: MOS Electrostatics

Lecture 2.6: Mobile Charge: ETSOI

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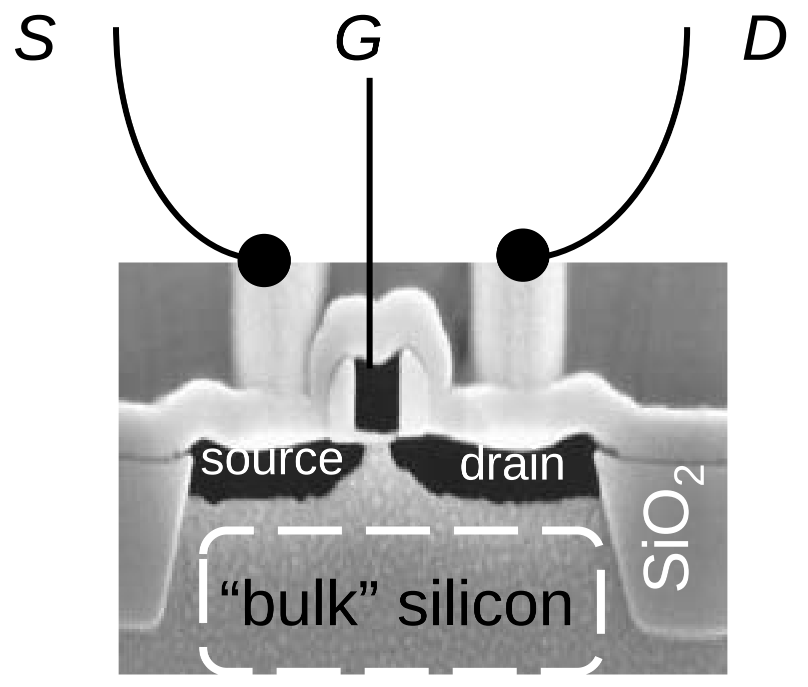
Bulk MOSFETs



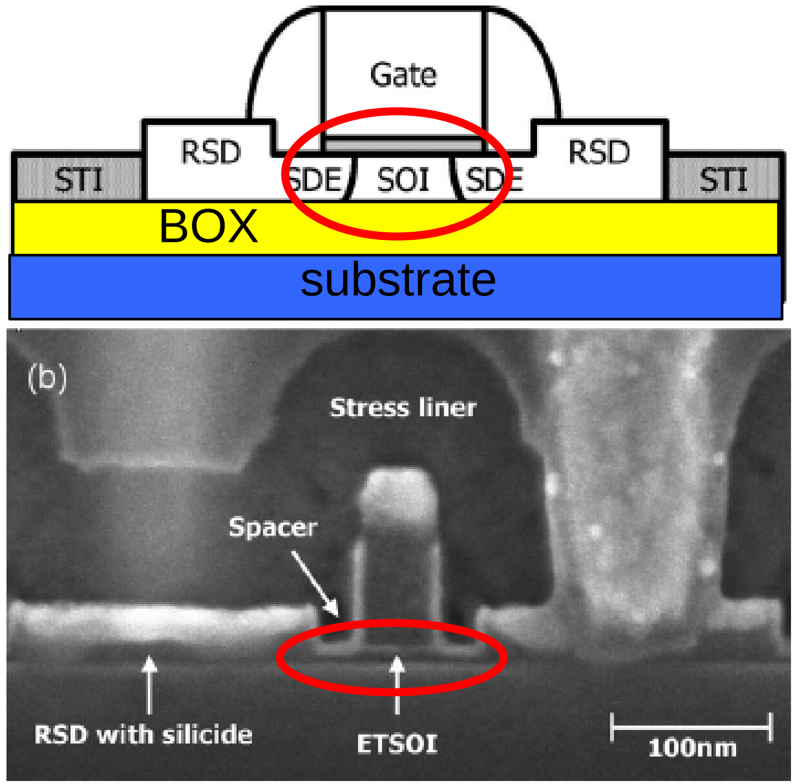
(Texas Instruments, ~ 2000)

12" wafers are 775 micrometers thick

Silicon on Insulator (SOI) MOSFETs

Bottom Oxide

Si substrate



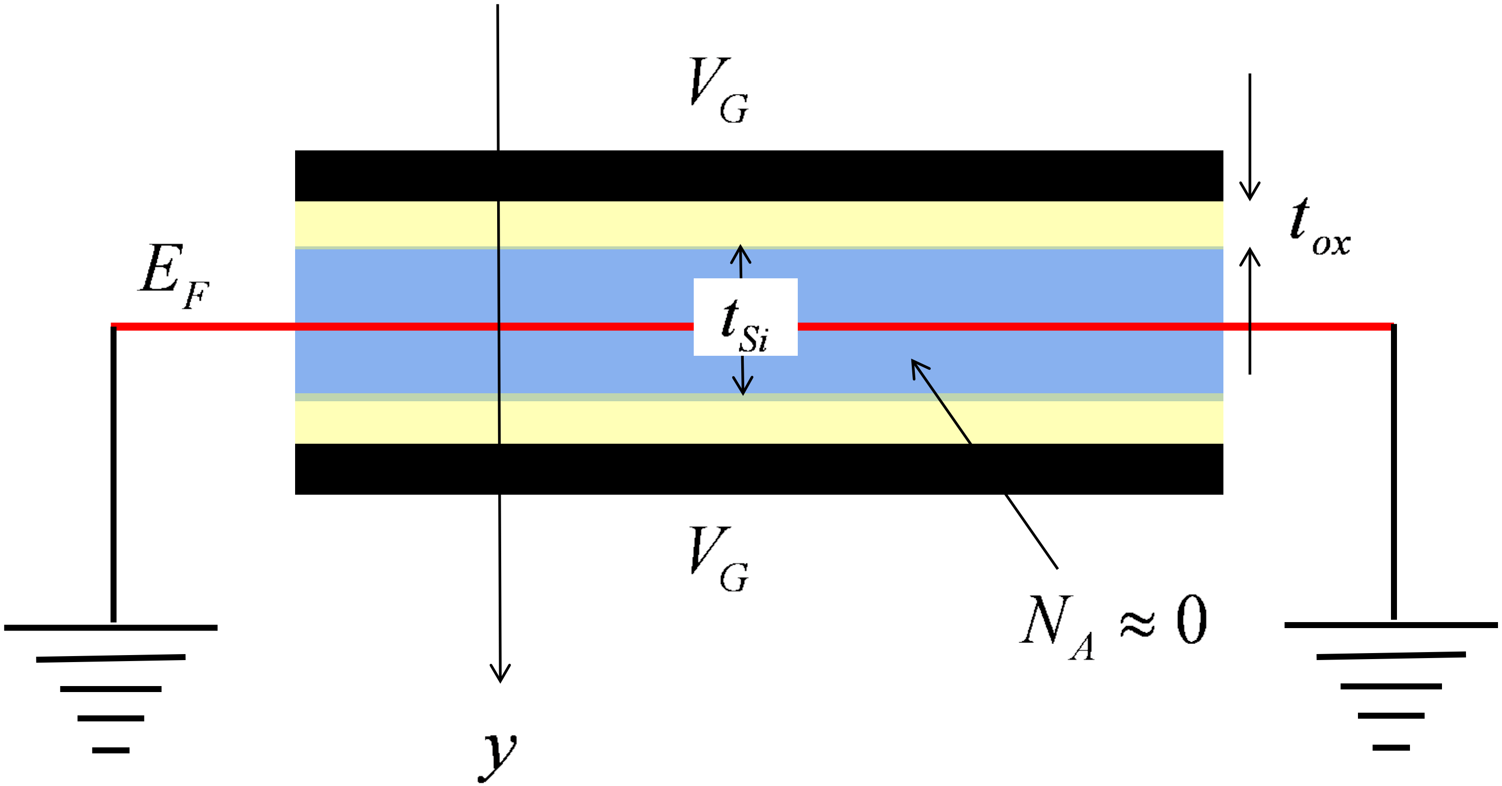
A. Majumdar, Z. Ren, S. J. Koester, and W. Haensch, Undoped-Body Extremely Thin SOI MOSFETs With Back Gates, *IEEE Trans. Electron Dev*., **56**, 2270-2276, 2009.

The question

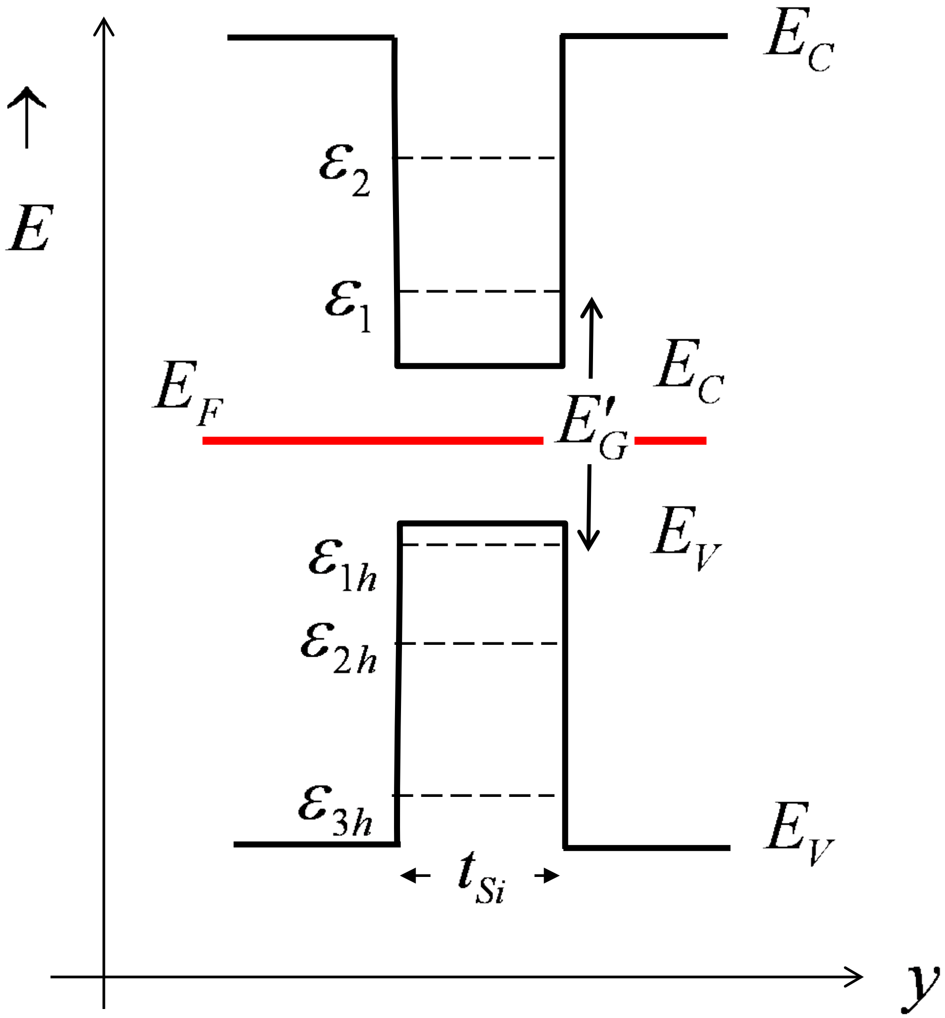
What are the $Q_n(\psi_S)$ and $Q_n(V_{GS})$ relations for an **E**xtremely **T**hin **S**ilicon **O**n **I**nsulator (ETSOI) MOSFET?

We will assume a symmetrical, double gate geometry, which makes this discussion relevant to FinFETs as well.

Extremely-thin body double gate-C



ETSOI energy band diagram

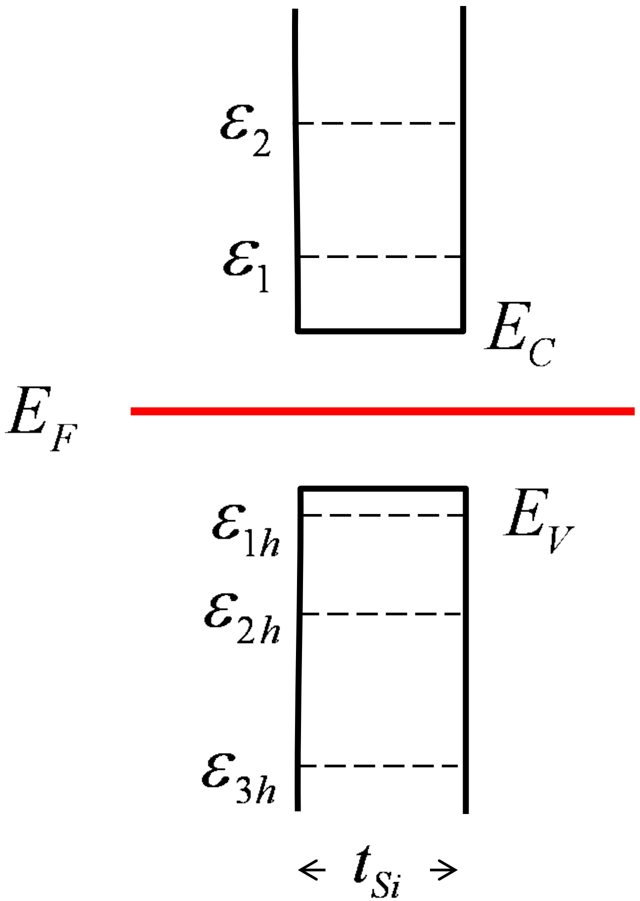


$$\varepsilon_n = \frac{\hbar^2 n^2 \pi^2}{2m^* t_{Si}^2}$$

$$E'_G = E_G + \varepsilon_1 + \varepsilon_{1h}$$

(Neglect band bending, so the potential is constant.)

2D carrier densities



$$n_{S1} = N_C^{2D} \mathcal{F}_0\left(\eta_{F1}\right) \text{ cm}^{-2}$$

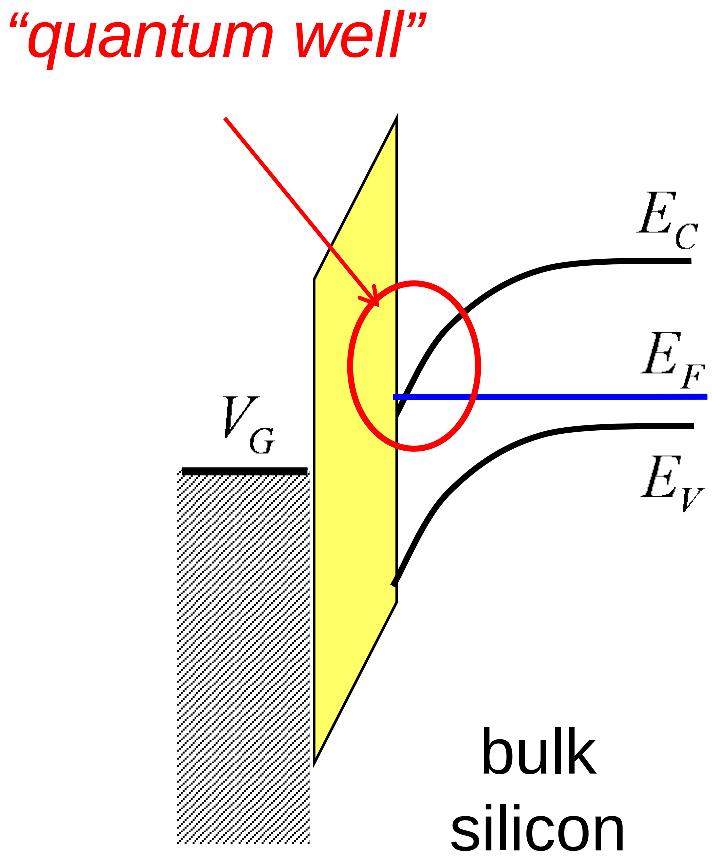
$$N_C^{2D} = g_V \frac{m_n^* k_B T}{\pi \hbar^2} \text{ cm}^{-2}$$

$$\eta_{F1} = \frac{\left(E_F - E_C - \varepsilon_1\right)}{k_B T}$$

Boltzmann statistics:

$$n_{S1} = N_C^{2D} e^{\left(E_F - E_C - \varepsilon_1\right)/k_B T} \text{ cm}^{-2}$$

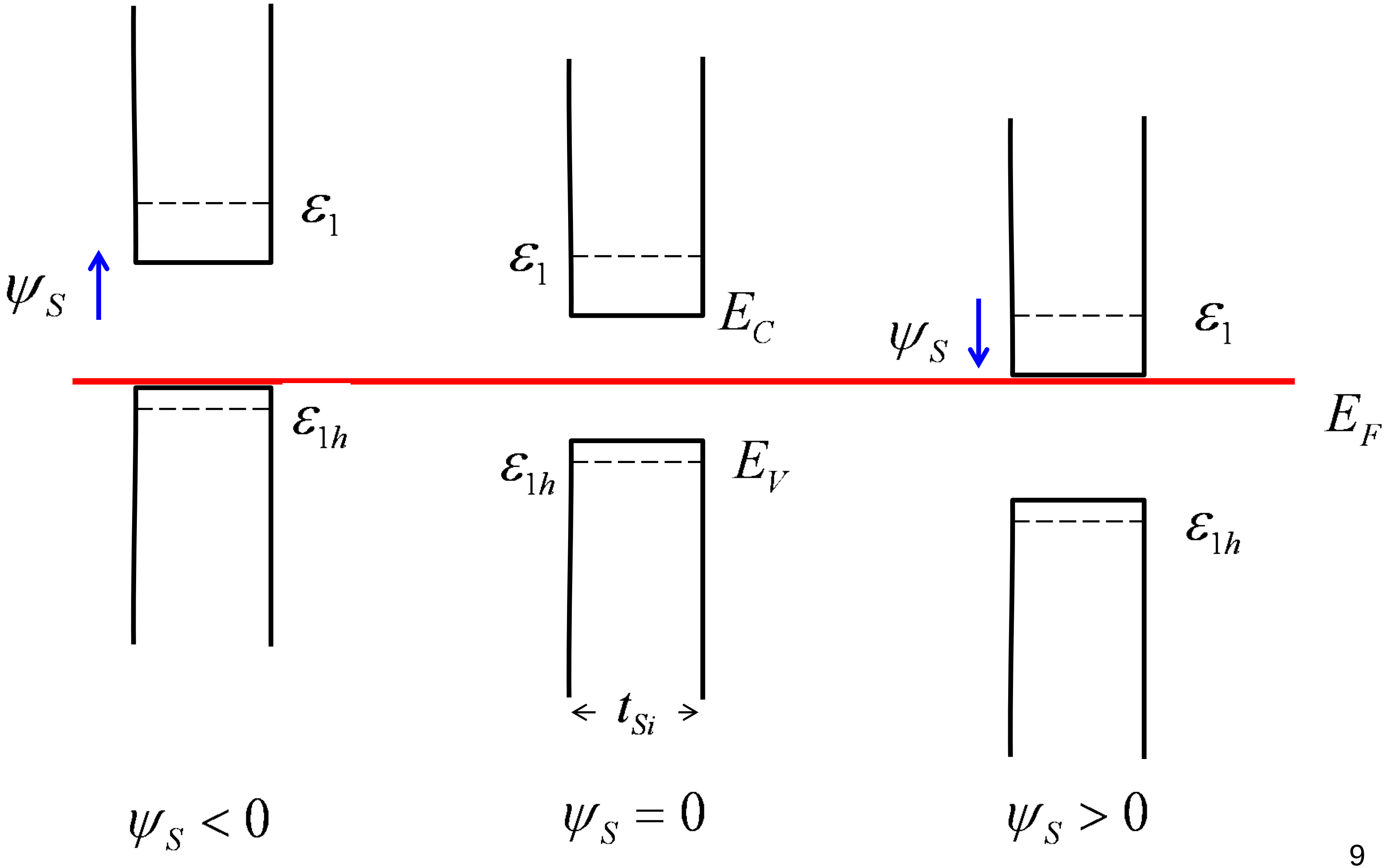
Quantum confinement in a bulk MOS-C



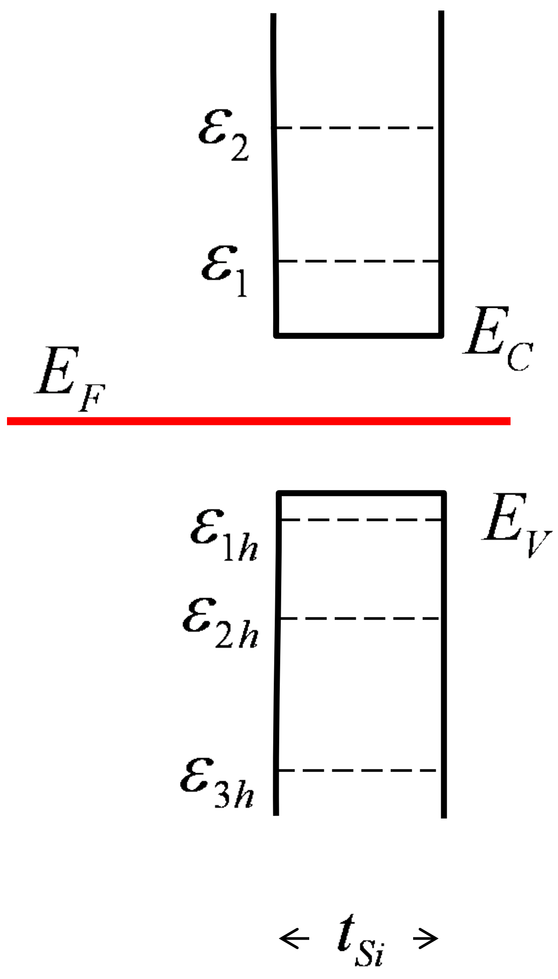
In the bulk, the confining potential is due to electrostatics.

In Extremely Thin SOI, the confining potential is due to the physical structure.

ETSOI for various potentials



Carrier densities and potential



$$n_{S1} = N_C^{2D} e^{(E_F - E_C - \varepsilon_1)/k_B T} \text{ cm}^{-2}$$

$$E_C = E_{C0} - q\psi_S$$

$$n_{S1} = N_C^{2D} e^{(E_F - E_{C0} - \varepsilon_1 + q\psi_S)/k_B T}$$

$$n_{S1} = N_C^{2D} e^{(E_F - E_{C0} - \varepsilon_1)/k_B T} \; e^{q\psi_S/k_B T}$$

$$n_S = n_{S0} e^{q\psi_S/k_B T}$$

$$p_S = p_{S0} e^{-q\psi_S/k_B T}$$

(These eqns. assume that only 1 subband is occupied.)

Mobile sheet charge (per cm^2)

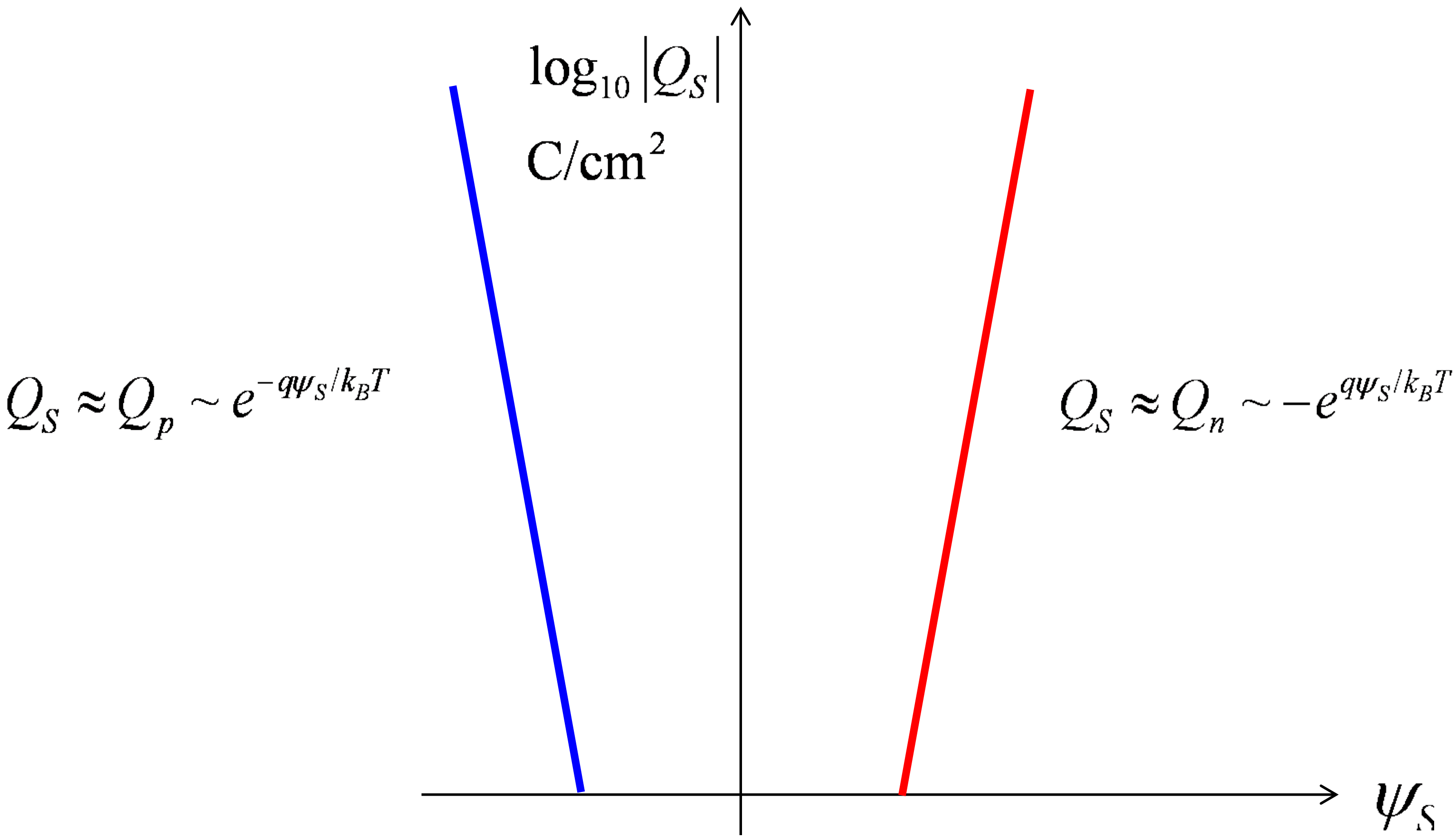
$$Q_S = q\left(p_S - n_S\right) \quad \mathrm{C/cm^2}$$

$$\boxed{Q_n\left(\psi_S\right) = -q n_{S0}\, e^{q\psi_S/k_BT}}$$

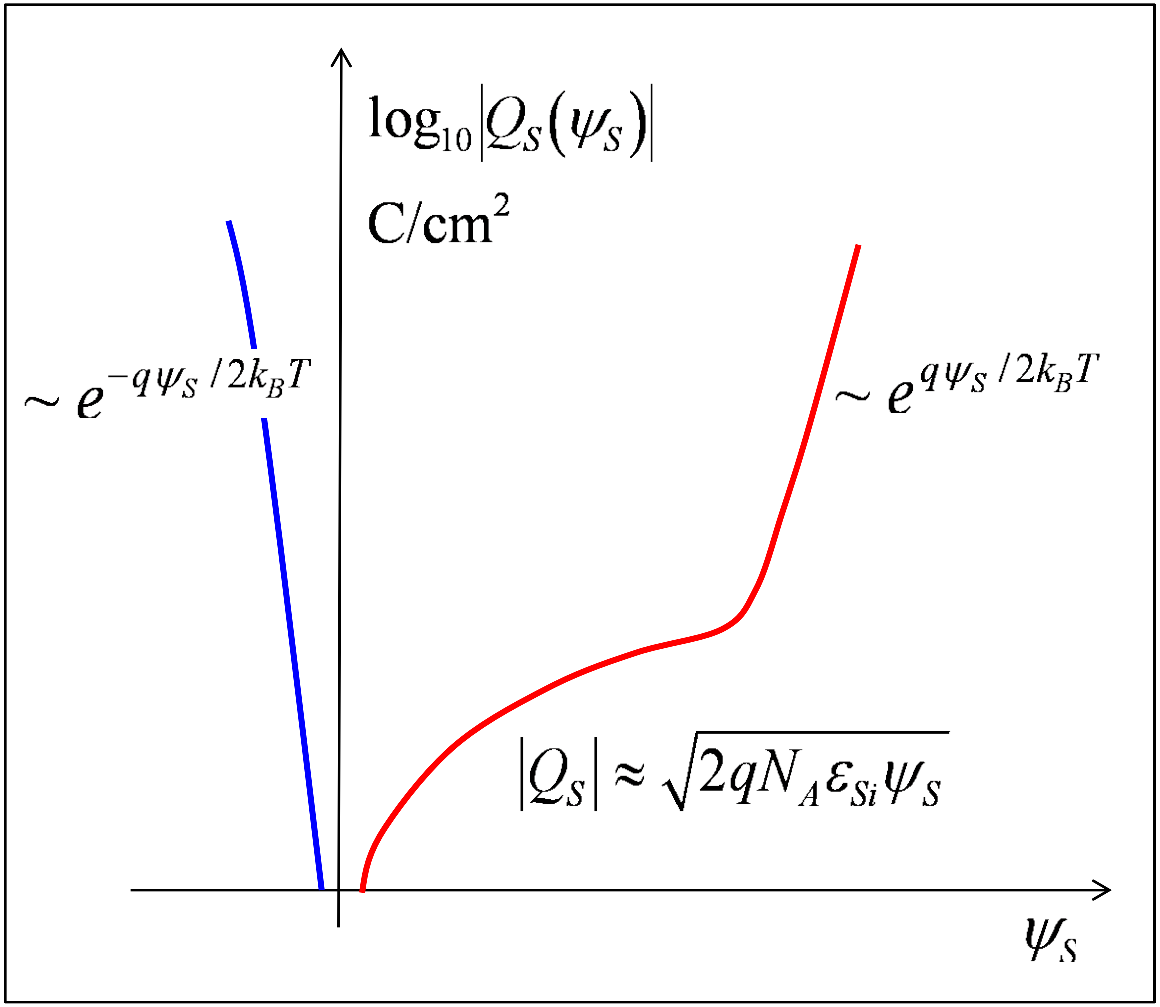
Valid above and below threshold.

Charge vs. potential

$$Q_S(\psi_S) = q\left(p_{S0}\, e^{-q\psi_S/k_BT} - n_{S0}\, e^{q\psi_S/k_BT}\right)$$



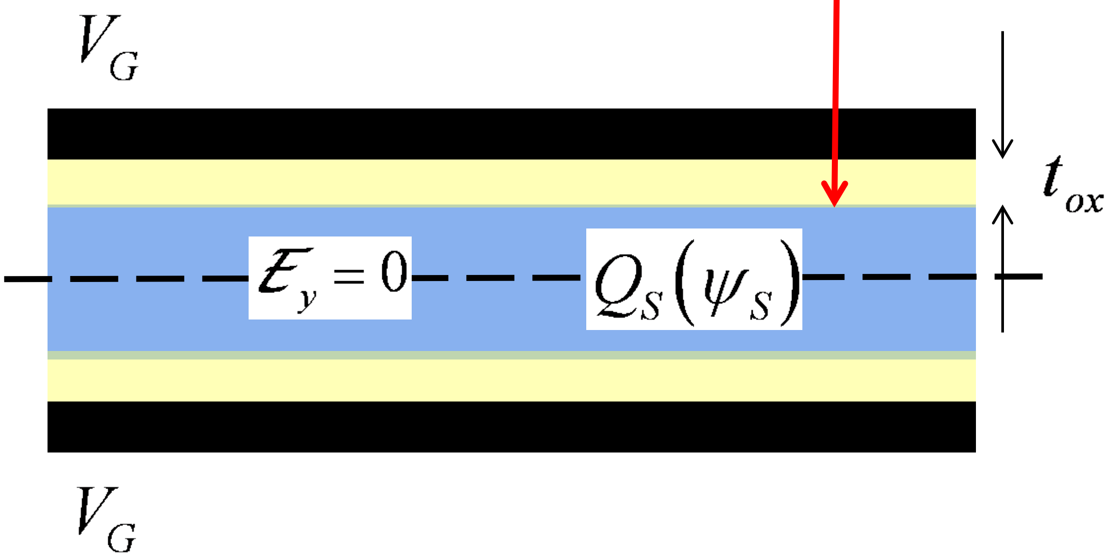
Recall: $Q_S(\psi_S)$ for bulk MOS



Gate voltage vs. potential

$$\epsilon_{ox}\mathcal{E}_{ox} = -Q_S(\psi_S)/2$$

$$\Delta V_{ox} = \mathcal{E}_{ox} t_{ox} = -Q_S(\psi_S)/2C_{ox}$$



$$V_G = \Delta V_{ox} + \psi_S$$

$$V_G = -\frac{Q_S(\psi_S)}{2C_{ox}} + \psi_S$$

subthreshold

$$V_G = -\frac{Q_S(\psi_S)}{2C_{ox}} + \psi_S \qquad Q_S(\psi_S) \approx 0 \rightarrow V_G \approx \psi_S$$

$$\psi_S = \frac{V_G}{m}$$ bulk

$$m = 1 + C_D / C_{ox}$$

Subthreshold charge vs. gate voltage

$$Q_n(\psi_S) = -q n_{S0}\, e^{q\psi_s/k_B T}$$

$V_G \approx \psi_S$ (subthreshold)

$$Q_n(V_G) \approx -q n_{S0}\, e^{qV_{GS}/k_B T}$$

$m = 1$

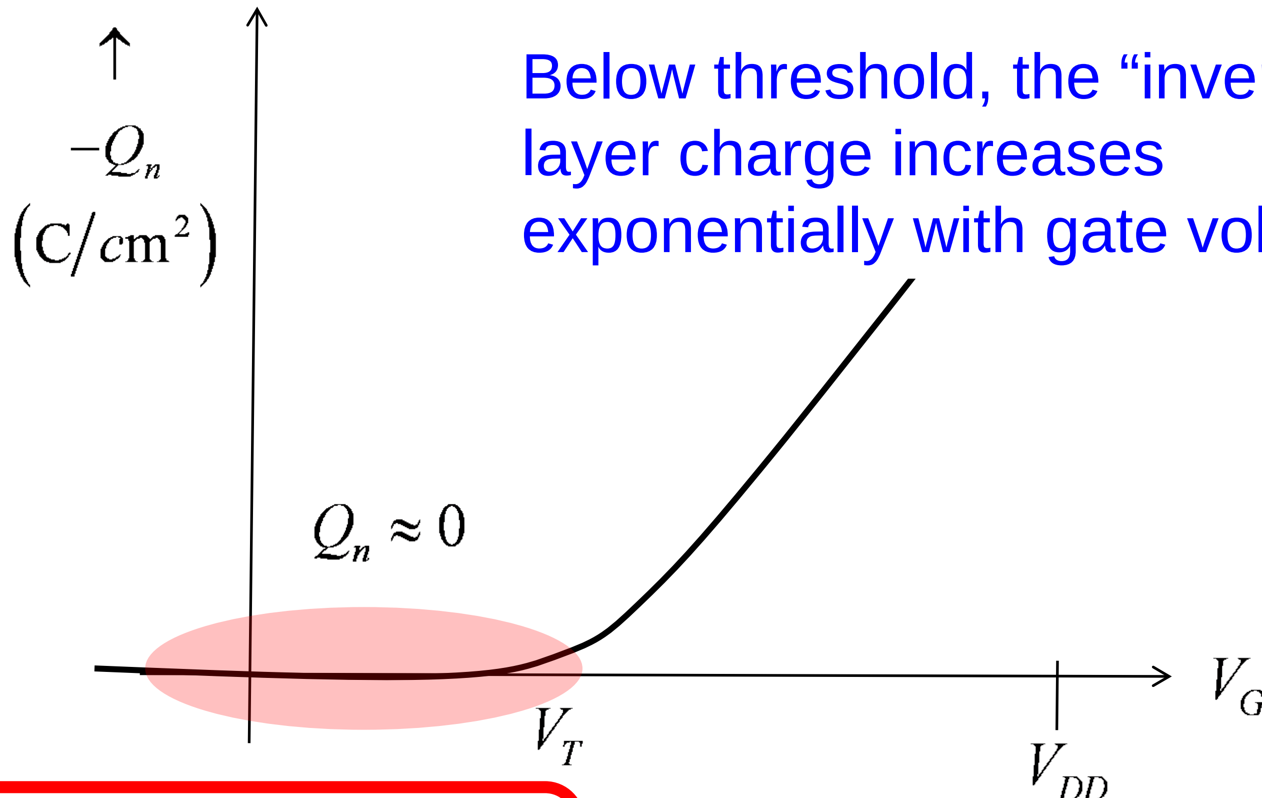
$$Q_n(V_G) \approx -C_Q \left(\frac{k_B T}{q}\right) e^{q(V_G - V_T)/k_B T}$$

$$V_T \equiv \frac{k_B T}{q} \ln\left(\frac{N_C^{2D}}{n_{SO}}\right)$$

"quantum capacitance" $C_Q \equiv q^2 D_{2D}(E_F)$

Subthreshold charge vs. gate voltage

Below threshold, the "inversion" layer charge increases exponentially with gate voltage.

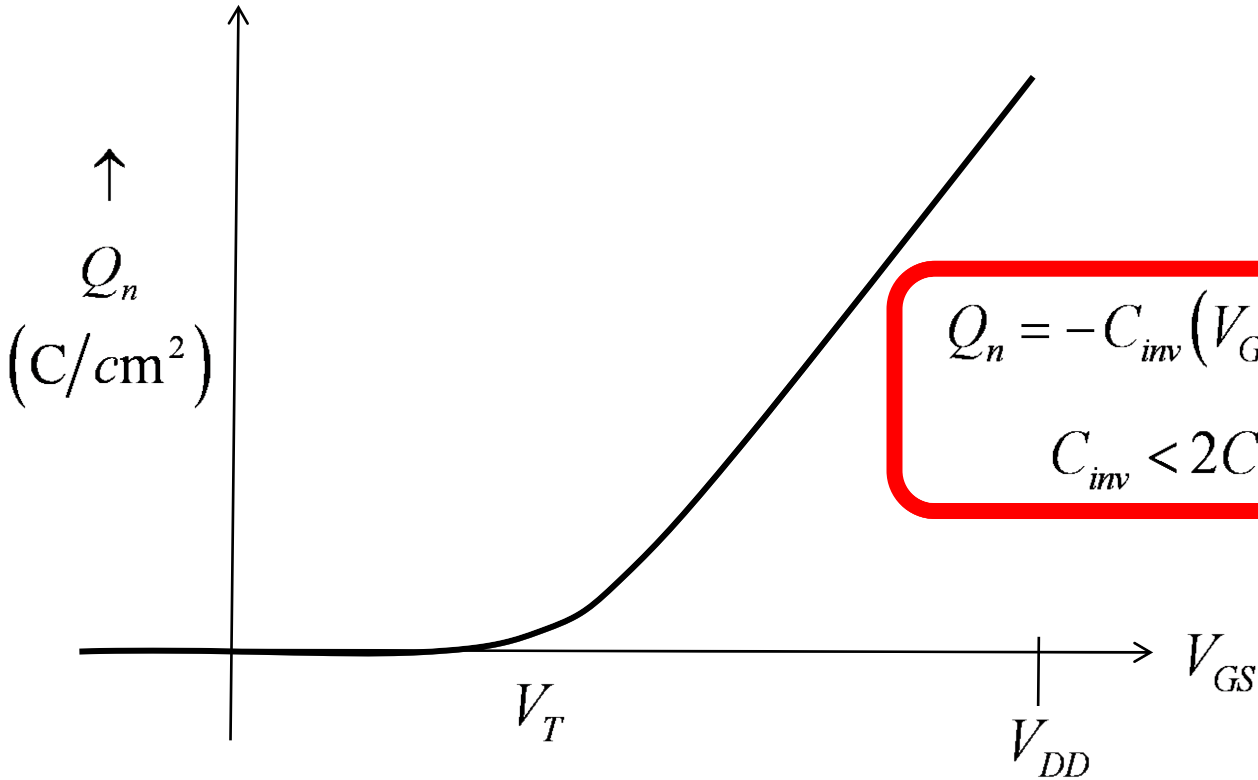


$$\boxed{Q_n\left(V_G\right) \approx -C_Q\left(\frac{k_BT}{q}\right)e^{q\left(V_G-V_T\right)/k_BT}}$$

$$Q_n\left(V_G\right) = -\left(m-1\right)C_{ox}\left(\frac{k_BT}{q}\right)e^{q\left(V_G-V_T\right)/mk_BT}$$

(bulk MOS)

Charge vs. gate voltage **above threshold**



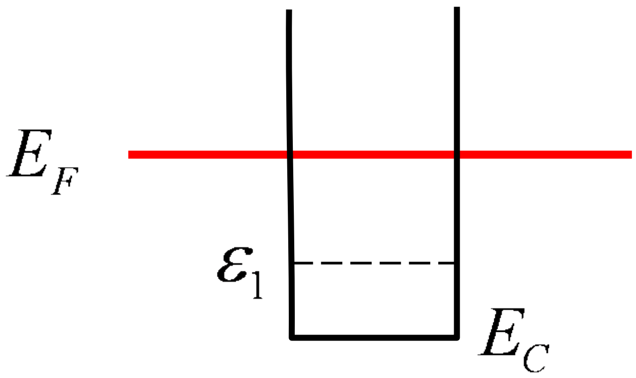
$$Q_n = -C_{inv}\left(V_G - V_T\right)$$

$$C_{inv} < 2C_{ox}$$

$$\frac{1}{C_{inv}} = \frac{1}{2C_{ox}} + \frac{1}{C_S(\mathrm{inv})} \qquad C_S = \frac{d\left(-Q_S\right)}{d\psi_S}$$

Quantum capacitance (T = 0 K)

$$C_S = \frac{d(-Q_n)}{d\psi_S} = \frac{d(qn_S)}{d\psi_S} = q^2 D_{2D} = C_Q$$



$$C_{inv} = \frac{2C_{ox}C_Q}{2C_{ox} + C_Q} < 2C_{ox}$$

$$C_Q = q^2 D_{2D}$$

$$n_S = D_{2D}\left(E_F - E_C - \varepsilon_1\right)$$

$$E_C = E_{C0} - q\psi_S$$

$$n_S = D_{2D}\left(E_F - E_{C0} + q\psi_S - \varepsilon_1\right)$$

Mobile charge vs. gate voltage

ETSOI

$$V_G << V_T: \qquad Q_n(V_G) = -C_Q\left(\frac{k_BT}{q}\right)e^{q(V_G-V_T)/k_BT}$$

$$V_G >> V_T: \qquad Q_n(V_G) = -C_{inv}(V_G - V_T) \qquad C_{inv} \approx 2C_{ox}$$

bulk

$$V_G << V_T: \qquad Q_n(V_G) = -(m-1)C_{ox}\left(\frac{k_BT}{q}\right)e^{q(V_G-V_T)/mk_BT}$$

$$V_G >> V_T: \qquad Q_n = -C_{inv}(V_G - V_T) \qquad C_{inv} \approx C_{ox}$$

Aside

$$SS = \left(\left. \frac{\partial \log_{10} I_{DS}}{\partial V_{GS}} \right|_{V_{DS}} \right)^{-1} = 2.3 m k_B T$$

m = 1 for fully depleted structures.

Summary

We have considered 1D MOS electrostatics – in the direction normal to the channel.

We now understand how the mobile charge varies with gate voltage above and below threshold.

Next Lecture: How does two-dimensional electrostatics affect MOSFETs?