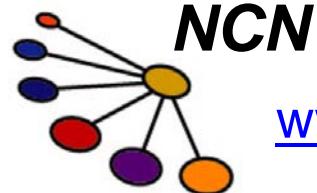


EE-612:

Lecture 3

MOS Capacitors

Mark Lundstrom
Electrical and Computer Engineering
Purdue University
West Lafayette, IN USA
Fall 2008



www.nanohub.org

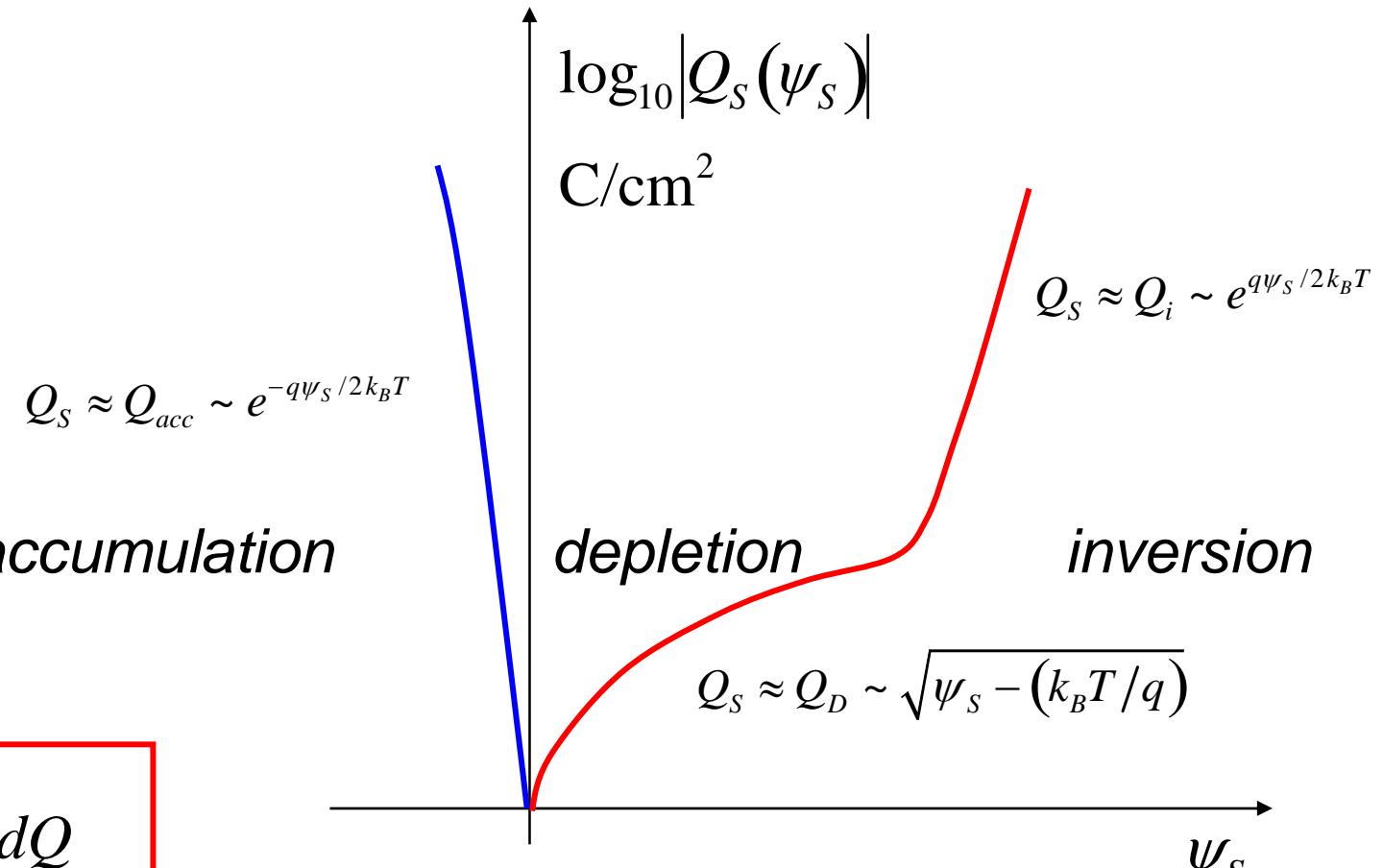
Lundstrom EE-612 F08

PURDUE
UNIVERSITY

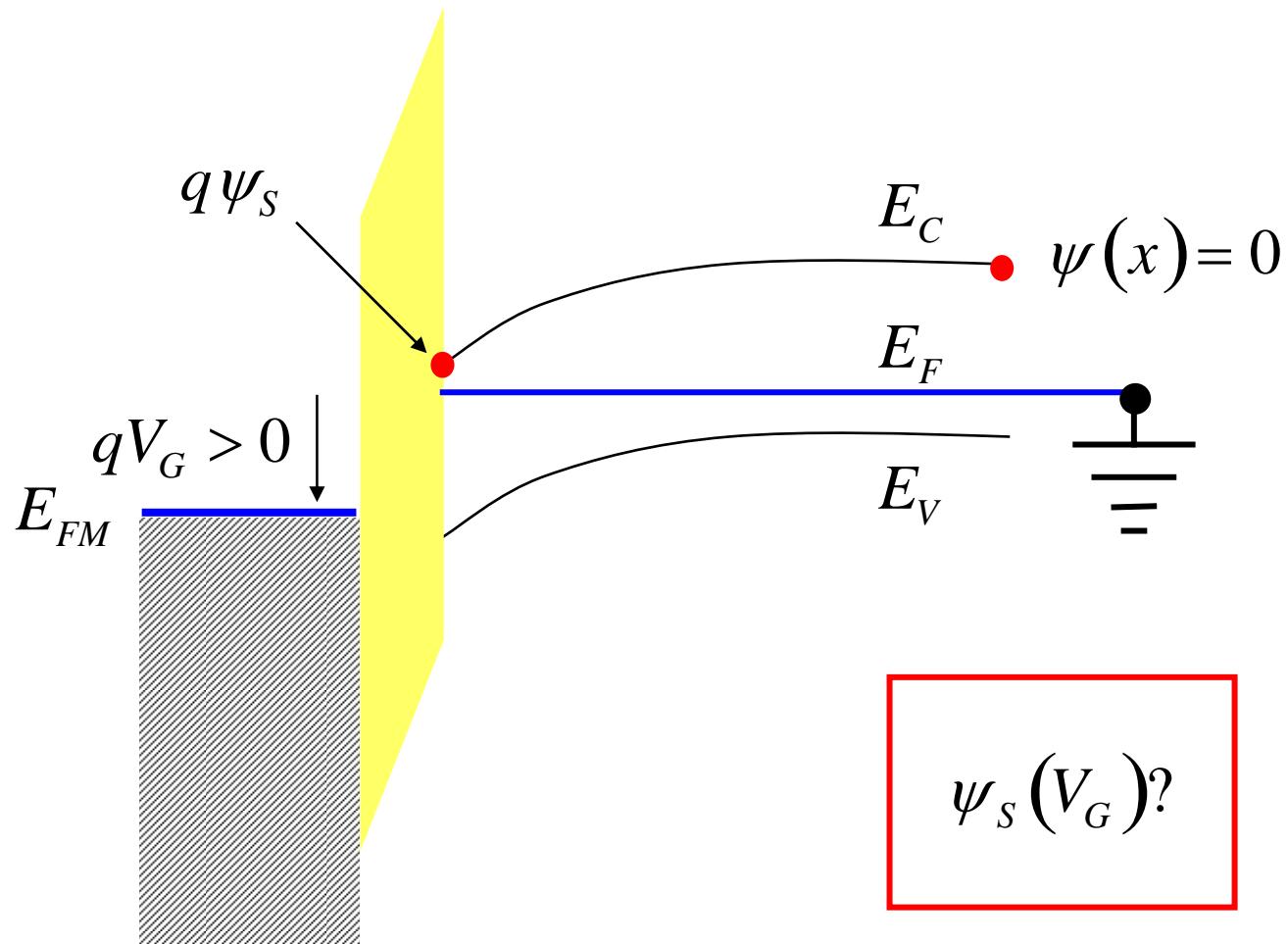
outline

- 1) Short review
- 2) Gate voltage / surface potential relation
- 3) The flatband voltage
- 4) MOS capacitance vs. voltage
- 5) Gate voltage and inversion layer charge

1) short review (bulk semiconductor)



1) short review



outline

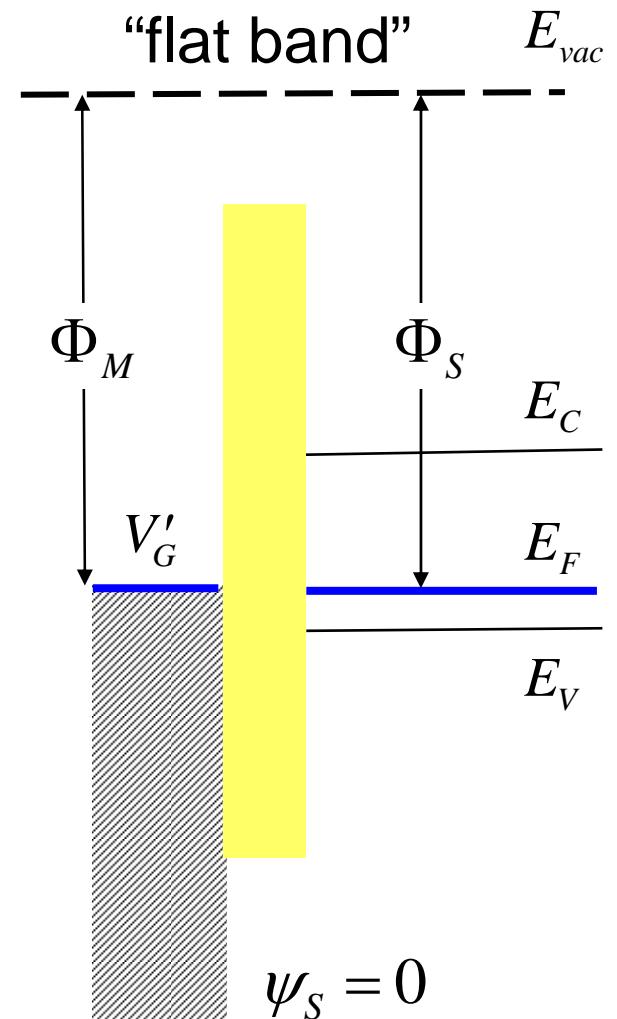
- 1) Short review
- 2) Gate voltage / surface potential relation**
- 3) The flatband voltage
- 4) MOS capacitance vs. voltage
- 5) Gate voltage and inversion layer charge

2) flat-band conditions

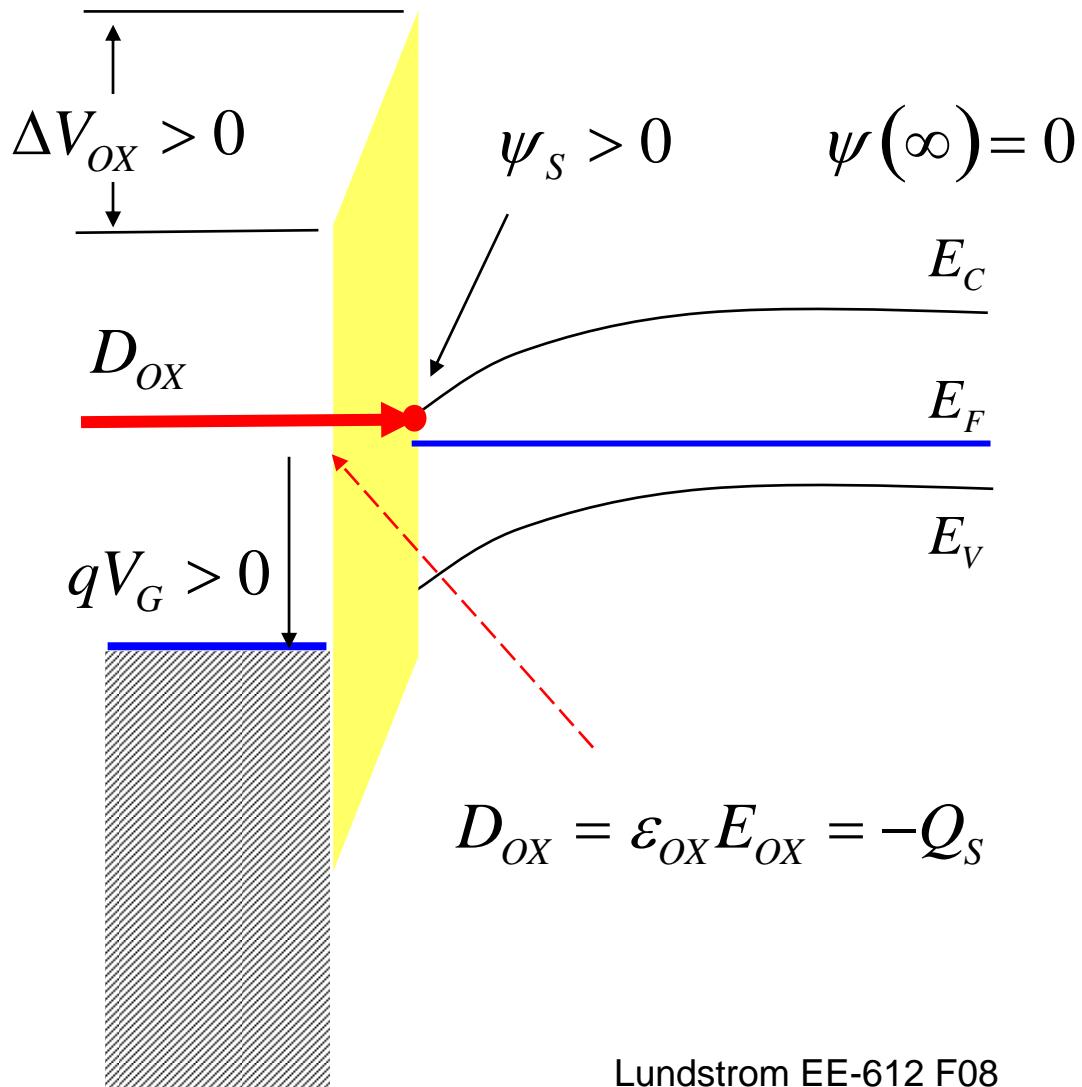
- when the gate electrode Fermi level lines up with the semiconductor Fermi level, the bands are flat in the semiconductor
- this occurs at $V'_G = 0$ when the gate electrode workfunction equals the semiconductor workfunction

$$\Phi_M = \Phi_S \text{ eV}$$

$$\phi_M = \phi_S \text{ V}$$



gate voltage and ψ_S



$$V'_G = \psi_S + \Delta V_{OX}$$

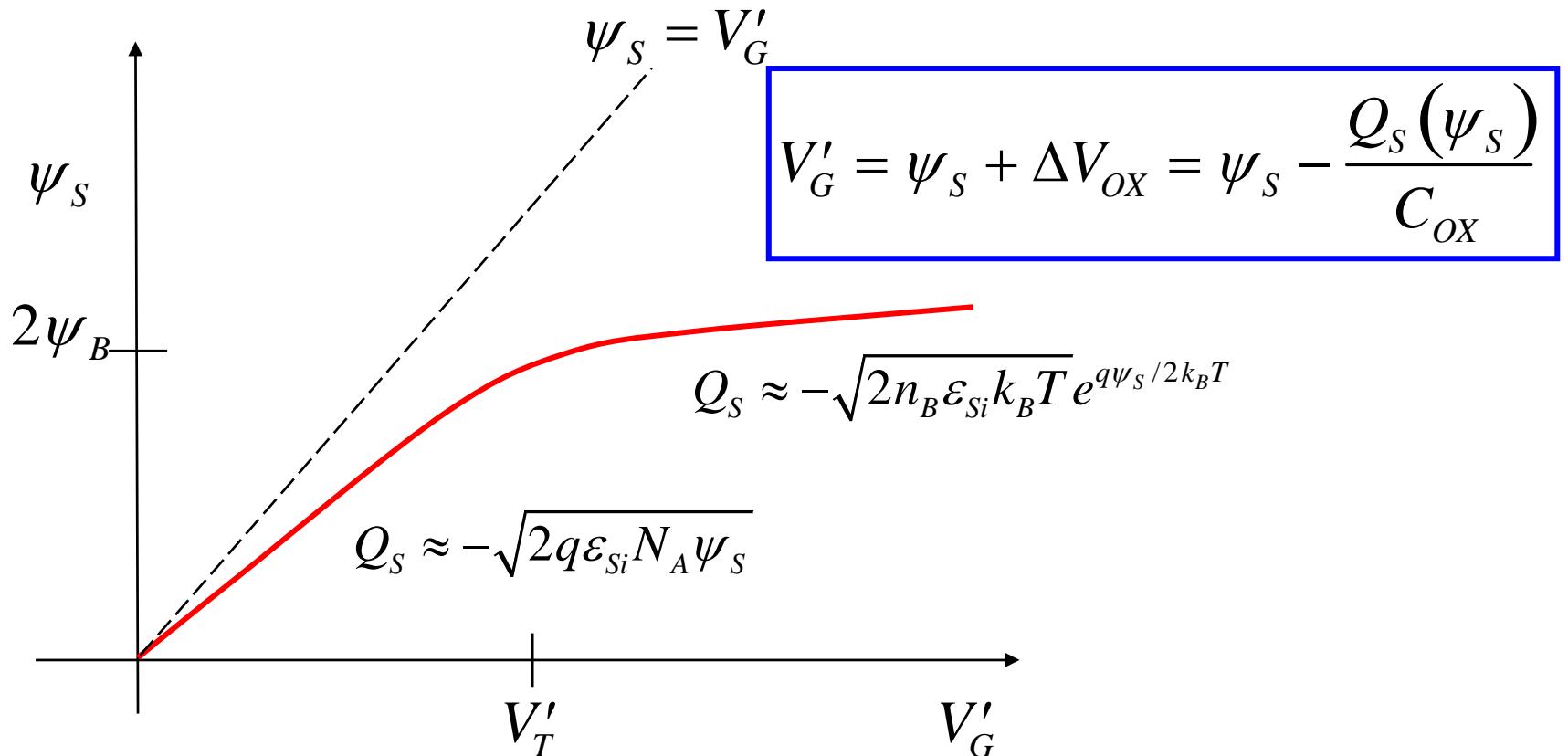
$$V'_G = \psi_S + E_{OX} t_{OX}$$

$$V'_G = \psi_S - \frac{Q_S}{\epsilon_{OX}} t_{OX}$$

$$V'_G = \psi_S - \frac{Q_S}{C_{OX}}$$

$$C_{OX} = \frac{\epsilon_{OX}}{t_{OX}} \text{ F/cm}^2$$

gate voltage and ψ_S



threshold voltage, V_T

$$\psi_S = 2\psi_B \quad \text{onset of inversion}$$

$$V'_G = V'_T = 2\psi_B - \frac{Q_S(2\psi_B)}{C_{OX}}$$

$$Q_S(2\psi_B) \approx Q_D(2\psi_B) = -\sqrt{2q\epsilon_{Si}N_A(2\psi_B)}$$

$$V'_T = 2\psi_B + \sqrt{2q\epsilon_{Si}N_A(2\psi_B)} / C_{OX}$$

outline

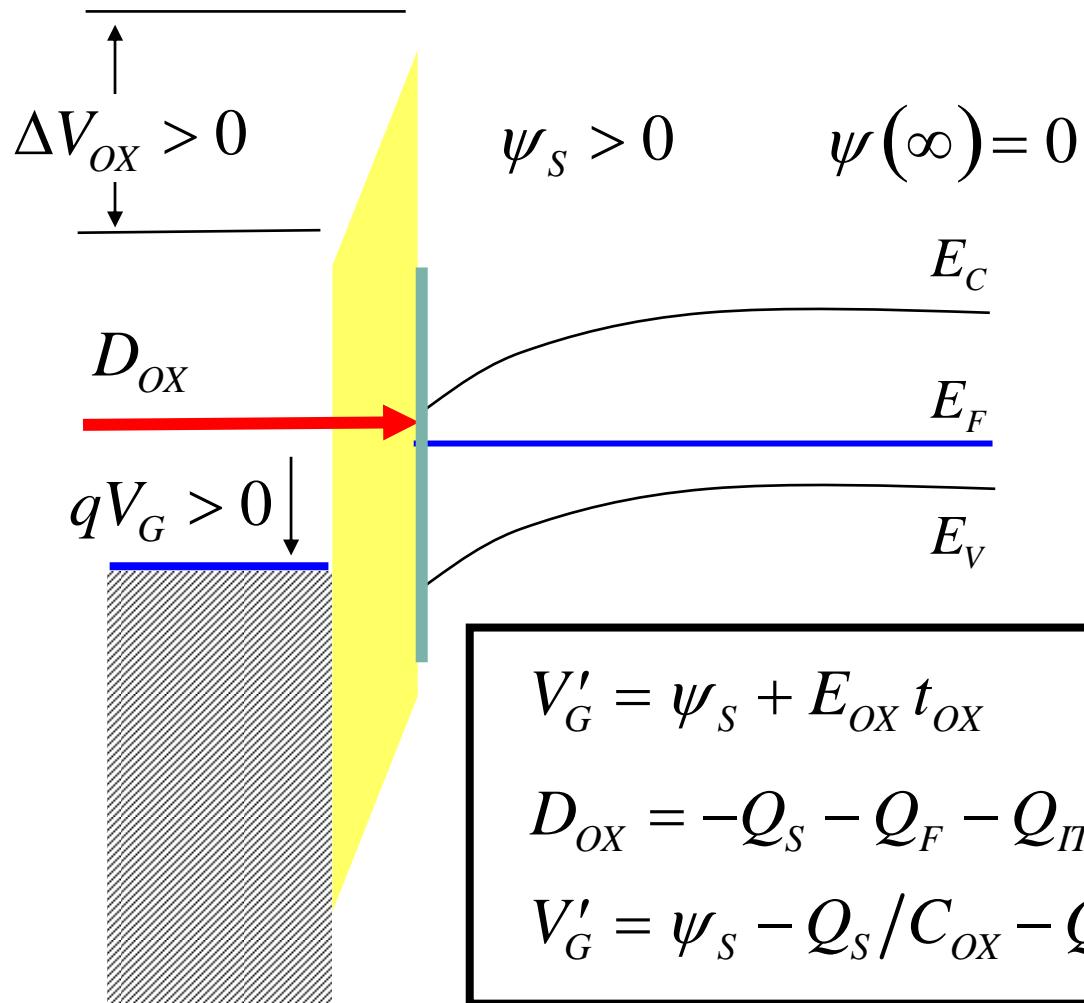
- 1) Short review
- 2) Gate voltage / surface potential relation
- 3) The flatband voltage**
- 4) MOS capacitance vs. voltage
- 5) Gate voltage and inversion layer charge

flatband voltage

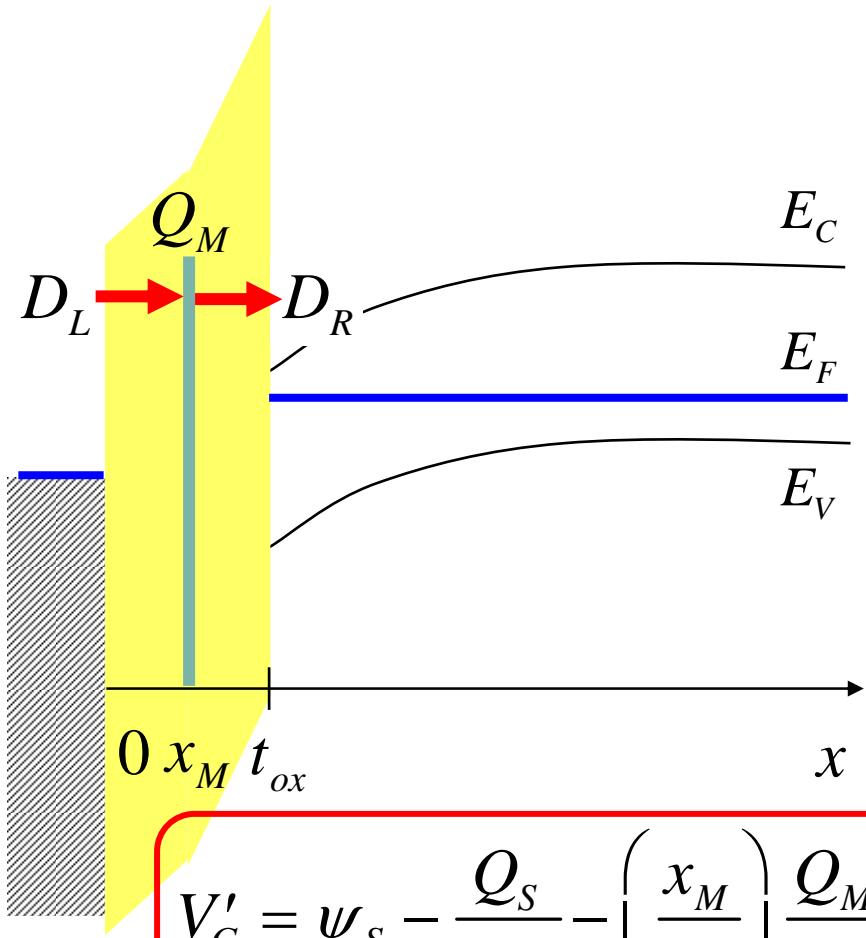
In an ideal MOS-C, $\psi_S = 0$ when $V_G' = V_{FB} = 0$.

In a real MOS-C, ***charges at the oxide-silicon interface***, in the oxide, and gate-semiconductor ***workfunction differences*** all shift the flatband voltage.

interface charge



charge in the oxide



$$V'_G = \psi_s - \frac{Q_s}{C_{OX}} - \left(\frac{x_M}{t_{OX}} \right) \frac{Q_M}{C_{OX}}$$

$$-D_L + D_R = Q_M$$

$$D_R = -Q_S$$

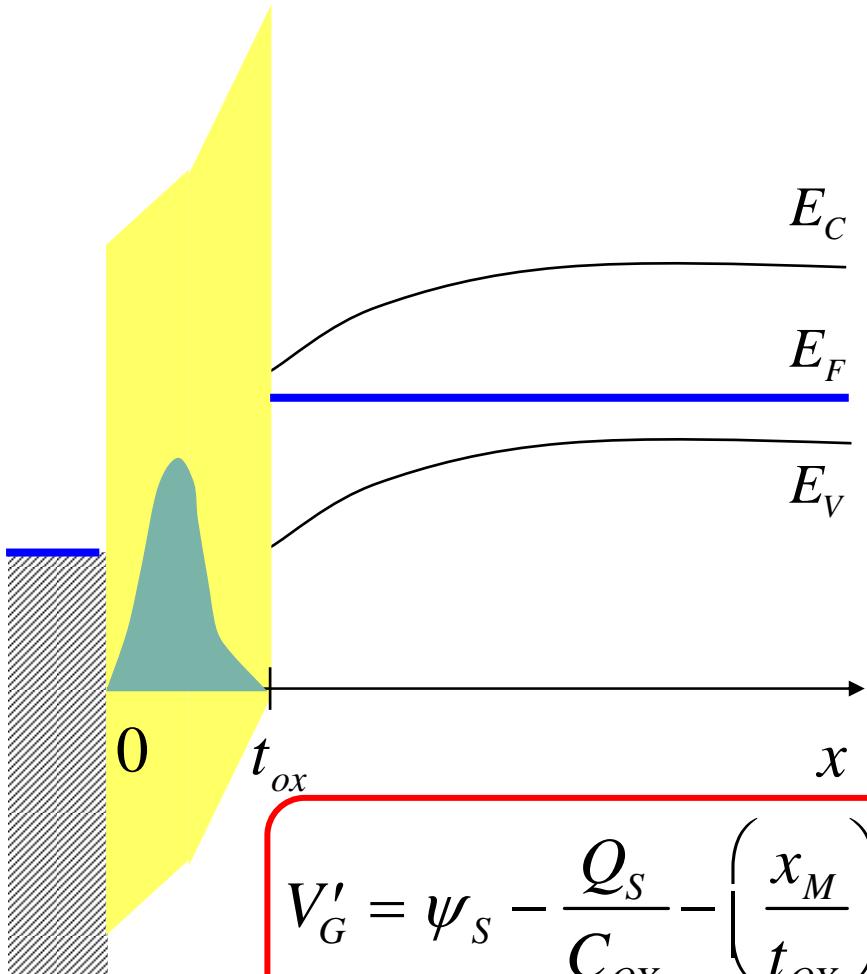
$$E_R = -Q_S / \epsilon_{OX}$$

$$E_L = E_R - Q_M / \epsilon_{OX}$$

$$\Delta V_{OX} = x_M E_L + (t_{OX} - x_M) E_R$$

$$\Delta V_{OX} = -\frac{Q_S}{C_{OX}} - \left(\frac{x_M}{t_{OX}} \right) \frac{Q_M}{C_{OX}}$$

distributed charge in the oxide



$$Q_M = \int_0^{t_{ox}} Q(x) dx$$

$$x_M = \frac{\int_0^{t_{ox}} x Q(x) dx}{\int_0^{t_{ox}} Q(x) dx}$$

additional information

For more information on the oxide-silicon interface and the origin of the various charges, see:

- 1) R.F. Pierret, *Semiconductor Device Fundamentals*, pp. 650-671
Addison-Wesley, 1996

- 2) J.A. Del Alamo, EE 6720J/ 3.43J Integrated Microelectronic Devices, Fall 2002
Lecture 22: “The Si Surface and MOS Structure”

Available from MIT OpenCourseWare:

<http://ocw.mit.edu>

‘Electrical Engineering and Computer Science’
‘Graduate’

gate oxides 2008

- Typically SiON with $k \sim 4.6$ for 15% N_2 (not SiO_2 with $k = 3.9$).
- Use of thicker oxides with higher k gives less gate leakage.
- SiON is more resistant to boron penetration.
- But, SiON degrades mobility and reliability (NBTI). Engineering the N_2 profile may help.
- Typically grown in dry O_2 , followed by plasma nitridation and rapid thermal anneal. Results in 10-15% N_2 .
- $N_{IT} \sim 5 \times 10^{10} \text{ cm}^{-2}$
- Oxide scaling has stopped at $\sim 1.1 \text{ nm}$ due to gate leakage. Introduction of high- k beginning at 45-32 nm node.

pause and re-cap

$$V'_G = \psi_s + \Delta V_{ox} = \psi_s - \frac{Q_s}{C_{ox}}$$

fast charge

$$V'_G = \psi_s - \frac{Q_s}{C_{ox}} - Q_F/C_{ox} - Q_{IT}(\psi_s)/C_{ox} - \left(\frac{x_M}{t_{ox}} \right) \frac{Q_M}{C_{ox}}$$

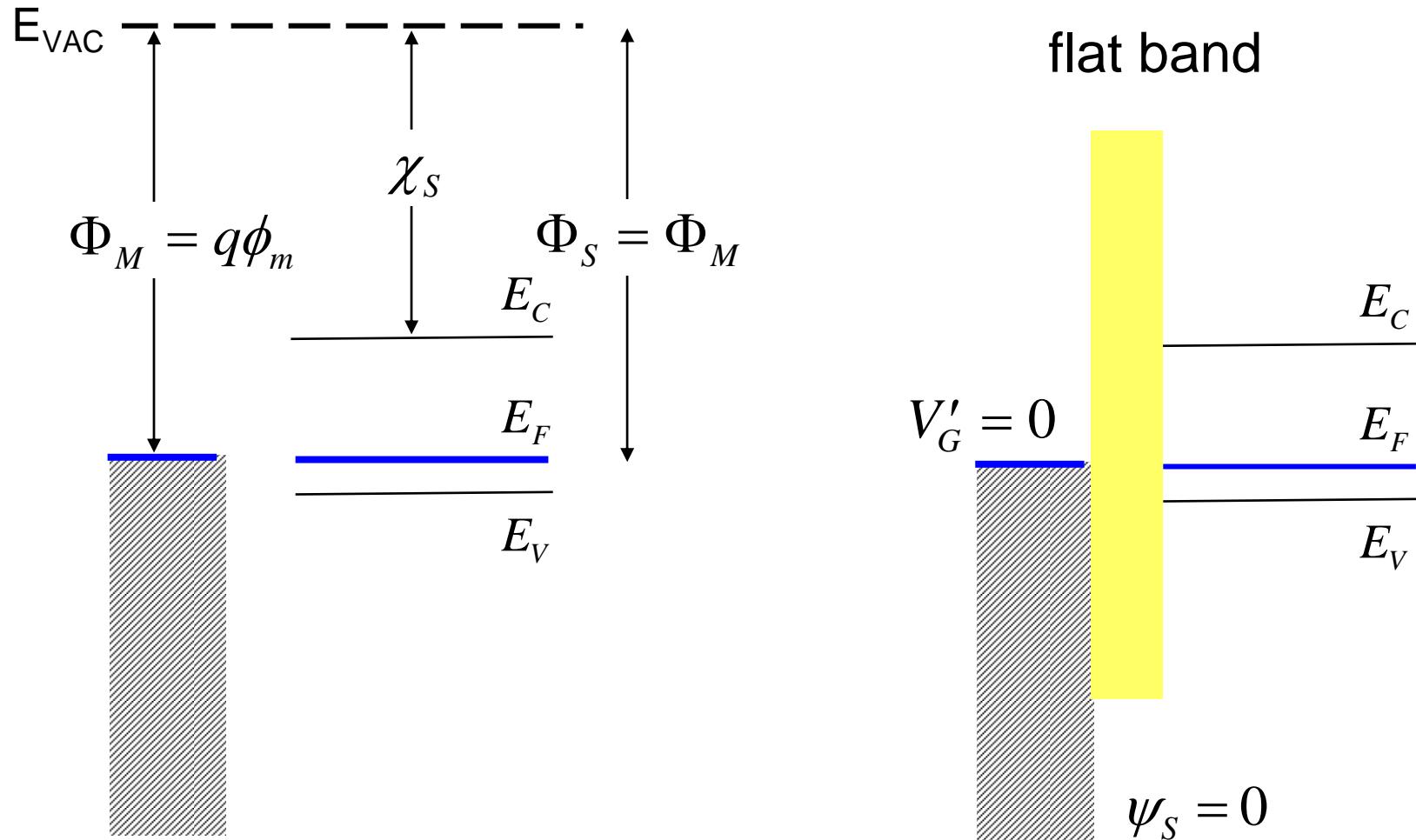
fixed charge

charge in oxide

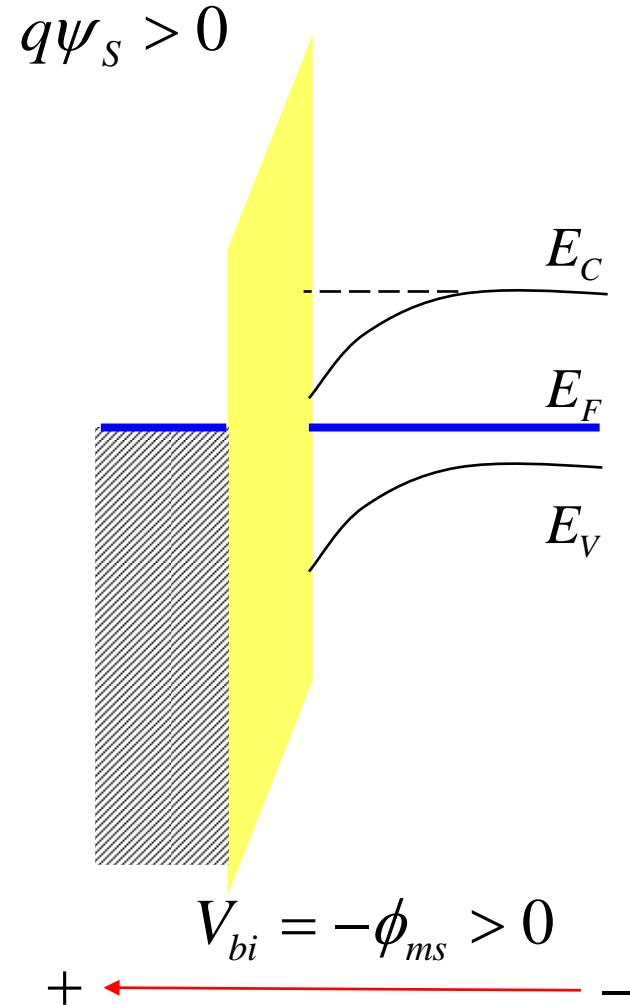
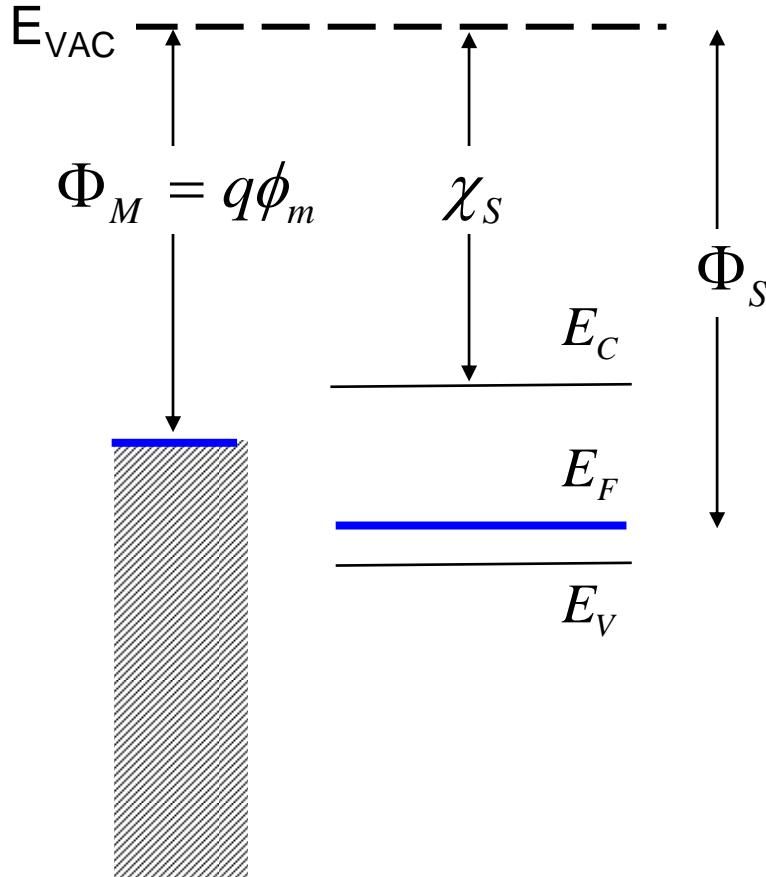
Under flatband conditions: $\psi_s = Q_s = 0$

$$V'_{FB} = -Q_F/C_{ox} - Q_{IT}(\psi_s = 0)/C_{ox} - \left(\frac{x_M}{t_{ox}} \right) \frac{Q_M}{C_{ox}}$$

gate-semiconductor workfunction differences

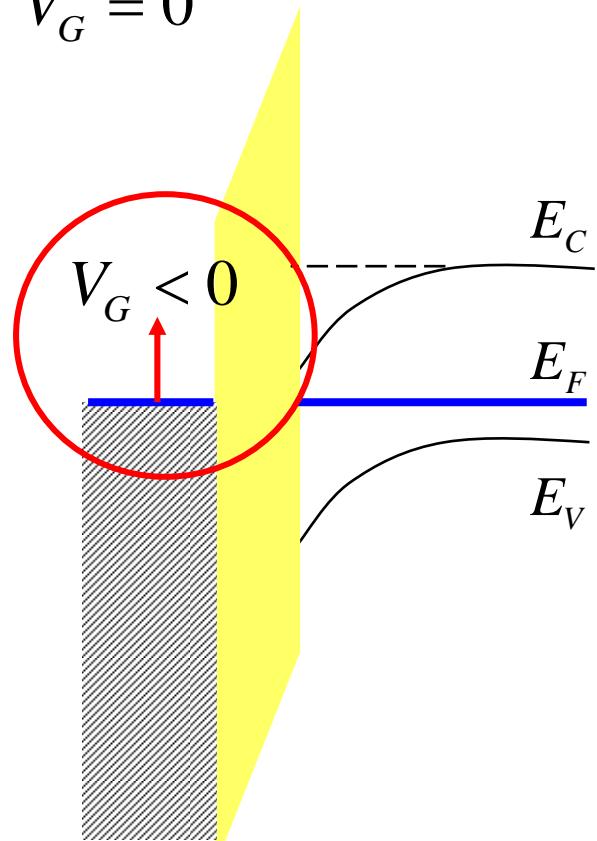


$$\Phi_M < \Phi_S$$



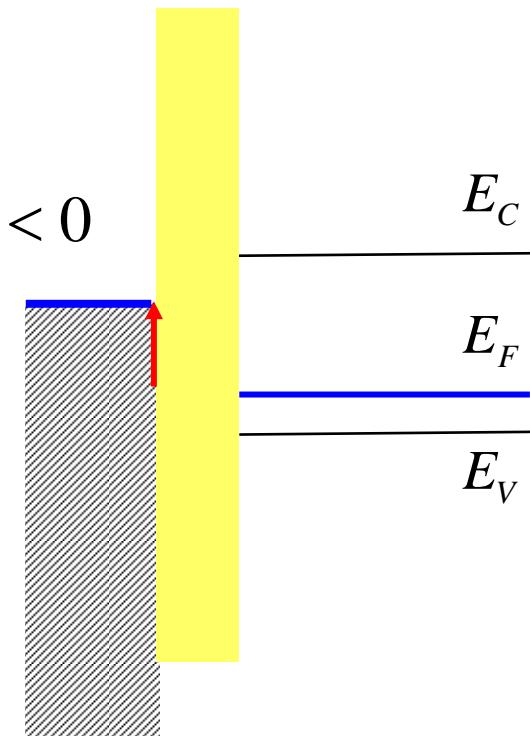
flatband voltage

$$V_G = 0$$



$$V_{FB} = \phi_{ms} = -V_{bi} < 0$$

$$V_G = V_{FB} < 0$$



flatband voltage

recall:

$$V'_G = \psi_s - \frac{Q_s}{C_{ox}}$$

$$V'_G = V_G - V_{FB}$$

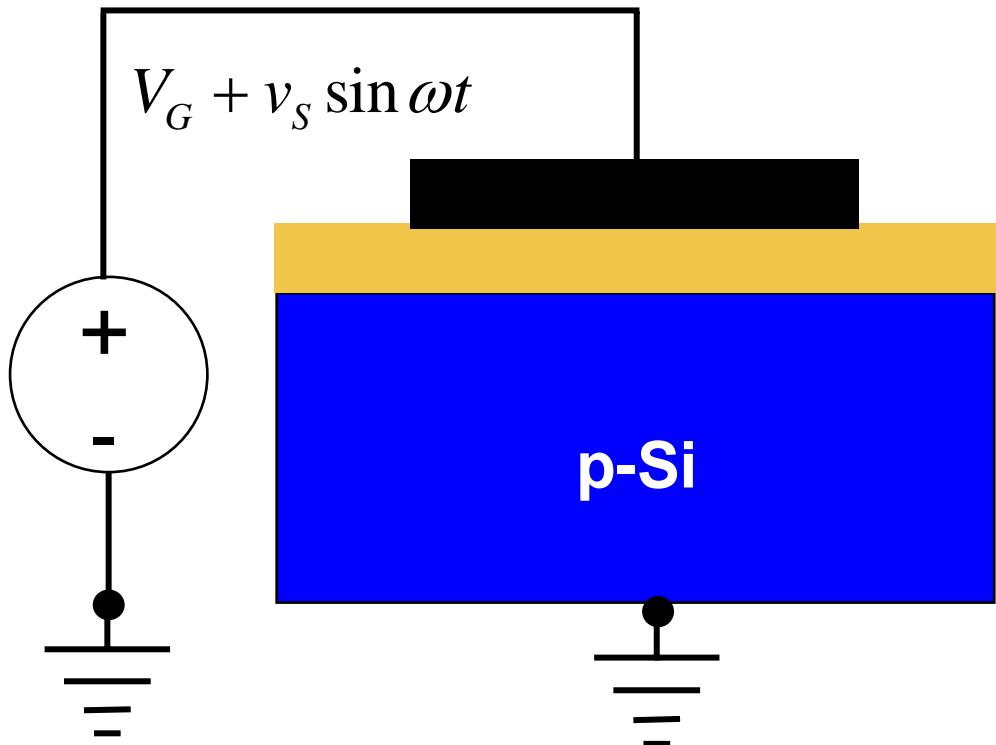
$$V_G = V_{FB} + \psi_s - \frac{Q_s}{C_{ox}}$$

$$V_{FB} = \phi_{ms} - \frac{Q_F}{C_{ox}} - \frac{Q_{IT}(\psi_s)}{C_{ox}} - \left(\frac{x_M}{t_{ox}} \right) \frac{Q_M}{C_{ox}}$$

outline

- 1) Short review
- 2) Gate voltage / surface potential relation
- 3) The flatband voltage
- 4) MOS capacitance vs. voltage**
- 5) Gate voltage and inversion layer charge

capacitance



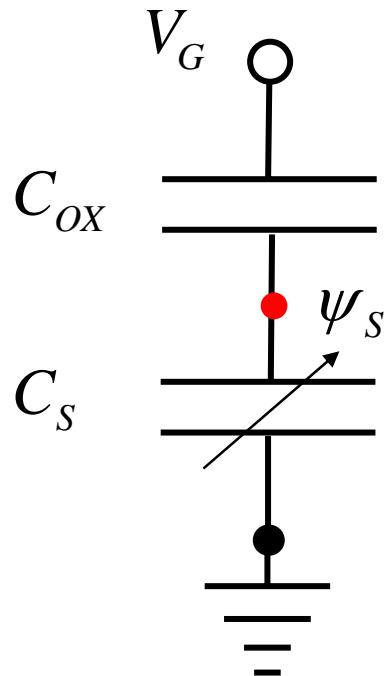
$$C_G \equiv \frac{dQ_G}{dV_G} = \frac{d(-Q_S)}{dV_G}$$

$$V_G = V_{FB} + \psi_S - \frac{Q_S}{C_{OX}}$$

$$\frac{dV_G}{d(-Q_S)} = \frac{d\psi_S}{d(-Q_S)} + \frac{1}{C_{OX}}$$

$$\frac{1}{C_G} = \frac{1}{C_S} + \frac{1}{C_{OX}}$$

capacitance



$$\frac{1}{C_G} = \frac{1}{C_S} + \frac{1}{C_{OX}}$$

$$C_S \equiv \frac{d(-Q_S)}{d\psi_S}$$

$$Q_S(\psi_S)$$

*already
understood!*

a closer look

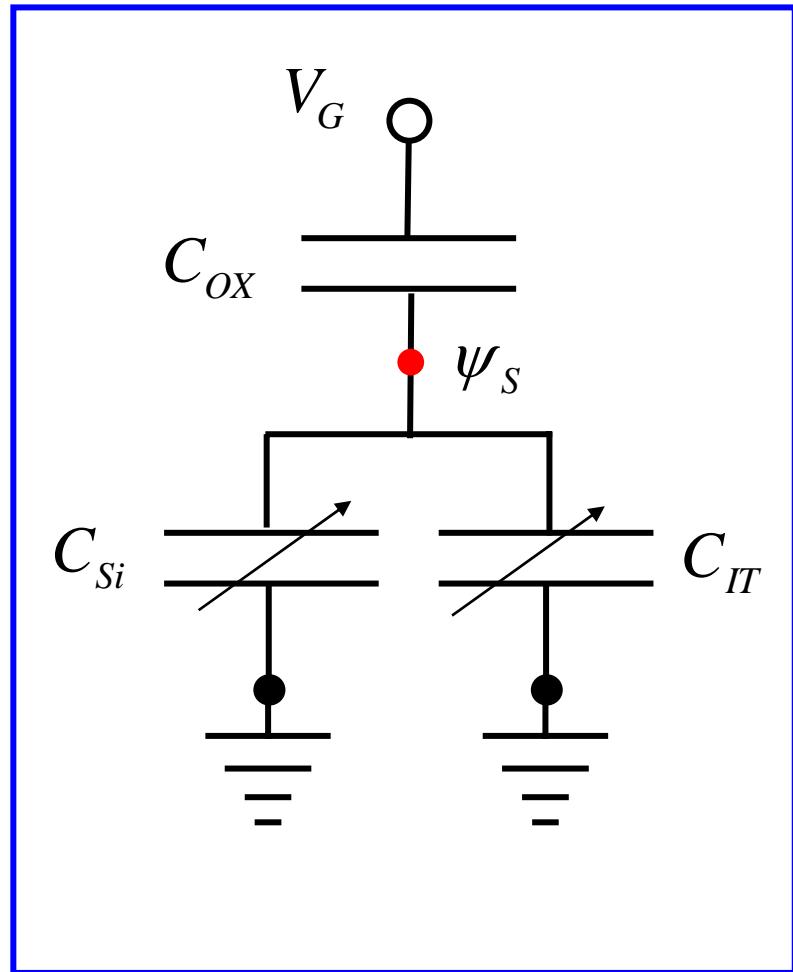
$$V_G = V_{FB} + \psi_s - \frac{Q_s}{C_{OX}}$$

$$V_{FB} = \phi_{ms} - \frac{Q_F}{C_{OX}} - \frac{Q_{IT}(\psi_s)}{C_{OX}} - \left(\frac{x_M}{t_{OX}} \right) \frac{Q_M}{C_{OX}} = \bar{V}_{FB} - \frac{Q_{IT}(\psi_s)}{C_{OX}}$$



$$\frac{1}{C_G} = \frac{1}{(C_s + C_{IT})} + \frac{1}{C_{OX}}$$

surface state capacitance

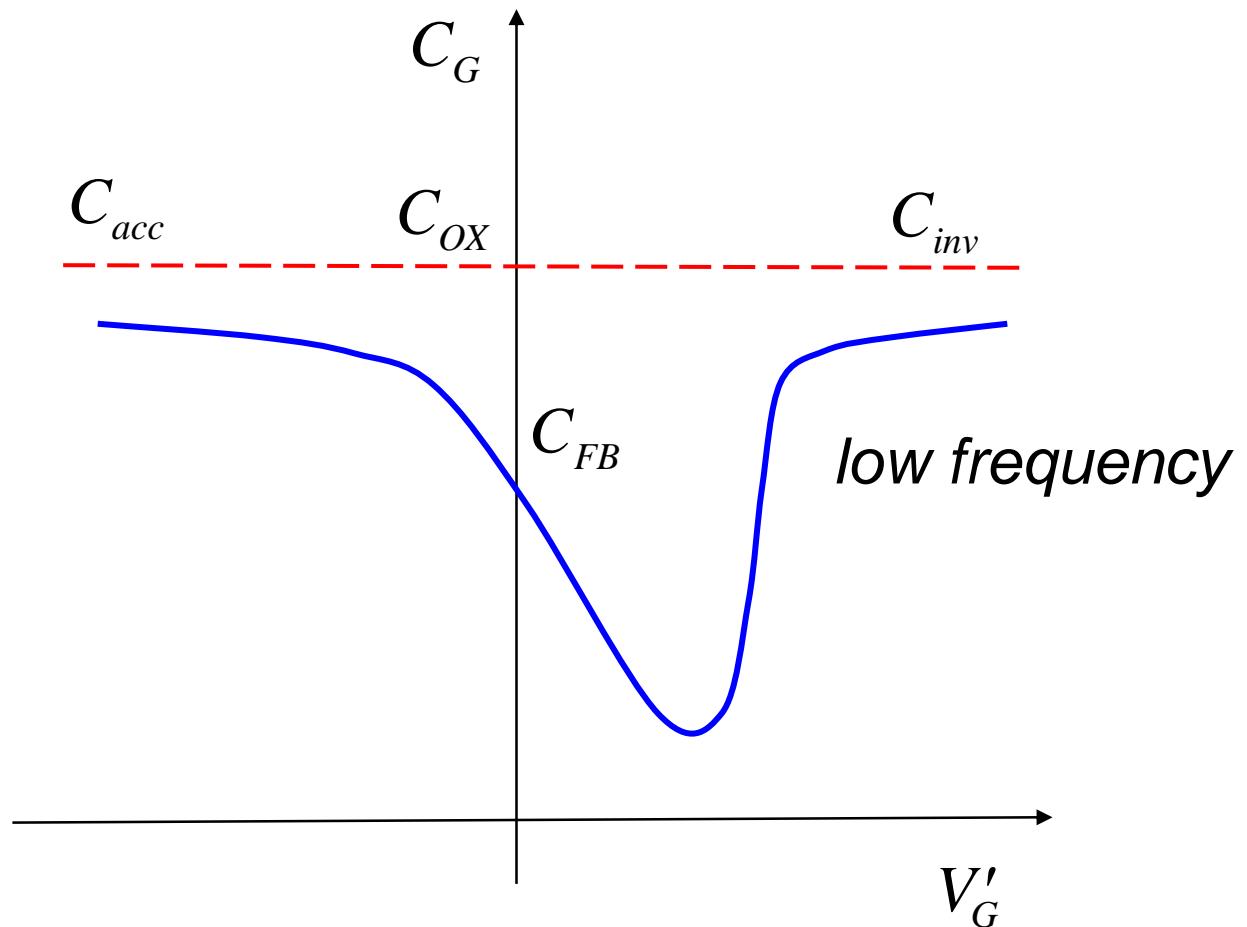


$$\frac{1}{C_G} = \frac{1}{(C_S + C_{IT})} + \frac{1}{C_{OX}}$$

$$C_S \equiv \frac{d(-Q_S)}{d\psi_S}$$

$$C_{IT} \equiv \frac{d|Q_{IT}|}{d\psi_S}$$

capacitance vs. voltage



(i) accumulation capacitance

$$C_s \equiv \frac{d(-Q_{acc})}{d\psi_s}$$

$$V_G = \psi_s - \frac{Q_{acc}}{C_{ox}}$$

$$Q_{acc} \sim e^{-q\psi_s/2k_B T}$$

$$Q_{acc} = -C_{ox}(V'_G - \psi_s)$$

$$C_s \equiv \frac{Q_{acc}}{(2k_B T / q)}$$

$$C_s = \frac{-C_{ox}(V'_G - \psi_s)}{(2k_B T / q)}$$

$$\frac{C_s}{C_{ox}} = \frac{-(V'_G - \psi_s)}{(2k_B T / q)} \gg 1$$

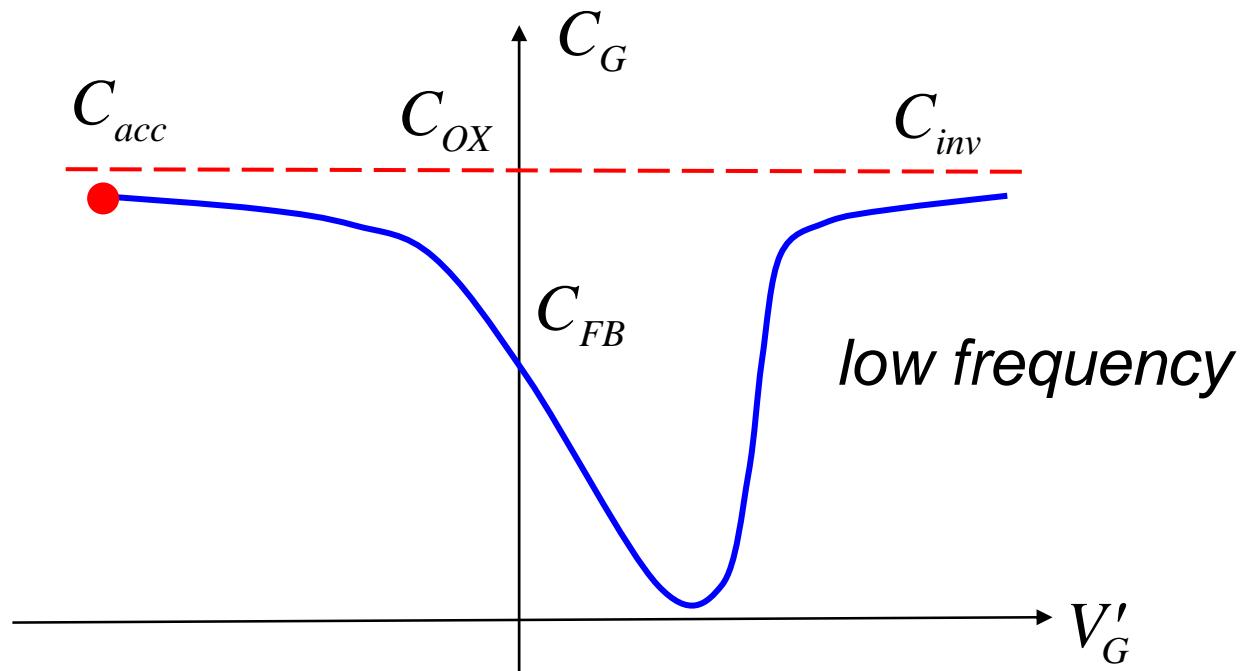
another way to look at it

$$C_{OX} = \frac{\epsilon_{OX}}{t_{OX}}$$

$$C_S \equiv \frac{\epsilon_{Si}}{t_{acc}}$$

$$\frac{C_S}{C_{OX}} = \frac{\epsilon_{Si}}{\epsilon_{OX}} \frac{t_{OX}}{t_{acc}} \gg 1$$

accumulation capacitance



$$\frac{1}{C_{acc}} = \frac{1}{C_S} + \frac{1}{C_{OX}} \quad C_{acc} \approx C_{OX}$$

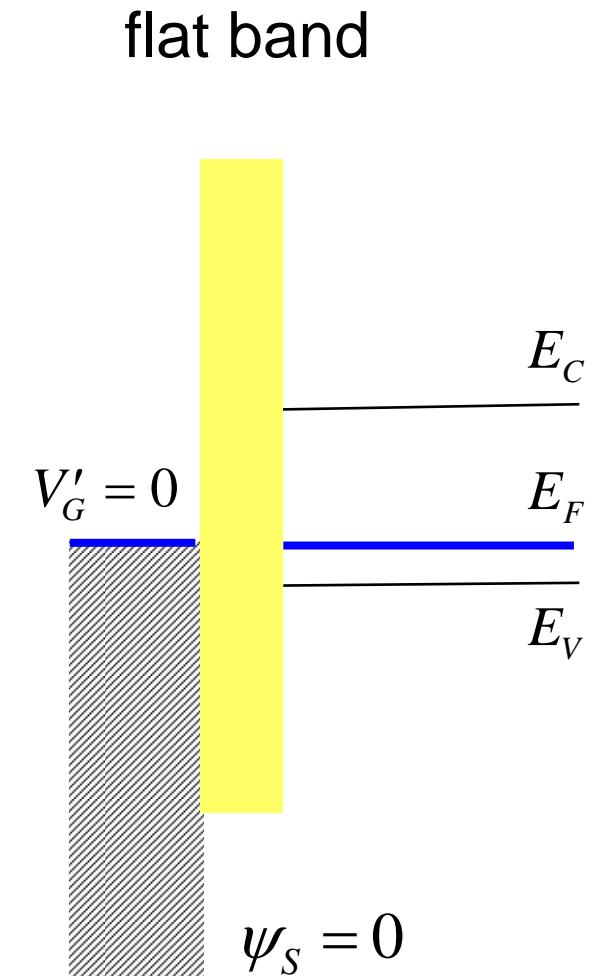
flat band capacitance

$$Q_S = 0$$

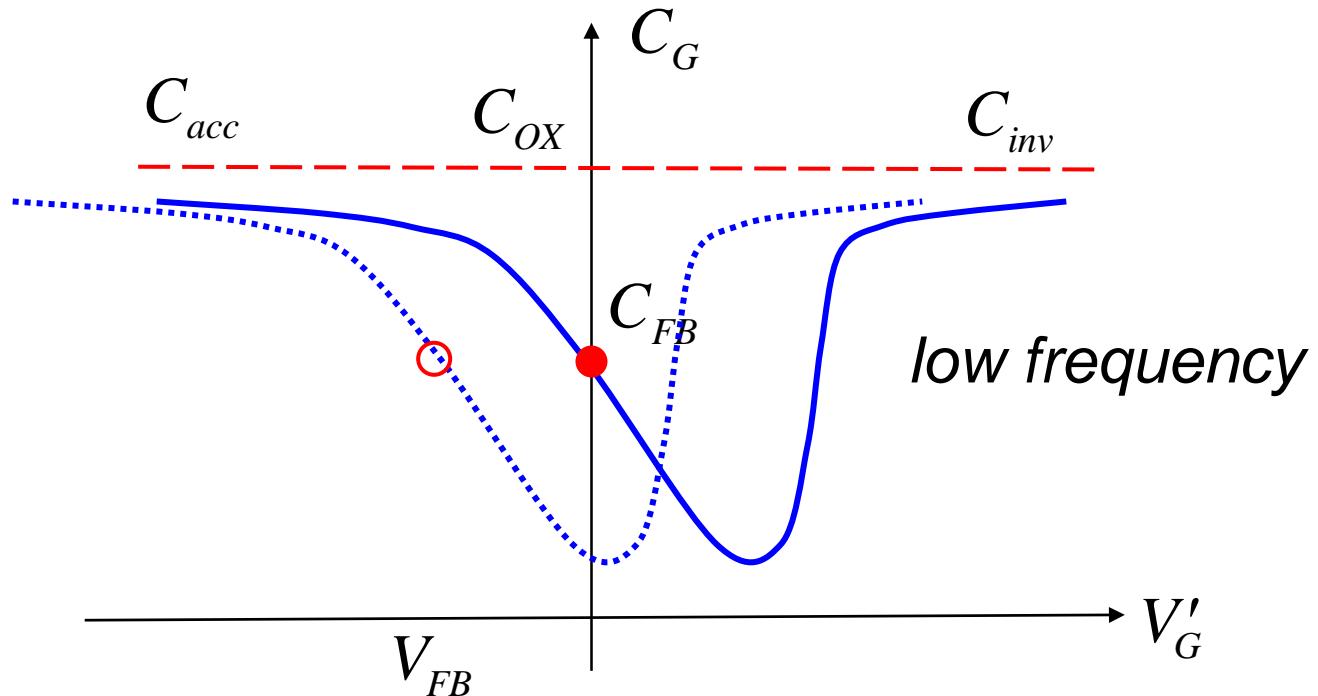
$$C_S(FB) = \frac{-dQ_S}{d\psi_S} = \frac{\epsilon_{Si}}{L_D}$$

$$L_D = \sqrt{\frac{\epsilon_{Si} k_B T}{q^2 N_A}}$$

See Lundstrom's notes on the Poisson-Boltzmann eqn. for a derivation of C_{FB} .



flat band capacitance



low frequency

$$\frac{1}{C_{FB}} = \frac{L_D}{\epsilon_{Si}} + \frac{1}{C_{OX}} \quad C_{FB} < C_{OX}$$

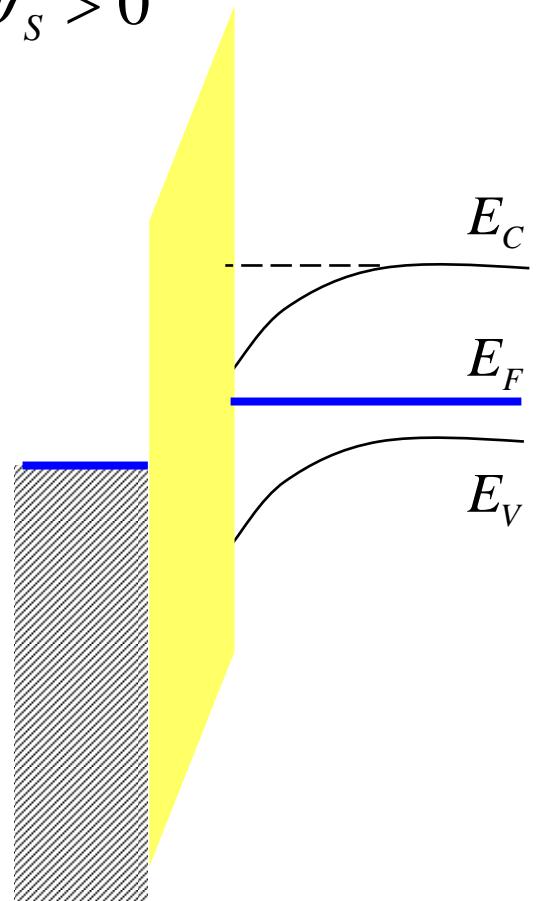
depletion capacitance

$$Q_S = Q_D = -\sqrt{2q\epsilon_{Si}N_A\psi_S}$$

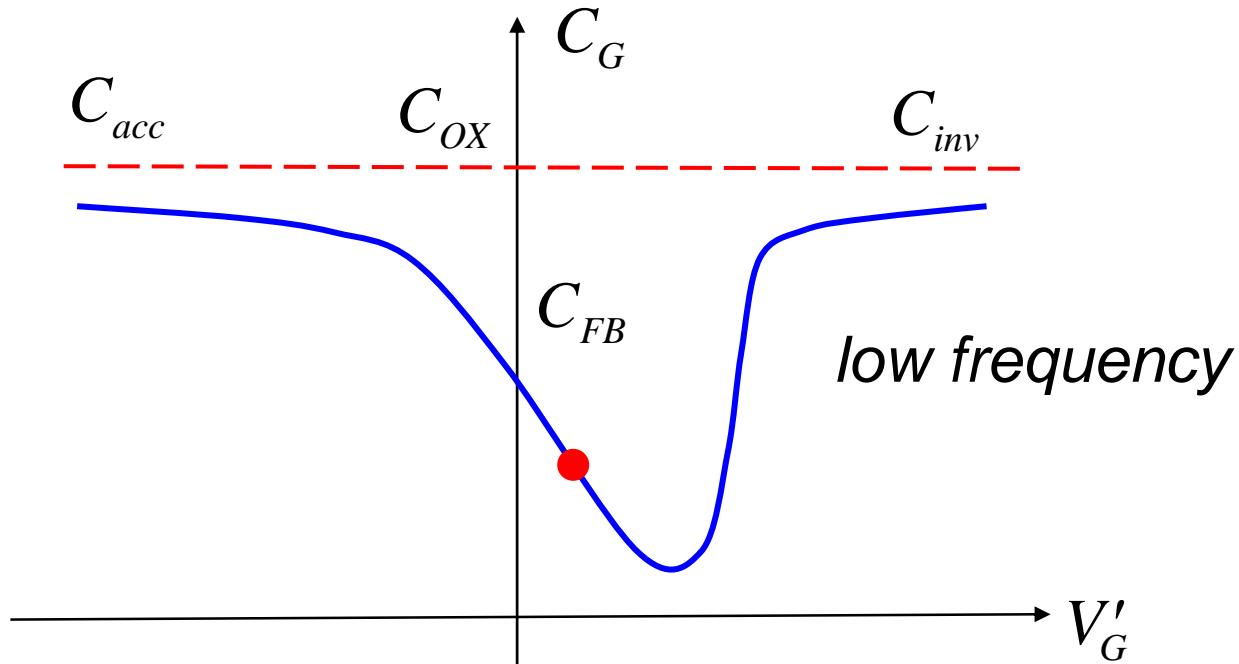
$$C_S = C_D = \frac{-dQ_S}{d\psi_S} = \frac{\epsilon_{Si}}{W_D}$$

$$W_D = \sqrt{\frac{2\epsilon_{Si}\psi_S}{qN_A}}$$

$$q\psi_S > 0$$



depletion capacitance



$$\frac{1}{C_{depl}} = \frac{W_D}{\epsilon_{Si}} + \frac{1}{C_{OX}} \quad C_{depl} < C_{OX}$$

inversion capacitance

$$C_s \equiv \frac{d(-Q_{inv})}{d\psi_s}$$

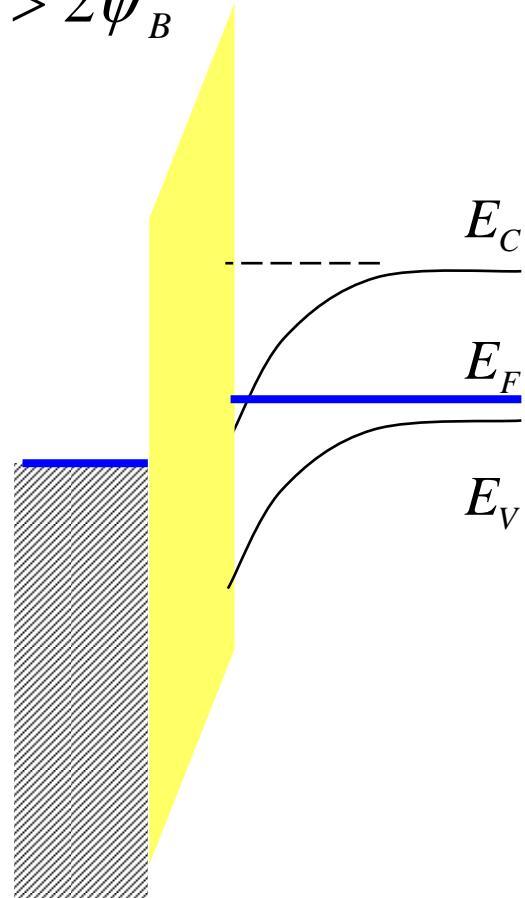
$$Q_{inv} \sim e^{+q\psi_s/2k_B T}$$

$$C_s \equiv \frac{-Q_{inv}}{(2k_B T / q)}$$

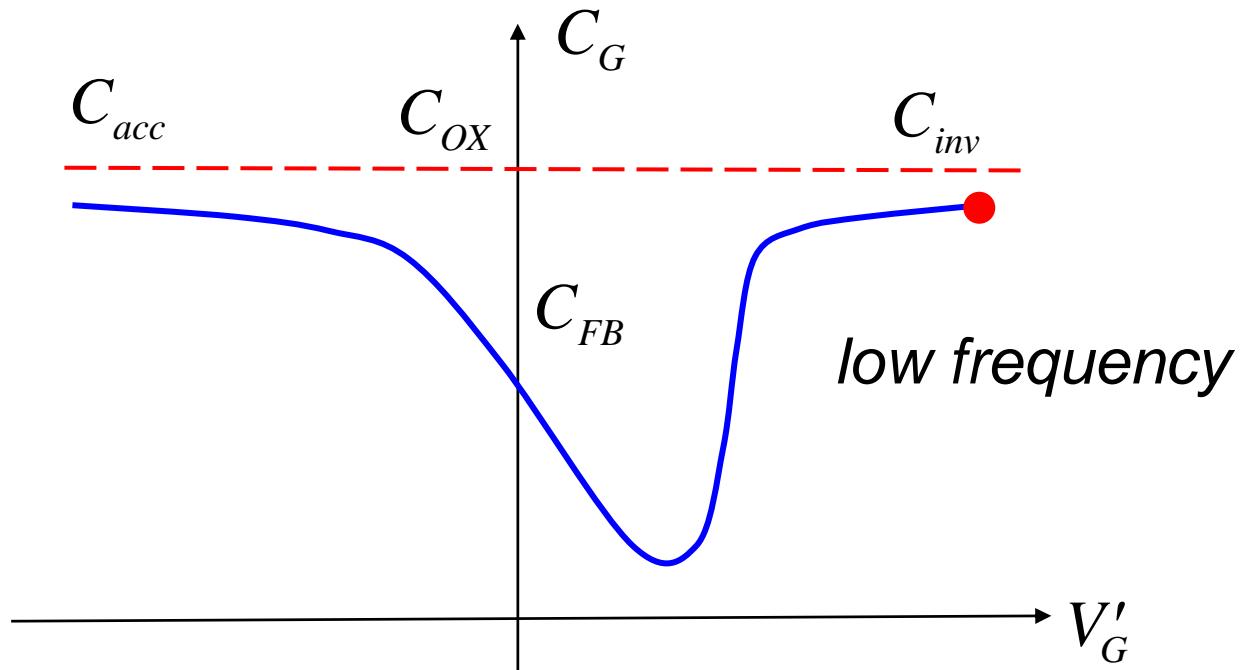
$$C_s = \frac{C_{ox}(V_G - V_T)}{(2k_B T / q)}$$

$$\frac{C_s}{C_{ox}} = \frac{(V_G - V_T)}{(2k_B T / q)} \gg 1$$

$$\psi_s > 2\psi_b$$

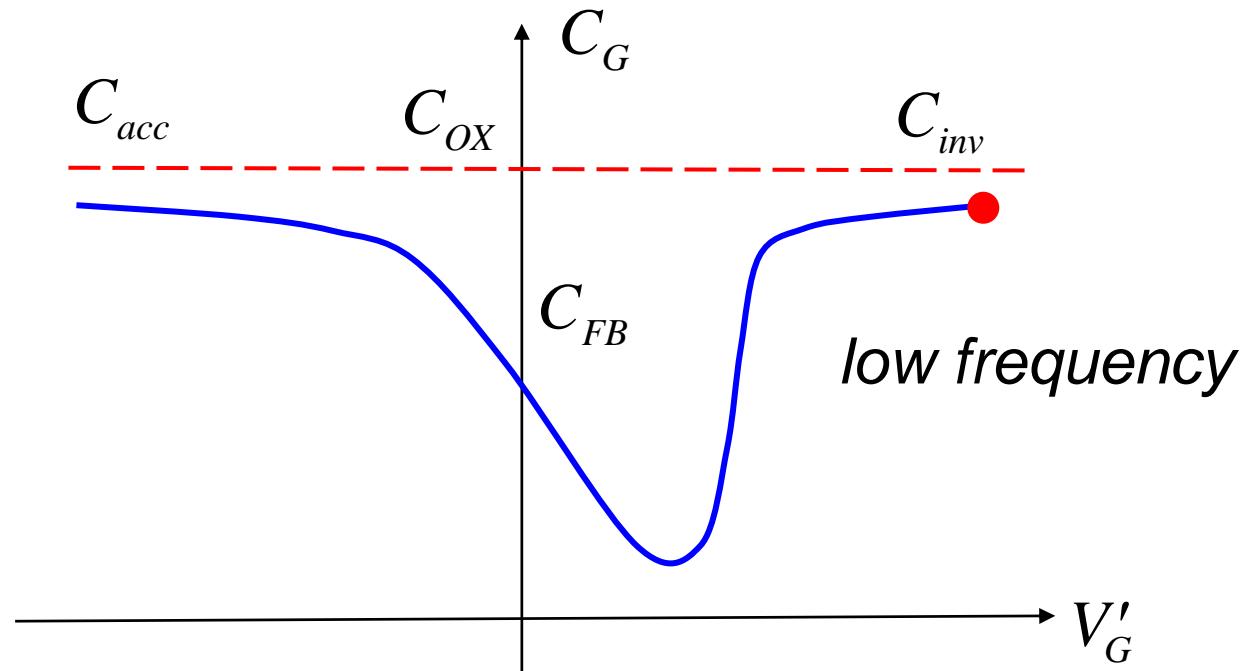


inversion capacitance



$$\frac{1}{C_{inv}} = \frac{1}{C_S} + \frac{1}{C_{OX}} \quad C_{inv} \approx C_{OX}$$

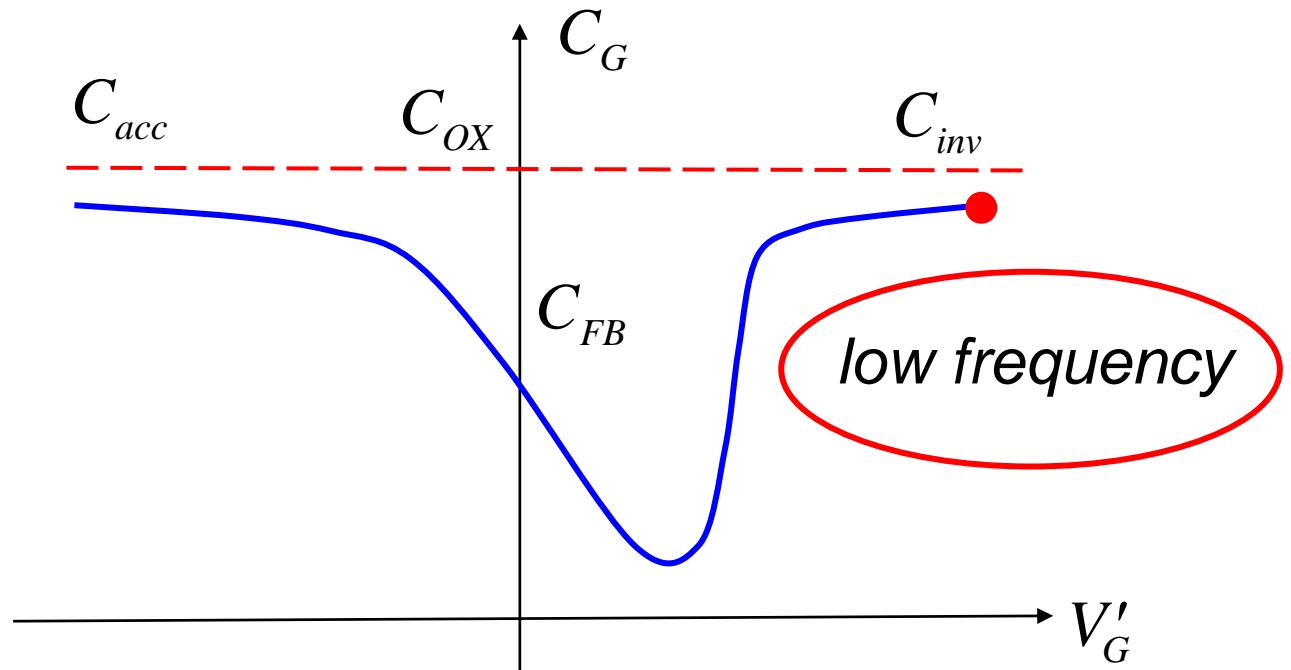
EOT(electrical) in inversion



$$C_{inv} \equiv \frac{\epsilon_{ox}}{EOT_{electrical}}$$

$$EOT_{electrical} > t_{ox}$$

role of frequency



inversion capacitance (high frequency)

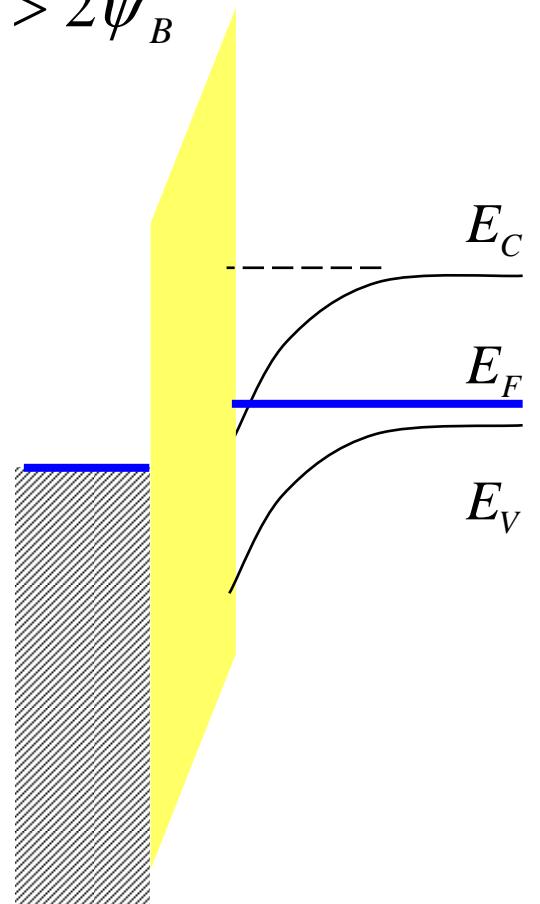
$$Q_S = Q_D(\psi_S) + Q_i(\psi_S)$$

$$\psi_S > 2\psi_B$$

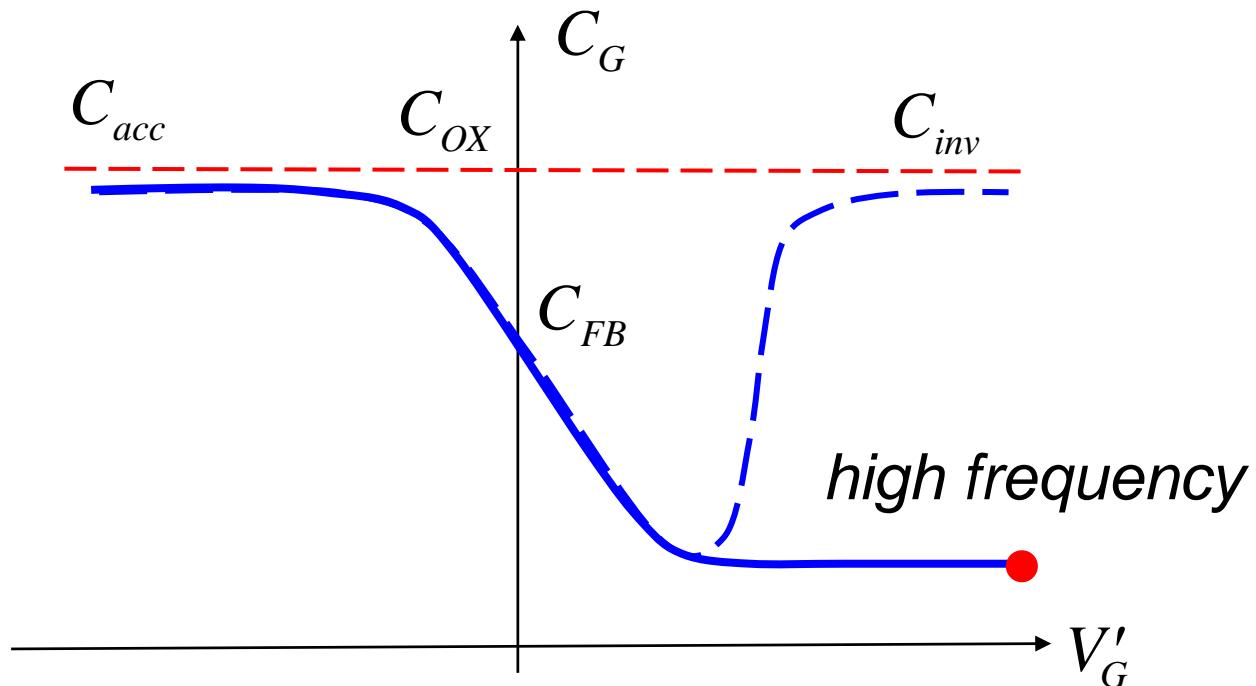
$$C_S = -\frac{dQ_S}{d\psi_S} = -\frac{dQ_D(\psi_S)}{d\psi_S} - \frac{dQ_i(\psi_S)}{d\psi_S}$$

$$C_S \approx -\left. \frac{dQ_D}{d\psi_S} \right|_{\psi_S=2\psi_B} = \frac{\epsilon_{Si}}{W_{dm}}$$

$$W_{dm}(2\psi_B) = \sqrt{\frac{2\epsilon_{Si}(2\psi_B)}{qN_A}}$$

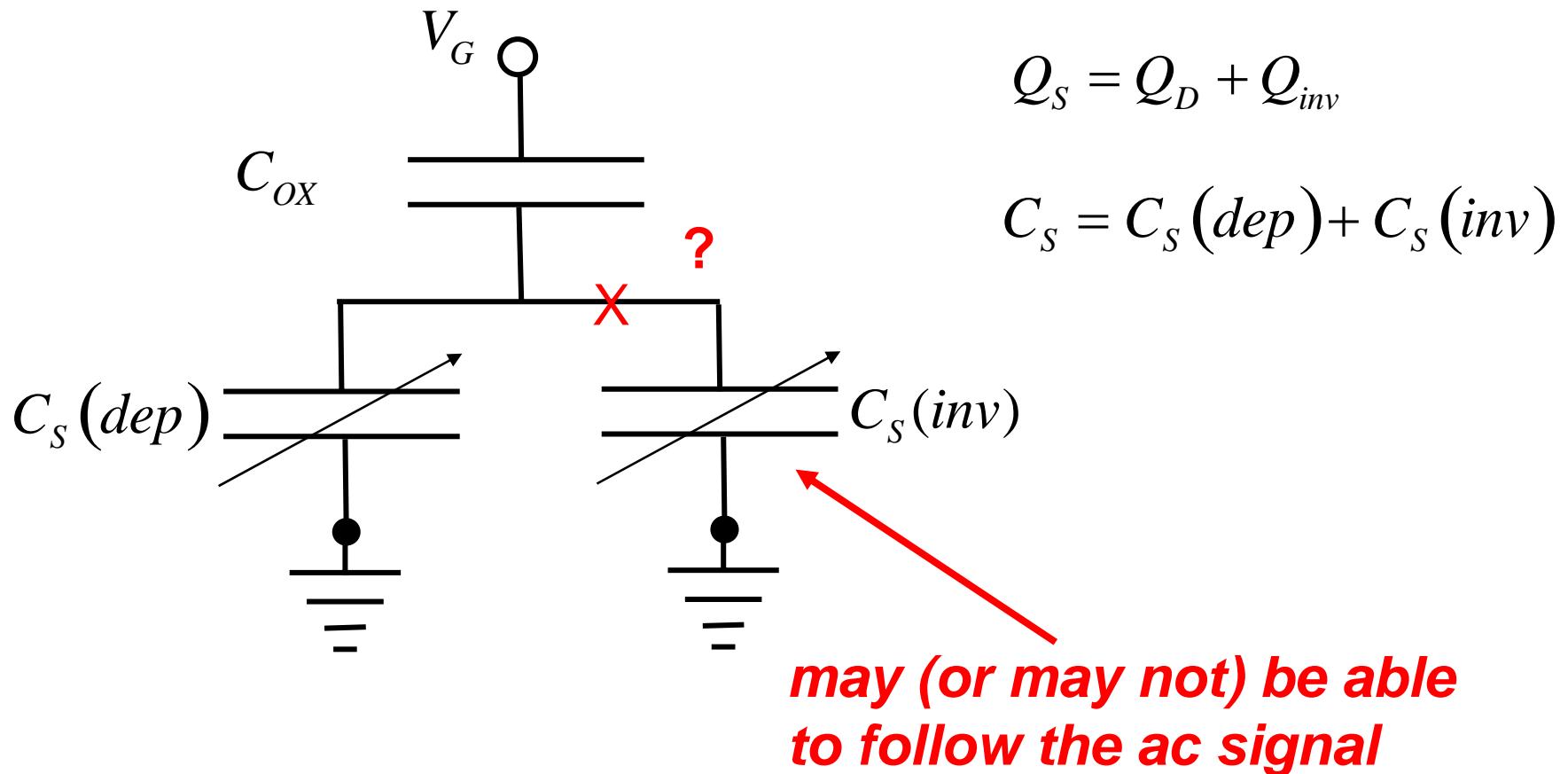


inversion capacitance (high frequency)

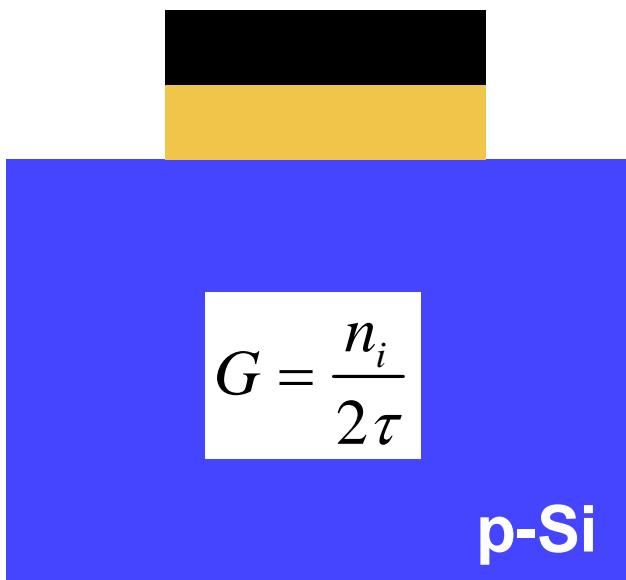


$$\frac{1}{C_{inv}} = \frac{W_{dm}}{\epsilon_{Si}} + \frac{1}{C_{OX}} \quad C_{inv} < C_{OX}$$

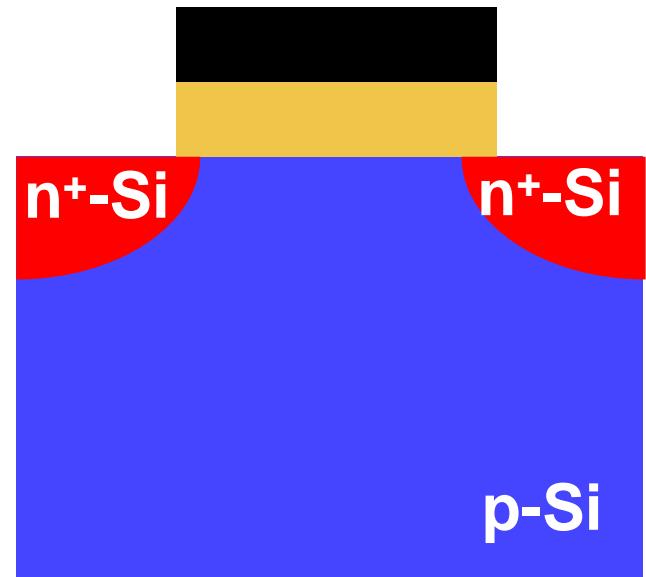
low vs. high frequency



low or high frequency?

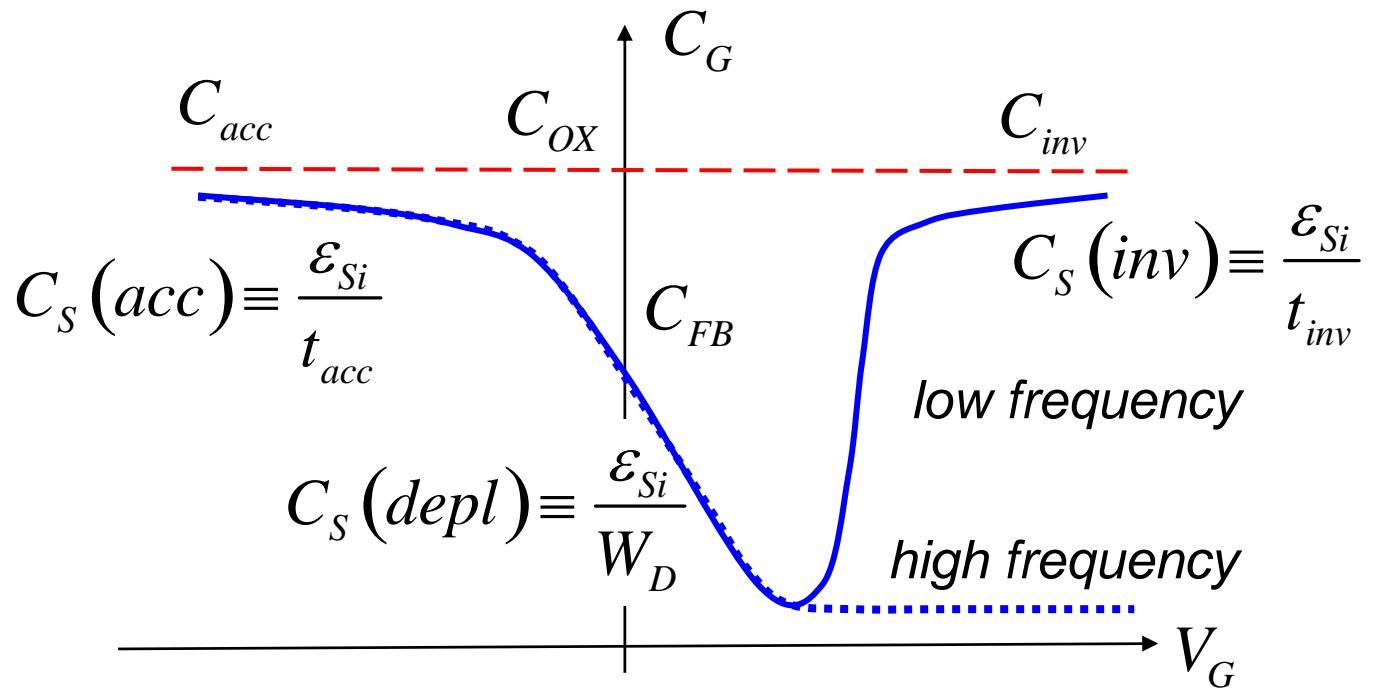


typically observe hi-
frequency CV



typically observe low-
frequency CV

MOS CV recap



outline

- 1) Short review
- 2) Gate voltage / surface potential relation
- 3) The flatband voltage
- 4) MOS capacitance vs. voltage
- 5) **Gate voltage and inversion layer charge**

inversion charge - gate voltage relation

$$V_G = V_{FB} + \psi_s - \frac{Q_s(\psi_s)}{C_{OX}}$$

At threshold:

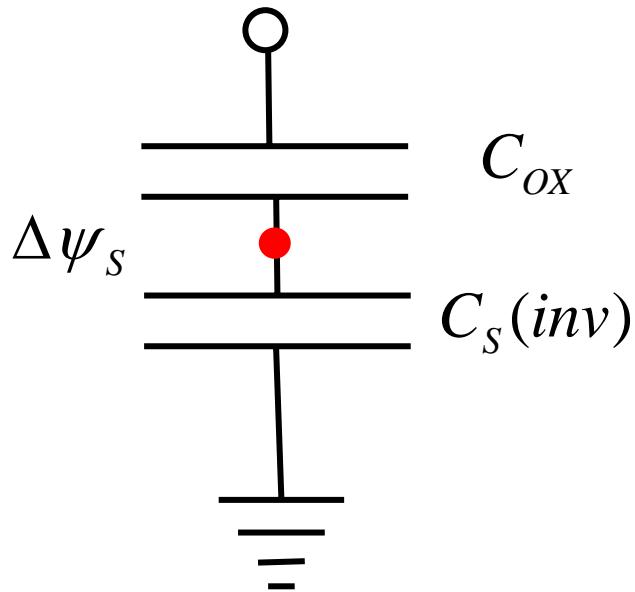
$$V_T = V_{FB} + 2\psi_B - \frac{Q_D(2\psi_B)}{C_{OX}}$$

Beyond threshold:

$$V_G - V_T = \psi_s - 2\psi_B - \frac{[Q_I + Q_D(\psi_s)]}{C_{OX}} + \frac{Q_D(2\psi_B)}{C_{OX}}$$

surface potential beyond threshold

$$\Delta V = (V_G - V_T)$$



$$\Delta \psi_S = \Delta V \frac{C_{OX}}{C_S(inv) + C_{OX}}$$

inversion charge - gate voltage relation (ii)

Beyond threshold:

$$V_G - V_T = \psi_S - 2\psi_B - \frac{Q_I + Q_D(\psi_S)}{C_{OX}} + \frac{Q_D(2\psi_B)}{C_{OX}}$$

$$\Delta\psi_S = \Delta V \frac{C_{OX}}{C_{inv} + C_{OX}} ; \quad 0$$

$$V_G - V_T \approx -\frac{Q_i}{C_{OX}}$$

$$Q_I \approx -C_{OX} (V_G - V_T)$$

inversion charge - gate voltage relation (iii)

Beyond threshold:

$$V_G - V_T = \psi_S - 2\psi_B - \frac{Q_I + Q_D(\psi_S)}{C_{OX}} + \frac{Q_D(2\psi_B)}{C_{OX}}$$

$$V_G - V_T \approx \Delta\psi_S - \frac{Q_I}{C_{OX}} \quad (\text{neglect depletion charge variation})$$

$$\Delta\psi_S = \Delta V \frac{C_{OX}}{C_s(inv) + C_{OX}}$$

$$Q_I = -C_G (V_G - V_T)$$

$$C_G = \frac{C_{OX} C_s(inv)}{C_s(inv) + C_{OX}}$$

summary

- 1) Short review
- 2) Gate voltage / surface potential relation
- 3) The flatband voltage
- 4) MOS capacitance vs. voltage
- 5) Gate voltage and inversion layer charge