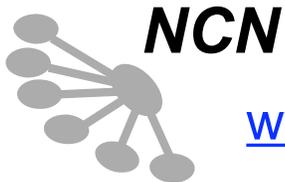


EE-612: Lecture 5 Poly Si Gate MOS Capacitors

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Fall 2006



www.nanohub.org

Lundstrom EE-612 F06

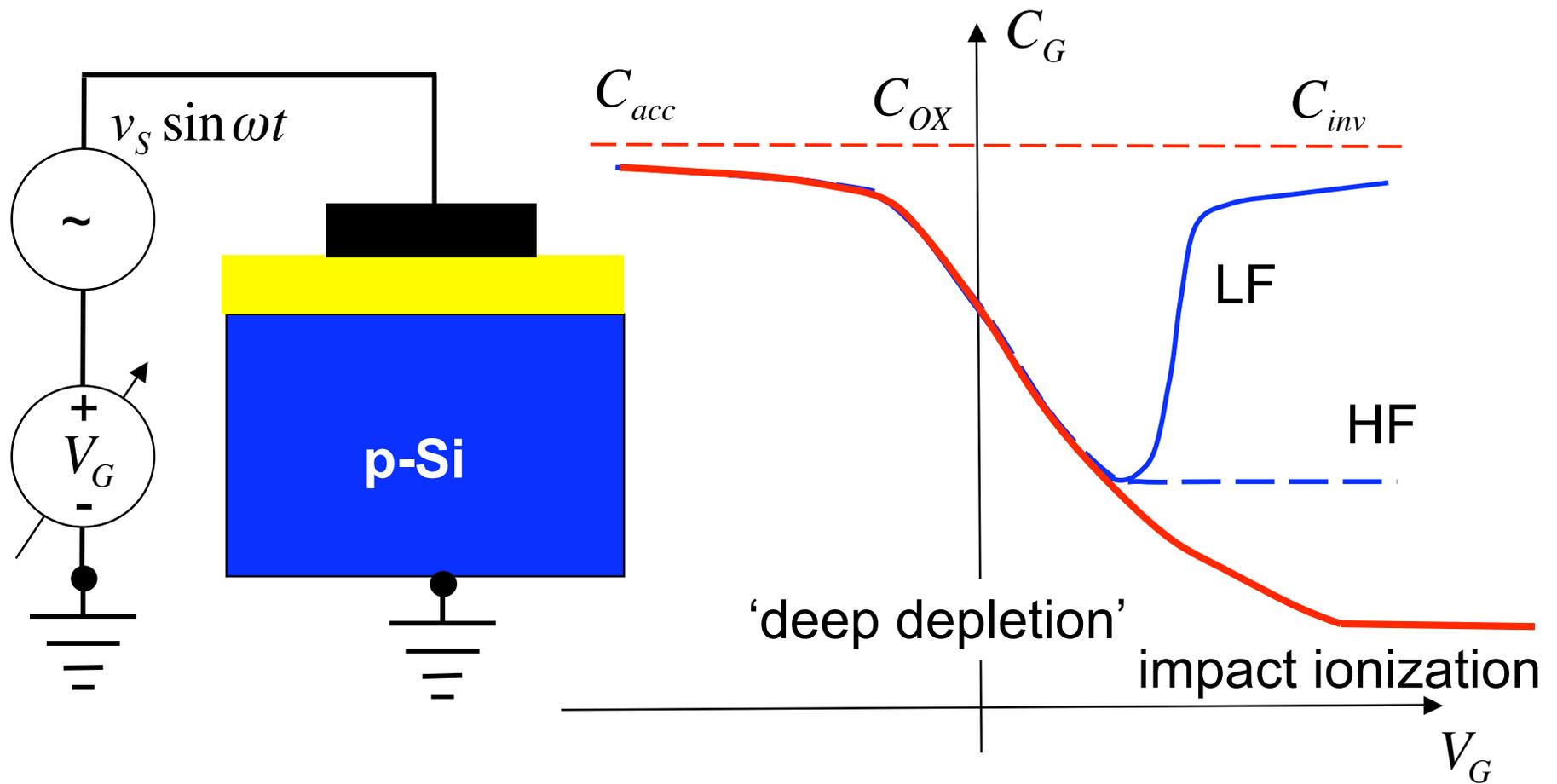
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1

outline

- 1) Review
- 2) Workfunction of poly gates
- 3) Capacitance vs. Voltage
- 4) Discussion

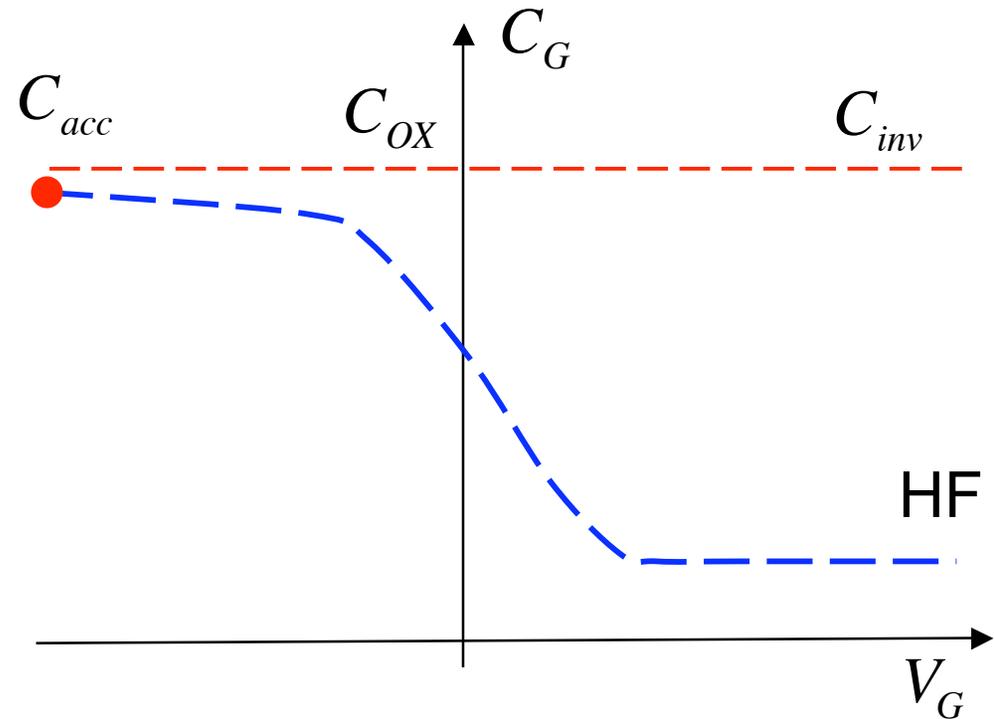
1) review



traditional analysis

Step 1: estimate t_{ox}

$$C_{acc} \approx A_G C_{OX} = A_G \frac{K_{ox} \epsilon_0}{t_{ox}}$$



From measured, C_{acc} ,
solve for t_{ox} .

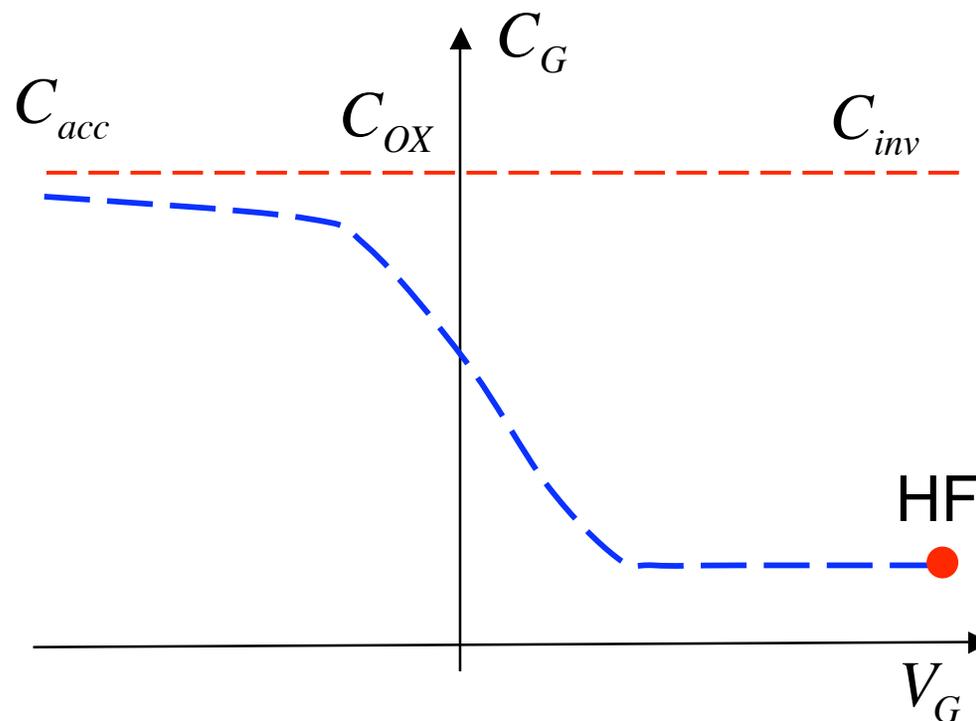
traditional analysis

Step 2: determine N_A

$$\frac{1}{C_{min}} \approx \frac{1}{A_G C_{OX}} + \frac{W_{dm}}{A_G \epsilon_{Si}}$$

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

$$\psi_B = \frac{k_B T}{q} \ln(N_A/n_i)$$



From measured, C_{min} ,
solve iteratively for N_A .

traditional analysis

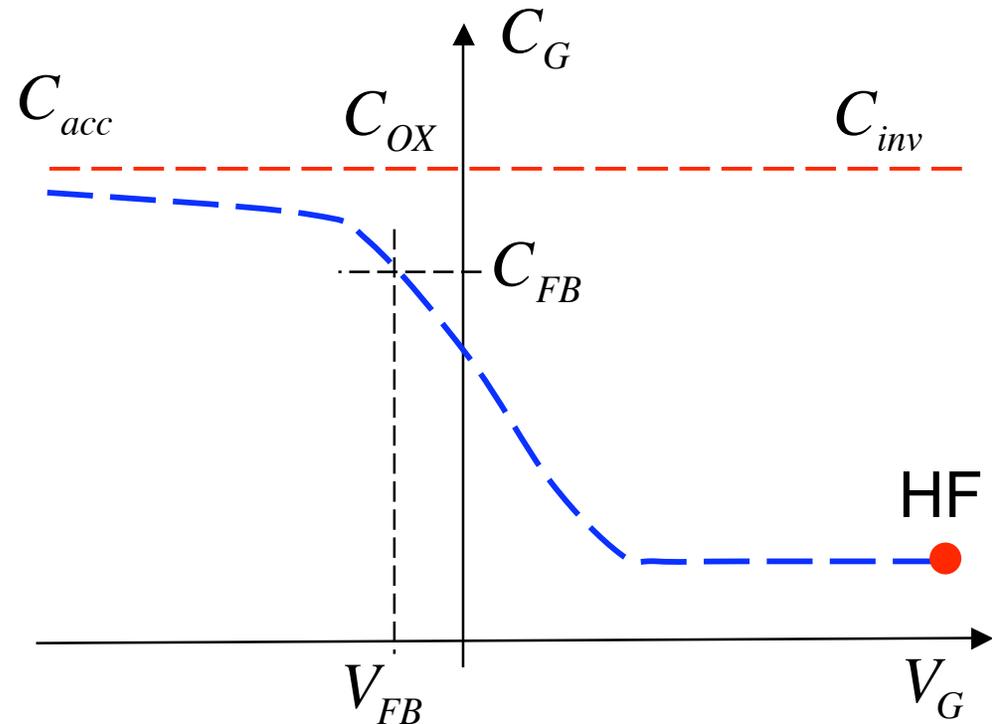
Step 3: determine V_{FB}

$$C_S = \epsilon_{Si} / L_D$$

$$L_D = \sqrt{\epsilon_{Si} k_b T / q^2 N_A}$$

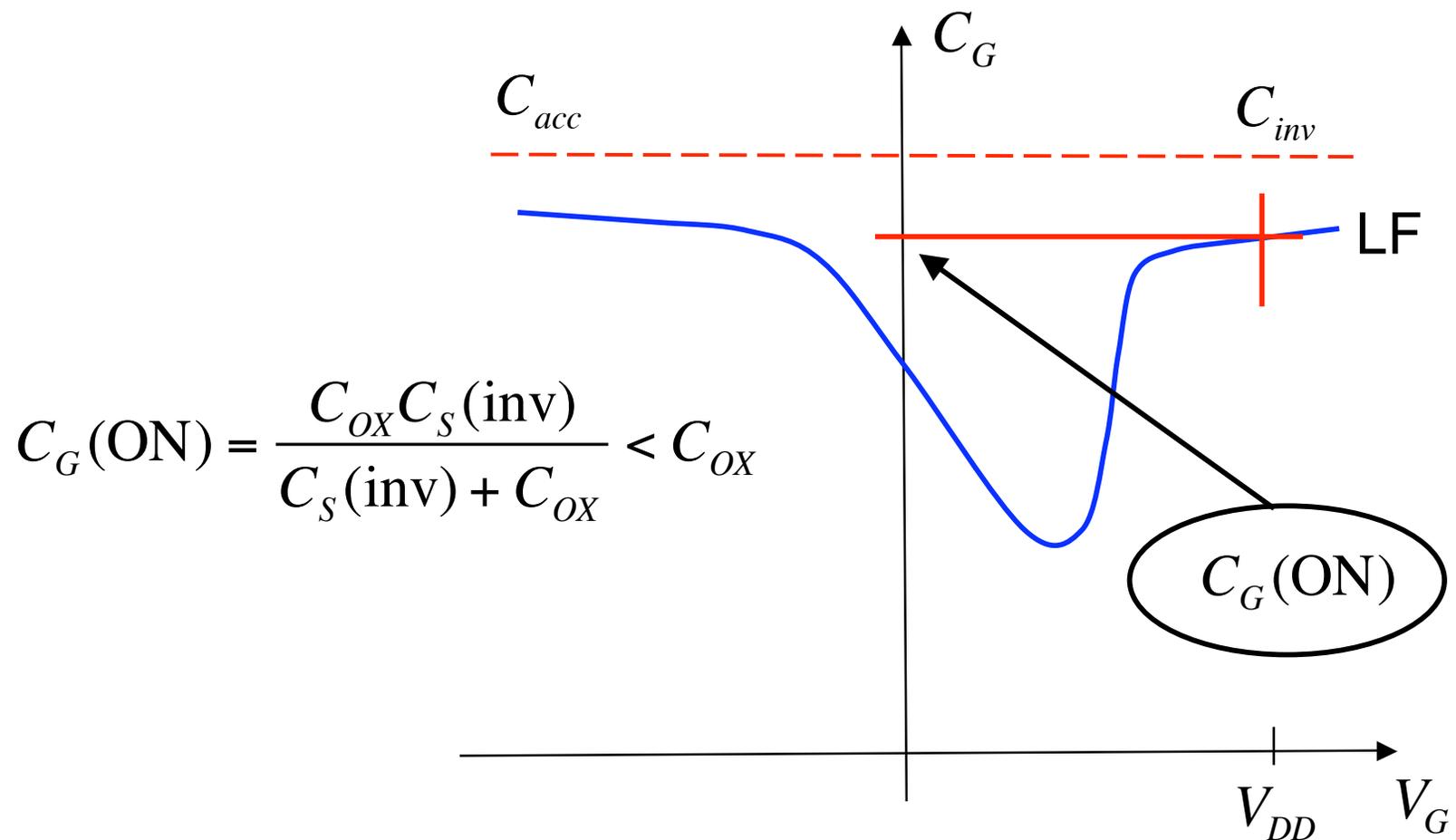
$$\frac{1}{C_{FB}} = \frac{1}{A_G C_{OX}} + \frac{L_D}{A_G \epsilon_{Si}}$$

$$V_{FB} = \phi_{ms} - Q_F / C_{OX}$$



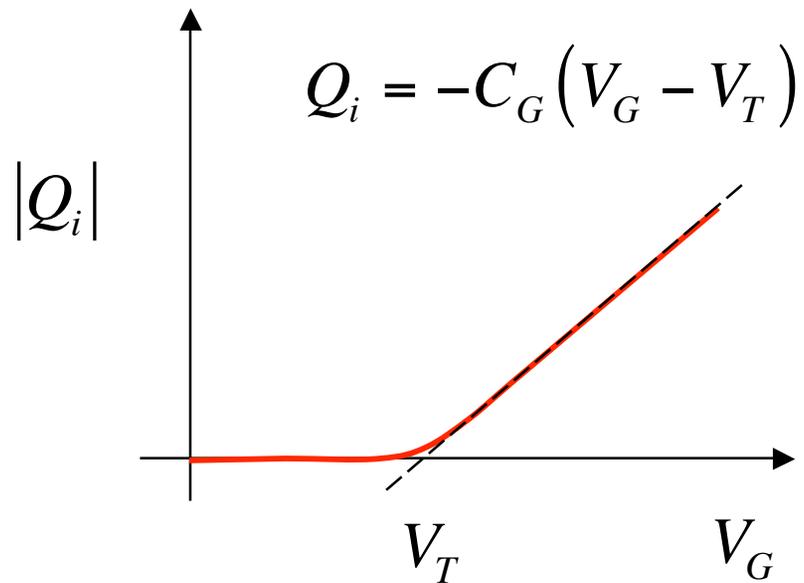
From known, C_{FB} ,
determine experimental V_{FB} .

gate capacitance in inversion



gate capacitance in inversion

$$C_G \equiv \frac{\epsilon_{OX}}{EOT_{elec}}$$

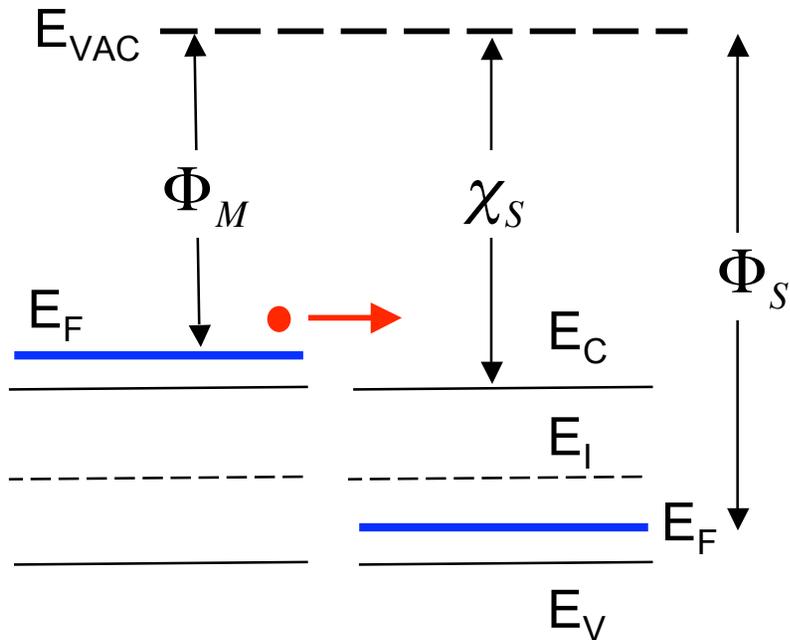


$$C_{OX} = \frac{\epsilon_{OX}}{t_{ox}} \quad C_{inv} \equiv \frac{\epsilon_{Si}}{t_{inv}} \quad \longrightarrow \quad EOT_{elec} = t_{OX} + \left(\frac{\epsilon_{OX}}{\epsilon_{Si}} \right) t_{inv} > t_{OX}$$

outline

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n⁺ poly silicon gate



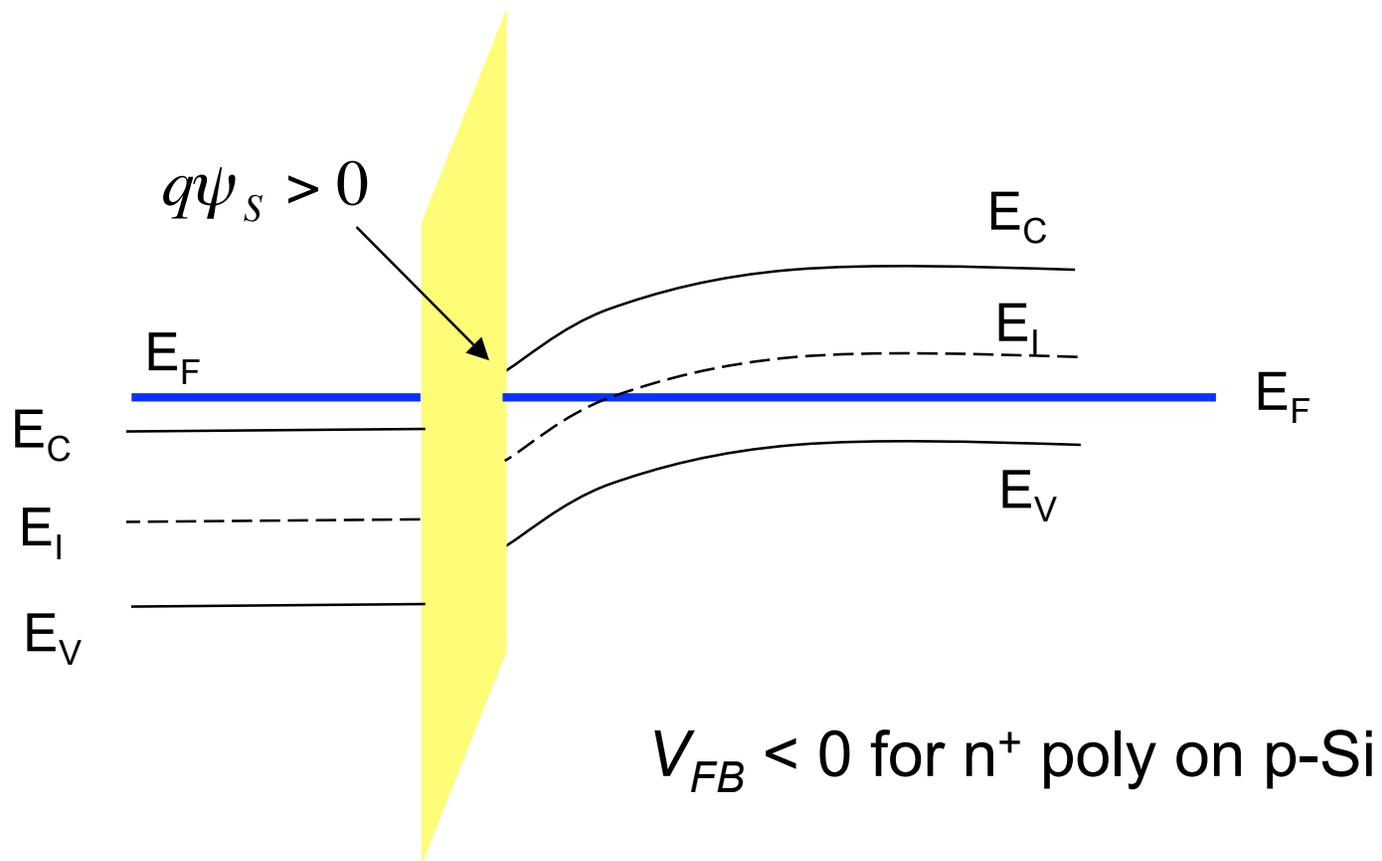
$$q\phi_m = \chi_{Si} - (E_F - E_C)$$

$$q\phi_s = \chi_{Si} + (E_C - E_F)$$

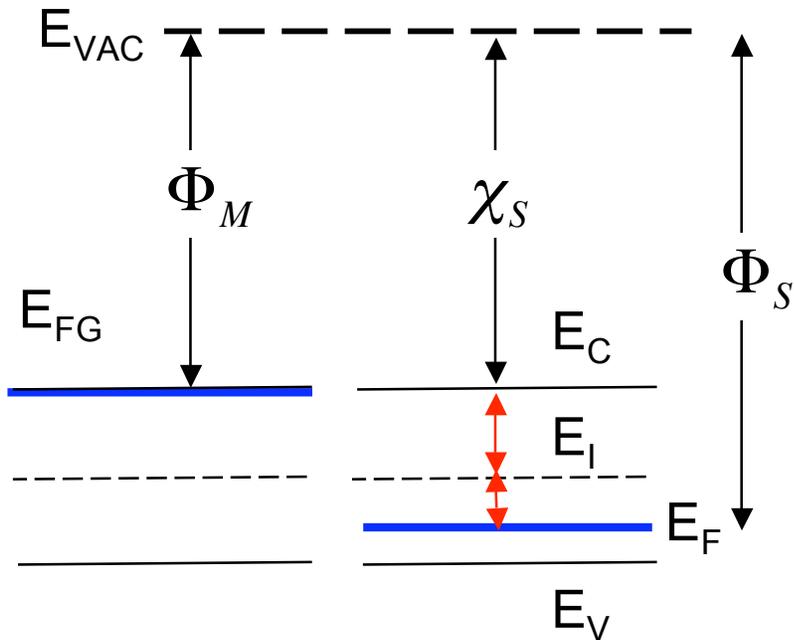
$$\phi_{ms} = -\frac{k_B T}{q} \ln\left(\frac{n_i^2}{N_A N_D}\right) = -V_{bi}$$

$$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \quad (\text{expected results for a pn junction})$$

equilibrium e-band diagram



n⁺ poly silicon gate (approximate)



$$E_{FG} \approx E_C$$

$$q\phi_M = \chi_{Si}$$

$$q\phi_S = \chi_{Si} + (E_C - E_I) + (E_I - E_F)$$

$$(E_C - E_I) \approx E_G/2$$

$$(E_I - E_F) = q\psi_B = k_B T \ln(N_A/n_i)$$

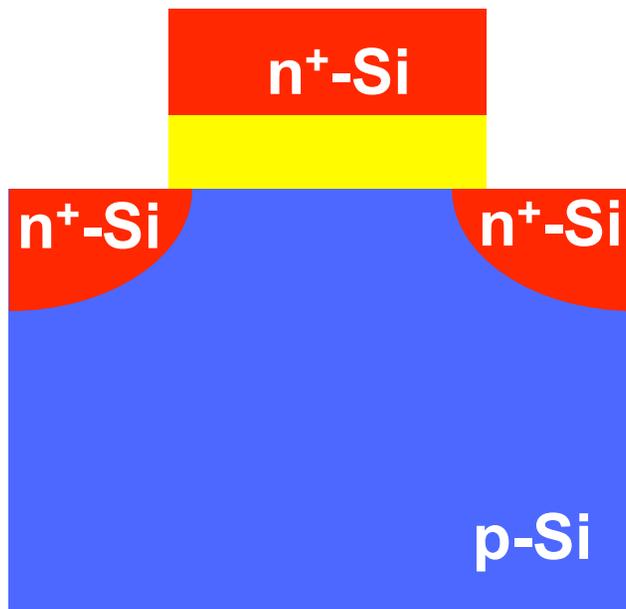
$$\phi_{ms} \approx -0.55 - \psi_B \approx -1 \text{ V}$$

$$\phi_{ms} \approx -\frac{E_G}{2q} - \psi_B$$

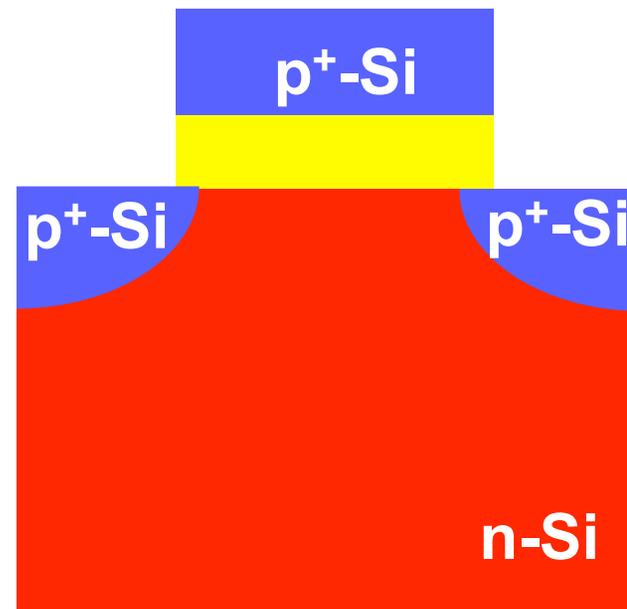
exercise

Repeat the discussion on the previous three slides for a p^+ poly gate on an n-Si substrate.

CMOS technology



NMOS

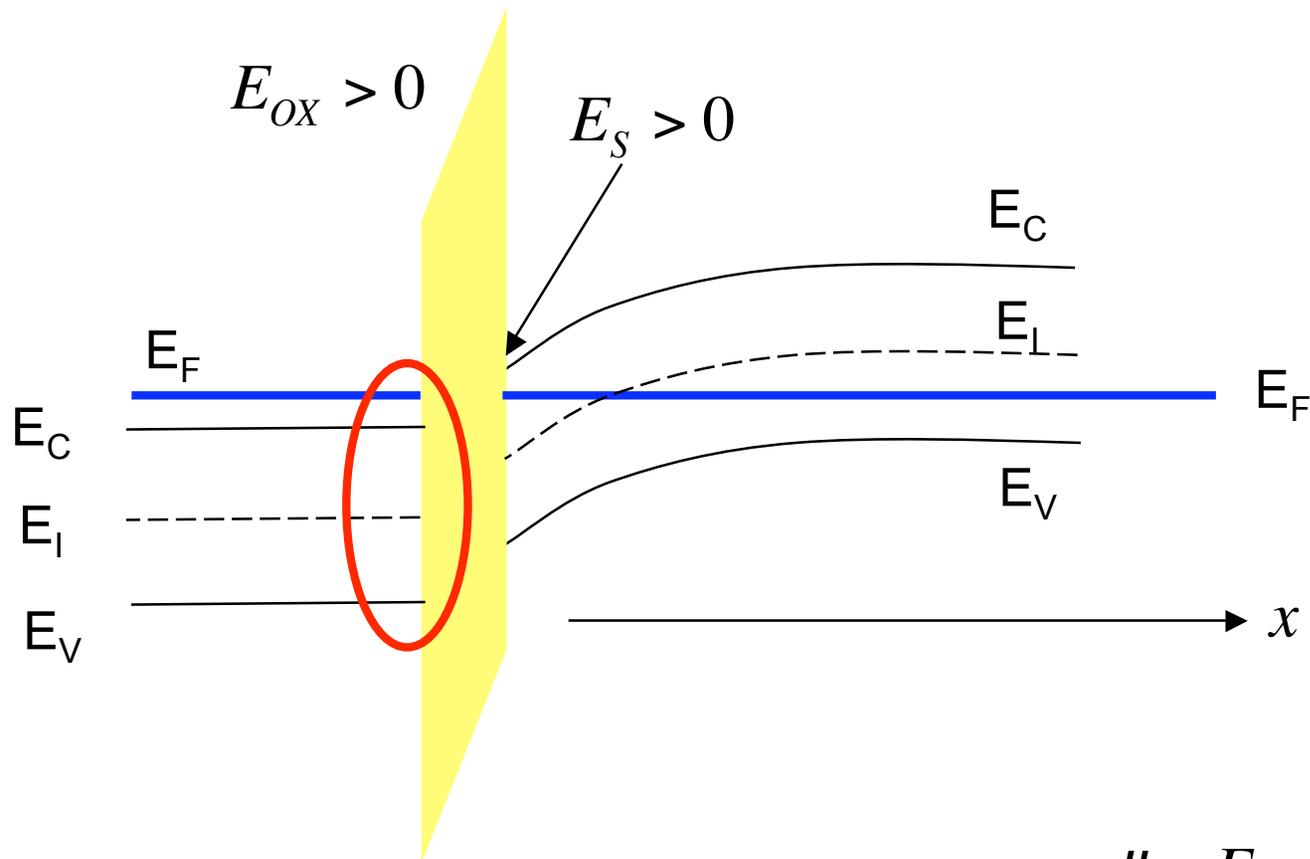


PMOS

outline

- 1) Review
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- 3) Capacitance vs. Voltage**
- 4) Discussion

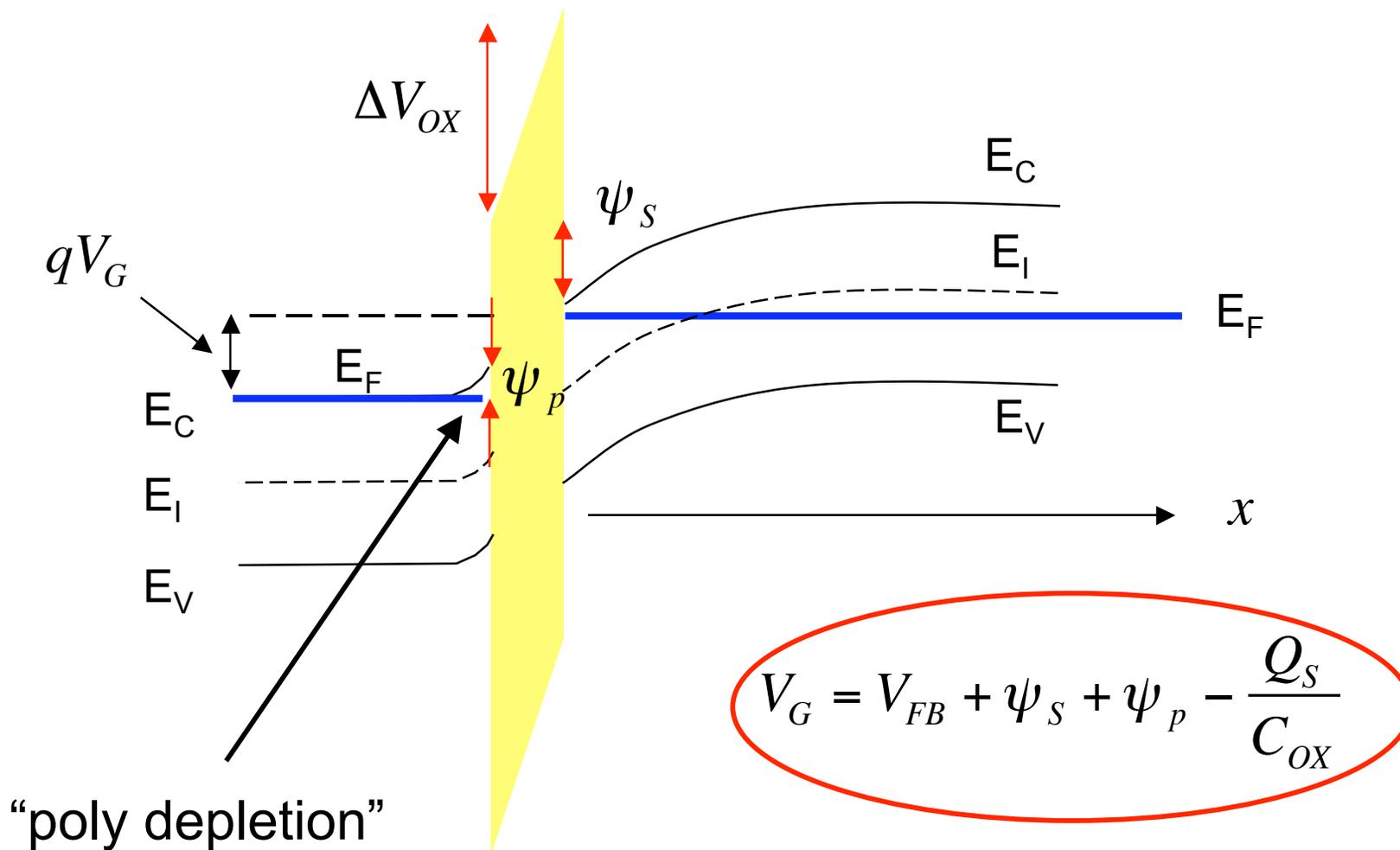
equilibrium e-band diagram (again)



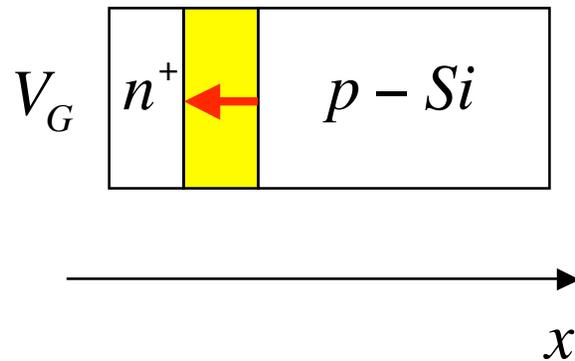
must have $E_x > 0$ in the poly-Si

recall
$$E_x = \frac{1}{q} \frac{dE_C}{dx}$$

e-band diagram for poly gate



state of substrate and poly for $V'_G < 0$



$$1) V_G < V_{FB}$$

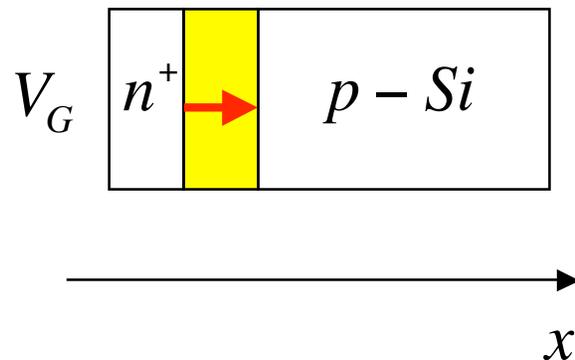
$$E_{OX} < 0$$

p-Si substrate accumulated

n^+ -poly gate accumulated

Exercise: draw the energy band diagram

state of substrate and poly for $0 < V_G < V_T$



$$2) V_{FB} < V_G < V_T$$

$$E_{OX} > 0$$

$$\psi_S < 2\psi_B$$

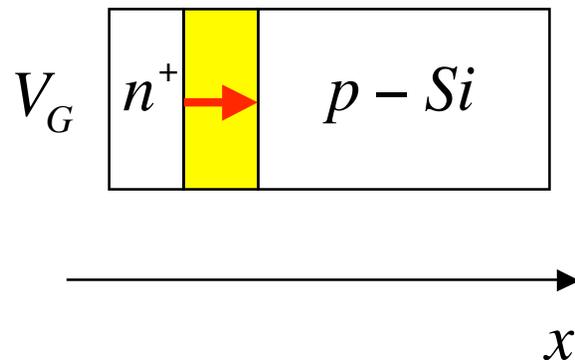
$$\psi_p < 2\psi_B(\text{poly})$$

p-Si substrate depleted

n⁺-poly gate depleted

Exercise: draw the energy band diagram

$$V_T < V_G < V_T(\text{poly})$$



$$3) V_T < V_G < V_T(\text{poly})$$

$$E_{OX} > 0$$

$$\psi_S > 2\psi_B$$

$$\psi_P < 2\psi_B(\text{poly})$$

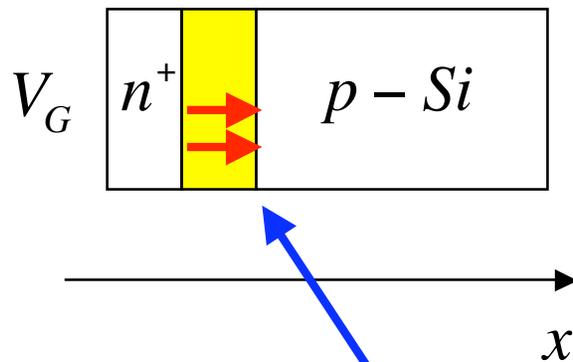
$$V_T = V_{FB} + 2\psi_B + \psi_P + \sqrt{2q\epsilon_{Si}N_A(2\psi_B)}/C_{OX}$$

p-Si substrate ***inverted***

n⁺-poly gate depleted

Exercise: draw the energy band diagram

$$V_G > V_T(\text{poly})$$



$$4) V_G > V_T(\text{poly})$$

$$E_{OX} \gg 0$$

$$\psi_S > 2\psi_B$$

$$\psi_p > 2\psi_B(\text{poly})$$

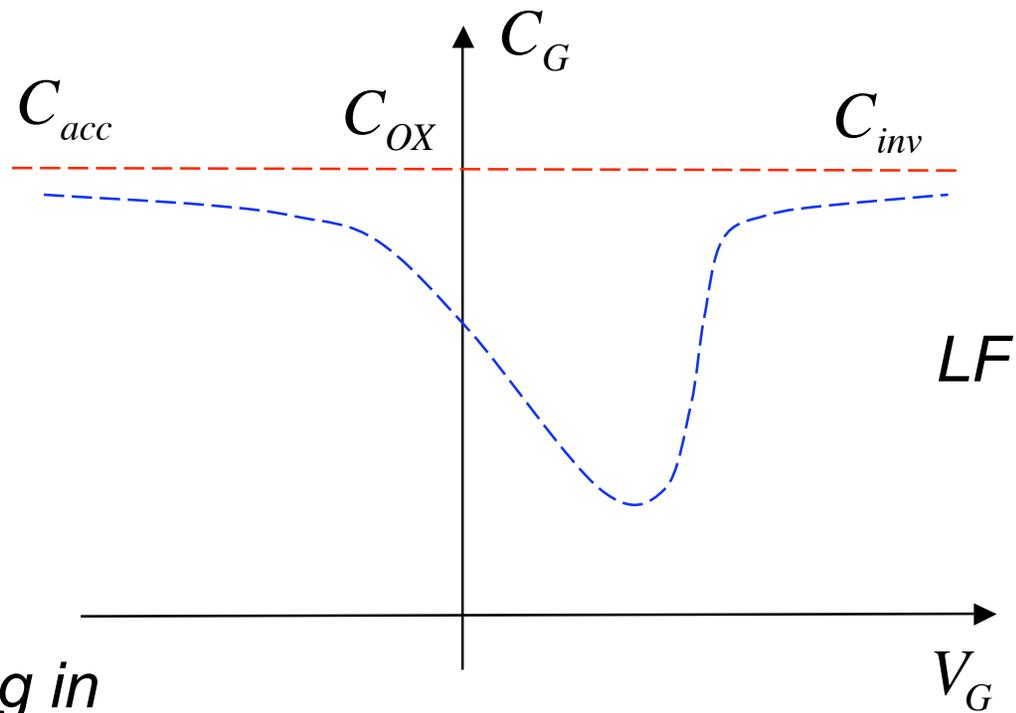
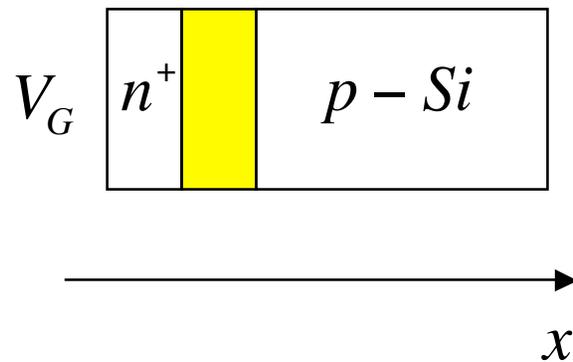
$$V_T(\text{poly}) = V_{FB} + 2\psi_B + 2\psi_B(\text{poly}) + \sqrt{2q\epsilon_{Si}N_D[2\psi_B(\text{poly})]}/C_{OX}$$

p-Si substrate **inverted**

n⁺-poly gate **inverted**

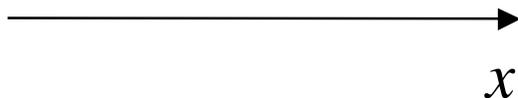
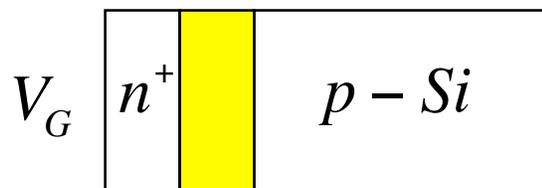
Exercise: draw the energy band diagram

C-V



How does band bending in the poly-Si change the MOS CV characteristic?

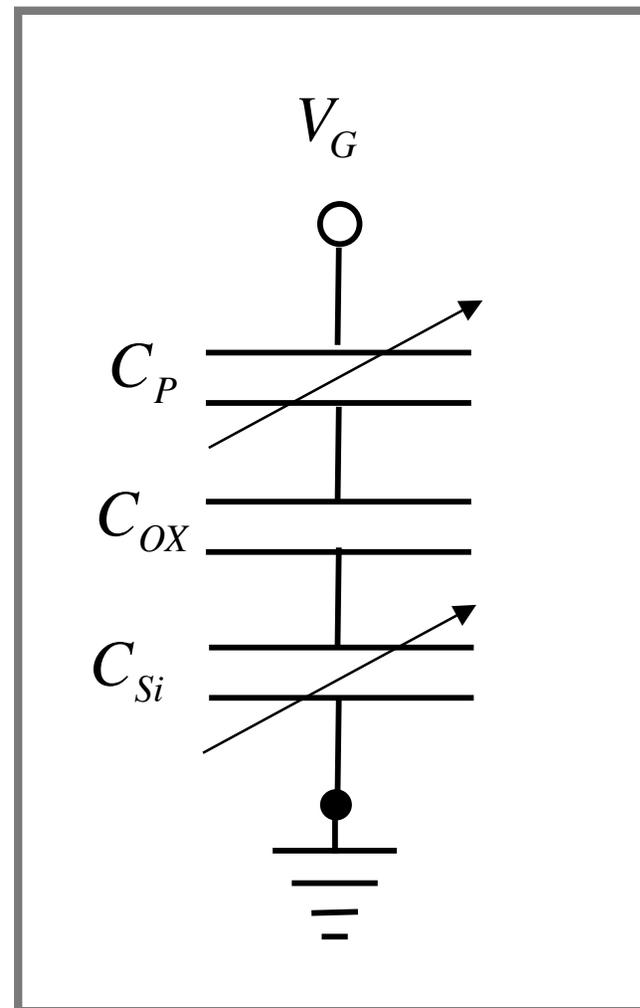
Capacitance



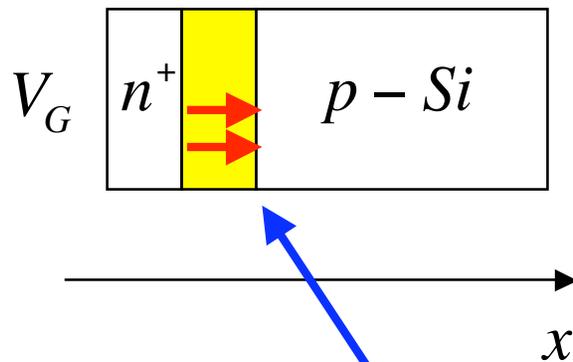
$$V_G = V_{FB} + \psi_S + \psi_P - \frac{Q_S}{C_{OX}}$$

$$C_G \equiv \frac{dQ_G}{dV_G} \quad Q_G = Q_P = -Q_S$$

$$\frac{1}{C_G} = \frac{1}{C_P} + \frac{1}{C_{OX}} + \frac{1}{C_{Si}}$$



$$V_G > V_T(\text{poly})$$



$$4) V_G > V_T(\text{poly})$$

$$E_{OX} \gg 0$$

$$\psi_S > 2\psi_B$$

$$\psi_p > 2\psi_B(\text{poly})$$

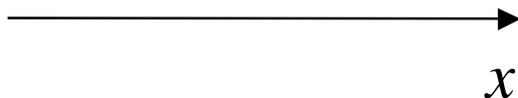
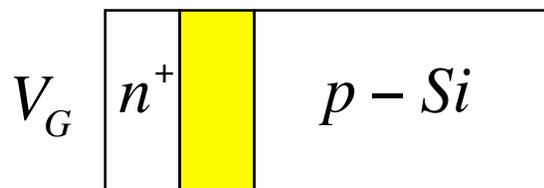
$$V_T(\text{poly}) = V_{FB} + 2\psi_B + 2\psi_B(\text{poly}) + \sqrt{2q\epsilon_{Si}N_D[2\psi_B(\text{poly})]}/C_{OX}$$

p-Si substrate **inverted**

n⁺-poly gate **inverted**

Exercise: draw the energy band diagram

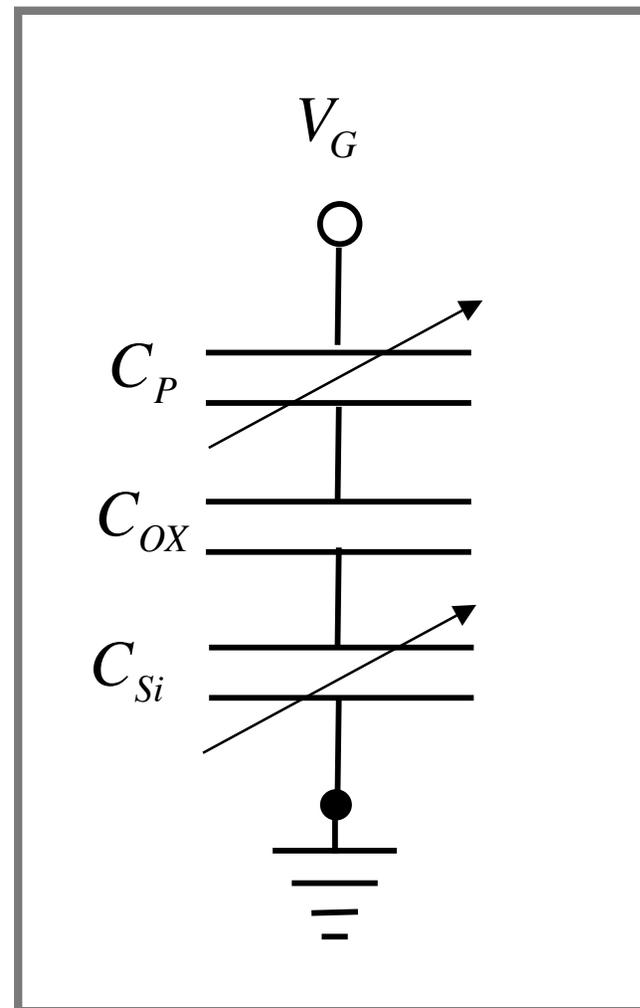
Capacitance



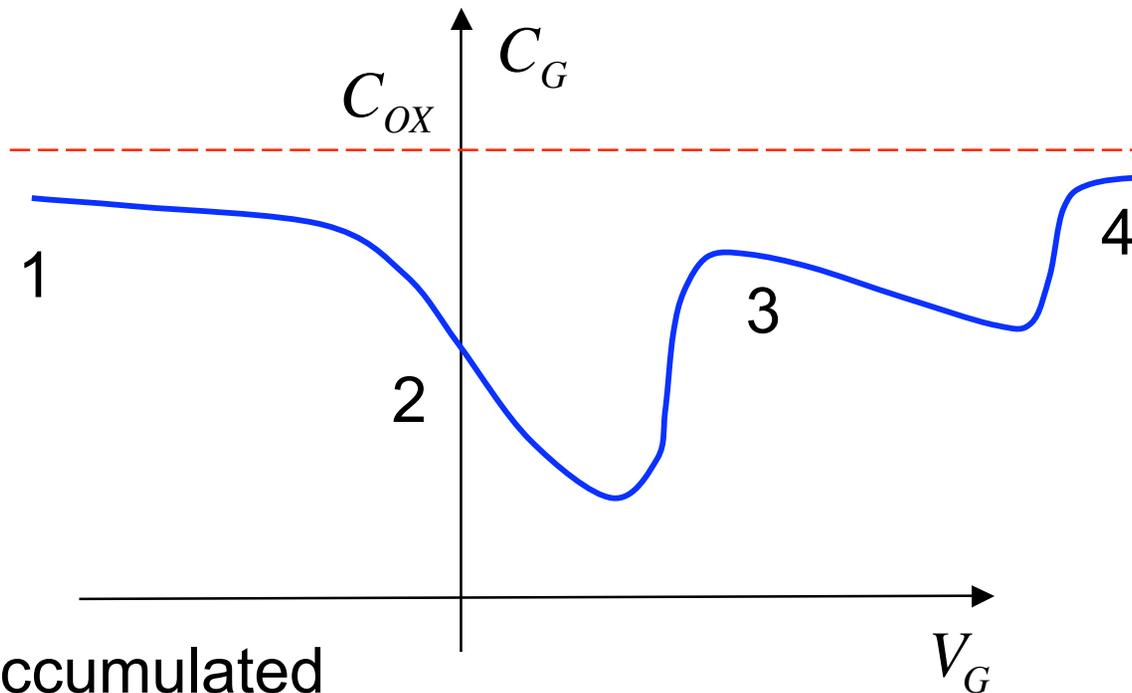
$$V_G = V_{FB} + \psi_S + \psi_P - \frac{Q_S}{C_{OX}}$$

$$C_G \equiv \frac{dQ_G}{dV_G} \quad Q_G = Q_P = -Q_S$$

$$\frac{1}{C_G} = \frac{1}{C_P} + \frac{1}{C_{OX}} + \frac{1}{C_{Si}}$$



capacitance vs. voltage



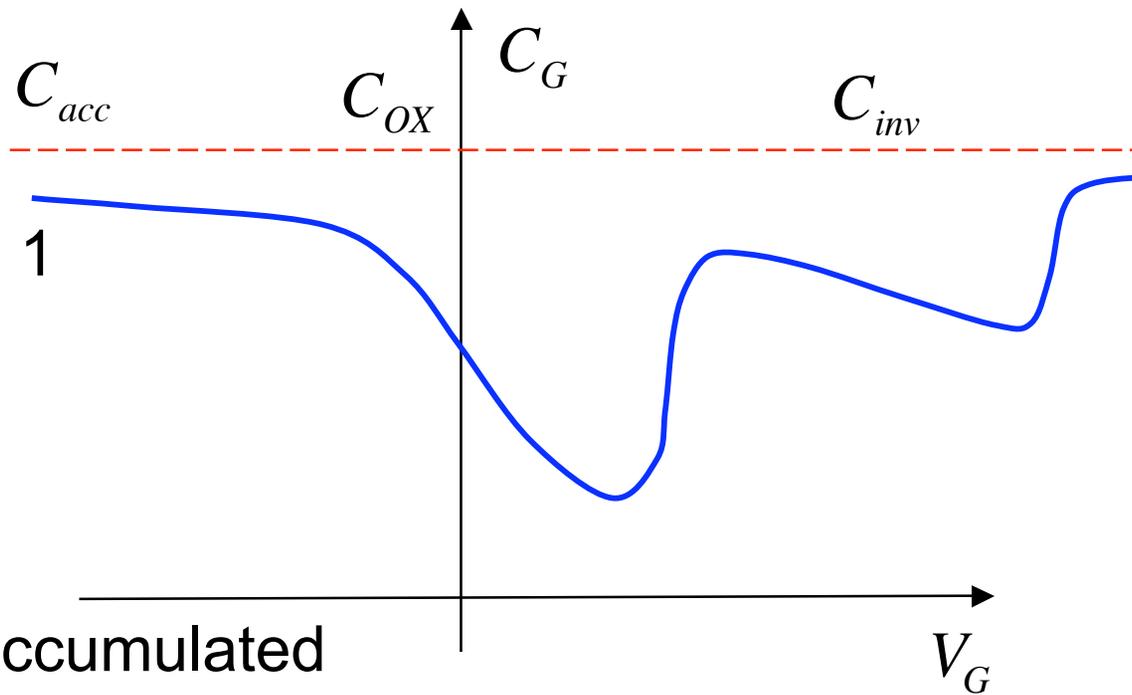
1: both accumulated

2: both depleted

3: substrate inverted, poly depleted

4: both inverted

capacitance vs. voltage



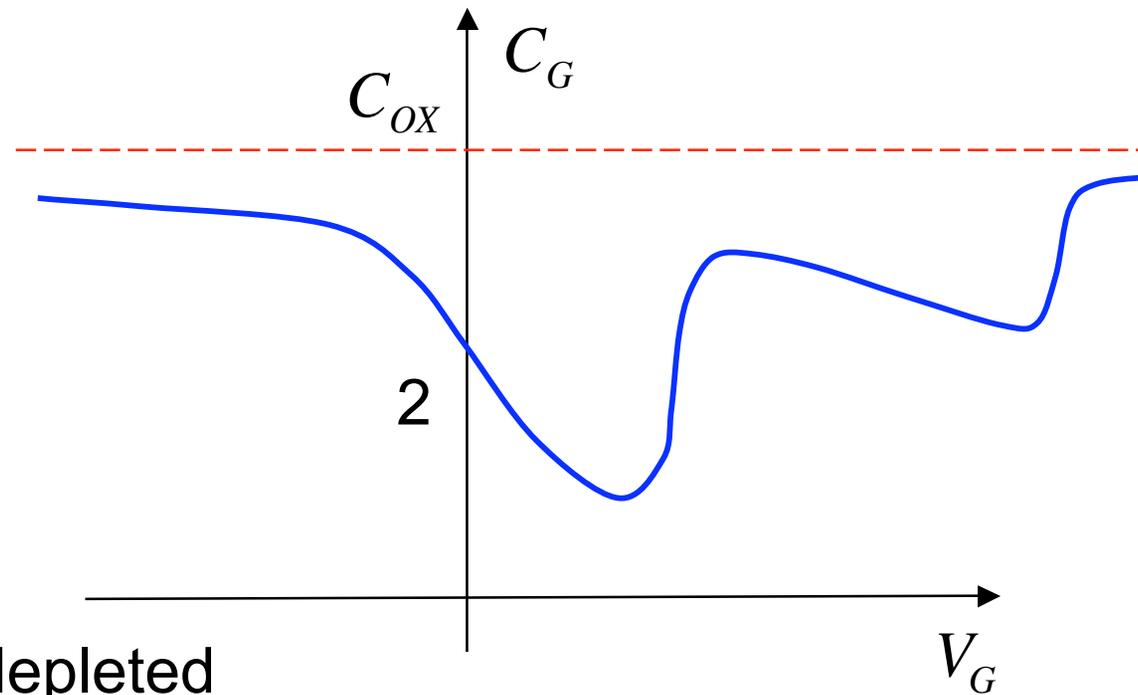
1: both accumulated

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

$$C_S = C_P = C_{acc} = |Q_S| / (2k_B T / q)$$

$$\frac{1}{C_G} = \frac{2}{C_{acc}} + \frac{1}{C_{OX}}$$

capacitance vs. voltage



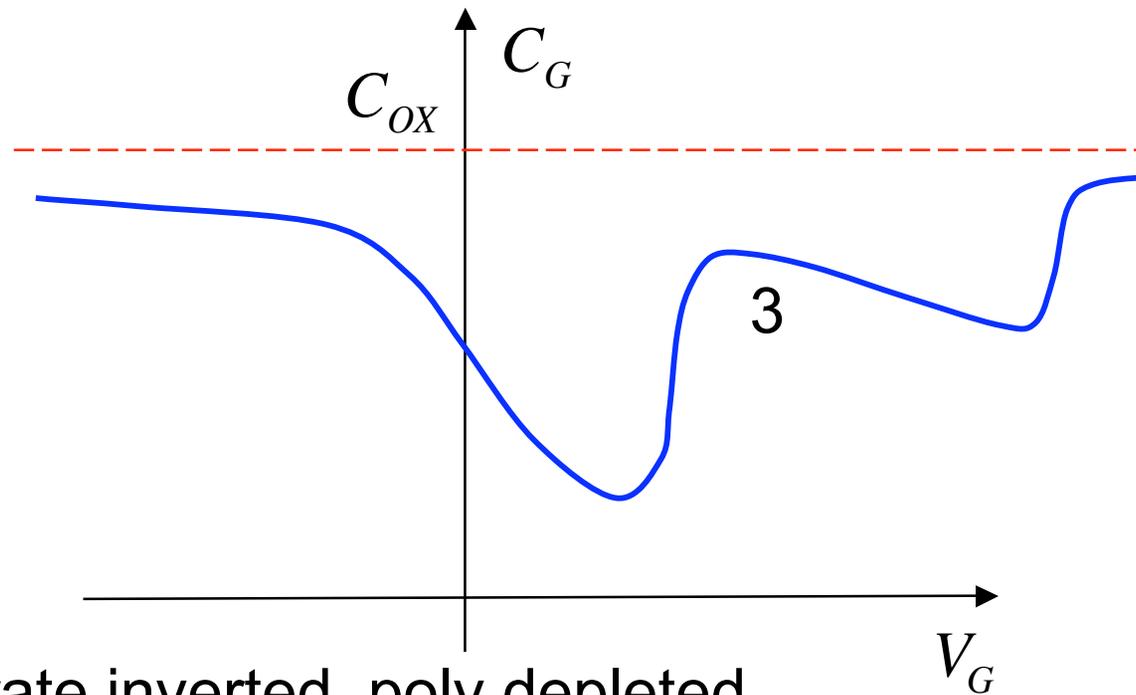
2: both depleted

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

$$C_S = \frac{\epsilon_{Si}}{W_D} \quad C_P = \frac{\epsilon_{Si}}{W_P}$$

$$\frac{1}{C_G} = \frac{\epsilon_{Si}}{W_P} + \frac{1}{C_{OX}} + \frac{\epsilon_{Si}}{W_D}$$

capacitance vs. voltage



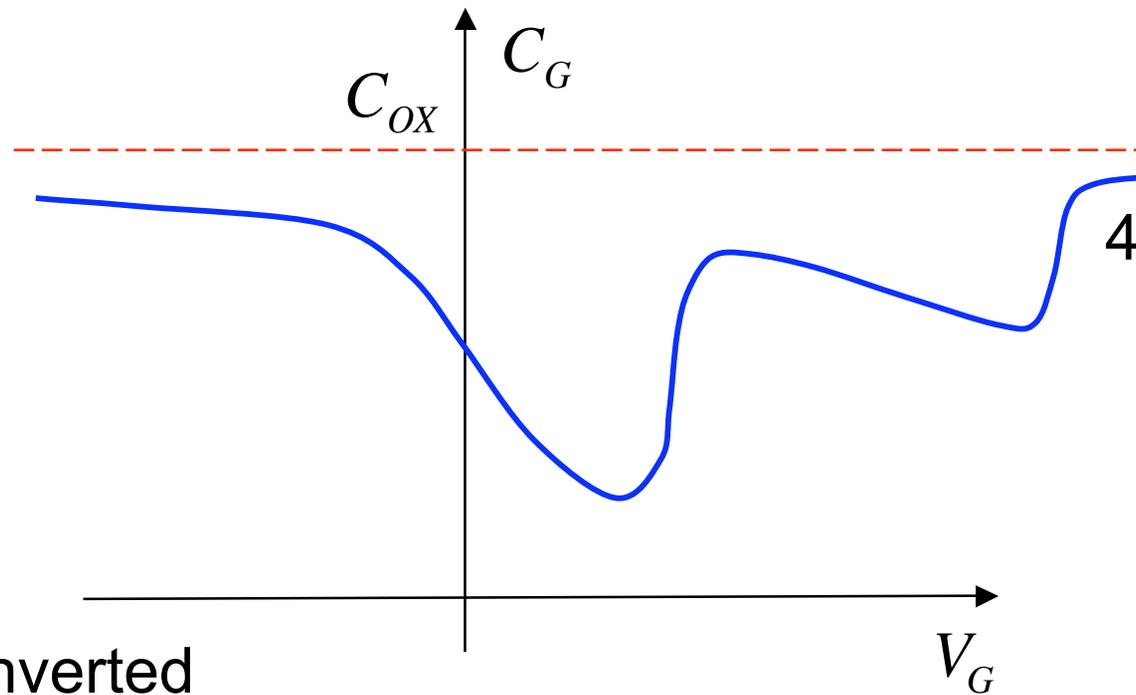
3: substrate inverted, poly depleted

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

$$C_S = C_{inv} \quad C_P = \frac{\epsilon_{Si}}{W_P}$$

$$\frac{1}{C_G} = \frac{1}{C_{inv}} + \frac{1}{C_{OX}} + \frac{\epsilon_{Si}}{W_P}$$

capacitance vs. voltage



4: both inverted

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

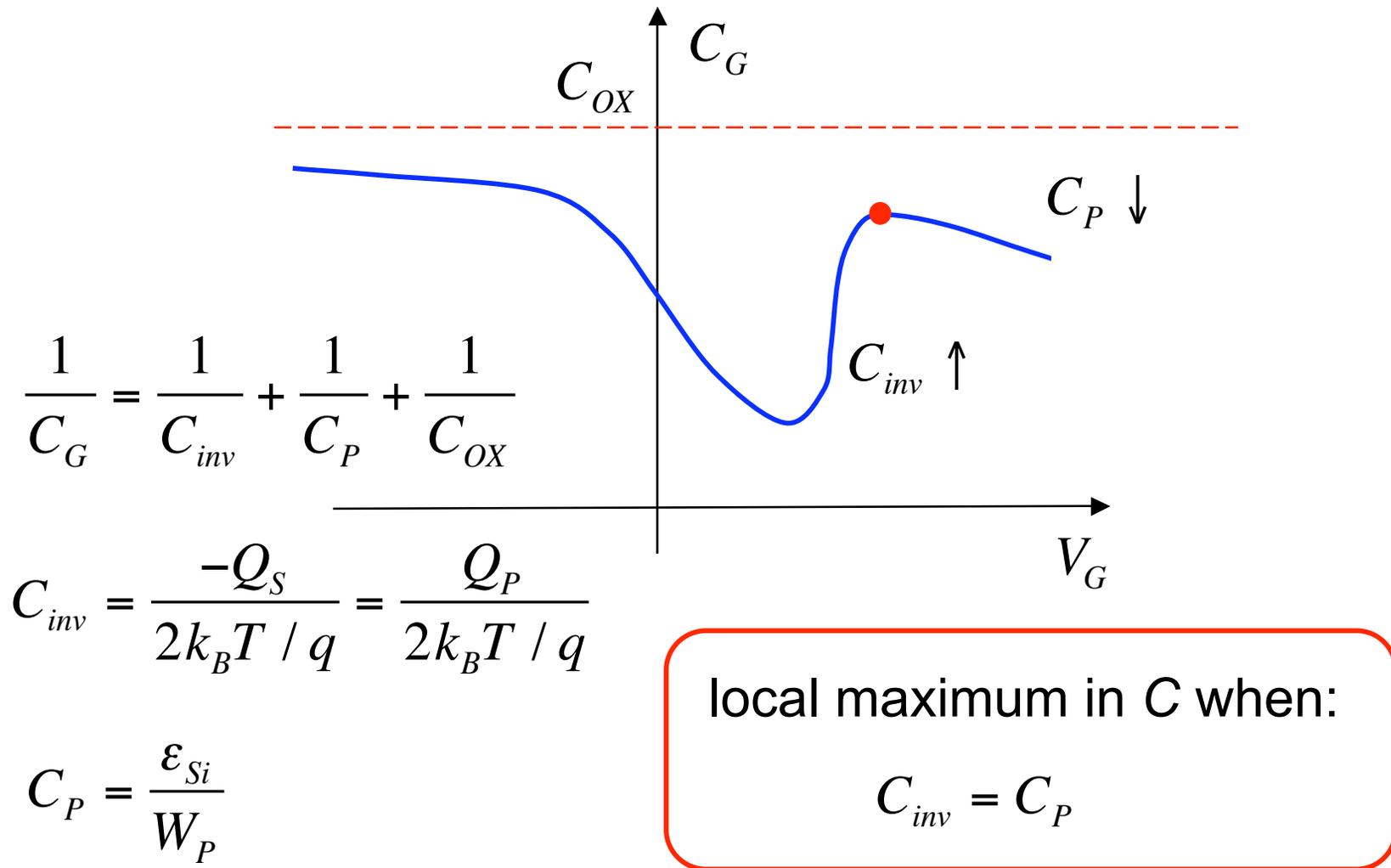
$$C_S = C_{inv} \quad C_P = C_{inv}$$

$$\frac{1}{C_G} = \frac{2}{C_{inv}} + \frac{1}{C_{OX}}$$

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local maximum in C



local maximum in C

$$C_{inv} = C_P \quad (1)$$

$$\frac{Q_P}{2k_B T / q} = \frac{\epsilon_{Si}}{W_P} \quad (2)$$

$$\frac{\epsilon_{Si}}{W_P} = \frac{\epsilon_{Si}}{W_P} \times \frac{qN_P}{qN_P} = \frac{q\epsilon_{Si}N_P}{Q_P}$$

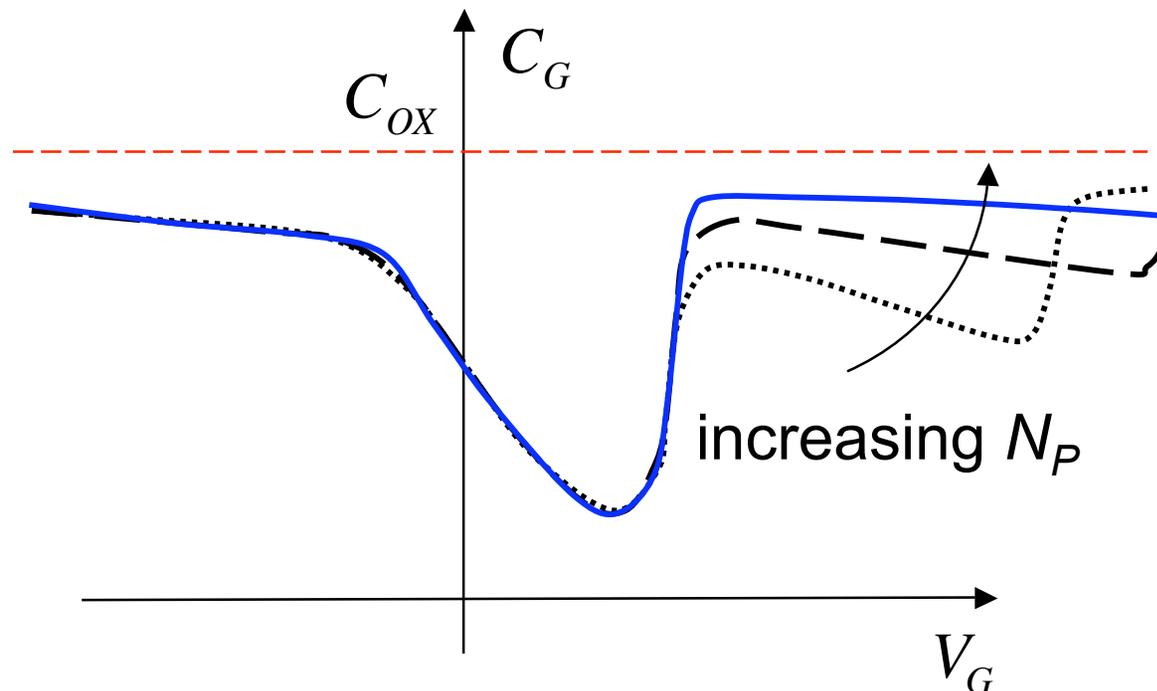
$$Q_P^2 = 2k_B T \epsilon_{Si} N_P$$

$$\frac{1}{C_{MAX}} = \frac{1}{C_{OX}} + \sqrt{\frac{8k_B T}{\epsilon_{Si} q^2 N_P}}$$

$$\frac{C_{MAX}}{C_{OX}} = \frac{1}{1 + \sqrt{8k_B T \epsilon_{OX}^2 / \epsilon_{Si} q^2 t_{OX}^2 N_P}}$$

- need high N_P ($\sim 10^{20} \text{ cm}^{-3}$) to achieve $C_{MAX} \approx C_{OX}$
- poly depletion increasingly difficult to manage as $t_{OX} \downarrow$
- metal gates?

poly depletion and N_P



The ITRS considers 3 scenarios, $N_P = 1e20, 1.5e20, 3e20 \text{ cm}^{-3}$

ITRS 2005 Edition, Process Integration, Devices, and Structures, Table 40b, pp. 13-15 , <http://www.itrs.net/reports.html>

ITRS definitions

1) “Equivalent oxide thickness (EOT)”

$$EOT \equiv \frac{3.9}{K_{ins}} t_{ins}$$

(high-k gate dielectrics)

2) “Equivalent oxide thickness electrical (EOT_{elec})”

$$C_G(ON) \equiv \frac{\epsilon_{OX}}{EOT_{elec}}$$

V_G

ITRS 2005 Edition, Process Integration, Devices, and Structures, Table 40b, pp. 13-15 , <http://www.itrs.net/reports.html>

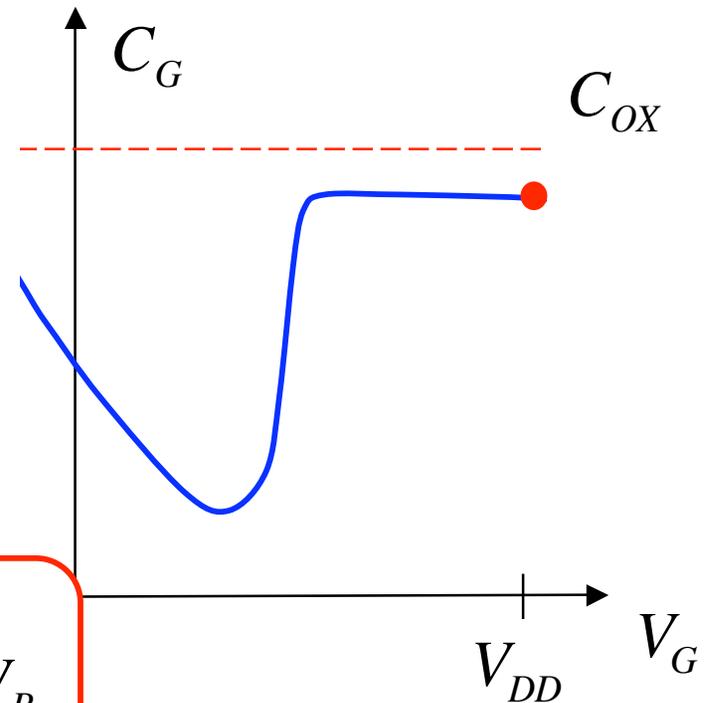
equivalent oxide thickness electrical

$$\frac{1}{C_G(\text{ON})} = \frac{1}{C_{inv}} + \frac{1}{C_P} + \frac{1}{C_{OX}}$$

$$\frac{1}{C_G(\text{ON})} = \frac{t_{inv}}{\epsilon_{Si}} + \frac{W_P}{\epsilon_{Si}} + \frac{EOT}{\epsilon_{OX}}$$

$$C_G(\text{ON}) = \frac{\epsilon_{OX}}{EOT_{elec}}$$

$$EOT_{elec} == EOT + \left(\frac{\epsilon_{OX}}{\epsilon_{Si}} \right) t_{inv} + \left(\frac{\epsilon_{OX}}{\epsilon_{Si}} \right) W_P$$



equivalent oxide thickness electrical (2006)

70 nm node (2006)

physical gate length: 28 nm

$$V_{DD} = 1.1V$$

$$EOT = 1.1nm$$

poly depl. and inv. layer thickness = 7.4Å (0.74nm)

$$EOT_{elec} = 18.4Å (1.84nm)$$

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