

EE-612: Lecture 4

Poly Si Gates and Quantum Mechanical Effects

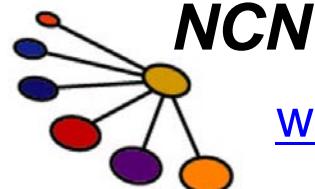
Mark Lundstrom

Electrical and Computer Engineering

Purdue University

West Lafayette, IN USA

Fall 2008



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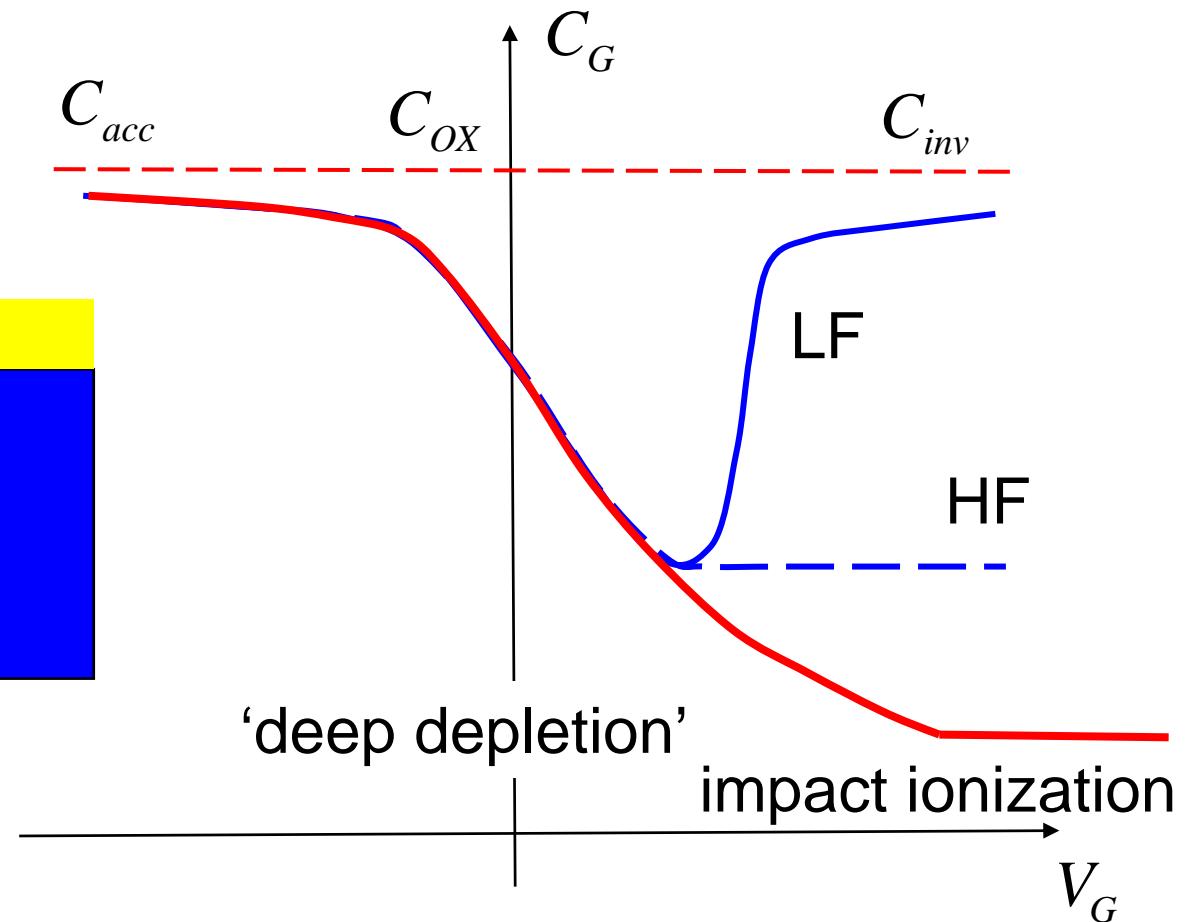
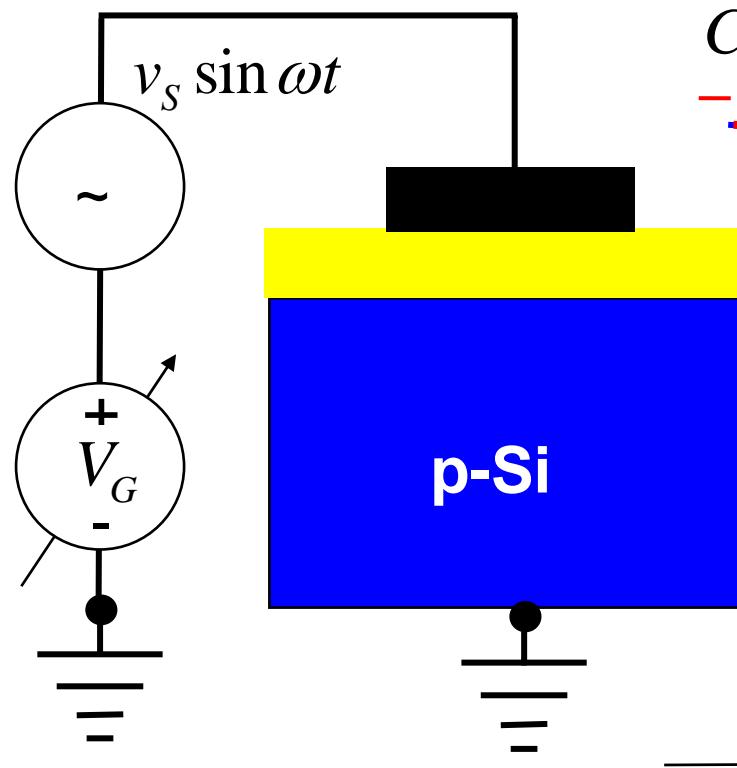
Lundstrom EE-612 F08

PURDUE
UNIVERSITY

outline

- 1) Review
- 2) Workfunction of poly gates
- 3) CV with poly depletion
- 4) Quantum mechanics and V_T
- 5) Quantum mechanics and C
- 6) Summary

1) review



quantum capacitance

- 1) What is quantum capacitance?
- 2) What is the quantum capacitance limit?

Boltzmann

$$n_S \propto e^{q\psi_S/k_B T}$$

T = 0K

$$n_S^* = \frac{m^*}{\pi \hbar^2} (E_F - E_C)$$

$$E_C = \text{const} - q\psi_S$$

$$C_S = \frac{dQ_I}{d\psi_S} = \frac{qn_S}{k_B T/q}$$

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

quantum capacitance: example

$$n_s \approx 10^{13} \text{ cm}^{-2}$$

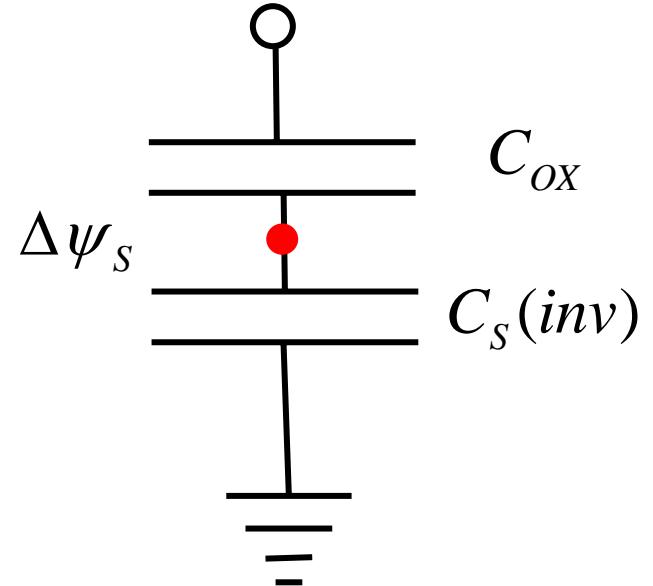
$$C_s = \frac{qn_s}{k_B T/q} \approx 6.5 \times 10^{-5} \text{ F/cm}^2$$

$$C_Q = q^2 \frac{m^*}{\pi h^2} \approx 2.5 \times 10^{-5} \text{ F/cm}^2$$

quantum C limit:

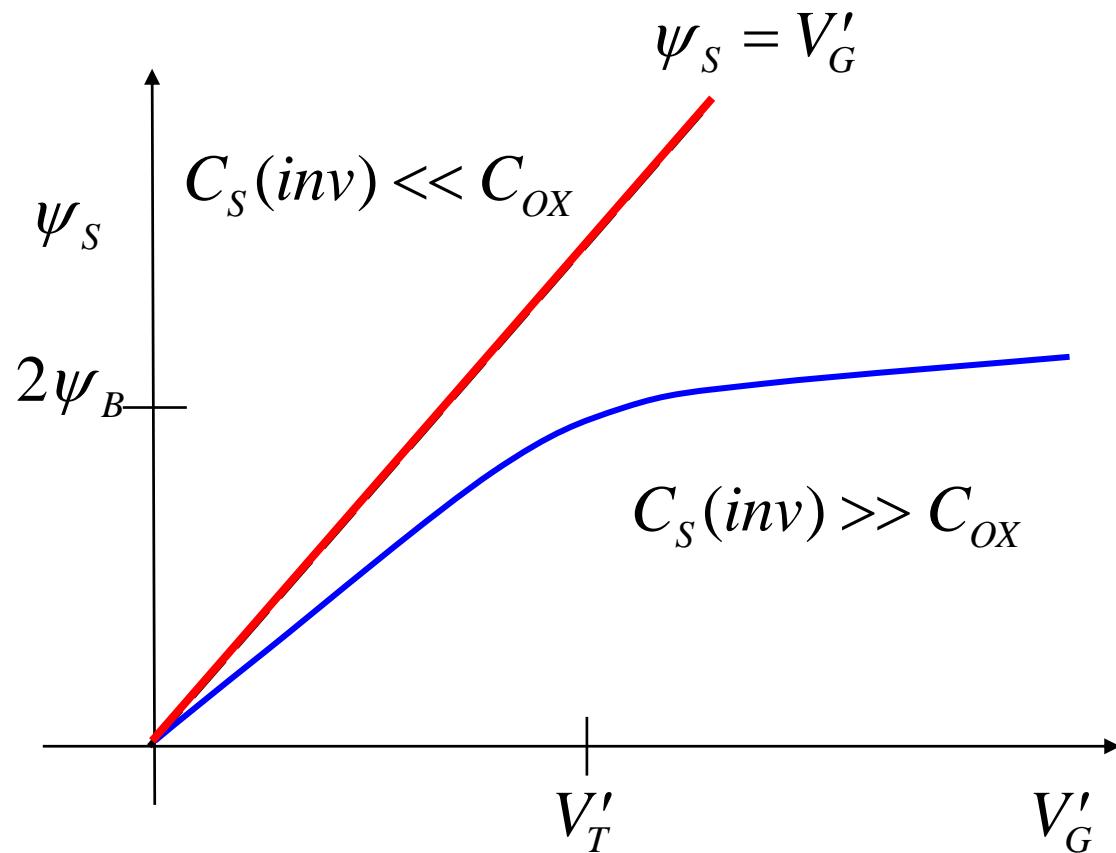
$$C_s \ll C_{ox}$$

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



$$\Delta\psi_s = \Delta V \frac{C_{ox}}{C_s(\text{inv}) + C_{ox}}$$

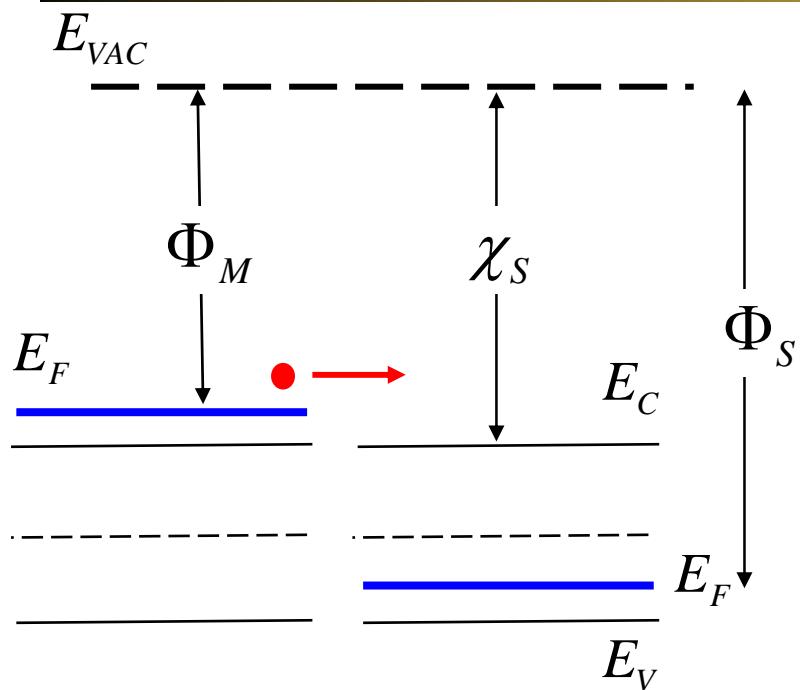
surface potential vs. gate voltage



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n^+ poly silicon gate



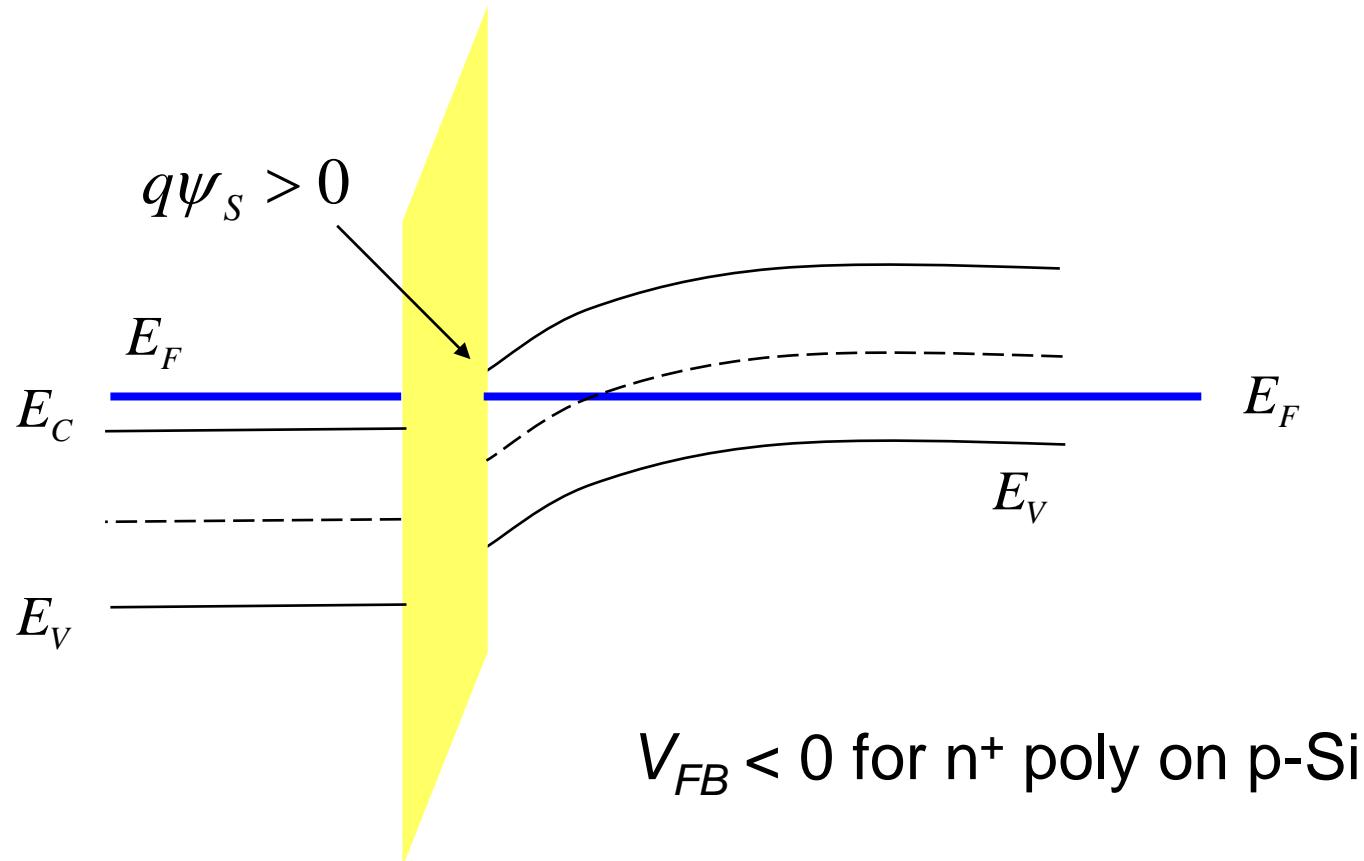
$$q\phi_m = \chi_{Si} - (E_F - E_C)$$

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

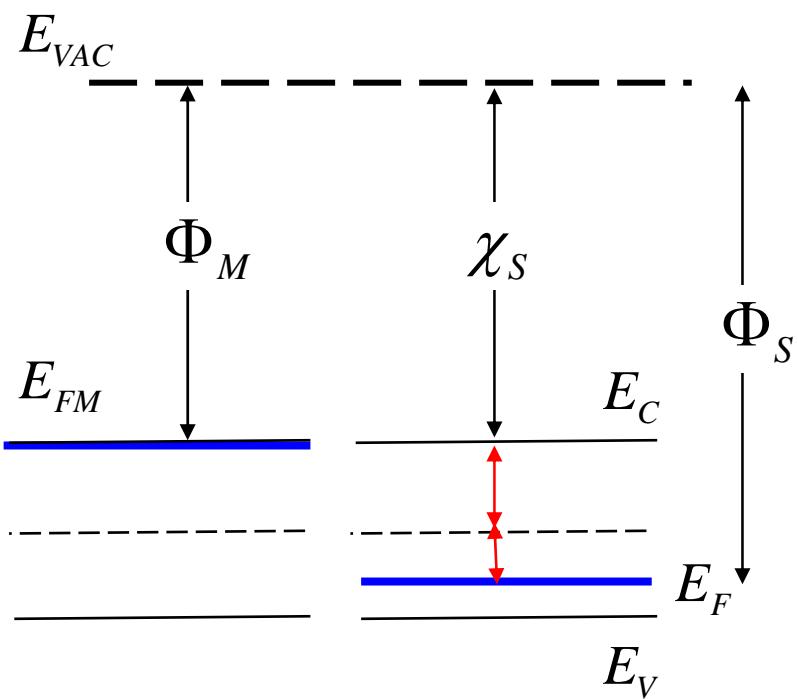
$$\phi_{ms} = -\frac{k_B T}{q} \ln\left(\frac{n_i^2}{N_A N_D}\right) = -V_{bi}$$

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

equilibrium e-band diagram



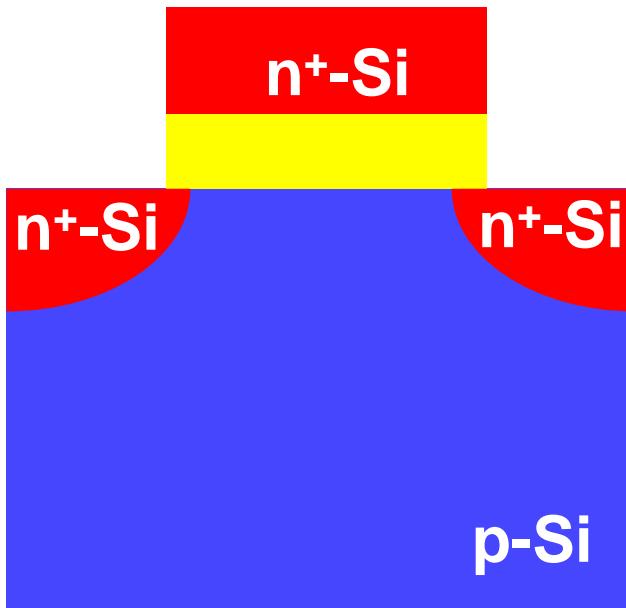
n^+ poly silicon gate (approximate)



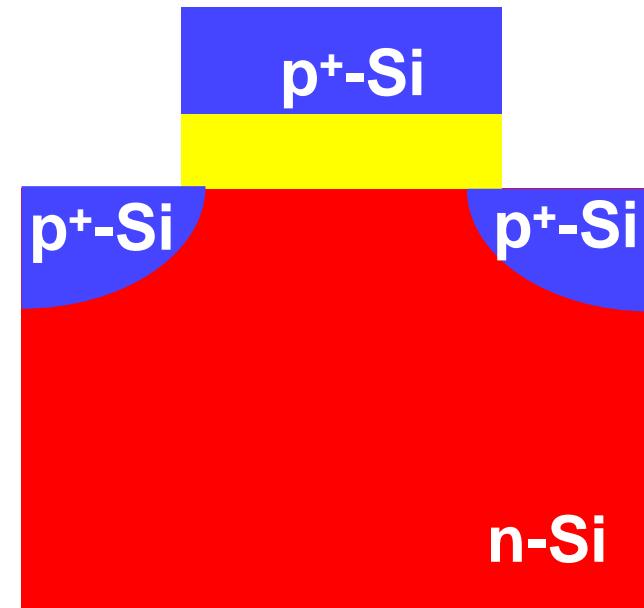
$$\phi_{ms} \approx -\frac{E_G}{2q} - \psi_B$$

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

CMOS technology



NMOS

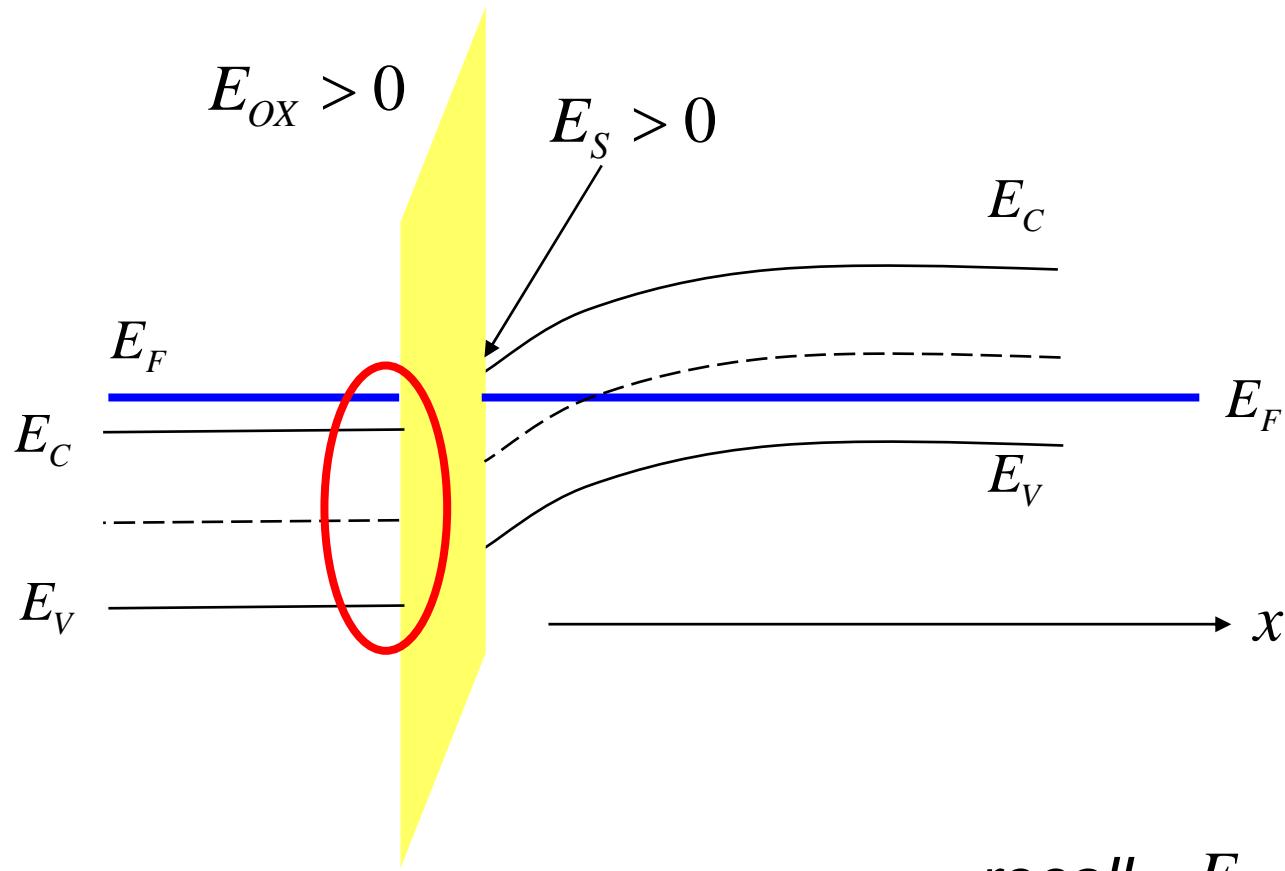


PMOS

outline

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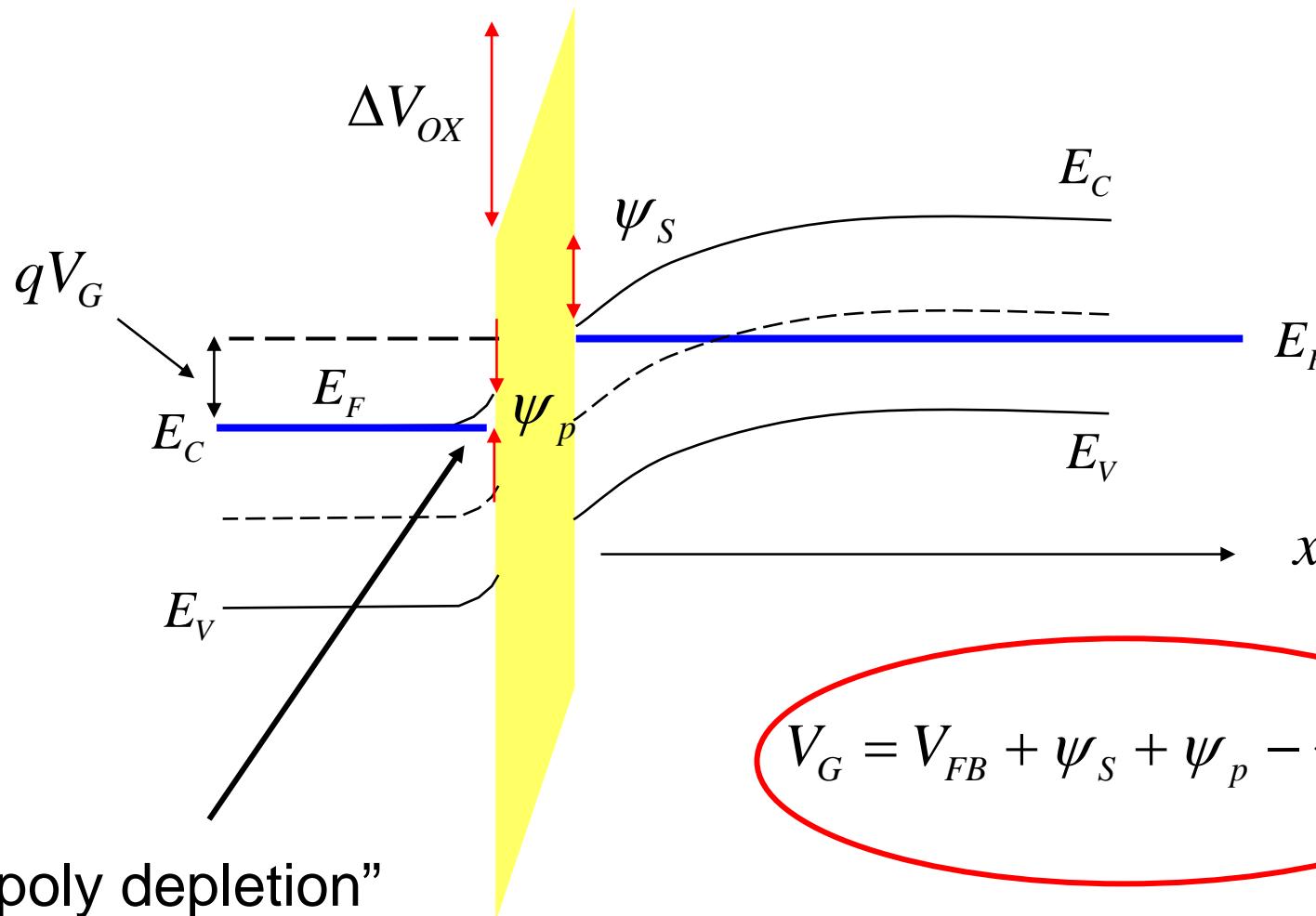
equilibrium e-band diagram (again)



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

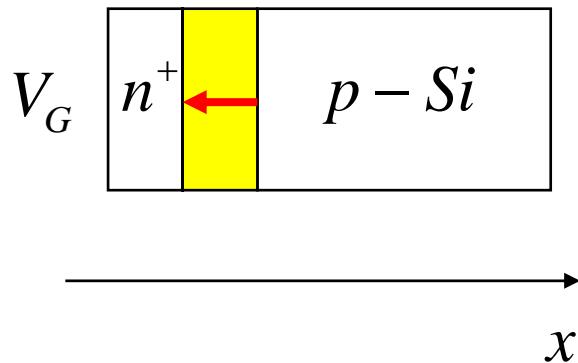
$$\text{recall } E_x = \frac{1}{q} \frac{dE_C}{dx}$$

e-band diagram for poly gate



"poly depletion"

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



1) $V_G < V_{FB}$

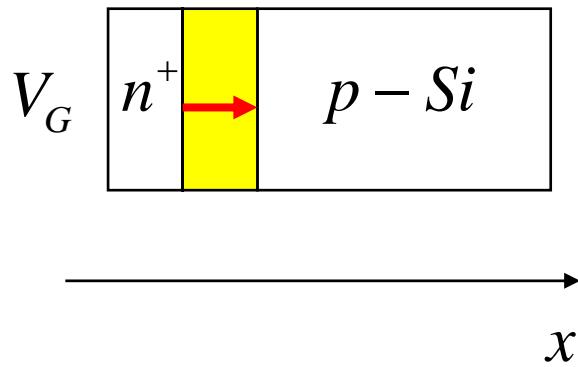
$E_{OX} < 0$

p-Si substrate accumulated

n⁺-poly gate accumulated

Exercise: draw the energy band diagram

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



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

$$E_{OX} > 0$$

$$\psi_S < 2\psi_B$$

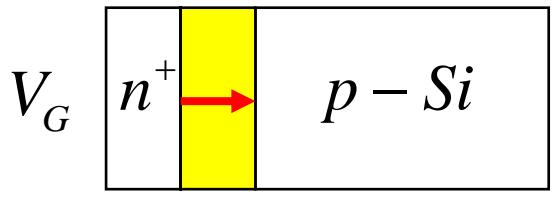
$$\psi_p < 2\psi_B(\text{poly})$$

p-Si substrate depleted

n⁺-poly gate depleted

Exercise: draw the energy band diagram

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



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

$$E_{OX} > 0$$

\xrightarrow{x}

$$\psi_S > 2\psi_B$$

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

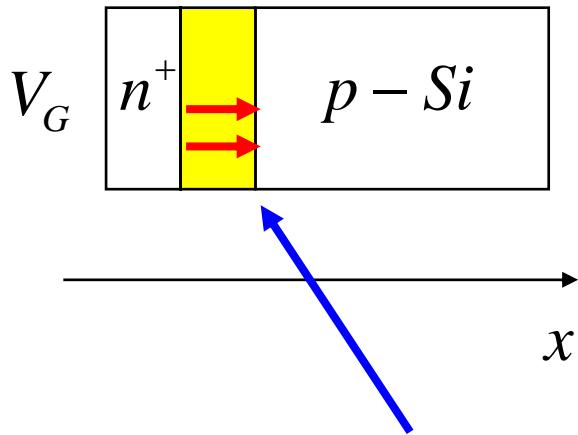
$$V_T = V_{FB} + 2\psi_B + \psi_p + \sqrt{2q\varepsilon_{Si}N_A(2\psi_B)} / C_{OX}$$

p-Si substrate ***inverted***

n^+ -poly gate depleted

Exercise: draw the energy band diagram

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



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

$$E_{OX} \gg 0$$

$$\psi_s > 2\psi_b$$

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

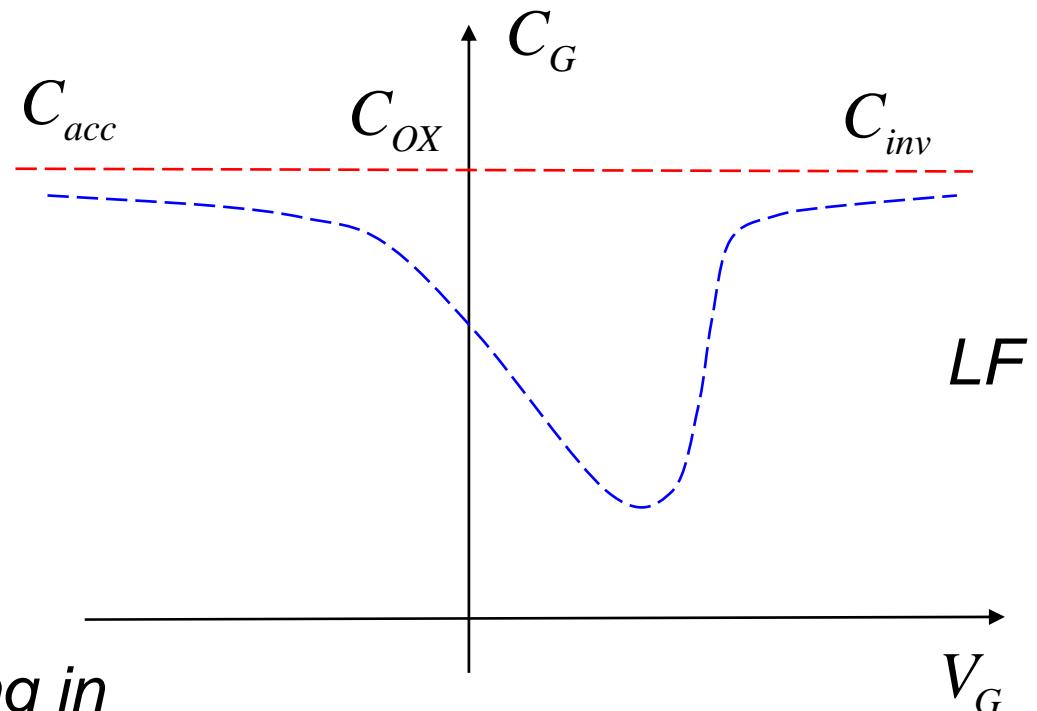
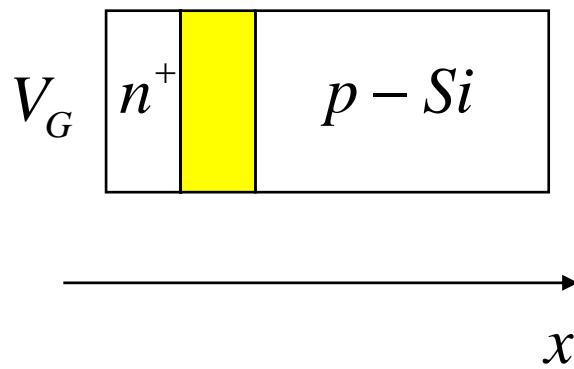
$$V_T(\text{poly}) = V_{FB} + 2\psi_b + 2\psi_b(\text{poly}) + \sqrt{2q\epsilon_{Si}N_D[2\psi_b(\text{poly})]} / C_{OX}$$

p-Si substrate ***inverted***

n^+ -poly gate ***inverted***

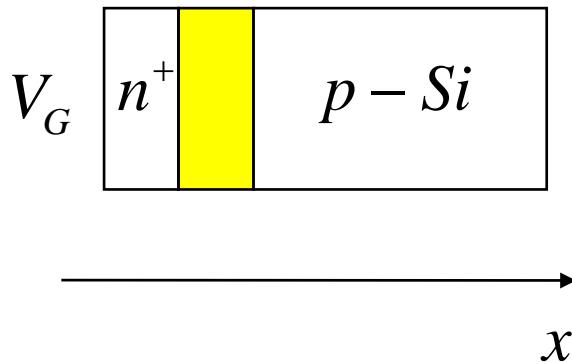
Exercise: draw the energy band diagram

C-V



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

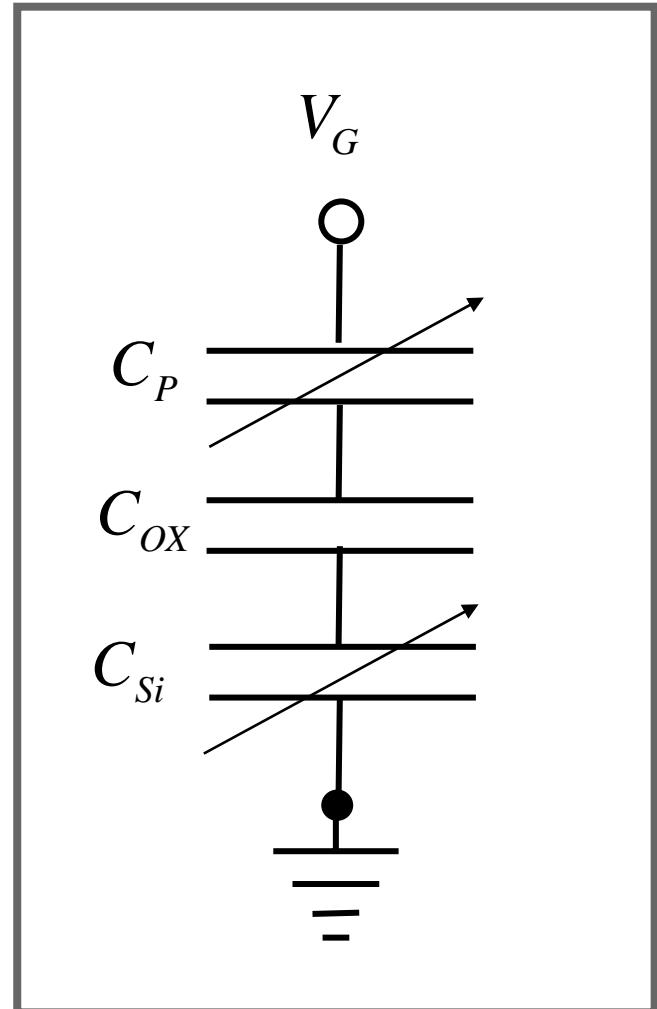
capacitance



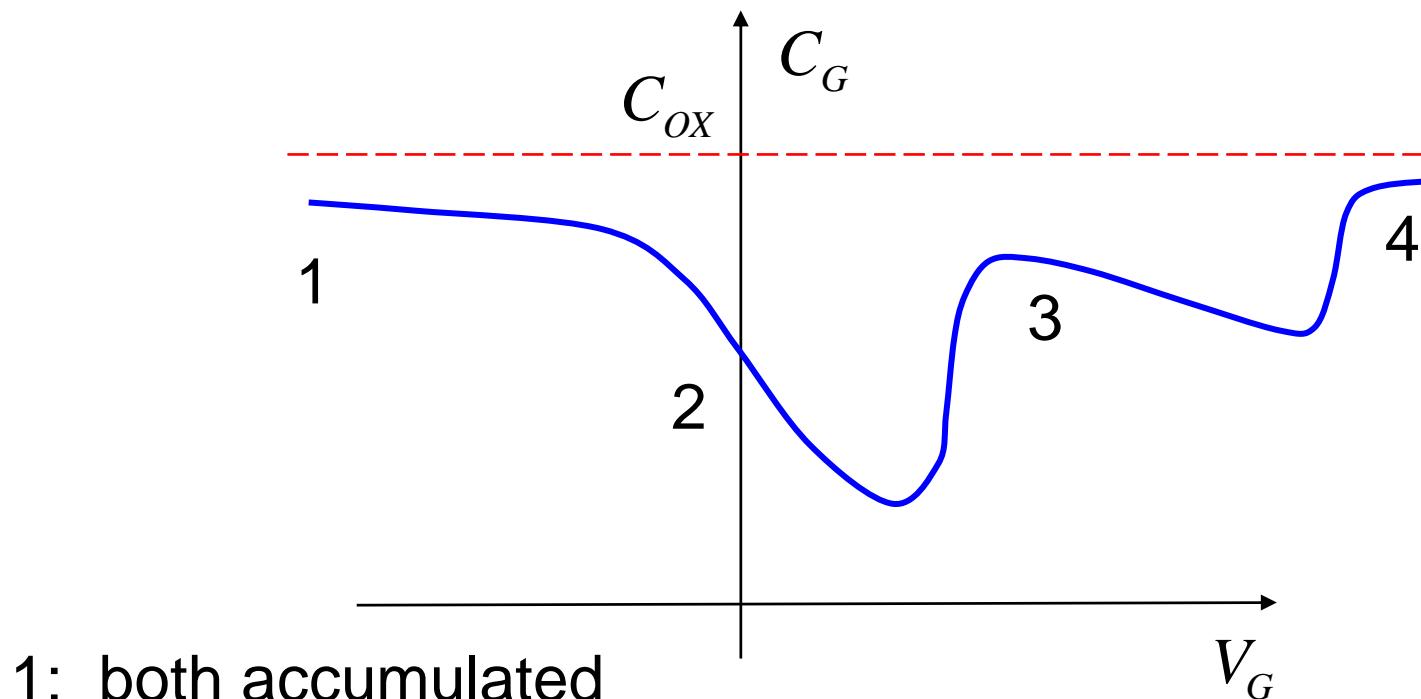
$$V_G = V_{FB} + \psi_s + \psi_p - \frac{Q_s}{C_{OX}}$$

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

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



capacitance vs. voltage



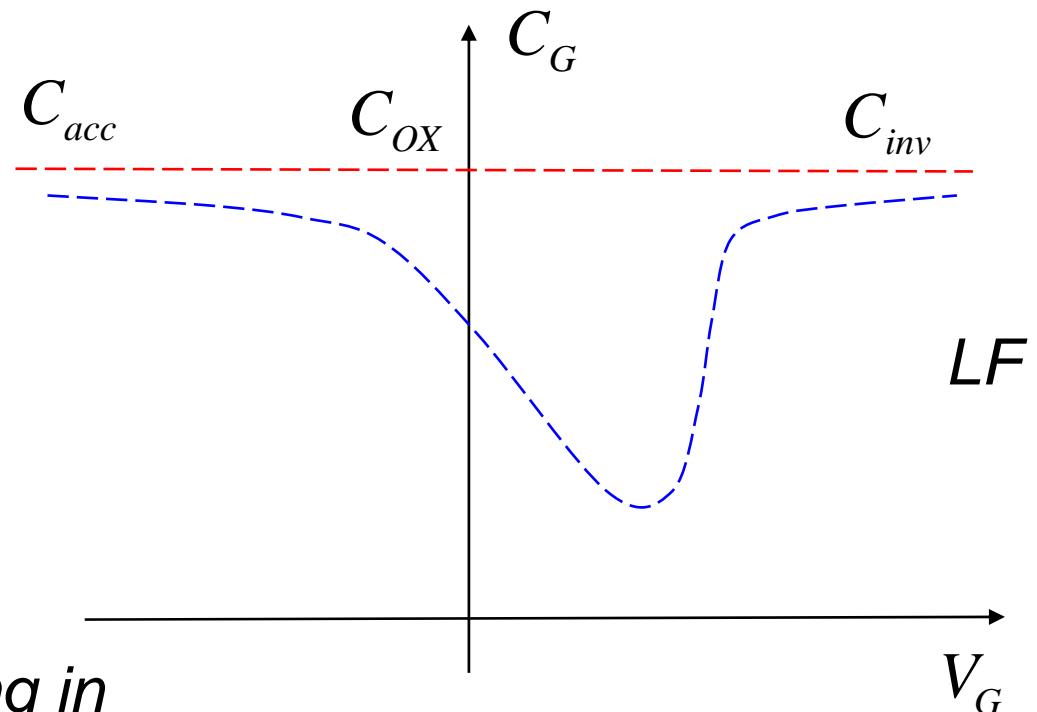
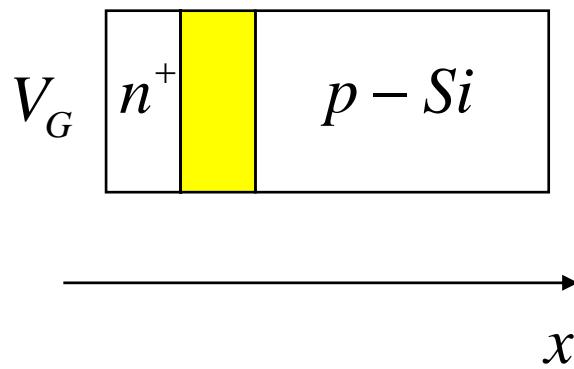
1: both accumulated

2: both depleted

3: substrate inverted, poly depleted

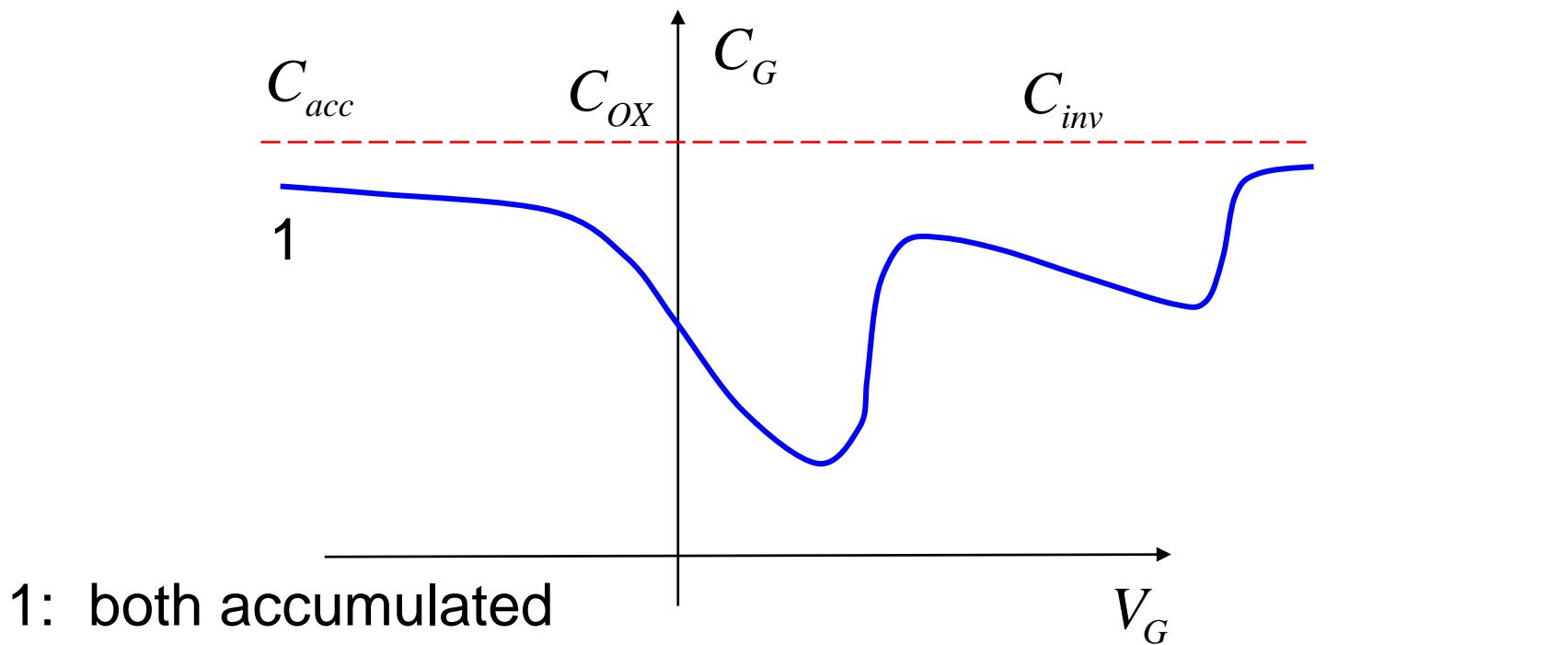
4: both inverted

C-V



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

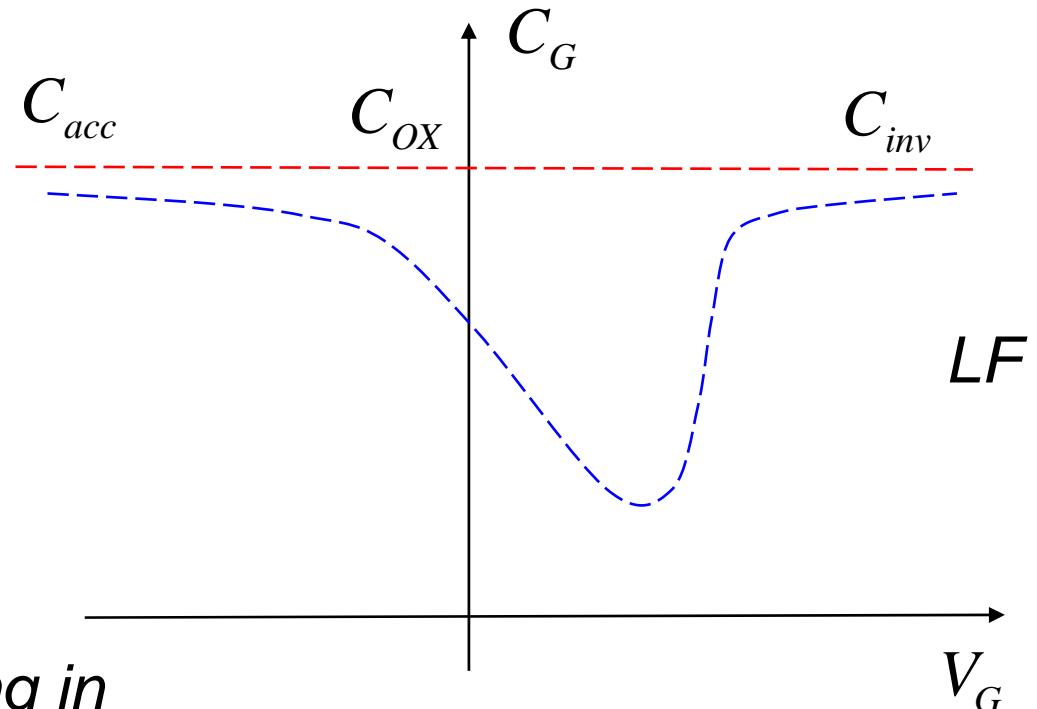
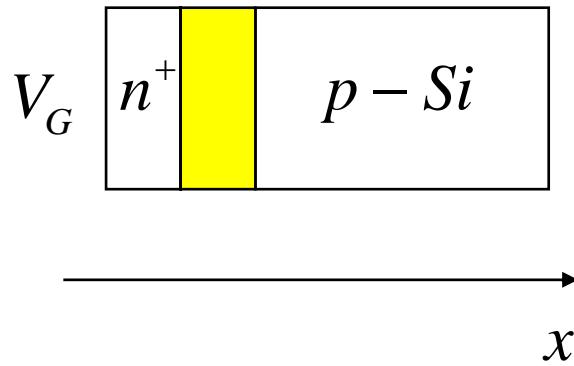
capacitance vs. voltage



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

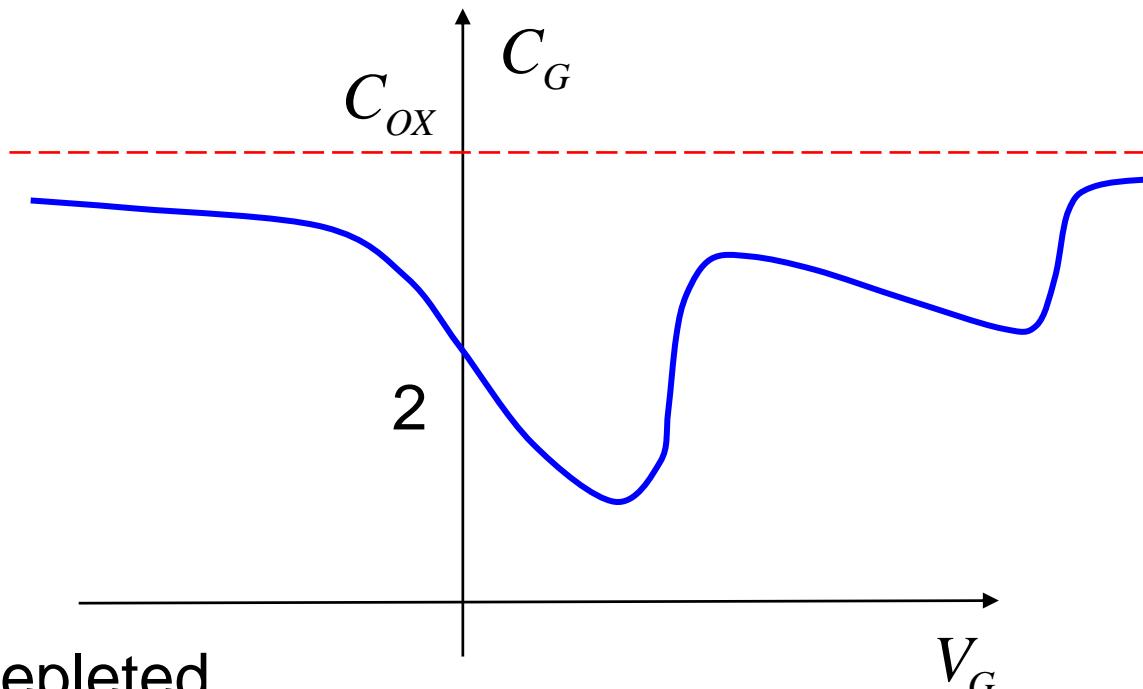
$$\frac{1}{C_G} = \frac{1}{C_{acc}/2} + \frac{1}{C_{ox}}$$

C-V



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

capacitance vs. voltage



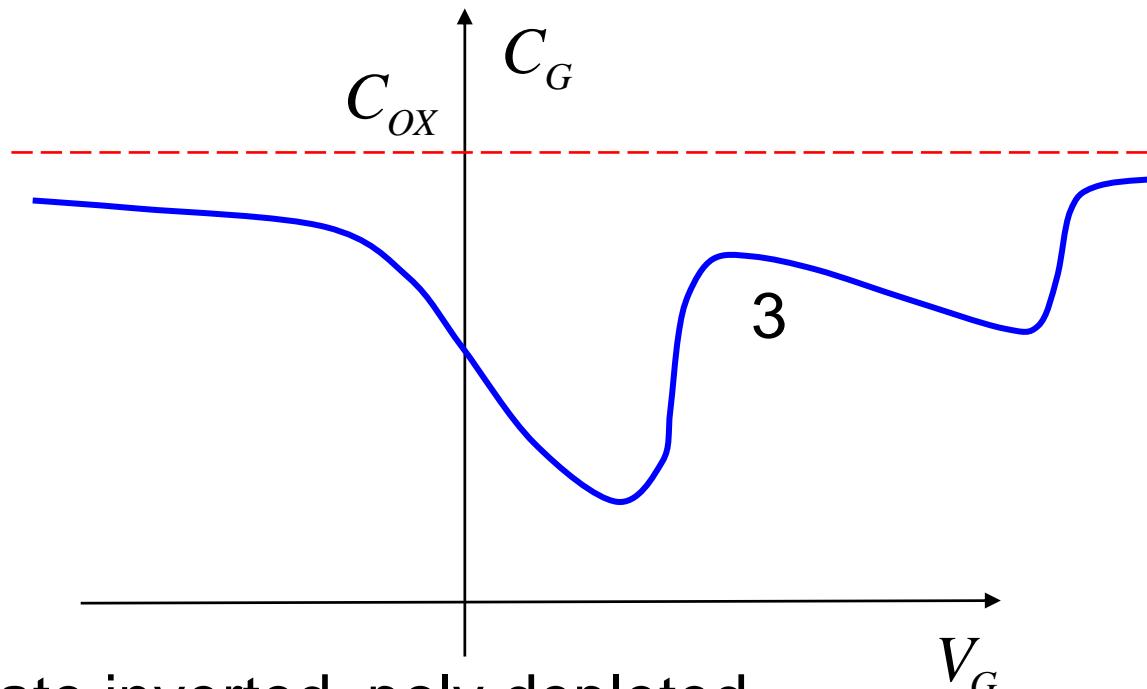
2: both depleted

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

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

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

capacitance vs. voltage



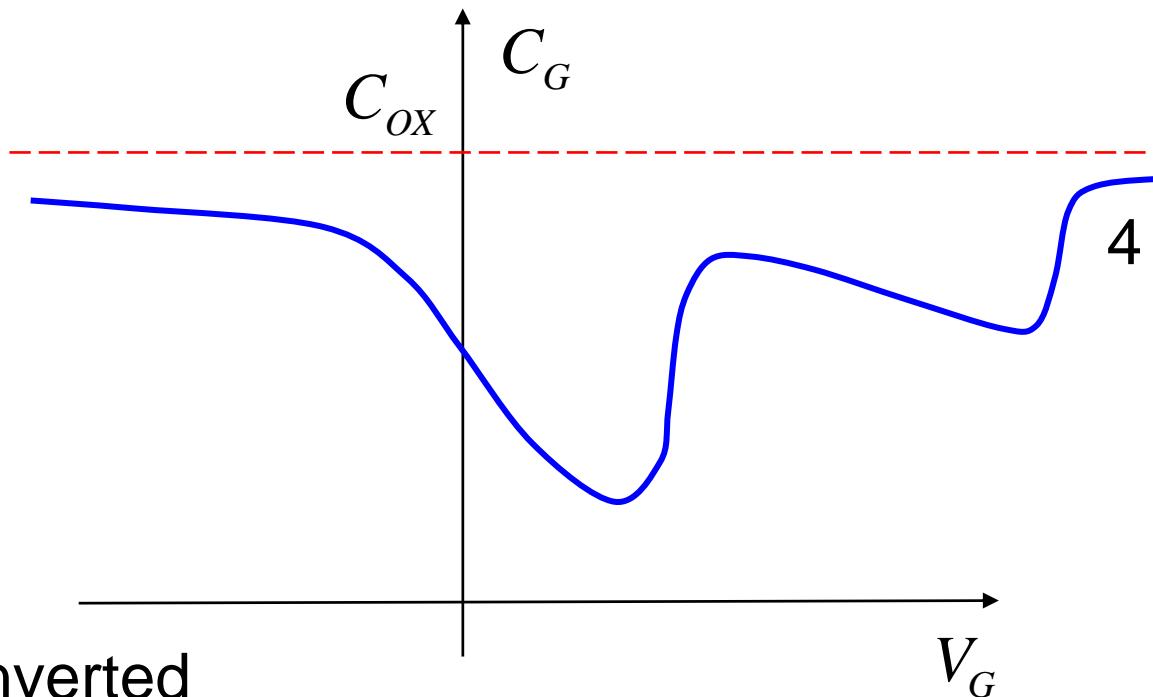
3: substrate inverted, poly depleted

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

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

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

capacitance vs. voltage



4: both inverted

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

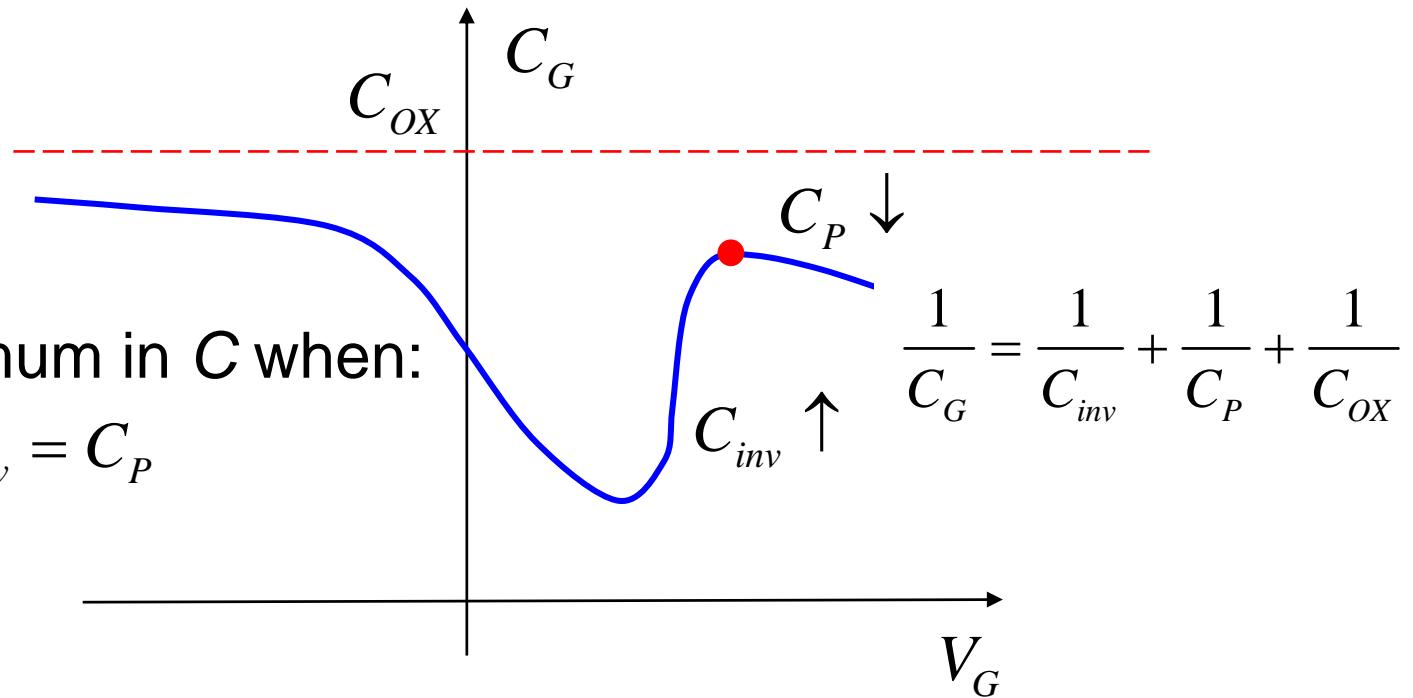
$$C_S = C_{inv} \quad C_P = C_{inv}$$

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

local maximum in C

local maximum in C when:

$$C_{inv} = C_P$$



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

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

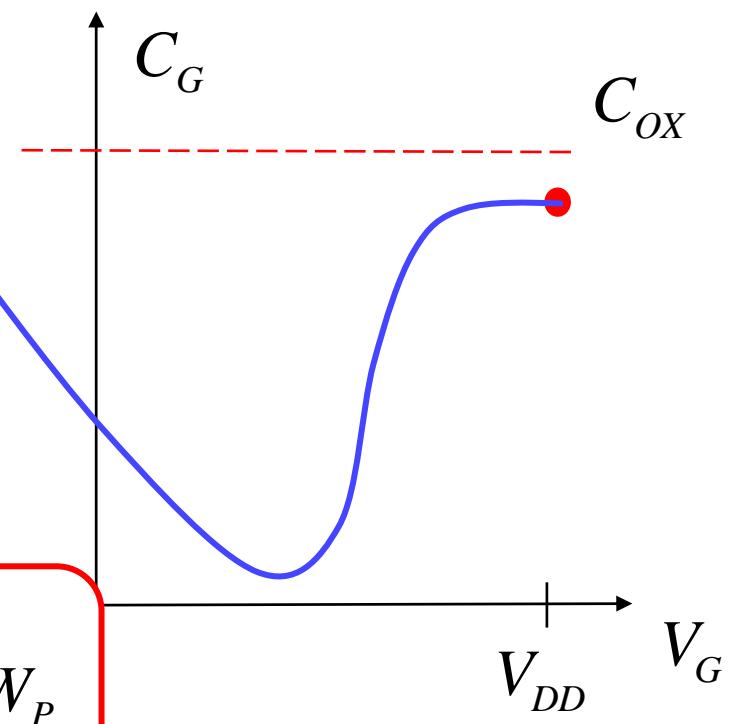
equivalent oxide thickness electrical

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

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

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

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



equivalent oxide thickness electrical (2006)

68 nm node (2007):

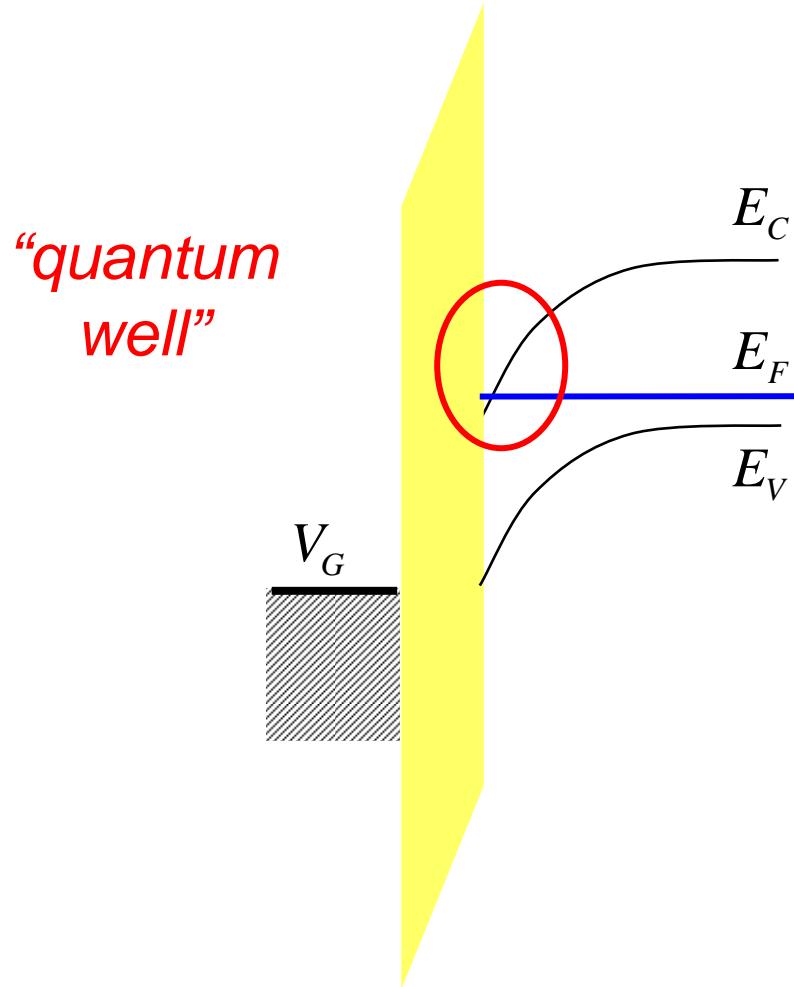
EOT = 1.1nm

$EOT_{elec} = 1.84\text{nm}$

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quantum confinement in an MOS-C



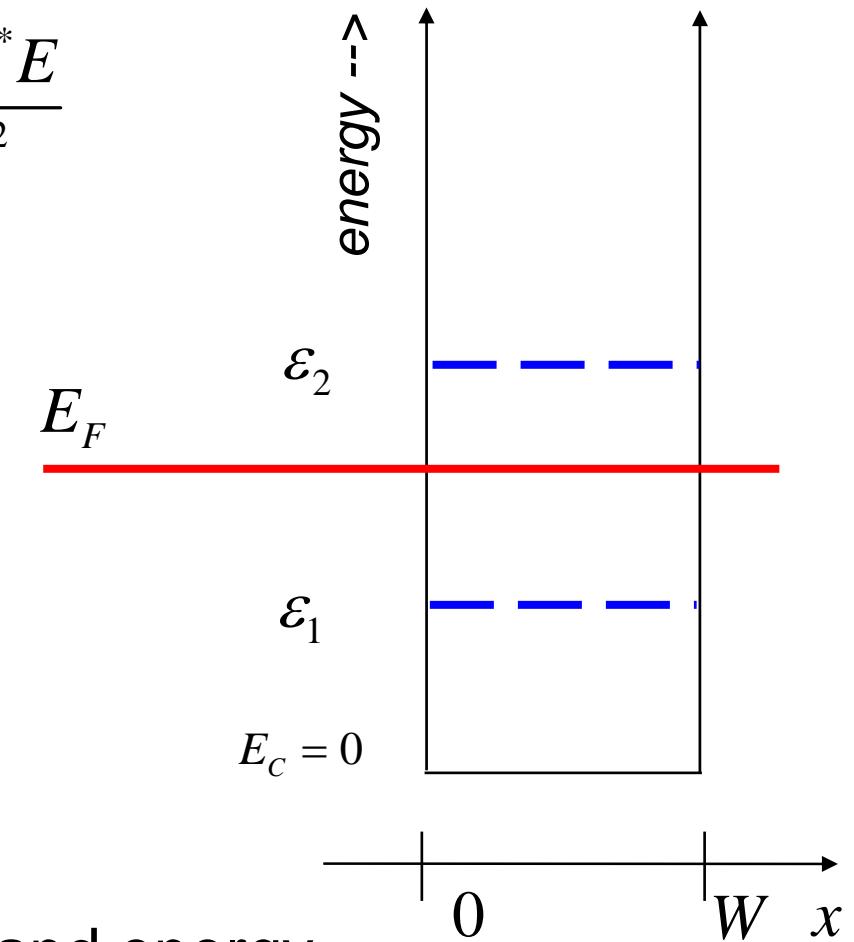
energy levels

$$\frac{d^2\psi(x)}{dx^2} + k^2\psi = 0 \quad k^2 = \frac{2m^*E}{\hbar^2}$$

$$\psi(x) = \sin k_n x$$

$$E_n = \frac{\hbar^2 k_n^2}{2m^*} = \frac{\hbar^2 n^2 \pi^2}{2m^* W^2}$$

light mass
narrow width \Rightarrow high subband energy



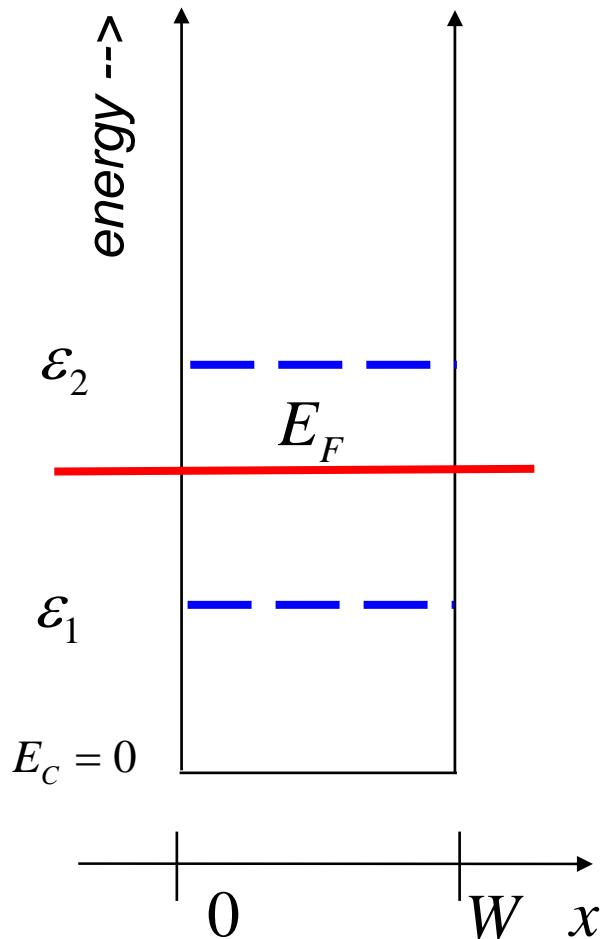
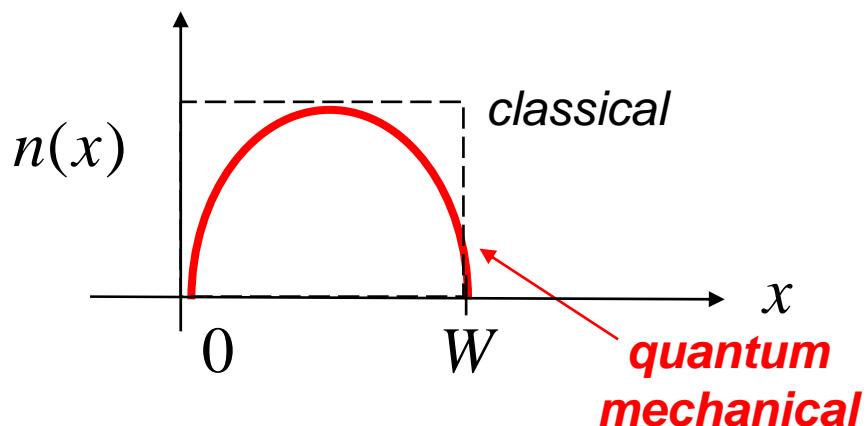
carrier densities

classically:

$$n(x) = N_C F_{1/2} \left[(E_F - E_C)/k_B T \right] \text{cm}^{-3}$$

quantum mechanically:

$$n(x) \sim \psi^*(x)\psi(x) \text{ cm}^{-3}$$

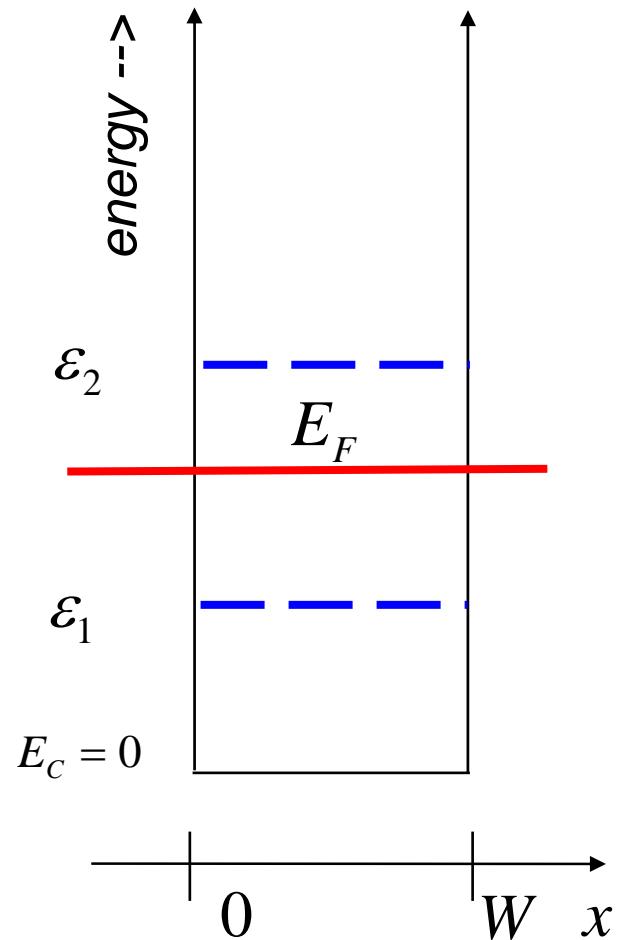
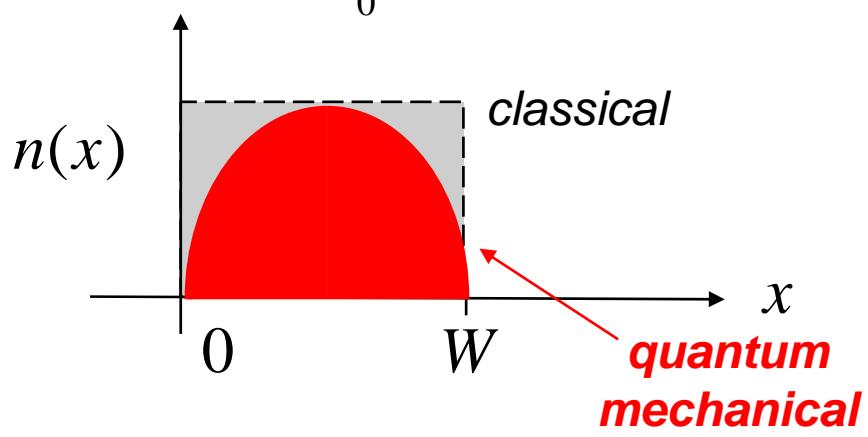


carrier densities (ii)

$$n_s = \int_0^W n(x) dx \text{ cm}^{-2}$$

quantum mechanical:

$$n_s \sim \int_0^W \psi^*(x)\psi(x)dx$$



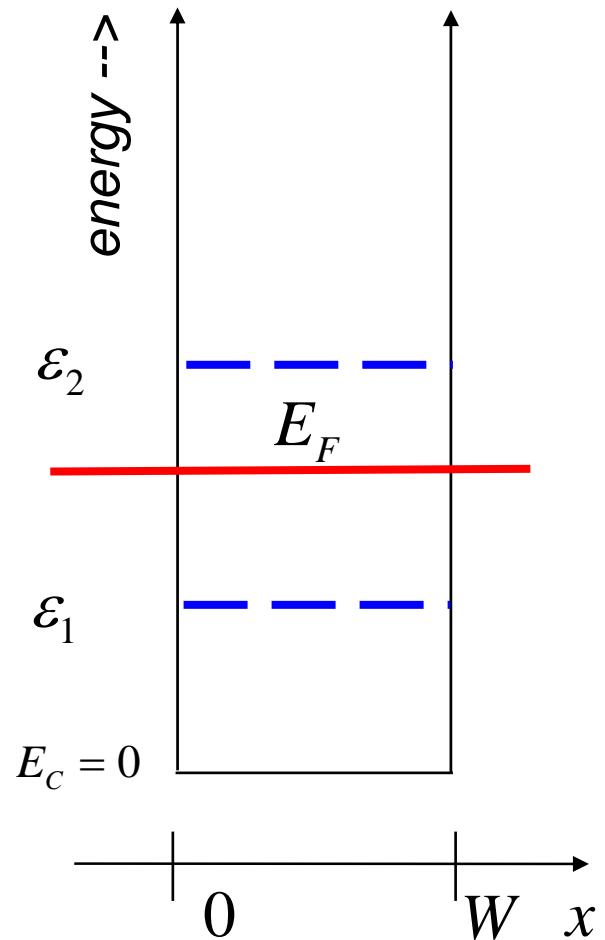
carrier densities (iii)

$$n_s = \int_0^W n(x) dx \text{ cm}^{-2}$$

$$n_s = \int_0^\infty g_{2D}(E) f_0(E) \text{ cm}^{-2}$$

$$g_{2D}(E) = \frac{m^*}{\pi \hbar^2}$$

$$n_s = \frac{m^* k_B T}{\pi \hbar^2} \ln \left(1 + e^{(E_F - \varepsilon)/k_B T} \right)$$



QM shift of V_T

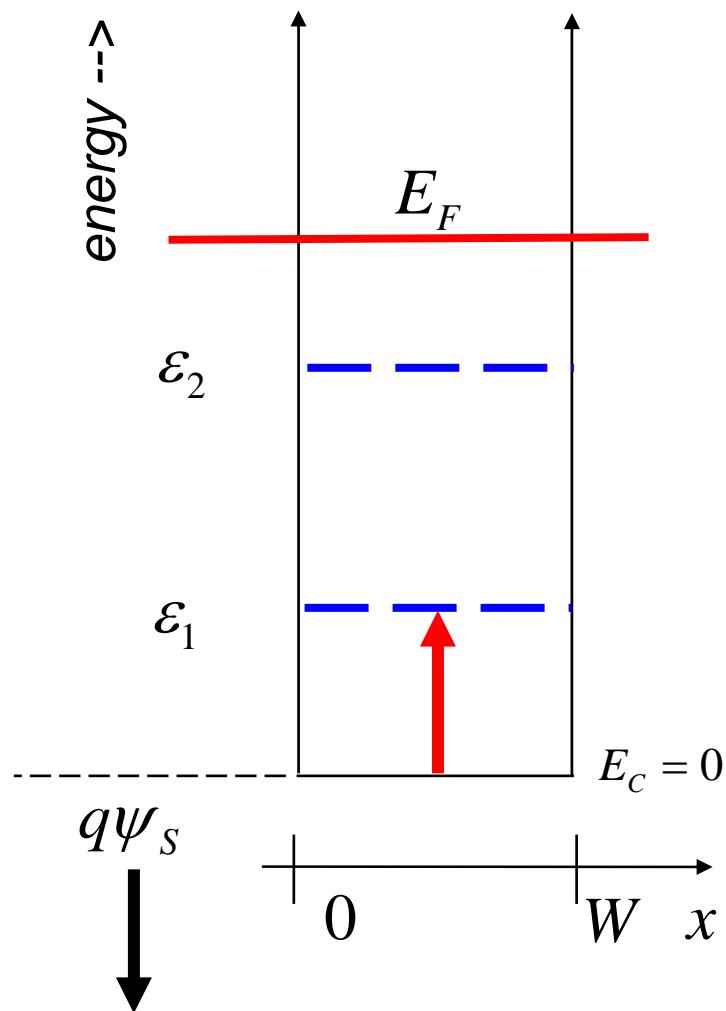
- to first order, QM simply raises E_C by ε_1
- ψ_S must increase by $\Delta\psi_S^{QM}$ to achieve inversion

$$\psi_S = 2\psi_B$$

\Rightarrow

$$\psi_S = 2\psi_B + \Delta\psi_S^{QM}$$

$$\Delta\psi_S^{QM} ; \quad \varepsilon_1 / q$$

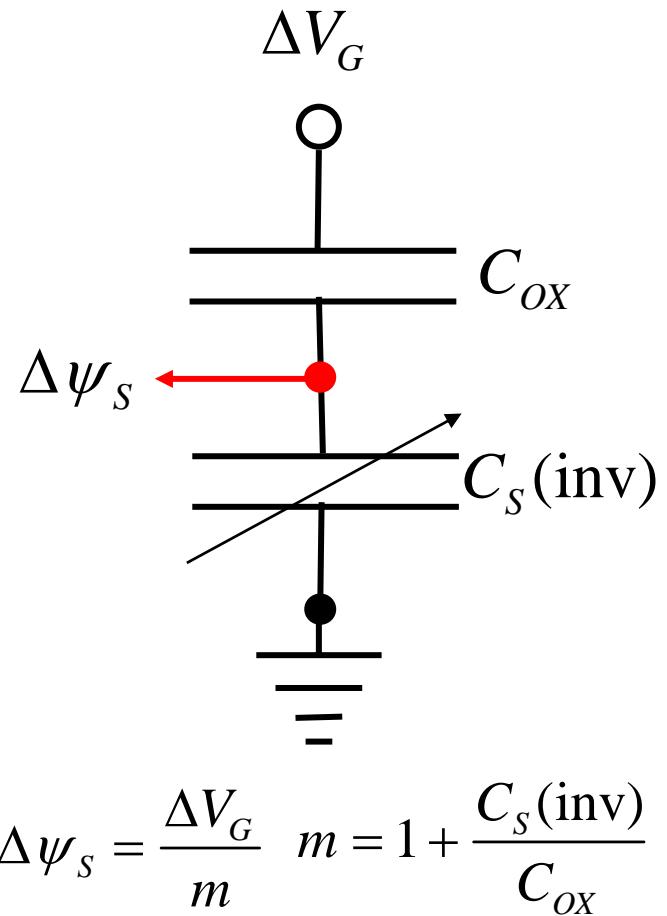


QM shift of V_T (ii)

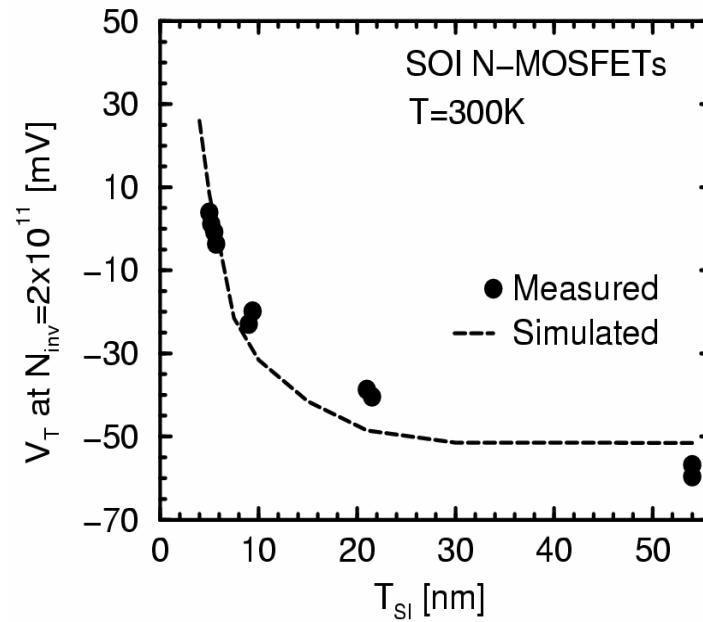
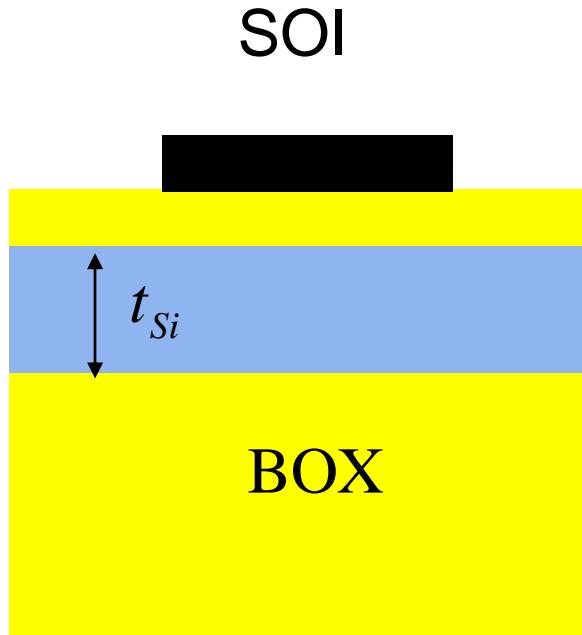
$$\Delta\psi_s^{QM} ; \varepsilon_1 / q$$

$$\Delta V_T = m \Delta\psi_s^{QM}$$

$$V_T = V_{FB} + 2\psi_B + m \Delta\psi_s^{QM} - \frac{Q_D (2\psi_B + \Delta\psi_s^{QM})}{C_{ox}}$$

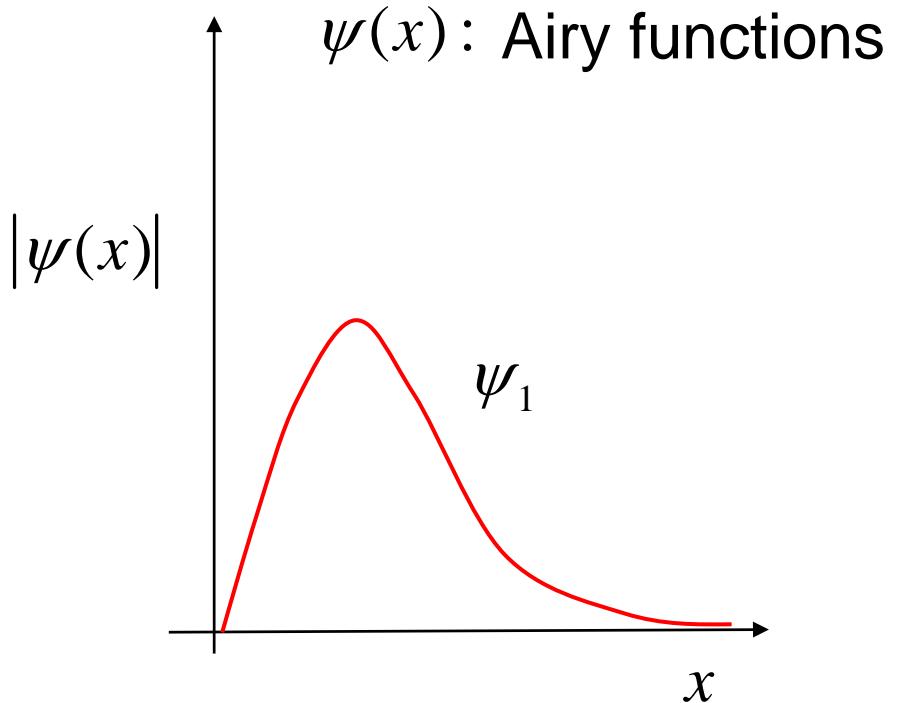
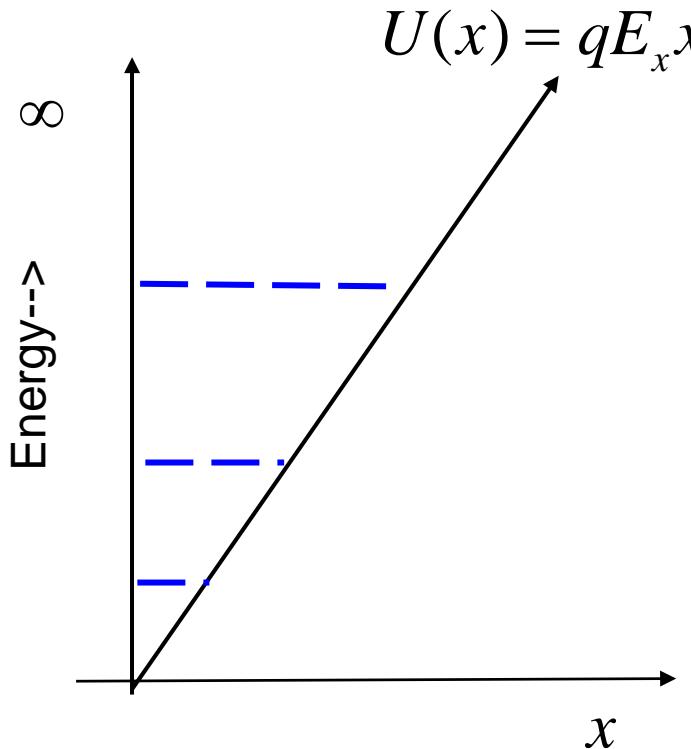


QM shift V_T (iv)



(D.Esseni et al. IEDM 2000 and TED 2001)

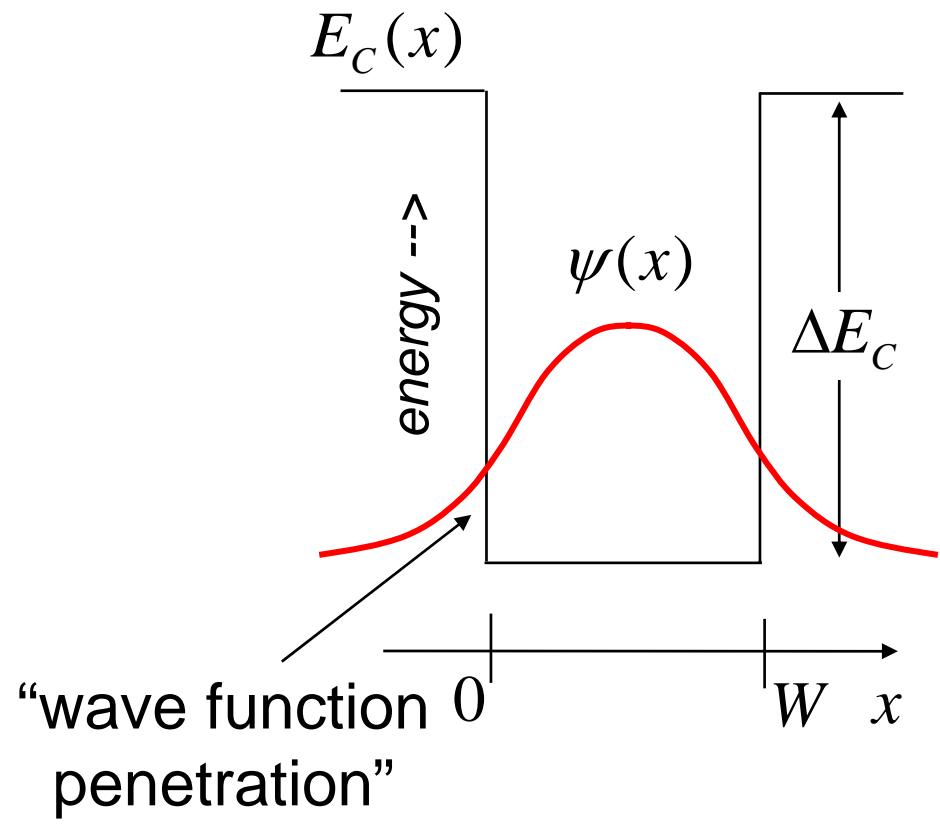
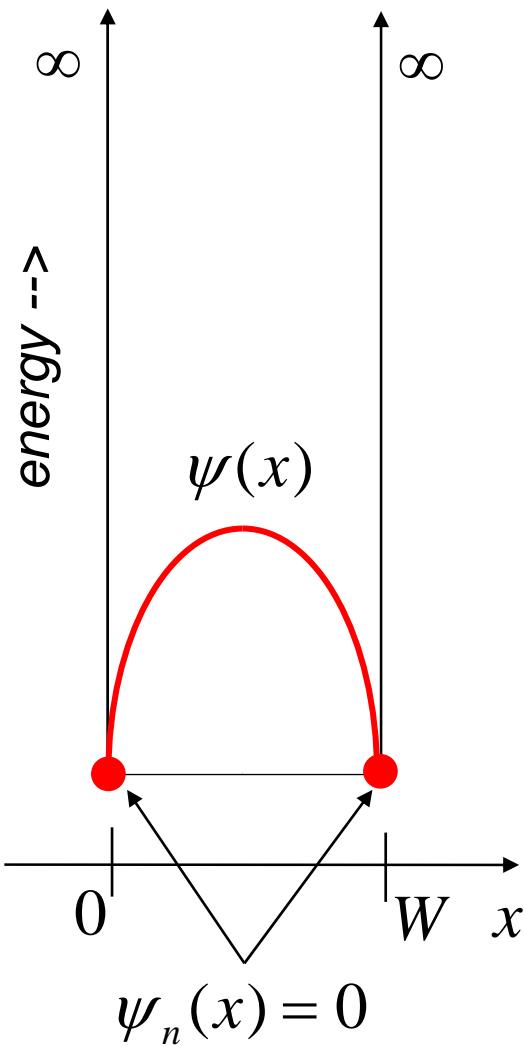
triangular quantum well



$$\varepsilon_i = \left[\frac{3hqE_x}{4\sqrt{2m^*}} \left(i + 3/4 \right) \right]^{2/3} \quad i = 1, 2, 3, \dots$$

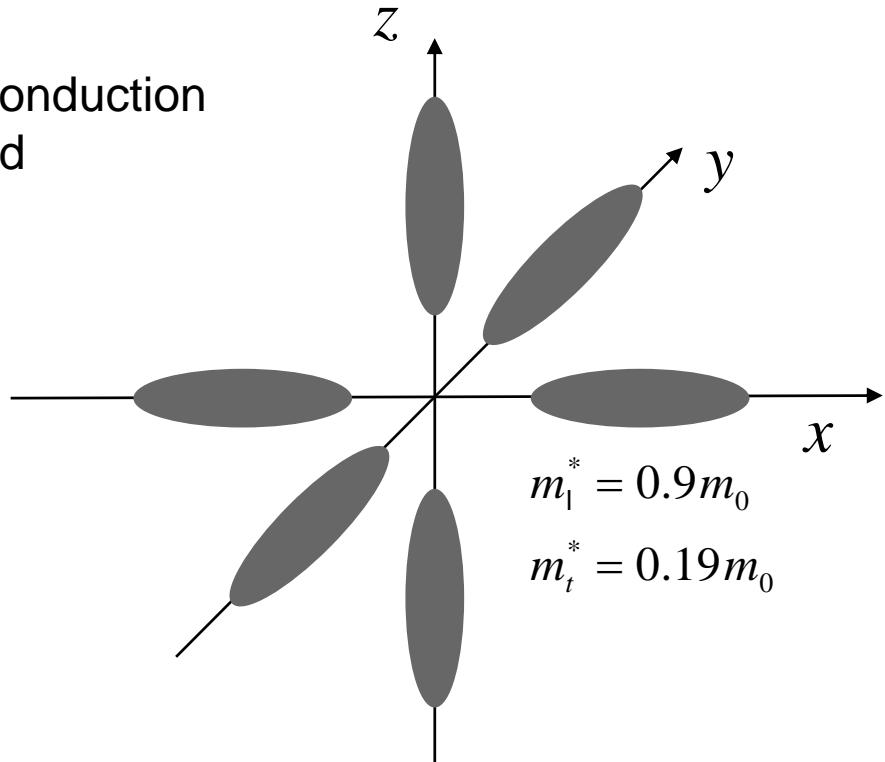
$$\langle x \rangle = \frac{2E_i}{3qE}$$

infinite vs. finite height quantum well



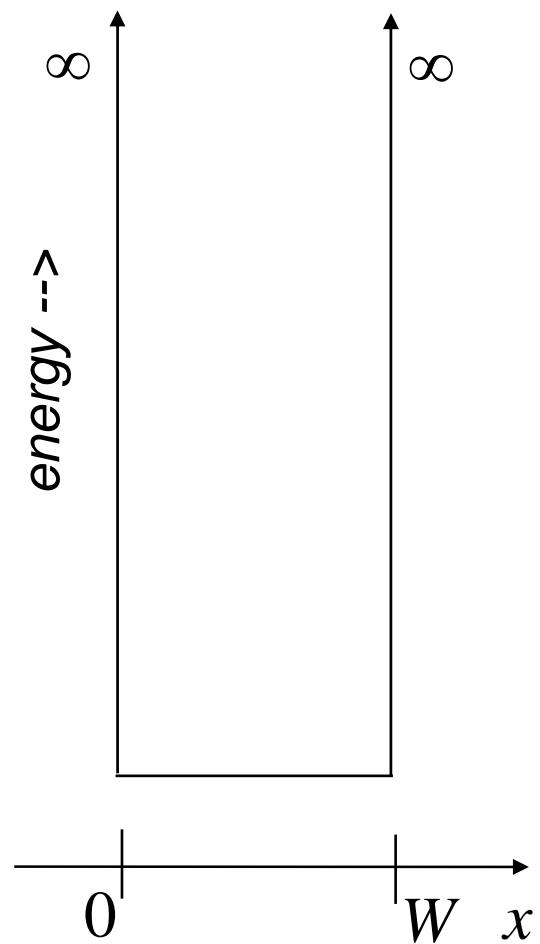
bandstructure effects on QM confinement

Si conduction band

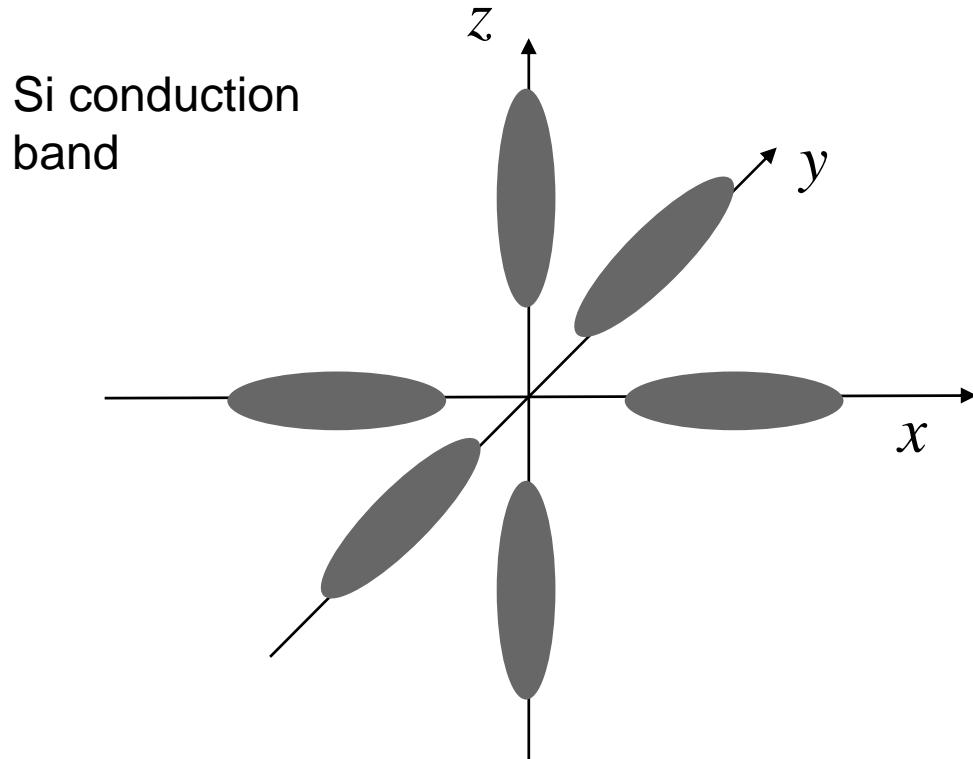


$$E_n = \frac{\hbar^2 n^2 \pi^2}{2m^*}$$

$$m^* = ?$$

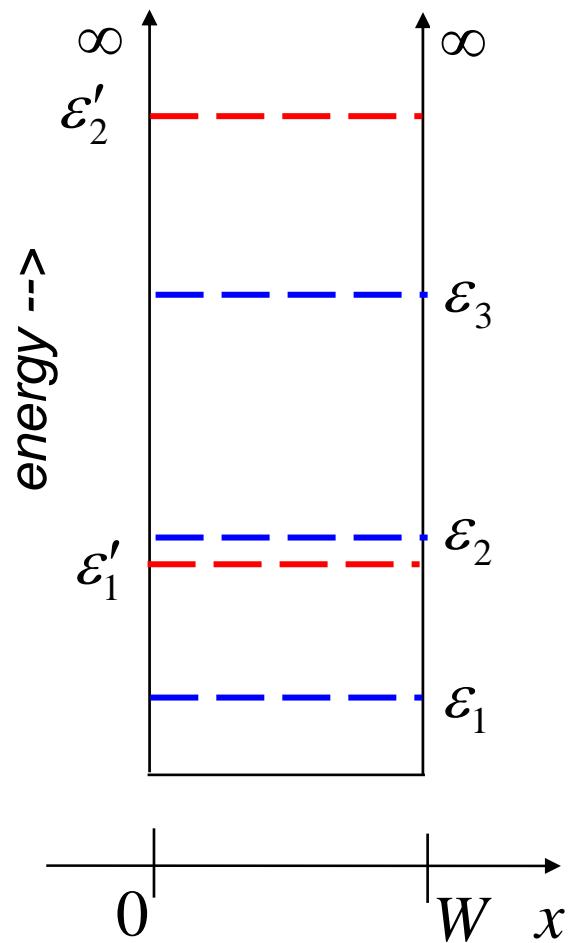


bandstructure effects on QM confinement



unprimed ladder: $m^* = m_l^*$ $g = 2$

primed ladder: $m^* = m_t^*$ $g = 4$



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semiconductor capacitance

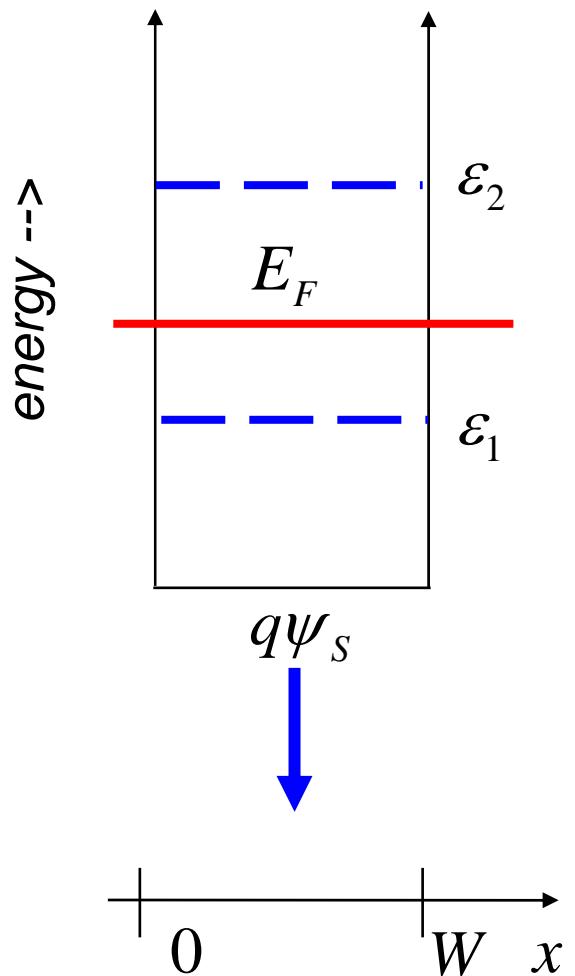
$$C_s(\text{inv}) \equiv \frac{\partial(-Q_i)}{\partial\psi_s}$$

$$Q_i = qn_s = q \frac{m^* k_B T}{\pi \hbar^2} \ln \left(1 + e^{(E_F - E_C + \varepsilon_1)/k_B T} \right)$$

$$E_C = \text{const} - q\psi_s$$

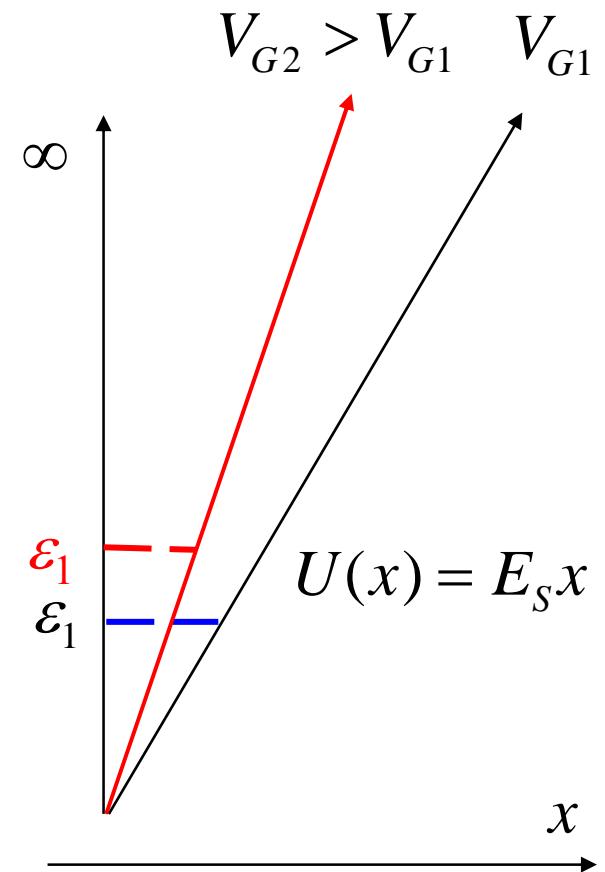
$$C_s \approx C_Q$$

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



C_s in a bulk semiconductor

$$C_s = C_Q \left[1 - \frac{\partial(\epsilon_1 / q)}{\partial \psi_s} \right] < C_Q$$



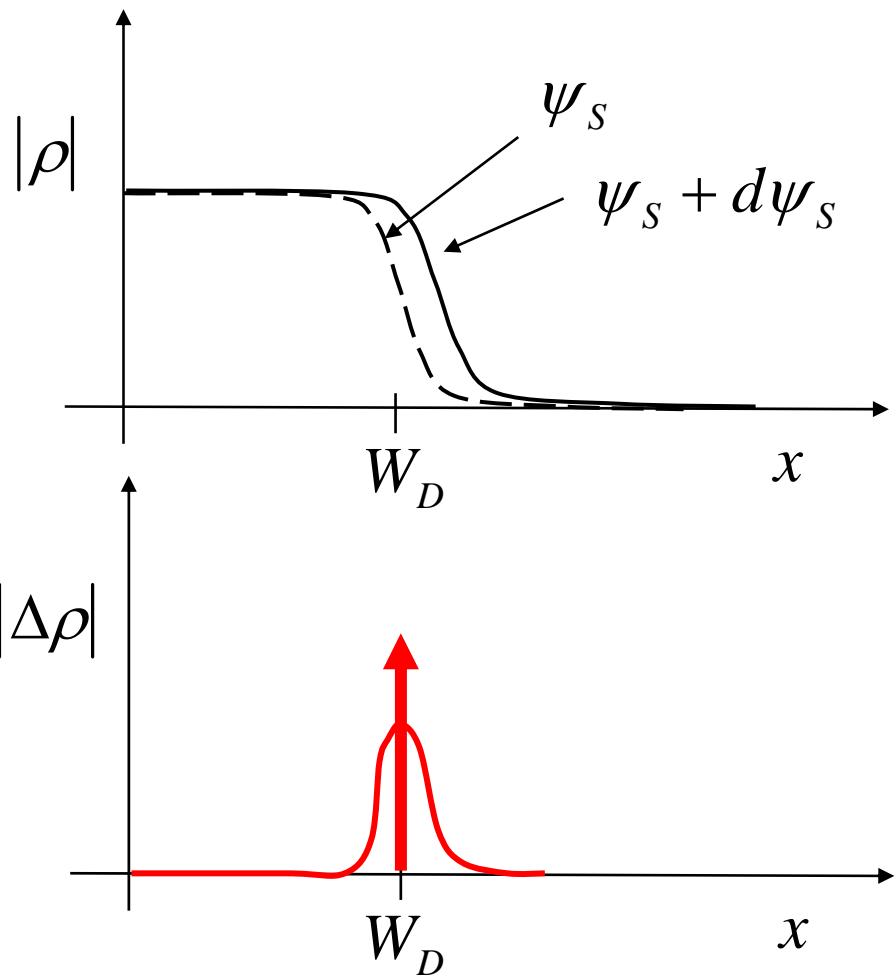
another view of how QM affects $C_S(\text{inv})$

$$0 < \psi_s < 2\psi_b$$

$$C_s = C_d$$

$$C_d = \frac{|\Delta\rho|}{\Delta\psi_s}$$

$$C_d = \frac{\epsilon_{Si}}{W_D}$$



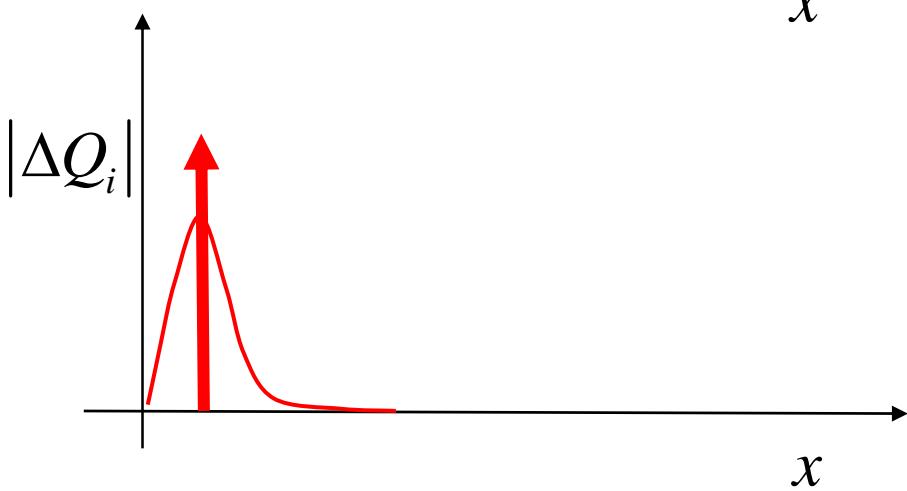
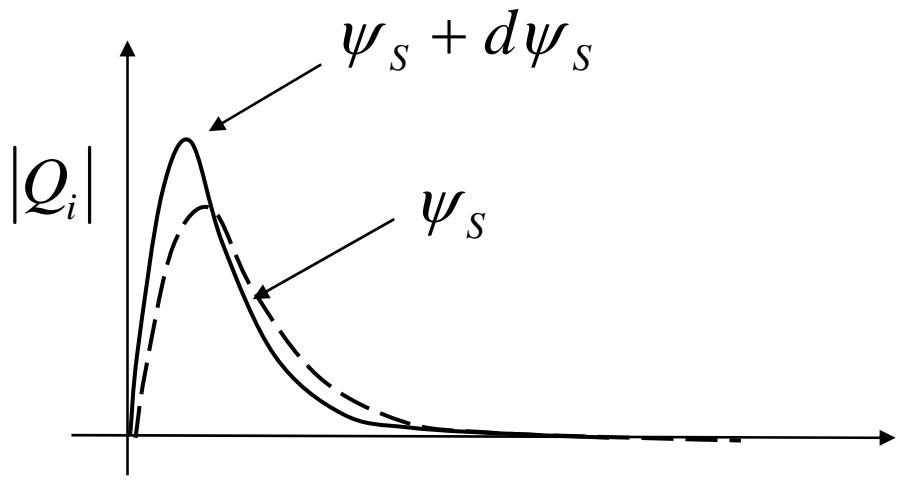
another view: quantum mechanical

$$2\psi_B < \psi_S$$

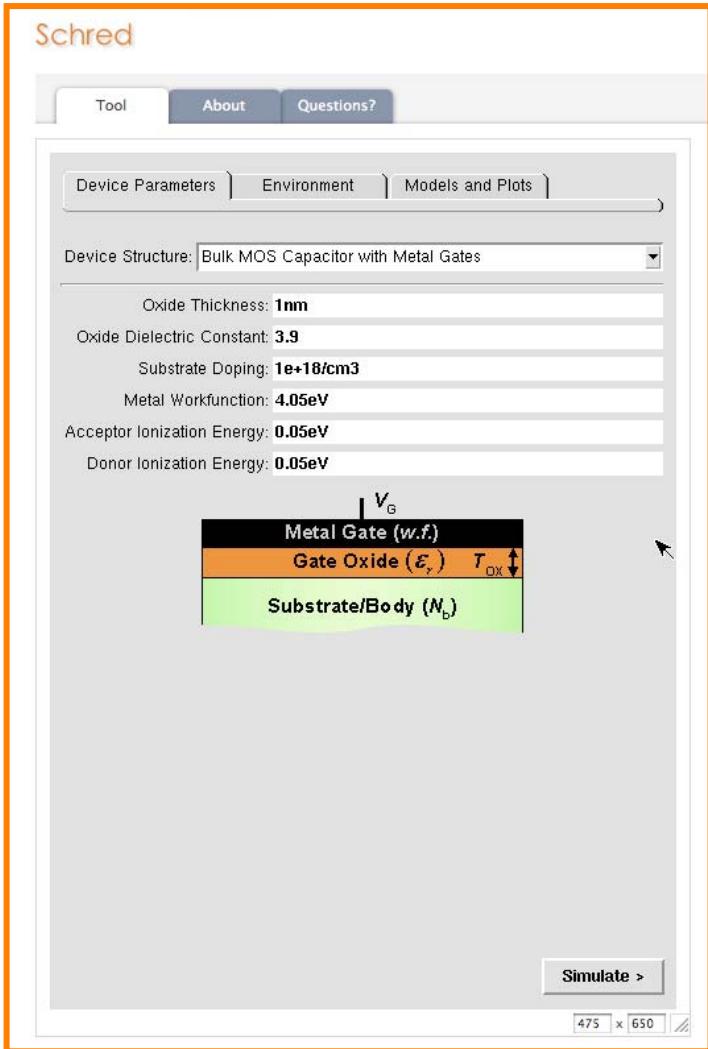
$$C_s = C_s(\text{inv})$$

$$C_s(\text{inv}) = \frac{|\Delta Q_i|}{\Delta \psi_S}$$

$$C_s(\text{inv}) = \frac{\epsilon_{Si}}{t_{inv}(QM)}$$



Schrödinger-Poisson simulation



HW3

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outline

- 1) Review
- 2) Workfunction of poly gates
- 3) CV with poly depletion
- 4) Quantum mechanics and V_T
- 5) Quantum mechanics and C
- 6) Summary**

summary

- 1) Polysilicon depletion lowers the gate cap and increases the effective electrical thickness of the gate insulator.
- 2) Quantum confinement increases V_T
- 3) Quantum confinement lowers the gate cap and further increases the effective electrical thickness of the gate insulator.