Essentials of MOSFETs

Unit 3: MOS Electrostatics

Lecture 3.10: Unit 3 Recap

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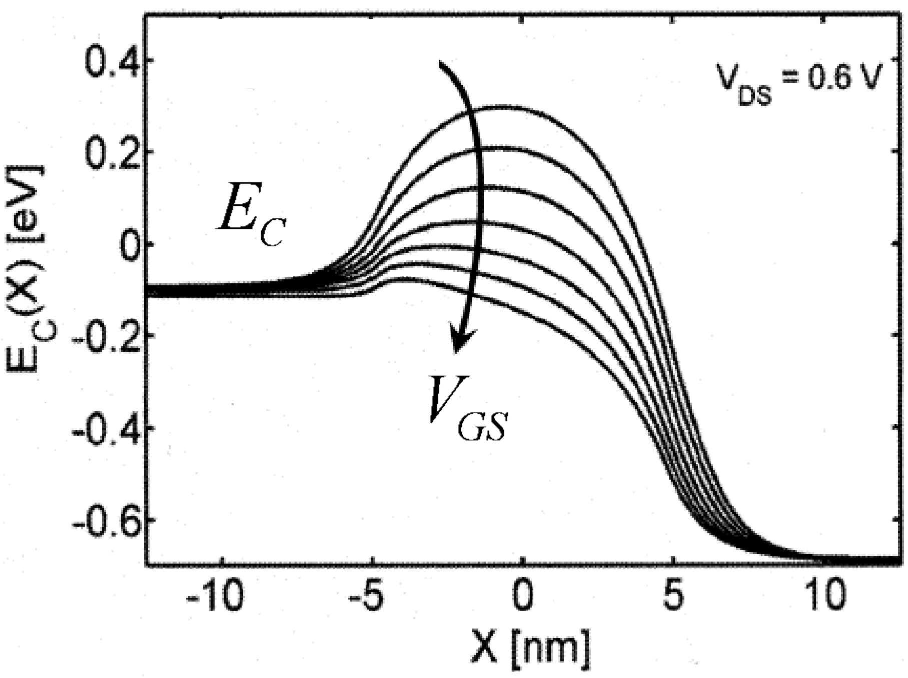
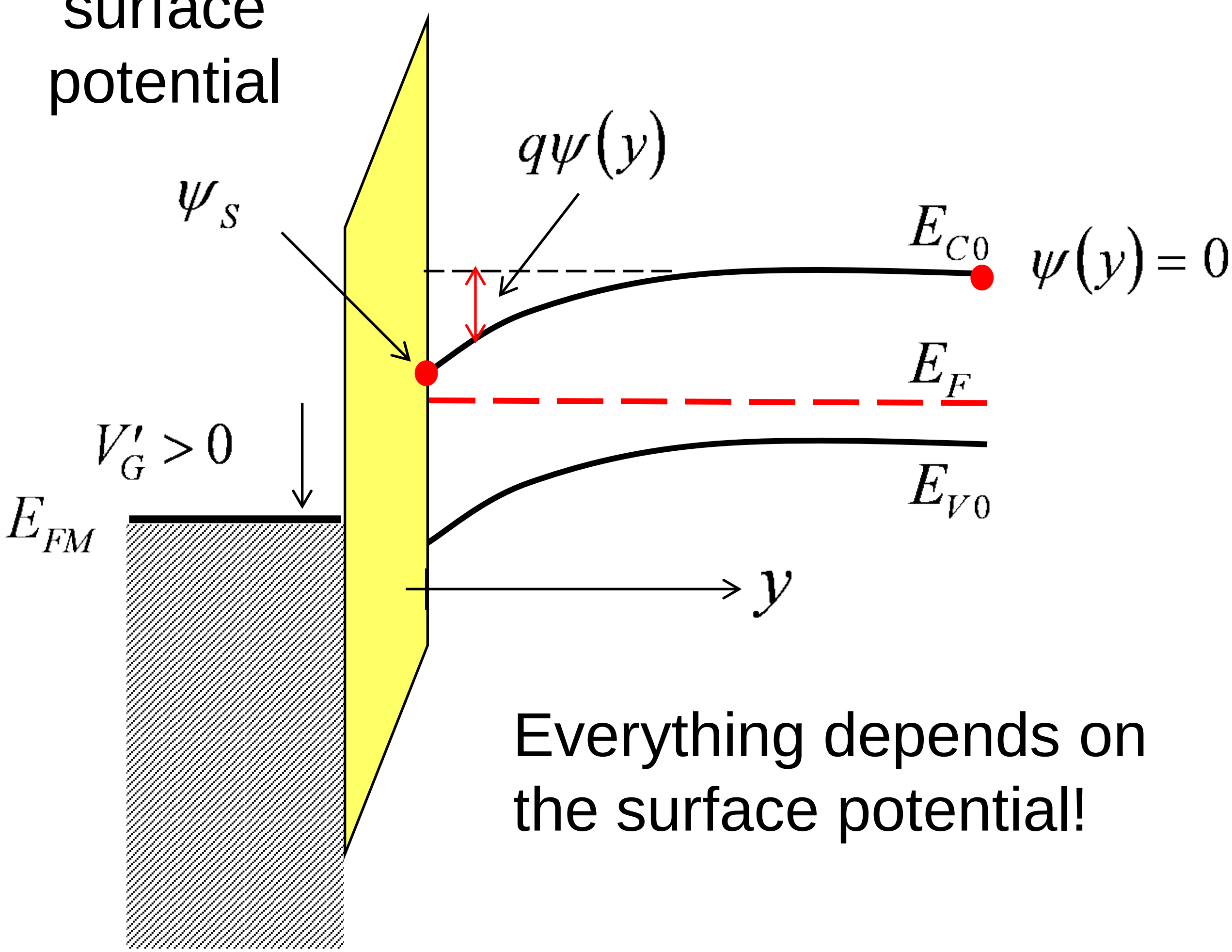
Unit 3



Unit 3: electrostatics

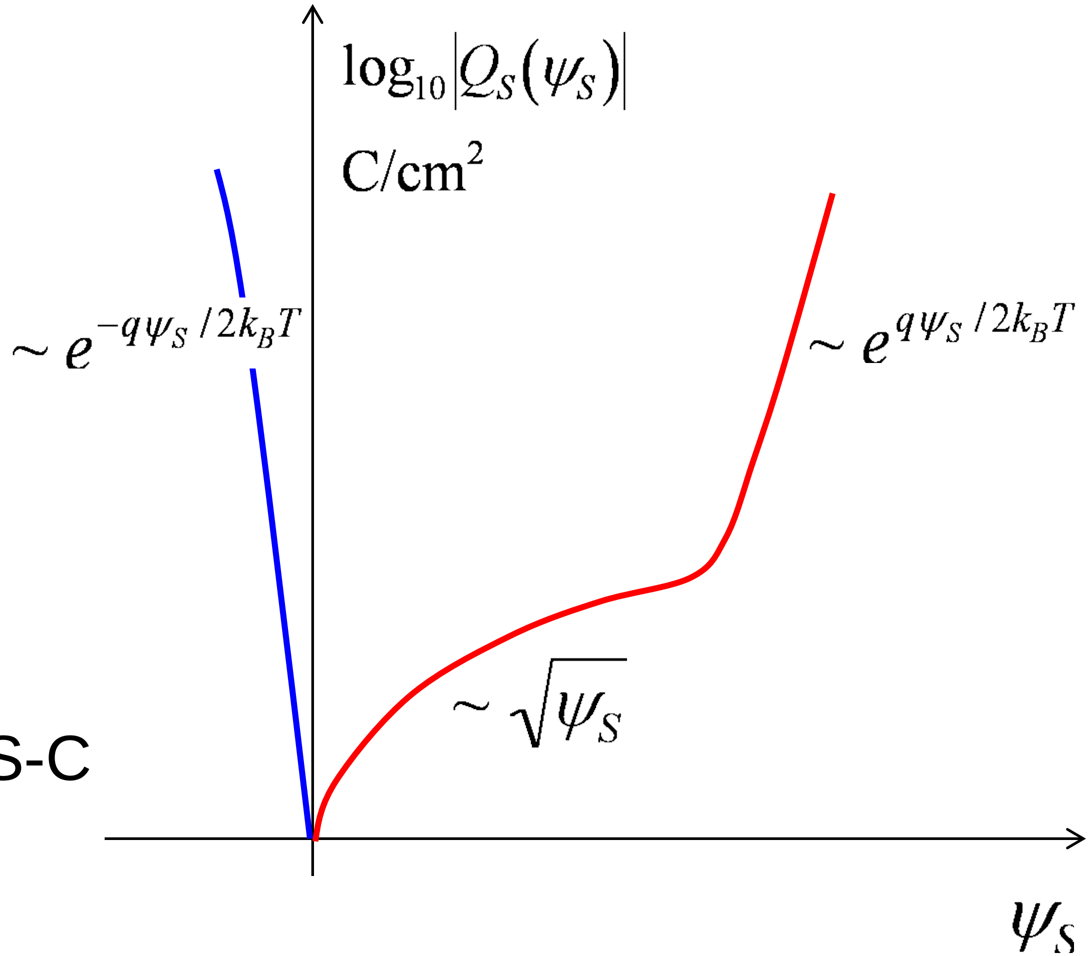
$$I_D/W = \left|Q_n\left(V_{GS}, V_{DS}\right)\right|\left\langle \upsilon_x\left(V_{GS}, V_{DS}\right)\right\rangle$$

Energy band approach to MOS electrostatics



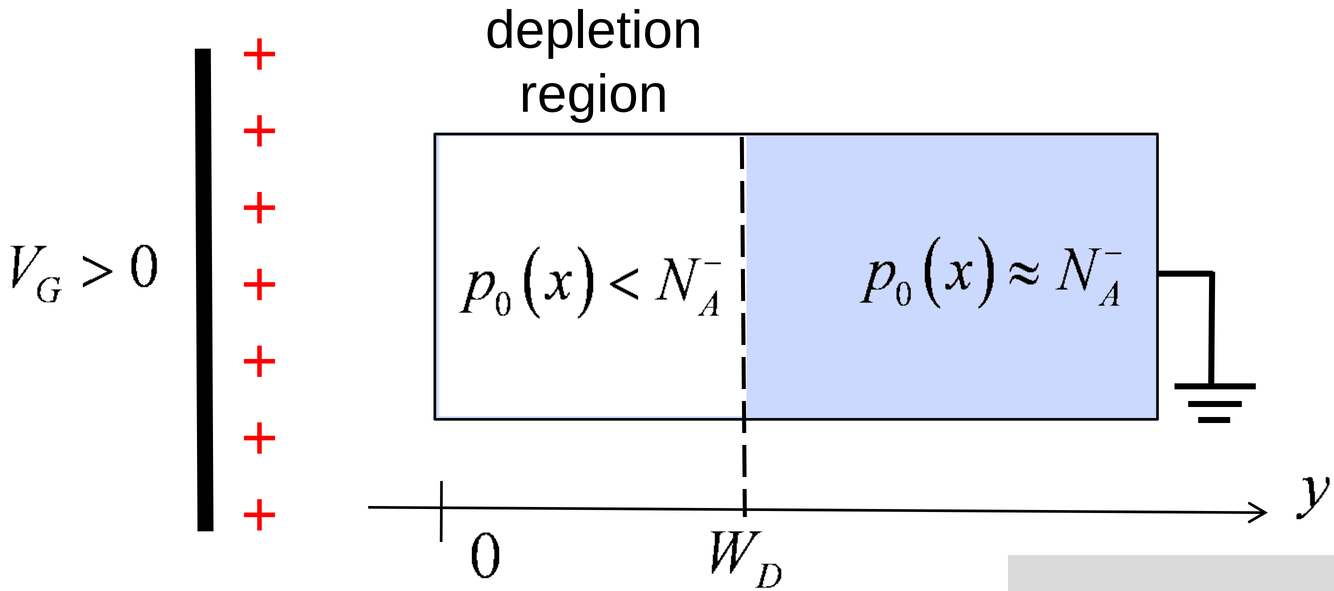
Everything depends on the surface potential!

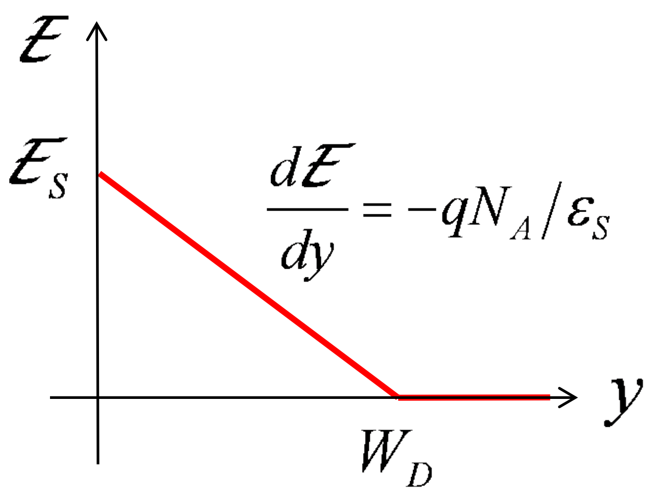
Charge vs. surface potential



P-type MOS-C

Depletion approximation



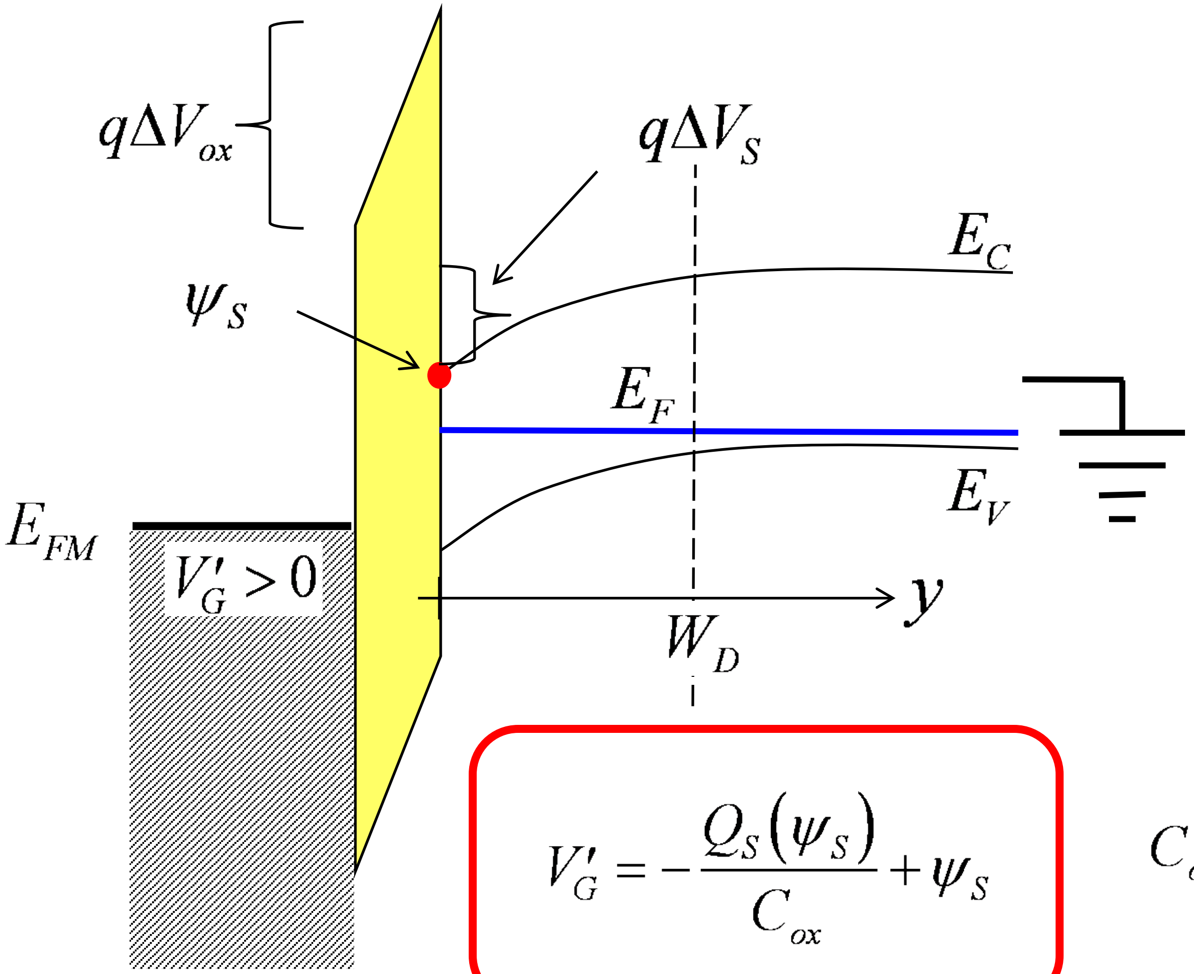


$$W_D = \sqrt{2\varepsilon_S \psi_S / qN_A} \ \text{m}$$

$$\mathcal{E}_S = \frac{2\psi_S}{W_D} \ \text{V/m}$$

$$Q_D = -\sqrt{2qN_A \varepsilon_S \psi_S} \ \text{C/m}^2$$

Gate voltage and surface potential



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

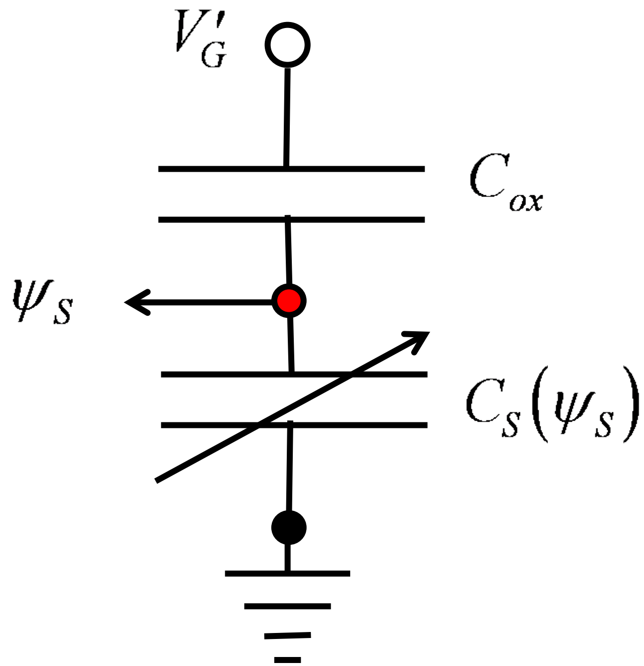
$$\boxed{V_G' = -\frac{Q_S(\psi_S)}{C_{ox}} + \psi_S}$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \ \mathrm{F/cm^2}$$

Approximate gate vs. surface potential

$$V_G' = -\frac{Q_S(\psi_S)}{C_{ox}} + \psi_S \quad \text{(exact)}$$

approximate solution



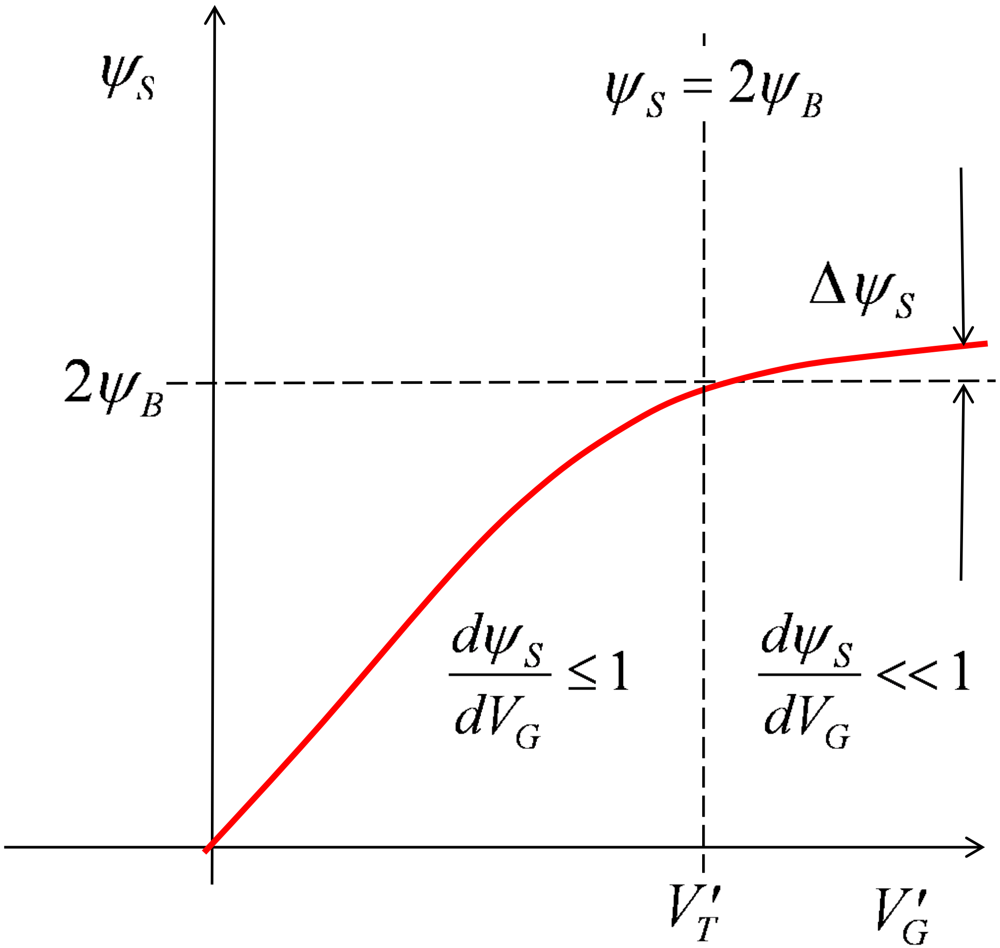
$$\psi_S \approx \frac{V_G'}{m}$$

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

$$m \geq 1$$

(depletion)

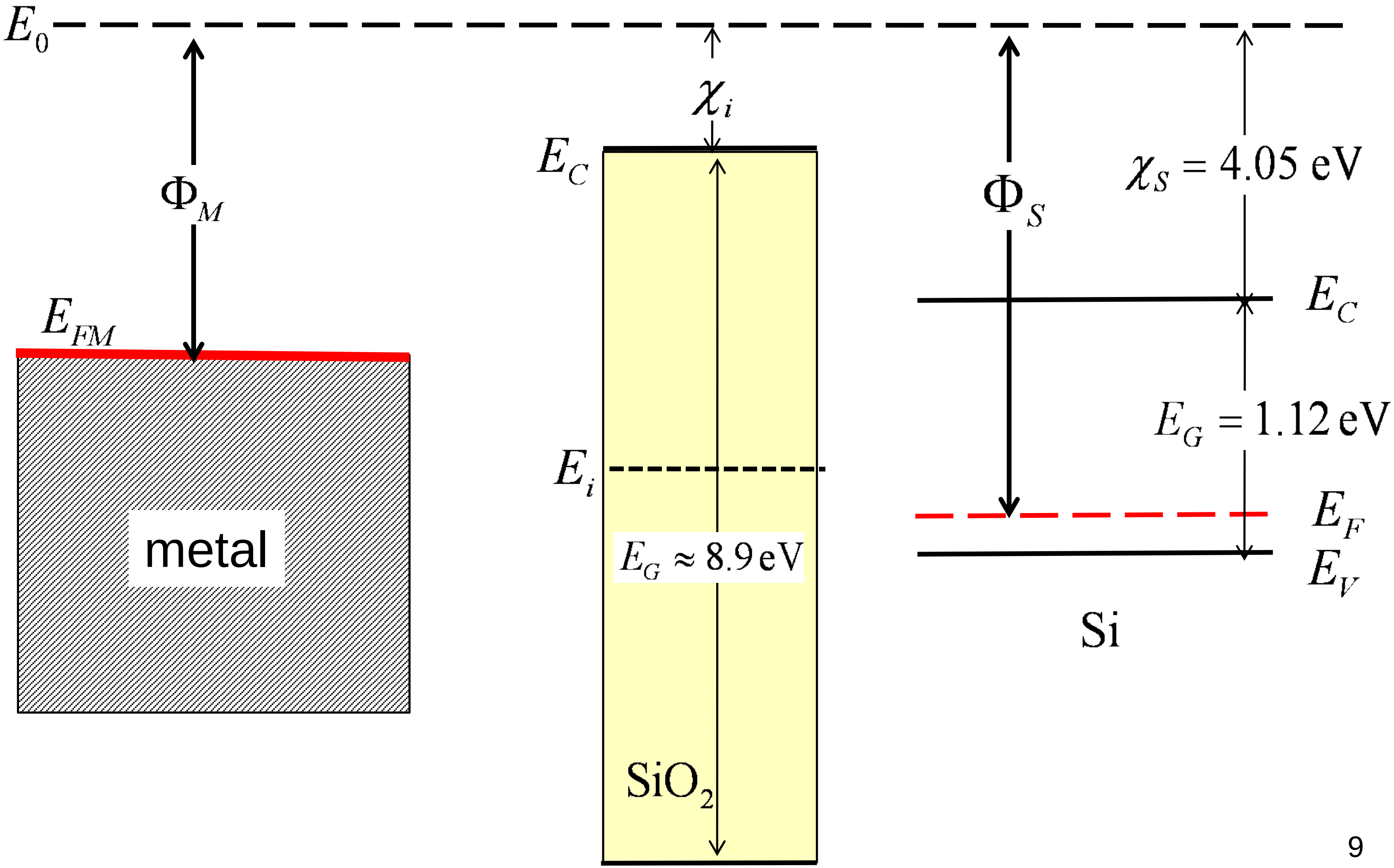
Surface potential vs. gate voltage



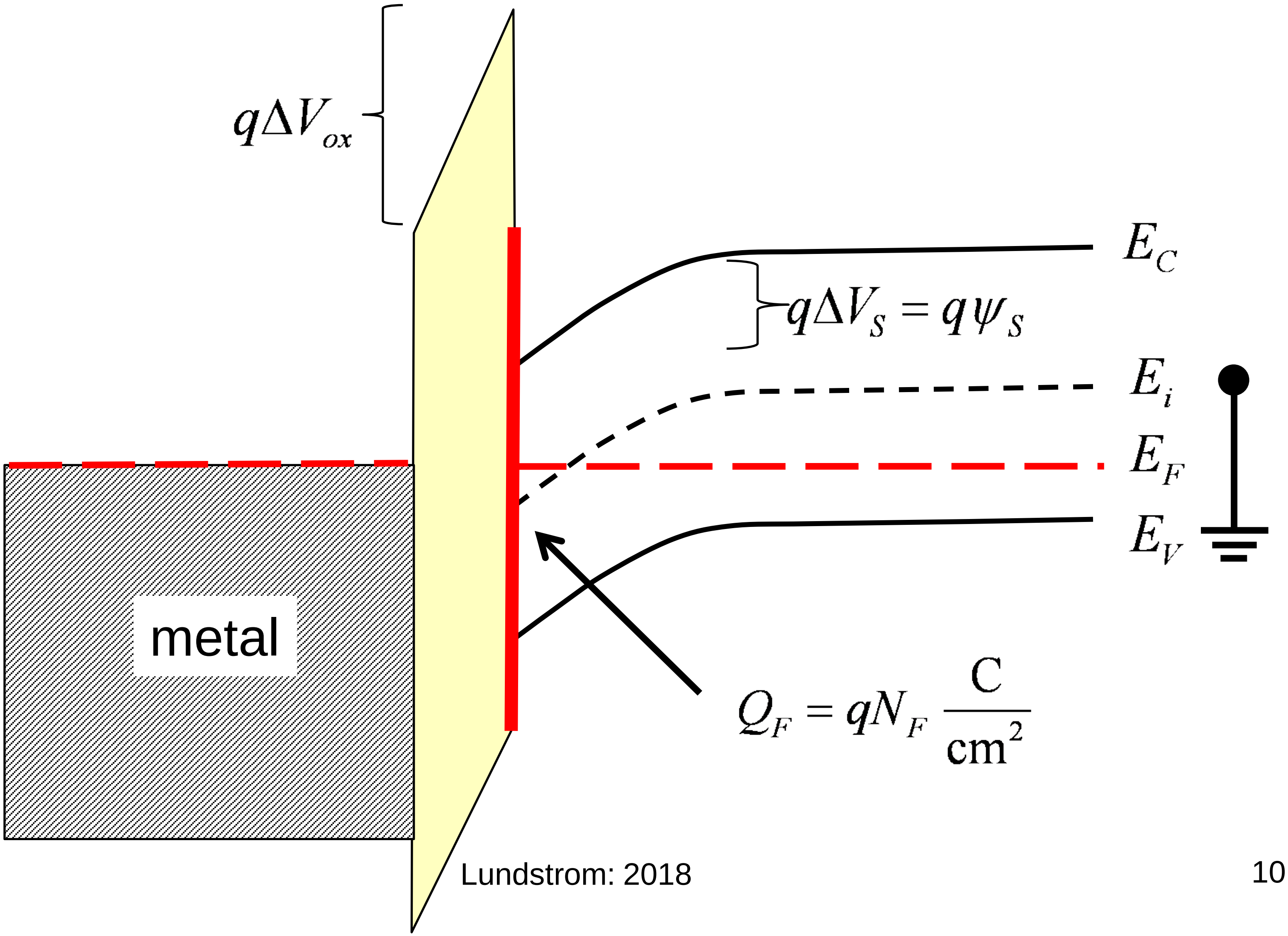
$$\psi_B = \frac{k_B T}{q} \ln\left(\frac{N_A}{n_i}\right)$$

$$V_T' = \frac{\sqrt{2qN_A \varepsilon_S (2\psi_B)}}{C_{ox}} + 2\psi_B$$

Workfunctions



Charge at the oxide-semiconductor interface

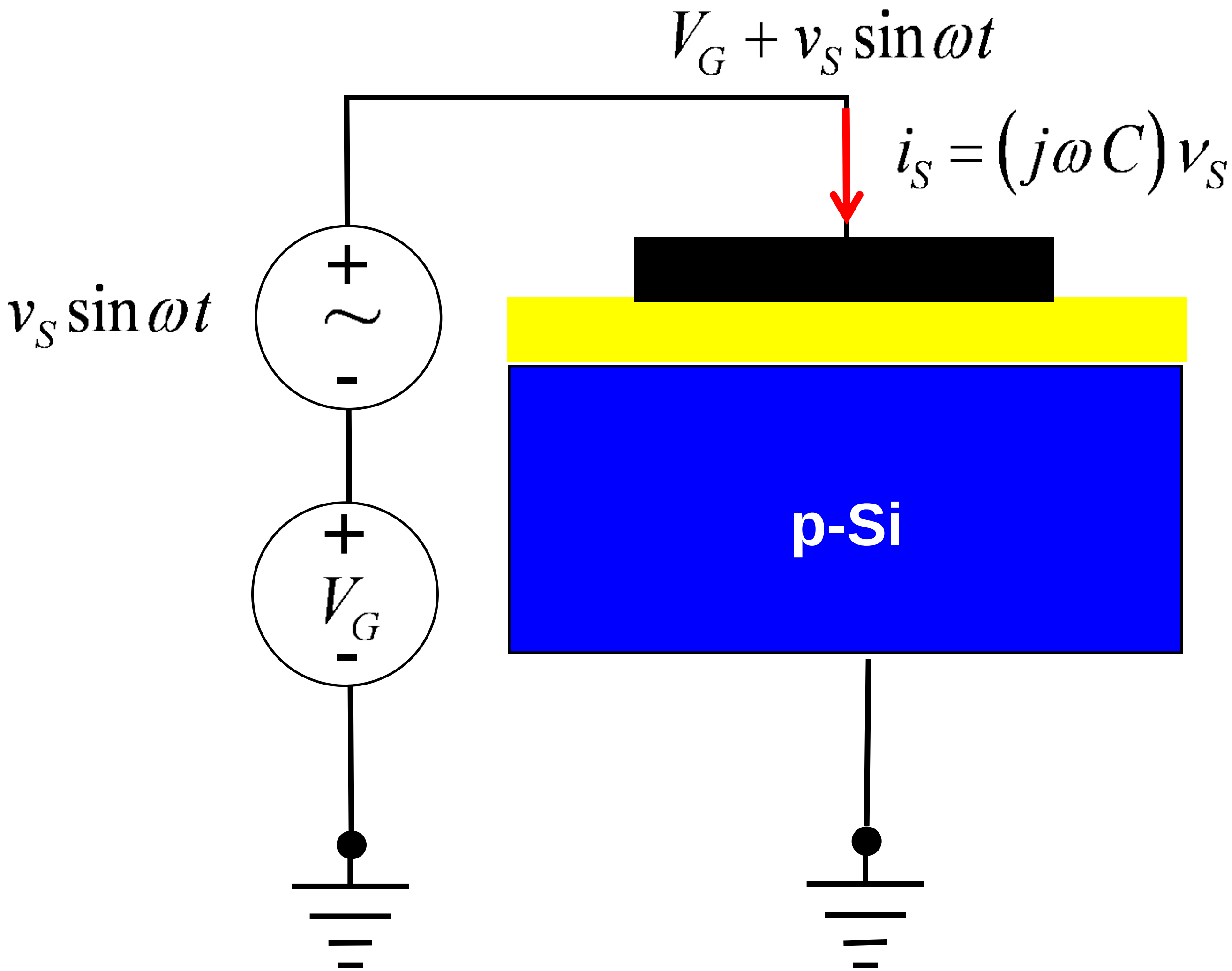


Flatband voltage

$$\boxed{\begin{gathered} V_G = V_{FB} - \frac{Q_S(\psi_S)}{C_{ox}} + \psi_S \\[2em] V_{FB} = \phi_{ms} - \frac{Q_F}{C_{ox}} \end{gathered}}$$

$$\text{for } V_G = 0,\ \ \psi_S \neq 0$$

MOS small signal capacitance



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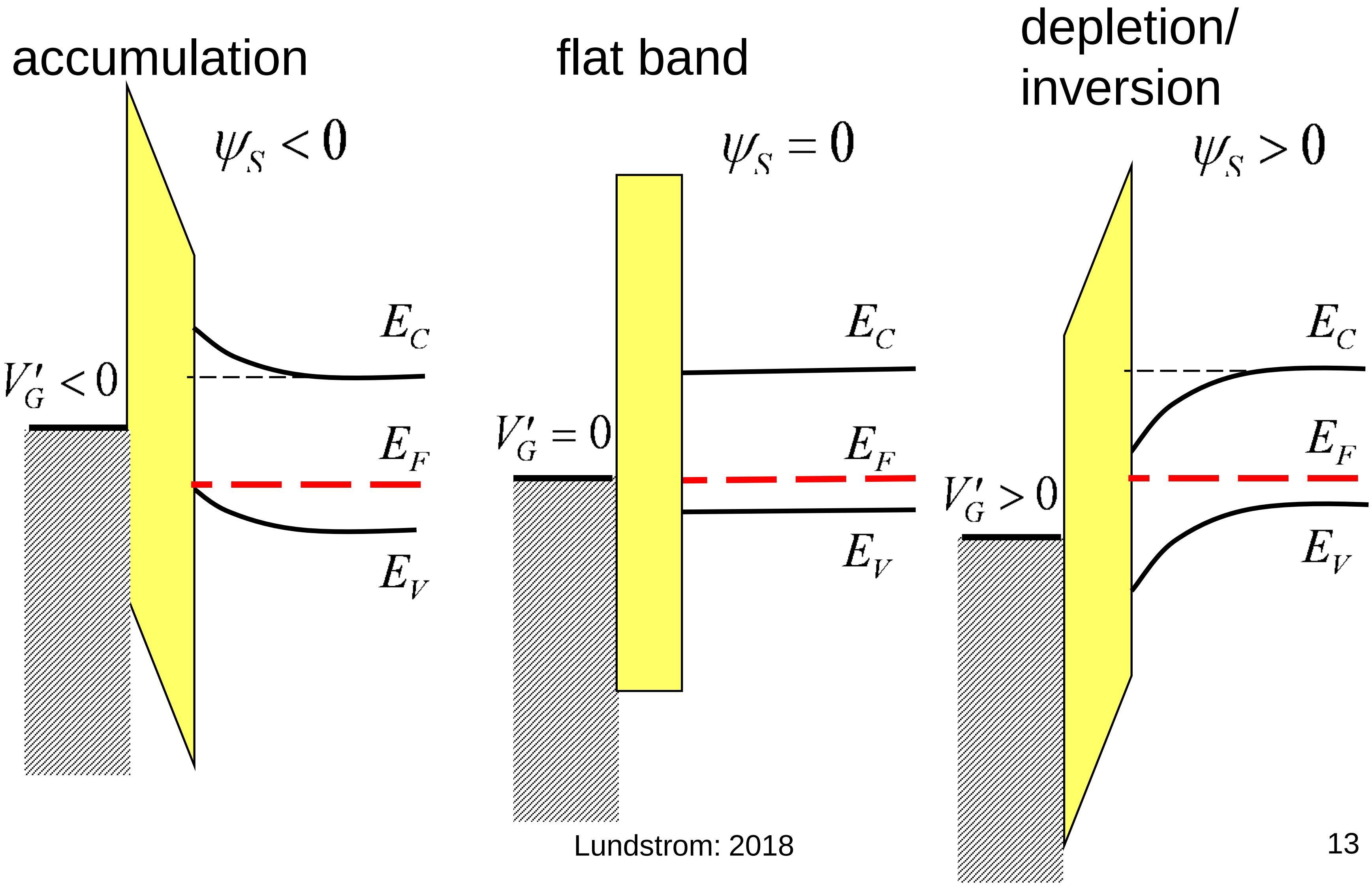
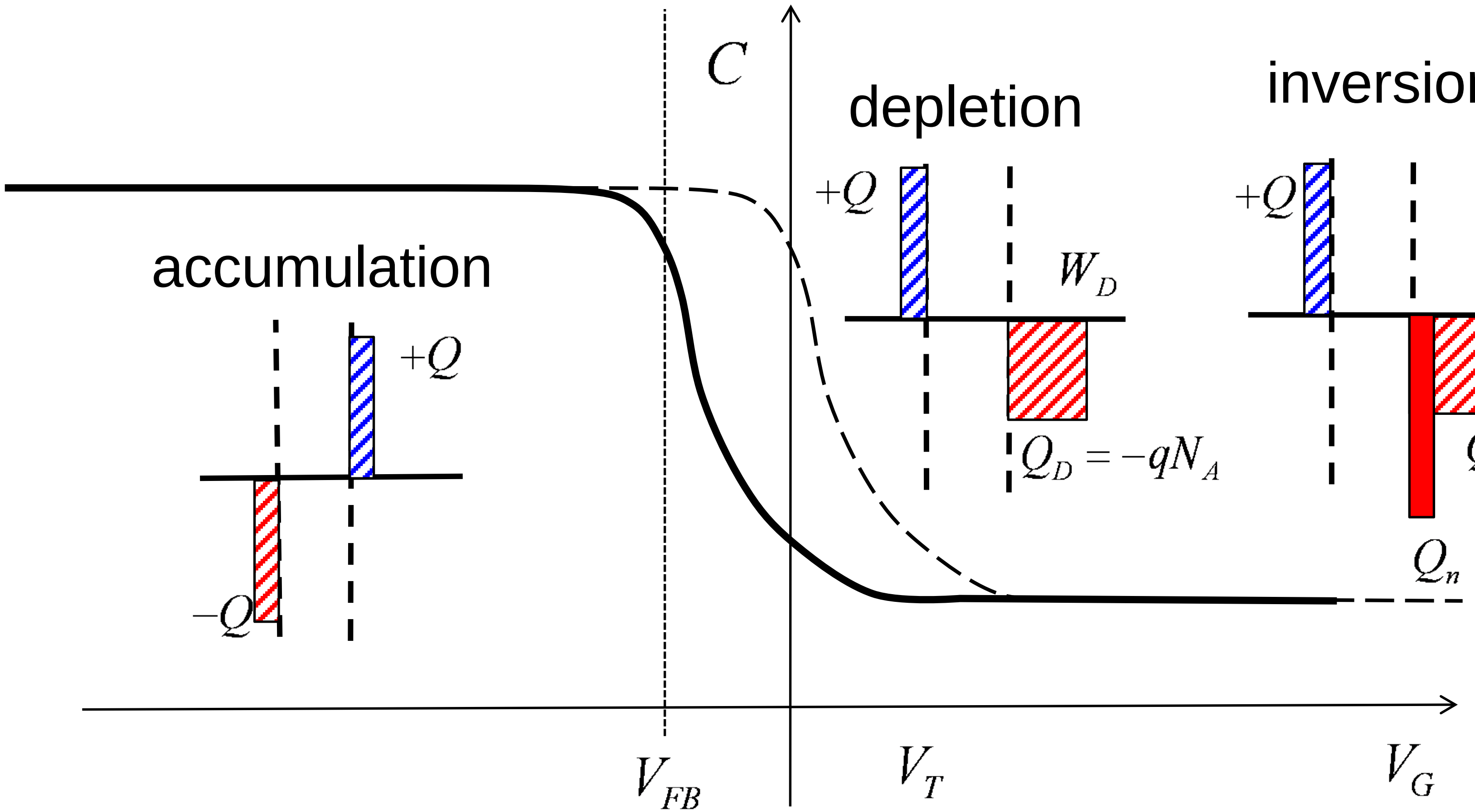
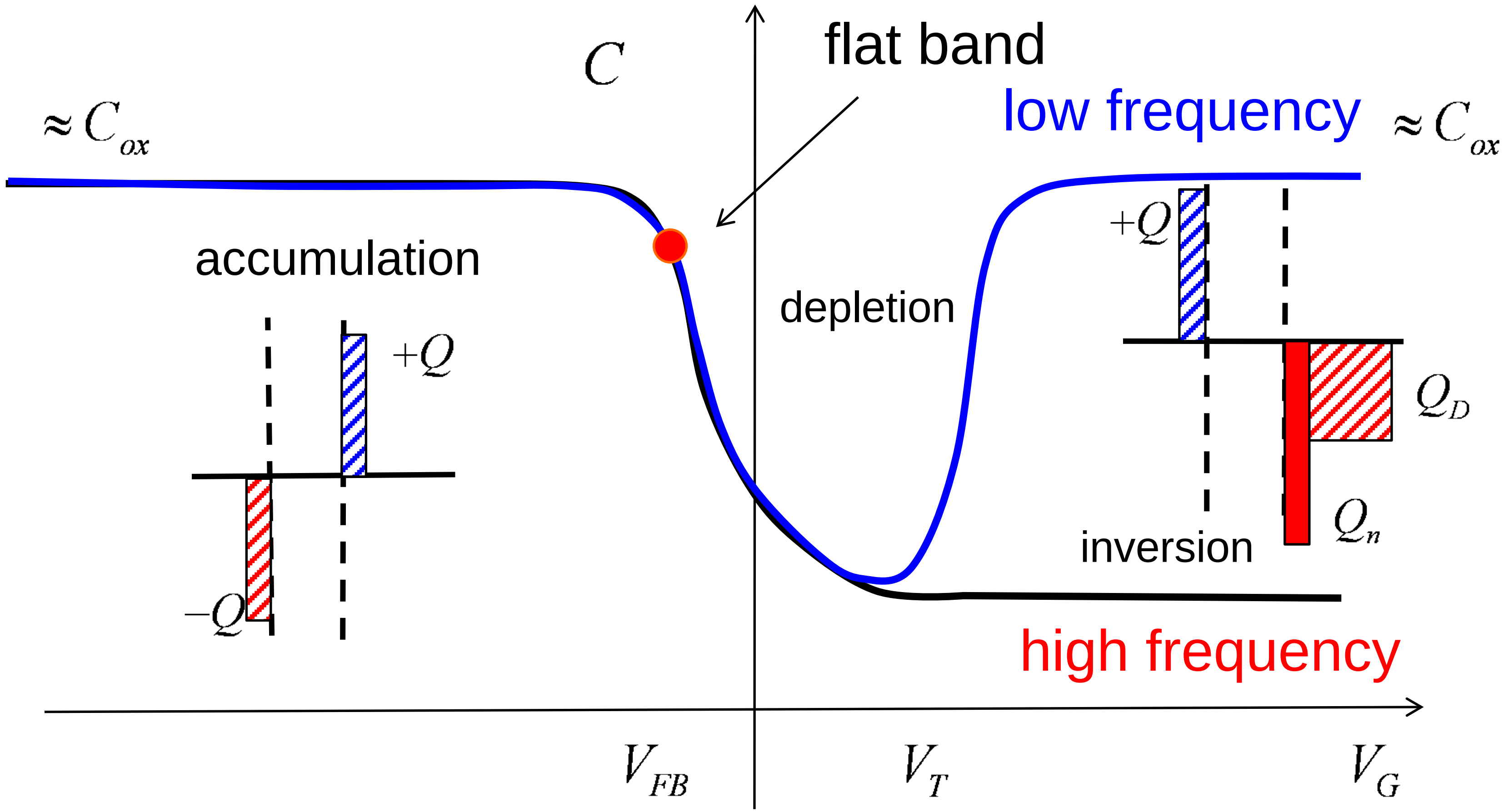
DC bias from accumulation to inversion



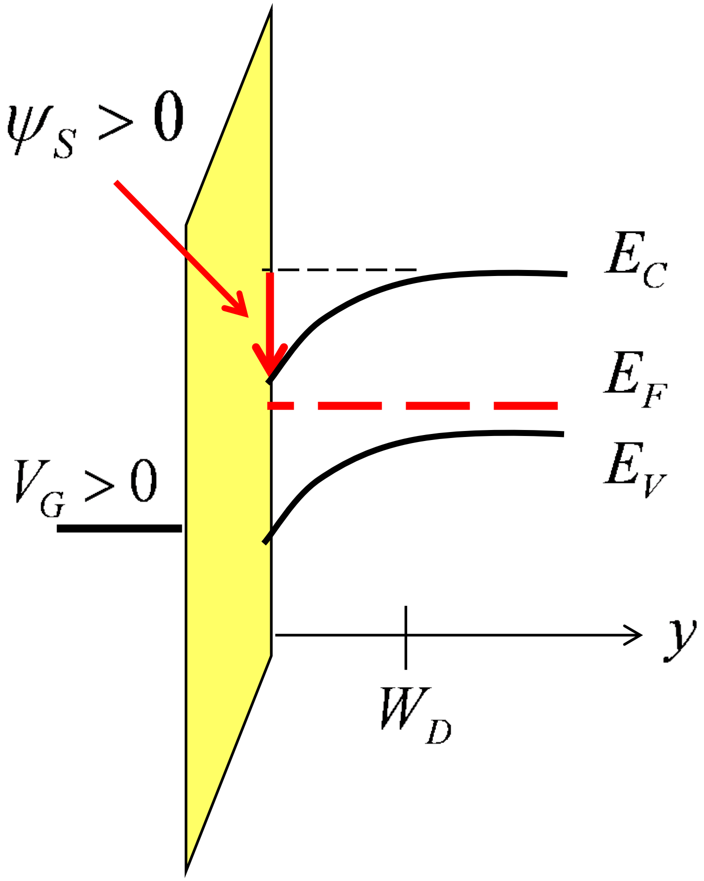
MOS high frequency CV



High frequency vs. low frequency CV



Mobile charge



The mobile charge carries the current.

$$Q_n = -q\int_0^\infty n(y)\,dy \ \ \mathrm{C/cm^2}$$

(electrons in a P-type semiconductor)

Expect: $Q_n \propto e^{q\psi_S/k_BT}$

Mobile charge vs. **surface potential**

Bulk semiconductor:

$$\psi_S < 2\psi_B: \qquad Q_n(\psi_S) \approx -\left(\frac{n_i^2 k_B T / N_A}{\sqrt{\left(2qN_A\psi_S/\varepsilon_S\right)^{1/2}}}\right) e^{q\psi_S/k_BT}$$

$$\psi_S > 2\psi_B: \qquad Q_n(\psi_S) = -\sqrt{2\varepsilon_S k_B T\left(n_i^2/N_A\right)} \times e^{q\psi_S/2k_BT}$$

Fully depleted, ultra thin body:

$$\psi_S > 0: \qquad Q_n(\psi_S) = -qn_{S0}\, e^{q\psi_S/k_BT}$$

Mobile charge vs. **gate voltage**

bulk

$$V_G << V_T : \quad Q_n(V_G) = -(m-1)C_{ox}\left(\frac{k_B T}{q}\right)e^{q(V_G - V_T)/mk_B T}$$

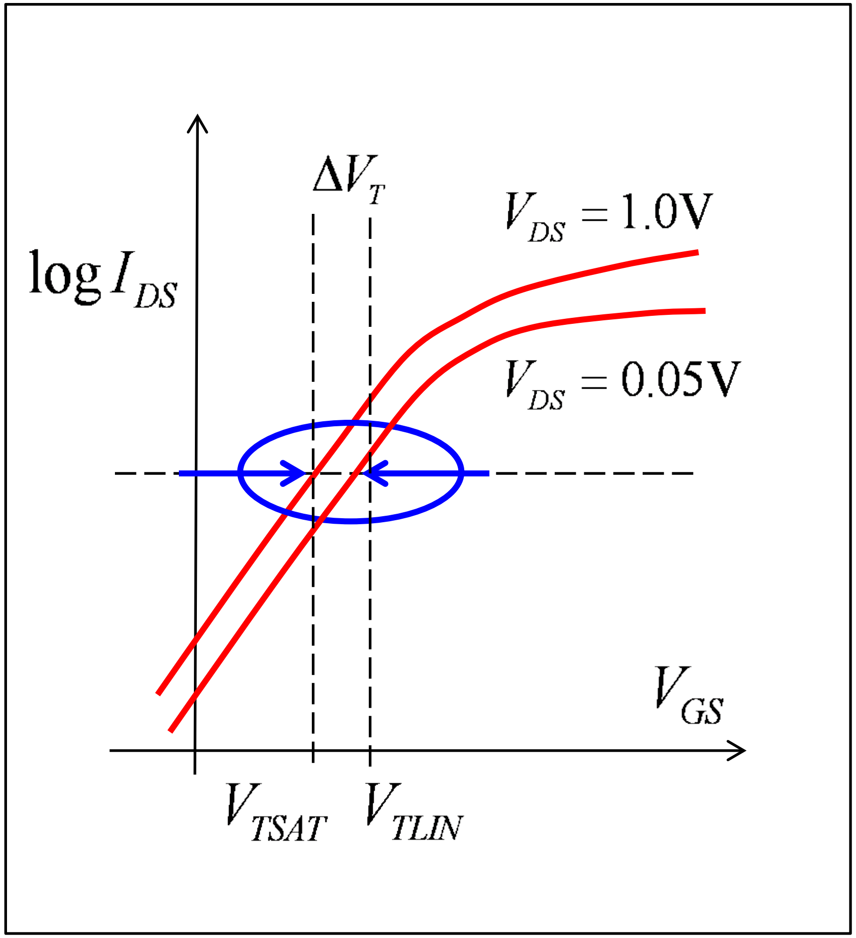
$$V_G >> V_T : \quad Q_n = -C_{inv}(V_G - V_T) \qquad C_{inv} < C_{ox}$$

FD UTB

$$V_G << V_T : \quad Q_n(V_G) = -C_Q\left(\frac{k_B T}{q}\right)e^{q(V_G - V_T)/k_B T} \qquad m = 1$$

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

2D electrostatics

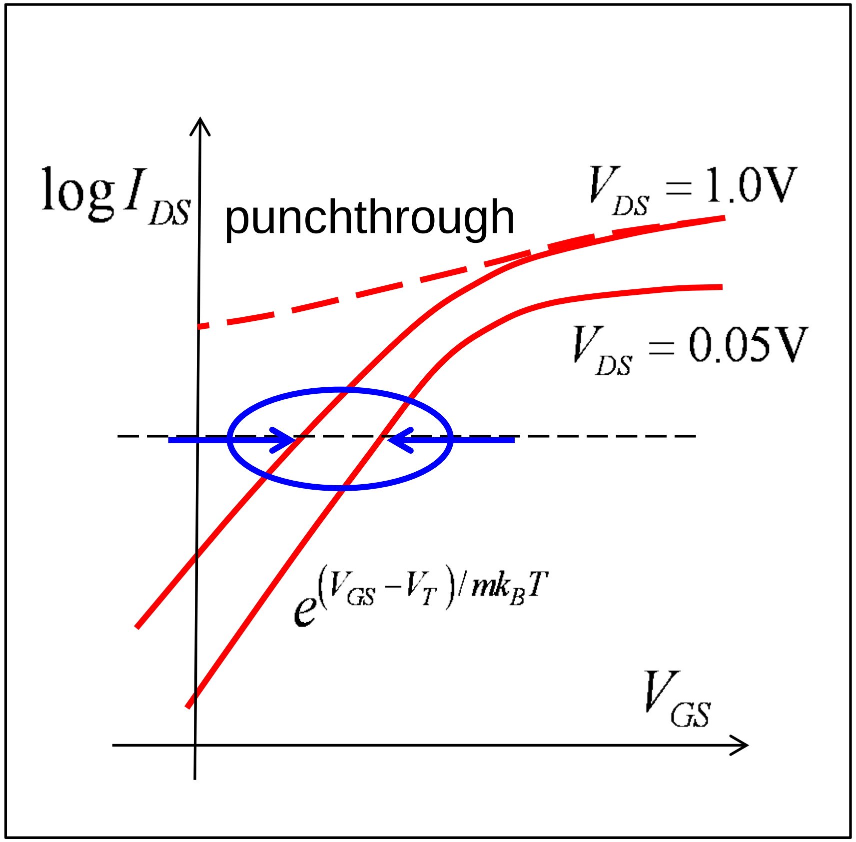


1) Threshold voltage decreases as the drain voltage increases

2) Threshold voltage decreases as the channel length decreases

3) DIBL increases as channel length decreases

2D electrostatics

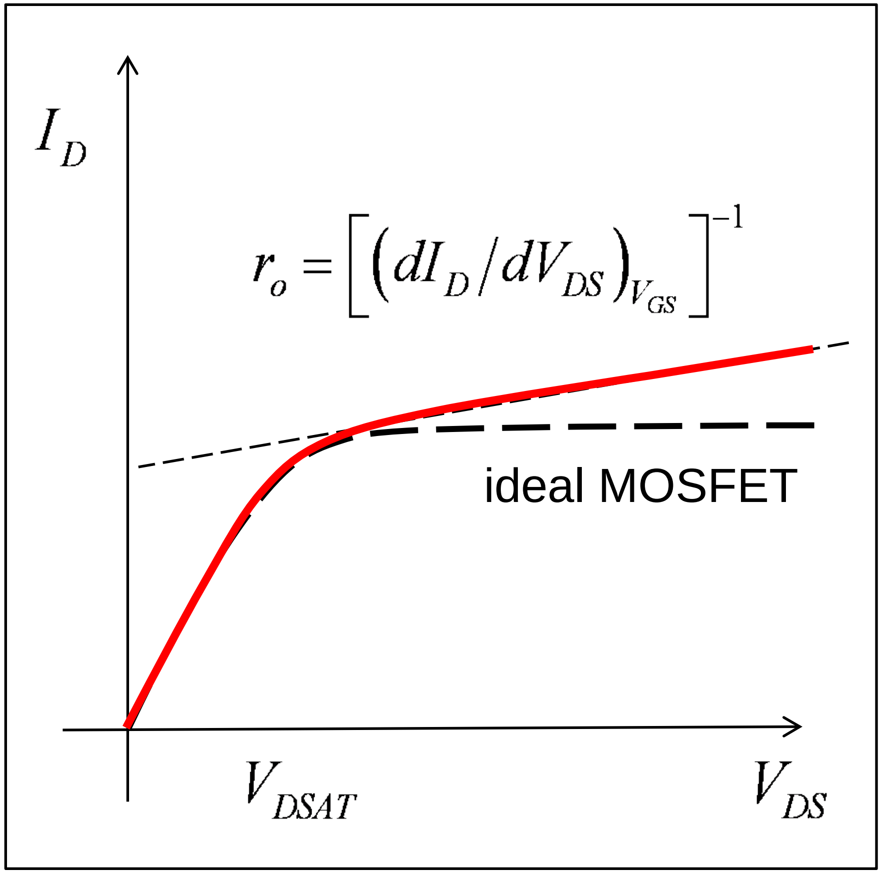


1) SS may increase as the drain voltage increases

2) SS may increase as the channel length decreases

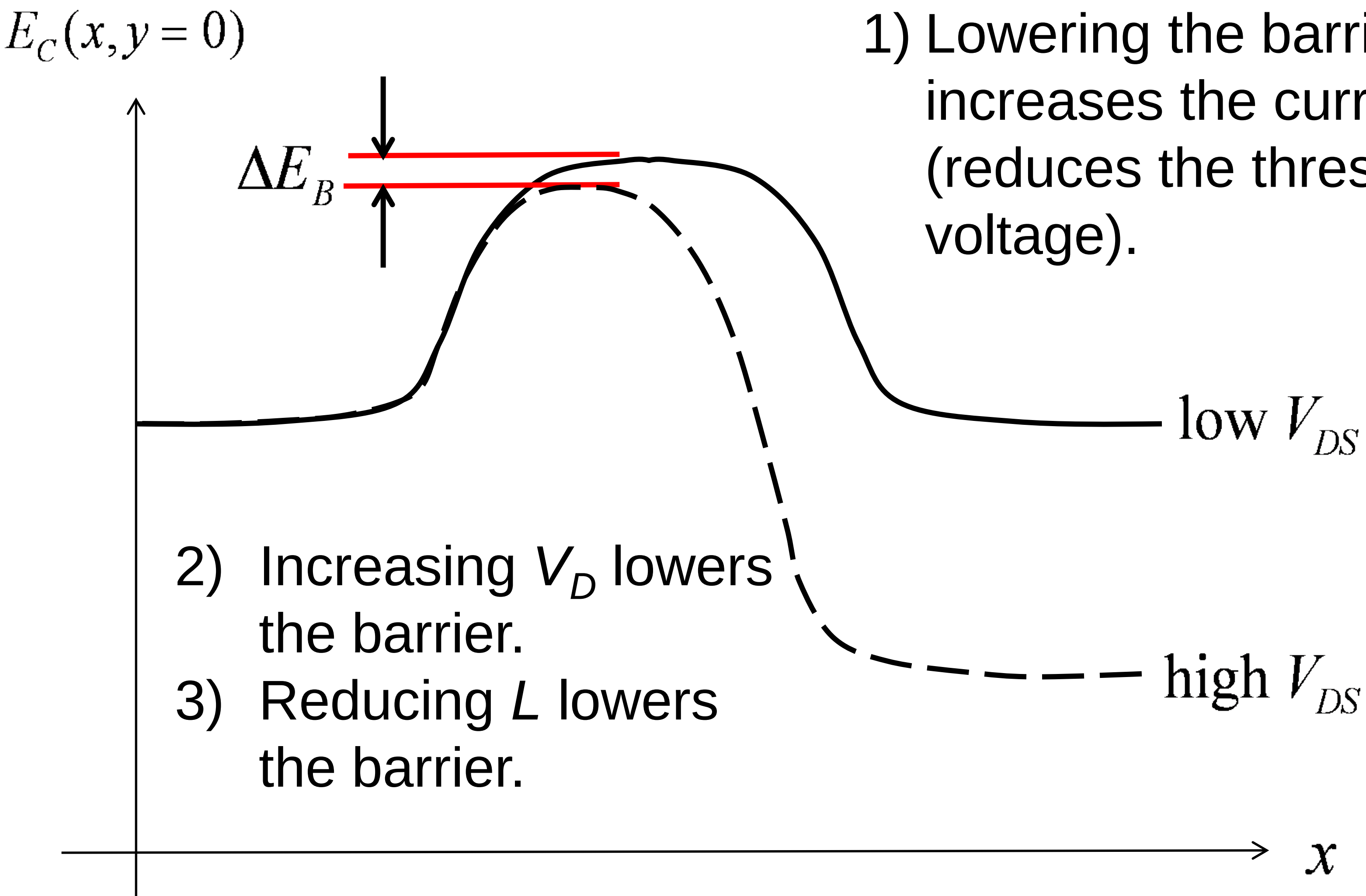
3) In severe cases, the device may "punch through"

2D electrostatics



1) Output resistance decreases as channel length decreases.

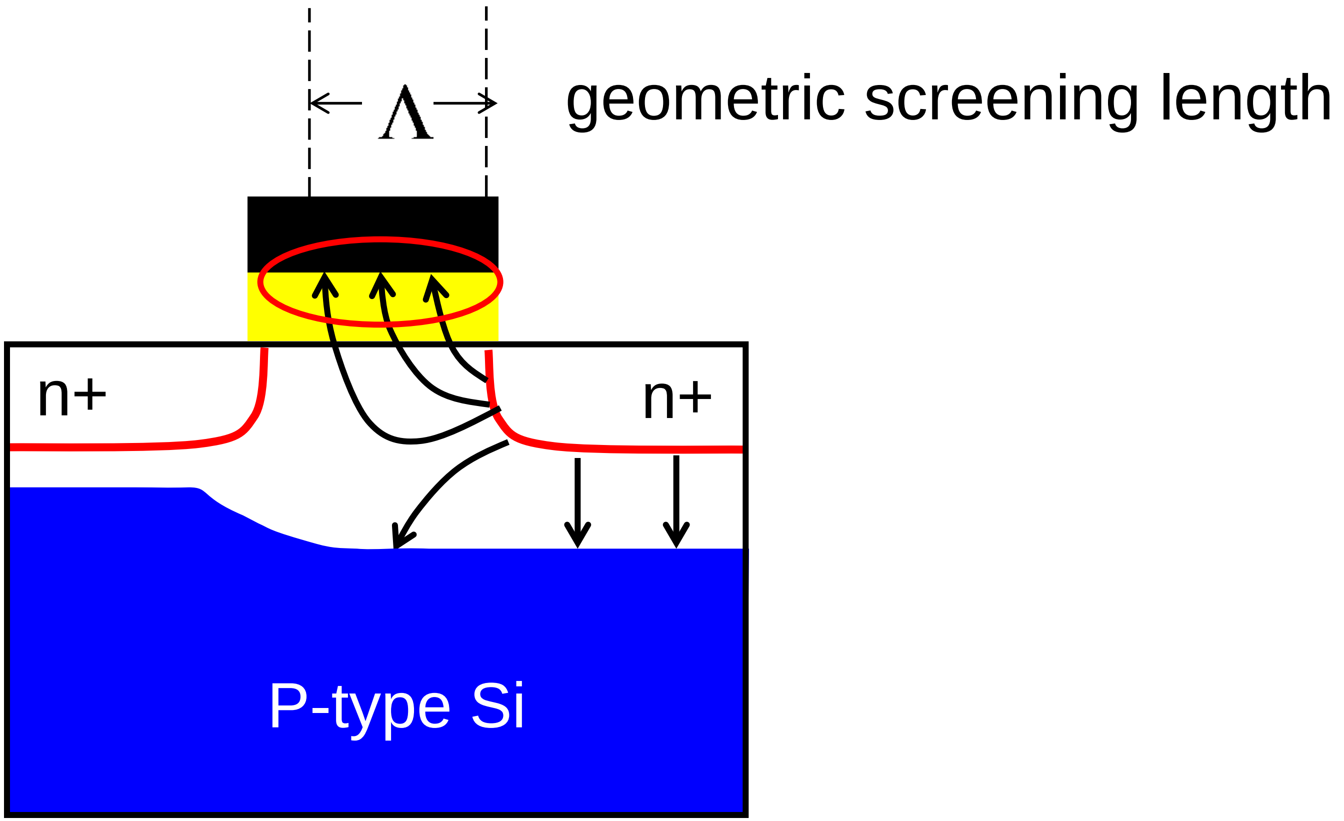
Barrier lowering view of 2D electrostatics



1) Lowering the barrier increases the current (reduces the threshold voltage).

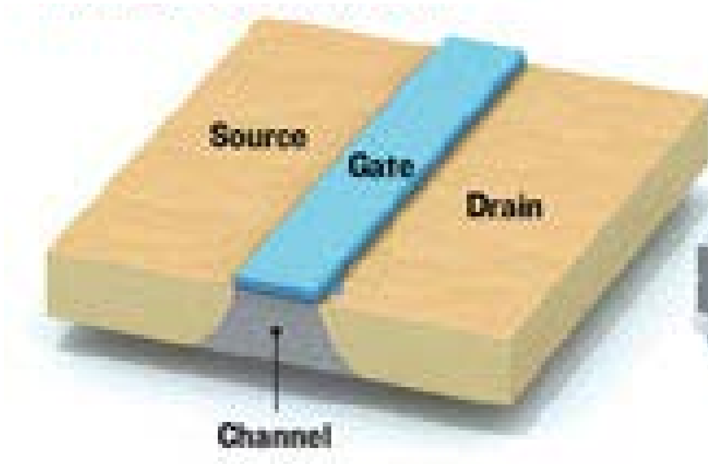
2) Increasing V_D lowers the barrier.
3) Reducing L lowers the barrier.

Controlling 2D electrostatics

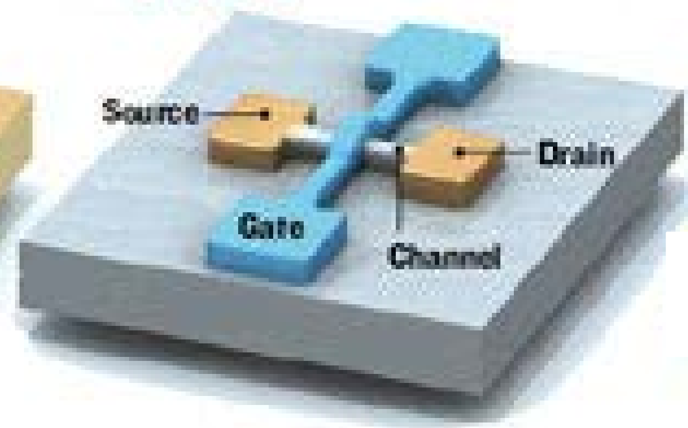


2D electrostatics

planar transistor



FinFET



“Transistors go Vertical,” *IEEE Spectrum*, Nov. 2007.

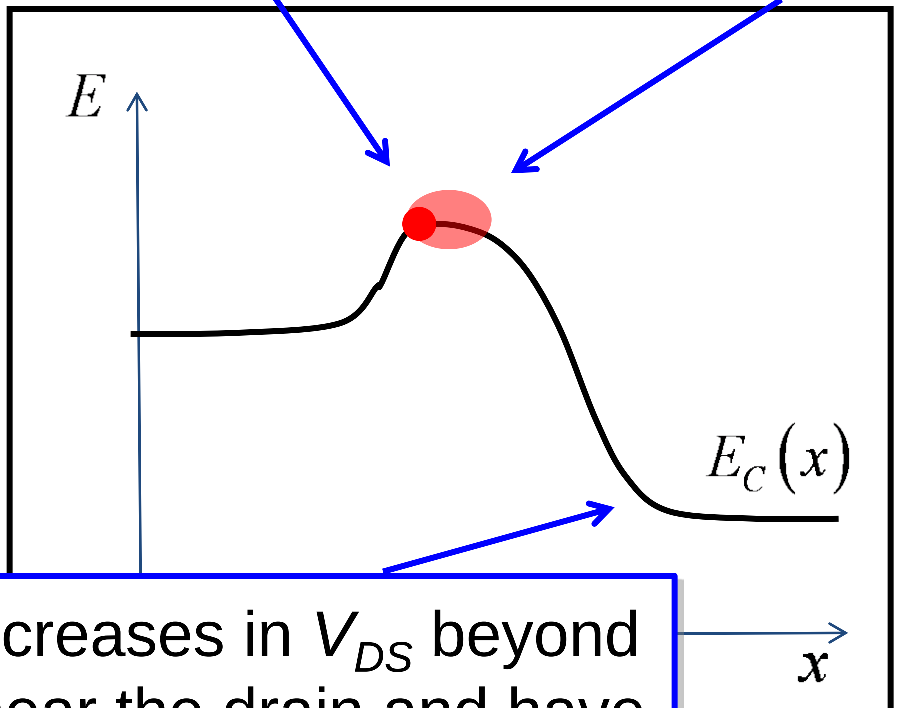
See also: “Integrated Nanoelectronics of the Future,” Robert Chau, Brian Doyle, Suman Datta, Jack Kavalieros, and Kevin Zhang, *Nature Materials*, **6**, 2007

"Well-tempered MOSFET"

1) $Q_n(0) \approx -C_{inv}(V_{GS} - V_T)$

2) region under strong control of gate (m ~ 1)

$$V_T = V_{T0} - \delta V_{DS}$$
$$m = \text{constant}$$



3) Additional increases in V_{DS} beyond V_{DSAT} drop near the drain and have a **small effect** on I_D (small DIBL)

Level 0 VS model

1) $I_D/W = \left|Q_n\left(V_{GS}\right)\right|\left\langle \upsilon_x\left(V_{DS}\right)\right\rangle$

2) $Q_n\left(V_{GS}, V_{DS}\right) = -C_{ox}\left(V_{GS} - V_T\right) \quad \left(V_{GS} > V_T\right)$

$V_T = V_{T0} - \delta V_{DS}$

$Q_n\left(V_{GS}\right) = 0 \qquad \left(V_{GS} \leq V_T\right)$

3) $\left\langle \upsilon\left(V_{DS}\right)\right\rangle = F_{SAT}\left(V_{DS}\right)\upsilon_{sat}$

4) $F_{SAT}\left(V_{DS}\right) = \dfrac{V_{DS}/V_{DSAT}}{\left[1 + \left(V_{DS}/V_{DSAT}\right)^{\beta}\right]^{1/\beta}}$

5) $V_{DSAT} = \upsilon_{sat} L/\mu_n$

There are only 8 device-specific parameters in this model:

$$C_{ox}, V_{T0}, \delta, \upsilon_{sat}, \mu_n, L$$

$$R_{SD} = R_S + R_D, \beta$$

Lundstrom: 2018

Level 1 VS Model

1) $I_D/W = \left|Q_n\left(V_{GS},V_{DS}\right)\right|\left\langle \upsilon_x\left(V_{DS}\right)\right\rangle$

2) $Q_n\left(V_{GS},V_{DS}\right) = -C_{inv}m\left(k_BT/q\right)\ln\left(1+e^{q\left(V_{GS}-V_T+\alpha\left(k_BT_L/q\right)F_f\right)/mk_BT}\right)$

$V_T = V_{T0} - \delta V_{DS}$

3) $\left\langle \upsilon_x\left(V_{DS}\right)\right\rangle = F_{SAT}\left(V_{DS}\right)\upsilon_{sat}$

4) $F_{SAT}\left(V_{DS}\right) = \dfrac{V_{DS}/V_{DSAT}}{\left[1+\left(V_{DS}/V_{DSAT}\right)^{\beta}\right]^{1/\beta}}$

5) $V_{DSAT} = \dfrac{\upsilon_{sat}L}{\mu_n}$

Only 10 device-specific parameters in this model:

$C_{inv}, V_{T0}, \delta, m, \upsilon_{sat}, \mu_n,$
$L, R_{SD} = R_S + R_D,$
α, β

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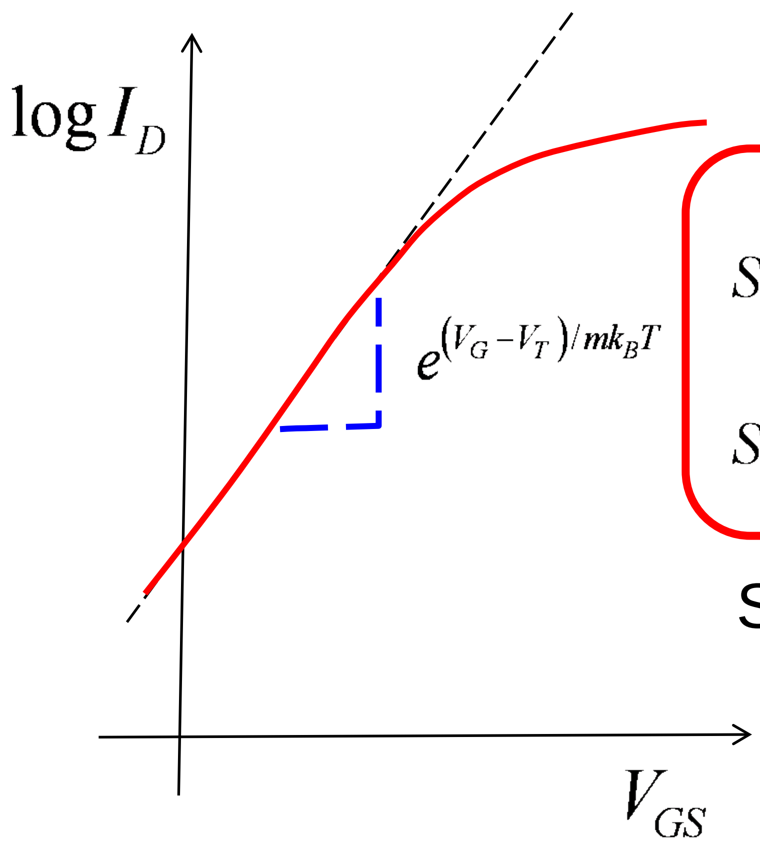
Subthreshold swing



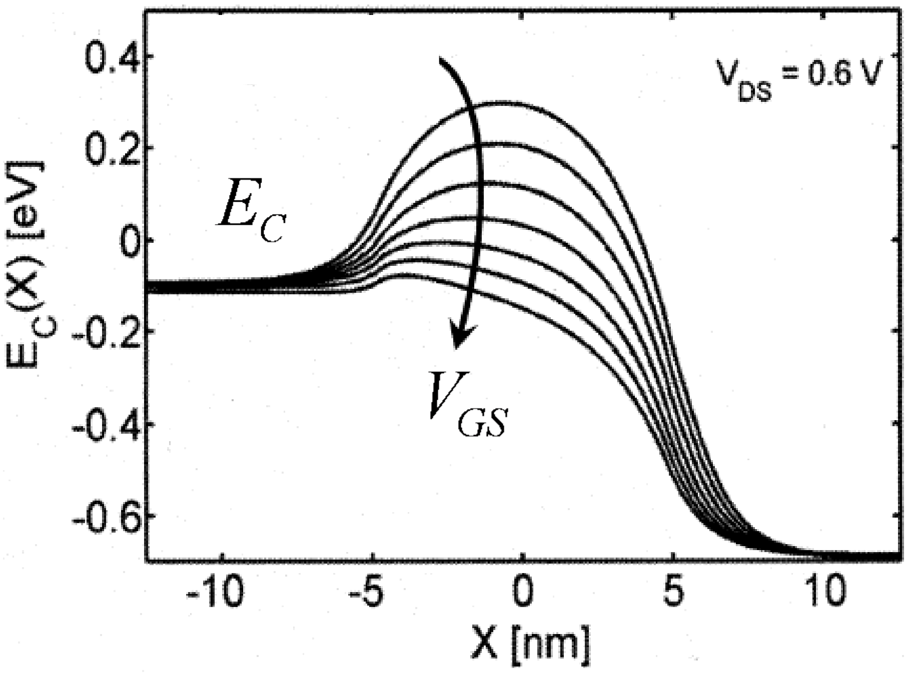
$$SS = \left(\frac{\partial\left(\log_{10} I_D\right)}{V_{GS}} \right)^{-1} = 2.3m\left(k_BT/q\right)\ \frac{\text{mV}}{\text{dec}}$$

$$SS \geq 60\ \frac{\text{mV}}{\text{dec}}$$

SS determines the minimum V_{DD}

$$P_D \propto V_{DD}^2$$

On to Unit 4



Unit 3: electrostatics

$$I_D/W = -Q_n(V_{GS}, V_{DS})\langle \upsilon_x(V_{GS}, V_{DS})\rangle$$

Unit 4: transport