Fundamentals of Nanotransistors

Unit 2: MOS Electrostatics

Lecture 2.9:
Unit 2 Summary

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Outline: Unit 2

Lecture 2.1: Introduction

Lecture 2.2: Depletion Approximation
Lecture 2.3: Gate Voltage and Surface Potential
Lecture 2.4: Flatband Voltage
Lecture 2.5: Mobile Charge: Bulk MOS
Lecture 2.6: Mobile Charge: ETSOI
Lecture 2.7: 2D Electrostatics
Lecture 2.8: The VS Model Revisited

Lecture 2.9 Summary

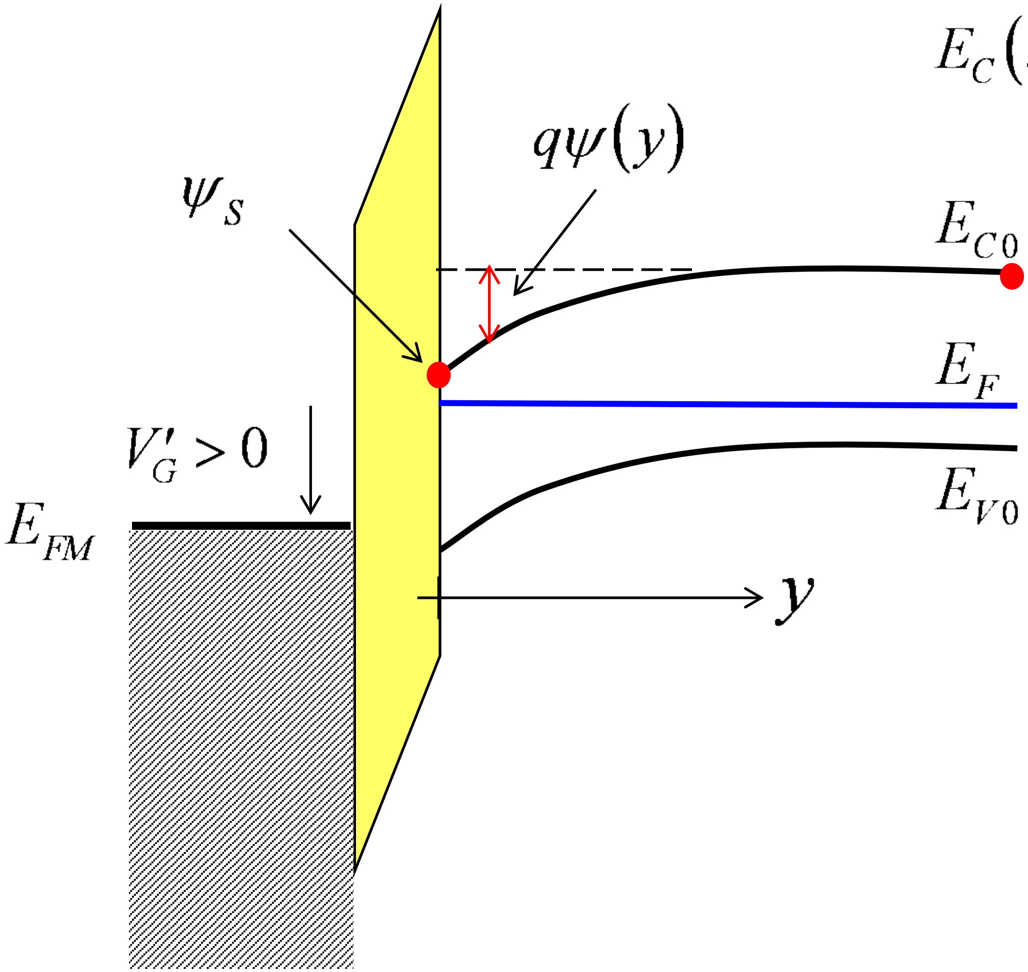
Our goal in Unit 2

$$I_{DS}/W = -Q_n\left(V_{GS}, V_{DS}\right)\left\langle \upsilon\left(V_{DS}\right)\right\rangle$$

Unit 2:
MOS electrostatics

Lecture 2.1

surface potential



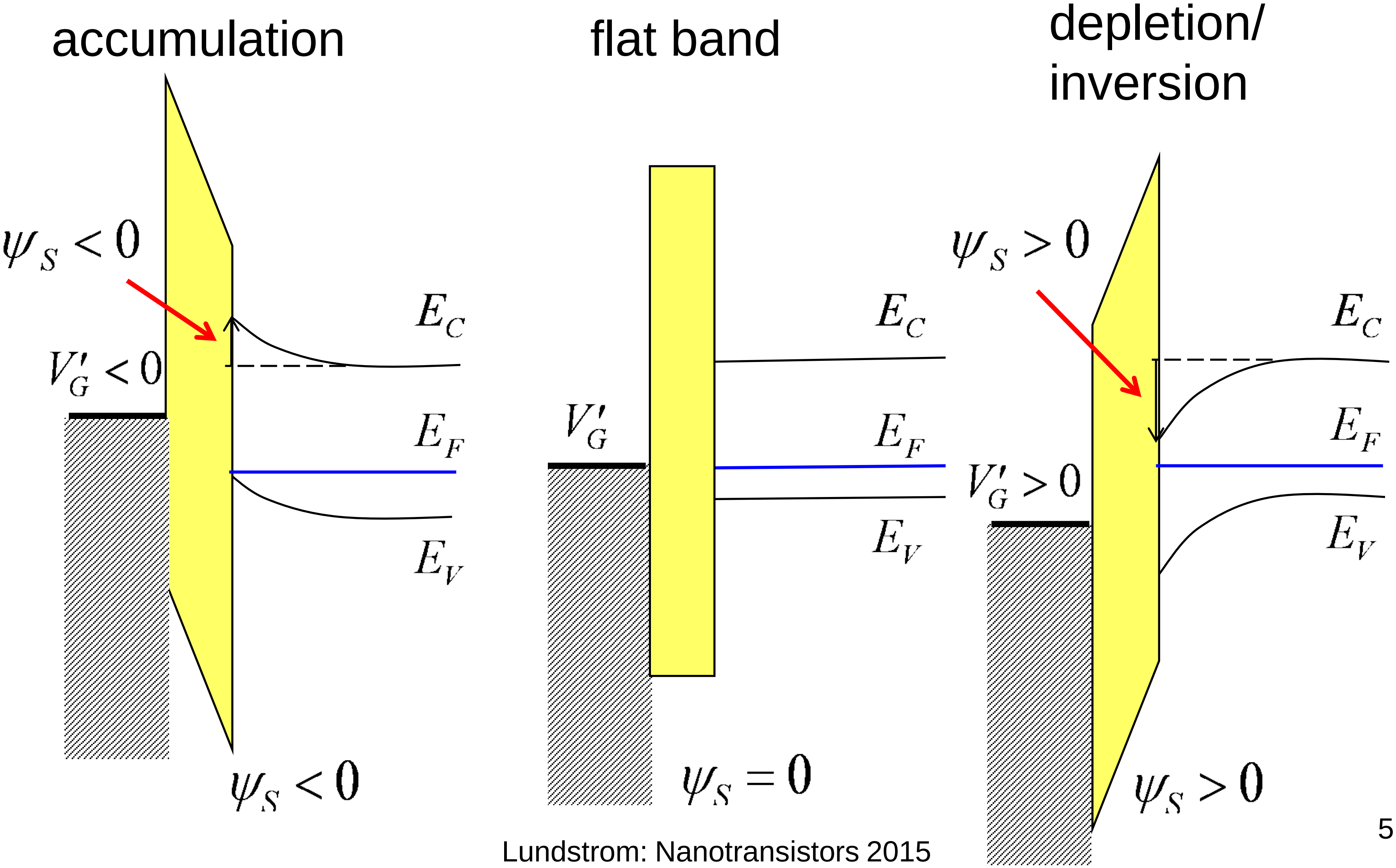
$$E_C(x \to \infty) = E_{C0}$$

$\psi(y) = 0$ (arbitrary reference)

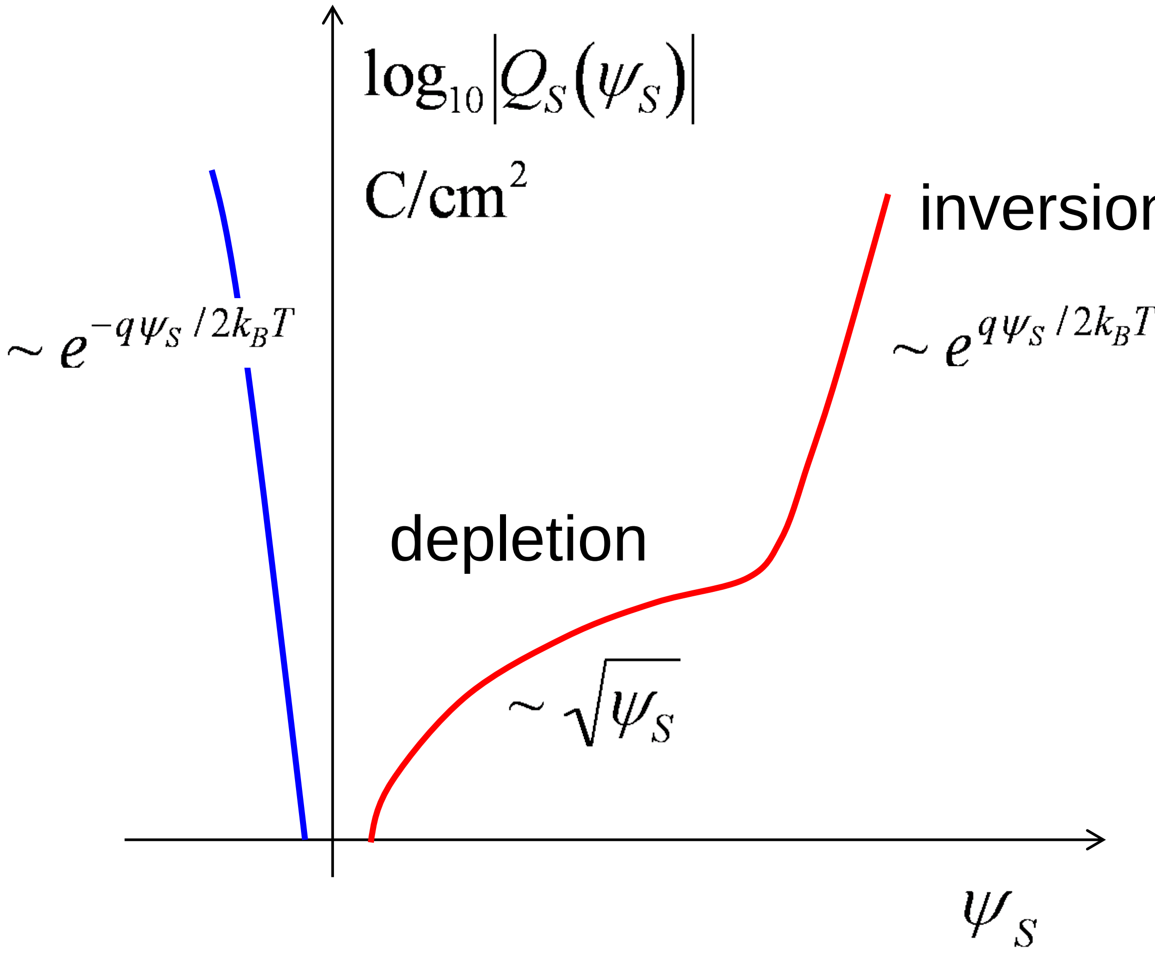
$$E_C(y) = E_{C0} - q\psi(y)$$

$$\psi(y) = \frac{E_{C0} - E_C(y)}{q}$$

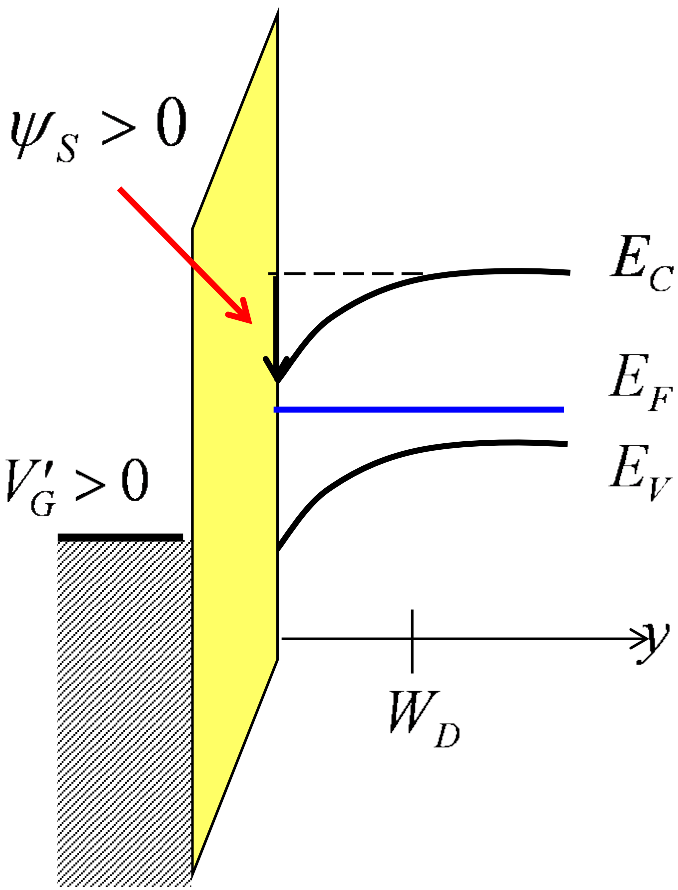
Accumulation, Depletion, and Inversion

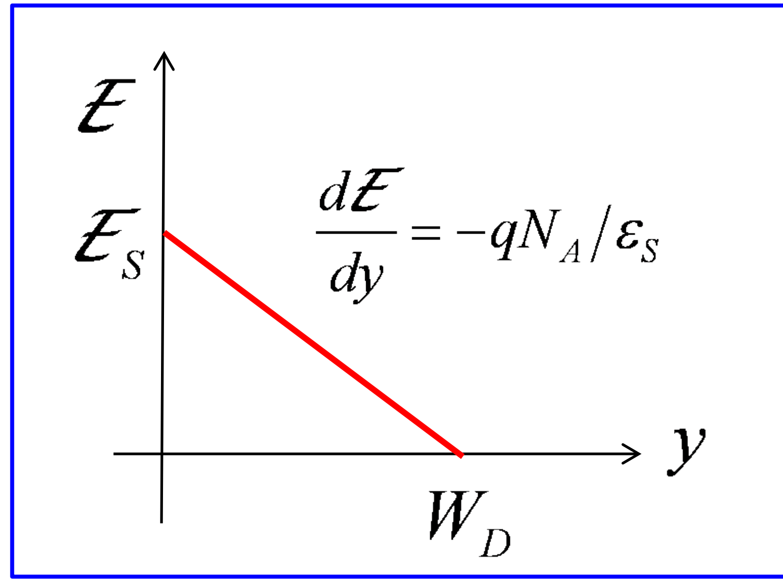


Sheet charge in the semiconductor



Lecture 2.2: Depletion Approximation



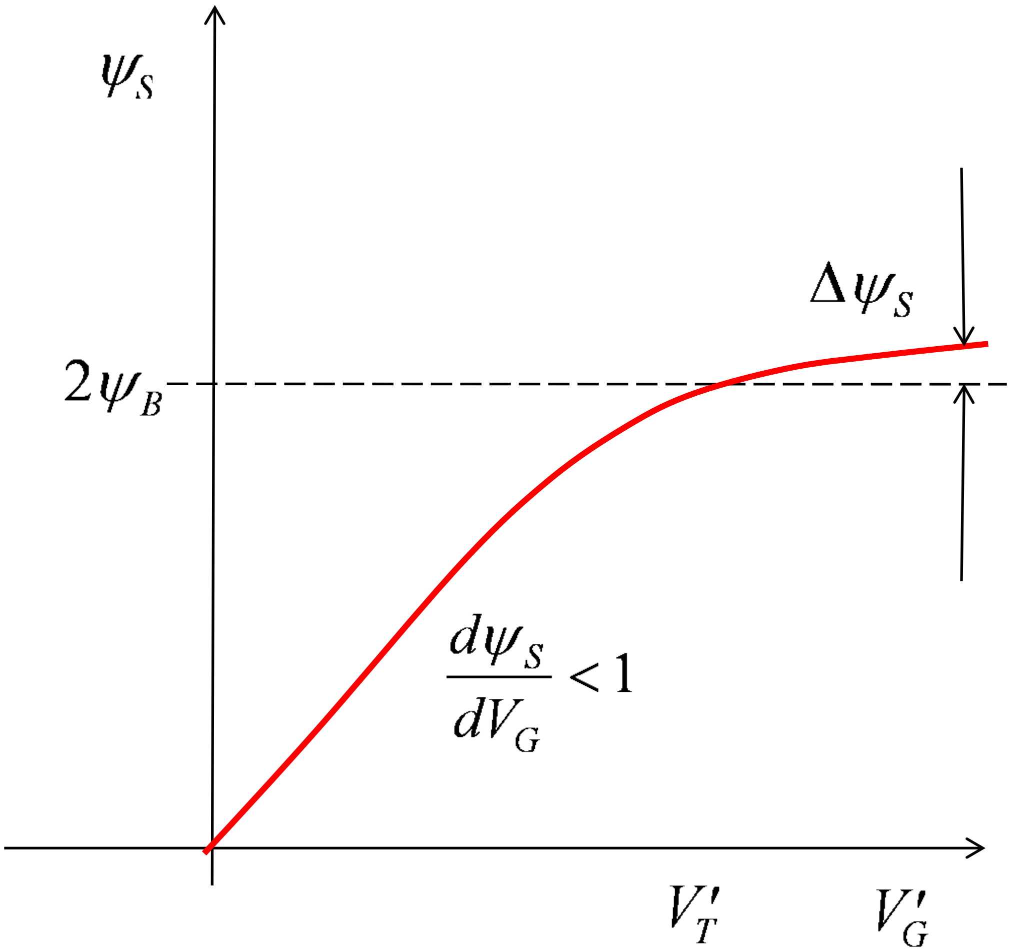


$$W_D = \sqrt{2\varepsilon_S \psi_S / qN_A}$$

$$\mathcal{E}_S = \sqrt{2qN_A \psi_S / \varepsilon_S}$$

$$Q_D = -qN_A W_D = -\sqrt{2qN_A \varepsilon_S \psi_S} \ \ \mathrm{C/cm^2}$$

Lecture 2.3: Gate voltage



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

Threshold voltage

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

$$\psi_S = 2\psi_B$$

$$Q_S(\psi_S) \approx Q_D(2\psi_B)$$

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

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

Gate voltage vs. surface potential: depletion

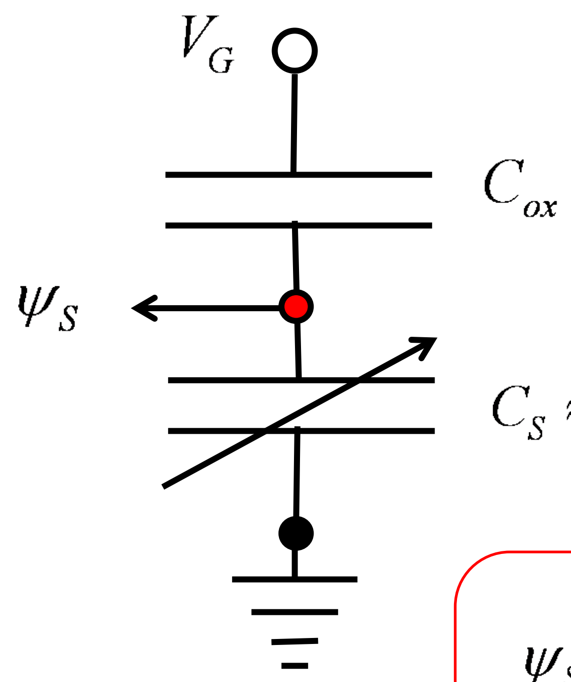
$$V_G' = -\frac{Q_S(\psi_S)}{C_{ox}} + \psi_S$$

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

$$Q_D = -\sqrt{2qN_A\varepsilon_S\psi_S}$$

$$V_G' = \frac{\sqrt{2qN_A\varepsilon_S\psi_S}}{C_{ox}} + \psi_S$$

approximate solution



$$C_S \approx C_D = \frac{\varepsilon_S}{W_D}$$

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

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

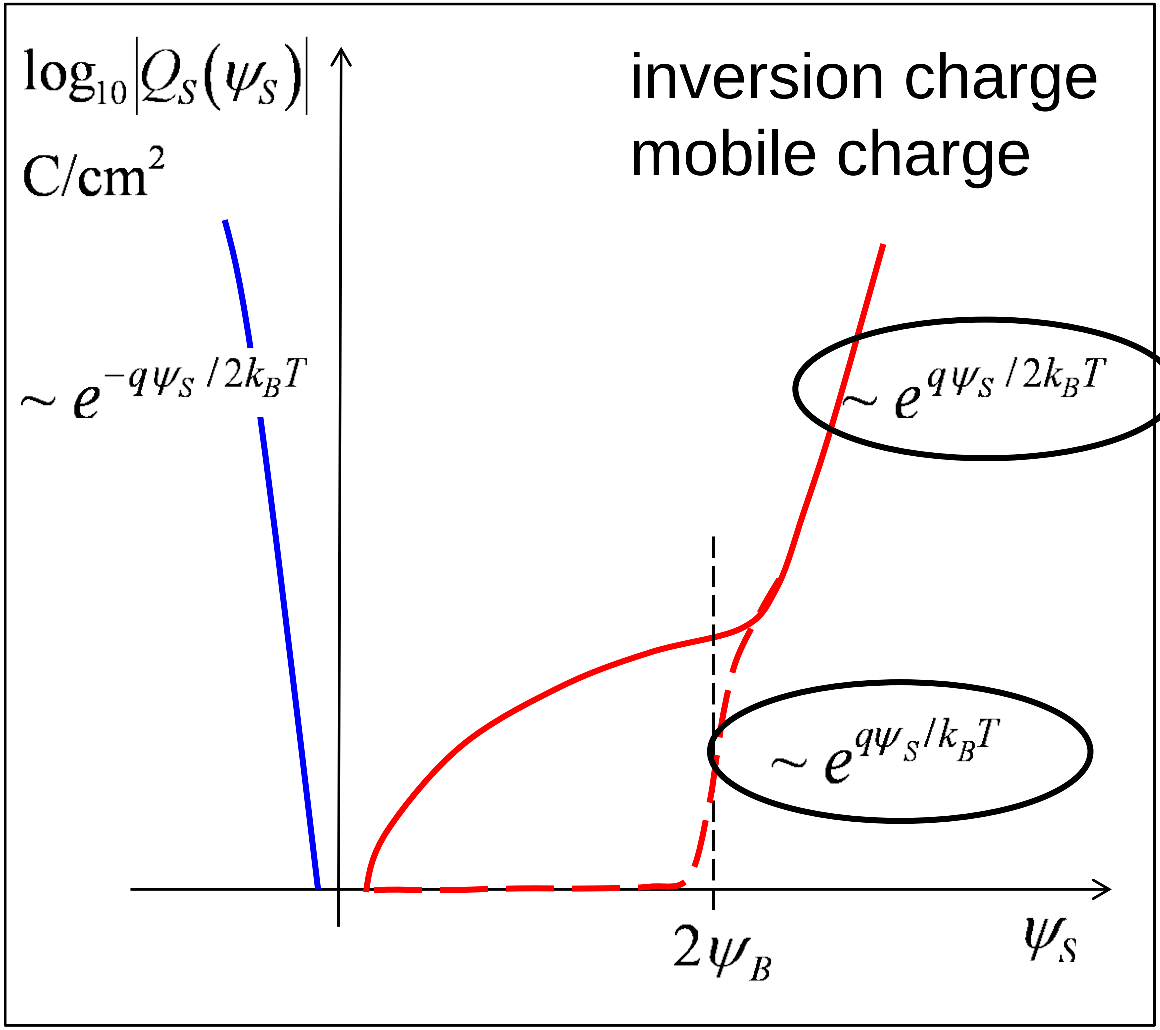
Lecture 2.4: Flatband Voltage

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

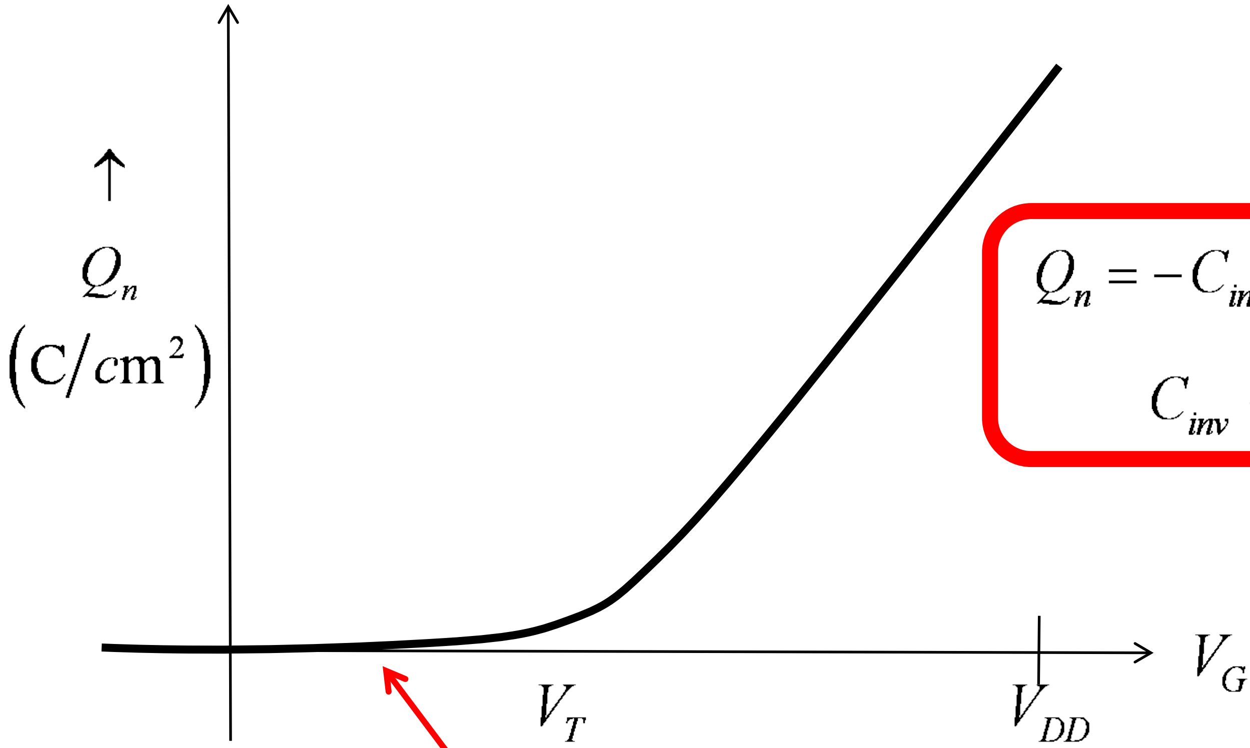
$$V_G = V_{FB} - \frac{Q_S(\psi_S)}{C_{ox}} + \psi_S$$

$$V_{FB} = \phi_{ms} - \frac{Q_F}{C_{ox}}$$

Lecture 2.5: Mobile charge (bulk)



Mobile charge vs. gate voltage



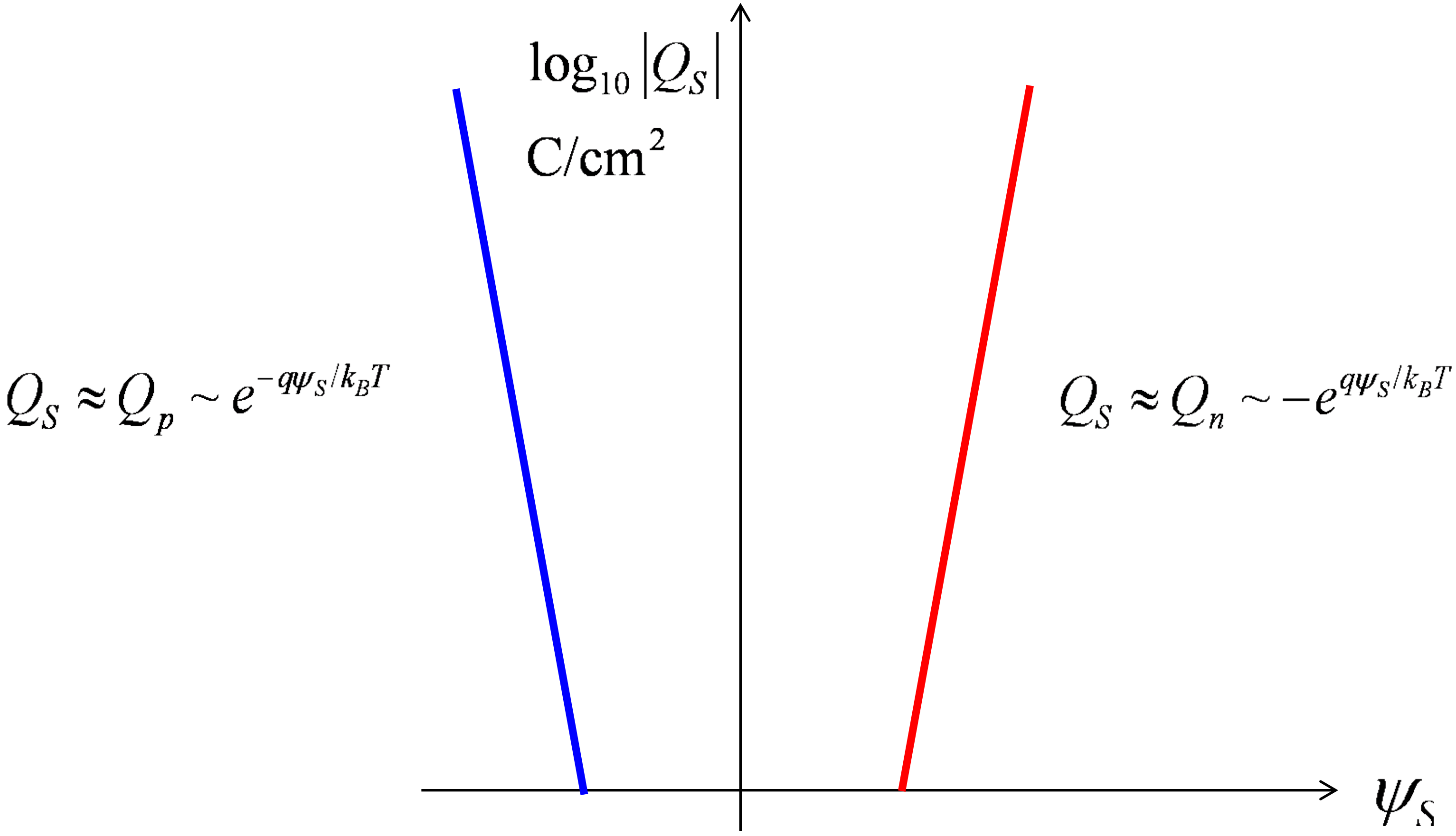
$$Q_n = -C_{inv}\left(V_G - V_T\right)$$

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

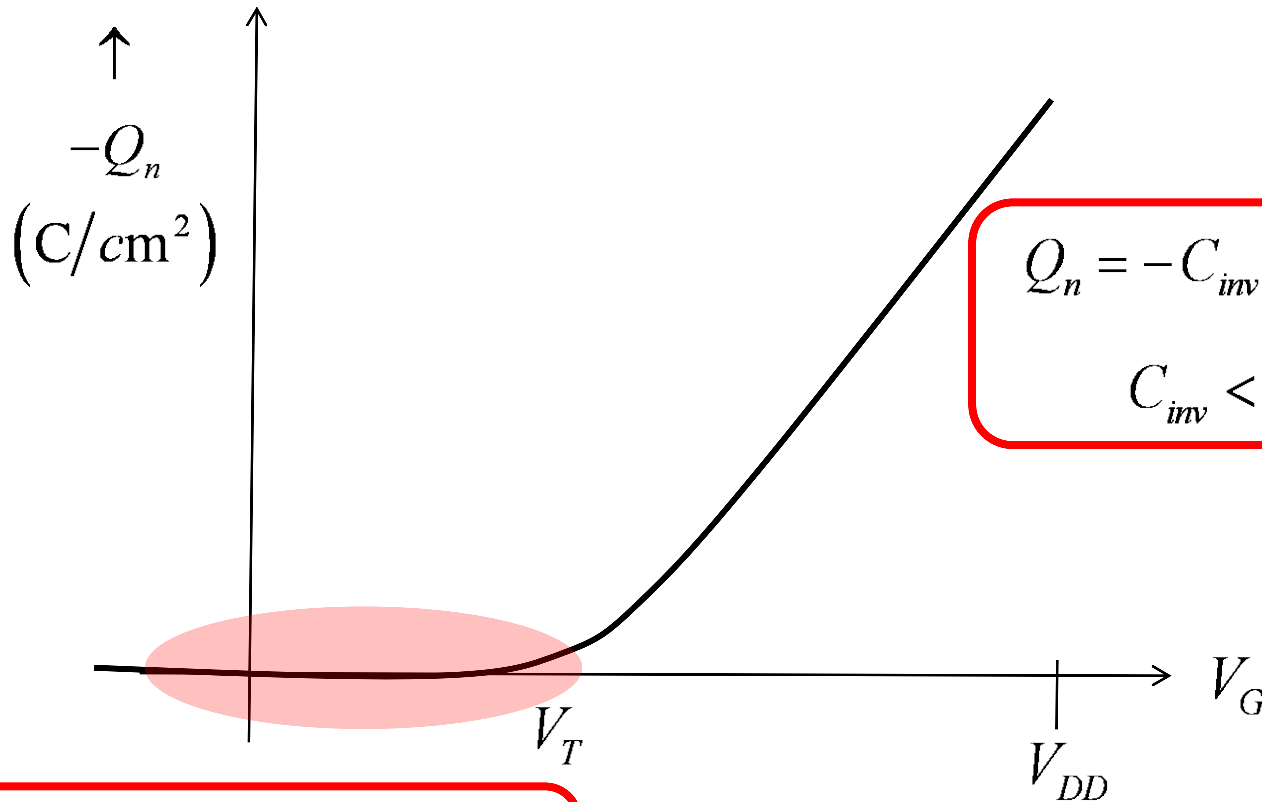
$$Q_n\left(V_G\right) = -(m-1)C_{ox}\left(\frac{k_B T}{q}\right)e^{q\left(V_G - V_T\right)/mk_B T}$$

Lecture 2.6: Mobile charge (ETSOI)

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



Mobile charge vs. gate voltage



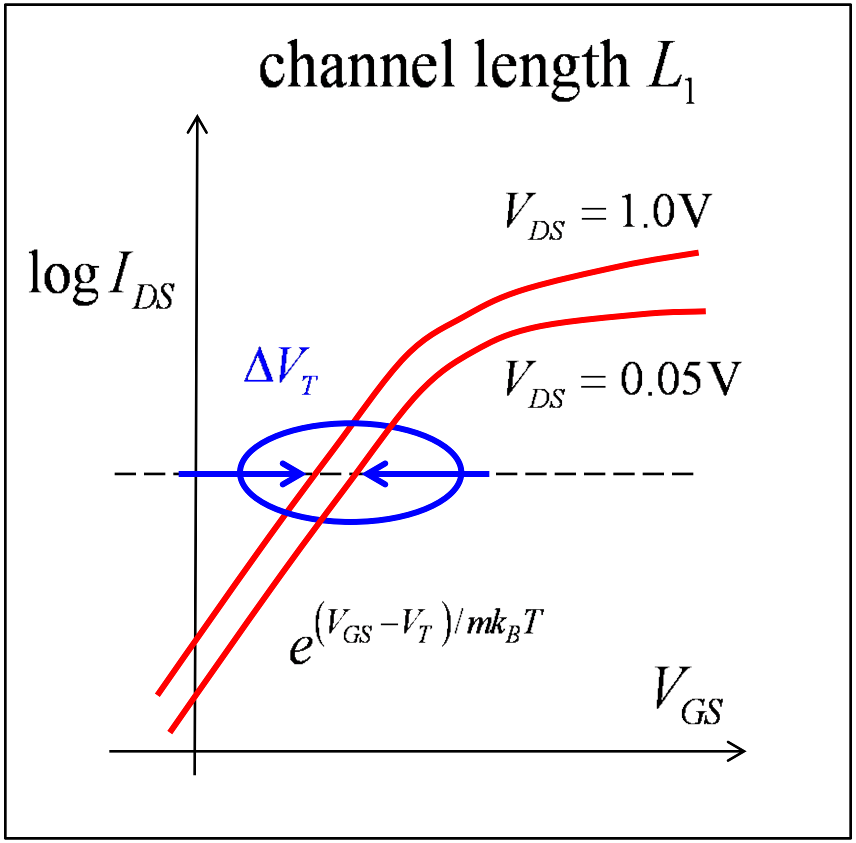
$$Q_n = -C_{inv}\left(V_G - V_T\right)$$

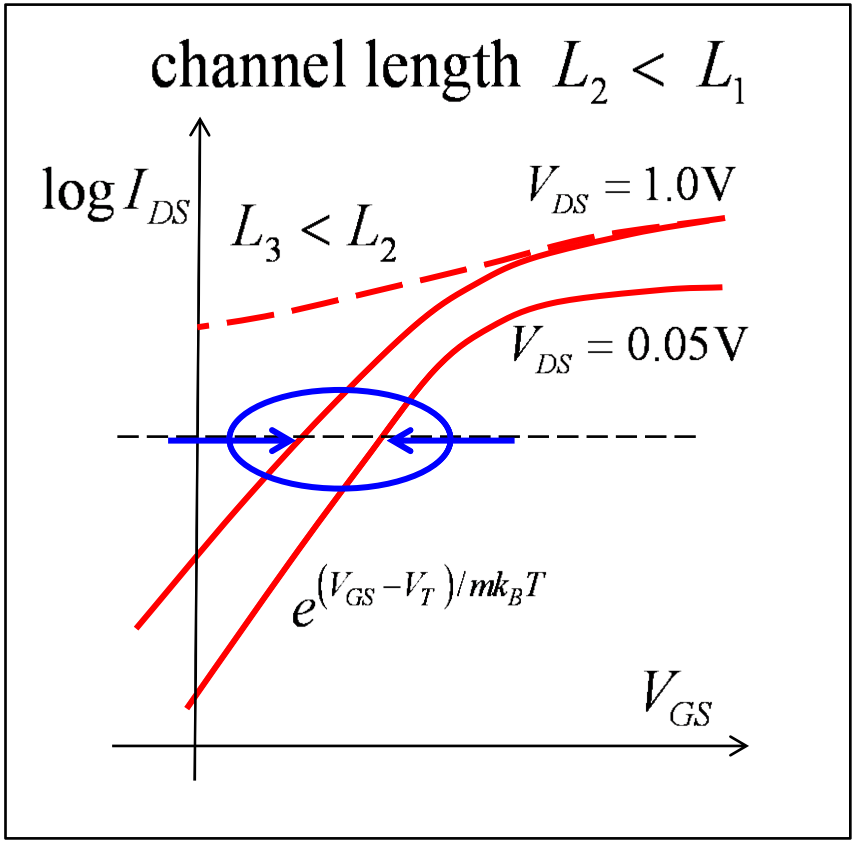
$$C_{inv} < 2C_{ox}$$

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

$$m = 1$$

Lecture 2.7: 2D electrostatics





1) DIBL increases with decreasing *L* and increasing V_{DS}
2) SS may increase with decreasing *L* and increasing V_{DS}
3) Punch through is a severe 2D effect.

2D electrostatics

1) Effective doping

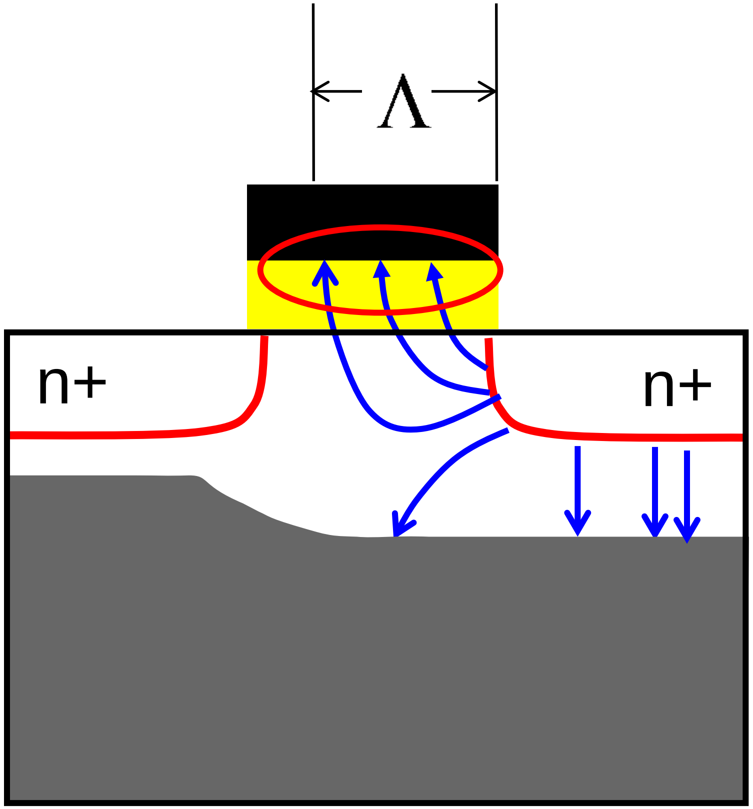
2) Barrier lowering

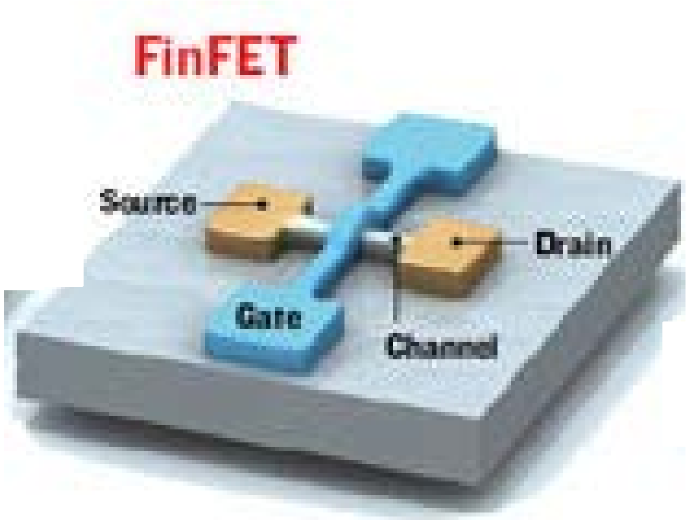
3) Geometric screening length

4) Capacitor model (in lecture notes)

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = \frac{-qN_A(x,y)}{\varepsilon_S}$$

2D electrostatics





"Transistors go Vertical,"
IEEE Spectrum, Nov. 2007.

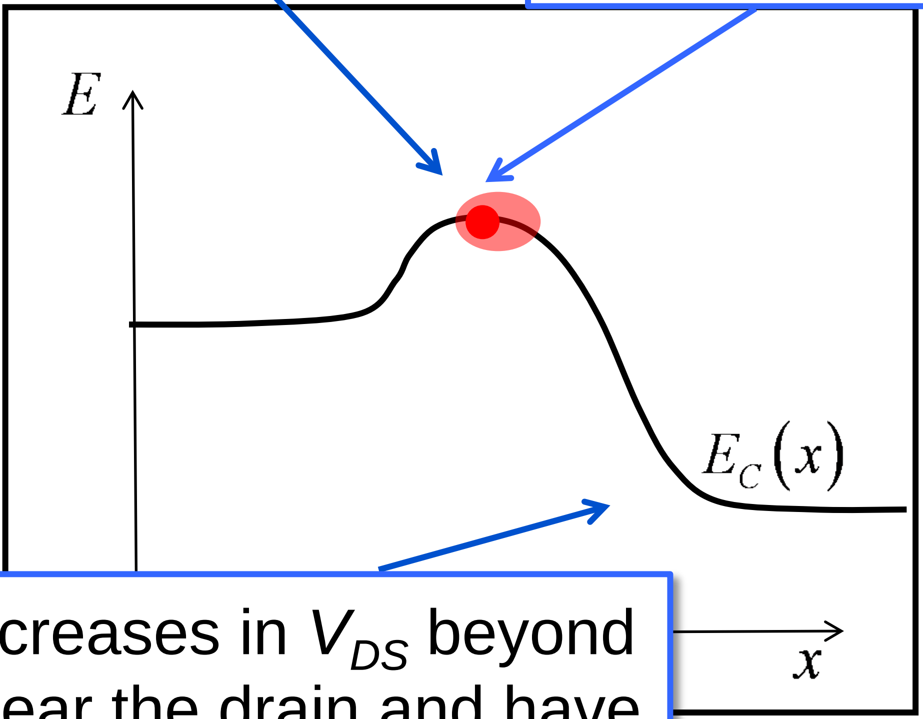
"Well-tempered MOSFET"

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

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_{DS} (small DIBL)

Lecture 2.8: VS model revisited

1) $I_{DS}/W = -Q_n(V_{GS})\langle \upsilon(V_{DS})\rangle$

2) $Q_n(V_{GS},V_{GS}) = -C_{inv} m (k_B T/q)\ln\left(1 + e^{q\left(V_{GS}-V_T+\alpha(k_B T_L/q)F_f\right)/mk_B T}\right)$

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

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

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

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

Only 10 device-specific parameters in this model:

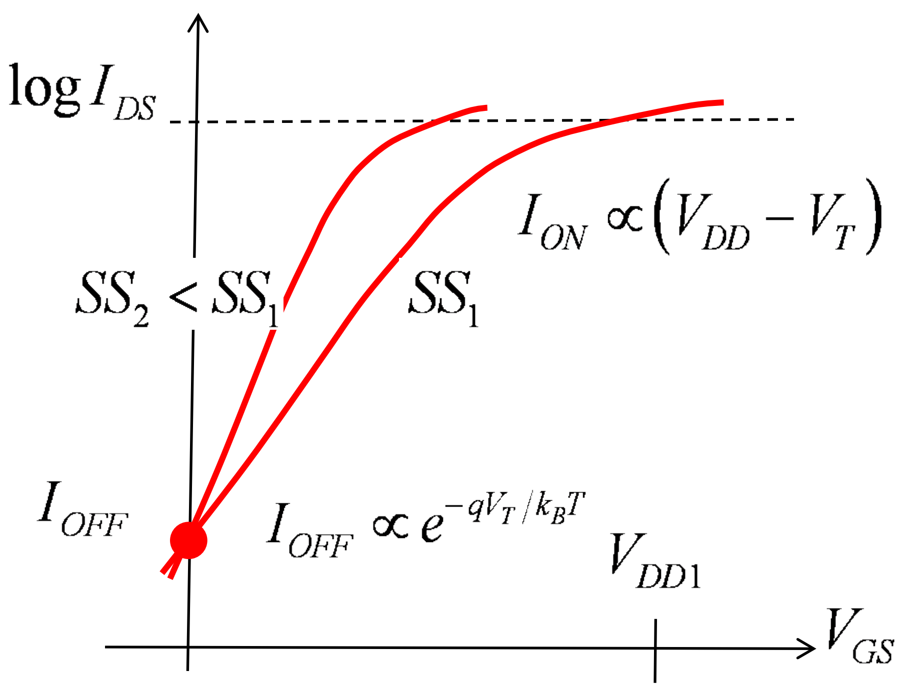
$C_{inv}, V_T, \delta, m, \upsilon_{sat}, \mu_n, L$

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

Subthreshold Swing

$$S = 2.3m\left(k_B T/q\right)\ \frac{\text{mV}}{\text{dec}} \qquad m = \left(1 + C_\Sigma / C_{ox}\right) \geq 1$$

Why is a small *SS* important?



$$SS > 60\ \frac{\text{mV}}{\text{dec}}\ \ (T = 300K)$$

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

Next: The ballistic MOSFET

transport

$$I_{DS}/W = -Q_n\left(V_{GS},V_{DS}\right)\left\langle \upsilon\left(V_{DS}\right)\right\rangle$$

electrostatics