Fundamentals of Nanotransistors

Unit 3: The Ballistic Nanotransistor

Lecture 3.1: Introduction

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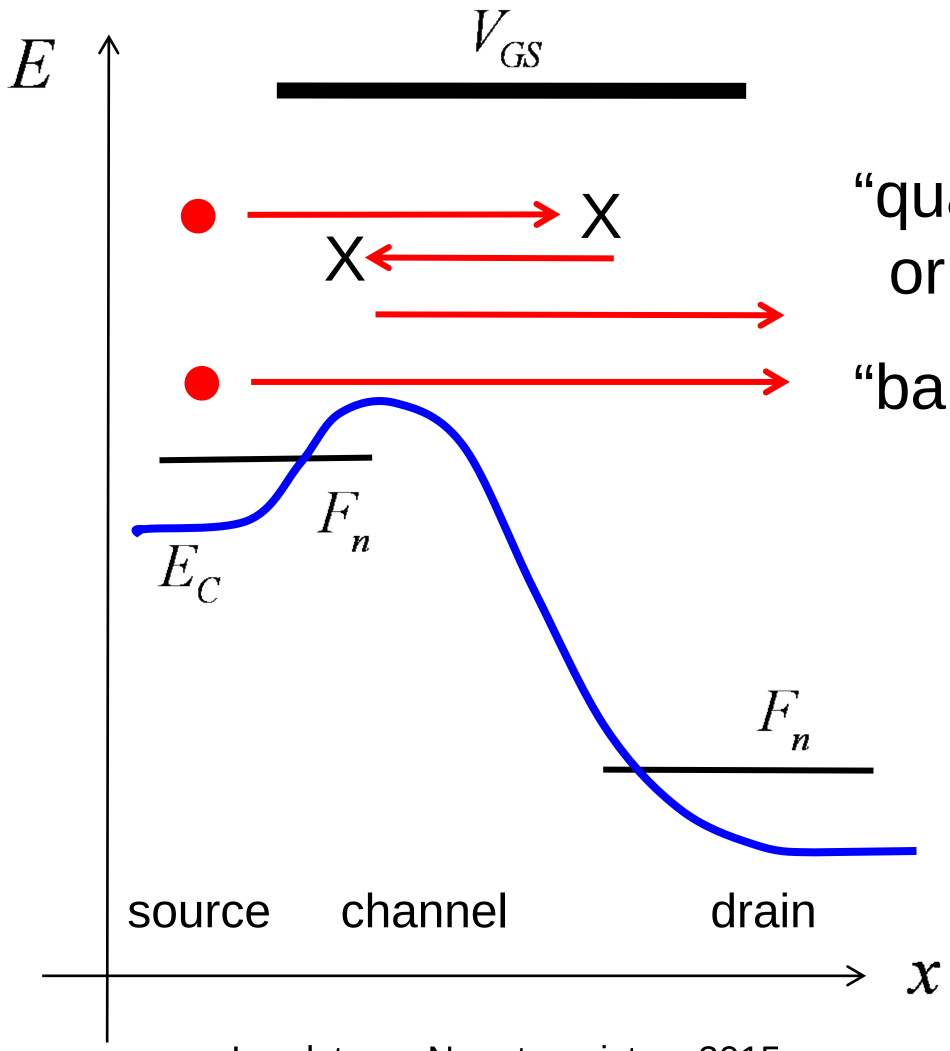
Unit 3

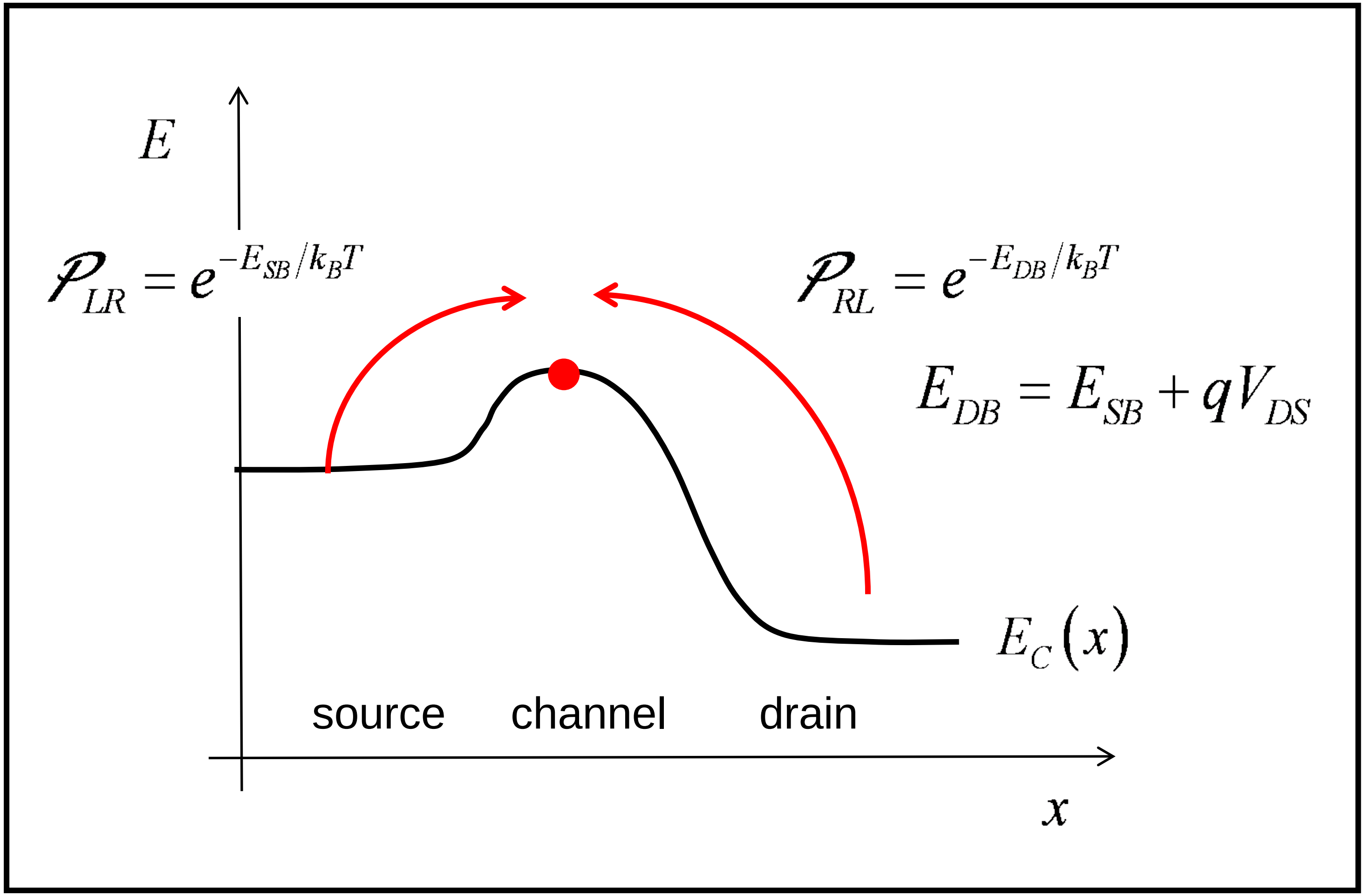
Ballistic vs. diffusive transport



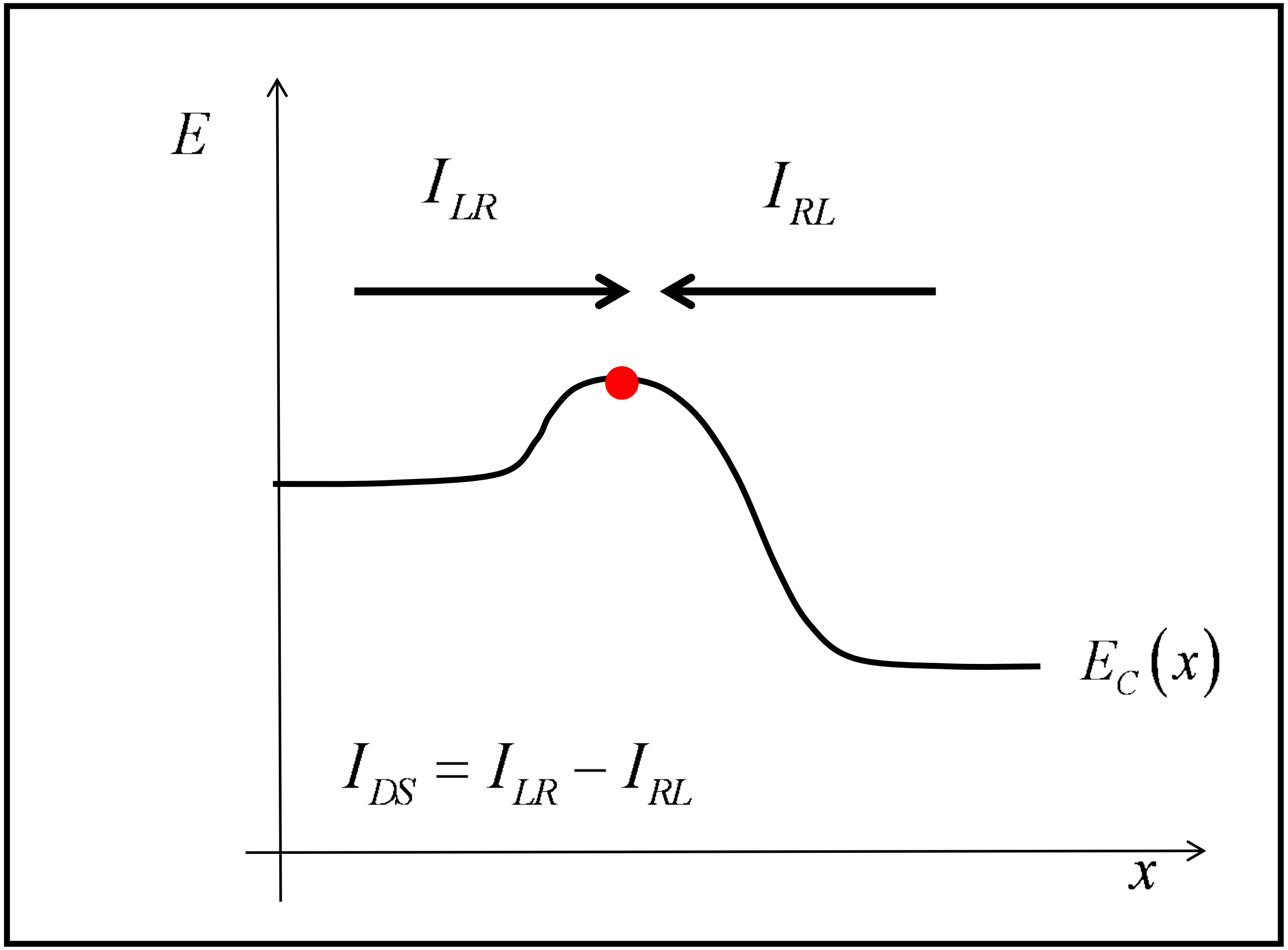
"quasi-ballistic"
or "diffusive"

"ballistic transport"

Thermionic emission



Thermionic emission



Ballistic current

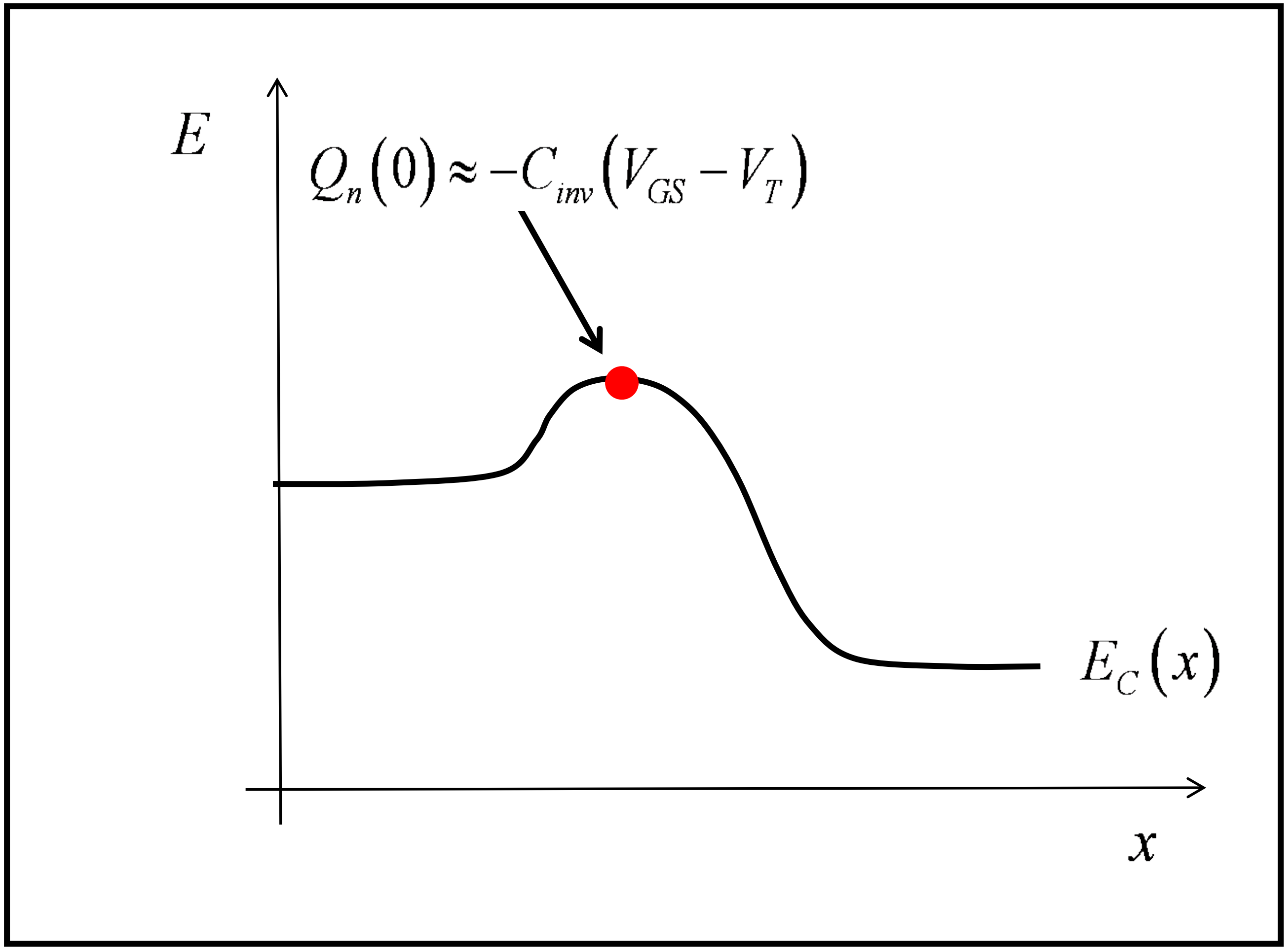
$$I_{DS} = I_{LR} - I_{RL}$$

$$I_{DS} = I_{LR}\left(1 - I_{RL}/I_{LR}\right)$$

$$\boxed{I_{DS} = I_{LR}\left(1 - e^{-qV_{DS}/k_BT}\right)}$$

$$I_{DS} = I_{LR}\left(1 - e^{-\Delta E_B/k_BT}\right)$$

MOS electrostatics



MOS electrostatics

$$I_{LR} = Wqn_S^+ \upsilon_T$$

$$I_{RL} = Wqn_S^- \upsilon_T$$

$$qn_S^+ = \frac{I_{LR}}{W\upsilon_T}$$

$$qn_S^- = \frac{I_{RL}}{W\upsilon_T}$$

$$Q_n = -q\left(n_S^+ + n_S^-\right)$$

$$Q_n = -\frac{\left(I_{LR} + I_{RL}\right)}{W\upsilon_T}$$

$$Q_n = -\frac{I_{LR}}{W\upsilon_T}\left(1 + I_{RL}/I_{LR}\right)$$

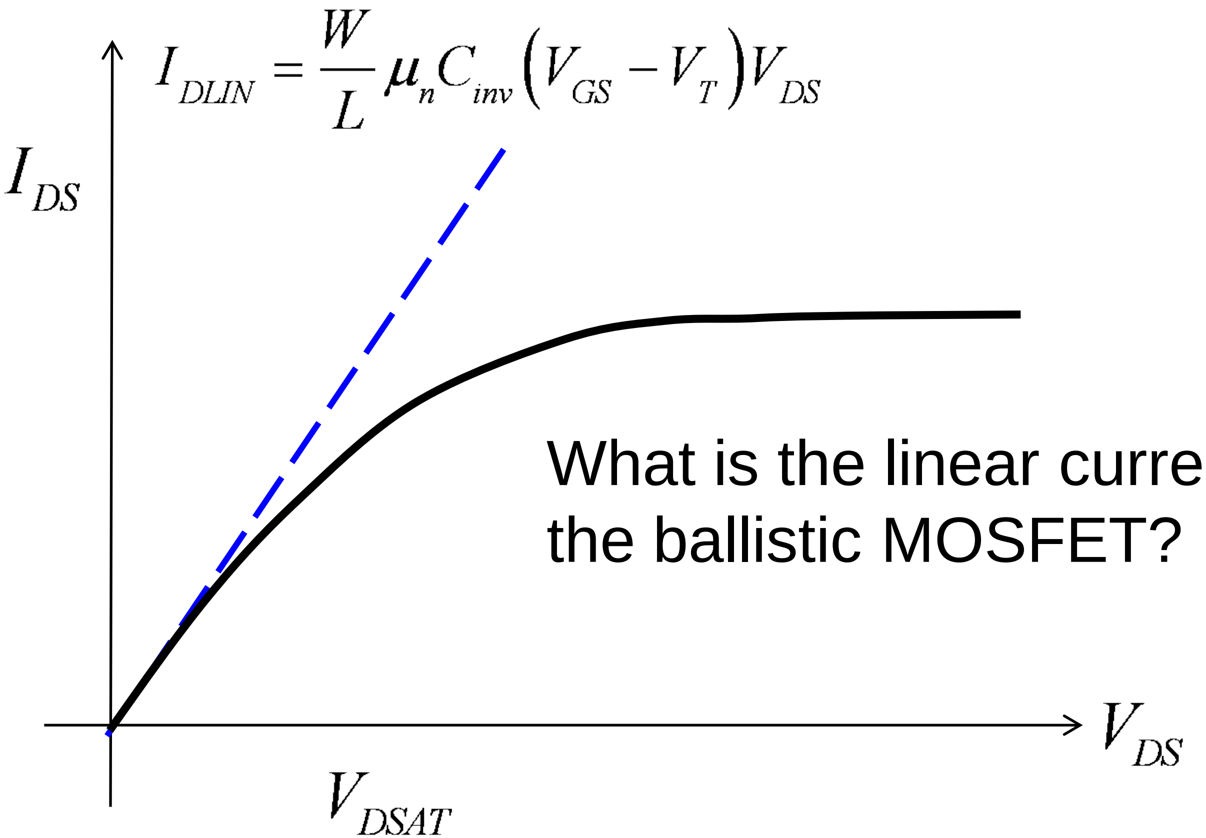
$$Q_n = -\frac{I_{LR}}{W\upsilon_T}\left(1 + e^{-qV_{DS}/k_BT}\right)$$

Ballistic IV characteristics

$$I_{DS} = I_{LR}\left(1 - e^{-qV_{DS}/k_BT}\right) \quad Q_n(0) = -\frac{I_{LR}}{W\upsilon_T}\left(1 + e^{-qV_{DS}/k_BT}\right)$$

$$\boxed{I_{DS} = W\left|Q_n(0)\right|\upsilon_T \frac{\left(1 - e^{-qV_{DS}/k_BT}\right)}{\left(1 + e^{-qV_{DS}/k_BT}\right)}}$$

Recall: traditional model in linear region



What is the linear current for the ballistic MOSFET?

Ballistic MOSFET: Linear region

$$I_{DS} = W\left|Q_n(0)\right|\upsilon_T \frac{\left(1-e^{-qV_{DS}/k_BT}\right)}{\left(1+e^{-qV_{DS}/k_BT}\right)}$$

$$V_{DS} << k_BT/q$$

$$e^x \approx 1 + x \quad (\text{small } x)$$

$$\boxed{I_{DS} = W\left|Q_n(0)\right|\frac{\upsilon_T}{2\left(k_BT/q\right)}V_{DS}}$$

$$I_{DS} = W\left|Q_n(0)\right|\upsilon_T \frac{1-\left(1-qV_{DS}/k_BT\right)}{1+\left(1-qV_{DS}/k_BT\right)}$$

Traditional vs. ballistic linear current

Diffusive

$$I_{DLIN} = \frac{W}{L}\mu_n \left|Q_n\left(x=0\right)\right| V_{DS}$$

$$I_{DLIN} = \frac{W}{L}\mu_n C_{inv}\left(V_{GS}-V_T\right)V_{DS}$$

Ballistic

$$I_{DLIN}^{ball} = W\left(\frac{\upsilon_T}{2\left(k_B T/q\right)}\right)\left|Q_n\left(x=0\right)\right| V_{DS}$$

$$I_{DLIN}^{ball} = W\left(\frac{\upsilon_T}{2\left(k_B T/q\right)}\right) C_{inv}\left(V_{GS}-V_T\right)V_{DS}$$

$$I_{DLIN}^{ball} = \frac{W}{L}\left(\frac{\upsilon_T L}{2\left(k_B T/q\right)}\right)\left|Q_n\left(x=0\right)\right| V_{DS}$$

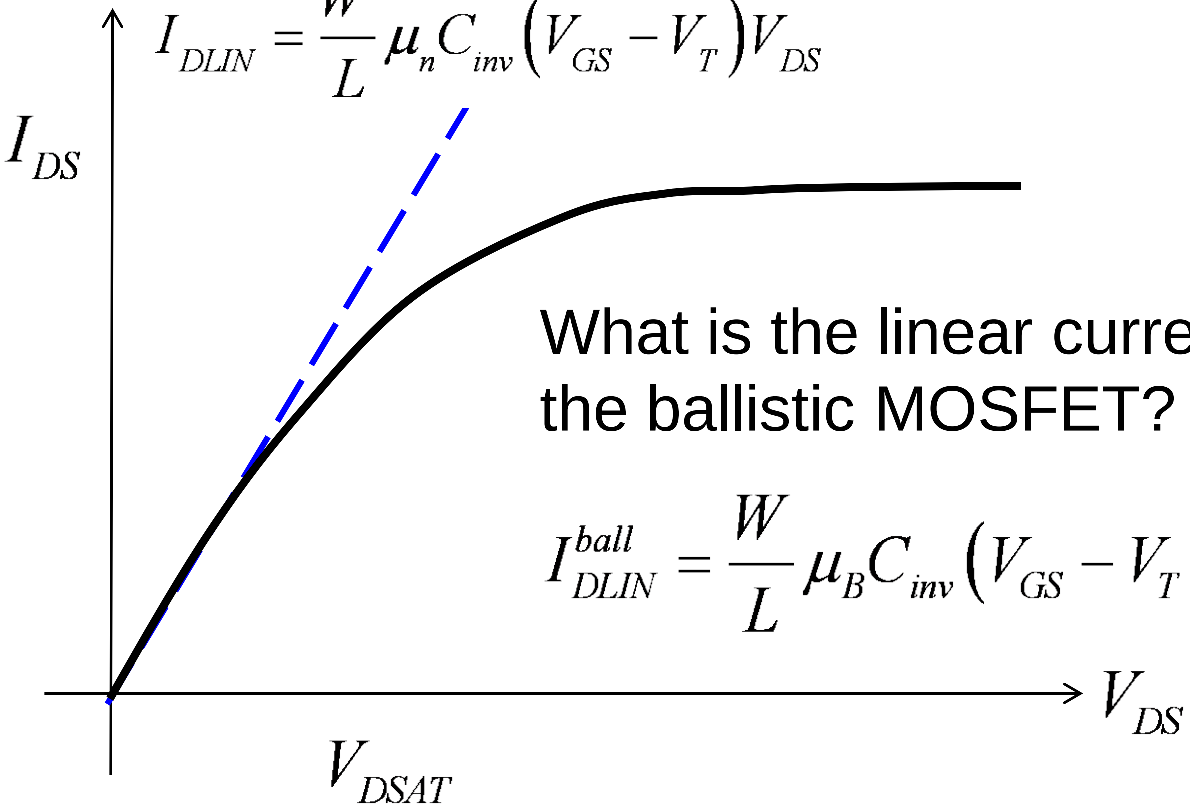
Independent of *L*

$$\mu_B \equiv \frac{\upsilon_T L}{2\left(k_B T/q\right)}$$

"ballistic mobility"

Ballistic model in linear region

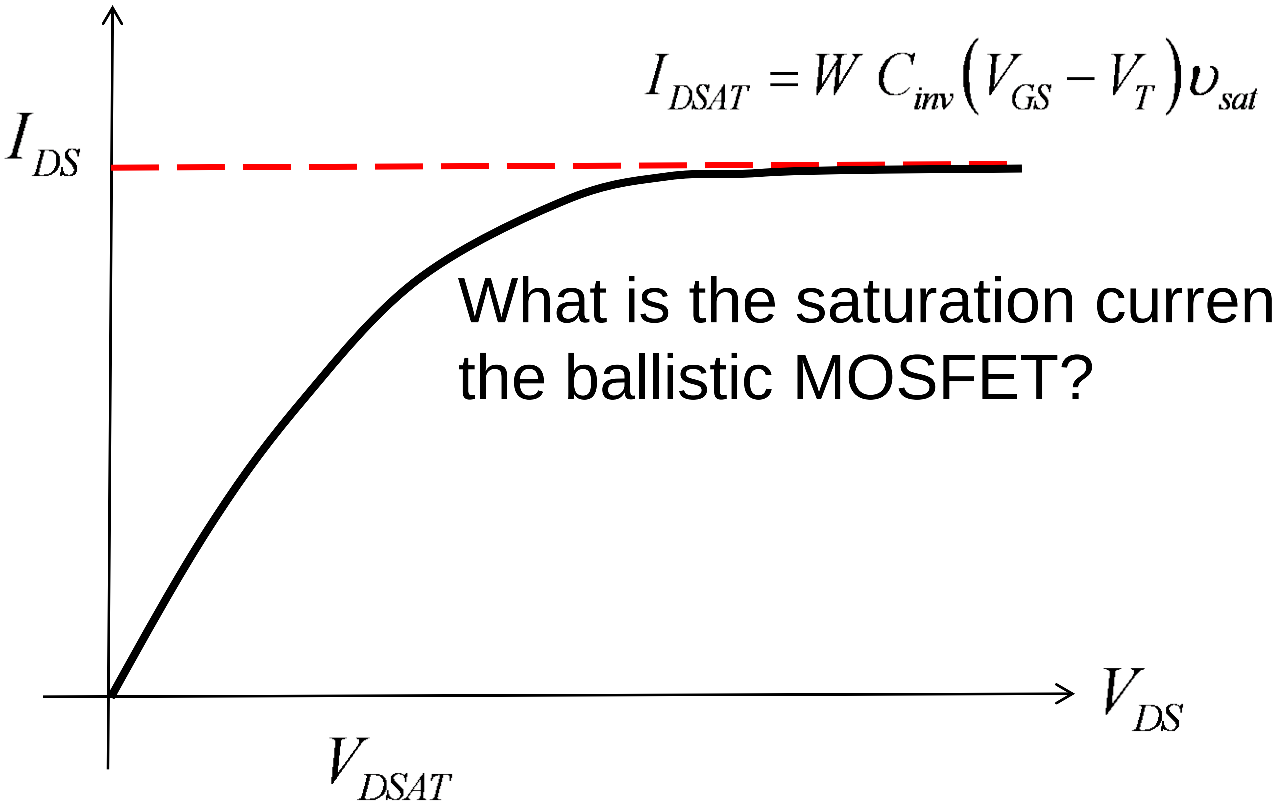
$$I_{DLIN} = \frac{W}{L}\mu_n C_{inv}\left(V_{GS} - V_T\right)V_{DS}$$



What is the linear current for the ballistic MOSFET?

$$I_{DLIN}^{ball} = \frac{W}{L}\mu_B C_{inv}\left(V_{GS} - V_T\right)V_{DS}$$

Recall: Traditional model in saturation



What is the saturation current for the ballistic MOSFET?

Ballistic MOSFET: Saturation region

$$I_{DS} = W\left|Q_n(0)\right|\upsilon_T \frac{\left(1 - e^{-qV_{DS}/k_BT}\right)}{\left(1 + e^{-qV_{DS}/k_BT}\right)}$$

$$V_{DS} >> k_BT/q$$

$$e^{-x} \approx 0 \quad (\text{large } x)$$

$$I_{DS} = W\left|Q_n(0)\right|\upsilon_T$$

$$\boxed{I_{DSAT} = W\left|Q_n(0)\right|\upsilon_T}$$

Traditional vs. ballistic saturation current

Diffusive

$$I_{DSAT} = W\left|Q_n\left(x=0\right)\right|\upsilon_{sat}$$

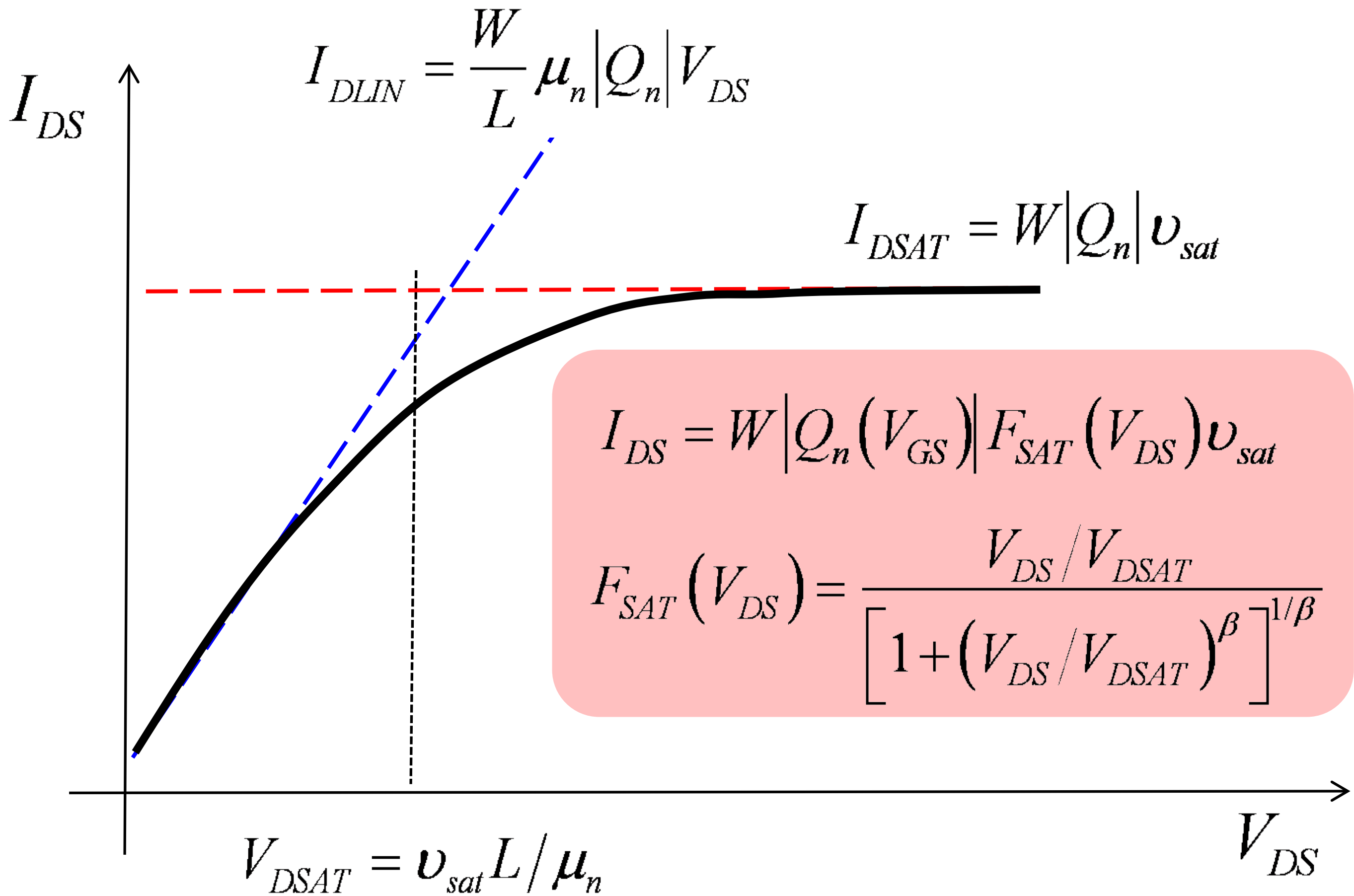
$$I_{DSAT} = W\,C_{inv}\left(V_{GS}-V_T\right)\upsilon_{sat}$$

Ballistic

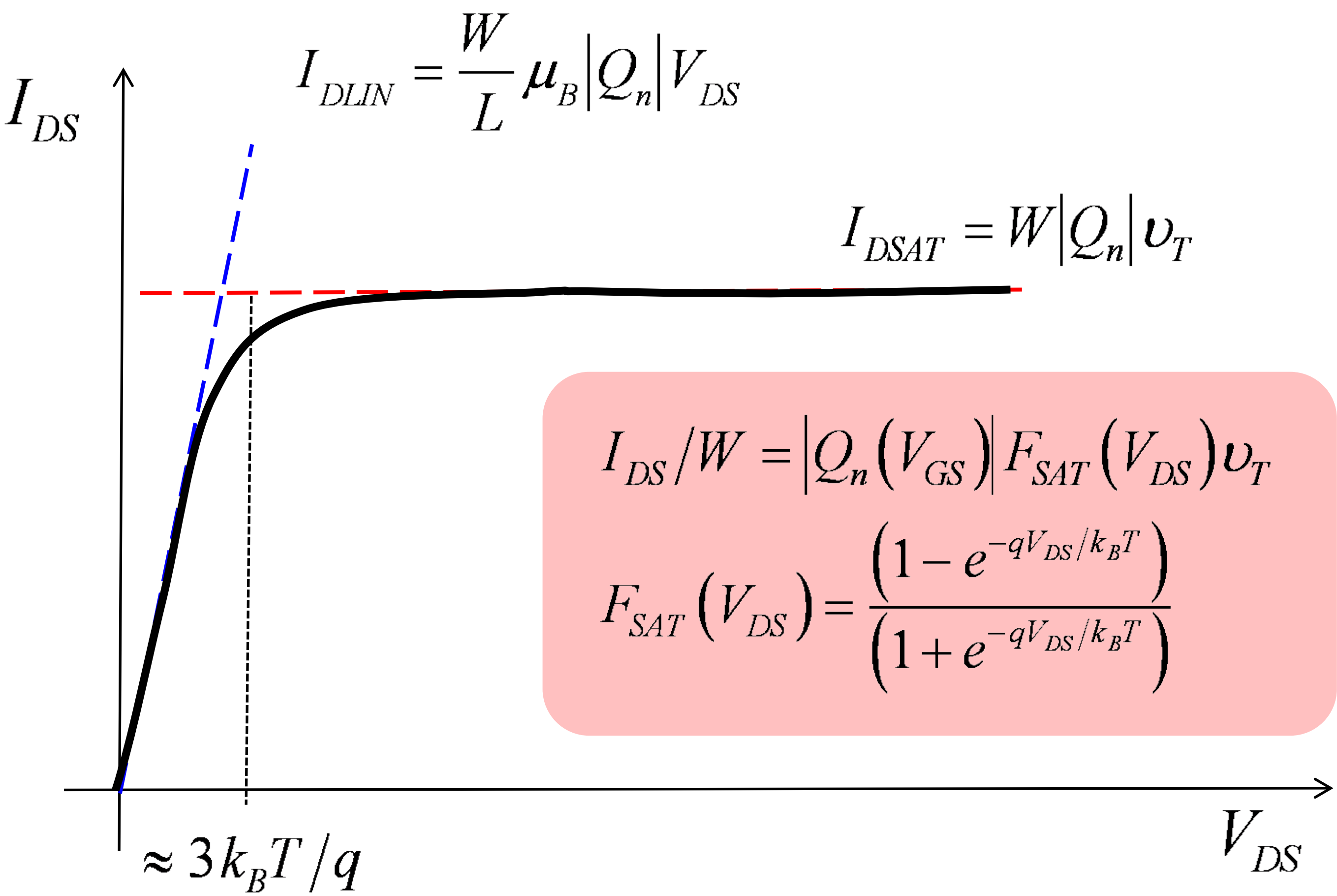
$$I_{DSAT} = W\left|Q_n\left(x=0\right)\right|\upsilon_{T}$$

$$I_{DSAT} = W\,C_{inv}\left(V_{GS}-V_T\right)\upsilon_{T}$$

Recall: VS model



Ballistic model



$$I_{DS}/W = |Q_n(V_{GS})| F_{SAT}(V_{DS})\upsilon_T$$

$$F_{SAT}(V_{DS}) = \frac{\left(1 - e^{-qV_{DS}/k_BT}\right)}{\left(1 + e^{-qV_{DS}/k_BT}\right)}$$

The ballistic MOSFET

$$I_{DS} = W\left|Q_n(0)\right|\upsilon_T \frac{\left(1 - e^{-qV_{DS}/k_BT}\right)}{\left(1 + e^{-qV_{DS}/k_BT}\right)}$$

Assumptions:

1) Non-degenerate (Boltzmann) statistics for carriers

1) No scattering

Transport

1) Drift-diffusion equation:

$$J_n = nq\mu_n \mathcal{E} + qD_n \frac{dn}{dx}$$

2) Landauer approach:

$$I = \frac{2q}{h}\int \mathcal{T}(E)M(E)(f_1 - f_2)dE$$

Next lecture: Introduce the Landauer approach.