Fundamentals of Nanotransistors

Unit 3: The Ballistic Nanotransistor

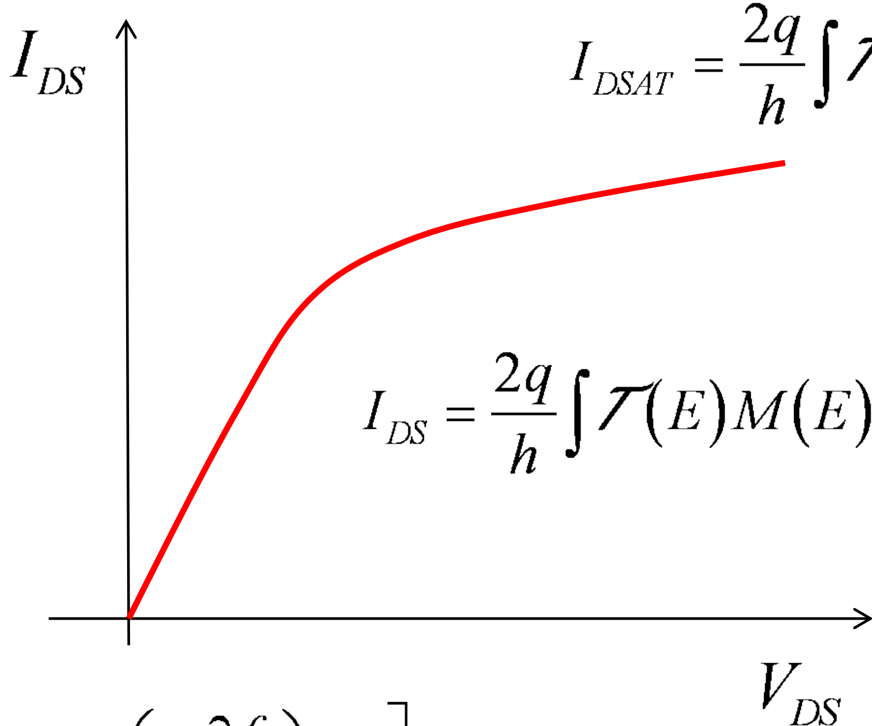
Lecture 3.6: Revisiting the VS Model

Mark Lundstrom

lundstro@purdue.edu
Electrical and Computer Engineering
Birck Nanotechnology Center
Purdue University, West Lafayette, Indiana USA

Ballistic model

$$I_{DSAT} = \frac{2q}{h}\int \mathcal{T}(E)M(E)f_S(E)dE$$

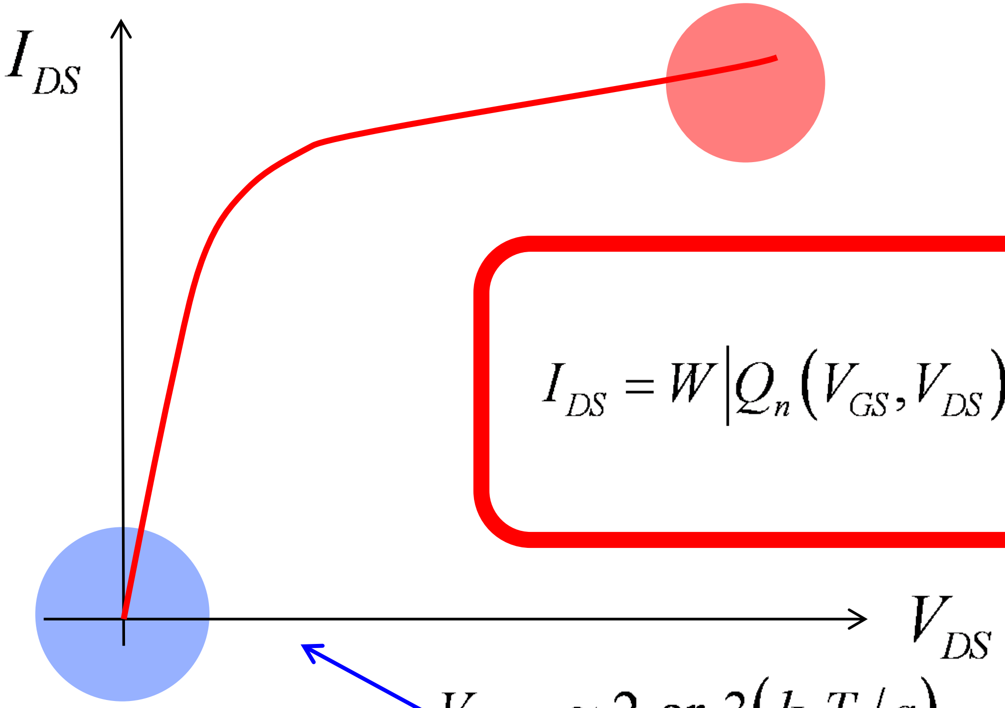


$$I_{DS} = \frac{2q}{h}\int \mathcal{T}(E)M(E)\left(f_S - f_D\right)dE$$

$$I_{DLIN} = \left[\frac{2q^2}{h}\int \mathcal{T}(E)M(E)\left(-\frac{\partial f_0}{\partial E}\right)dE\right]V_{DS}$$

Ballistic model (nondegenerate)

$$I_{DSAT} = W\left|Q_n\left(V_{GS}, V_{DS}\right)\right|\upsilon_T$$



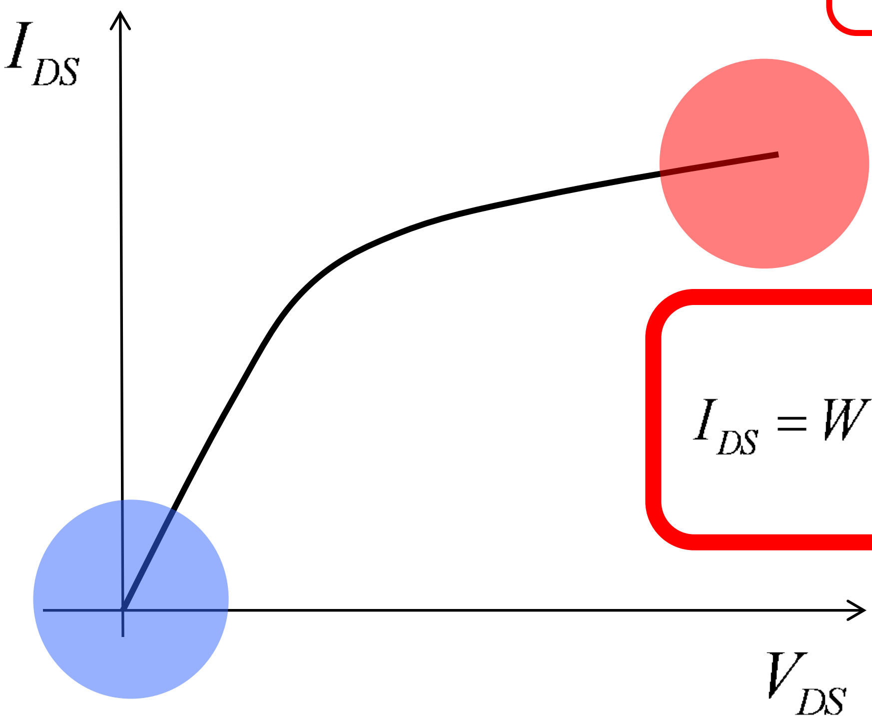
$$\boxed{I_{DS} = W\left|Q_n\left(V_{GS}, V_{DS}\right)\right|\upsilon_T\left(\frac{1-e^{-qV_{DS}/k_BT}}{1+e^{-qV_{DS}/k_BT}}\right)}$$

$$V_{DSAT} \approx 2 \text{ or } 3\left(k_BT/q\right)$$

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

"Traditional" VS model for the MOSFET

$$I_{DSAT} = W\,Q_n\left(V_{GS}, V_{DS}\right)\upsilon_{sat}$$



$$I_{DS} = W\left|Q_n\left(V_{GS}, V_{DS}\right)\right| F_{SAT}\left(V_{DS}\right)\upsilon_{sat}$$

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

Lecture 2.8

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

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

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

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

Only 10 device-specific parameters in this model:

$C_{inv}, L,$

$V_T, \delta, m, \upsilon_{sat}, \mu_n, R_{SD} = R_S + R_D,$

α, β

Connecting the two: linear region

ballistic theory

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

$$I_{DLIN} = \frac{W}{L}\left(\frac{\upsilon_T L}{2k_BT/q}\right)\left|Q_n\left(V_{GS},V_{DS}\right)\right|V_{DS}$$

$$\mu_B \equiv \frac{\upsilon_T L}{2k_BT/q}$$

"ballistic mobility"

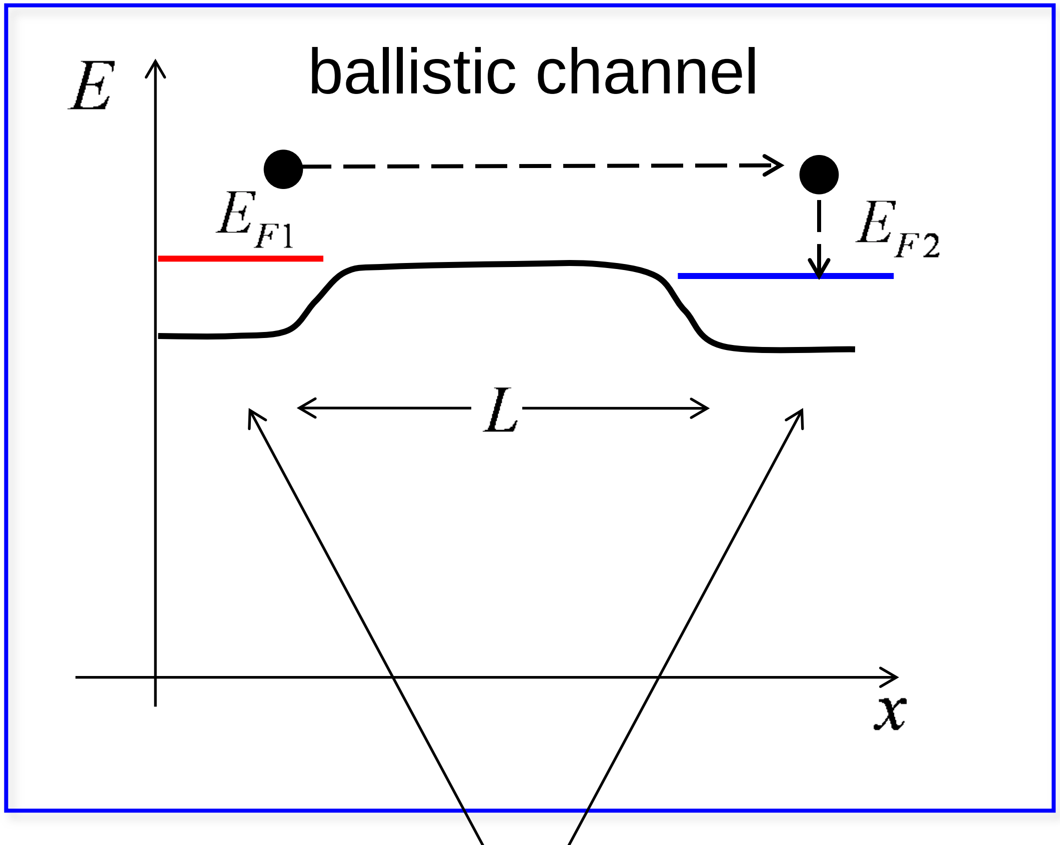
$$I_{DLIN} = \frac{W}{L}\mu_B\left|Q_n\left(V_{GS},V_{DS}\right)\right|V_{DS}$$

diffusive theory

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

$$\mu_n \rightarrow \mu_B$$

Meaning of “ballistic mobility”



strong scattering in the S/D regions

$$\mu_B = \frac{\upsilon_T L}{2 k_B T / q}$$

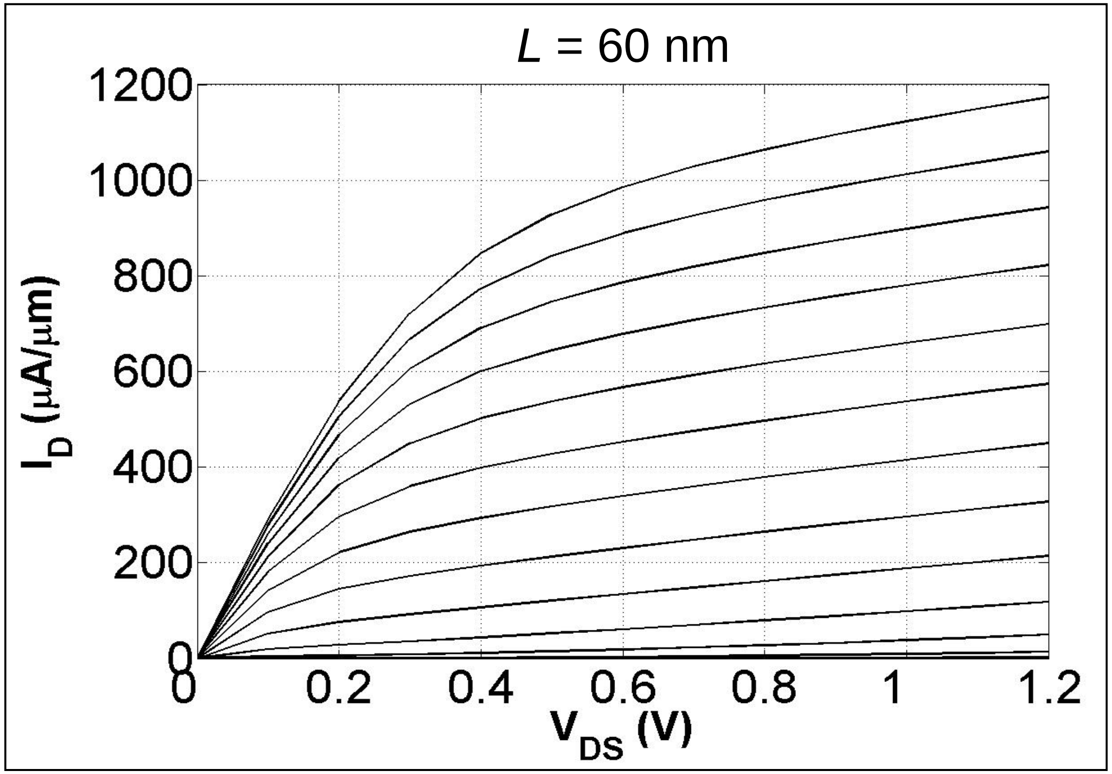
$$\mu_n = \frac{\upsilon_T \lambda_0}{2 k_B T / q}$$

$$\lambda_0 \rightarrow L$$

$$\mu_B \propto L$$

$$I_{DLIN} \propto \mu_B \frac{W}{L}$$

Ballistic mobility example



$$\mu_n \approx 250 \text{ cm}^2/\text{V-s}$$

$$\mu_B = \frac{\upsilon_T L}{2 k_B T / q}$$

$$\mu_B \approx 1385 \text{ cm}^2/\text{V-s}$$

$$\mu_B >> \mu_n$$

(Thanks to Shuji Ikeda of ATDF for supplying these devices in Dec. 2007)

Connecting the two: saturation region

ballistic theory

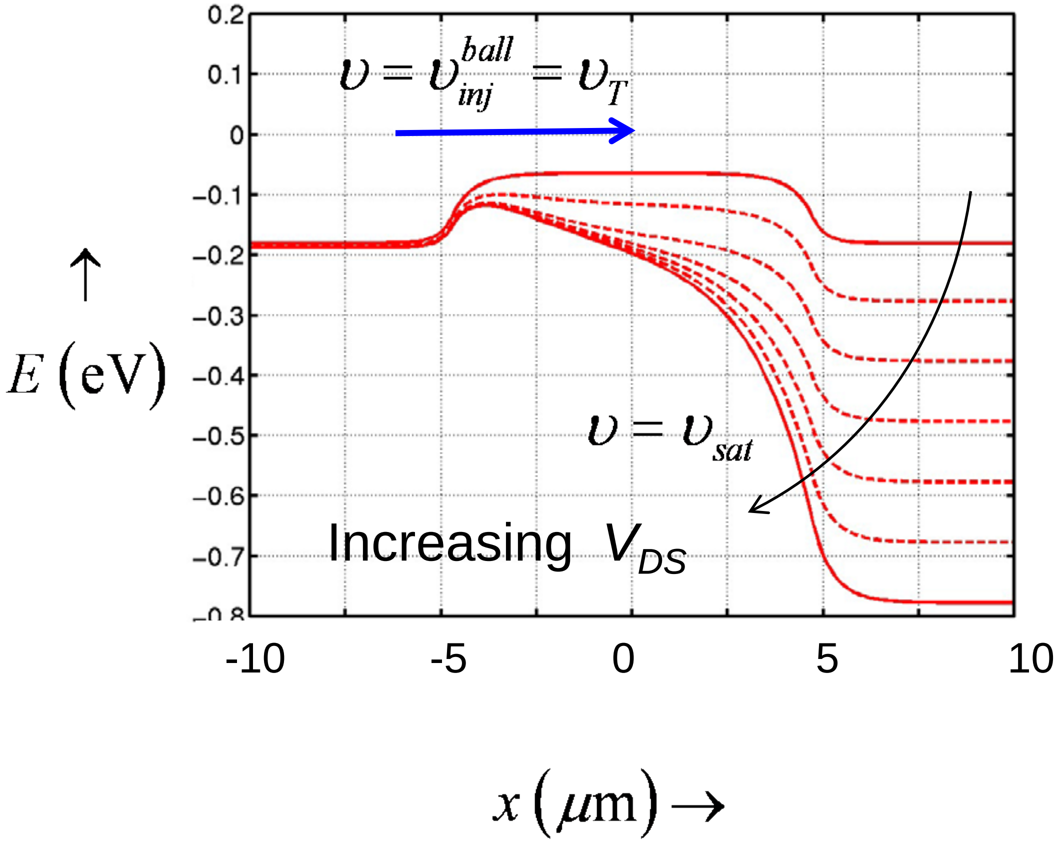
$$I_{DSAT} = W\left|Q_n\left(V_{GS}, V_{DS}\right)\right|\upsilon_T$$

traditional theory

$$I_{DSAT} = W\left|Q_n\left(V_{GS}, V_{DS}\right)\right|\upsilon_{sat}$$

$$\upsilon_{sat} \rightarrow \upsilon_T$$

Injection vs. saturation velocity



$\upsilon_{sat} \rightarrow \upsilon_T$

Lecture 1.7

1674 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 56, NO. 8, AUGUST 2009

A Simple Semiempirical Short-Channel MOSFET Current–Voltage Model Continuous Across All Regions of Operation and Employing Only Physical Parameters

Ali Khakifirooz, *Member, IEEE*, Osama M. Nayfeh, *Member, IEEE*, and Dimitri Antoniadis, *Fellow, IEEE*

$$\frac{1}{\mu_n} \rightarrow \frac{1}{\mu_{app}}$$ "apparent mobility"

$$\upsilon_{sat} \rightarrow \upsilon_{inj}$$ "injection velocity"

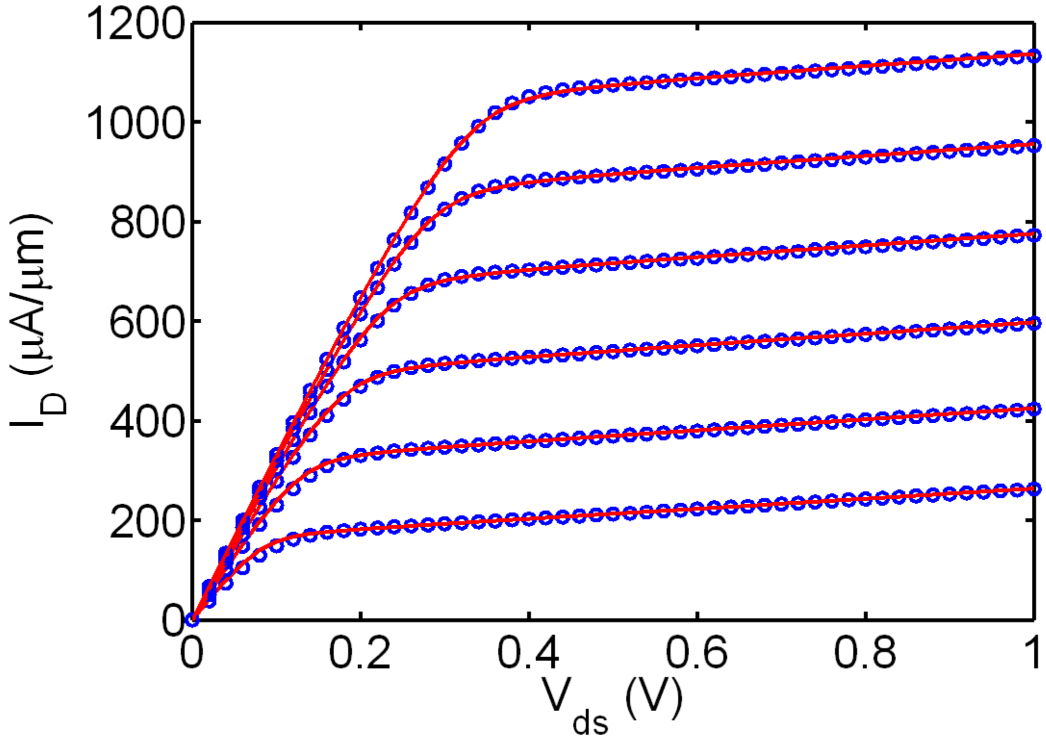
Question

Can we fit the empirical VS model to the ballistic theory model?

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

If so, then what do the fitted parameters in the VS model mean?

Ballistic example



Lines: ballistic theory

Symbols: VS fit to ballistic theory

$$\mu_{app} = 654 \text{ cm}^2/\text{V-s}$$

$$\upsilon_{inj} = 1.24 \times 10^7 \text{ cm/s}$$

(Parameters from a 30 nm ETSOI device used (series resistance included).

Fig. 15.1 *Fundamentals of Nanotransistors*, World Scientific Lecture Notes, 2015.

Ballistic example: *discussion*

Are the fitted VS parameters the expected values?

VS fit parameters:

$$\upsilon_{inj} = 1.24 \times 10^7 \text{ cm/s}$$

$$\mu_{app} = 654 \text{ cm}^2/\text{V-s}$$

$$\upsilon_T = \sqrt{\frac{2k_B T}{\pi m^*}} \qquad m^* = 0.19 m_0$$

$$\upsilon_T = 1.20 \times 10^7 \text{ cm/s} \quad ✓$$

$$\mu_B = \frac{\upsilon_T L}{2 k_B T/q} \qquad L = 30 \text{ nm}$$

$$\mu_B = 692 \text{ cm}^2/\text{V-s} \quad ✓$$

Measured characteristics vs. ballistic theory

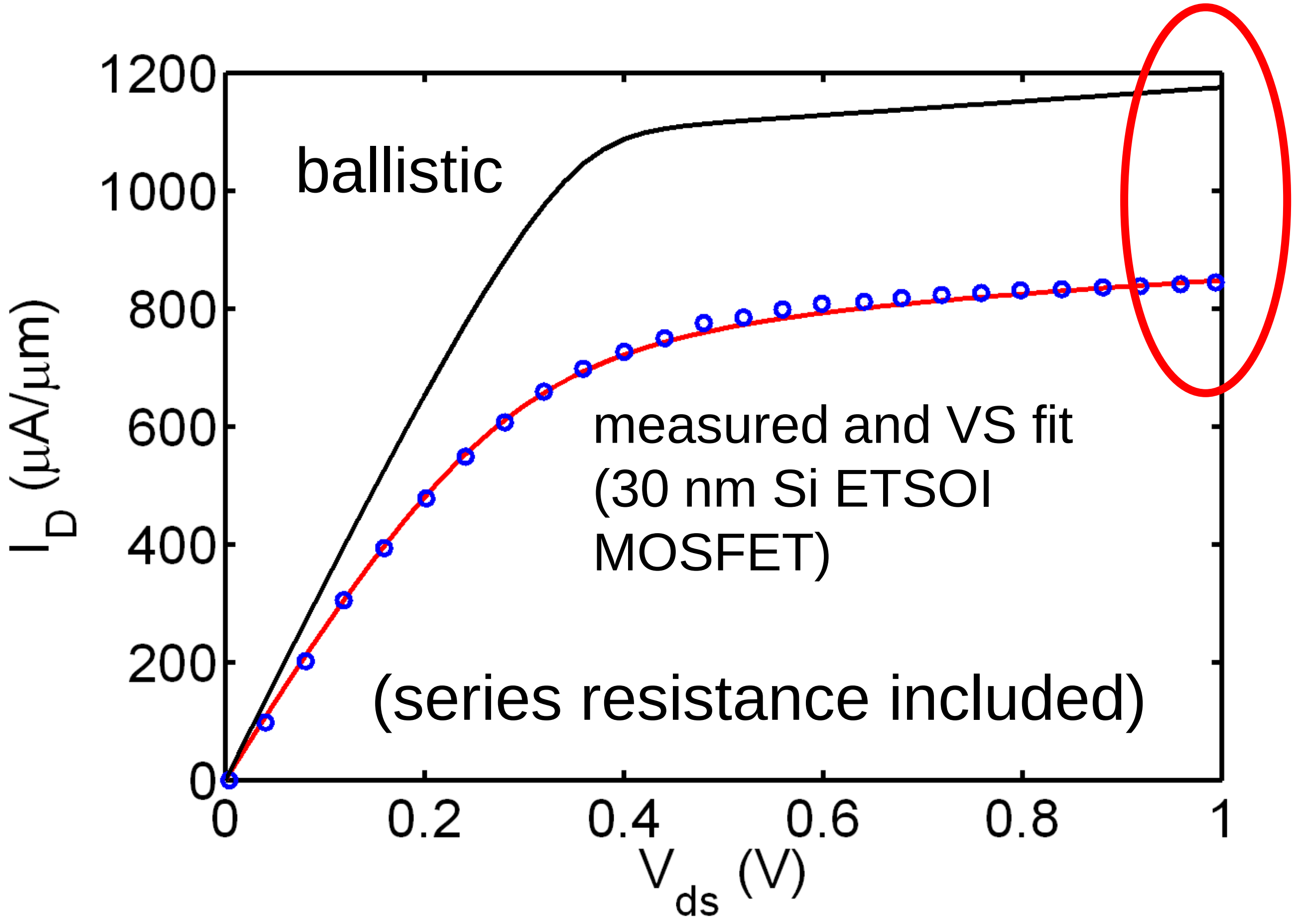


Fig. 15.2 *Fundamentals of Nanotransistors*, World Scientific Lecture Notes, 2015.

Measured vs. ballistic: III-V HEMT

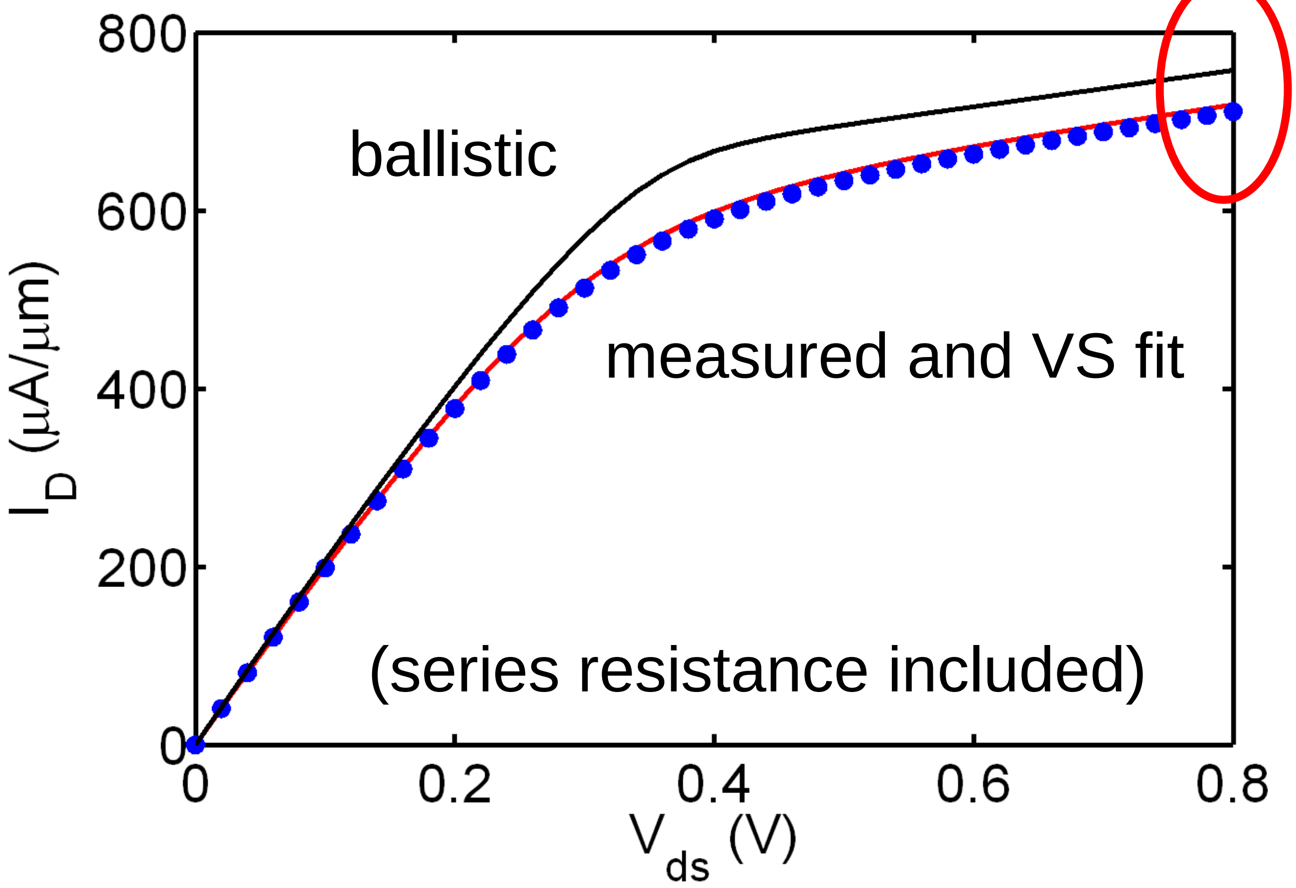


Fig. 15.3 *Fundamentals of Nanotransistors*, World Scientific Lecture Notes, 2015.

Summary

1) The apparent mobility and injection velocity in the semi-empirical VS model have a clear, physical interpretation in the ballistic limit.

2) Si MOSFETs operate at a significant fraction, but well below, the ballistic limit. (We will discuss why in Unit 4.)

3) III-V FETs operate quite close to the ballistic limit. (We will discuss why in Unit 4.)

Unit 4

In Unit 4, we will learn how to describe transistors that operate below the ballistic limit by including carrier **backscattering** in the model.