Fundamentals of Nanotransistors

Unit 4: Transmission Theory of the MOSFET

Lecture 4.1: Introduction

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Unit 4

Lecture 4.1: Introduction

Lecture 4.2: Carrier Scattering and Transmission
Lecture 4.3 MFP and Diffusion Coefficient
Lecture 4.4: Transmission Theory of the MOSFET: I
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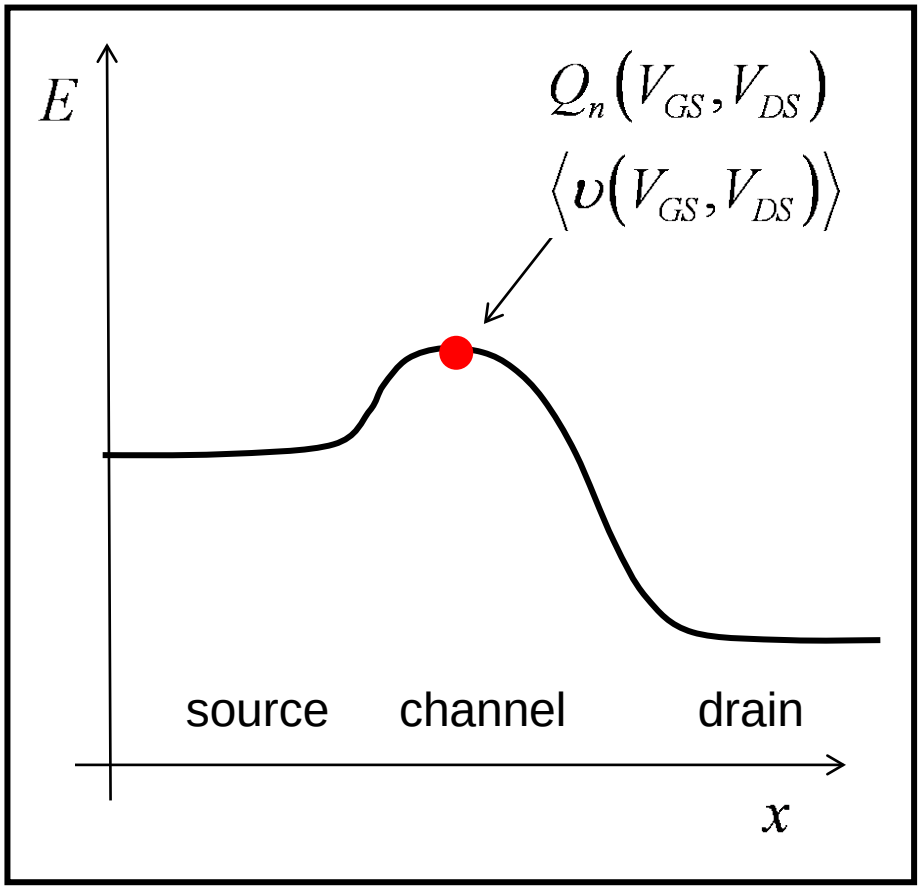
Lecture 4.6: Connection to the VS Model
Lecture 4.7: Analysis of Experiments
Lecture 4.8: Limits of MOSFETs

Lecture 4.9 Summary

Velocity at the VS (ballistic case)



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

$$\mathcal{T}(E) = 1$$

$$\langle \upsilon(V_{DS}) \rangle = \upsilon_{inj}^{ball} F_{SAT}(V_{DS})$$

Velocity at the VS

$$I_{DS} = W\left|Q_n\left(V_{GS},V_{DS}\right)\right|\left\langle \upsilon\left(V_{GS},V_{DS}\right)\right\rangle \qquad \mathcal{T}(E)=1 \qquad \left\langle \upsilon\left(V_{DS}\right)\right\rangle = \upsilon_{inj}^{ball} F_{SAT}\left(V_{DS}\right)$$

(nondegenerate)

Non-degenerate (Maxwell-Boltzmann) statistics:

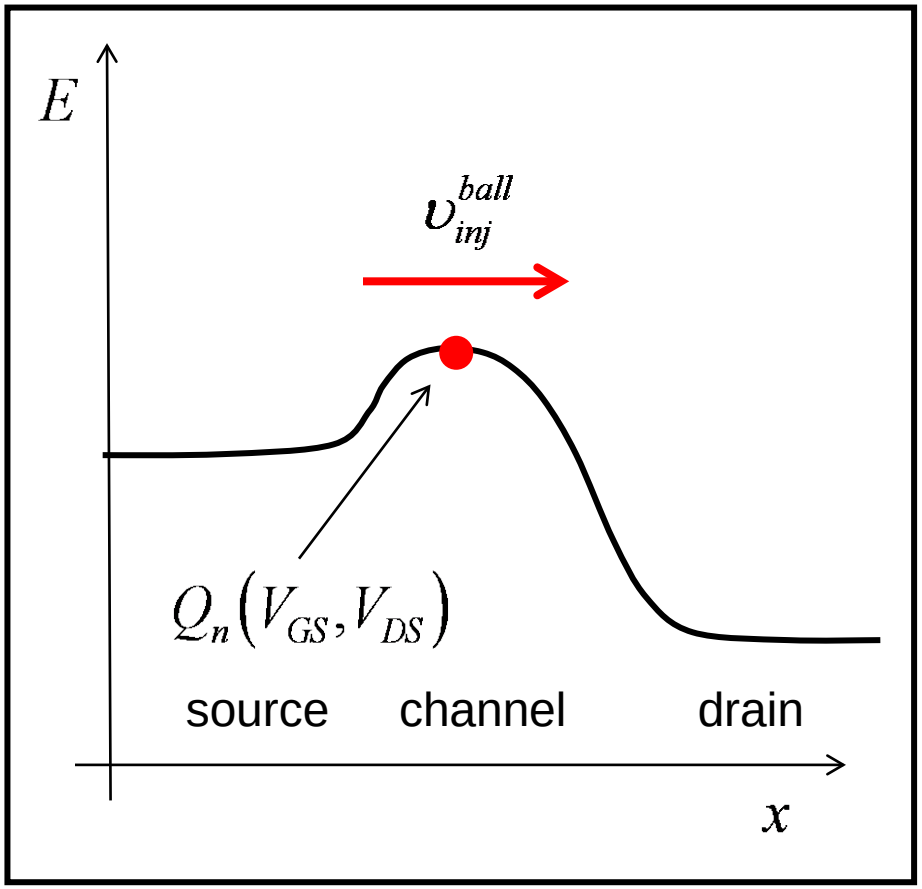
$$F_{SAT}\left(V_{DS}\right) = \left(\frac{1-e^{-qV_{DS}/k_BT}}{1+e^{-qV_{DS}/k_BT}}\right) \qquad \upsilon_{inj}^{ball} = \upsilon_T$$

General (2D, Fermi-Dirac) statistics:

$$F_{SAT}\left(V_{GS},V_{DS}\right) = \upsilon_{inj}^{ball}\left[\frac{1-\mathcal{F}_{1/2}\left(\eta_{FD}\right)/\mathcal{F}_{1/2}\left(\eta_{FS}\right)}{1+\mathcal{F}_0\left(\eta_{FD}\right)/\mathcal{F}_0\left(\eta_{FS}\right)}\right] \qquad \upsilon_{inj}^{ball}\left(V_{GS}\right) = \upsilon_T\frac{\mathcal{F}_{1/2}\left(\eta_{FS}\right)}{\mathcal{F}_0\left(\eta_{FS}\right)}$$

$$\eta_{FS} = \frac{E_{FS}-E_C}{k_BT}$$

Velocity at the VS (On-state)



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

$$\mathcal{T}(E) = 1$$

$$\left\langle \upsilon(V_{DS})\right\rangle = \upsilon_{inj}^{ball} F_{SAT}(V_{DS})$$

$$F_{SAT}(V_{DS} >> V_{DSAT}) \rightarrow 1$$

$$\left\langle \upsilon(V_{DS})\right\rangle \rightarrow \upsilon_{inj}^{ball} = \upsilon_T$$

(nondegenerate)

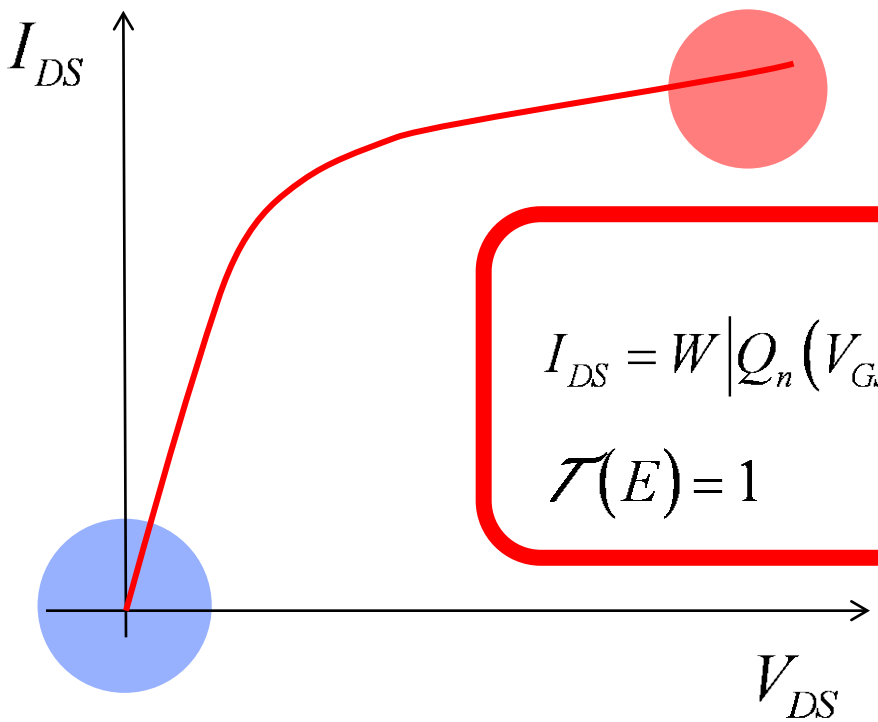
Question:

$$I_{DS} = W\left|Q_n\left(V_{GS},V_{DS}\right)\right|\left\langle \upsilon\left(V_{GS},V_{DS}\right)\right\rangle \qquad \mathcal{T}(E)=1 \qquad \left\langle \upsilon\left(V_{DS}\right)\right\rangle = \upsilon_{inj}^{ball} F_{SAT}\left(V_{DS}\right)$$

How do the drain saturation function and the injection velocity change when the transmission is less than one?

Ballistic IV

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



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

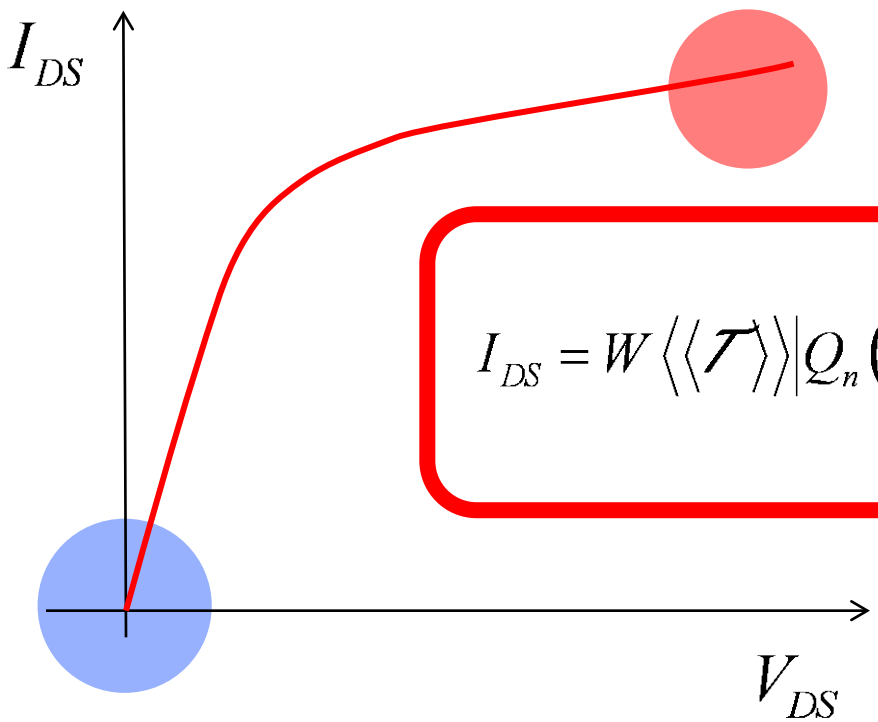
$$\mathcal{T}(E) = 1$$

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

Transmission model?

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

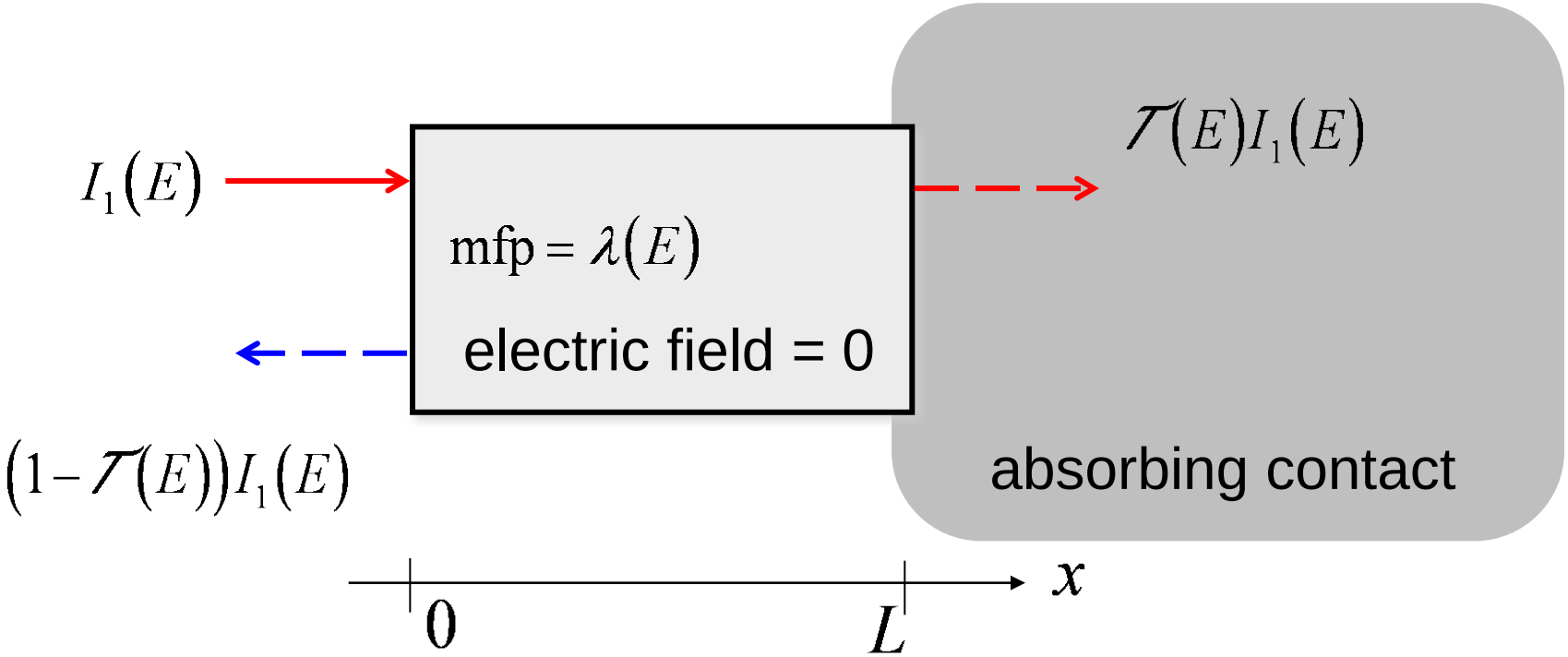
NO!



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

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

Transmission



$$\mathcal{T}(E) = f\left(\Lambda(E)/L\right)$$

$\Lambda(E)$: MFP

Transmission and transport

$\mathcal{T}(E) << 1$ Diffusive transport

$\mathcal{T}(E) = 1$ Ballistic transport

$0 \leq \mathcal{T}(E) \leq 1$ Diffusive to ballistic transport

Unit 4 objectives

1) Establish the relation between transmission and scattering (mean-free-path).

2) Derive the IV characteristics of a MOSFET for which the transmission is anywhere between zero and one.