Unit 4: Transmission Theory of the MOSFET

Lecture 4.9: Unit 4 and Course Summary

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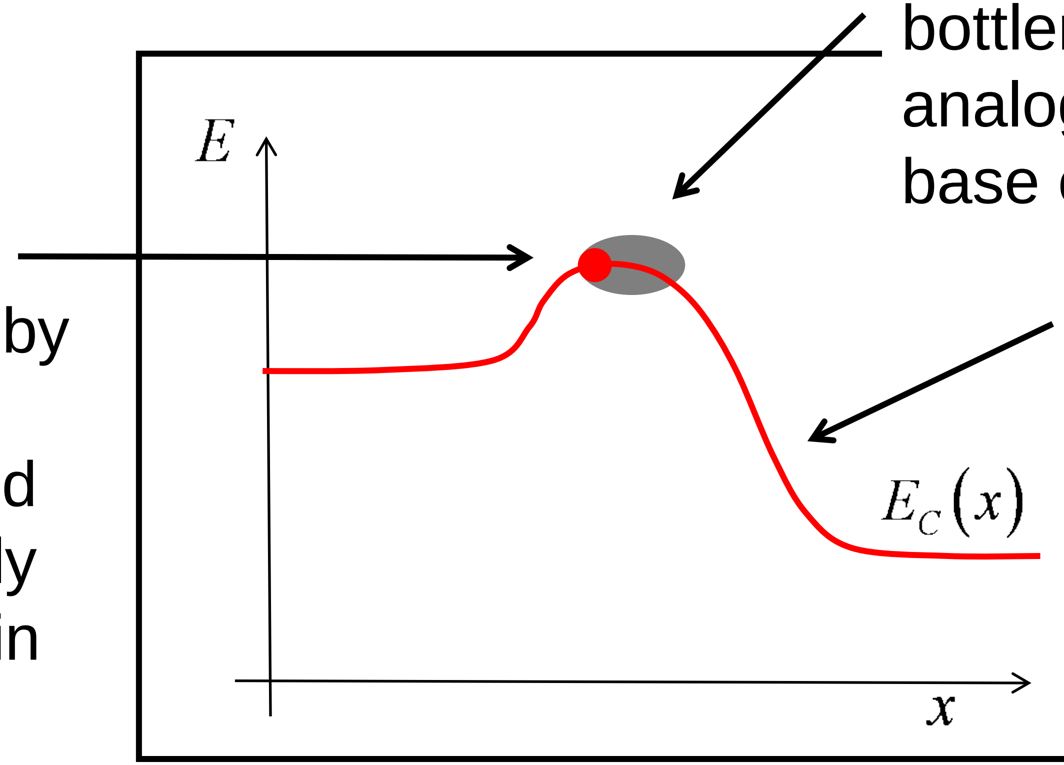
Course objectives

1) To develop an understanding of how modern, nanoscale transistors work – focusing on the simple, physically sound, essential physics.

2) To relate this new understanding to the traditional theory of transistors.

Essential physics of transistors

1) Virtual Source. Barrier controlled by the gate voltage and only weakly by the drain voltage.

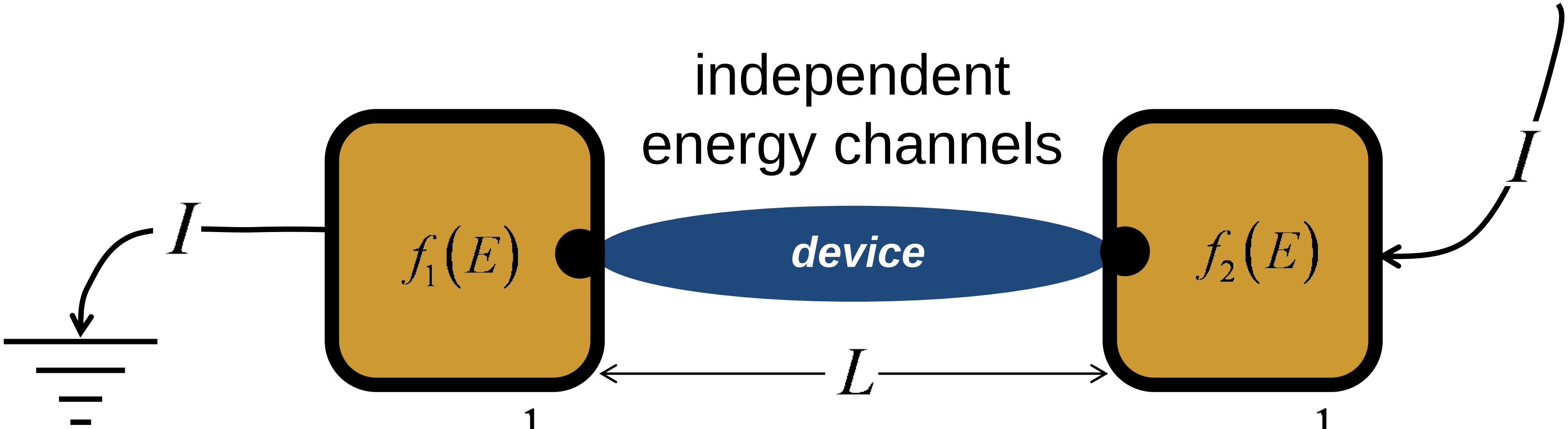


2) Transport bottleneck – analogous to the base of a BJT.

3) High-field portion. "Absorbing contact" Analogous to the collector of a BJT.

E.O. Johnson, "The IGFET: A Bipolar Transistor in Disguise," *RCA Review*, **34**, pp. 80-94, 1973.

Landauer Approach



$$f_1(E) = \frac{1}{1+e^{(E-E_{F1})/k_BT}}$$

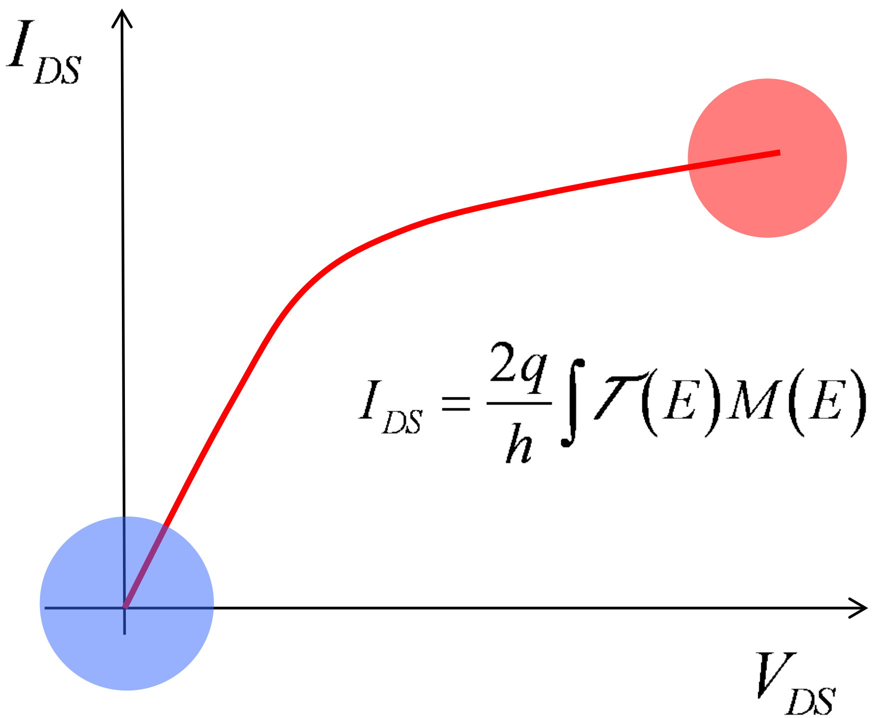
$$f_2(E) = \frac{1}{1+e^{(E-E_{F2})/k_BT}}$$

$$E_{F2} = E_{F1} - qV$$

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

$$n_S = \int_{E_C}^{\infty}\left(\frac{D_{2D}(E)}{2}f_1(E)+\frac{D_{2D}(E)}{2}f_2(E)\right)dE \ \ \text{m}^{-2}$$

Transmission theory of MOSFETs



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

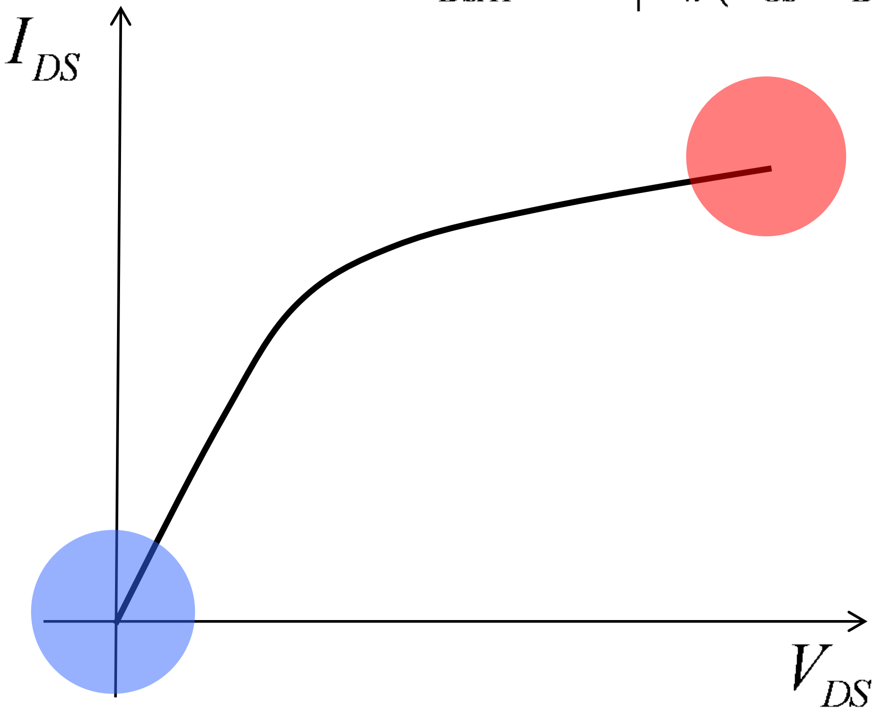
Transmission theory of the MOSFET

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

$$\upsilon_{inj} = \left(\frac{\mathcal{T}_{SAT}}{2-\mathcal{T}_{SAT}}\right)\upsilon_T$$

$$\mathcal{T}_{SAT} = \frac{\lambda_0}{\lambda_0 + \ell}$$

$$\ell << L$$



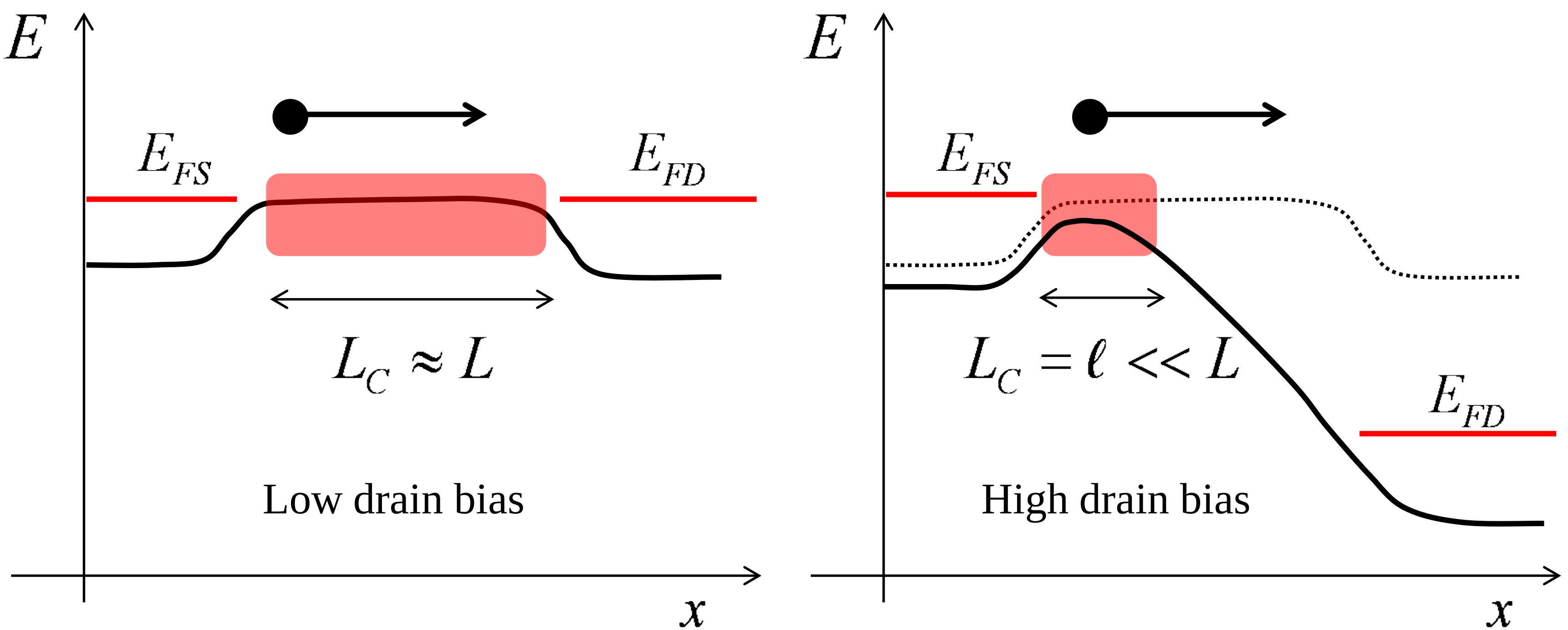
$$I_{DLIN} = \frac{W}{L}\mu_{app}\left|Q_n\left(V_{GS}, V_{DS}\right)\right| V_{DS}$$

$$\mu_{app} = \left(\frac{\mathcal{T}_{LIN} L \upsilon_T}{2k_B T/q}\right) \qquad \mathcal{T}_{LIN} = \frac{\lambda_0}{\lambda_0 + L}$$

Lundstrom: Nanotransistors 2015

Scattering in nanotransistors

$$\mathcal{T}_{LIN} = \frac{\lambda_0}{\lambda_0 + L} \qquad \mathcal{T}(V_{DS}) = \frac{\lambda_0}{\lambda_0 + L_C(V_{DS})} \qquad \mathcal{T}_{SAT} = \frac{\lambda_0}{\lambda_0 + \ell}$$



MIT VS model

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

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) $V_{DSAT} = \dfrac{\upsilon_{inj} L}{\mu_{app}}$

Only 10 device-specific parameters in this model:

$C_{inv}, L,$

$V_T, \delta, m, \upsilon_{inj}, \mu_{app}, R_{SD} = R_S + R_D,$

α, β

MIT VS model

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"

Relating the transmission and traditional models

1) $$\mu_n \rightarrow \mu_{app} = \left(\frac{\mathcal{T}_{LIN} L \upsilon_T}{2 k_B T / q} \right) = \frac{\mu_n \mu_B}{\mu_n + \mu_B}$$

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

2) $$\upsilon_{sat} \rightarrow \upsilon_{inj} = \left(\frac{\mathcal{T}_{SAT}}{2 - \mathcal{T}_{SAT}} \right) \upsilon_{inj}^{ball} = \left[\frac{1}{\upsilon_{inj}^{ball}} + \frac{1}{D_n / \ell} \right]^{-1}$$

$$\upsilon_{inj}^{ball} = \upsilon_T \qquad D_n = \frac{\upsilon_T \lambda_0}{2}$$

(nondegenerate carrier statistics)

Landauer Approach

Semiclassical Transport

Boltzmann Transport Equation (BTE)

Dissipative Quantum Transport

Non-equilibrium Green's Function (NEGF)

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

Transmission model: Limitations

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

How good is the assumption that the use of equilibrium MOS electrostatics is valid out of equilibrium?

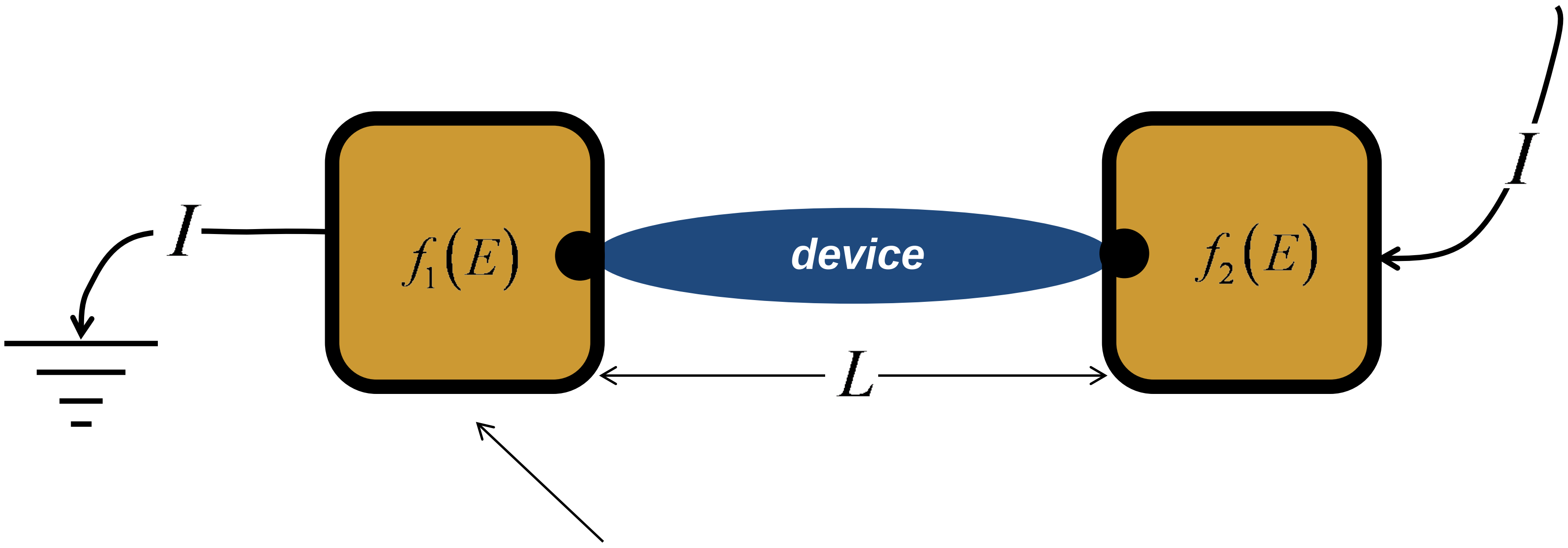
Transmission model: Limitations

How good is the assumption that the near-equilibrium MFP can be used under high drain bias>

$$\mathcal{T}_{SAT} = \frac{\lambda_0}{\lambda_0 + \ell}$$

Exactly how do we compute the critical length?

Transmission model: Limitations



How well does the assumption of ideal, “Landauer contacts” apply to real devices?

Transmission model: Limitations

For more discussion about the simplifying assumptions of the transmission model, see Lecture 20 in *Fundamentals of Nanotransistor*, World Scientific Lecture Notes, 2015.

Summary

1) Nanoscale transistors have already had a profound impact on the world that we live in – and the impact over the next few decades is likely to be even more significant.

2) Nanotransistors provide an interesting vehicle for exploring and understanding transport at very small length scales.

3) The Landauer approach provides a simple way to understand carrier transport in nanotransistors.

4) The operating principles of this important nanodevice are remarkably easy to understand.

Final thoughts

1) My hope is that you now understand the simple, essential physics of nanoscale transistors.

2) and that you understand how the transmission model is related to the traditional model of MOSFETs.

3) and that you have gained an appreciation of the usefulness of the Landauer approach for analyzing small **and** large devices.