Fundamentals of Nanotransistors

Unit 4: Transmission Theory of the MOSFET

Lecture 4.6: Connection to the VS Model

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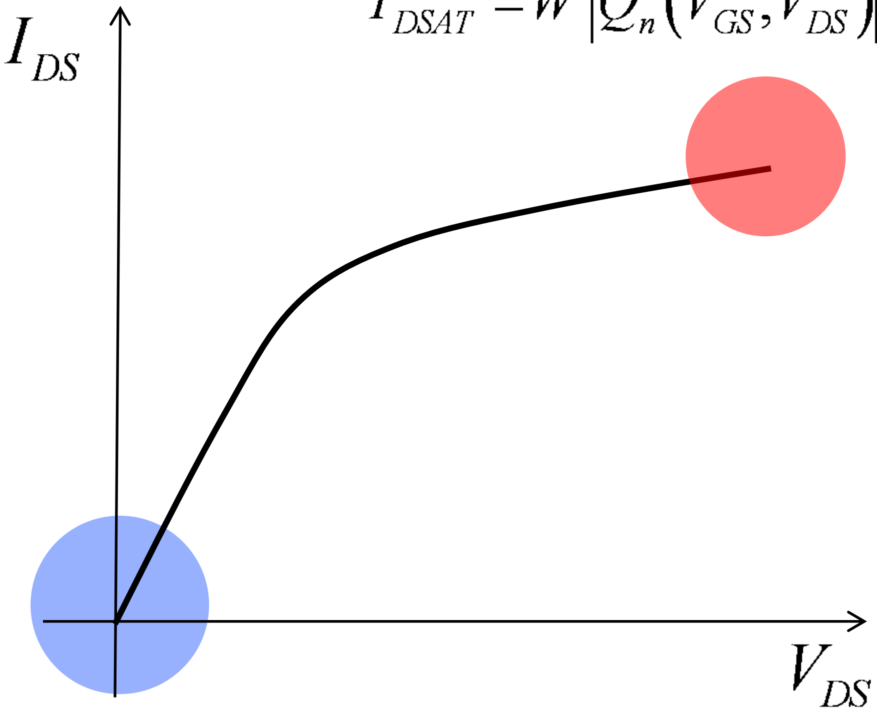
Transmission model



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

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

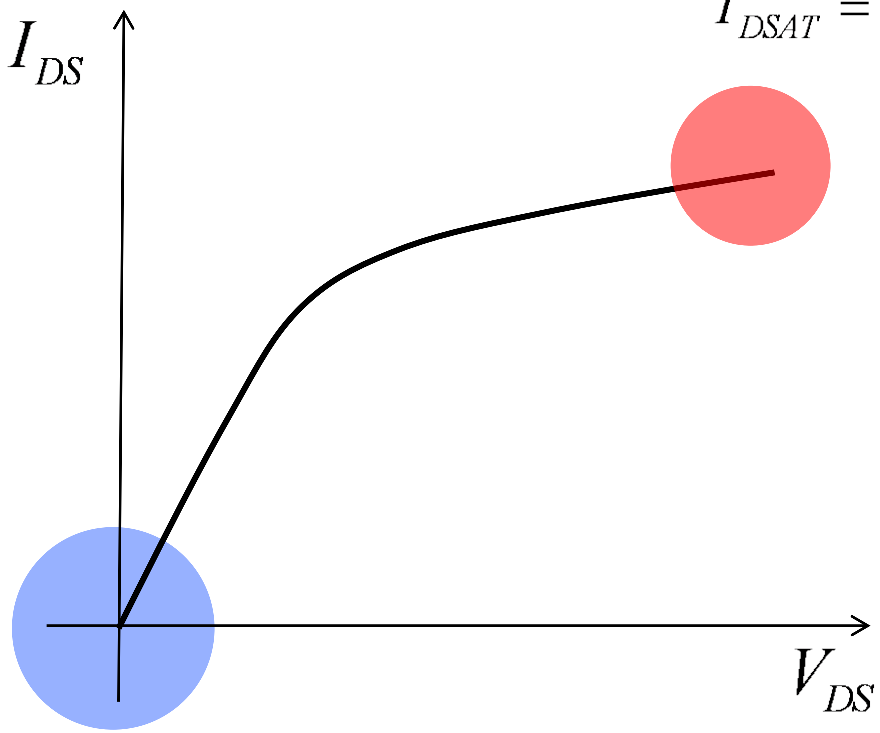
$$\mathcal{T}_{SAT} = \frac{\lambda_0}{\lambda_0 + \ell}$$

$$\ell << L$$

$$I_{DLIN} = W\left|Q_n\left(V_{GS}, V_{DS}\right)\right|\left(\mathcal{T}_{LIN}\frac{\upsilon_T}{2k_BT/q}\right)V_{DS} \qquad \mathcal{T}_{LIN} = \frac{\lambda_0}{\lambda_0 + L}$$

Traditional (diffusive) model

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



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

Connection: Linear region

Traditional:

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

Transmission:

$$I_{DS} = \mathcal{T}_{LIN}\left(WC_{inv}\left(V_{GS} - V_T\right)\frac{\upsilon_T}{\left(2k_BT/q\right)}\right)V_{DS} \qquad \mathcal{T}_{LIN} = \frac{\lambda_0}{\lambda_0 + L}$$

$$I_{DS} = \frac{W}{L+\lambda_0}\mu_n C_{inv}\left(V_{GS} - V_T\right)V_{DS}$$

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

$$1/\mu_{app} = 1/\mu_n + 1/\mu_B$$

Apparent mobility

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

$$\frac{1}{\mu_{app}} = \frac{1}{\mu_n} + \frac{1}{\mu_B}$$

"Mathiessen's Rule"

$$\mu_n = \frac{\upsilon_T \lambda_0}{2 k_B T / q}$$ due to scattering in the channel

$$\mu_B = \frac{\upsilon_T L}{2 k_B T / q}$$ ballistic mobility (due to scattering in the source and drain)

Example

Estimate the apparent mobility for a 22 nm N-MOSFET.

$$\mu_n \approx 200 \text{ cm}^2/\text{V-s}$$

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

$$\upsilon_T = \sqrt{\frac{2 k_B T}{\pi m_t^*}} = 1.2 \times 10^7 \text{ cm/s}$$

(Assumes confinement in the <100> direction.)

$$\mu_B \approx 500 \text{ cm}^2/\text{V-s}$$

$$\frac{1}{\mu_{app}} = \frac{1}{\mu_n} + \frac{1}{\mu_B} = \frac{1}{200} + \frac{1}{500}$$

$$\mu_{app} \approx 140 \ \frac{\text{cm}^2}{\text{V-s}}$$

This device operates in the quasi-ballistic regime.

Connection: Saturation region

Traditional:

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

above threshold

Transmission:

$$I_{DSAT} = WC_{inv}\left(V_{GS} - V_T\right)\left(\frac{\mathcal{T}_{SAT}}{2-\mathcal{T}_{SAT}}\right)\upsilon_T$$

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

$$I_{DSAT} = WC_{inv}\left(V_{GS} - V_T\right)\left[\frac{1}{\upsilon_T} + \frac{1}{\left(D_n/\ell\right)}\right]^{-1}$$

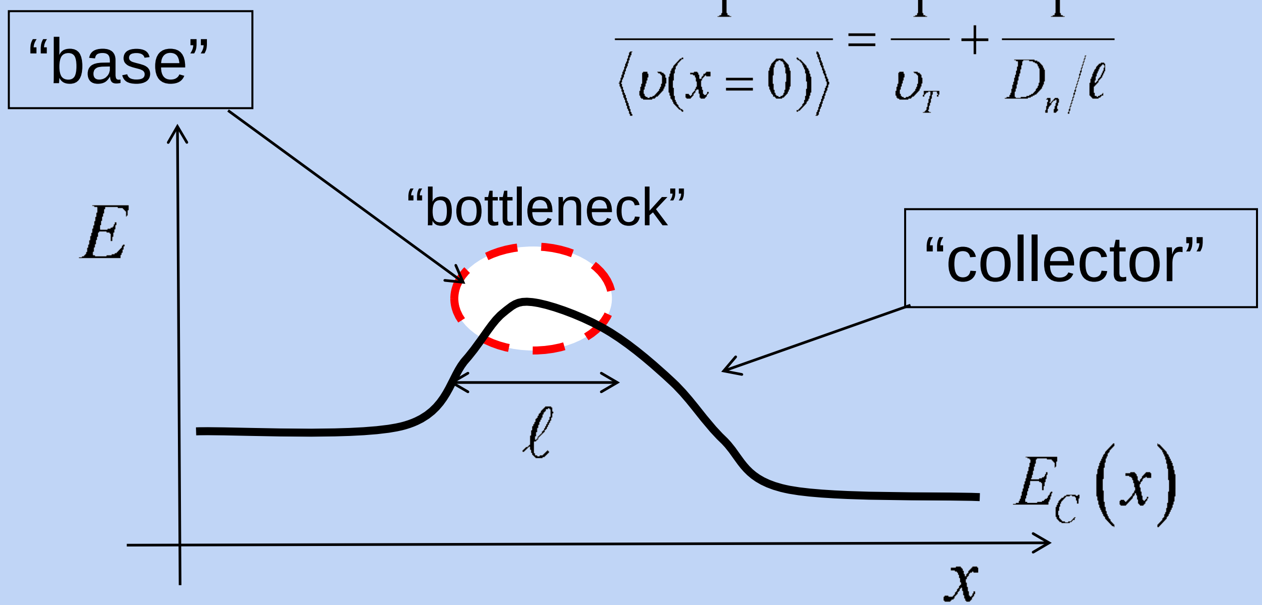
$$D_n = \frac{\upsilon_T \lambda_0}{2}$$

How do we interpret this result?

Saturation current in a nanoscale MOSFET

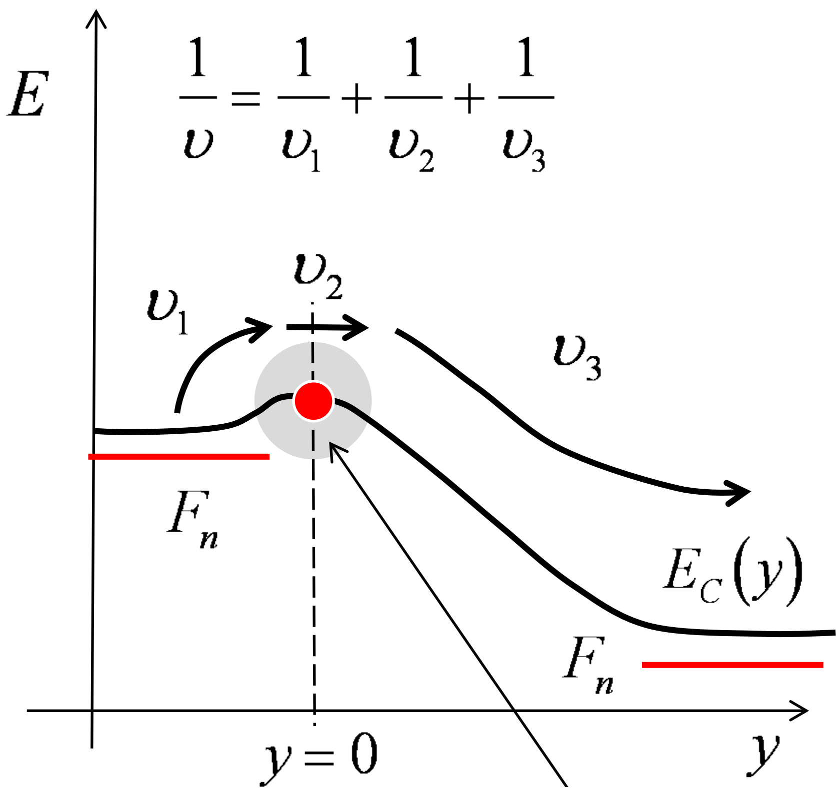
$$I_{DS} = WC_{inv}\left(V_{GS} - V_T\right)\left\langle \upsilon(x=0)\right\rangle$$

$$\frac{1}{\left\langle \upsilon(x=0)\right\rangle} = \frac{1}{\upsilon_T} + \frac{1}{D_n/\ell}$$



Injection velocity

$$\frac{1}{\upsilon} = \frac{1}{\upsilon_1} + \frac{1}{\upsilon_2} + \frac{1}{\upsilon_3}$$



$$Q_n \approx C_{inv}\left(V_{GS} - V_T\right) \quad \mathrm{C/cm^2}$$

$$\frac{1}{\upsilon} \approx \frac{1}{\upsilon_1} + \frac{1}{\upsilon_2}$$

$$\frac{1}{\upsilon_{inj}} = \frac{1}{\upsilon_T} + \frac{1}{D_n/\ell}$$

VS model for the MOSFET

$$I_{DS} = W\,Q_n\left(V_{GS}, V_{DS}\right)\left\langle \upsilon(0)\right\rangle$$

$$\left\langle \upsilon(0)\right\rangle = \left\{ \frac{V_D / V_{DSAT}}{\left[1 + \left(V_D / V_{DSAT}\right)^{\beta}\right]^{1/\beta}} \right\} \upsilon_{sat} = F_{SAT}\left(V_{DS}\right)\upsilon_{sat}$$

$$V_{DSAT} = \frac{\upsilon_{sat} L}{\mu_n}$$

υ_{sat}

μ_n

a more physical VS model for a MOSFET

1) $\mu_n \rightarrow \mu_{app}$ $\qquad$ $$\frac{1}{\mu_{app}} = \frac{1}{\mu_n} + \frac{1}{\mu_B}$$

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

$$\upsilon_{inj}^{ball} = \upsilon_T \quad \text{(non-degenerate carrier statistics)}$$

Summary

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"

Next lecture

Using the VS model to characterize the electrical performance of nanotransistors.