Essentials of MOSFETs

Unit 4:
Transmission Theory of the MOSFET

Lecture 4.6:
The VS Model Revisited

Mark Lundstrom

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

PURDUE
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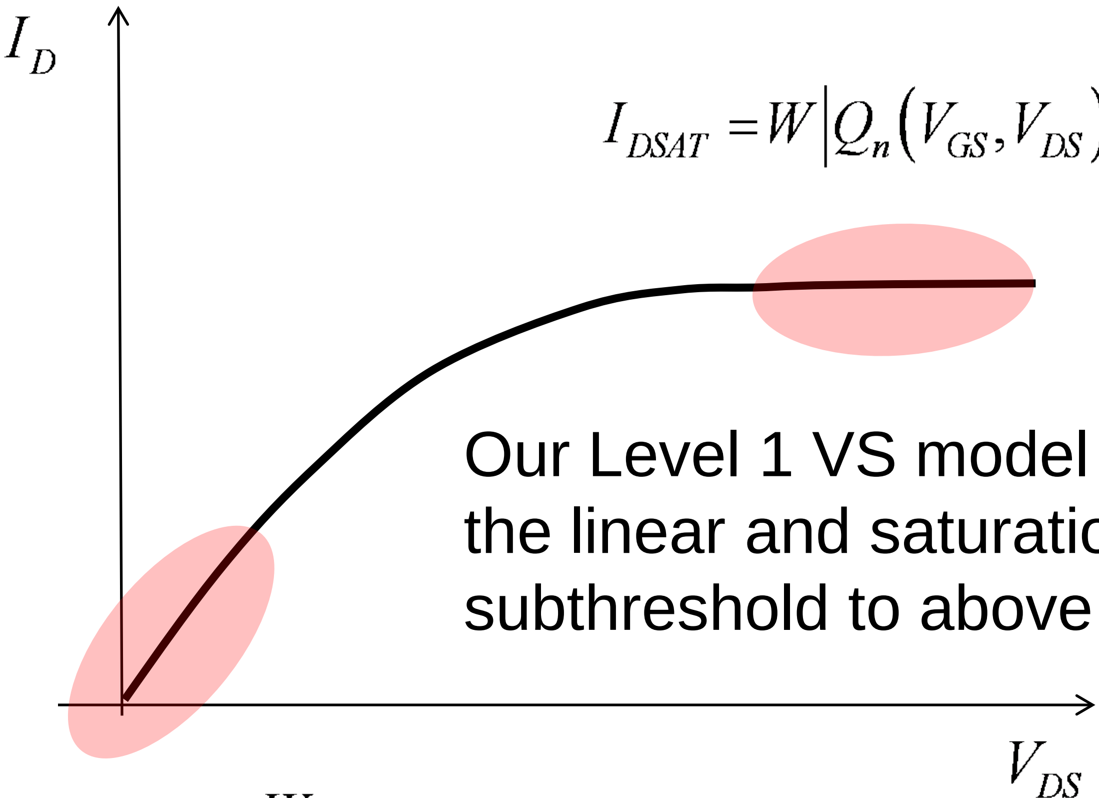
Traditional (diffusive) model



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

Our Level 1 VS model smoothly connects the linear and saturation regions (and subthreshold to above threshold too).

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

Level 1 VS model

1) $I_D/W = \left|Q_n\left(V_{GS},V_{DS}\right)\right|\left\langle \upsilon_x\left(V_{DS}\right)\right\rangle$

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

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

3) $\left\langle \upsilon_x\left(V_{DS}\right)\right\rangle = F_{SAT}\left(V_{DS}\right)\upsilon_{sat}$

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

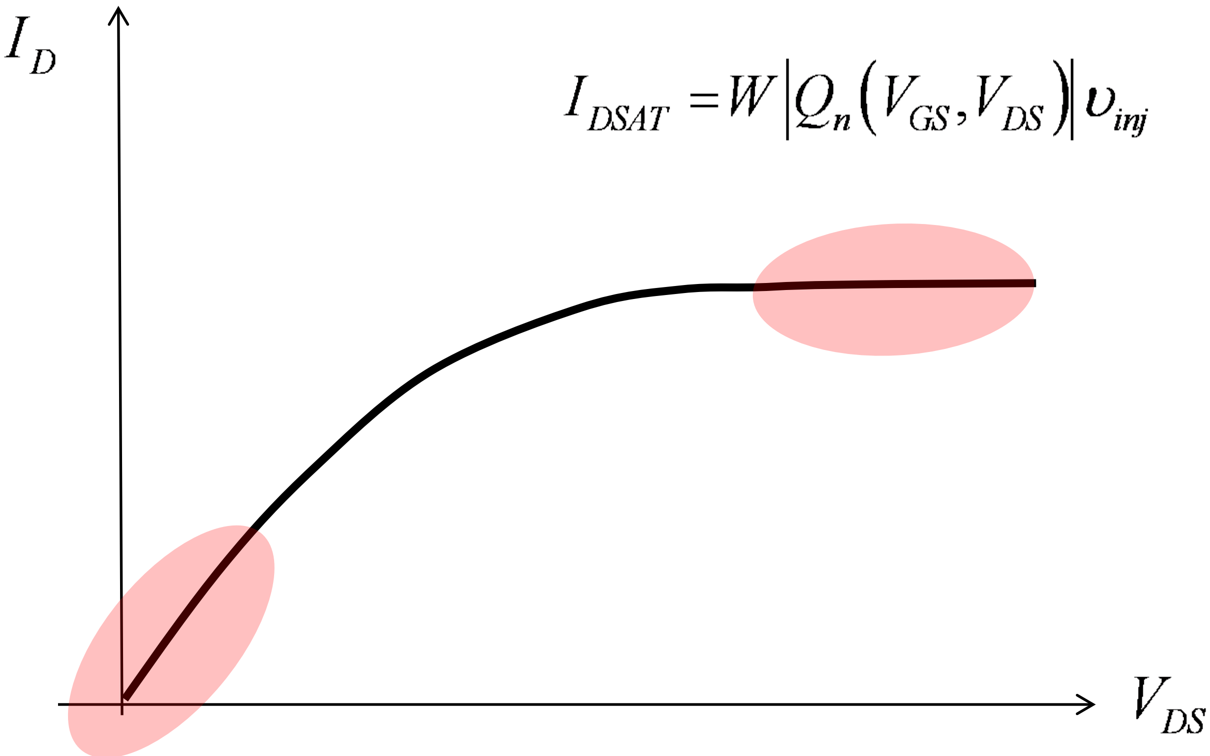
Only 10 device-specific parameters in this model:

$C_{inv}, V_{T0}, \delta, m, \upsilon_{sat}, \mu_n,$

$L, R_{SD} = R_S + R_D,$

α, β

Transmission model



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

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

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

$$\ell << L$$

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

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

Level 2 VS model

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

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

Level 2 VS model

1) $I_D/W = \left|Q_n\left(V_{GS}, V_{DS}\right)\right| \left\langle \upsilon_x\left(V_{DS}\right)\right\rangle$

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

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

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

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

Still only 10 device-specific parameters in this model:

$C_{inv}, V_{T0}, \delta, m, \upsilon_{inj}, \mu_{app},$

$L, R_{SD} = R_S + R_D,$

α, β

Transport physics at the nanoscale

Let’s take a quick, second look at how our VS model treats:

1) Transport in the linear region

2) Transport in the saturation region

Linear region: The apparent MFP

$$\frac{1}{\mu_{app}} = \frac{1}{\mu_n} + \frac{1}{\mu_B} \qquad \mu_n = \frac{\upsilon_T \lambda_0}{(2k_BT/q)} \qquad \mu_B = \frac{\upsilon_T L}{(2k_BT/q)} \qquad \boxed{\mu_{app} = \frac{\upsilon_T \lambda_{app}}{(2k_BT/q)}}$$

"Mathiessen's Rule"

$$\boxed{\frac{1}{\lambda_{app}} = \frac{1}{\lambda_0} + \frac{1}{L}}$$

The apparent MFP is the shorter of the scattering limited MFP in the bulk and the channel length.

Saturation region: Injection velocity

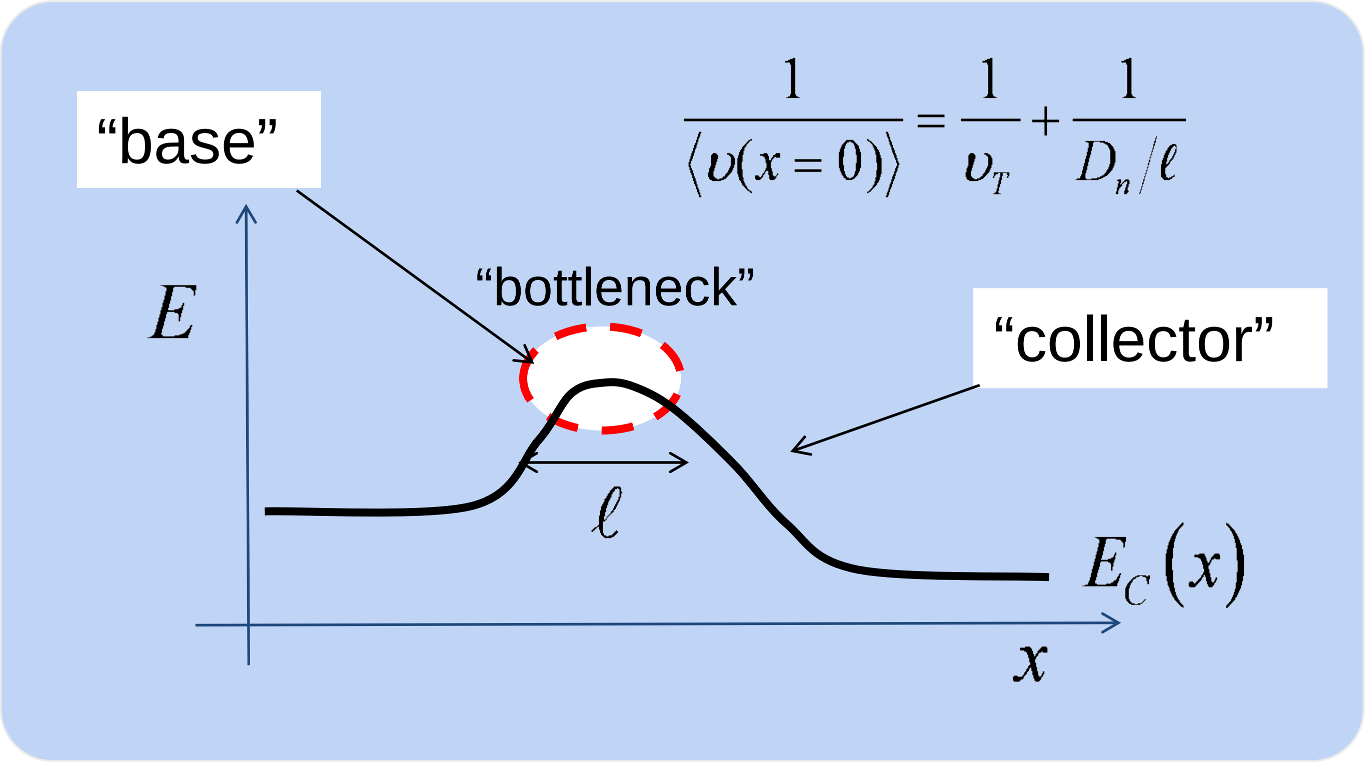
$$I_{DSAT} = W\left|Q_n\right|\upsilon_{inj} \qquad \upsilon_{inj} = \left(\frac{\mathcal{T}_{SAT}}{2-\mathcal{T}_{SAT}}\right)\upsilon_T \qquad \mathcal{T}_{SAT} = \frac{\lambda_0}{\lambda_0 + \ell}$$

$$\boxed{I_{DSAT} = W\left|Q_n\right|\left[\frac{1}{\upsilon_T} + \frac{1}{\left(D_n/\ell\right)}\right]^{-1}} \qquad D_n = \frac{\upsilon_T \lambda_0}{2}$$

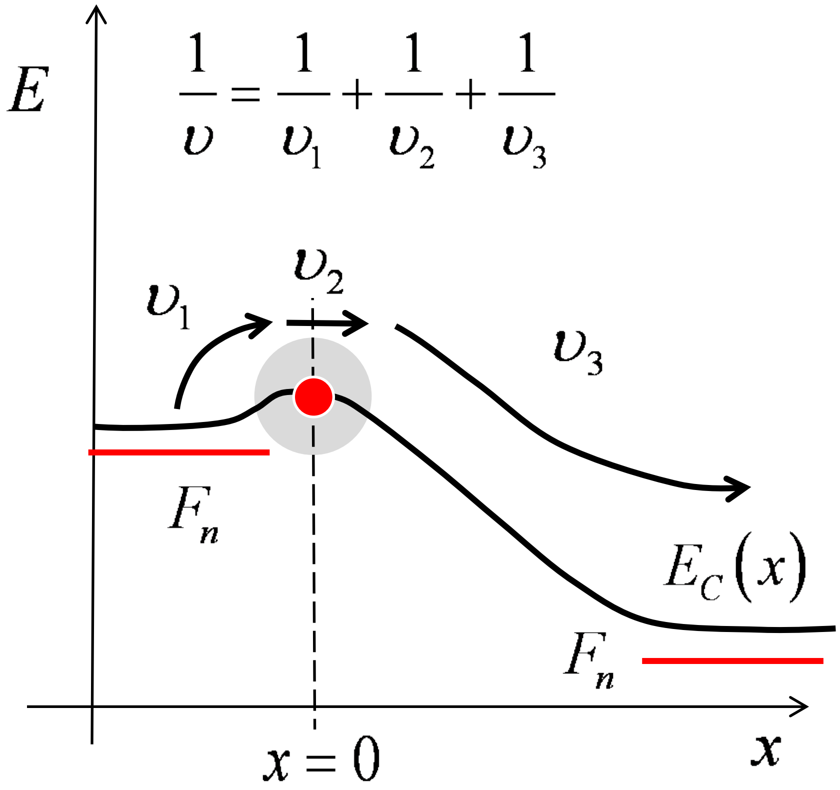
How do we interpret this result?

Saturation current in a nanoscale MOSFET

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



Injection velocity



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

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

Summary

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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

How to use the VS model to characterize the electrical performance of nanotransistors.