Essentials of MOSFETs

Unit 2: Essential Physics of the MOSFET

Lecture 2.5: The Virtual Source Model

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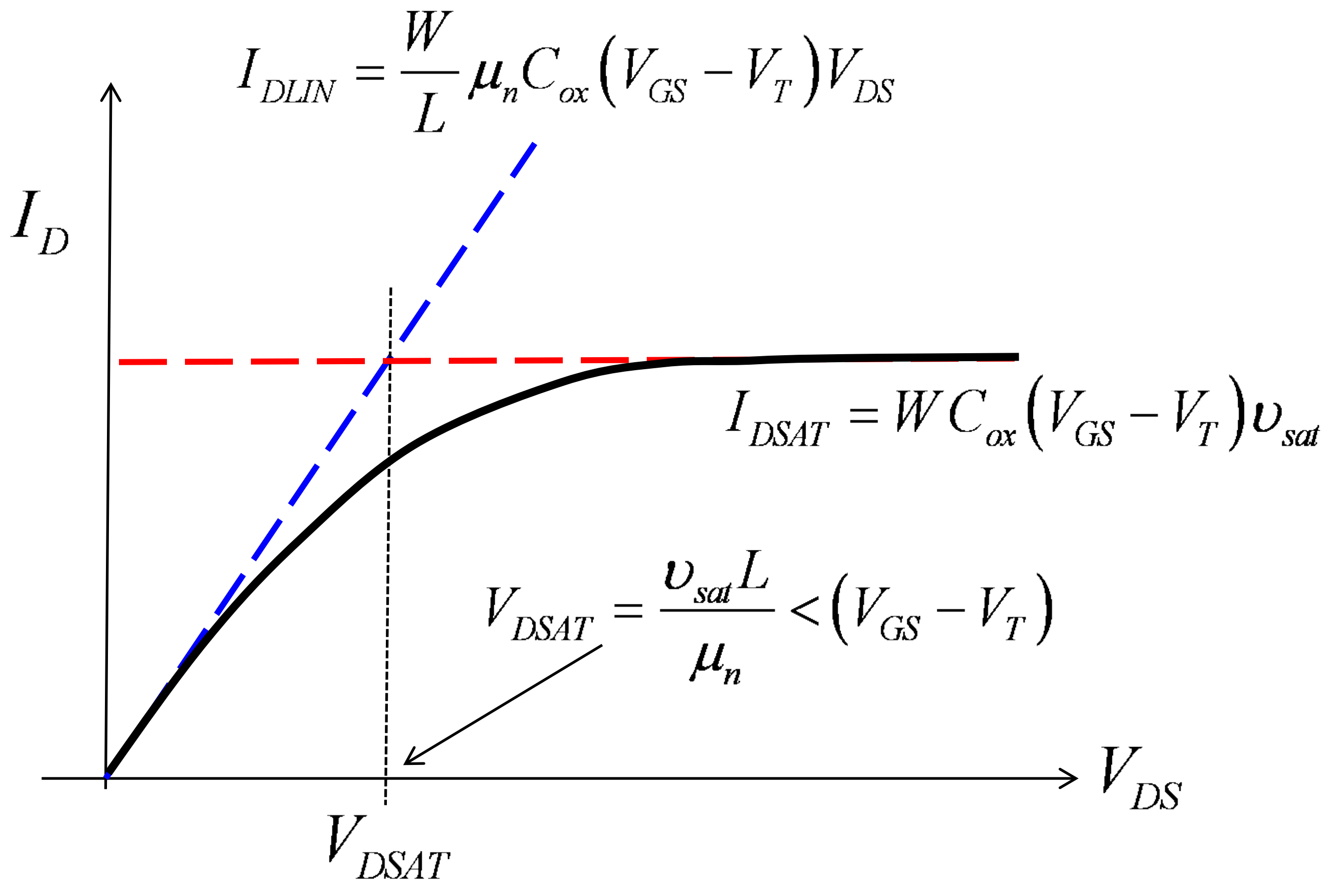
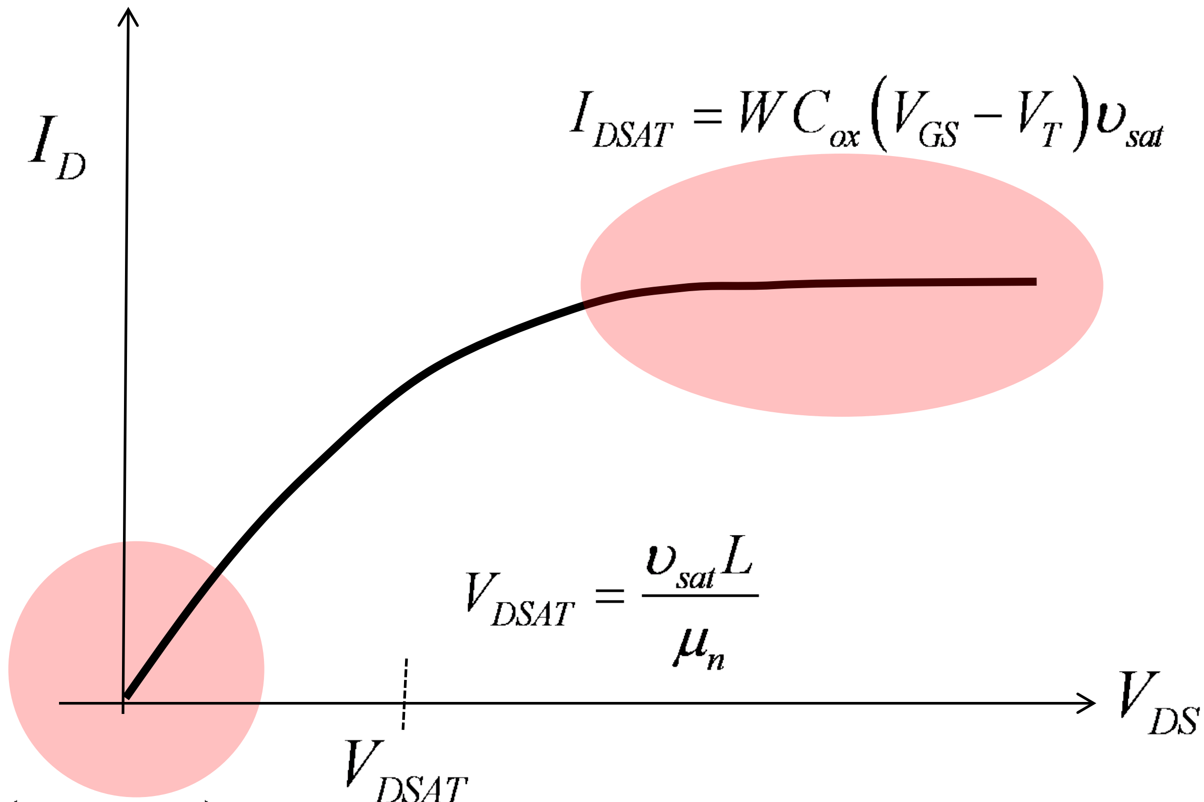
Velocity saturated MOSFET: IV (review)



We have developed a 2-piece approximation to the MOSFET IV characteristic.

From a two-piece to continuous model



$$I_{DSAT} = W C_{ox}\left(V_{GS} - V_T\right)\upsilon_{sat}$$

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

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

Can we produce a model that smoothly goes from the linear to saturation regions?

The MIT Virtual Source (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

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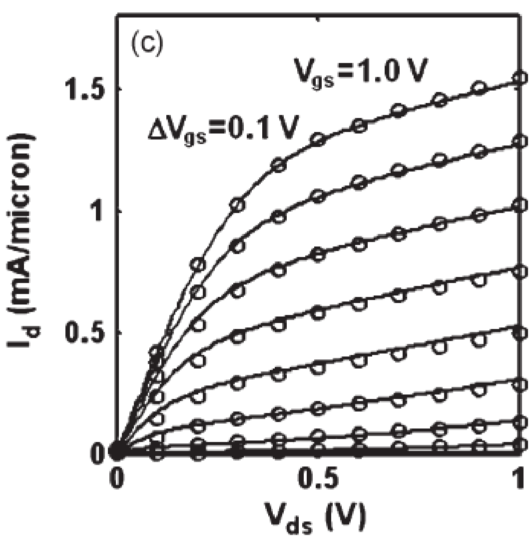
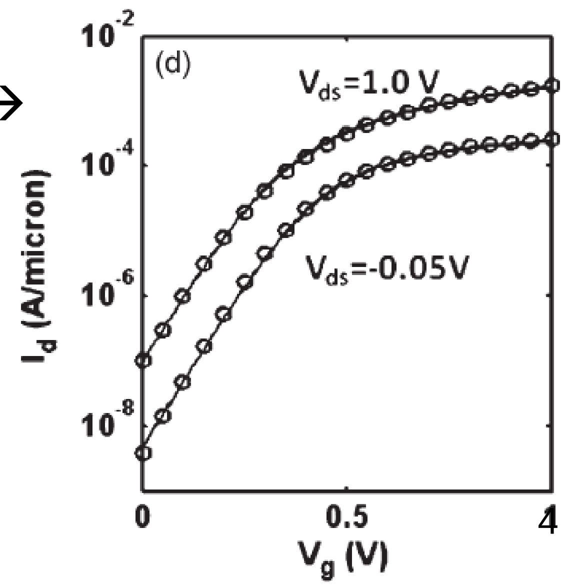


← 32 nm technology →



Lundstrom: 2018

Piecewise model for $I_D(V_{GS}, V_{DS})$

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

$$V_{GS} \geq V_T : \quad Q_n\left(V_{GS}\right) = -C_{ox}\left(V_{GS} - V_T\right)$$

$$V_{GS} < V_T : \quad Q_n\left(V_{GS}\right) = 0$$

$$V_{DS} \leq V_{DSAT} : \left\langle \upsilon_x\left(V_{DS}\right)\right\rangle = \left(\mu_n \frac{V_{DS}}{L}\right)$$

$$V_{DS} > V_{DSAT} : \left\langle \upsilon_x\left(V_{DS}\right)\right\rangle = \upsilon_{sat}$$

If we can make the average velocity go smoothly from the low V_{DS} to high V_{DS} limits, then we will have a smooth model for $I_D(V_{GS}, V_{DS})$ – above threshold.

From low V_{DS} to high V_{DS}

$$\frac{1}{\langle \upsilon_x(V_{DS})\rangle} = \frac{1}{\mu_n V_{DS}/L} + \frac{1}{\upsilon_{sat}} \rightarrow$$

$$\langle \upsilon_x(V_{DS})\rangle = \left[\frac{V_{DS}/V_{DSAT}}{1+V_{DS}/V_{DSAT}}\right]\upsilon_{sat}$$

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

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

$$F_{SAT}(V_{DS}) = \frac{V_{DS}/V_{DSAT}}{\left[1+(V_{DS}/V_{DSAT})^{\beta}\right]^{1/\beta}}$$

The extra parameter, β, is empirically adjusted to fit the IV characteristic. Typically, $\beta \approx 1.4 - 1.8$ for both N-MOSFETs and for P-MOSFETs. (semi-empirical)

Empirical saturation function

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

$$F_{SAT}(V_{DS}) \equiv \frac{V_{DS}/V_{DSAT}}{\left[1+\left(V_{DS}/V_{DSAT}\right)^{\beta}\right]^{1/\beta}}$$

$$V_{DS} << V_{DSAT} : F_{SAT}(V_{DS}) \rightarrow \frac{V_{DS}}{V_{DSAT}}$$

$$\langle \upsilon_x(V_{DS}) \rangle \rightarrow \frac{V_{DS}}{V_{DSAT}}\upsilon_{sat}$$

$$\langle \upsilon_x(V_{DS}) \rangle \rightarrow \frac{V_{DS}}{\upsilon_{sat}L/\mu_n}\upsilon_{sat}$$

$$\langle \upsilon_x(V_{DS}) \rangle \rightarrow \mu_n \frac{V_{DS}}{L} \quad ✓$$

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

$$\langle \upsilon_x(V_{DS}) \rangle \rightarrow \upsilon_{sat} \quad ✓$$

Saturation function: $F_{SAT}(V_D)$

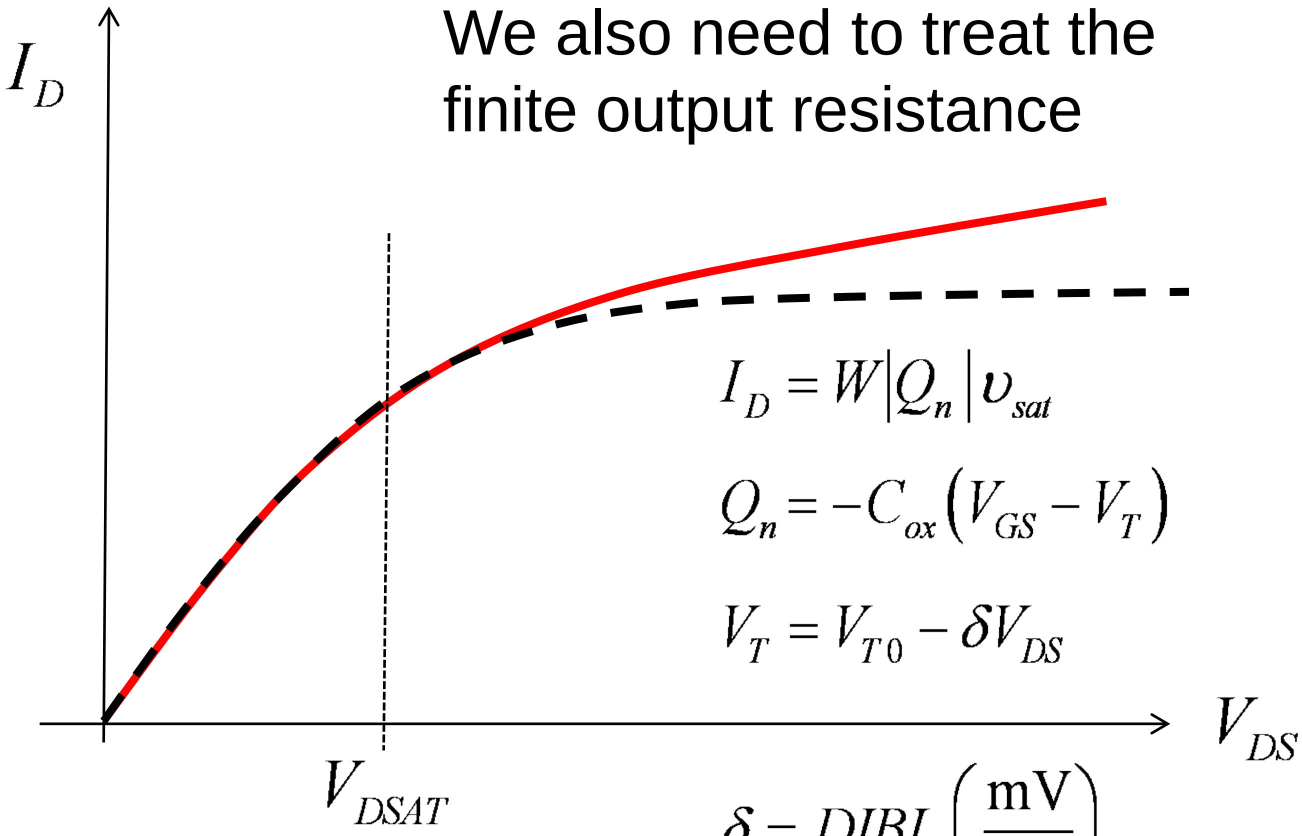
$$\langle \upsilon_x(V_{DS}) \rangle = F_{SAT}(V_{DS})\,\upsilon_{sat}$$

$$F_{SAT}(V_{DS}) = \frac{V_{DS}/V_{DSAT}}{\left[1+\left(V_{DS}/V_{DSAT}\right)^{\beta}\right]^{1/\beta}}$$

Although this is just an empirical method to produce a smooth curve that properly goes between the small and large V_D limits, it works very well in practice (and for several types of FETs), which suggests that it captures something important about MOSFETs.

Output resistance

We also need to treat the finite output resistance



$$I_D = W\left|Q_n\right|\upsilon_{sat}$$

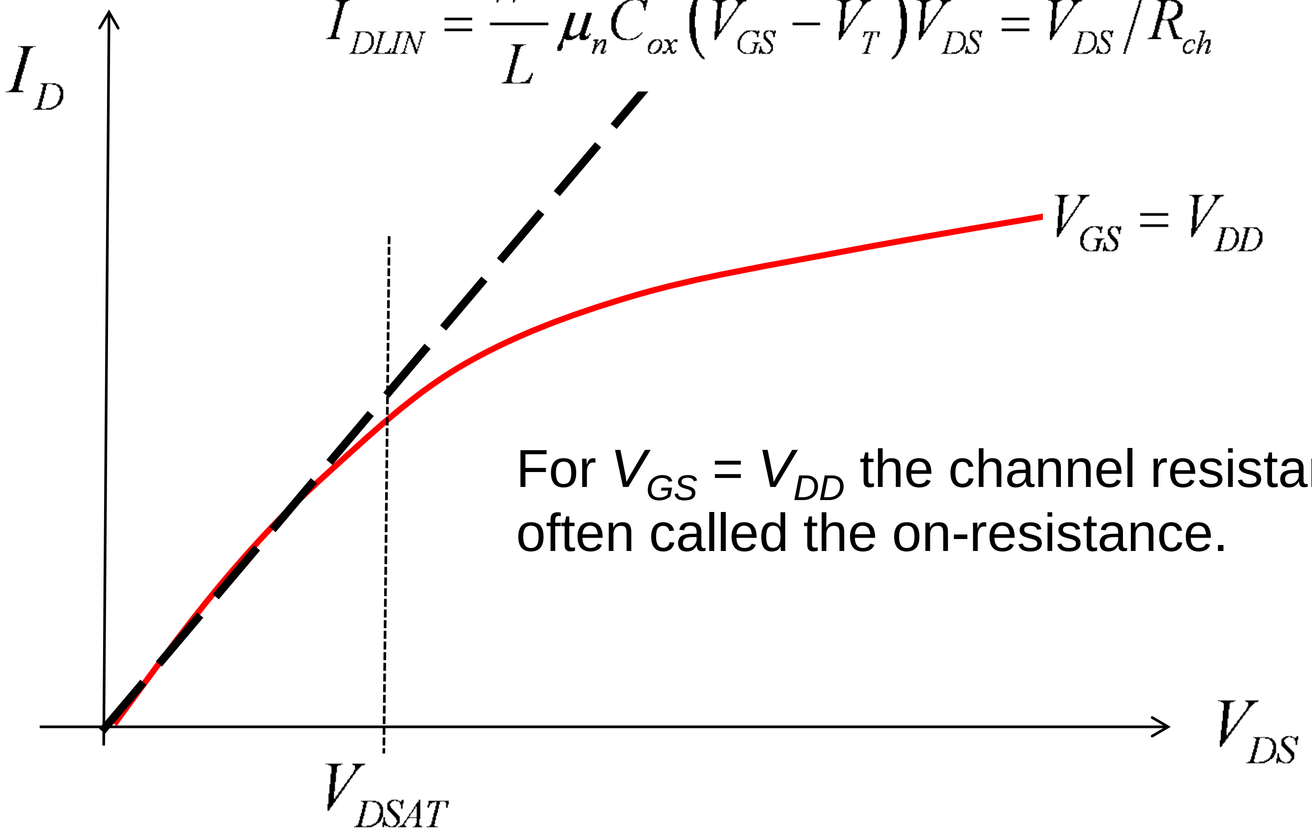
$$Q_n = -C_{ox}\left(V_{GS} - V_T\right)$$

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

$$\delta = DIBL\left(\frac{\text{mV}}{\text{V}}\right)$$

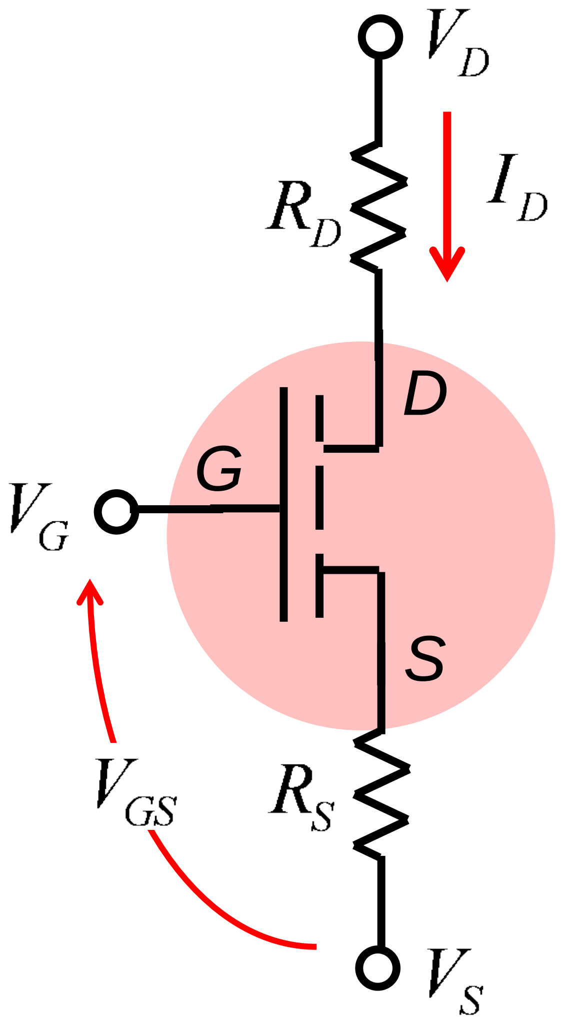
Channel resistance

$$I_{DLIN} = \frac{W}{L}\mu_n C_{ox}\left(V_{GS} - V_T\right)V_{DS} = V_{DS}/R_{ch}$$



For $V_{GS} = V_{DD}$ the channel resistance is often called the on-resistance.

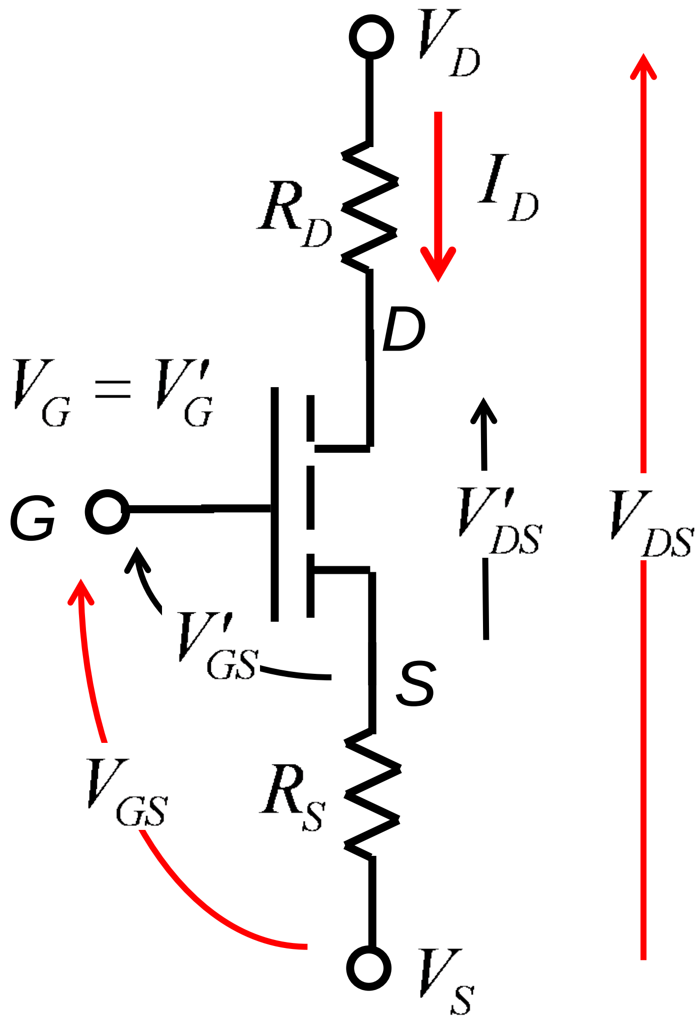
Series resistance



Parasitic resistances connect the intrinsic MOSFET to the contacts.

(There is a gate resistance too, which can be important for RF applications.)

Intrinsic vs. extrinsic voltages

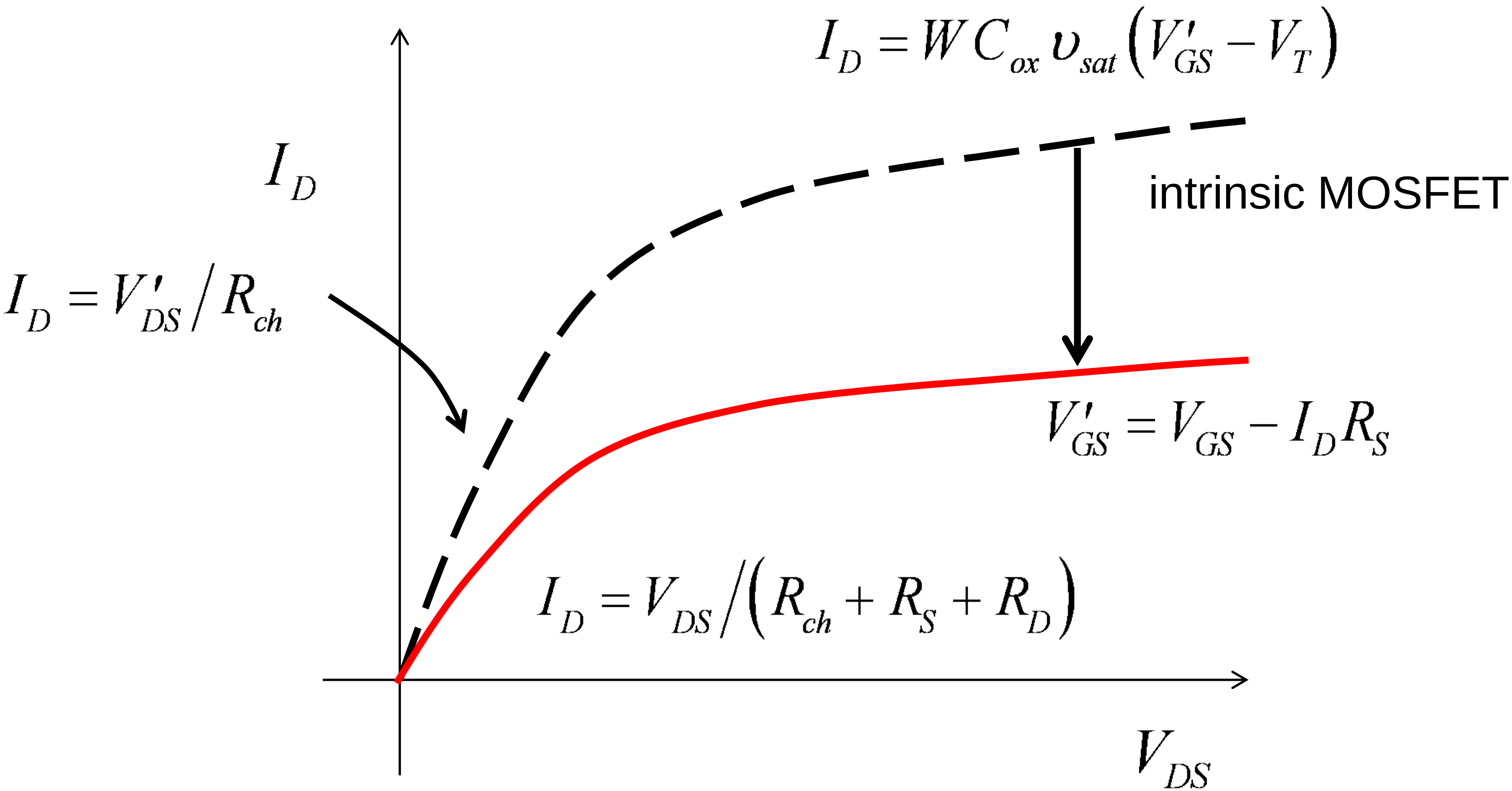


$$V'_G = V_G$$

$$V'_D = V_D - I_D\left(V'_G, V'_S, V'_D\right) R_D$$

$$V'_S = V_S + I_D\left(V'_G, V'_S, V'_D\right) R_S$$

Two effects of series resistances



Simple (level 0) VS model

1) $I_D / W = \left| Q_n\left(V'_{GS}\right) \right| \left\langle \upsilon\left(V'_{DS}\right) \right\rangle$

2) $Q_n\left(V'_{GS}\right) = -C_{ox}\left(V'_{GS} - V_T\right) \qquad \left(V'_{GS} > V_T\right)$

$V_T = V_{T0} - \delta V'_{DS}$

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

Lundstrom: 2018

There are only 8 device-specific parameters in this model:

$$C_{ox}, V_{T0}, \delta, \upsilon_{sat}, \mu_n, L$$

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

$$+ \quad \beta$$

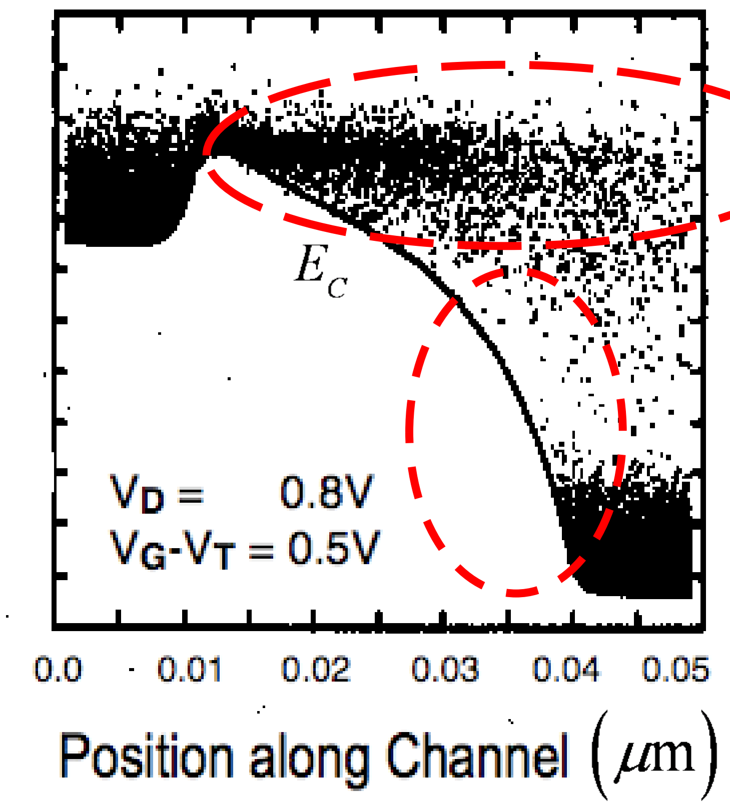
Physics of the VS model

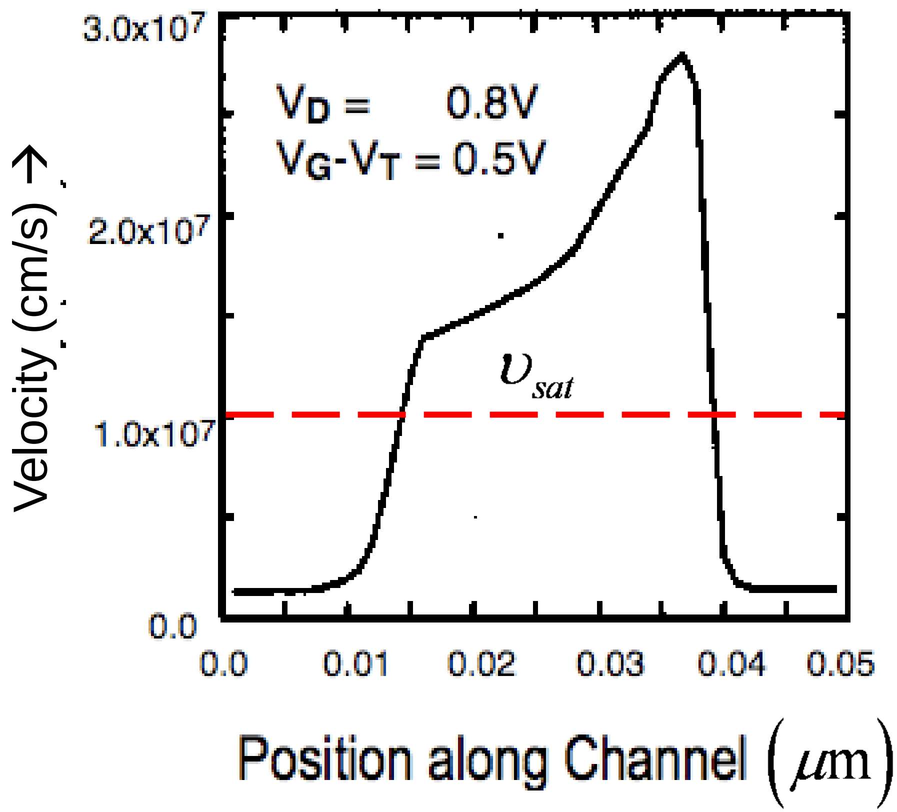
1) Diffusive (collision-dominated) transport is assumed, so that mobility is a well-defined concept.

2) We assume that the carrier velocity is clamped at the high-field (scattering limited) saturation velocity in the bulk.

Neither of these assumptions is valid for modern, nanoscale MOSFETs.

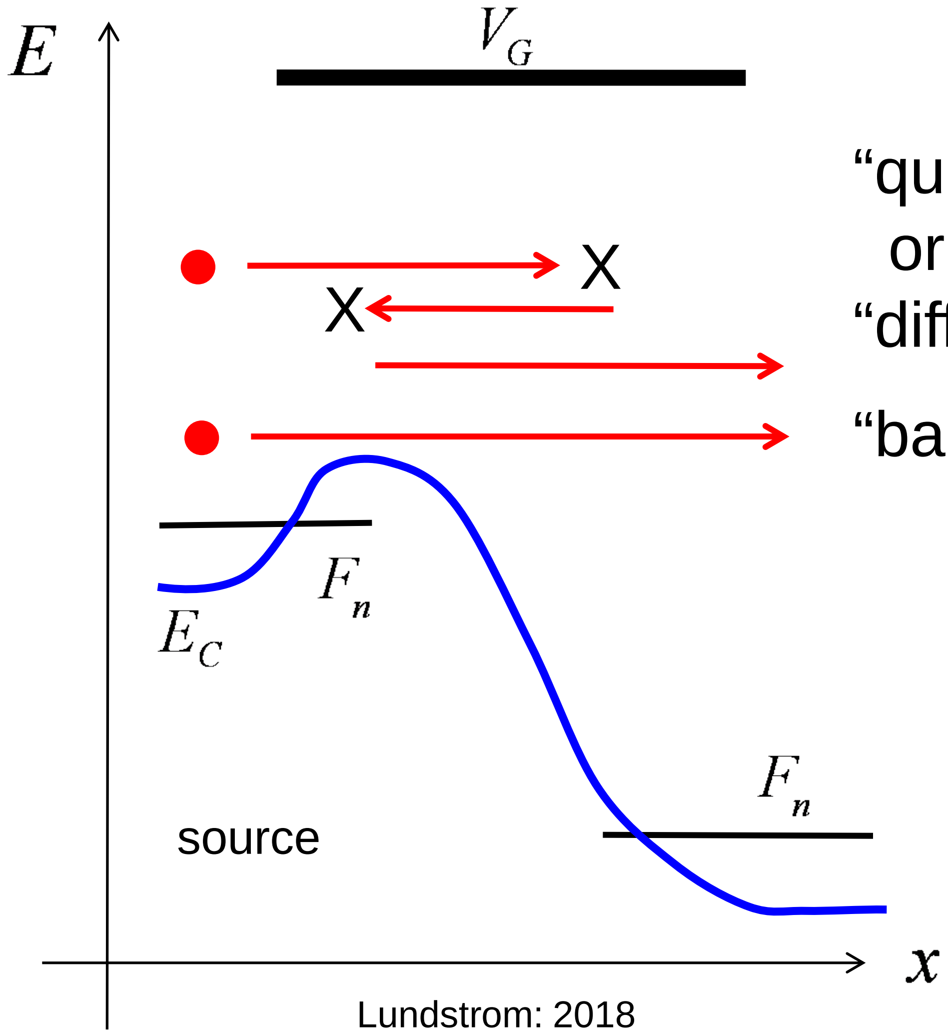
Velocity overshoot





D. Frank, S. Laux, and M. Fischetti, Int. Electron Dev. Mtg., Dec., 1992.

Importance of transport



"quasi-ballistic"
or
"diffusive"

"ballistic transport"

The MIT VS Model

In spite of these concerns, the MVS model does a remarkably good job of fitting the IV characteristics of nanoscale FETs.

The MIT VS Model

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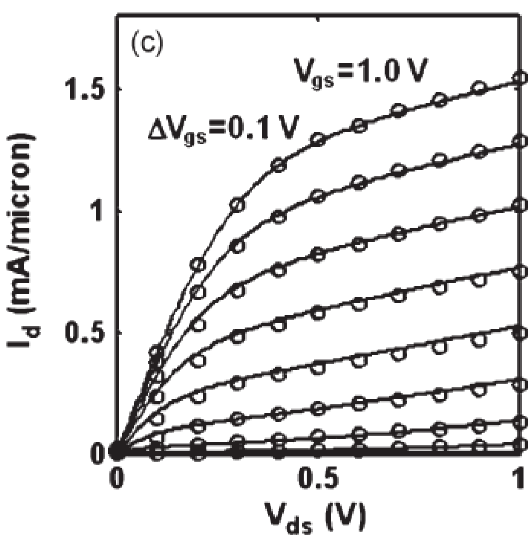

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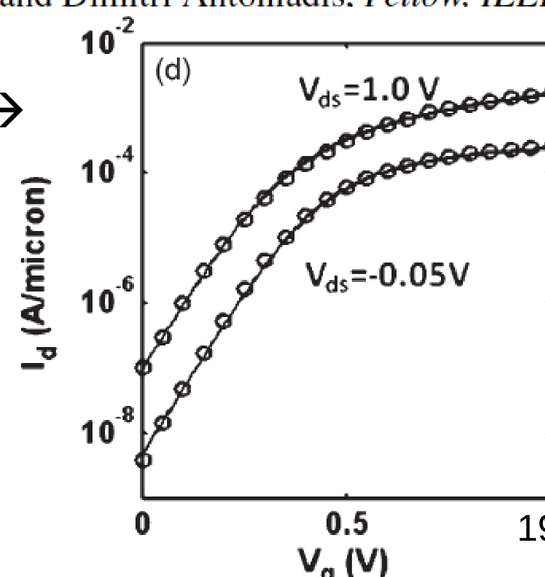


The MIT VS Model

In this course, we will show that the mobility and high-field saturation velocity should be re-interpreted:

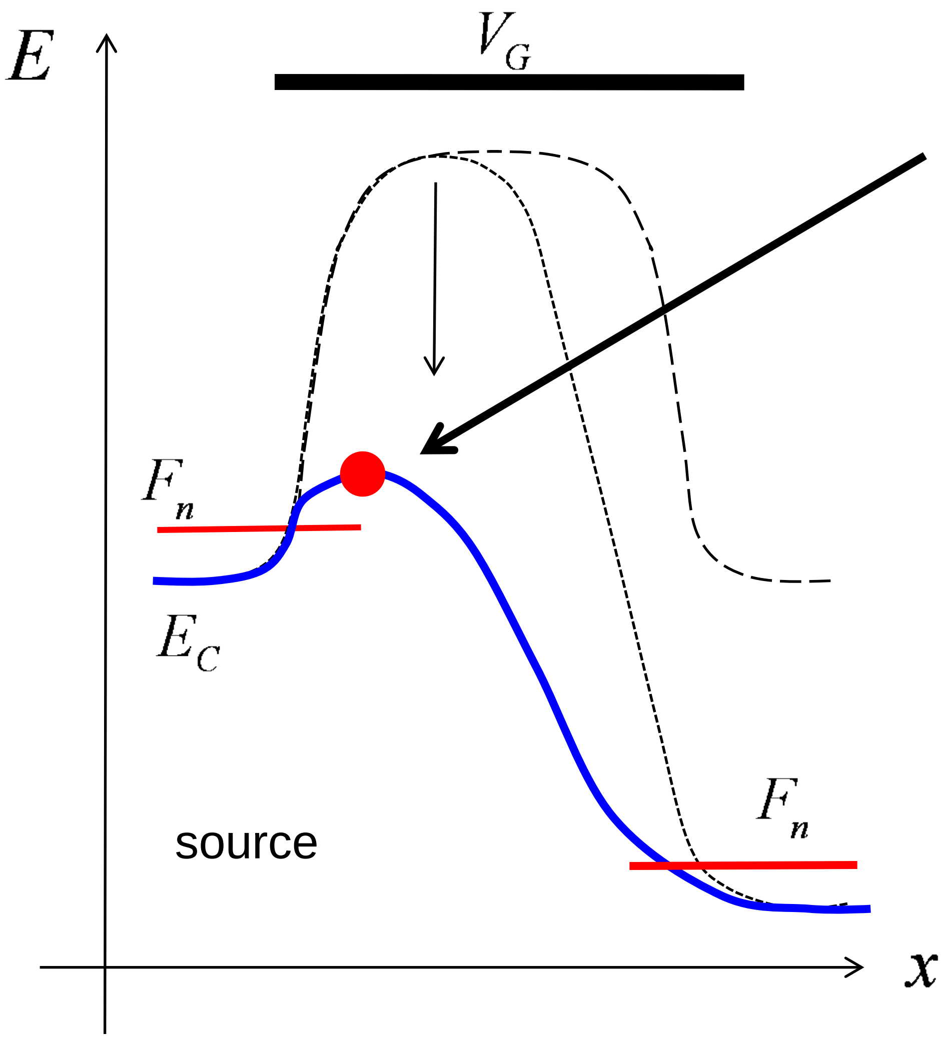
$$\frac{1}{\mu_n} \rightarrow \frac{1}{\mu_{app}}$$ "apparent mobility"

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

We will show that these two parameters have clear, well-defined physical interpretations.

https://nanohub.org/resources/21703

Focus on the "virtual source"



$$Q_n = -C_{ox}\left(V_{GS} - V_T\right)$$

nearly independent of drain bias

(This is true in an electrostatically well-designed MOSFET.)

Summary

1) $$I_D / W = Q_n\left(V'_{GS}, V'_{DS}\right)\left\langle \upsilon\left(V'_{DS}\right)\right\rangle$$

2) $$Q_n\left(V'_{GS}\right) = -C_{ox}\left(V'_{GS} - V_T\right) \qquad \left(V'_{GS} > V_T\right)$$

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$$+ \quad \beta$$