Fundamentals of Nanotransistors

Unit 1: Transistor Fundamentals

Lecture 1.7: Virtual Source Model

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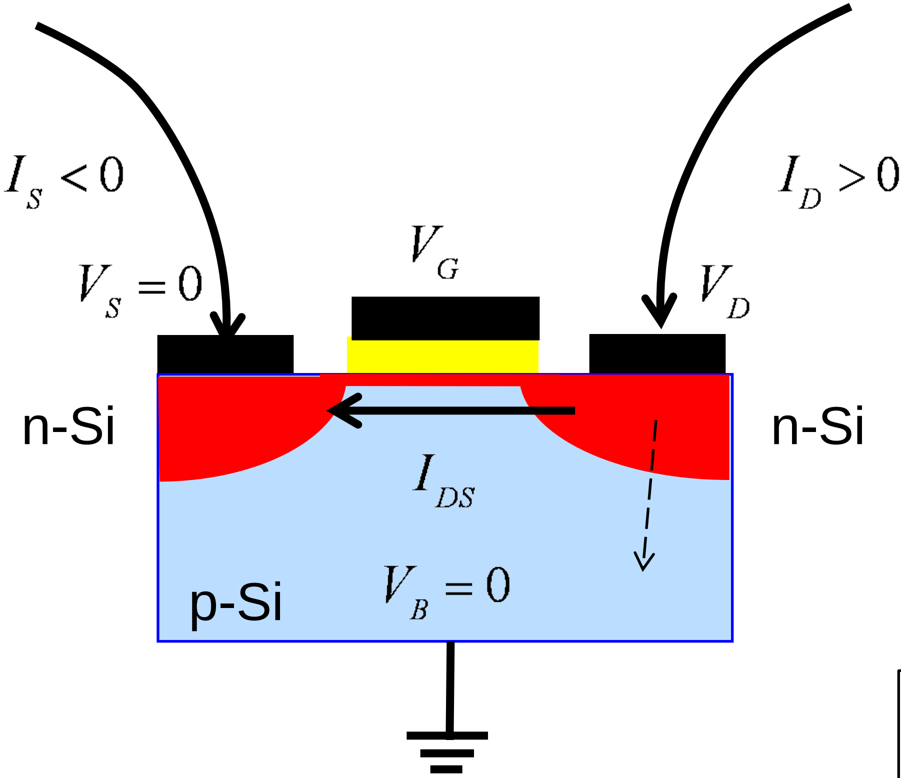
IV characteristics of MOSFETs

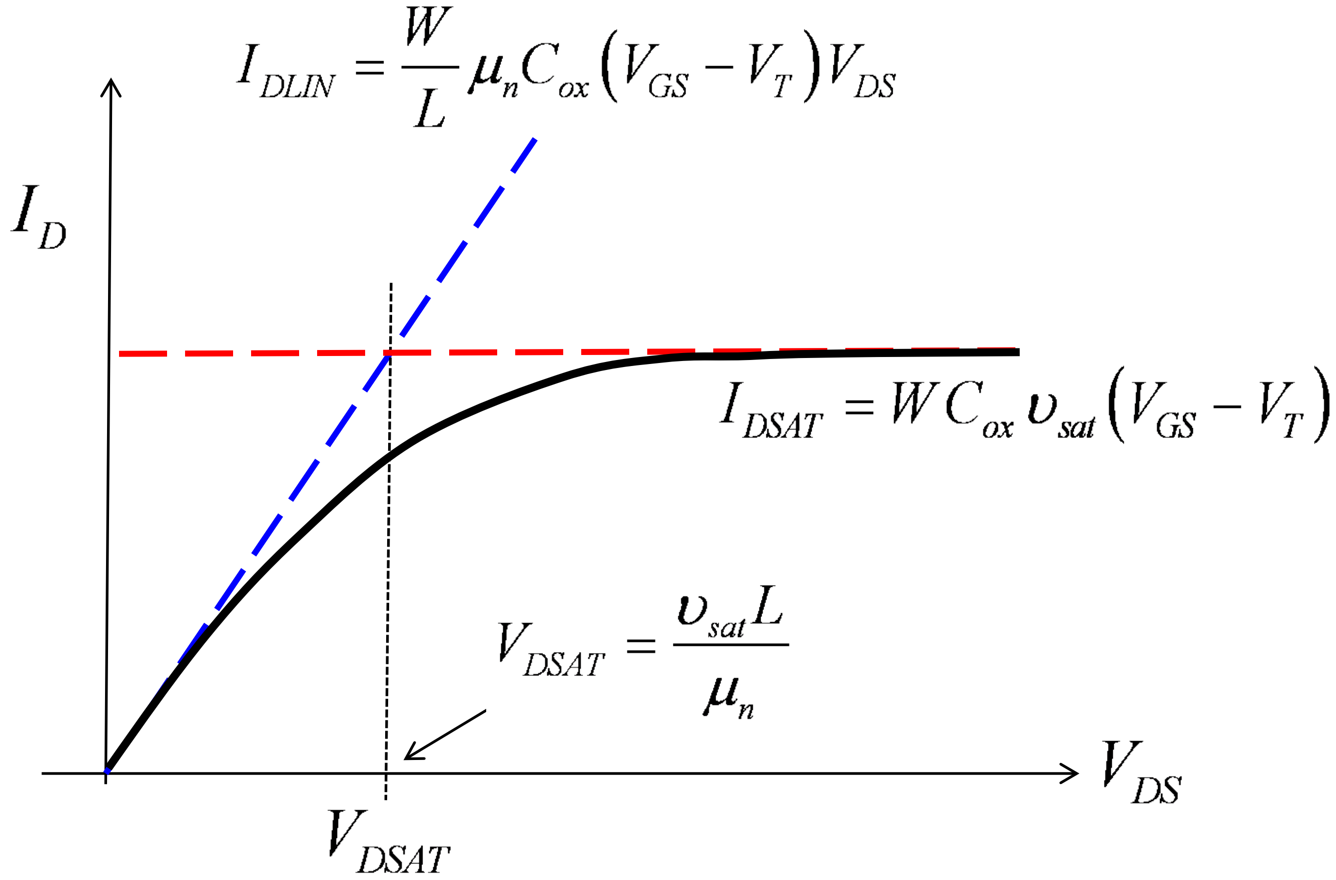


$$I_{DS}\left(V_{GS}, V_{DS}\right)$$

$$V_S = V_B = 0$$

Goal: To understand: $I_{DS}\left(V_S, V_G, V_D, V_B\right)$

MOSFET: IV (re-cap)



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

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

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

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

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

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

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

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}

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

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

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

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

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.

Empirical saturation function

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

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

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

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

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

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

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

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

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

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

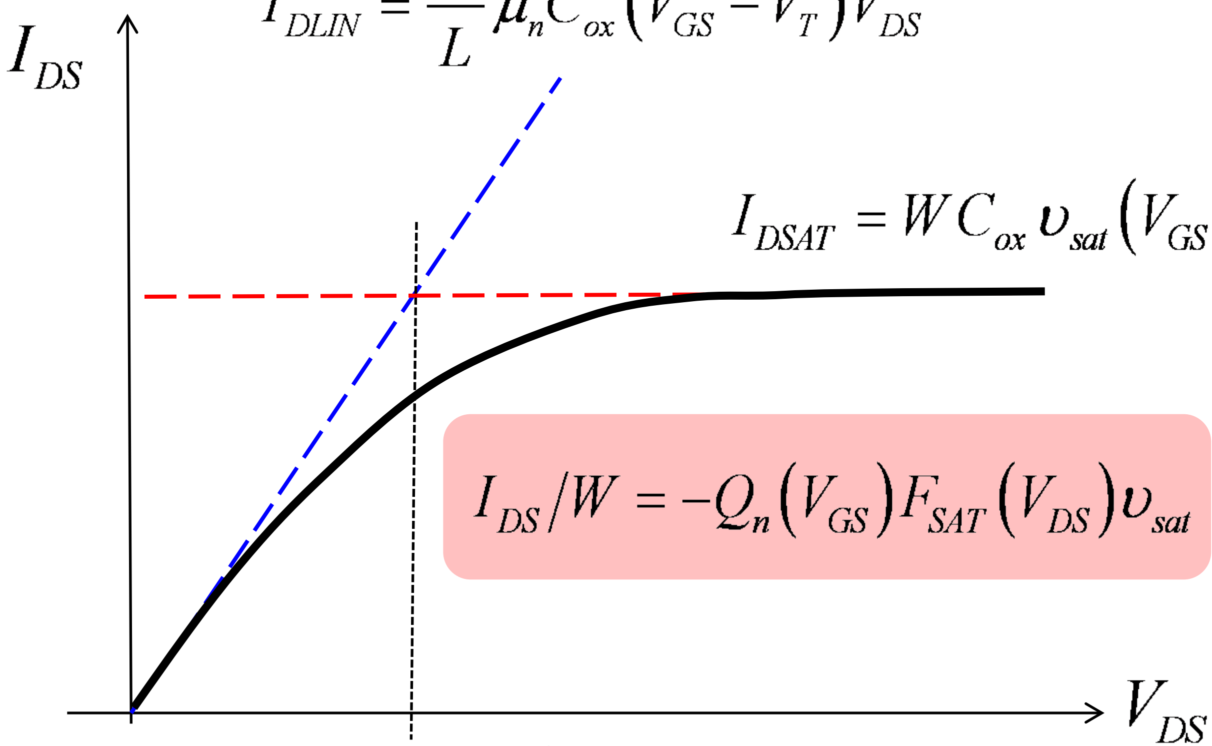
$$F_{SAT}(V_{DS}) = \frac{V_{DS}/V_{DSAT}}{\left[1+\left(V_{DS}/V_{DSAT}\right)^{\beta}\right]^{1/\beta}}$$

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

MOSFET: IV (re-cap)

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

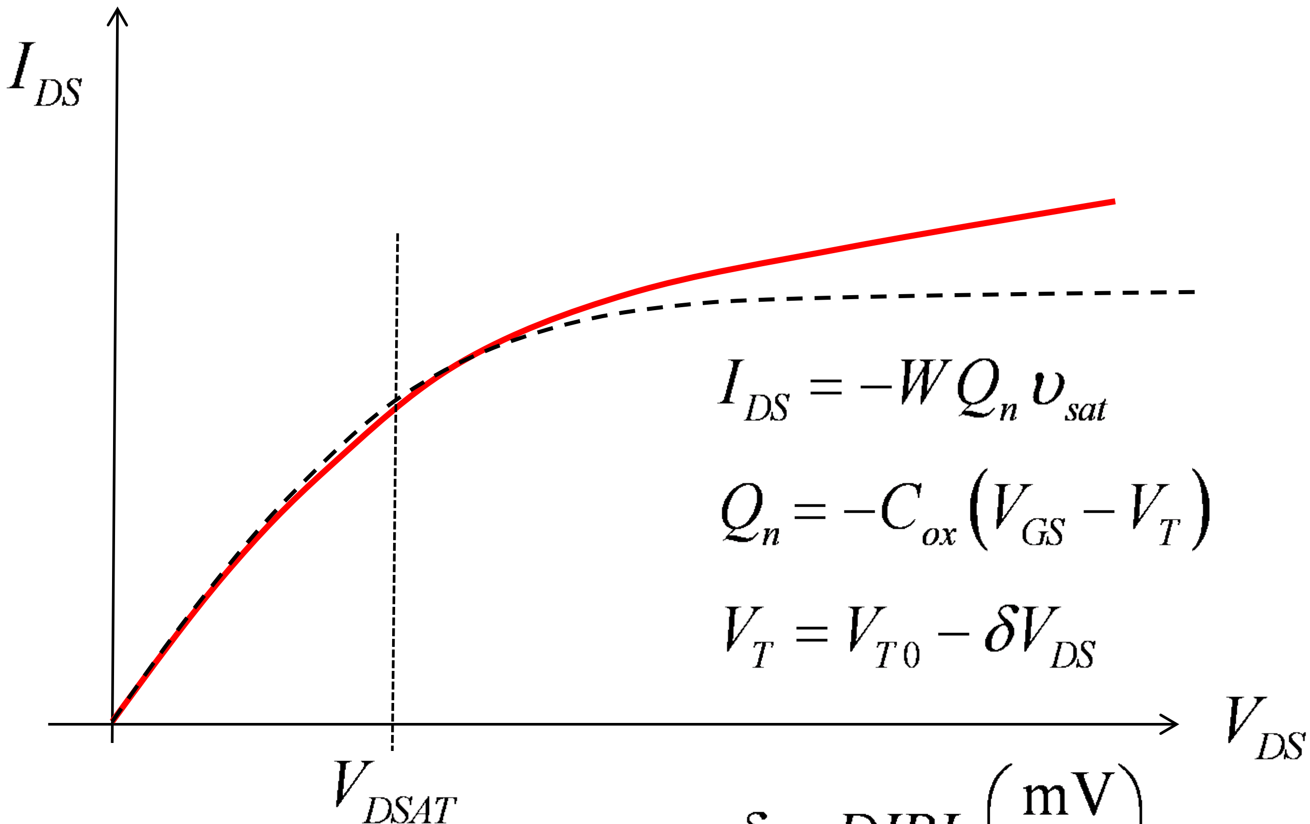
$$I_{DSAT} = W\,C_{ox}\,\upsilon_{sat}\left(V_{GS} - V_T\right)$$



$$I_{DS}/W = -Q_n\left(V_{GS}\right)F_{SAT}\left(V_{DS}\right)\upsilon_{sat}$$

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

Output resistance



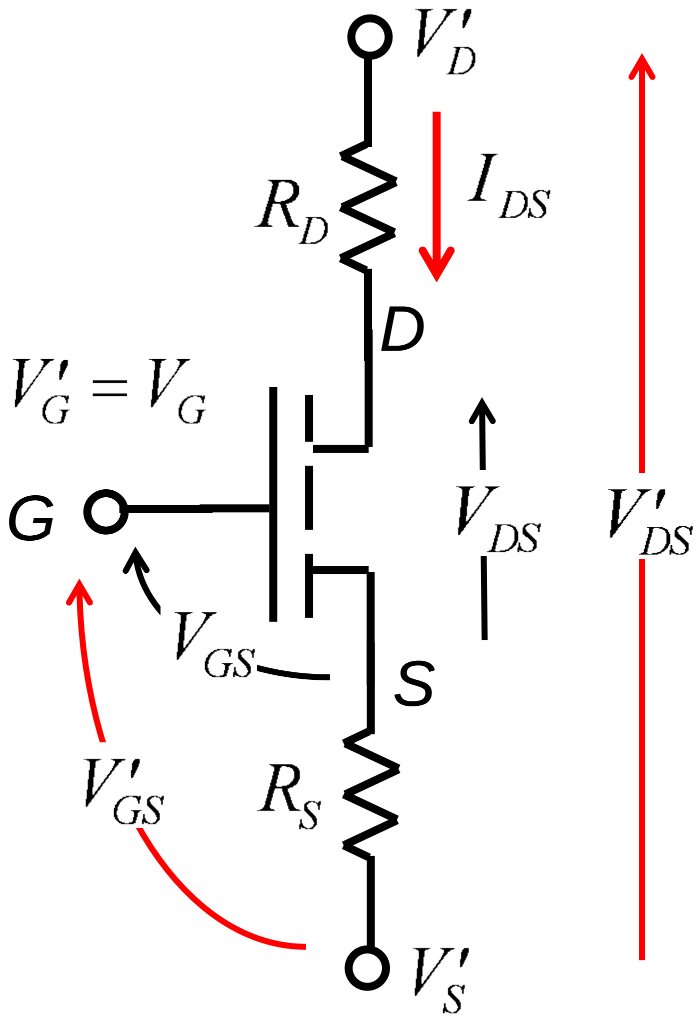
$$I_{DS} = -W Q_n \upsilon_{sat}$$

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

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

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

Intrinsic vs. extrinsic voltages



$$I_{DS}\left(V_{GS}, V_{DS}\right)$$

$$V_G = V_G'$$

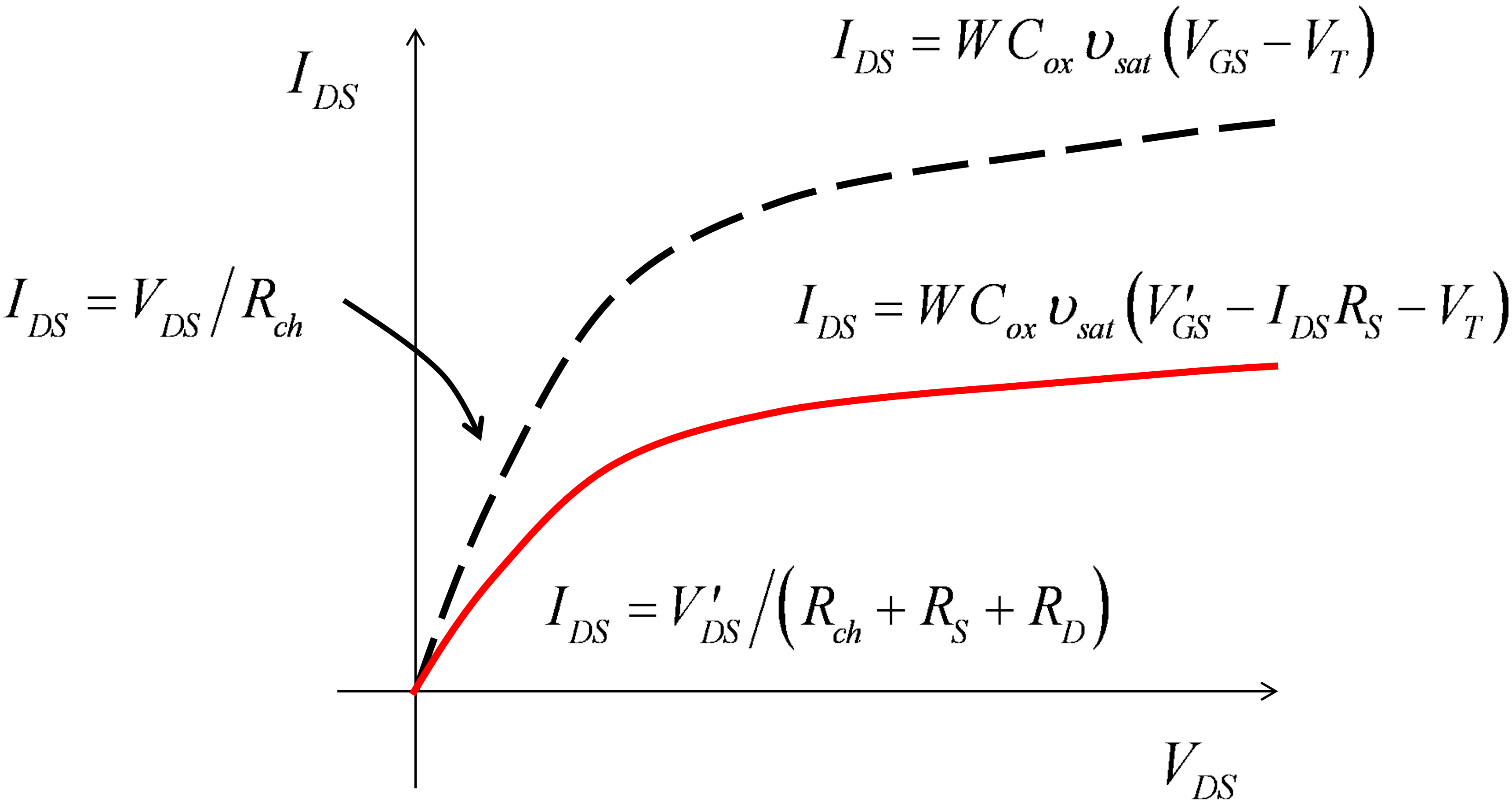
$$V_D = V_D' - I_{DS}\left(V_G, V_S, V_D\right) R_D$$

$$V_S = V_S' + I_{DS}\left(V_G, V_S, V_D\right) R_S$$

$$V_{DS} = V_{DS}' - I_{DS}\left(V_G, V_S, V_D\right)\left(R_S + R_D\right)$$

$$V_{GS} = V_{GS}' - I_{DS}\left(V_G, V_S, V_D\right) R_S$$

Effect of series resistances



Simple (Level 0) VS model

1) $I_{DS}/W = -Q_n(V_{GS})\langle \upsilon(V_{DS})\rangle$

2) $Q_n(V_{GS}) = -C_{ox}(V_{GS} - V_T) \qquad (V_{GS} > V_T)$

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

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

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

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

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

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

$$R_{SD} = R_S + R_D, \beta$$

The MIT VS Model

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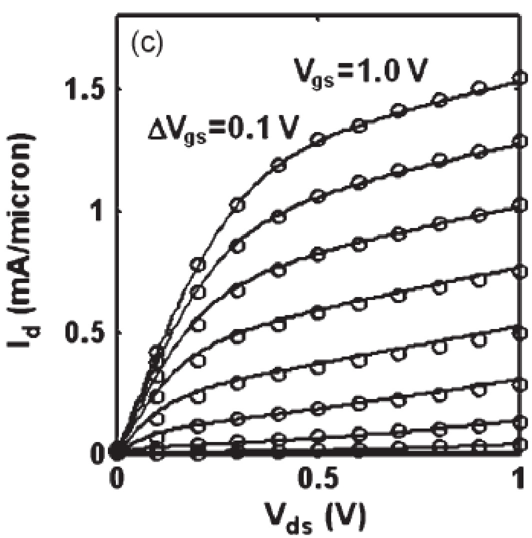
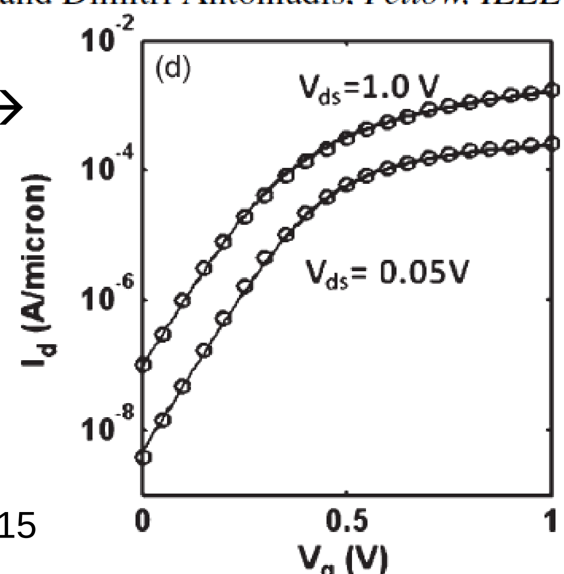
Ali Khakifirooz, *Member, IEEE*, Osama M. Nayfeh, *Member, IEEE*, and Dimitri Antoniadis, *Fellow, IEEE*



← 32 nm technology →



Summary

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

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