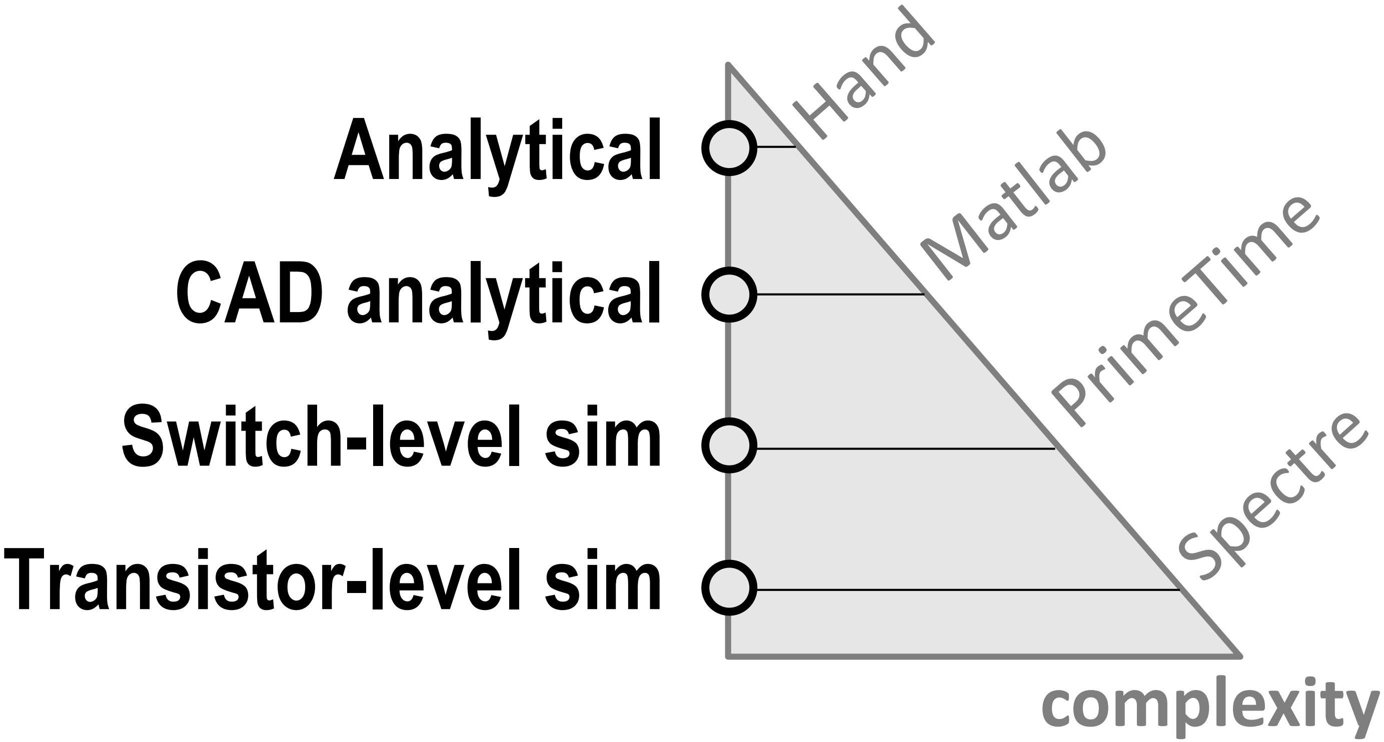
ECE115C –
Digital Electronic Circuits

Lecture 2:
MOS Transistor:
IV Model

115C vs. 189 Material

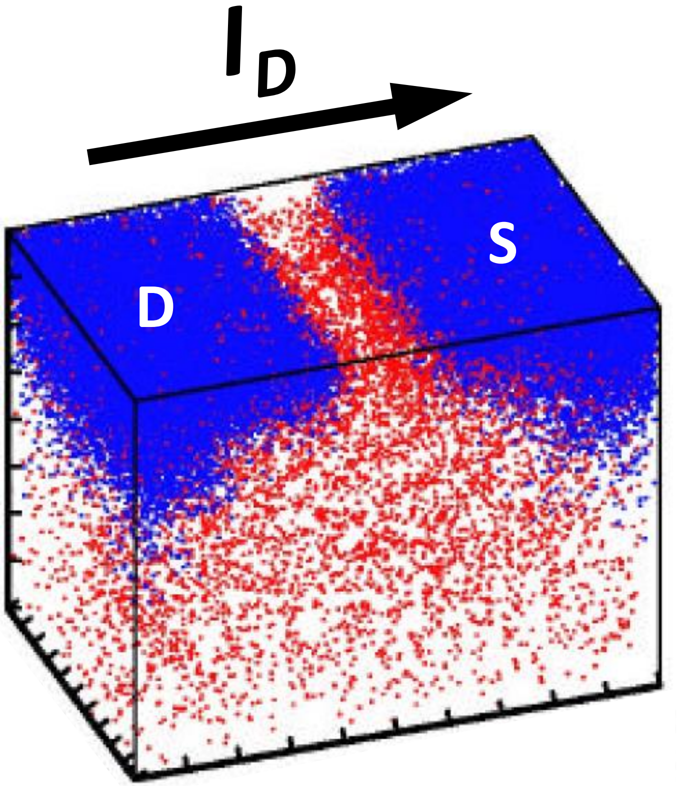
- Content marked with (189) indicates material that is optional in 115C and required in 189
- If (189) is in the slide title, it applies to the entire slide
- 115C students will have access to all (189) information as an additional resource and optional study
- 115C project will not require layout
  - 115C students will get layout experience on a relevant digital block (e.g. full adder cell)
- 189 students are required to do layout in their project

Levels of Modeling



Different complexity, accuracy, speed of convergence…

MOS Transistor Modeling

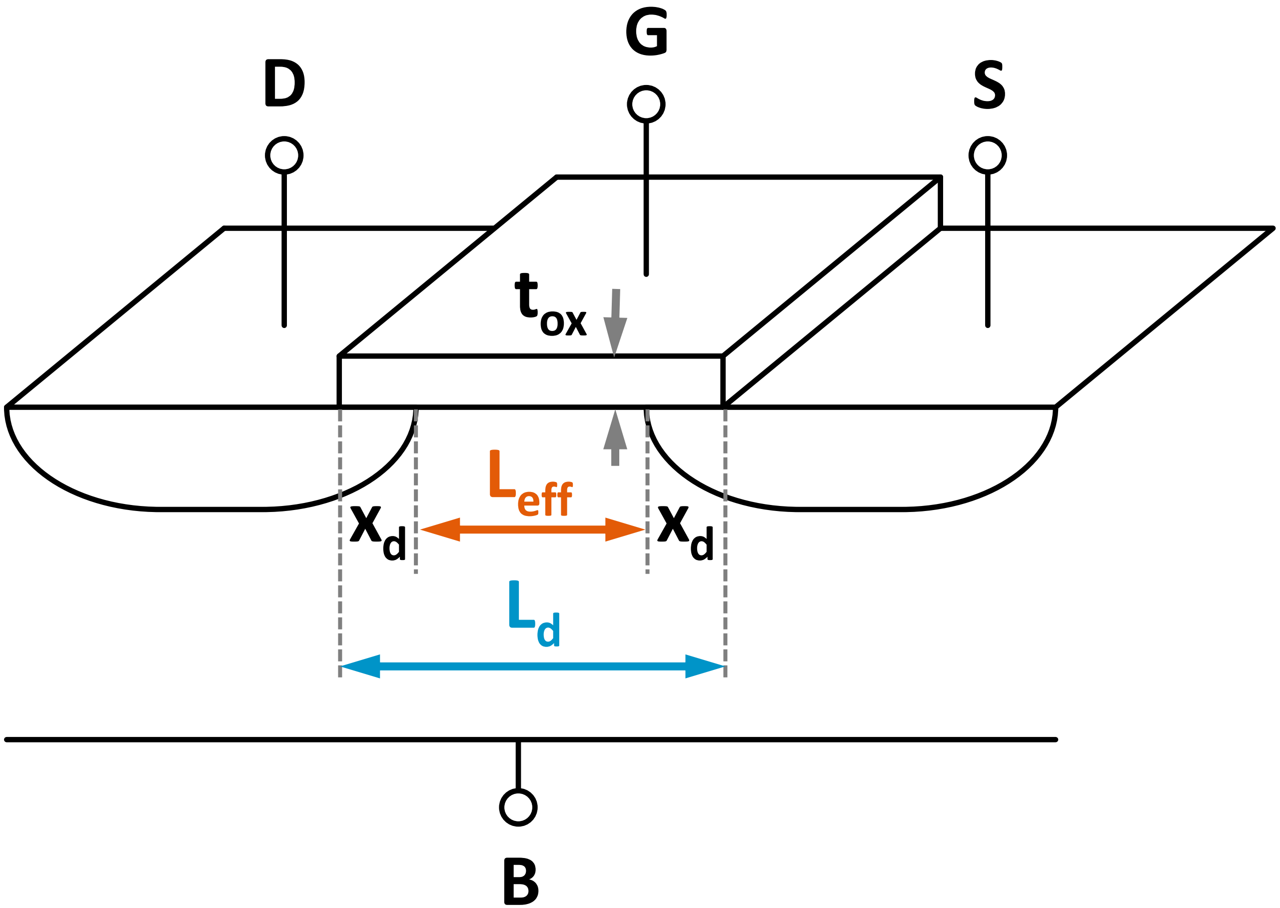


Our goal is to model delay and energy

not current

But have to start with current

MOSFET, Notations



Hand-analysis I-V formulas: $L = L_{eff}$

Important Concepts to Understand

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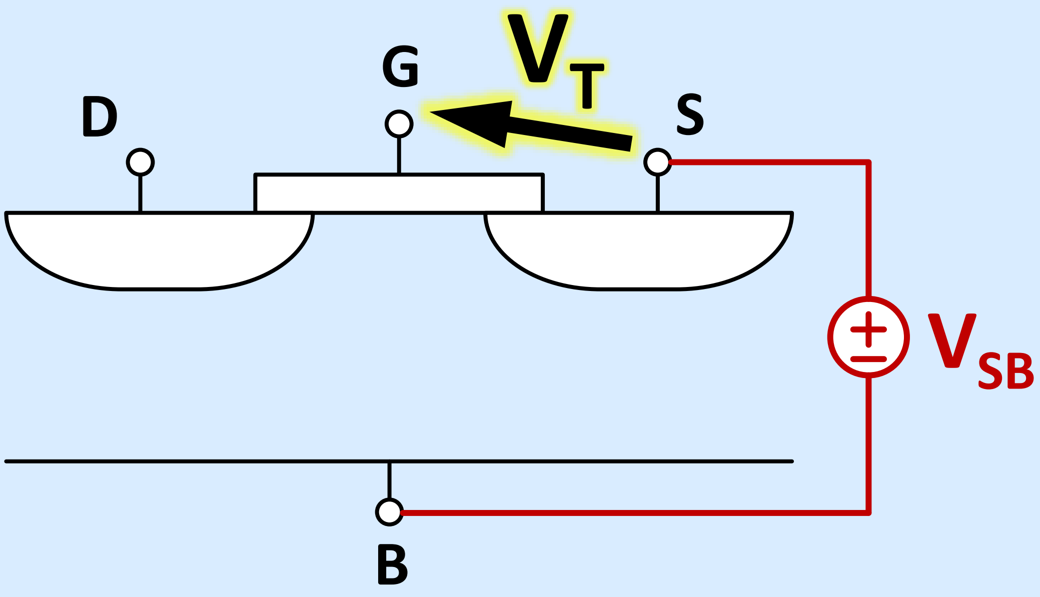
- Threshold voltage (V_T)
- Velocity saturation
- Channel length modulation

Threshold Voltage, V_T

$V_{SB} = 0$

V_{T0} is approx 0.2V for our process

$$V_T = V_{T0} + \gamma \cdot \left(\sqrt{|-2\Phi_F + V_{SB}|} - \sqrt{|2\Phi_F|}\right)$$



NMOS:

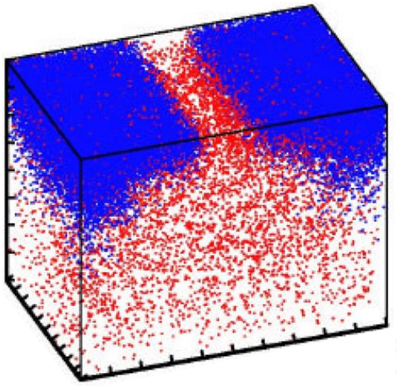
- $V_{SB} > 0$ (RBB)
- $V_{SB} < 0$ (FBB)

PMOS:

- $V_{SB} > 0$ (FBB)
- $V_{SB} < 0$ (RBB)

Outline

- **MOS Transistor**
  - Basic Operation
  - Modes of Operation
  - Deep sub-micron MOS



The Drain Current in Linear Regime

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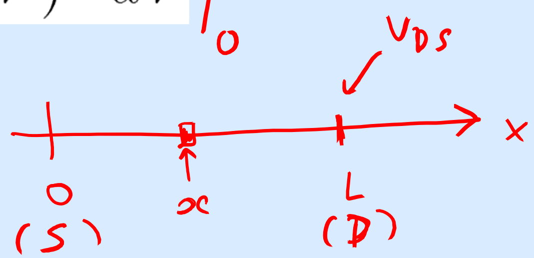
- **Combining velocity and charge:**

$$I_D \cdot dx = \mu_n \cdot C_{ox} \cdot W \cdot (V_{GS} - V_T - V) \cdot dV$$

- **Integrating over the channel:**



$$I_D = \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot \left[(V_{GS} - V_T) \cdot V_{DS} - \frac{V_{DS}^2}{2} \right]$$

Transconductance: $k_n' = \mu_n \cdot C_{ox}$

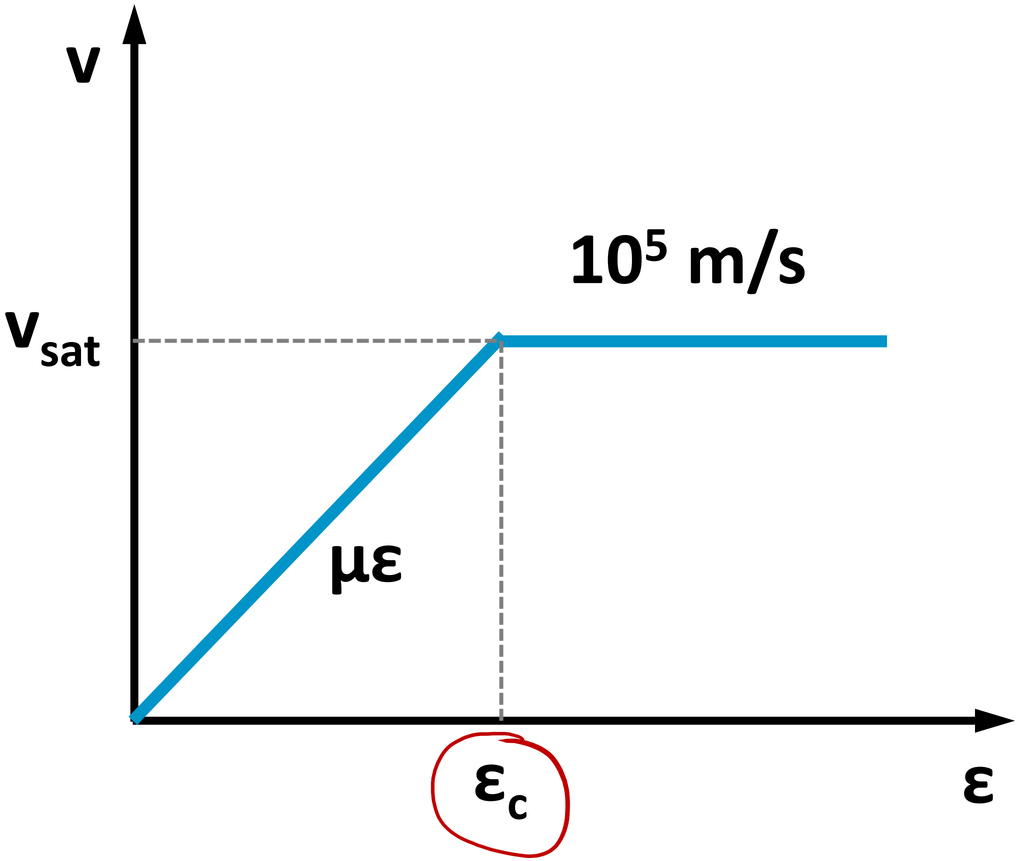
Gain factor: $k_n = k_n' \cdot \frac{W}{L}$

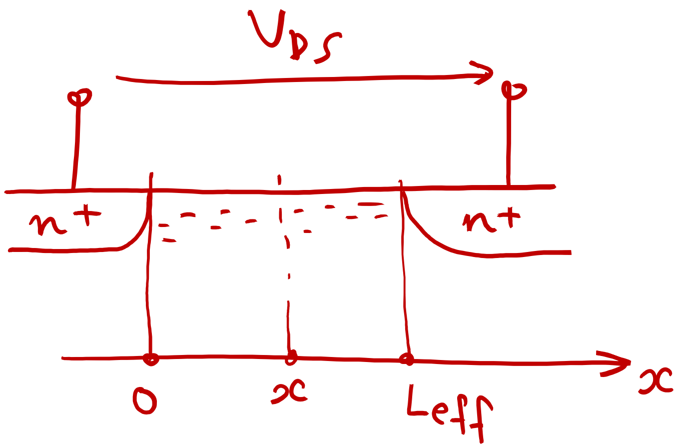
Small V_{DS} → ignore quadratic term → **linear** V_{DS} dependence

L = effective L = $L_d - 2x_d$

Velocity Saturation

- Carrier velocity saturates when critical field is reached



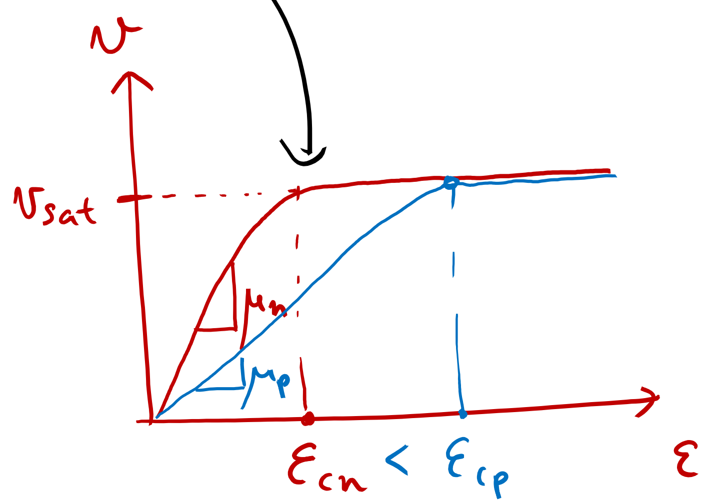


$$\mathcal{E} = \frac{V_{DS}}{L_{eff}}$$

Simple Model

$$v_n = \frac{\mu \mathcal{E}}{1 + \mathcal{E}/\mathcal{E}_c}, \quad \mathcal{E} \le \mathcal{E}_c$$

$$v_n = v_{sat}, \quad \mathcal{E} \ge \mathcal{E}_c$$



Continuity @ $\mathcal{E} = \mathcal{E}_c$

$$v_{sat} = \frac{\mu_n \cdot \mathcal{E}_c}{2}$$

$$v_n^{sat} = v_p^{sat}$$

$$\mathcal{E}_{cn} < \mathcal{E}_{cp}$$

A More General Model

- **Approximate velocity:**

$$v_n = \frac{\mu_n \cdot \xi}{1 + \xi/\xi_c} \quad \text{for } \xi \le \xi_c$$

$$v_n = v_{sat} \quad \text{for } \xi \ge \xi_c$$

A more general model:

$$v_n = \frac{\mu_n \cdot \xi}{\left(1 + (\xi/\xi_c)^n\right)^{1/n}}$$

we use n = 1

- **And integrate current again:**

$$I_D = \frac{\mu_n \cdot C_{ox}}{1 + \frac{V_{DS}}{\xi_c \cdot L}} \cdot \frac{W}{L} \cdot \left[(V_{GS} - V_T) \cdot V_{DS} - \frac{V_{DS}^2}{2}\right]$$

In **deep submicron**, there are three regions of operation:
(1) cutoff, (2) resistive (linear), and (3) **velocity saturation**

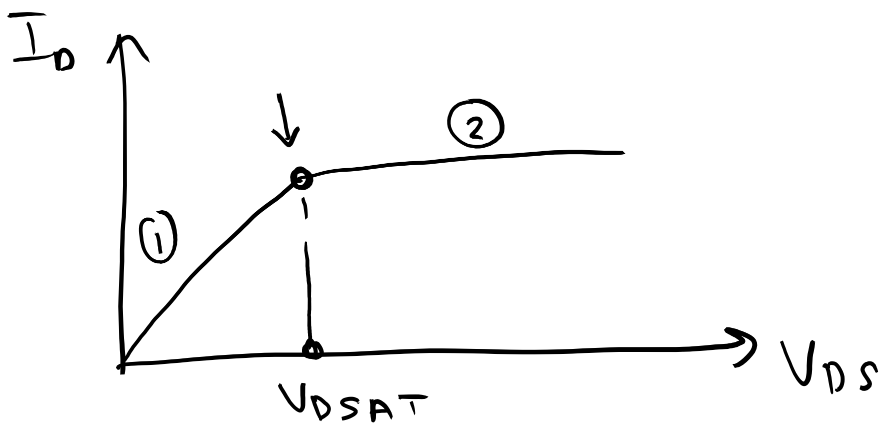
Including Velocity Saturation in the I_D Formula

① $$I_D = \frac{\mu_n \cdot C_{ox}}{1 + \frac{V_{DS}}{\mathcal{E}_c \cdot L}} \frac{W}{L} \left[\underbrace{(V_{GS} - V_T)}_{V_{GT}} \cdot V_{DS} - \frac{V_{DS}^2}{2} \right] = I_{DSAT}$$

@ $V_{DS} = V_{DSAT}$

② $$I_{DSAT} = v_{sat} \cdot C_{ox} \cdot W \left[V_{GS} - V_T - V_{DSAT} \right]$$

$v_{sat} \leftarrow \frac{\mu_n \mathcal{E}_c}{2}$ (continuity of $v(\mathcal{E})$ model)



Calculating Velocity Saturation, V_{DSAT}

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$$① = ② \Rightarrow \frac{\mu_n \mathcal{E}_c}{2} C_{ox} \cdot W \cdot (V_{GT} - V_{DSAT}) = \frac{\mu_n C_{ox}}{1 + \frac{V_{DSAT}}{\mathcal{E}_c \cdot L}} \frac{W}{L} \left[V_{GT} \cdot V_{DSAT} - \frac{V_{DSAT}^2}{2} \right]$$

$$\left(\frac{\mathcal{E}_c L}{2} + \frac{V_{DSAT}}{2} \right) (V_{GT} - V_{DSAT}) = V_{GT} V_{DSAT} - \frac{V_{DSAT}^2}{2}$$

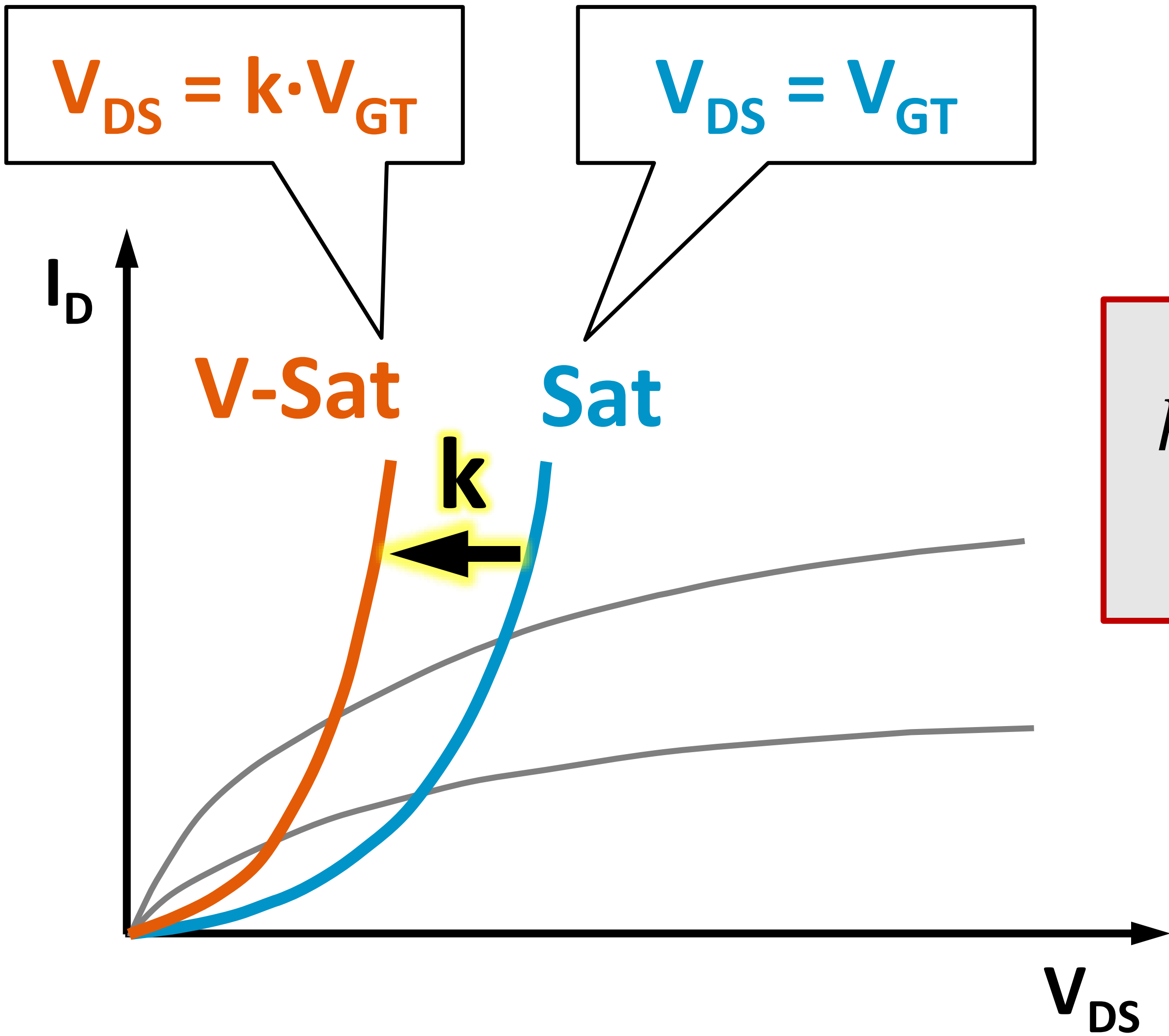
$$\frac{\mathcal{E}_c \cdot L}{2} V_{GT} - \frac{\mathcal{E}_c L}{2} V_{DSAT} - \frac{V_{GT} \cdot V_{DSAT}}{2} = 0$$

$$K(V_{GT}) = \frac{1}{1 + \frac{V_{GT}}{\mathcal{E}_c \cdot L}} < 1$$

$$\boxed{V_{DSAT} = \frac{V_{GT}}{1 + \frac{V_{GT}}{\mathcal{E}_c L}} = \underbrace{K(V_{GT})}_{<1} \cdot V_{GT}}$$

$$< V_{GT} - V_T$$

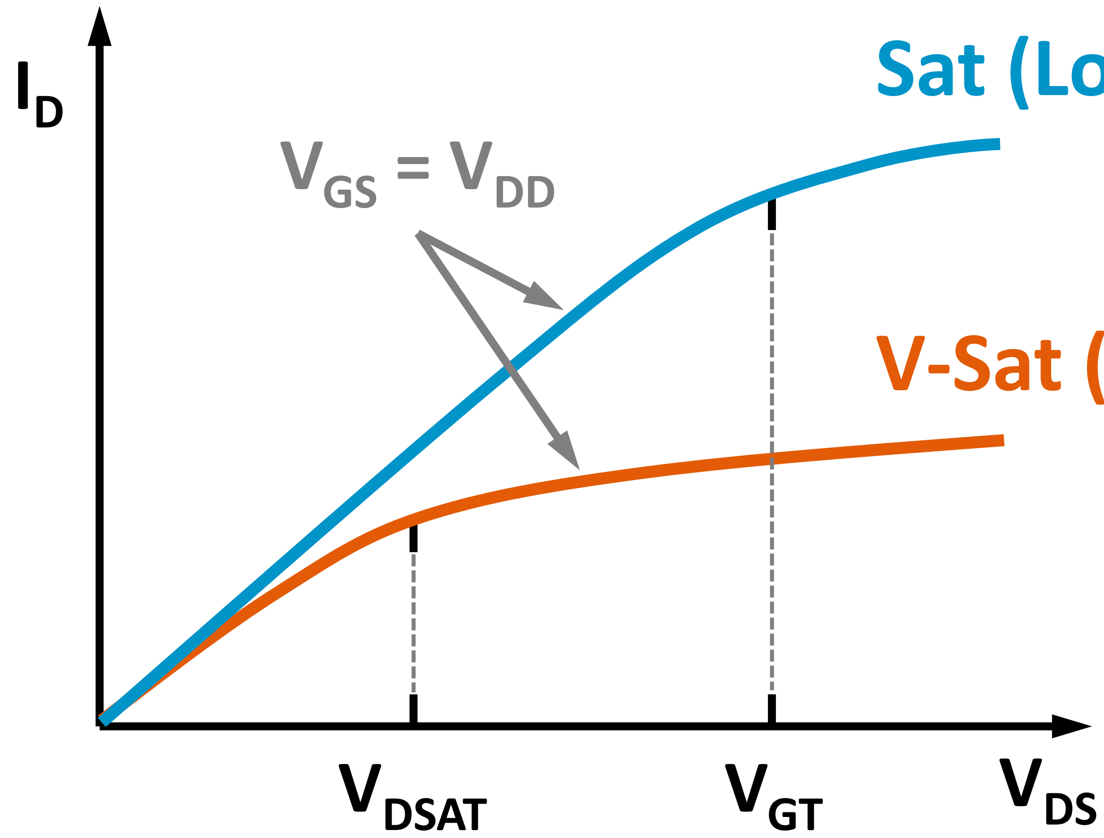
V-Sat Occurs at LOWER V_{DS} than Sat



$$k = \frac{1}{1 + \frac{V_{GT}}{\epsilon_c \cdot L}}$$

$k = k(V_{GT})$

V-Sat: Less Current for Same V_{GS}



Channel Length Modulation (CLM)

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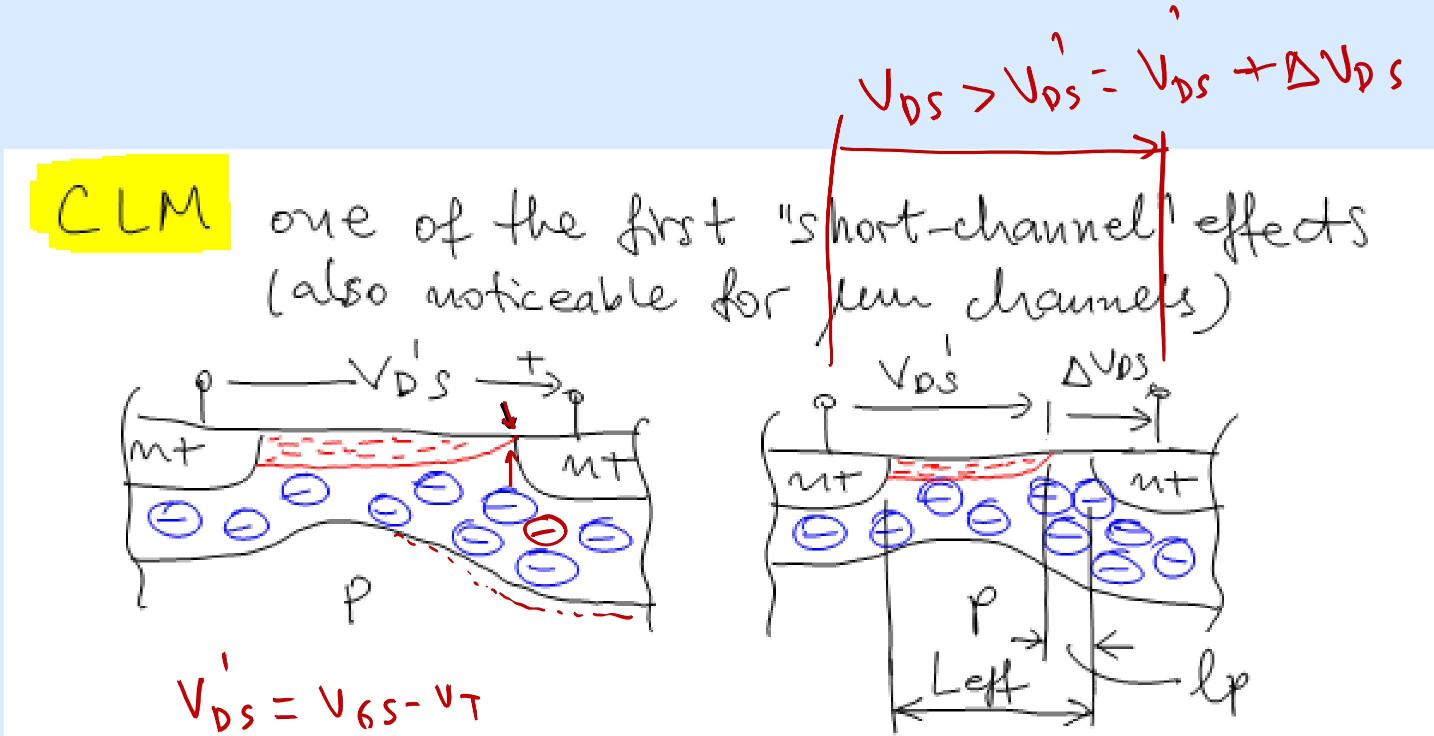
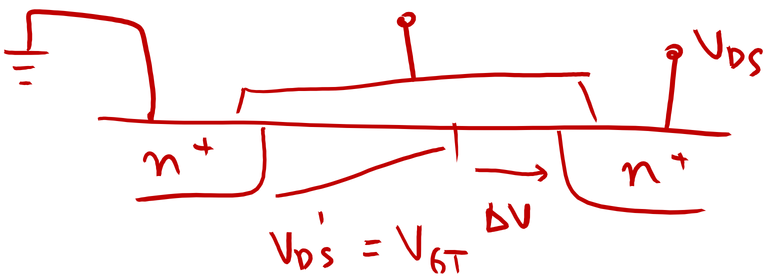
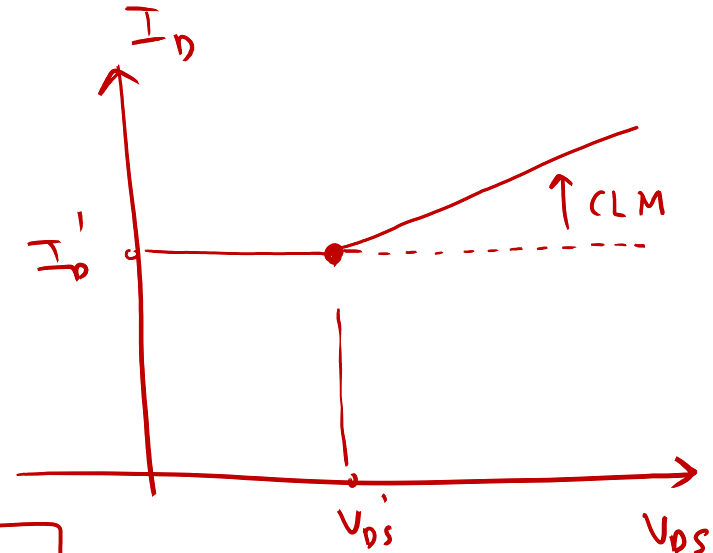
- Channel pinch-off



Modeling Channel Length Modulation (CLM)

- **Many empirical models**
  - Goal: get a simple model that is convenient for hand analysis



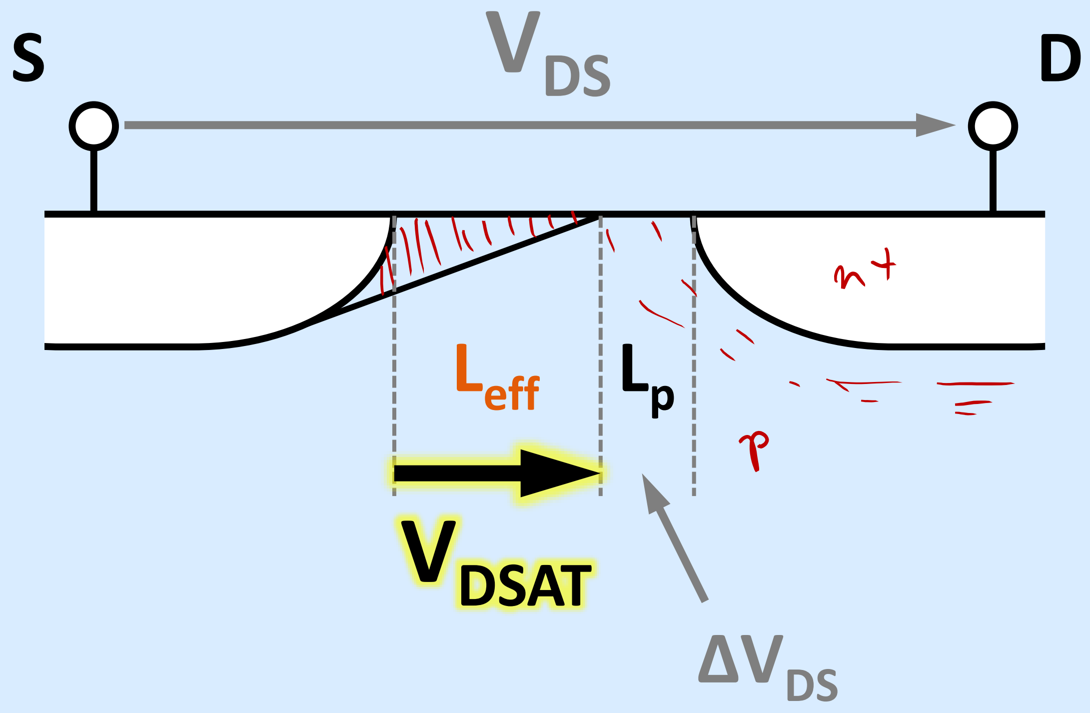


$$I_D = I_D' \cdot (1 + \lambda \cdot V_{DS})$$

CLM parameter

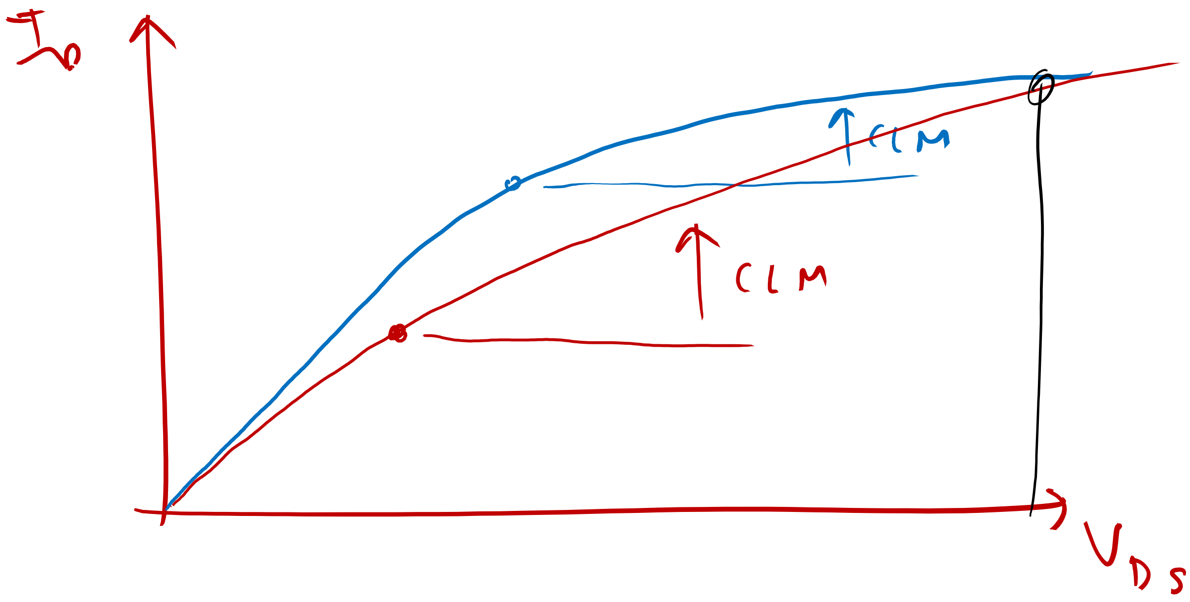
CLM Holds in V-Sat

$V_{DS} > V_{DSAT}$



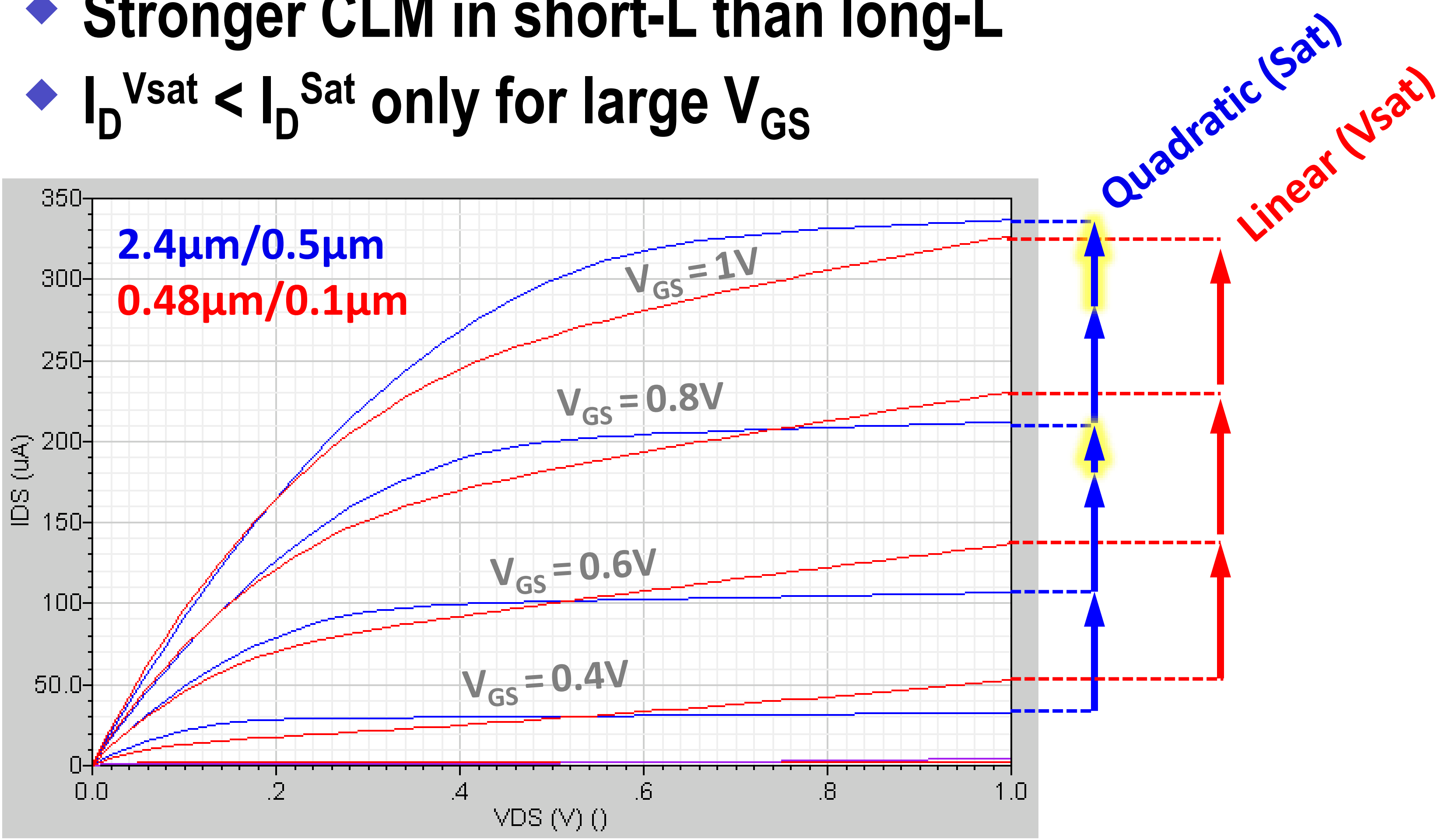
Saturation vs. Velocity Saturation

- V-Sat occurs for lower V_{DS} than Sat

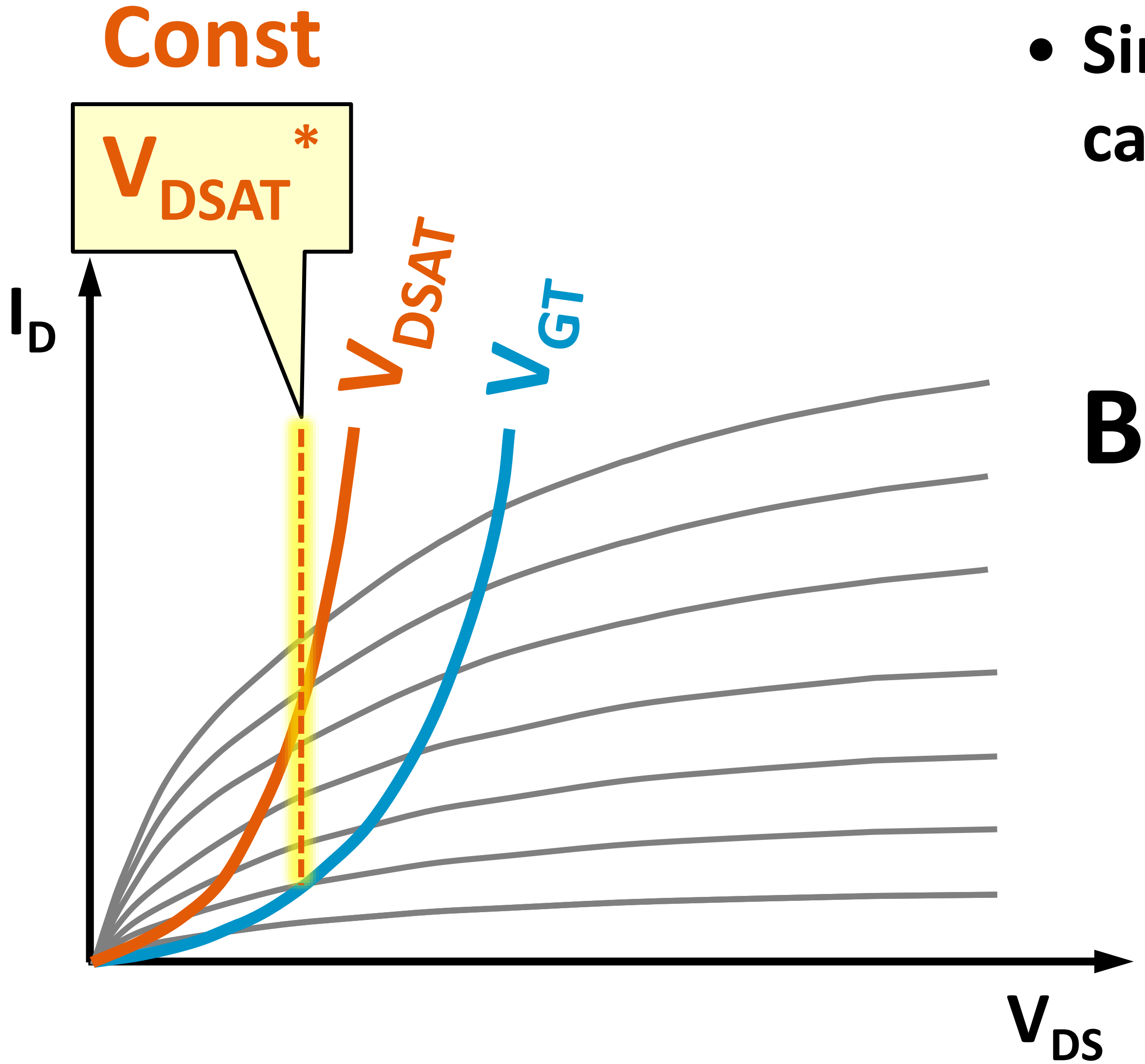


Simulation: Long vs. Short Channel (90nm)

- $I_D^{VSat}(V_{GS})$ linear, $I_D^{Sat}(V_{GS})$ quadratic
- Stronger CLM in short-L than long-L
- $I_D^{Vsat} < I_D^{Sat}$ only for large V_{GS}



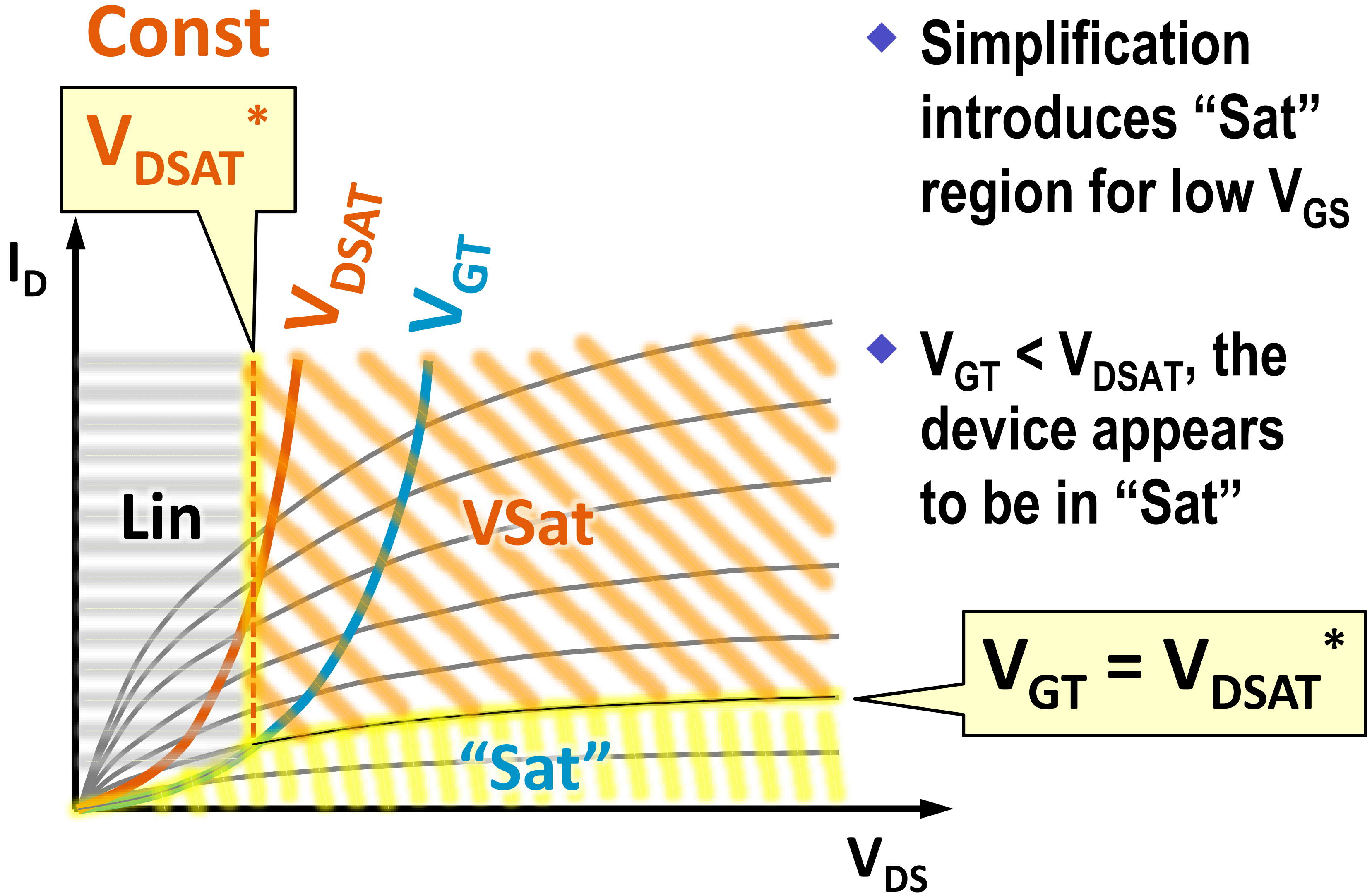
Simplification: V_{DSAT} = Constant



- **Simplifies hand calculations**

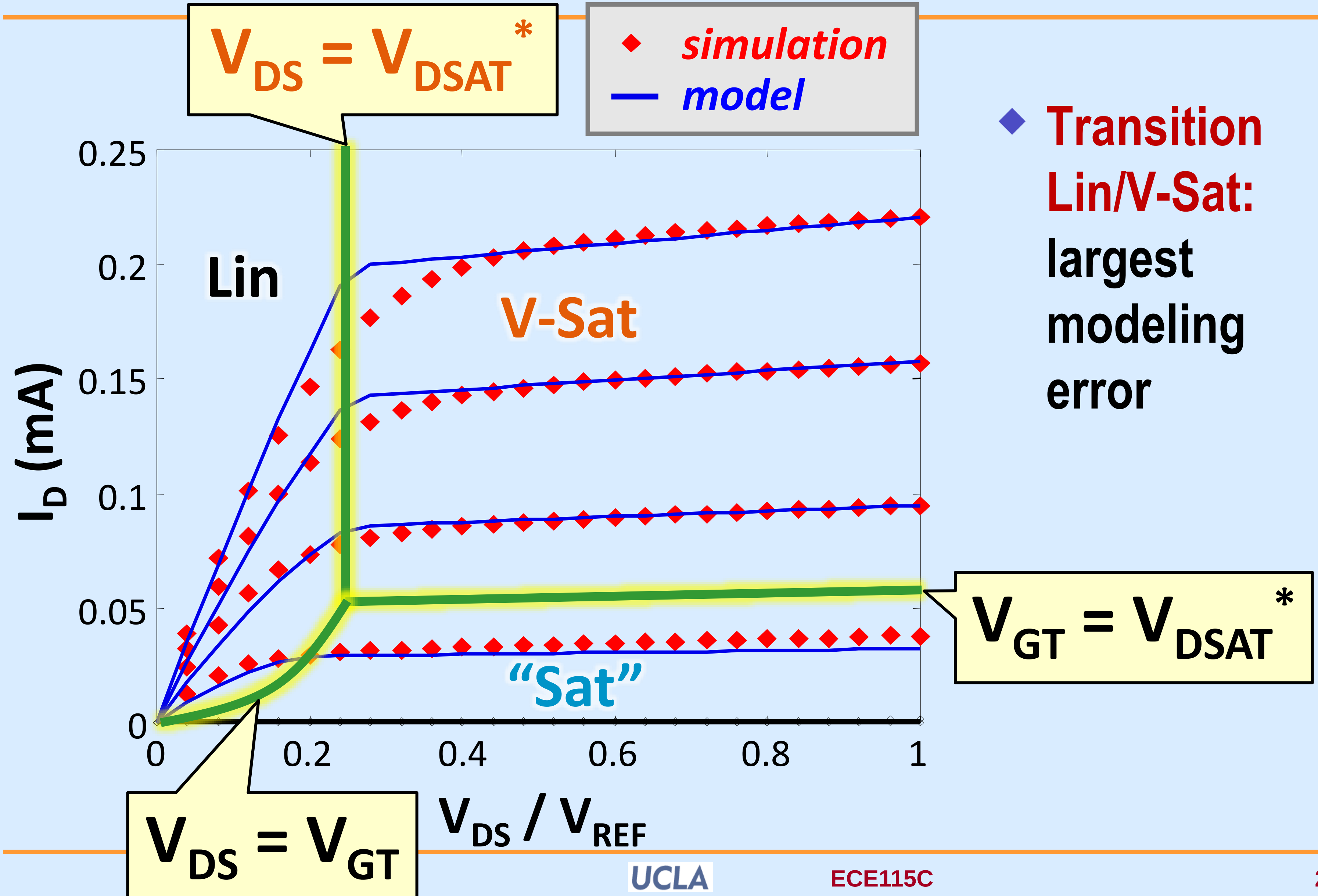
BUT…

Regions of Operation



- Simplification introduces "Sat" region for low V_{GS}
- $V_{GT} < V_{DSAT}$, the device appears to be in "Sat"

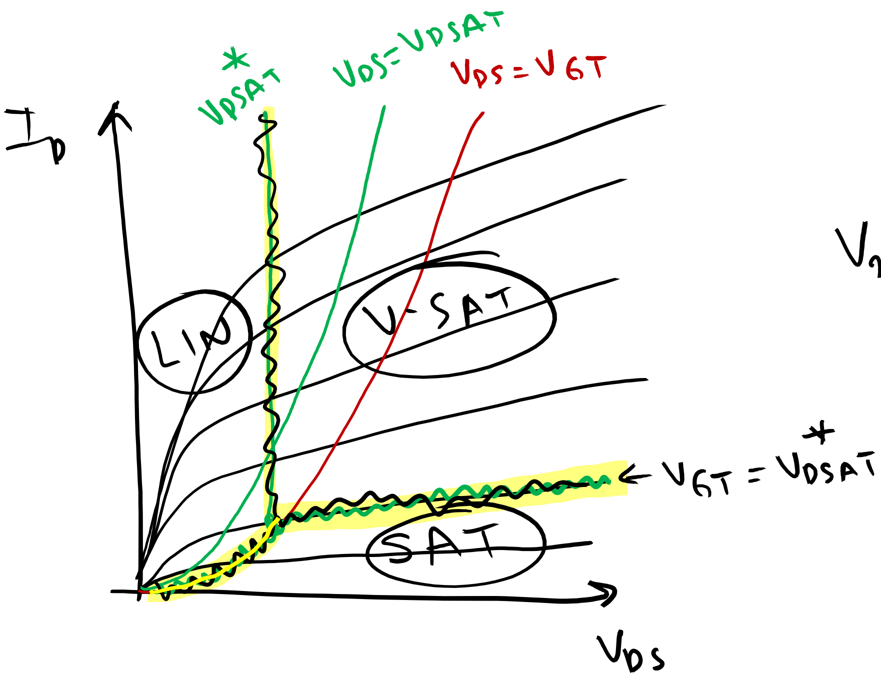
Unified Model vs. SPICE Simulation



- **Transition Lin/V-Sat:** largest modeling error

MOS Regions of Operation

- **Nano-scale MOS devices operate in velocity saturation**
  - Saturation still possible for low V_{GS} values (up to V_{DSAT})

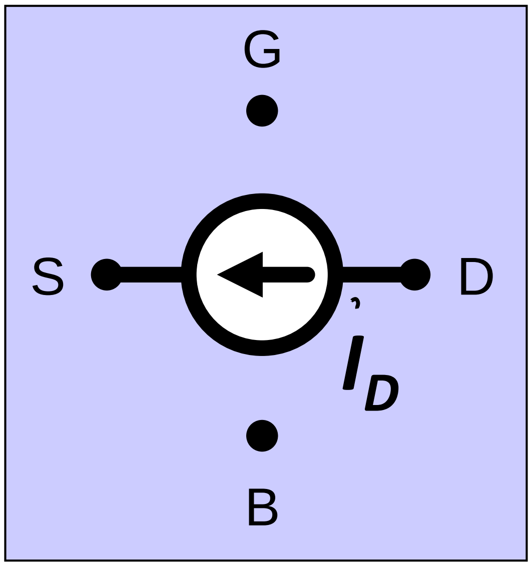


$$V_{min} = \min\{V_{GT}, V_{DS}, V_{DSAT}^*\}$$

"SAT" LIN V-SAT

MOS I-V Model: Active Region

$$V_{GT} = V_{GS} - V_T$$



Active region ($V_{GT} \geq 0$) Lin, Sat, V-Sat

$$I_D = k' \cdot \frac{W}{L} \cdot \left(V_{GT} \cdot V_{min} - \frac{V_{min}^2}{2}\right) \cdot (1 + \lambda \cdot V_{DS})$$

$$V_{min} = min(V_{DS}, V_{GT}, V_{DSAT}^{*})$$

Lin *"Sat"* *V-Sat*

Neglect CLM in linear region

Model Parameters: Active Region

V_{T0} : Threshold voltage

γ : Body effect

V_{DSAT}^{*} : Velocity saturation

k' : Transconductance ($k' = \mu \cdot C_{ox}$)

λ : Channel-length modulation (CLM)

- **CLM term $(1 + \lambda V_{DS})$ also included for linear region**
  - Empirical, no physical justification

Typical Values for 90nm

- $\varepsilon_{ox} \cdot \varepsilon_0 = 3.5 \cdot 10^{-11}$ F/m ($\varepsilon_{ox} = 3.9$)
- $t_{ox} = 2.3$ nm
- $C_{ox} = \varepsilon_{ox} / t_{ox} = 15.2$ fF/μm^2

- For W/L = 430nm/120nm
- $C_g = 0.65$ fF

$x_d = 15$ nm

- $L_{eff} = 70$ nm
- $\varepsilon_c = 4$ V/μm
- $V_{DSAT}^* = \varepsilon_c L = 0.3$ V

Unified Model: Observations

- **CLM term $(1 + \lambda V_{DS})$ also included for linear region**
  - Empirical, not grounded in physical considerations

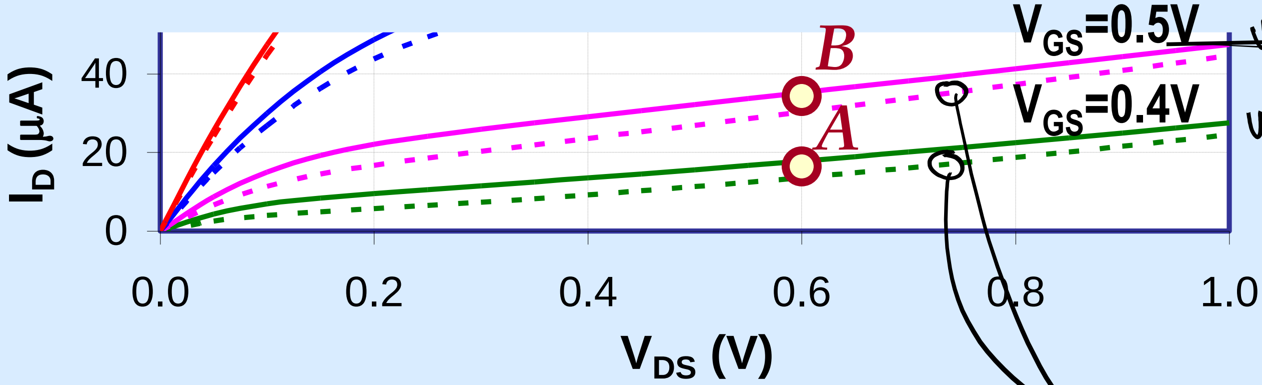
- **Five parameters: V_{T0}, γ, V_{DSAT}^{*}, k', λ**
  - Can determine from physics
  - Or choose values that best match simulation/measured data (match the best in regions that matter the most)
  - Use different model for $L >> L_{min}$ (in EE115C we assume $L = L_{min}$ unless otherwise specified)

Let's see how do we extract these parameters from the I-V curves

The Meaning of Model Parameters: V_{T0}

- **MOS in saturation**

$V_{DSAT} = 0.3V$



$V_{GT} = 0.3V$, $V_{GT} = 0.2V$ } "SAT"

with body bias ($V_{SB} > 0$)

SAT

$$\frac{I_A}{I_B} = \frac{(V_{GSA} - V_{T0})^2}{(V_{GSB} - V_{T0})^2} \Rightarrow \text{solve } \boxed{V_{T0}} \checkmark$$

The Meaning of Model Parameters: γ

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→ V_{TO} (see prev. slide)

→ V_T for known V_{SB}

$$V_T = V_{TO} + \gamma\left(\sqrt{-2\phi_F + V_{SB}} - \sqrt{|2\phi_F|}\right)$$

⟹ calc / estimate $\boxed{\gamma}$ ✓

The Meaning of Model Parameters: λ

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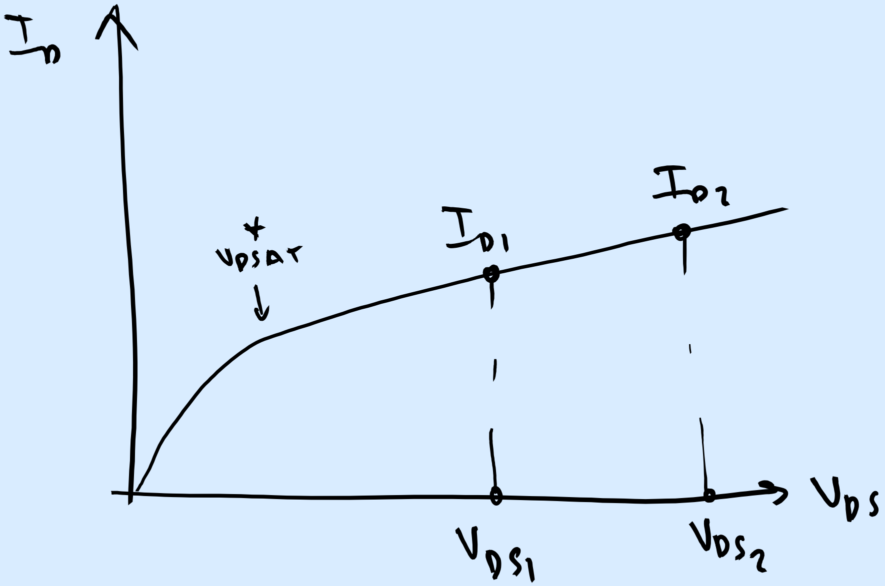

$$\frac{I_{D1}}{I_{D2}} = \frac{1+\lambda V_{DS1}}{1+\lambda V_{DS2}}$$

$\Rightarrow$ calc $\boxed{\lambda}$ ✓

The Meaning of Model Parameters: k'

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- assume V_{T0}, λ are known (from previous slides)

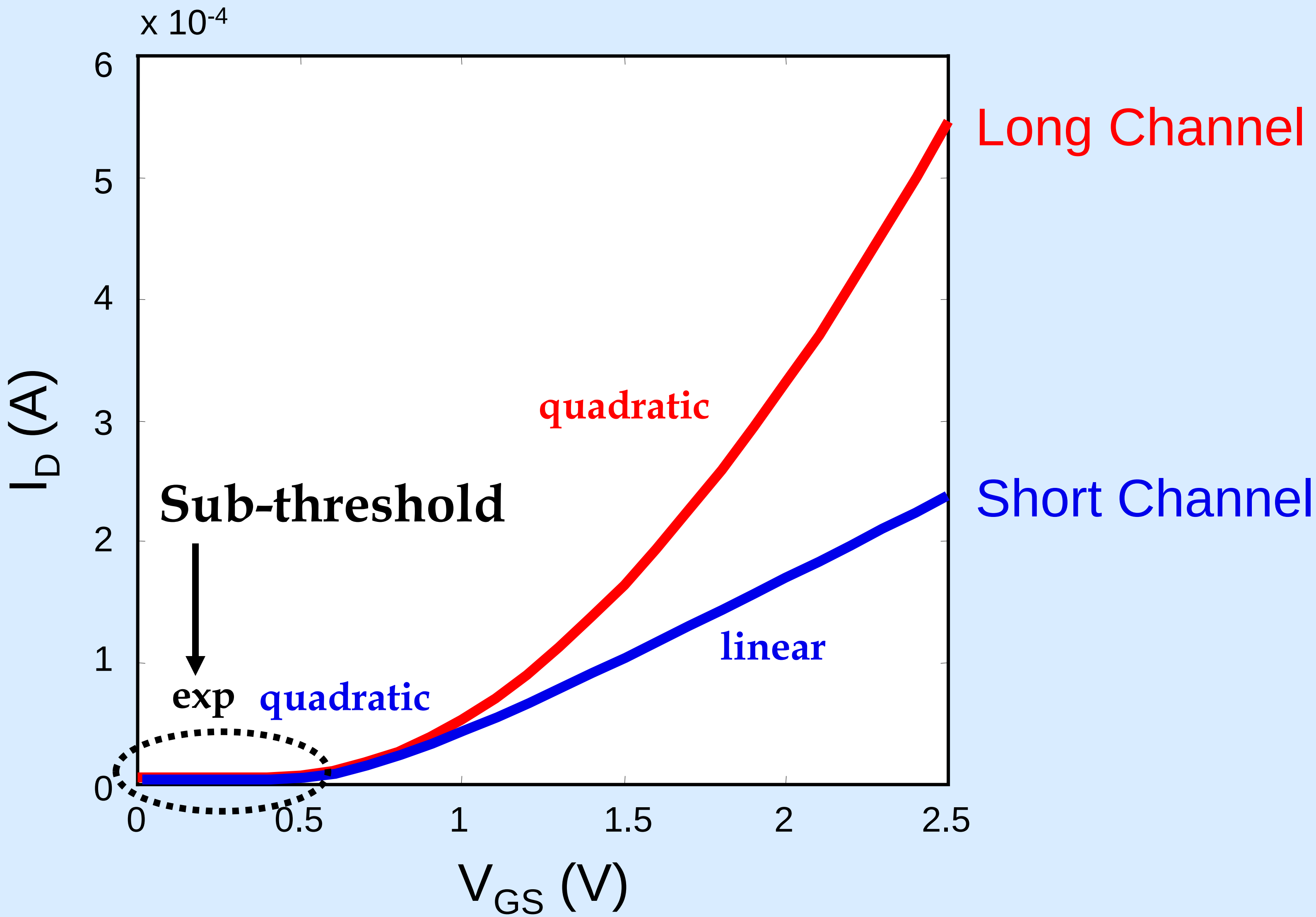
$$I_D = k' \frac{W}{L} V_{GT}^2 (1 + \lambda V_{DS})$$

$$\Rightarrow \boxed{k'} \checkmark$$

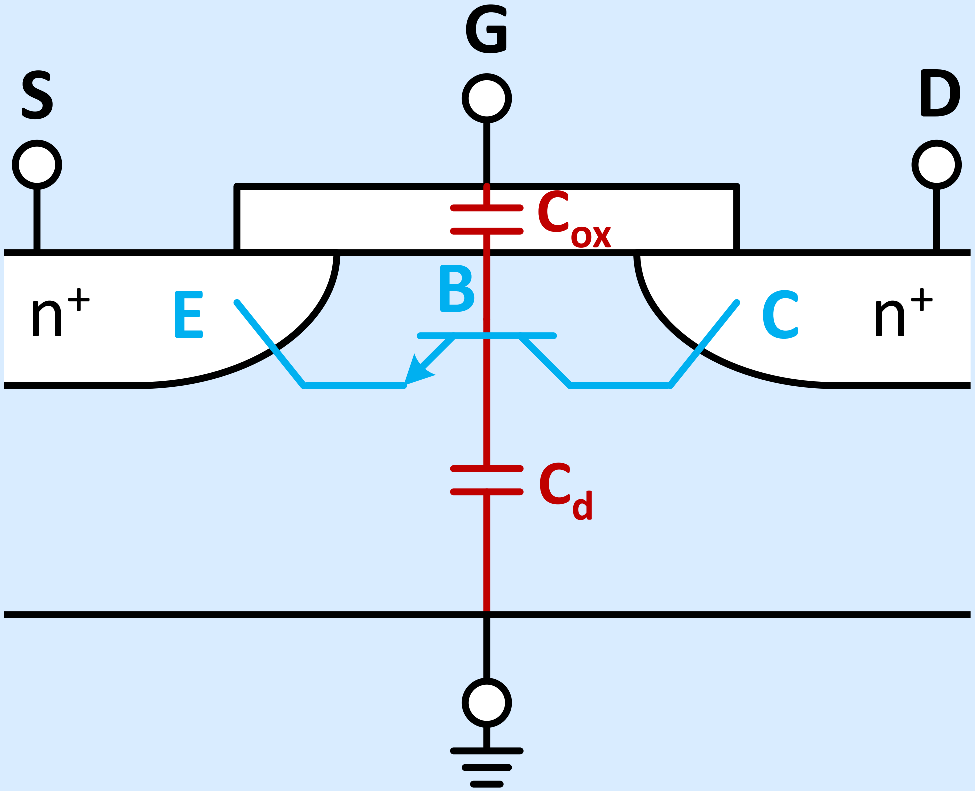
Sub-threshold Current

- **This is another topic of crucial importance in digital design (and not considered in EE115A/100 models)**
  - We need to consider sub-threshold current, because digital designs have many billions of transistors and when these are inactive, we may get some "surprise" power consumption

Sub-threshold I_D versus V_{GS} is Exponential (189)



Modeling the Sub-threshold Behavior



Parasitic BJT

$$I_C = I_0 e^{\frac{V_{BE}}{\Phi_t}}$$

$$V_{BE} = \frac{V_{GS}}{1 + \frac{C_d}{C_{ox}}}$$

$$n = 1 + \frac{C_d}{C_{ox}}$$

$$\Phi_t = \frac{kT}{q}$$

$$I_D = I_0 \cdot e^{\frac{V_{GS}}{n\Phi_t}} \cdot \left(1 - e^{-\frac{V_{DS}}{\Phi_t}}\right)$$

Sub-threshold I_D vs. V_{GS}

Physical model

$$I_D = I_0 \cdot \frac{W}{W_0} \cdot e^{\frac{V_{GS}}{n\Phi_t}} \cdot \left(1 - e^{-\frac{V_{DS}}{\Phi_t}}\right)$$

$$I_0 = \underbrace{\mu \frac{W_0}{L} \Phi_t^{\,2}}_{I_0'} e^{-\frac{V_T}{n\Phi_t}}$$

Empirical model

$$I_D = I_0' \cdot \frac{W}{W_0} \cdot 10^{\frac{V_{GS} - V_T + \overbrace{\gamma_D V_{DS}}^{\text{DIBL}}}{S}}$$

$$S = n\Phi_t \ln(10) \quad [\text{mV/dec}]$$

The Sub-threshold Slope Parameter

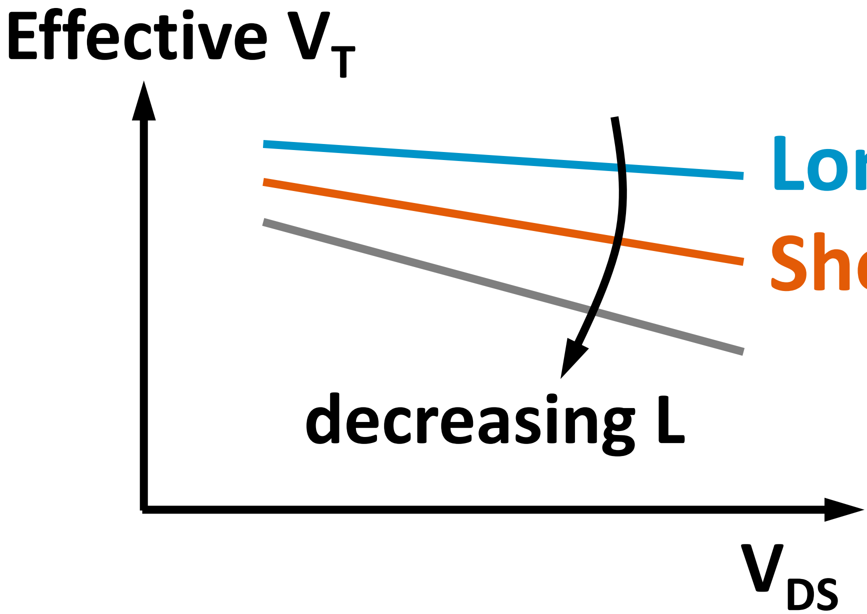
$$S = n\Phi_t \ln(10)$$ [mV/dec]

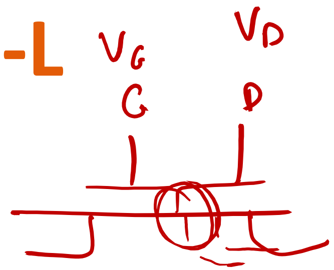
Change in V_{GS} that gives 10x change in I_{DS}

- n = 1 — 60 mV/dec — (ideal)
- n = 1.5 — 90 mV/dec — (typical)

- **S:** increases with temperature (Φ_t)
- **n:** intrinsic to device topology / structure

Drain Induced Barrier Lowering (DIBL)

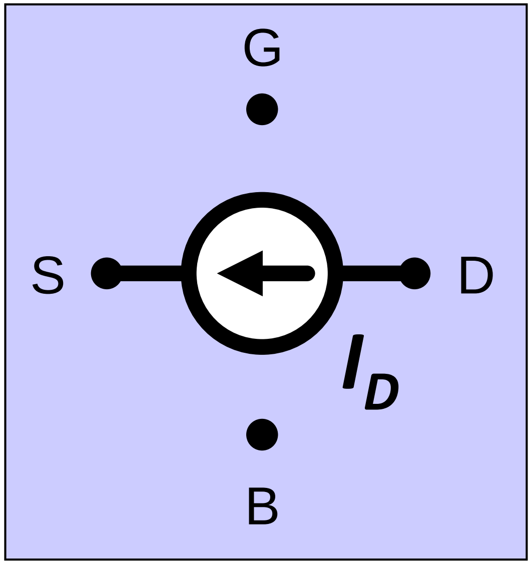




- **Field lines from the drain affect charge in the channel**
- **Typically derived for small V_{DS}, holds for large V_{DS}**
  - Even if we neglect CLM, I_{DS} will increase b/c of V_T drop
  - Device turned off by V_{GS} (below V_T) may turn on by V_{DS}

MOS I-V Model: Subthreshold

$$V_{GT} = V_{GS} - V_T$$



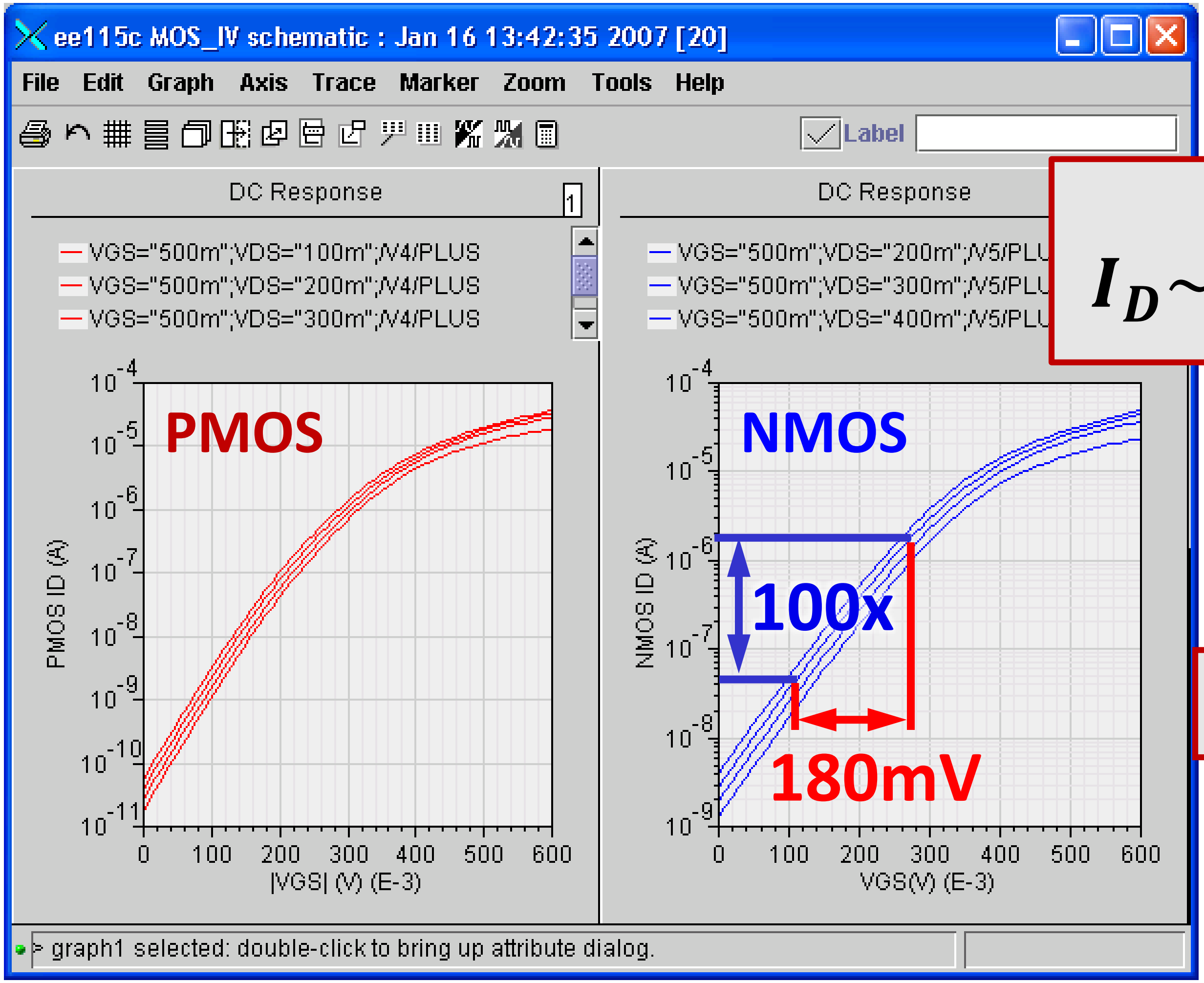
Subthreshold region ($V_{GT} \leq 0$)

$$I_D = I_0' \cdot \frac{W}{W_0} \cdot 10^{\frac{V_{GS} - V_T + \gamma_D \cdot V_{DS}}{S}}$$

Model parameters

- I_0' : Nominal leakage current
- S : Subthreshold slope
- γ_D : DIBL factor

90nm Simulation: Sub-threshold I_D vs. V_{GS}



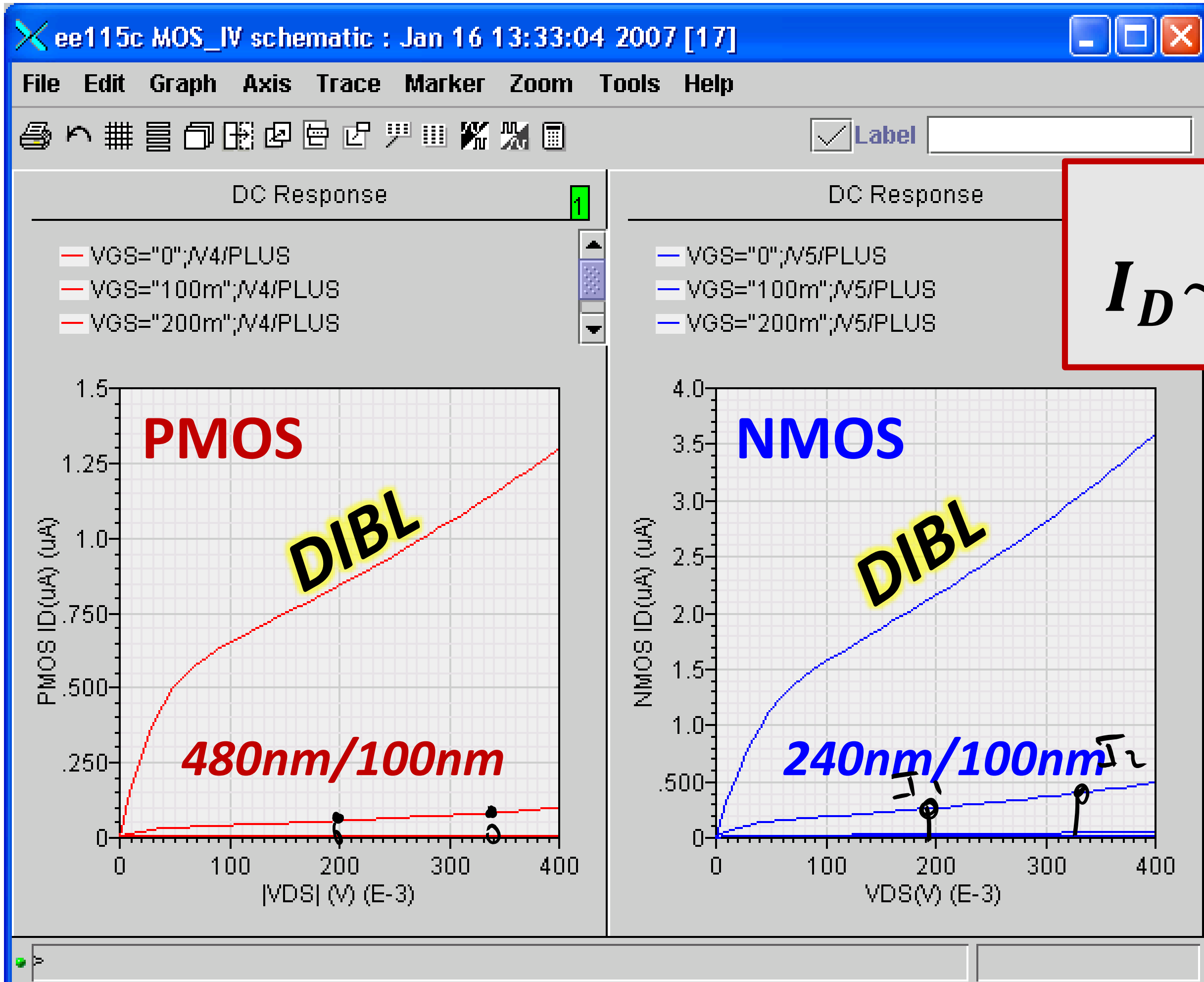
$$I_D \sim 10^{\frac{V_{GS}-V_T+\gamma_D V_{DS}}{S}}$$

V_{DS} : 0 to 0.4V

$$S = n\Phi_t \ln(10)$$

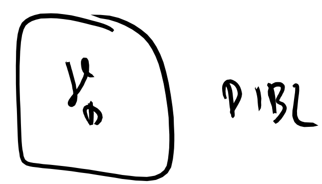
90mV/dec

90nm Simulation: Sub-threshold I_D vs. V_{DS}



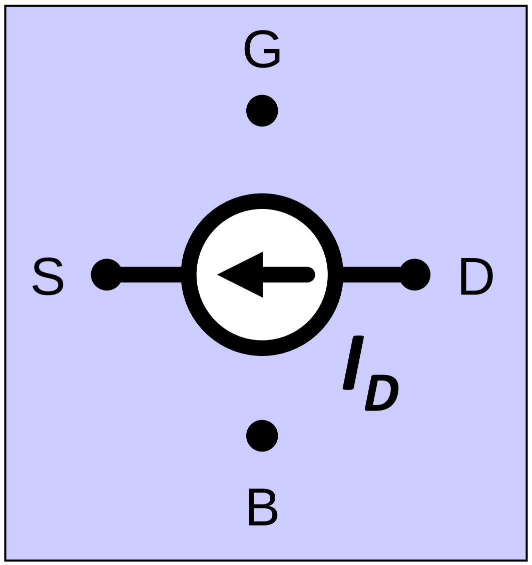
$$I_D \sim 10^{\frac{V_{GS}-V_T+\gamma_D V_{DS}}{S}}$$

V_{GS} : 0 to 0.3V



MOS I-V Model: Summary

$$V_{GT} = V_{GS} - V_T$$



Subthreshold region ($V_{GT} \leq 0$)

$$I_D = I_0' \cdot \frac{W}{W_0} \cdot 10^{\frac{V_{GS} - V_T + \gamma_D \cdot V_{DS}}{S}}$$

Active region ($V_{GT} \geq 0$) Lin, Sat, V-Sat

$$I_D = k' \cdot \frac{W}{L} \cdot \left(V_{GT} \cdot V_{min} - \frac{V_{min}^2}{2}\right) \cdot (1 + \lambda \cdot V_{DS})$$

$$V_{min} = min(V_{DS}, V_{GT}, V_{DSAT}{}^*)$$

Lin *"Sat"* *V-Sat*

.MODEL Parameters MOS1 (Basic Parameters)

- **.MODEL Modname NMOS/PMOS <VT0=*VT0*…>**

Name	Parameter	Units	Default	Example	Scale Factor
VTO	Threshold voltage	V	0	1.0	—
KP	Transconductance parameter	AV^{-2}	2.0×10^{-5}	1.0E-3	—
GAMMA	Bulk threshold parameter	$V^{1/2}$	0	0.5	—
PHI	Surface potential	V	0.6	0.7	—
LAMBDA	Channel length modulation parameter	V^{-1}	0	1.0E-4	—
RD	Drain ohmic resistance	Ω	0	10	—
RS	Source ohmic resistance	Ω	0	10	—
RSH	D and S diffusion sheet resistance	Ω/sq	0	10	*NRD* *NRS*
CBD	Zero-bias BD junction capacitance	F	0	5P	—
CBS	Zero-bias BS junction capacitance	F	0	1P	—
CJ	Zero-bias bulk junction bottom capacitance	Fm^{-2}	0	2.0E-4	*AD* *AS*
MJ	Bulk junction grading coefficient	—	0.5	0.5	
CJSW	Zero-bias bulk junction sidewall capacitance	Fm^{-1}	0	1.0E-9	*PD* *PS*
MJSW	Bulk junction grading coefficient	—	0.33	0.25	
PB	Bulk junction potential	V	1	0.6	
IS	Bulk junction saturation current	A	10^{-14}	1.0E-16	
CGDO	GD overlap capacitance per unit channel width	Fm^{-1}	0	4.0E-11	*W*
CGSO	GS overlap capacitance per unit channel width	Fm^{-1}	0	4.0E-11	*W*
CGBO	GB overlap capacitance per unit channel length	Fm^{-1}	0	2.0E-10	*L*
TOX	Thin-oxide thickness	m	∞	0.1U	
LD	Lateral diffusion	m	0	0.2U	

In Reality: GPDK090 Model (gpdk090_mos.scs)

```
section TT_s1v
parameters
+   s1v_rs_ne =     0.000000e+000   s1v_vsat_ne =    1.120000e+005   s1v_pldd_surf =   6.000000e+019
+   s1v_uc1_ne =    3.700000e-010   s1v_u0_ne =      2.000000e-002   s1v_nch_ne =      5.200000e+017
+   s1v_rsc_ne =    4.082483e-014   s1v_cgbo_ne =    1.482000e-011   s1v_prt_ne =      1.000000e+001
+   s1v_rdc_ne =    4.082483e-014   s1v_vth0_ne =    1.692662e-001   s1v_k2_ne =       0.000000e+000
+   s1v_cgdo_ne =   2.667600e-010   s1v_ckappa_ne =4.605336e+000     s1v_wint_ne =     6.000000e-009
+   s1v_k1_ne =     2.825346e-001   s1v_cgsl_ne =    1.111500e-010   s1v_nldd_surf =   3.000000e+019
+   s1v_js_ne =     3.366667e-006   s1v_hdif_ne =    1.400000e-007   s1v_rdsw_ne =     3.900000e-006
+   s1v_jsw_ne =    3.366667e-010   s1v_tox_ne =     2.330000e-009   s1v_cj_ne =       7.983537e-004
+   s1v_cjsw_ne =   4.790122e-011   s1v_ldif_ne =    1.000000e-008   s1v_xj_ne =       2.500000e-008
+   s1v_rd_ne =     0.000000e+000   s1v_pb_ne =      9.918524e-001   s1v_cf_ne =       4.594612e-011
+   s1v_lint_ne =   1.500000e-008   s1v_cjswg_ne =   1.995884e-011   s1v_rsh_ne =      1.000000e+001
+   s1v_u0_pe =     1.200000e-002   s1v_nch_pe =     4.000000e+017   s1v_rsc_pe =      2.886751e-014
+   s1v_cgbo_pe =   1.392363e-011   s1v_rdc_pe =     2.886751e-014   s1v_vth0_pe =     -1.359511e-001
+   s1v_k2_pe =     0.000000e+000   s1v_cgdo_pe =    2.506253e-010   s1v_ckappa_pe =   1.043477e+001
+   s1v_wint_pe =   5.000000e-009   s1v_k1_pe =      2.637520e-001   s1v_cgsl_pe =     1.044272e-010
+   s1v_js_pe =     3.350000e-006   s1v_hdif_pe =    1.400000e-007   s1v_rdsw_pe =     7.800000e-006
+   s1v_jsw_pe =    3.350000e-010   s1v_tox_pe =     2.480000e-009   s1v_cj_pe =       7.912252e-004
+   s1v_cjsw_pe =   4.747351e-011   s1v_ldif_pe =    1.000000e-008   s1v_xj_pe =       2.500000e-008
+   s1v_rd_pe =     0.000000e+000   s1v_pb_pe =      1.009805e+000   s1v_cf_pe =       4.527118e-011
+   s1v_lint_pe =   1.500000e-008   s1v_cjswg_pe =   1.978063e-011   s1v_rsh_pe =      2.000000e+001
+   s1v_rs_pe =     0.000000e+000   s1v_vsat_pe =    1.000000e+005
include "gpdk090_mos.scs" section = s1v_mos
endsection TT_s1v
```

This model continues on the next slide

GPDK090 Model (section s1v_mos)

```
section s1v_mos
model gpdk090_nmos1v bsim3v3 type = n
+   lmin =    0.0              lmax =    1.0              wmin =       0.0
+   wmax =    1.0              tnom =    25.0             version =    3.2
+   tox =     s1v_tox_ne       toxm =    s1v_tox_ne       xj =         s1v_xj_ne
+   nch =     s1v_nch_ne       lln =     1.0000000        lwn =        1.0000000
+   wln =     1.0000000        wwn =     -1.0000000       lint =       s1v_lint_ne
+   ll =      0.00             lw =      0.00             lwl =        0.00
+   wint =    s1v_wint_ne      wl =      0.00             ww =         0.00
+   wwl =     0.00             mobmod =  1                binunit =    2
+   xl =      0                xw =      0                dwg =        0.00
+   dwb =     0.00             acm =     12               ldif =       s1v_ldif_ne
+   hdif =    s1v_hdif_ne      rsh =     s1v_rsh_ne       rd =         s1v_rd_ne
+   rs =      s1v_rs_ne        rsc =     s1v_rsc_ne       rdc =        s1v_rdc_ne
+   vth0 =    s1v_vth0_ne      k1 =      s1v_k1_ne        k2 =         s1v_k2_ne
+   k3 =      -2.3000000       dvt0 =    3.86366          dvt1 =       1.2
+   dvt2 =    5.0299990E-02    dvt0w =   0.00             dvt1w =      0.00
+   dvt2w =   0.00             nlx =     1.2517999E-07    w0 =         -7.1353000E-09
+   k3b =     0.5576769        ngate =   4.0E20           vsat =       s1v_vsat_ne
+   ua =      -6.1879500E-10   ub =      1.8806652E-18    uc =         1.3823546E-10
+   rdsw =    s1v_rdsw_ne      prwb =    0.00             prwg =       0.00
+   wr =      1.0000000        u0 =      s1v_u0_ne        a0 =         2.3750000
+   keta =    -3.1429991E-02   a1 =      0.00             a2 =         0.9900000
+   ags =     0.8900000        b0 =      0.00             b1 =         0.00
```

And many more parameters… (compare to our 5-parameter model)

Spectre Netlist (NMOS, PMOS)

```
section s1v_mac
subckt s1v_ckt_nch (n11 n2 n33 n4)
parameters l=0.1u w=10u multi=1 factor=1 nrd=s1v_hdif_ne/factor/w nrs=s1v_hdif_ne/factor/w
+ Tox_ratio = 3.0e-9 / (s1v_tox_ne*s1v_tox_ne*s1v_tox_ne)
MAIN (n1 n2 n3 n4) gpdk090_nmos1v w=w l=l nrd=nrd nrs=nrs multi=multi
GDF1 (n2 n1) bsource i = w*0.6*s1v_xj_ne*4.97232*Tox_ratio*v(n2,n1)*v(n2,n3)*exp(-4.85669e11*s1v_tox_ne*…
GDF2 (n2 n3) bsource i = w*0.6*s1v_xj_ne*4.97232*Tox_ratio*v(n2,n3)*sqrt( (v(n2,n3) - 0.026*log(4.0e20 …
20 / s1v_nldd_surf)) + 1.0e-4 )*exp(-4.85669e11*s1v_tox_ne*(0.43-0.054*sqrt( (v(n2,n3) - 0.026*log(4.0e20 …
.0e20 / s1v_nldd_surf)) + …- 0.026*log(4.0e20 / s1v_nldd_surf))*(v(n2,n3) …s1v_nldd_surf)) + 1.0e-4 )))
rdn (n1 n11) resistor r= 6.8 *nrd/multi
rsn (n3 n33) resistor r= 6.8 *nrs/multi
ends s1v_ckt_nch

subckt s1v_ckt_pch (p11 p2 p33 p4)
parameters l=0.1u w=10u multi=1 factor=1 nrd=s1v_hdif_pe/factor/w nrs=s1v_hdif_pe/factor/w
+ Tox_ratio = 3.0e-9/(s1v_tox_pe*s1v_tox_pe*s1v_tox_pe)
MAIN (p1 p2 p3 p4) gpdk090_pmos1v w=w l=l nrd=nrd nrs=nrs multi=multi
GDF1 (p2 p1) bsource i = w*0.6*s1v_xj_pe*3.42537*Tox_ratio*v(p2, p1)*sqrt( (v(p2, p1)-
      0.026*log(9.32E19/s1v_pldd_surf))*(v(p2, p1)-0.026*log(9.32E1
9/s1v_pldd_surf)) + 1.0e-4 )*exp(-7.0645e11*s1v_tox_pe*(0.31-0.024*sqrt( (v(p2, p1)-
      0.026*log(9.32E19/s1v_pldd_surf))*(v(p2, p1)-0.026*log(9.32E19… s1v_pldd_surf)) + 1.0e-4 ))*(1.0+0.03*sqrt( (v(p2, p1)-
      0.026*log(9.32E19/s1v_pldd_surf))*(v(p2, p1)-0.026*log(9.32E19/s1v_pldd_surf)) + 1.0e-4 )))
GDF2 (p2 p3) bsource i = w*0.6*s1v_xj_pe*3.42537*Tox_ratio*…sqrt( (v(p2, p3)-…0.026*log(9.32E19/…)) + 1.0e-4 )))
rdp (p1 p11) resistor r = 7.1 * nrd / multi
rsp (p3 p33) resistor r = 7.1 * nrs / multi
ends s1v_ckt_pch
endsection s1v_mac
```

Technology Scaling

- **Scaling parameters**
  - Geometry: W, L, t_{ox}
  - Voltage: V_{DD}, V_T
- **Constant voltage**
  - Scale only geometry by S (~1.4)
- **Constant electric field**
  - Scale geometry and voltage by S (~1.4)
- **General**
  - Scale geometry by S
  - Scale voltage by U
  - S > U