A Simplified Methodology for the Extraction of Parameters of the ACM MOST Model

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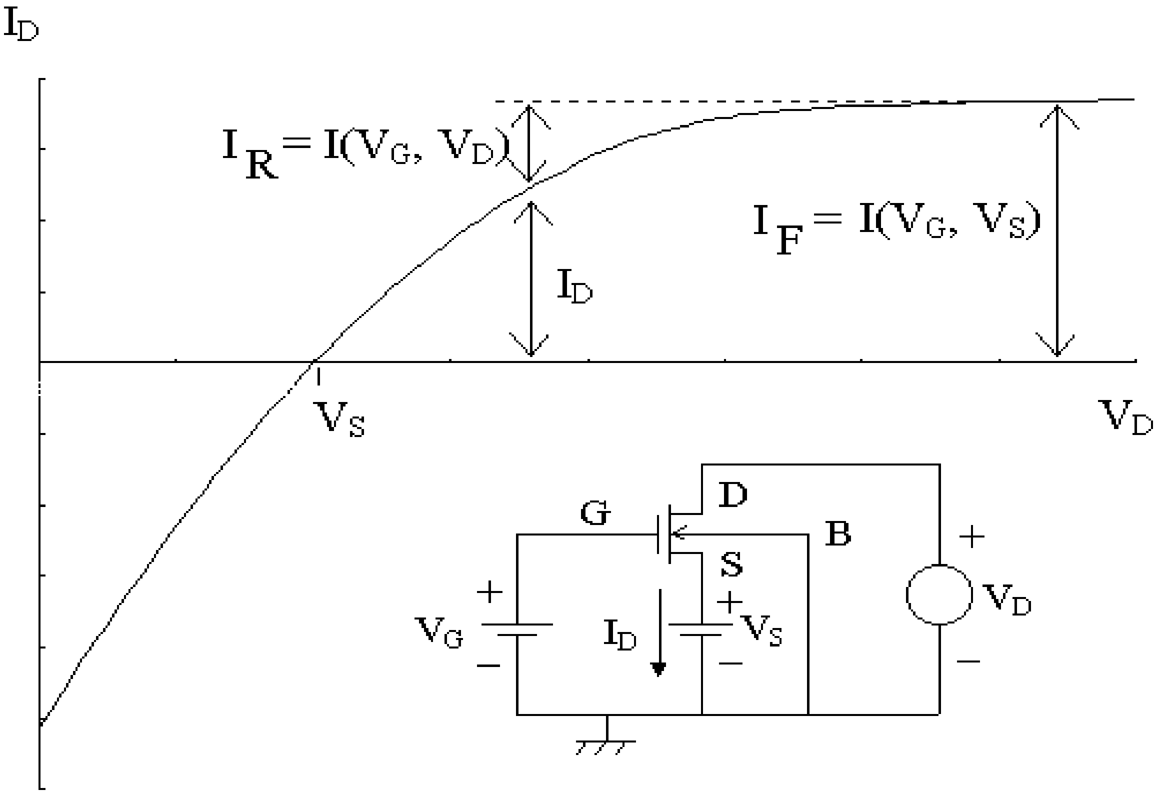
ACM MODEL
ADVANCED **C**OMPACT **M**OSFET MODEL

- √ A physically based MOSFET model
- √ Accurate in all regions of operation
- √ Source-to-drain intrinsic symmetry
- √ Charge conservation
- √ Small set of parameters

MOS transistor modeling

Forward and reverse currents: $I_D = I_F - I_R = I(V_G, V_S) - I(V_G, V_D)$



For large V_D, $I_R \rightarrow 0$; therefore, $I_D = I_F - I_R \cong I_F$

The current-based model $I_D = I_F - I_R$ **or** $I_D = I_S(i_f - i_r)$

where: $I_S = I_{SQ}\dfrac{W}{L}$ $I_{SQ} = \mu n C'_{ox}\dfrac{\phi_t^2}{2}$

$I_{F(R)}$: forward (reverse) current

$i_{f(r)}$: inversion level at source (drain)

I_S: specific (normalization) current

I_{SQ}: specific (normalization) sheet current is weakly dependent on V_G [$\mu(V_G)$, $n(V_G)$] $\Rightarrow$ I_{SQ} is a technological parameter

All large- and small-signal parameters can be written in terms of i_f and i_r $\Rightarrow$current-based model, appropriate for electrical characterization, hand analysis and design

The I x V relationship

$$V_P - V_{S(D)} = \phi_t \left[\sqrt{1+i_{f(r)}} - 2 + \ln\left(\sqrt{1+i_{f(r)}} - 1\right)\right] \qquad V_P \cong \frac{V_G - V_{T0}}{n}$$

a) weak inversion: $i_{f(r)} << 1$ $\quad V_P - V_{S(D)} \cong \phi_t \left[-1 + \ln\left(\frac{i_{f(r)}}{2}\right)\right] \Rightarrow$

$$I_D \cong 2I_S \exp\left(\frac{V_G - V_{T0} - nV_S}{n\phi_t} + 1\right)\left[1 - \exp\left(-\frac{V_{DS}}{\phi_t}\right)\right]$$

b) strong inversion at source and drain: $i_{f(r)} >> 1$

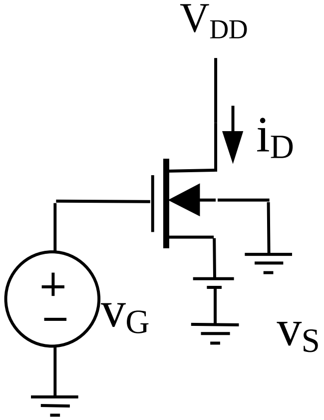
$$I_D \cong \frac{\mu n C'_{ox}}{2} \frac{W}{L}\left[(V_P - V_S)^2 - (V_P - V_D)^2\right]$$

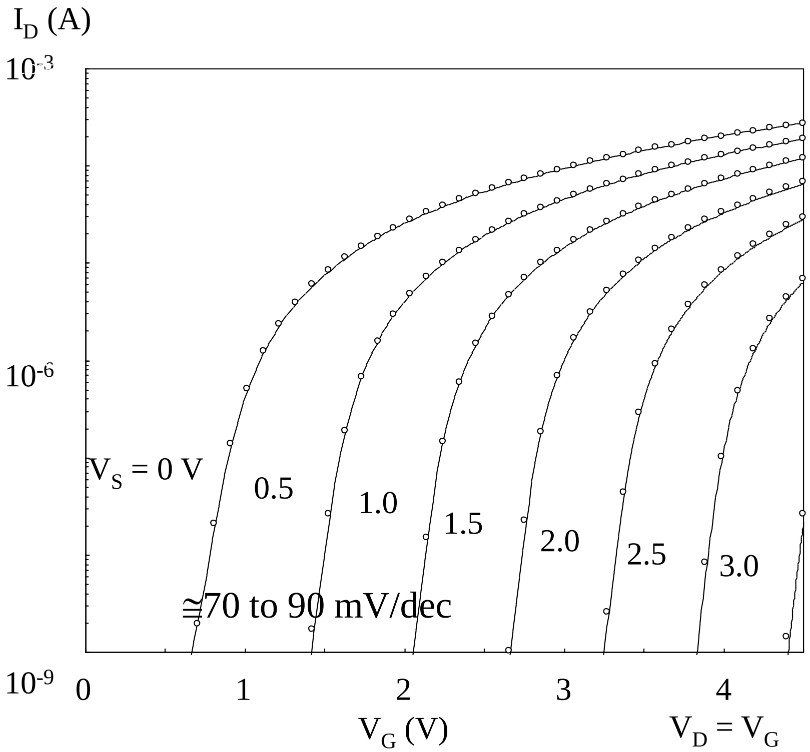
c) forward saturation: $i_f >> i_r \Rightarrow I_D$ is (almost) independent of V_D

c1) weak inversion: $I_D \cong 2I_{SQ} \frac{W}{L} \exp\left(\frac{V_G - V_{T0} - nV_S}{n\phi_t} + 1\right)$

c2) strong inversion $I_D \cong \frac{\mu C'_{ox}}{2n} \frac{W}{L}(V_G - V_{T0} - nV_S)^2 = I_{SQ} \frac{W}{L}\left(\frac{V_G - V_{T0} - nV_S}{n\phi_t}\right)^2$

Common-source characteristics of NMOS transistor in saturation





t_{ox} = 280 Å, W= L = 25 μm, V_{DD}=5V

(——) ACM model (o) experimental

Second order effects

- Drain-induced barrier lowering → V_T depends on both V_D and V_S

$$\hat{V}_{T0} = V_{T0} - \sigma(V_S + V_D)/2 \qquad \sigma = \mathrm{SIGMA}/L_{eff}^2$$

- Channel length modulation

$$\Delta L = \mathrm{PCLM} \cdot L_C \cdot \ln\left(1 + \frac{V_{DS} - V_{DS,SAT}}{L_C \mathrm{UCRIT}}\right)$$

- Mobility reduction due to transversal field

$$\mu = \frac{\mu_o}{1 + \theta(V_{GS} - V_{T0})}$$

- Velocity saturation

$v_{lim} = 5x10^6$ to $2x10^7$cm/s

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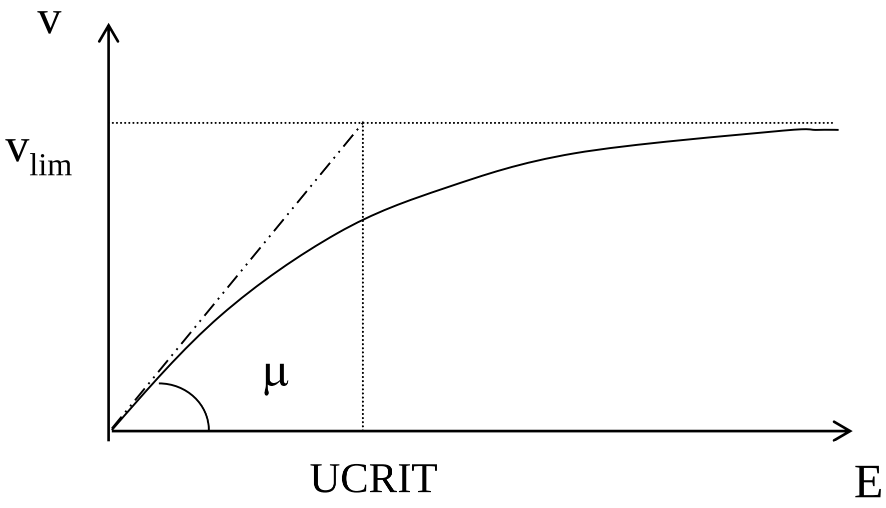


ACM Parameters

Parameter	Description	Units
VTO	Zero-bias threshold voltage	V
GAMMA	Body-effect parameter	$V^{1/2}$
PHI	Surface potential	V
TOX	Gate oxide thickness	m
LD	Lateral diffusion	m
XJ	Junction depth	m
UO	Low-field mobility	cm^2/Vs
VMAX	Saturation velocity	m/s
THETA	Mobility reduction parameter	V^{-1}
SIGMA	Drain-induced barrier lowering parameter	m^2
PCLM*	Channel length modulation parameter	-

*LAMBDA in a previous version of the ACM model

Mapping BSIM to ACM

ACM Parameter	BSIM 3V3 Parameter	Equation for determining the ACM parameter	Unit
VT0	VTH0	—	V
GAMMA	—	$\mathrm{GAMMA} = \frac{(2 \cdot \varepsilon_{SI} \cdot q \cdot NCH)^{1/2}}{C_{ox}}$	$V^{1/2}$
PHI	—	$\mathrm{PHI} = 2 \cdot \phi_t \cdot \ln\left(\frac{NCH}{n_i}\right)$	V
TOX	TOX	—	m
LD	DLC	—	m
XJ	XJ	—	m
U0	U0	—	$cm^2/V \cdot s$
VMAX	VSAT	—	m/s
THETA	—	$\mathrm{THETA} = \frac{UA}{TOX} + \frac{UB}{TOX^2} \cdot \left[\frac{(VDD - 2 \cdot V_{T0})}{(V_{DD} + V_{T0})^2 - (3 \cdot V_{T0})^2}\right]$	V^{-1}
SIGMA	—	$\mathrm{SIGMA} = \theta_{DIBL} \cdot ETA0 \cdot (L_{eff})^2$	m^2
PCLM	PCLM	—	—

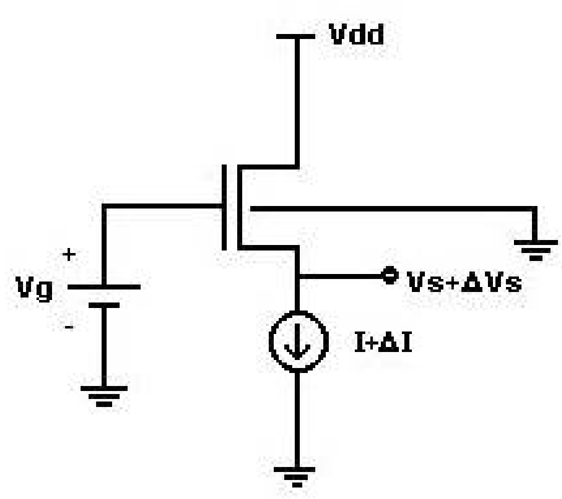
Strategy for parameter extraction:

- Parameters derived from device physics
- Bias the MOSFET in a region where the parameter to be extracted has significant effects
- Avoid “optimization”

If a parameter is difficult to extract, then its effects are not important

• Extraction of I_S (strong inversion $I>>I_S$)

Strong inversion & saturation $$I \cong I_S\left(\frac{V_G - V_{T0} - nV_S}{n\phi_t}\right)^2$$



$$I_S \cong I\times\left(\frac{\Delta I/I}{2\times\Delta V_S/\phi_t}\right)^2$$

$I=40\mu A$

$\Delta I=4\mu A$

$\Delta V_S/\phi_t=0.57$

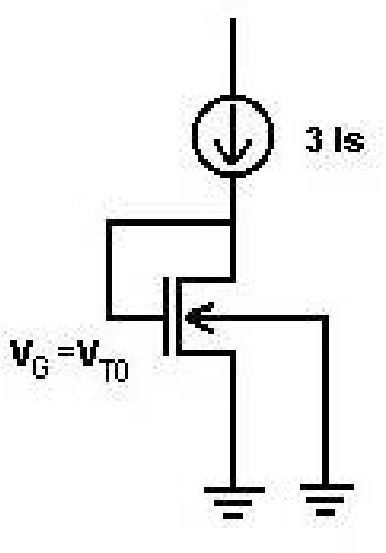
$\Rightarrow$ $\boxed{I_S = 310nA}$

A more accurate method, based on the g_m/I_D characteristic, can be used to determine I_S

- **Extraction of V_{T0}**

ACM Model:

$$V_P - \underset{0}{\cancel{V_S}} = \phi_t \left[\sqrt{1+i_f} - 2 + \ln\left(\sqrt{1+i_f} - 1 \right) \right] \qquad V_P \cong \frac{V_G - V_{T0}}{n}$$

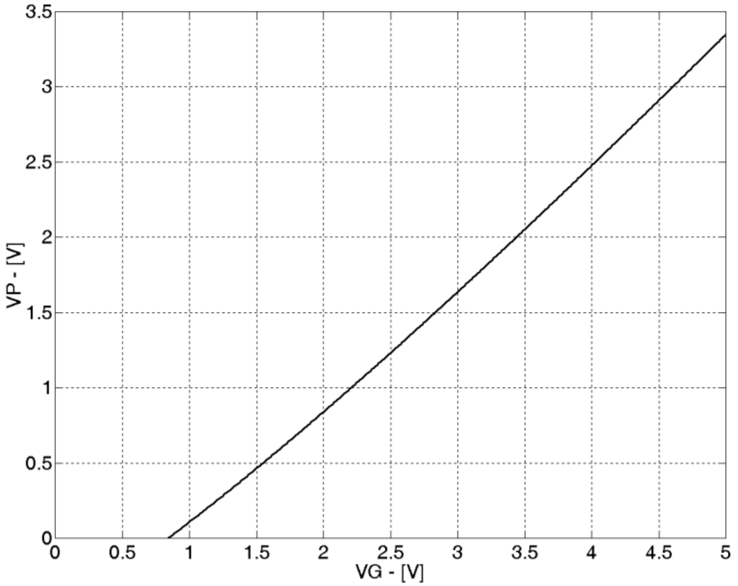


$$i_f = 3 \Longrightarrow V_G = V_{T0}$$

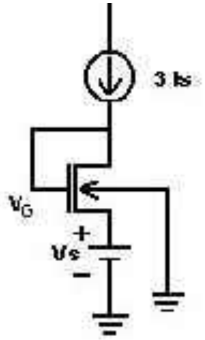
$$I = 3 \cdot I_S \Longrightarrow V_G = V_{T0}$$

$$\boxed{V_{TO} = 0.845\ \text{V}}$$

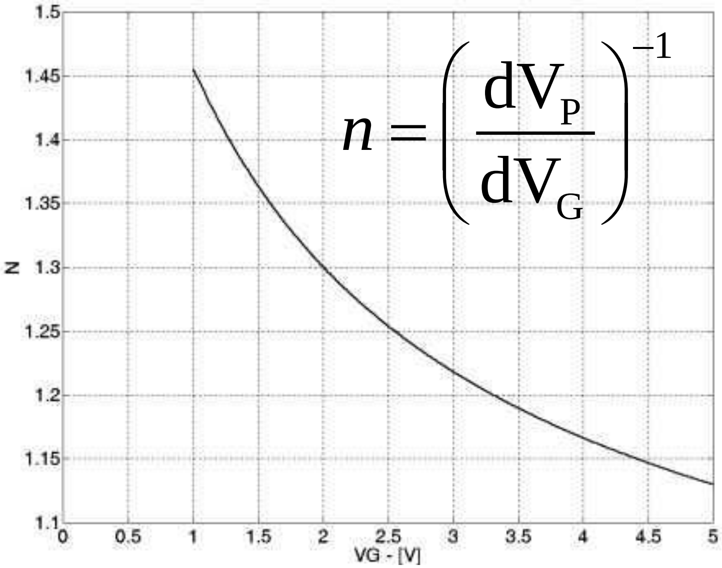
- Extraction of V_P



$$I = 3I_S$$



- Extraction of *n*



$$n = \left(\frac{\mathrm{d}V_P}{\mathrm{d}V_G} \right)^{-1}$$

- Calculation of GAMMA (γ)

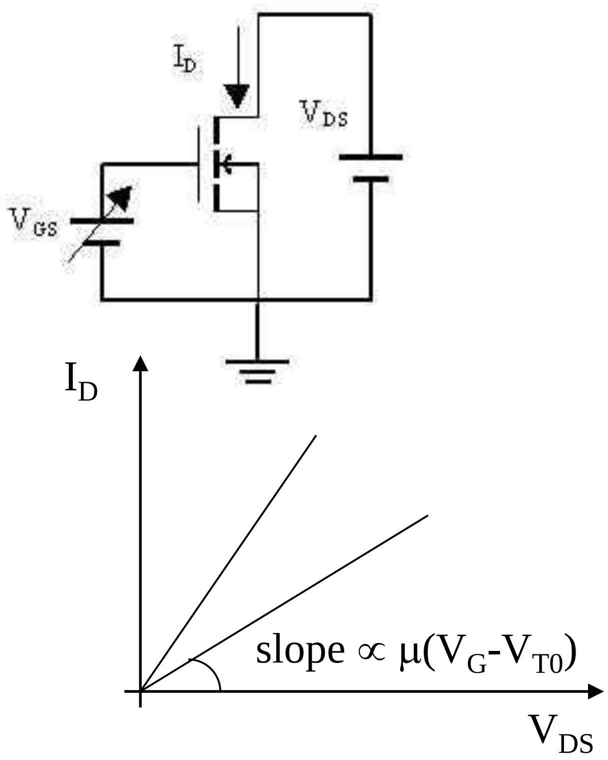
  $2\phi_F = 0.7$, $V_{GB} = 2.5V$, $n = 1.25$, $V_P = 1.23$

$$n = 1 + \frac{\gamma}{2\sqrt{2\phi_F + V_P}} \quad \Longrightarrow \quad \boxed{\mathrm{GAMMA} = 0.69\ \mathrm{V}^{1/2}}$$

- Extraction of μ_0 (U0) and θ (THETA)

Strong inversion, linear region $I_D \cong \frac{\mu n C'_{ox}}{2}\frac{W}{L}[(V_P - V_S)^2 - (V_P - V_D)^2]$

$$I_D = \mu n C'_{ox}\frac{W}{L}\left(V_P - \frac{V_D + V_S}{2}\right)\left(V_D - V_S\right) \quad ; \frac{1}{\mu C'_{ox}\frac{W}{L}} \cong \frac{(V_G - V_{T0})(V_{DS})}{I_D} \quad \text{for small } V_{DS}$$

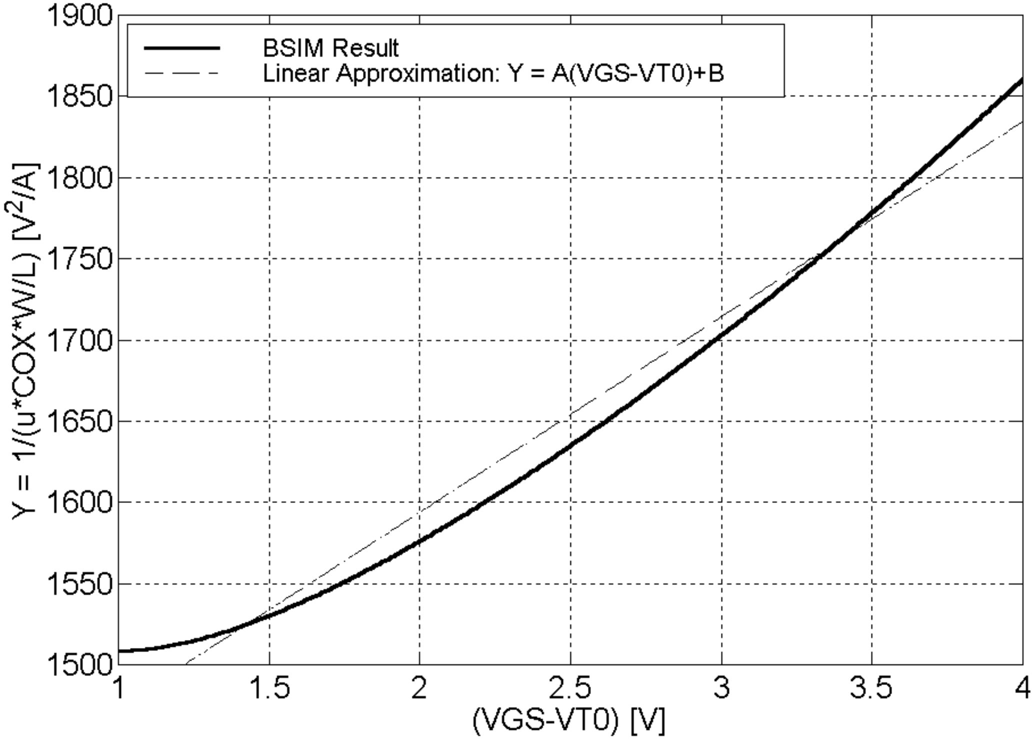


The plot

$\frac{V_{DS}(V_G - V_{T0})}{I_D}$ versus $(V_G - V_{T0})$

allows determining $\mu C'_{ox}\frac{W}{L}$

- **Extraction of μ_0 (U0) and θ (THETA)**



$$\mu = \frac{\mu_0}{1+\theta\left(V_G - V_{T0}\right)}$$

y-axis intersection $\Longrightarrow$ $$\mu_0 = \frac{1}{C'_{OX} \cdot (W/L) \cdot B} \cdot = 514\ \mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$$

slope A $\Longrightarrow$ $$\theta = \mu_0 \cdot C'_{OX} \cdot \left(\frac{W}{L}\right) \cdot A = 0.20\mathrm{V}^{-1}$$

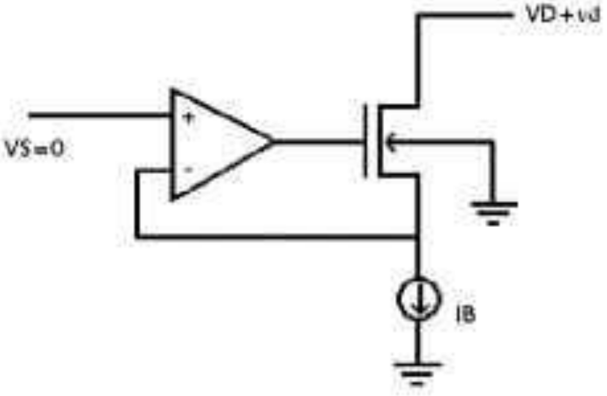
Short-channel effects:

- **DIBL**
- **CLM**
- **Weak avalanche**

Short-channel parameters are determined from either output conductance or voltage gain

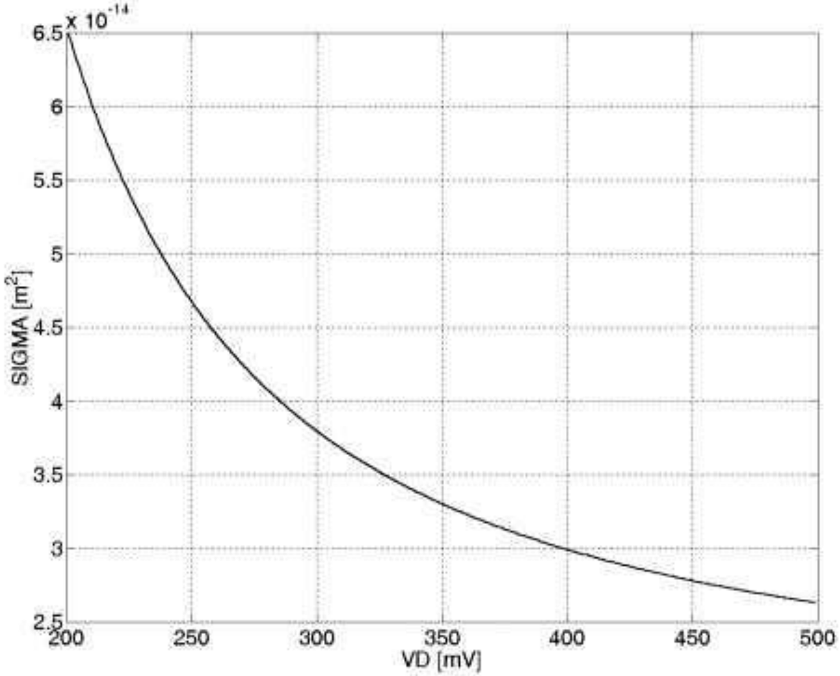
Typically, for short channel devices, DIBL is dominant in weak inversion while CLM prevails in strong inversion

•Extraction of SIGMA (weak inversion)



$$\mathrm{SIGMA} = \sigma \cdot \left(L_{\mathrm{eff}}\right)^2$$

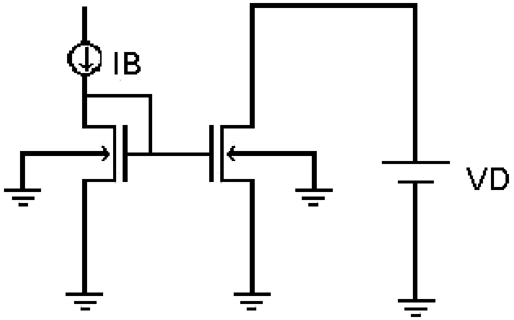
$$\sigma = -\frac{1}{\mathrm{Gain}} = -\frac{gm_d}{gm_g}$$



$$V_T = V_{T0} - \sigma \cdot \left(V_D + V_S\right)/2$$

$$\boxed{\mathrm{SIGMA} = 3.2 \times 10^{-15} m^2}$$

• Extraction of PCLM (strong inversion)



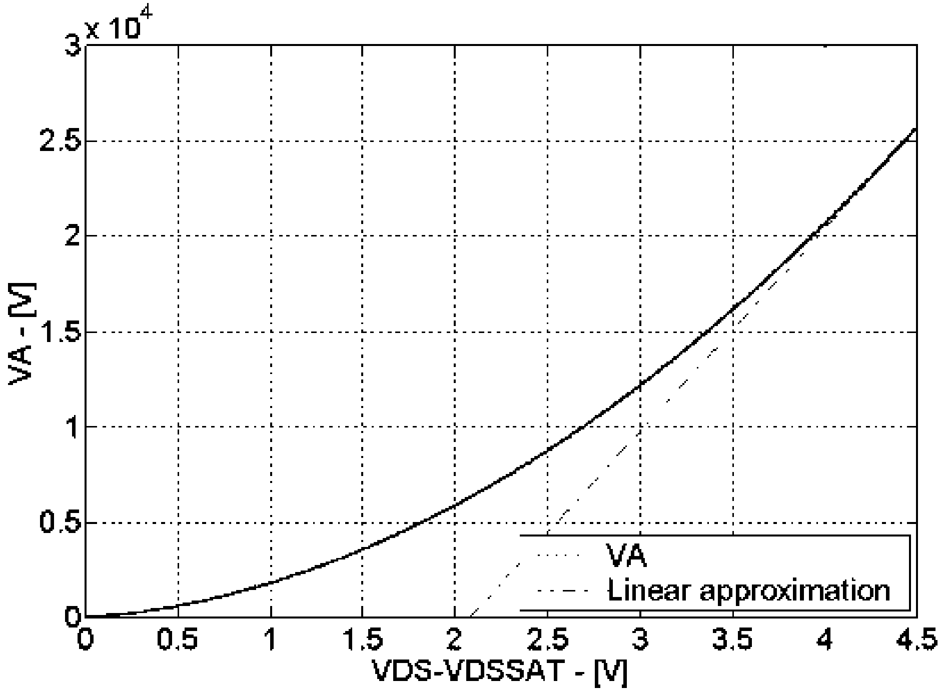
$$\Delta L = P_{CLM} \cdot L_C \cdot \ln\left[1 + \frac{\left(V_{DS} - V_{DSAT}\right)}{L_C \cdot U_{CRIT}}\right]$$

$$U_{CRIT} = \frac{V_{MAX}}{U0}$$

$$P_{CLM} = \frac{L_{eff}}{\frac{dV_A}{dV_{DS}} \cdot L_C} \cdot \left(\varepsilon \cdot \sqrt{1 + \frac{I_D}{I_S}} + 1\right)$$

$$L_C = \sqrt{\varepsilon_{Si} \cdot \frac{Xj}{Cox}} \qquad \varepsilon \cong \frac{\phi_t}{L_{eff} \cdot U_{CRIT}}$$

$$\boxed{P_{CLM} = 1.23}$$

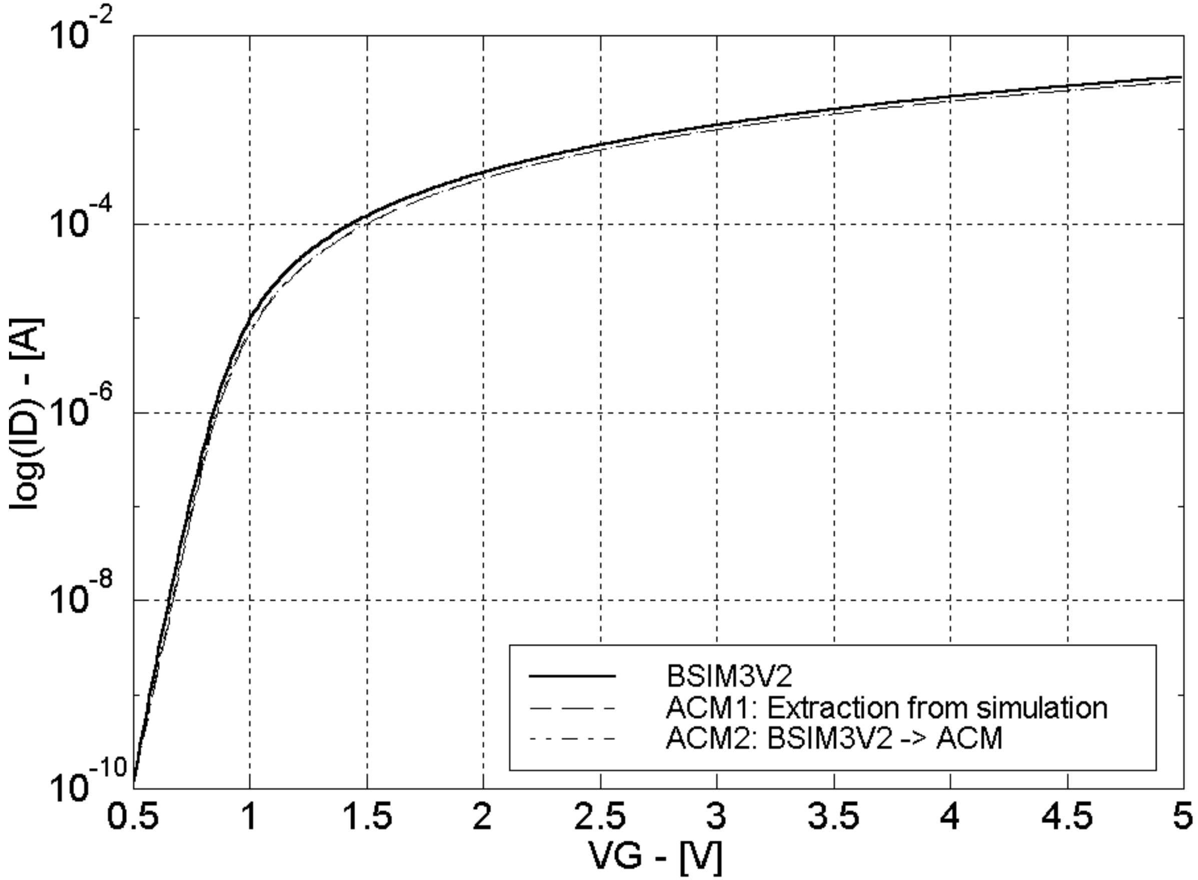


Results

Parameter	BSIM3 → ACM	From Simulation	Unit
VT0	0.836	0.845	V
GAMMA	0.71	0.69	$V^{1/2}$
PHI	0.81	0.7	V
TOX	$15.8 \cdot 10^{-9}$	$15.8 \cdot 10^{-9}$	m
LD	$209 \cdot 10^{-9}$	$209 \cdot 10^{-9}$	m
XJ	$300 \cdot 10^{-9}$	$300 \cdot 10^{-9}$	m
U0	487	514	$cm^2/V \cdot s$
VMAX	$9.08 \cdot 10^{4}$	$9.08 \cdot 10^{4}$	m/s
THETA	0.12	0.20	V^{-1}
SIGMA	$4.55 \cdot 10^{-16}$	$3.2 \cdot 10^{-15}$	m^2
PCLM	1.01	1.23	—

Results

Simulation of an n-MOS transistor using Smash™ from Dolphin



Parameters:
AMS 0.8μm
BSIM 3V3

Conclusions

- *Advantages*

√ Simple & Fast

√ Provides good results with low-cost equipment

√ Simple equations that emphasize the physical meaning of parameters

- *Disadvantages*

√ The extraction from simulation is dependent of the available models.

Links

- *Integrated Circuits Laboratory*
  - http://www.eel.ufsc.br/lci/
- *SMASH Circuit Simulator, Dolphin Integration, Meylan, France.*
  - http://www.dolphin.fr
- *Austria Mikro Systeme Internacional AG*
  - http://www.ams.co.at
- *BSIM3 Homepage:*
  - http://www-device.ECCS.Berkley.EDU/~bsim3