Advanced Compact MOSFET Model: Design-oriented ACM2 model

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"Scan me"

https://github.com/ACMmodel/MOSFET_model

About me

- Universidade Federal de Santa Catarina – UFSC - Brazil

$$V_{DD} < 100\ mV$$

- Undergrad and Masters in IC design - 2022
  - Subject : Ultra-Low-Voltage IC circuits
    - Dissertation: Ultra-Low-Voltage Standard Cell Library
      - ACM for low voltage circuits
- First contact with open-source IC design :
  - Chipathon - SSCS 2021 :
  - Analog-front-end for Biosignals – AFEbio
- Start PhD in 2023 : MOSFET Modeling
- Joint PhD between UFSC and Université Grenoble Alpes (Currently based)
  - Chipathon-SSCS & UNIC-CASS 2023 – Analog IC design
  - Live demonstration of the ACM2 at ISCAS 2024 with the open-source tools (XSCHEM)

Outline

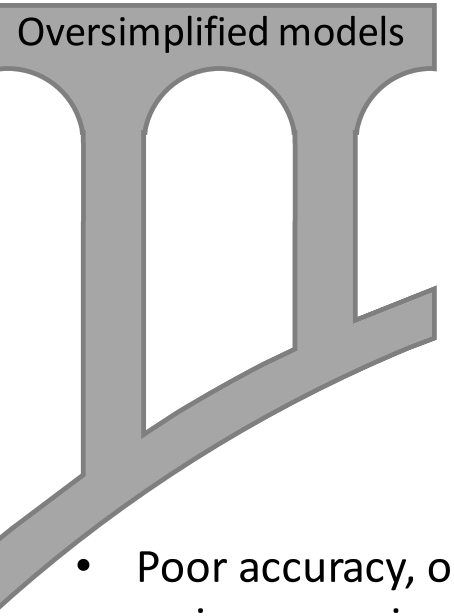
- Introduction: Compact models
- ACM2 model vs V_{GS} model
- ACM2 model vs PSP
- Parameter extraction and circuit example

What is a compact model ?

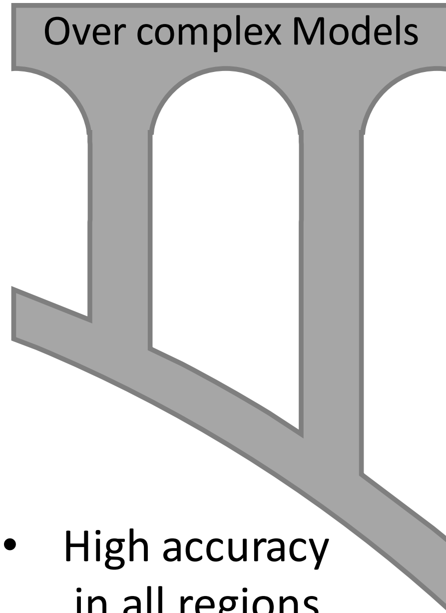
- Compact Model is the medium of information exchange between foundry and designer.
- Provides **detailed information** about device operation & characteristics
- However, needs to be:
    - **Simple** enough to be incorporated in circuit simulators
    - **Accurate** enough to predict behavior of circuits

Why the need for a design-oriented MOSFET model ?

- Provides a proper bridge between the electrical behavior of the MOSFET and circuit performance though simple analytical equations
- Allows analytical sizing of the transistors
- Avoids excessive dependency of the IC designer in using parametric simulations with complex models to define the operation point!



- Poor accuracy, only in one region
- 2/3 DC parameters

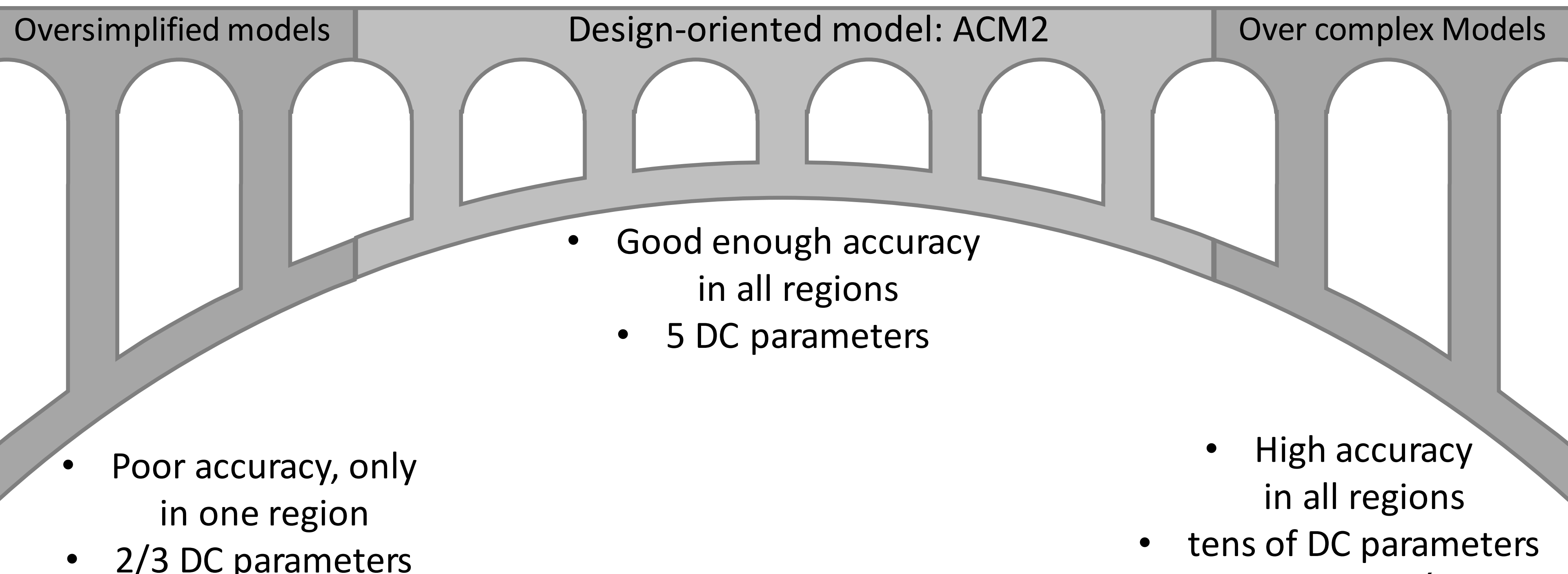


- High accuracy in all regions
- tens of DC parameters

Why the need for a design-oriented MOSFET model ?

- Provides a proper bridge between the electrical behavior of the MOSFET and circuit performance though simple analytical equations
- Allows analytical sizing of the transistors
- Avoids excessive dependency of the IC designer in using parametric simulations
- **Increase the designer intuition!**

IC designers bridge



Open-Source IC design

Open-source PDK

Open-source EDA tools

Few open-source IP & libraries

Available compact MOSFET models

We propose:

ACM2 : A Simple 5-DC-parameter MOSFET model

ACM2: A simple 5-DC-parameter MOSFET model

Complete Continuous All-region charge-based MOSFET model

$$V_P = \frac{V_{GB} - \boldsymbol{V_{T0}} + \boldsymbol{\sigma}(V_{DB} + V_{SB})}{\boldsymbol{n}}$$

$$\frac{V_P - V_{SB}}{\phi_t} = q_s - 1 + \ln(q_s)$$

- Used to calculate q_s
- Bridge between **WI** and **SI** regions

$$q_{dsat} = q_s + 1 + \frac{1}{\zeta} - \sqrt{\left(1 + \frac{1}{\zeta}\right)^2 + \frac{2q_s}{\zeta}}$$

$$\frac{V_{DS}}{\phi_t} = q_s - q_d + \ln\left(\frac{q_s - q_{dsat}}{q_d - q_{dsat}}\right)$$

- Used to calculate q_d
- Bridge between **Triode** and **Saturation** regions

$$I_D = \boldsymbol{I_S} \frac{(q_s + q_d + 2)}{1 + \zeta(q_s - q_d)}(q_s - q_d)$$

Specific current I_S	Threshold voltage V_{T0}	Slope factor n	DIBL factor σ	V_{sat} effect ζ

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Inversion charges in terms of the inversion levels

Unified Charge Control Model

$$\frac{V_P - V_{S(D)B}}{\phi_t} = q_{s(d)} - 1 + \ln q_{s(d)}$$

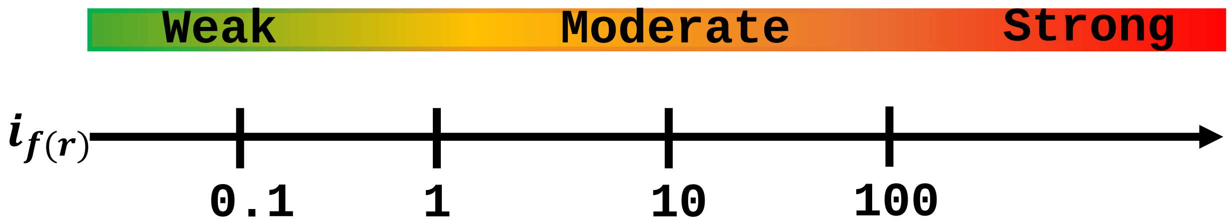
Relationship between normalized inversion charge and inversion level: $q_{s(d)} = \sqrt{1 + i_{f(r)}} - 1$

Unified (I)current Control Model

$$\frac{V_P - V_{S(D)B}}{\phi_t} = \sqrt{1 + i_{f(r)}} - 2 + \ln\left(\sqrt{1 + i_{f(r)}} - 1\right)$$

$$\frac{I_D}{I_S} = \frac{I_F - I_R}{I_S} = i_f - i_r$$

➡ $i_{f(r)}$ is the forward (reverse) inversion level



Oversimplified model vs ACM-3PM model @ Saturation

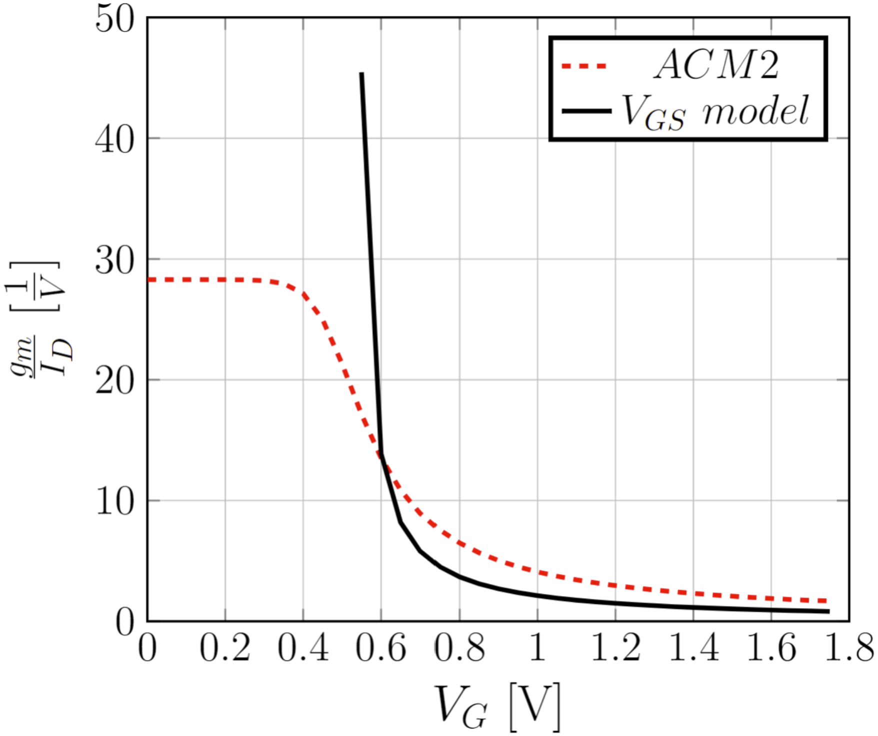
$$I_D = \frac{\beta}{2}(V_{GS} - V_T)^2$$

$$\frac{g_m}{I_D} = \frac{1}{V_{GS} - V_T}$$

$$i_f = \frac{I_D}{\boldsymbol{I_S}} \qquad V_P = \frac{V_{GB} - \boldsymbol{V_{T0}}}{\boldsymbol{n}}$$

$$\frac{V_P - V_{S(D)B}}{\phi_t} = \sqrt{1 + i_f} - 2 + \ln\left(\sqrt{1 + i_f} - 1\right)$$

$$\frac{g_m}{I_D} = \frac{2}{n\phi_t\left(\sqrt{1 + i_f}\right)}$$



Misconception about overdrive voltage:
NMOS example:

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

$$V_{OV} = V_P - V_{SB} = \frac{V_{GB} - V_T}{\boldsymbol{n}} - V_{SB}$$

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Physics-based saturation: design model

Normalized saturation current due to velocity saturation of carriers

$$i_{dsat} = \frac{2}{\zeta} q_{dsat}$$

Normalized current vs. normalized charge densities

$$\frac{I_D}{I_S} = i_{dsat} = \frac{(q_s + q_{dsat} + 2)}{1 + \zeta(q_s - q_{dsat})}(q_s - q_{dsat})$$

$$\zeta = \frac{(\mu_s \phi_t / L)}{v_{sat}}$$

$$q_{dsat} = q_s + 1 + \frac{1}{\zeta} - \sqrt{\left(1 + \frac{1}{\zeta}\right)^2 + \frac{2q_s}{\zeta}}$$

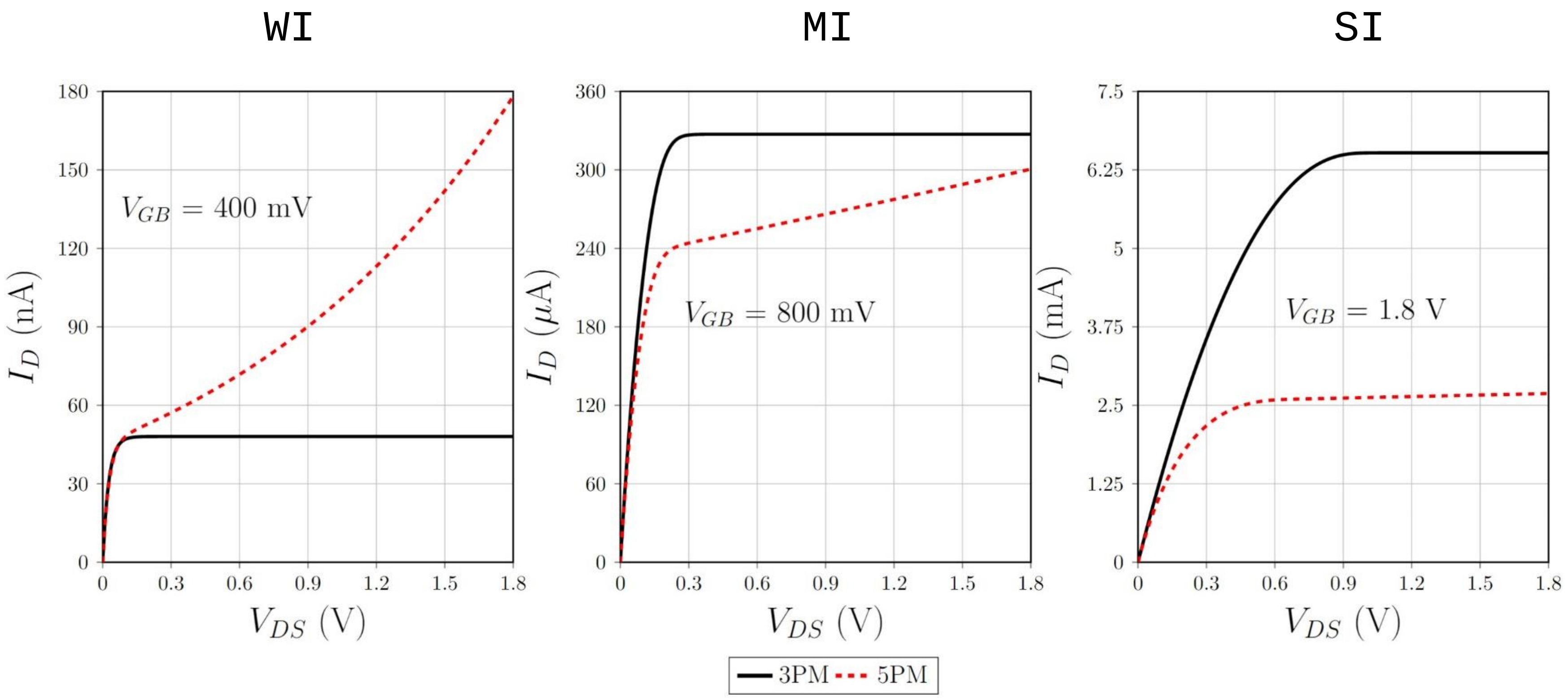
or, equivalently

$$q_s = \sqrt{1 + \frac{2}{\zeta} q_{dsat}} - 1 + \ q_{dsat}$$

Unified **C**harge **C**ontrol **M**odel *including the effect of* ***velocity saturation***

$$\frac{V_{DS}}{\phi_t} = q_s - q_d + \ln\left(\frac{q_s - q_{dsat}}{q_d - q_{dsat}}\right)$$

Output characteristics including DIBL and v_{sat}

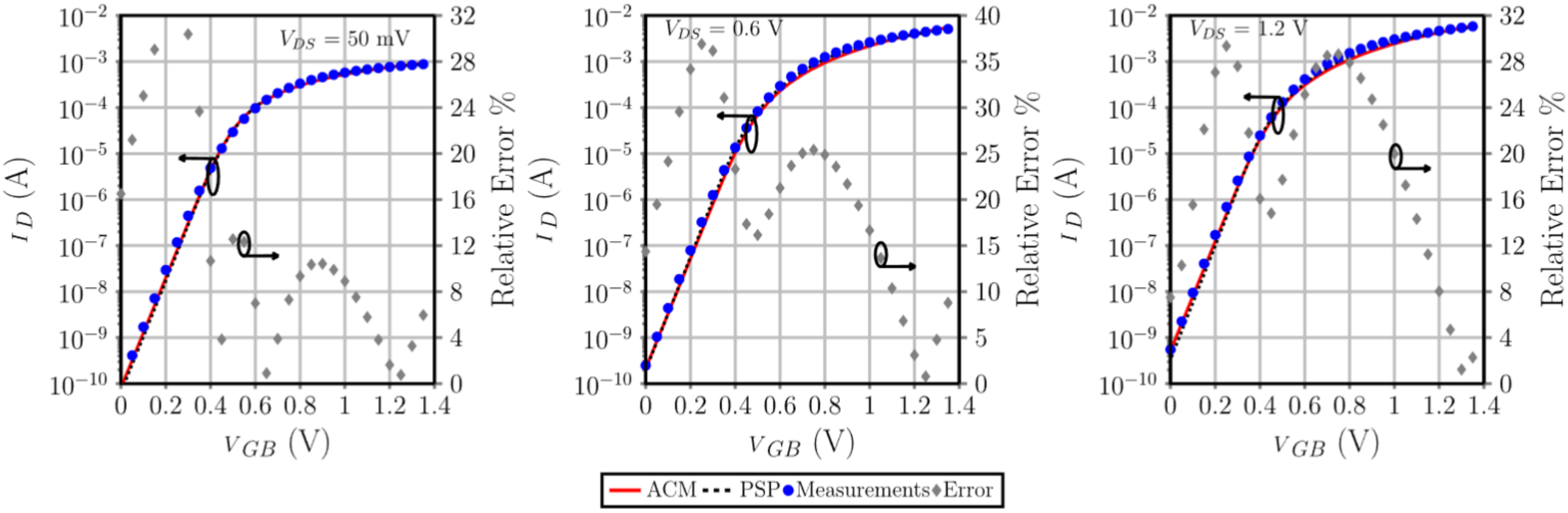


$DIBL\ model$: $V_T = V_{T0} \ -\sigma(V_{SB} + V_{DB})$

Transistor	$W/L\ [\mu m]$	$V_{T0}\ [mV]$	$I_S\ [\mu A]$	n	σ	ζ
NMOS	**5/0.18**	528	5.52	1.37	0.025	0.056

ACM2[1] vs PSP – 130 nm SiGe IHP[2]

I_D vs V_{GB}

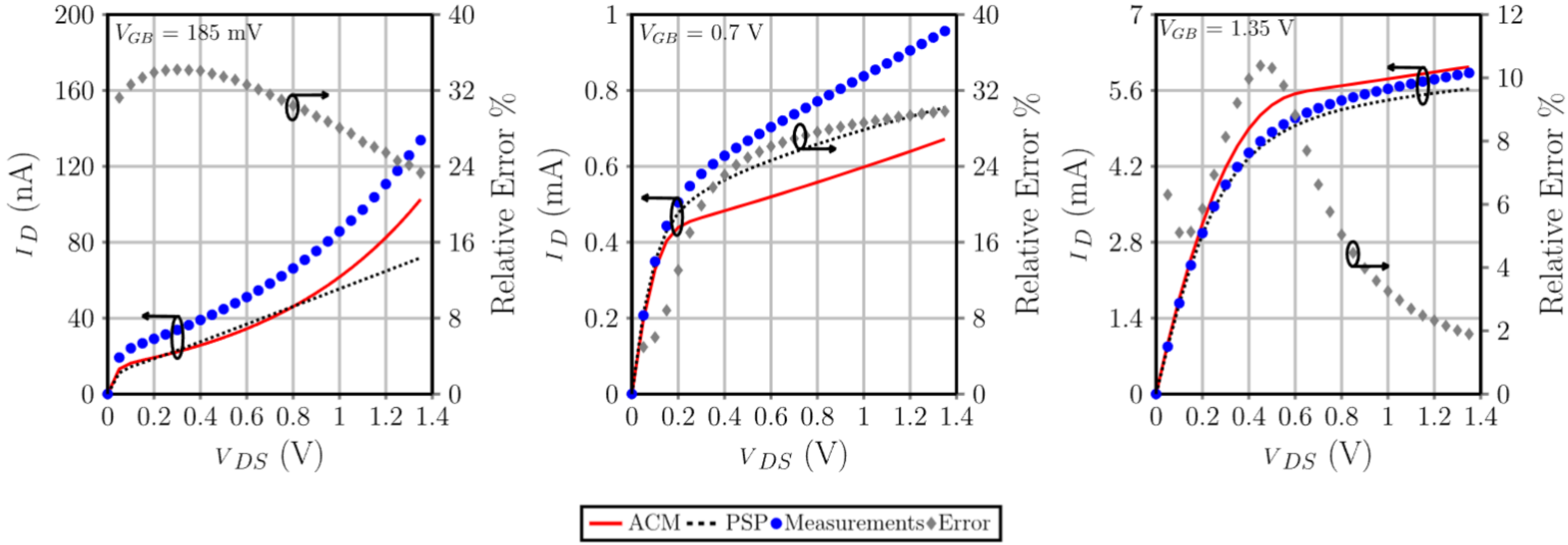


Characteristics of a LVT NMOS bulk transistor with W /L = 10µm/ 120 nm.

[1] ACM2 : implemented in verilog-A, compiled by OPENVAF, simulated in Ngspice
[2] Institut for High-Performance Microelectronics (IHP) open-source PDK

ACM2[1] vs PSP – 130 nm SiGe IHP[2]

I_D vs V_{DS}



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3PM-ACM model in a nutshell

$$I_D = I_S\left[i_f - i_r\right] \quad \text{where} \quad I_S = \mu C_{ox} n \frac{\phi_t^2}{2}\frac{W}{L} = I_{SH}\frac{W}{L}$$

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

If we choose $i_f = 3$ ➡ $V_{GB} = \boldsymbol{V_{T0}}$

$$\frac{V_{DS}}{\phi_t} = \sqrt{1+i_f} - \sqrt{1+i_r} + \ln\left(\frac{\sqrt{1+i_f}-1}{\sqrt{1+i_r}-1}\right)$$

DC eqs

$$g_{ms(d)} = \frac{2I_S}{\phi_t}\left(\sqrt{1+i_{f(r)}} - 1\right) \Rightarrow \frac{W}{L} = \frac{g_{ms(d)}\phi_t}{2I_{SH}\left(\sqrt{1+i_{f(r)}} - 1\right)}$$

$$g_m = \frac{g_{ms} - g_{md}}{n} \qquad \frac{g_m}{I_D} = \frac{d(\ln I_D)}{dV_G} = \frac{2}{n\phi_t\left(\sqrt{1+i_f} + \sqrt{1+i_r}\right)}$$

Small – signal eqs

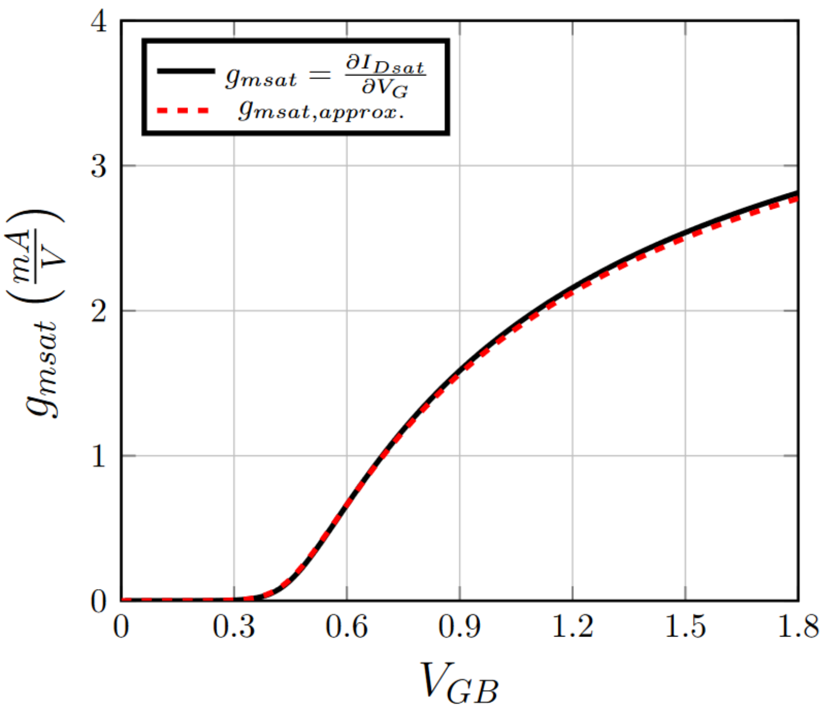
5PM-ACM2 :Transconductances in saturation

$$I_D = \frac{2I_S}{\zeta} q_{dsat} \quad \text{where} \quad \begin{cases} I_S = \mu C_{ox} n \frac{\phi_t^2}{2} \frac{W}{L} = I_{SH} \frac{W}{L} \\ q_{dsat} = q_s + 1 + \frac{1}{\zeta} - \sqrt{\left(1 + \frac{1}{\zeta}\right)^2 + \frac{2q_s}{\zeta}} \end{cases}$$

$$g_m \triangleq \frac{\partial I_D}{\partial V_G} \qquad g_{md} \triangleq \frac{\partial I_D}{\partial V_D}$$

$$g_m(q_s) \begin{cases} g_m = \frac{2I_S}{n\phi_t} \frac{q_s}{1 + \zeta(q_s + 1)} \\ g_{m3} = \frac{16I_S}{(n\phi_t)^3} \frac{q_s}{(q_s + 1)^3} \frac{2 - 2\zeta q_s - 3\zeta q_s^2}{(q_s + 1)^4} \end{cases}$$

$$g_m(i_{dsat}) \begin{cases} g_m = \frac{2I_S}{n\phi_t} \frac{\left(\sqrt{1 + i_{dsat}} - 1\right)}{\zeta\sqrt{i_{dsat}}} \end{cases}$$



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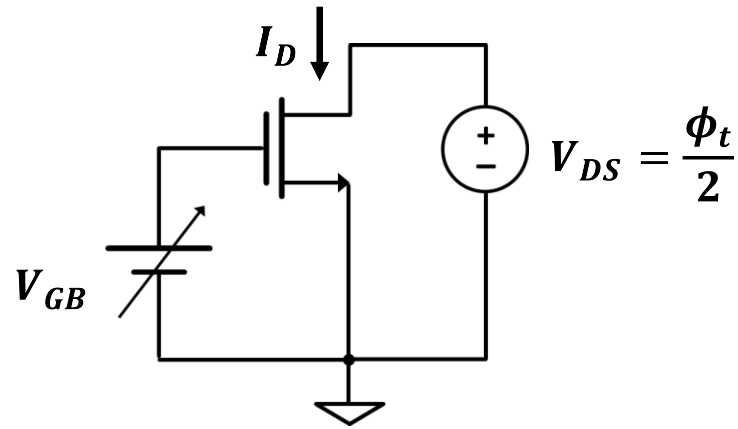
I_S, V_{T0} and n extraction

The g_m/I_D method



Let us choose: $V_{DS} = {}^{\phi_t}/_2$ and $i_f = 3$

$$\frac{V_{DS}}{\phi_t} = \sqrt{1+i_f} - \sqrt{1+i_r} + \ln\left(\frac{\sqrt{1+i_f}-1}{\sqrt{1+i_r}-1}\right)$$

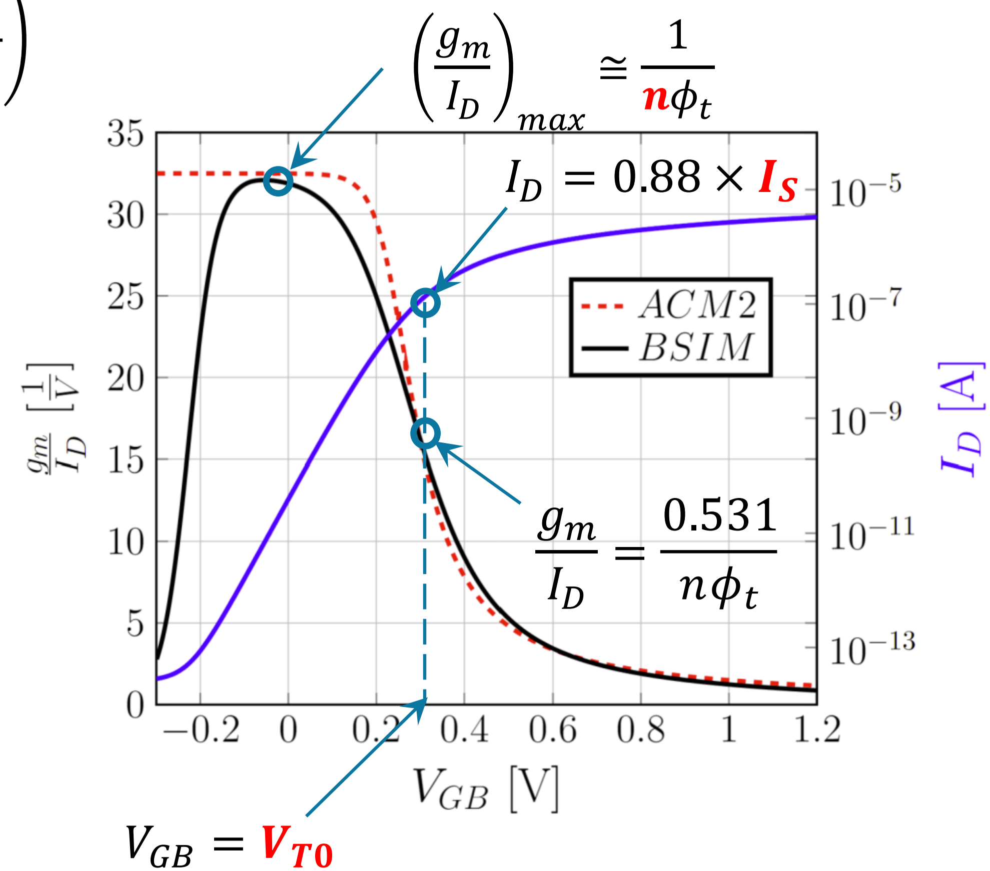
Thus : $i_r = 2.12$

$$\frac{g_m}{I_D} = \frac{d(\ln I_D)}{dV_G} = \frac{2}{n\phi_t\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)}$$

$$\frac{g_m}{I_D} = \frac{0.531}{n\phi_t} = 0.531\left(\frac{g_m}{I_D}\right)_{max}$$

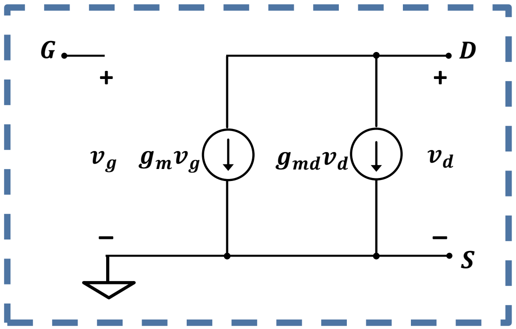
$$I_D = I_S(i_f - i_r)$$

$$I_D = (3-2.12)\, I_S = 0.88\, I_S$$

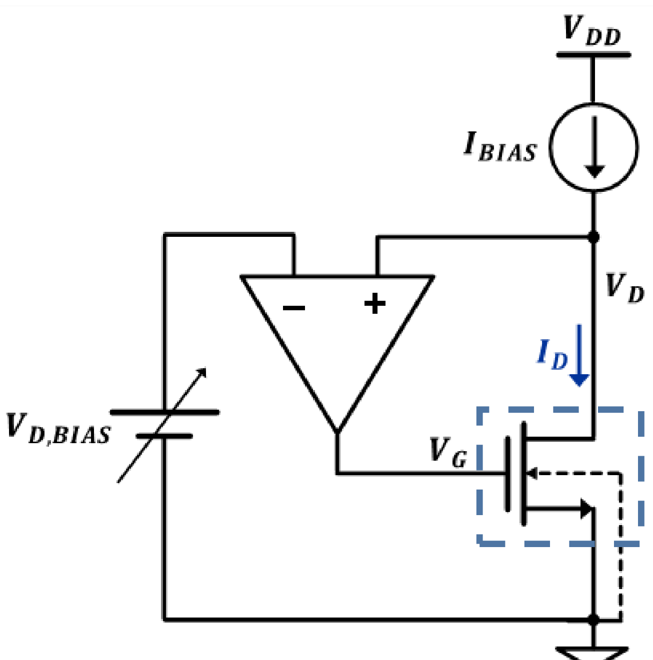


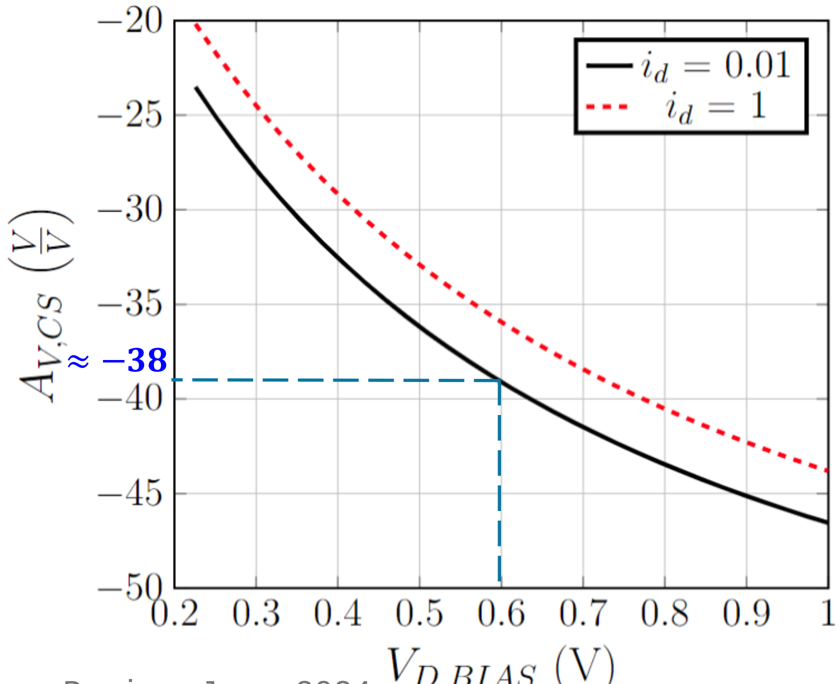
Extraction of σ

Common-Source Intrinsic-Gain method



$$A_{V,CS} = \frac{v_d}{v_g} = -\frac{g_m}{g_{md}} = -\frac{\frac{g_m}{I_{D,sat}}}{\frac{g_{md}}{I_{D,sat}}} = -\frac{\frac{1}{\phi_t}\left(\frac{1}{n}\right)\frac{2}{1+\sqrt{1+i_f}}}{\frac{1}{\phi_t}\left(\frac{\sigma}{n}\right)\frac{2}{1+\sqrt{1+i_f}}} = -\frac{1}{\sigma}$$





$$A_{V,CS} = -\frac{1}{\sigma}$$

$$\sigma = -\frac{1}{(-38)}$$

$$\boxed{\sigma = 0.026}$$

ζ extraction

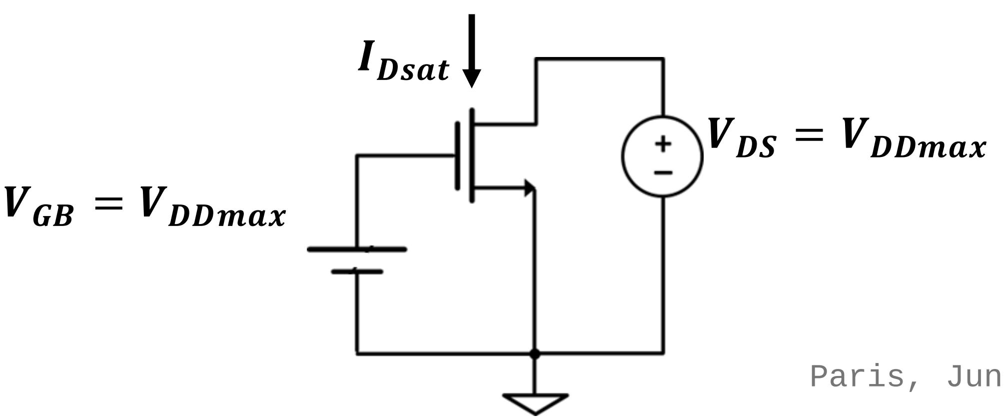
$$i_{dsat} = \frac{2}{\zeta} q_{dsat} \qquad q_s = \sqrt{1 + \frac{2}{\zeta} q_{dsat}} - 1 + \; q_{dsat}$$

$$\zeta = \frac{2\left(q_s + 1 - \sqrt{1 + i_{dsat}}\right)}{i_{dsat}}$$

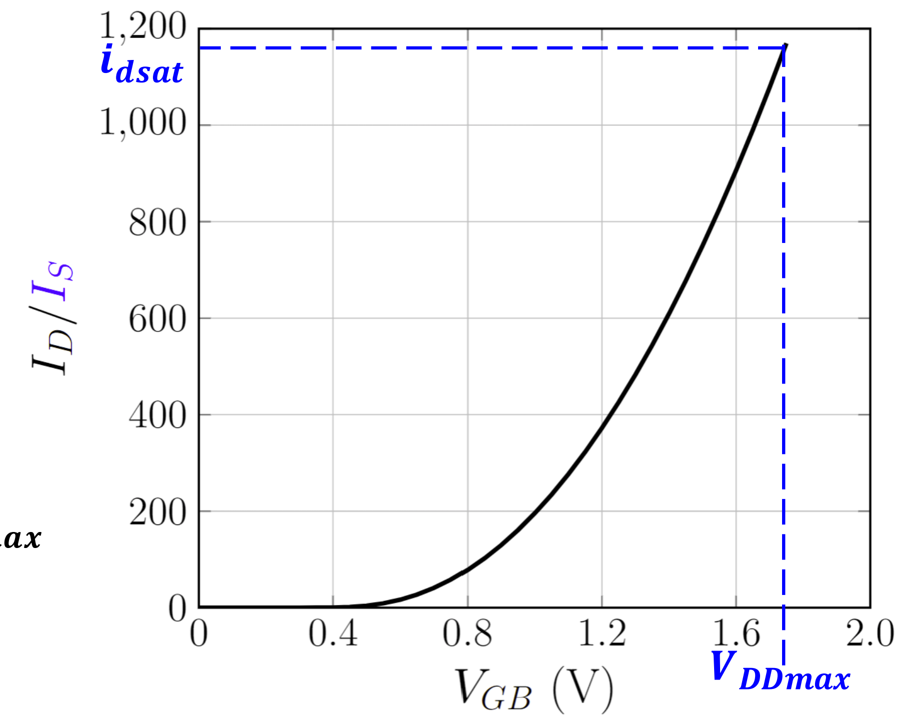
- q_s calculated using parameters ($\boldsymbol{V_{T0}}$, $\boldsymbol{n}$, $\boldsymbol{\sigma}$) and UCCM.

$$V_P = \frac{V_{GB} - \boldsymbol{V_{T0}} + \boldsymbol{\sigma}(V_{DB} + V_{SB})}{\boldsymbol{n}}$$

$$\frac{V_P - V_{S(D)B}}{\phi_t} = q_s - 1 + \ln(q_s)$$



- Measure
  $I_{Dsat} = I_D(V_G = V_D = V_{DDmax}$ and $V_S = V_B)$
  $i_{dsat} = I_{Dsat}/I_S$.



Github – ACM2

Github - Content

ACMmodel Merge pull request #26 from gabrielmaranhao/main 71ee7cd · 6 months ago

Examples	Update SKY130 and GF180 using ACM examples on xschem
Verilog-A	Update PMOS_ACM_2V0.va
docs	Delete 5PM_NewCAS.pdf
LICENSE	Update LICENSE
README.md	Update README.md

README ECL-2.0 license

Advanced Compact MOSFET model (ACM)

ACM is a simple MOSFET model to design and simulate Analog, Mixed-Signal, and RF circuits

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Verilog-A code Available!

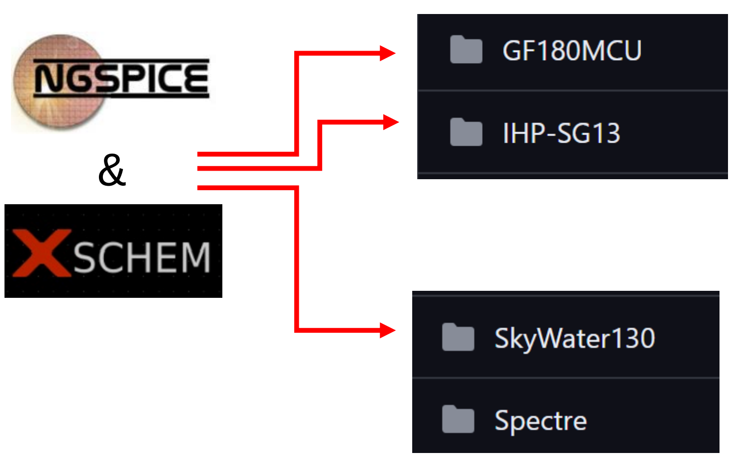
MOSFET_model / Verilog-A / NMOS_ACM_2V0.va

ACMmodel Update NMOS_ACM_2V0.va

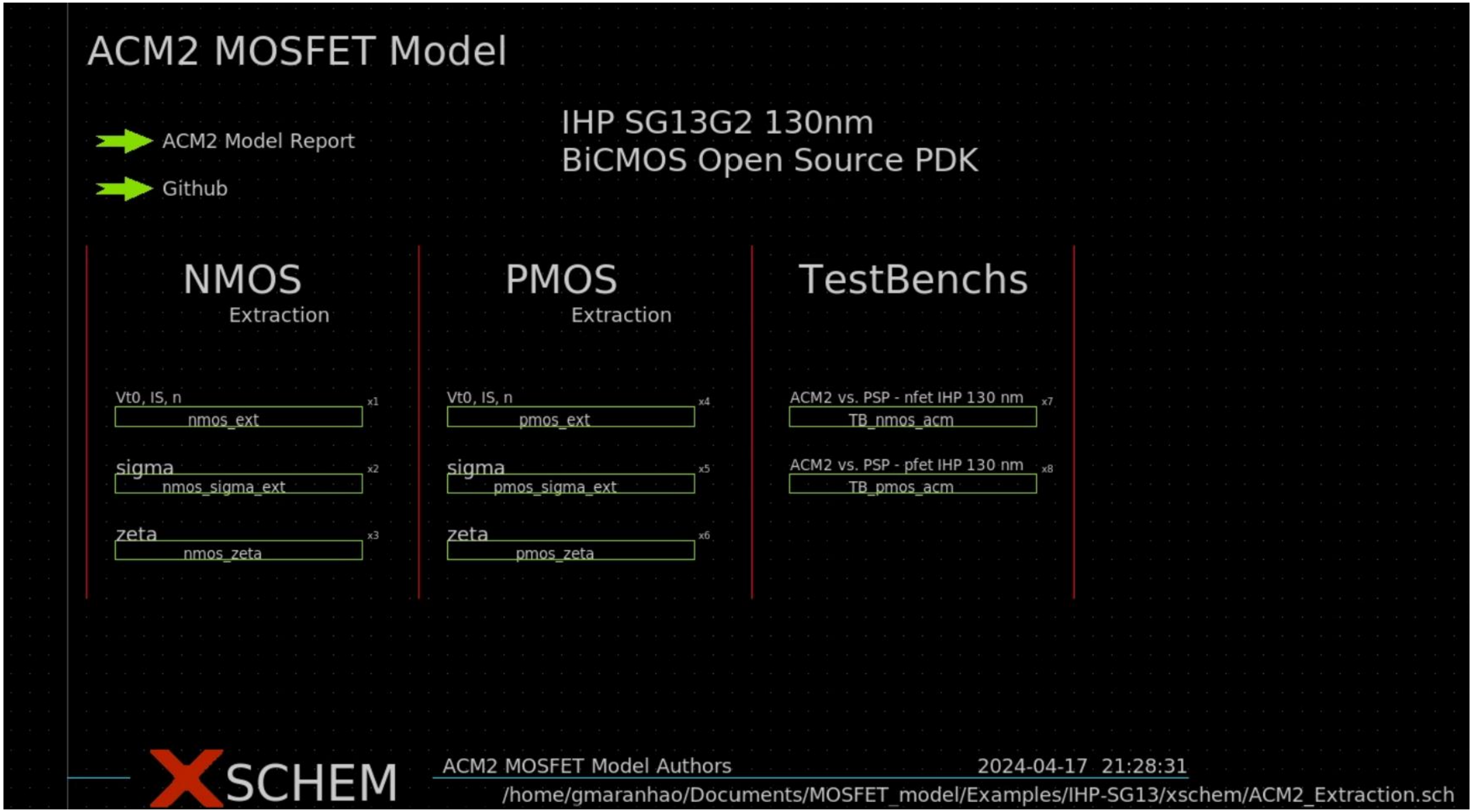
Code Blame 291 lines (245 loc) · 12.3 KB

```
//**************************************************************************
// *  ACM NMOS model (Verilog-A)                                           *
// *  07/2023    V2.0.0                                                    *
//**************************************************************************

// ************************************************************************
// * Copyright under the ECL-2.0 license                                   *
// * Universidade Federal de Santa Catarina                                *
// *                                                                       *
// * Current developers:  Deni Germano Alves Neto (Doctoral student, UFSC) *
// *                      Cristina Missel Adornes (Doctoral student, UFSC) *
// *                      Gabriel Maranhao        (Doctoral student, UFSC) *
// *                                                                       *
// * Project Supervisors:  Prof. Carlos Galup-Montoro                      *
// *                       Prof. Marcio Cherem Schneider                   *
// ************************************************************************

`include "constants.vams"
`include "disciplines.vams"

// function of the algorithm 443 to calculate de normalize charge densities
`define algo_443(Z,qn) \
        if(Z < 0.7385) begin \
                numeratorD = Z + (4.0/3.0)*Z*Z; \
                denominatorD = 1.0 + (7.0/3.0)*Z+(5.0/6.0)*Z*Z; \
                WnD = numeratorD/denominatorD; \
        end     else begin \
                numeratorD = ln(Z)*ln(Z)+2.0*ln(Z)-3.0; \
                denominatorD = 7.0*ln(Z)*ln(Z) + 58.0*ln(Z) +127.0; \
                WnD = ln(Z) - 24.0*(numeratorD/denominatorD); \
```

Examples of PDKs and circuit simulators using the ACM model



Automatic parameter extraction – IHP @ Xschem



Also, available for GF180 and SKY130

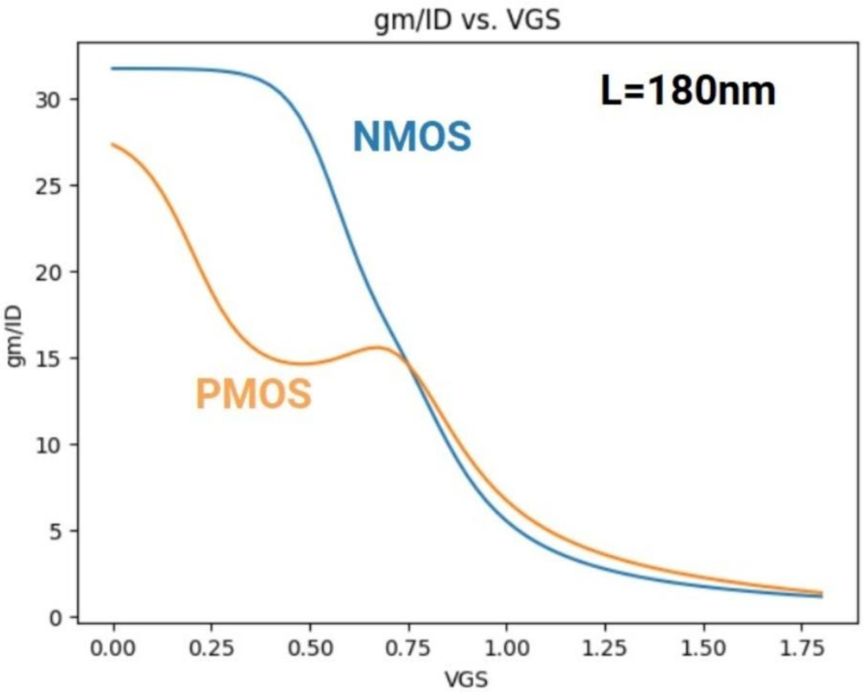
Automatic parameter extraction - "ACM2 PDK"

- Dependency of the parameters

$$V_{T0}, I_S, n, \sigma, \zeta$$

- Control Voltages- V_G, V_D, V_S, V_B
- Geometry – W & L
- Temperature
- Corners

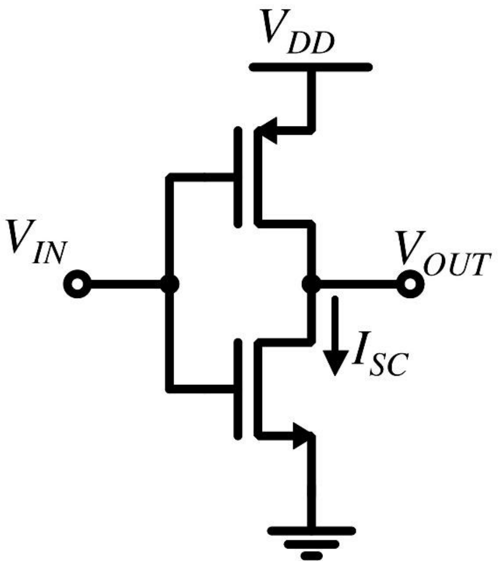
BSIM4 issues in sky130

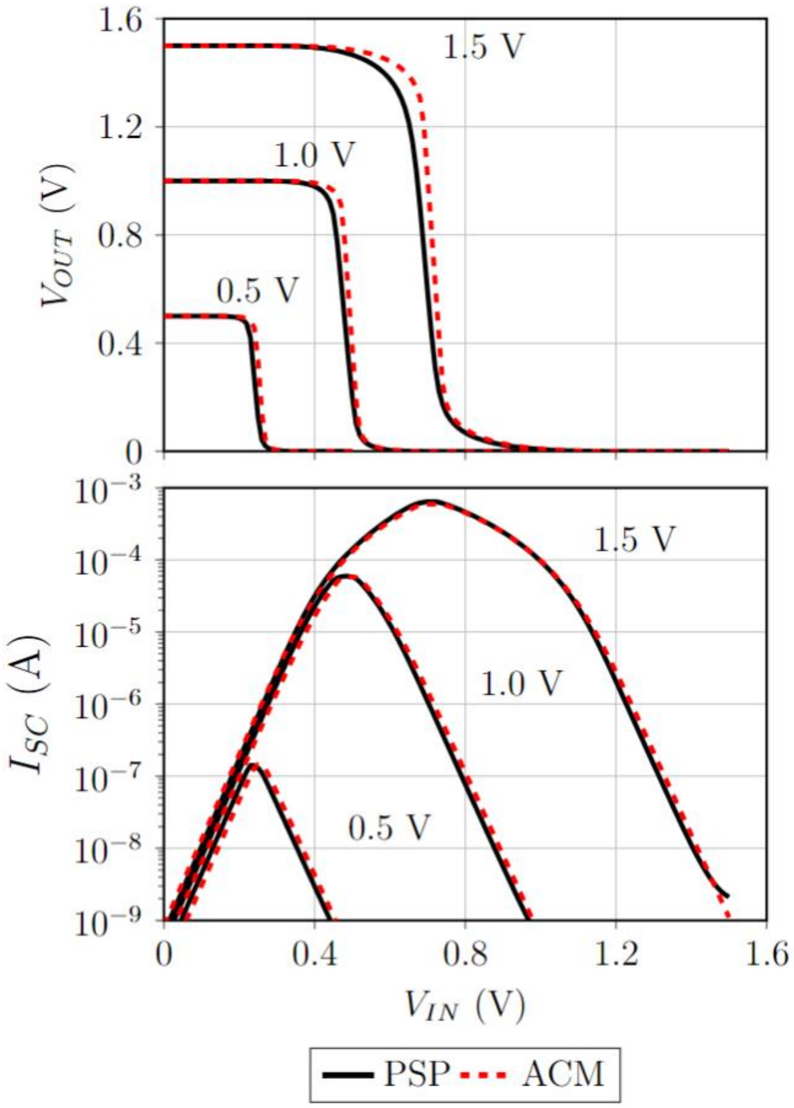


Thanks Tim Edwards for the sky130 samples

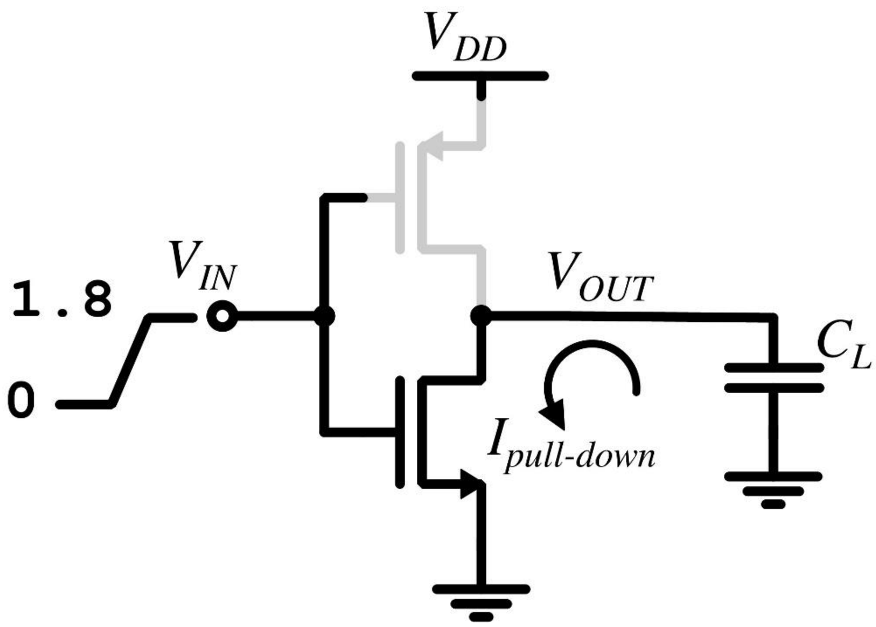
We need more samples to do measurements!
And Funding!

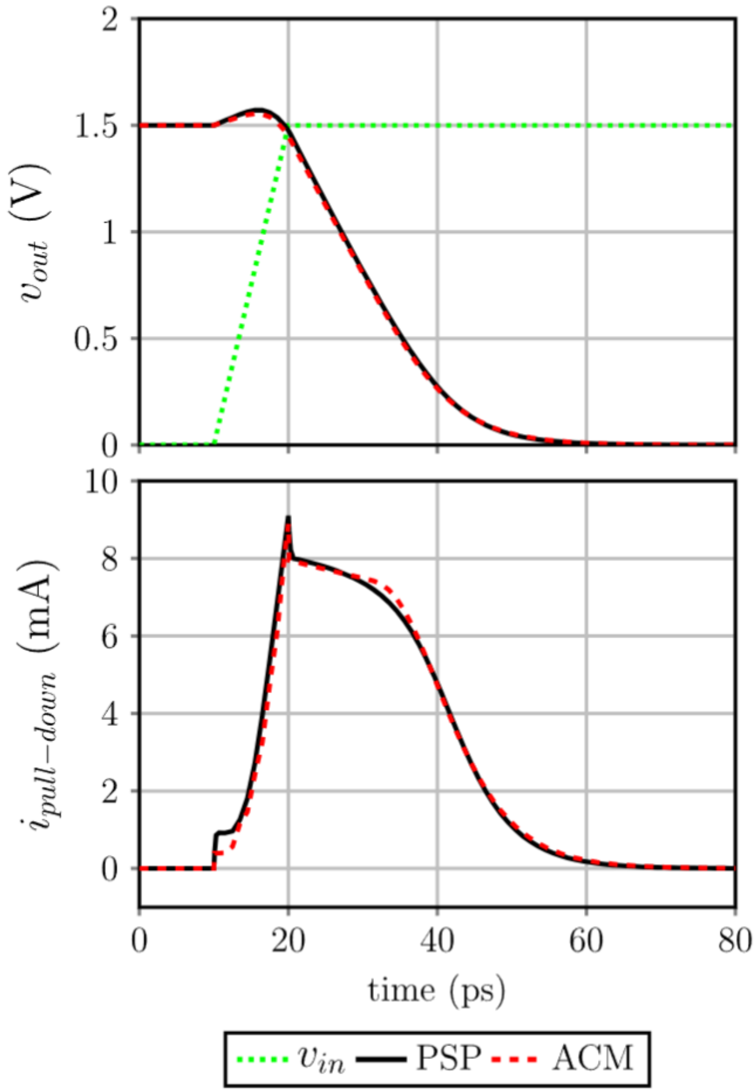
CMOS Inverter in 130 nm bulk
VTC and short-circuit current





CMOS Inverter in 130 nm bulk
Output Voltage and pull-down current





Summary – The ACM2 model

- *A truly compact MOSFET model with single-piece functions*
- *Implemented in Verilog-A for simulation*
- *Interchangeable between simulators (SPICE or SPECTRE)*
- *Verify in all three open-source PDKs (Sky130, GF180, IHP-SG13G2)*
- *Helpful to designers (only 5-DC-parameters)*
- *Simplified parameter extraction procedure*
  - *Accepts parameters extracted from simulations or chip measurements*

Acknowledgments

- **LCI-UFSC, Florianopolis, Brazil**
- **TIMA, Univ. Grenoble Alpes, France**
- **IHP, Frankfurt Oder, Germany**
- **Efabless**
- **STIC-AmSud multinational program**
- **CAPES and CNPq agencies, Brazil**

References

- D. G. Alves Neto, C. M. Adornes, G. Maranhão, M. K. Bouchoucha, M. J. Barragan, A. Cathelin, M. C. Schneider, S. Bourdel, C. Galup-Montoro, A 5-DC-Parameter MOSFET Model for Circuit Simulation in QucsStudio and Spectre, Newcas 2023.
- ACM2 Github: https://github.com/ACMmodel/MOSFET_model
- IHP Github : https://github.com/IHP-GmbH/IHP-Open-PDK

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- **Available in Github:**
  - **DC model**
  - **Small-signal model**
  - **Dynamic model**
  - **Thermal & Flicker noise models (1/f)**

What’s next?

- Introduction to open-source IC design at UFSC
- Short design course in

Questions ?

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