Advanced Compact MOSFET Model: Design-oriented ACM2 model

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https://github.com/ACMmodel/MOSFET_model

Outline

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

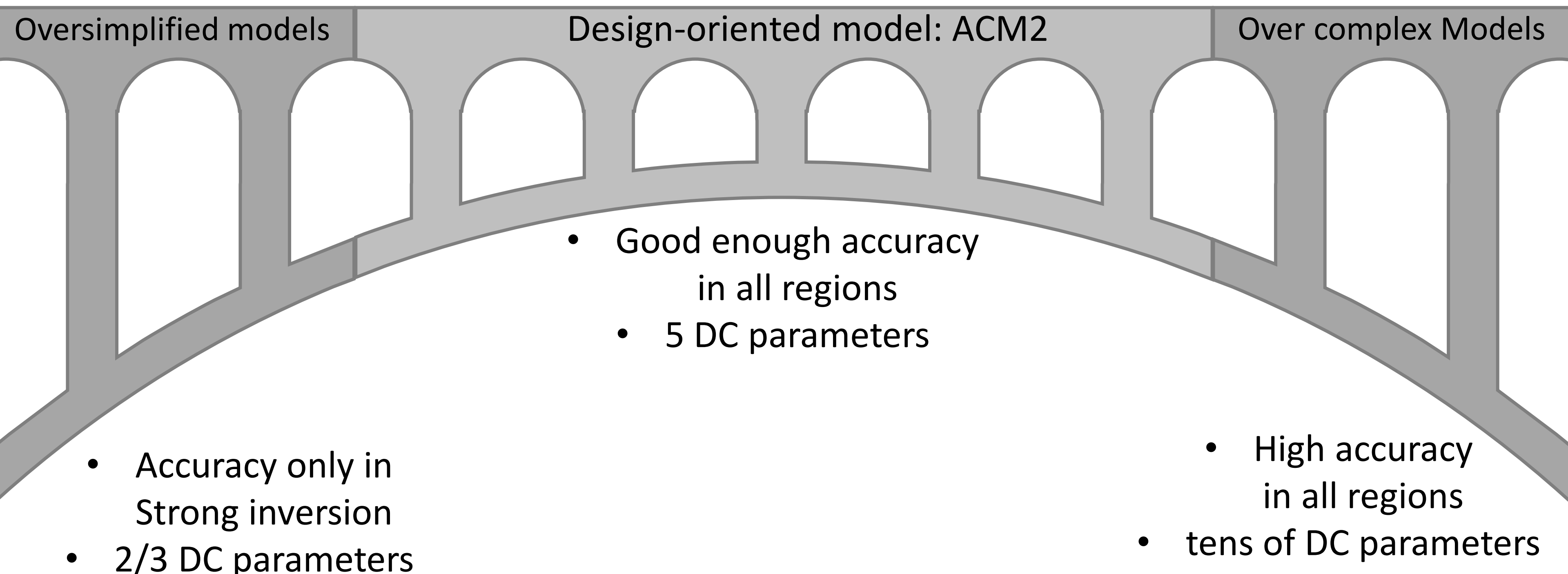
What is a compact model ?

- 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!

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

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

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

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

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

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

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:

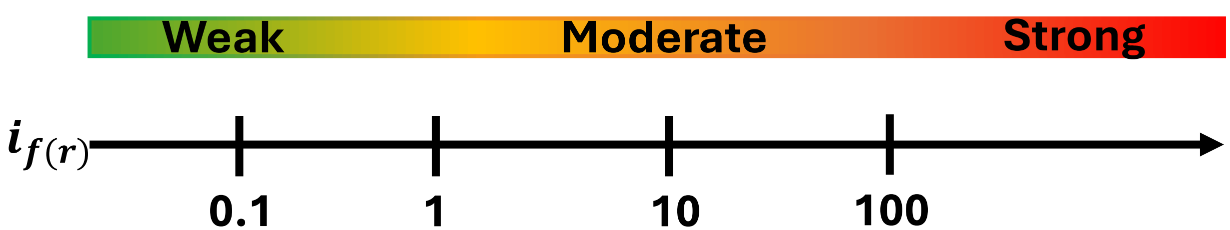
$$q_{s(d)} = \sqrt{1 + i_{f(r)}} - 1$$

Unified (I)current Control Model

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

$$I_D = I_F - I_R = I_S\left[i_f - i_r\right]$$

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



Oversimplified model vs ACM2 model @ Saturation

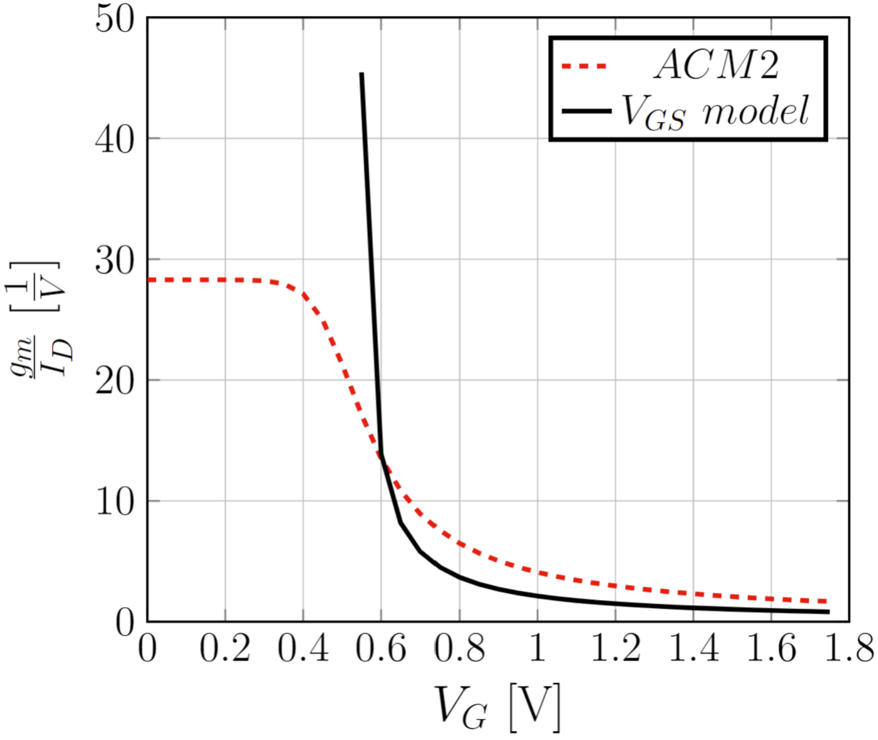
$$V_P = \frac{V_{GB} - V_T}{n}$$

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

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

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

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



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

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

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

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

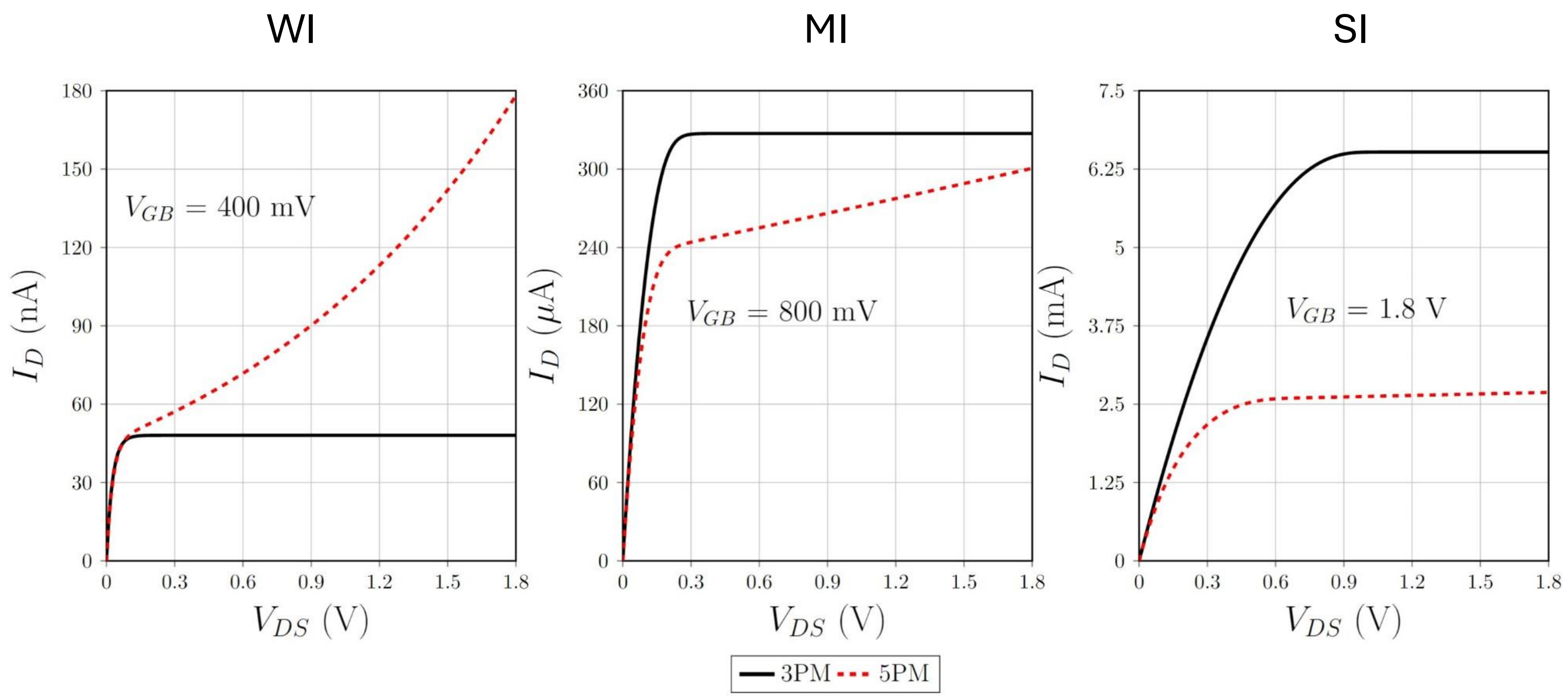
or, equivalently

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

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

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

Output characteristics including DIBL and v_{sat}

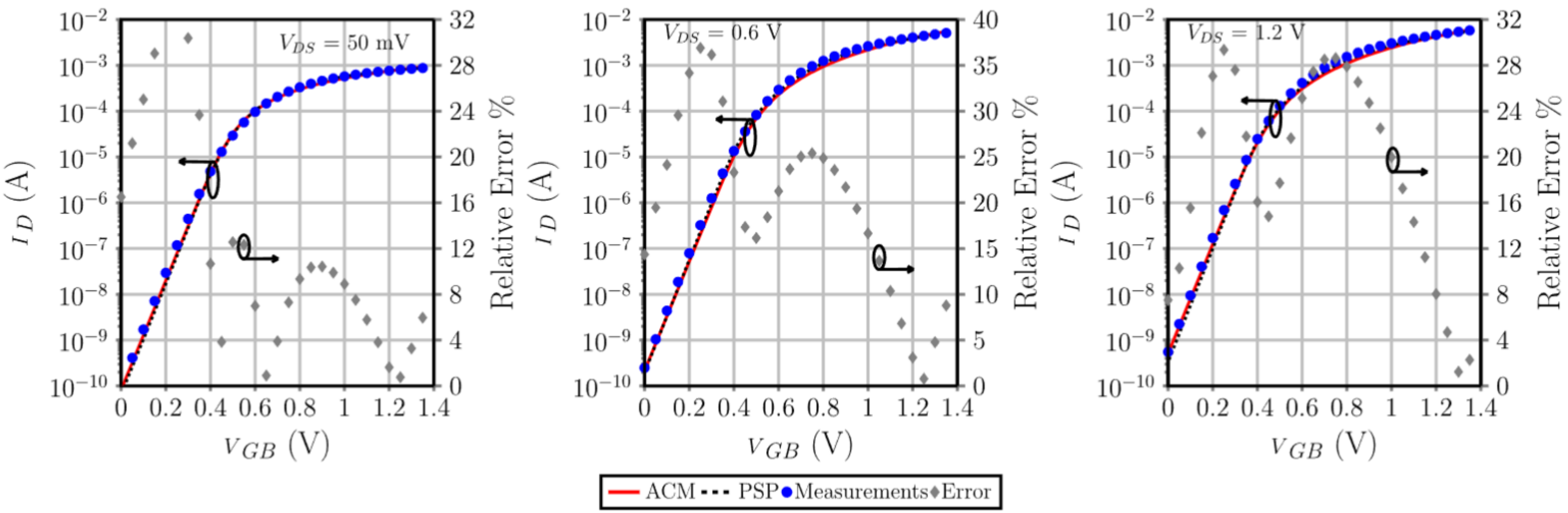


$DIBL\ model$: $V_T = V_{T0} - \sigma(V_{SB} + V_{DB})$

Transistor	W/L [μm]	V_{T0} [mV]	I_S [μA]	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}



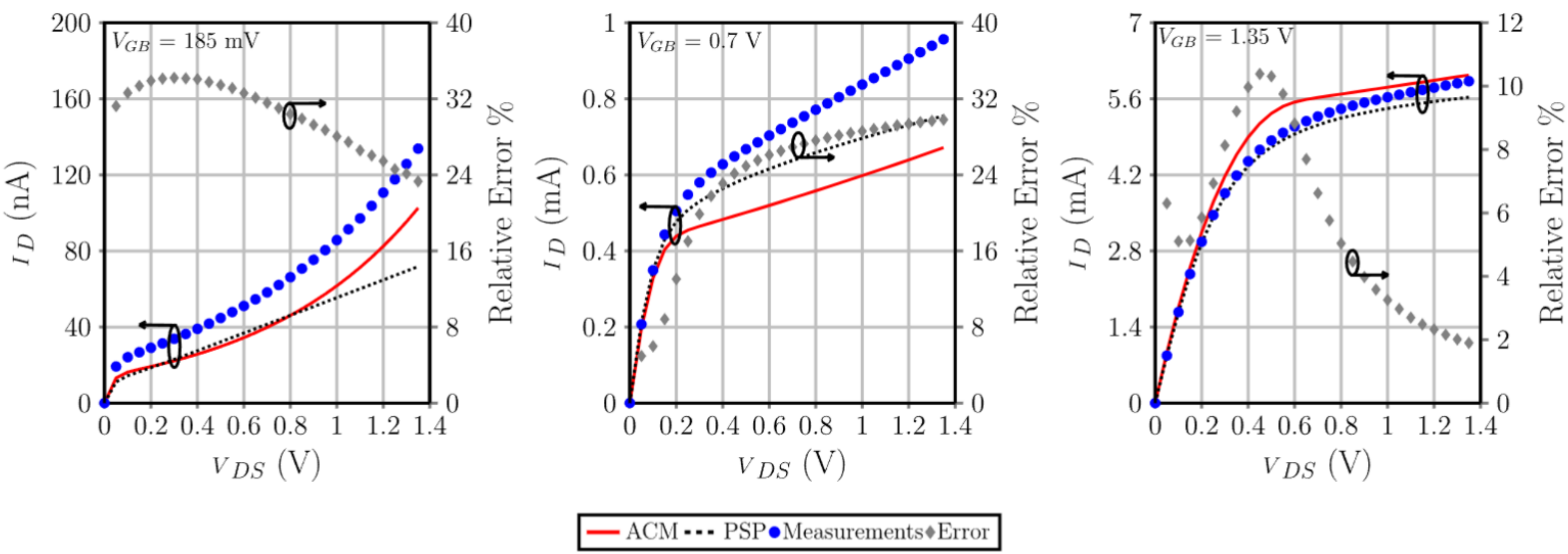
Characteristics of a LVT NMOS bulk transistor with W /L = 10µm/ 120 nm.

[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

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

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

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

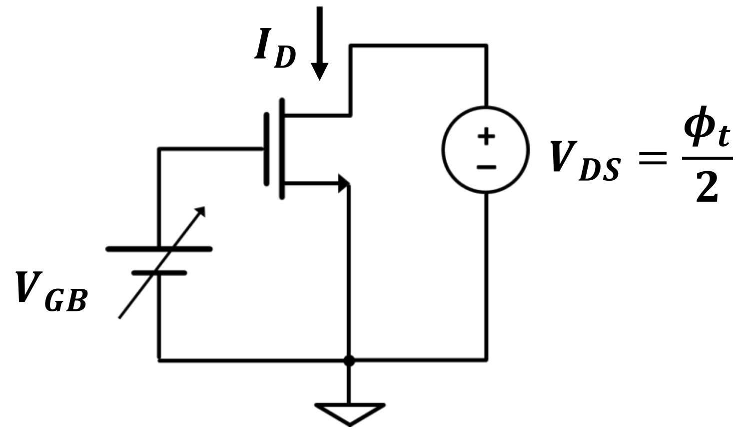
$$g_{ms(d)} = \frac{2I_S}{\phi_t}\left(\sqrt{1 + i_{f(r)}} - 1\right) \Rightarrow \frac{W}{L} = \frac{g_{ms(d)}\phi_t}{2I_{SH}\left(\sqrt{1 + i_{f(r)}} - 1\right)}$$

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

Small –signal eqs

I_S, V_{T0} and n extraction

The g_m/I_D method



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

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

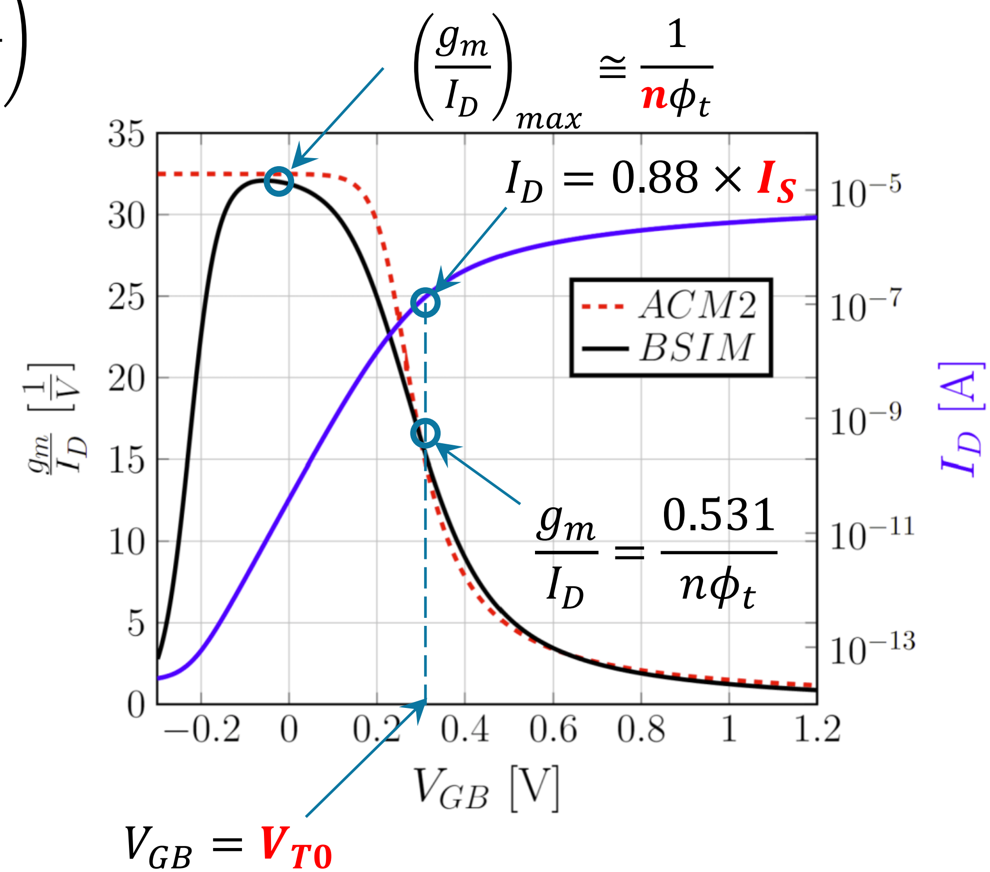
Thus : $i_r = 2.12$

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

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

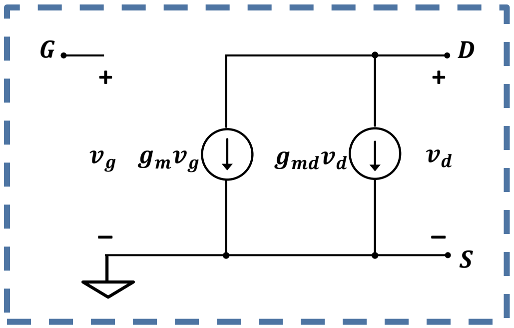
$$I_D = I_S(i_f - i_r)$$

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

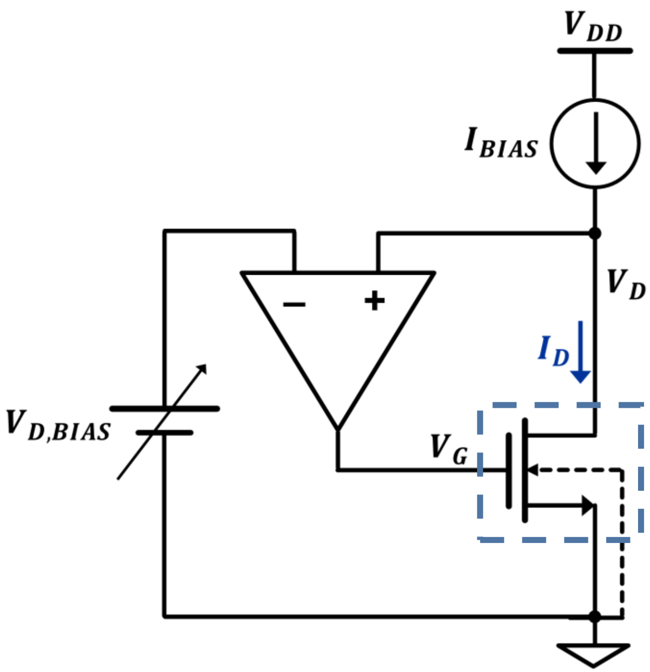


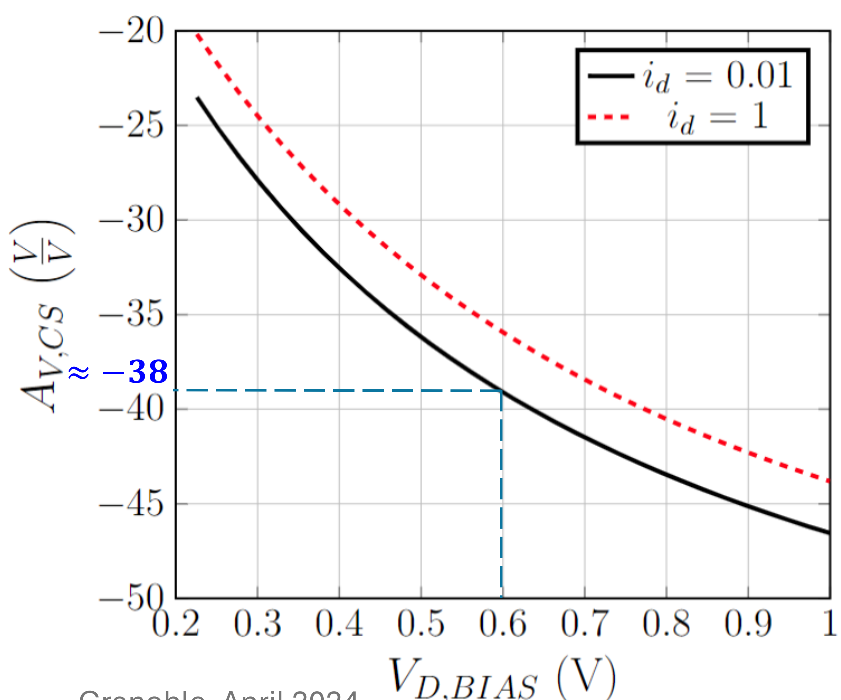
Extraction of σ

Common-Source Intrinsic-Gain method



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





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

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

$$\sigma = 0.026$$

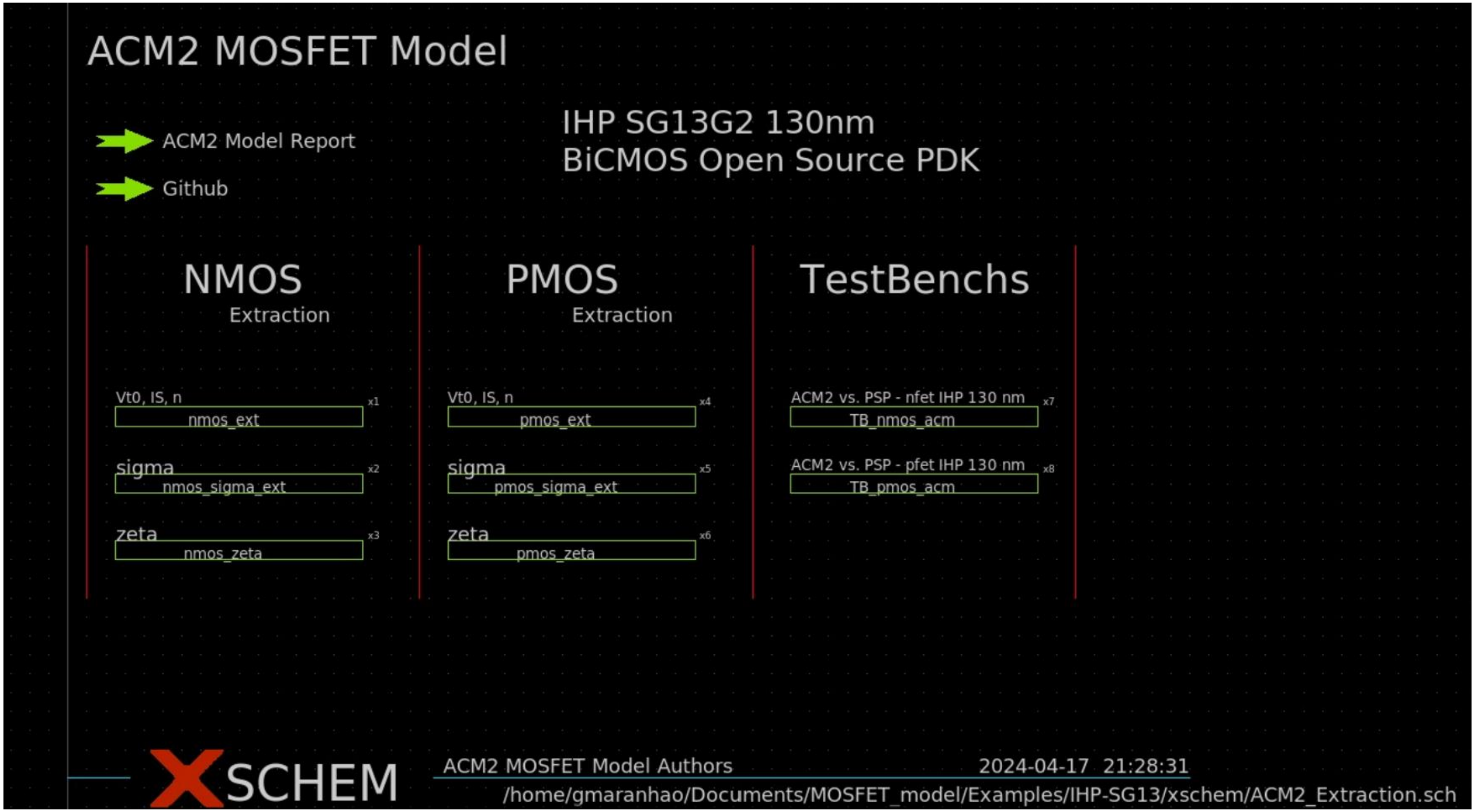
ζ extraction

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

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

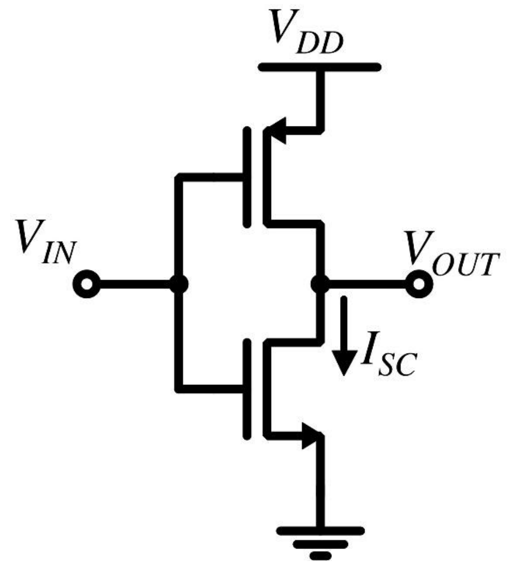
- q_s calculated using parameters (V_{T0} , n, σ) and UCCM.
- Measure $I_{Dsat} = I_D(V_G = V_D = V_{DDmax}\ and\ V_S = V_B)$ ⇨ $i_{dsat} = I_{Dsat}/I_S$.
- Example: NMOS transistor, V_G = V_D = V_{DDmax} and V_S = V_B = 0V.

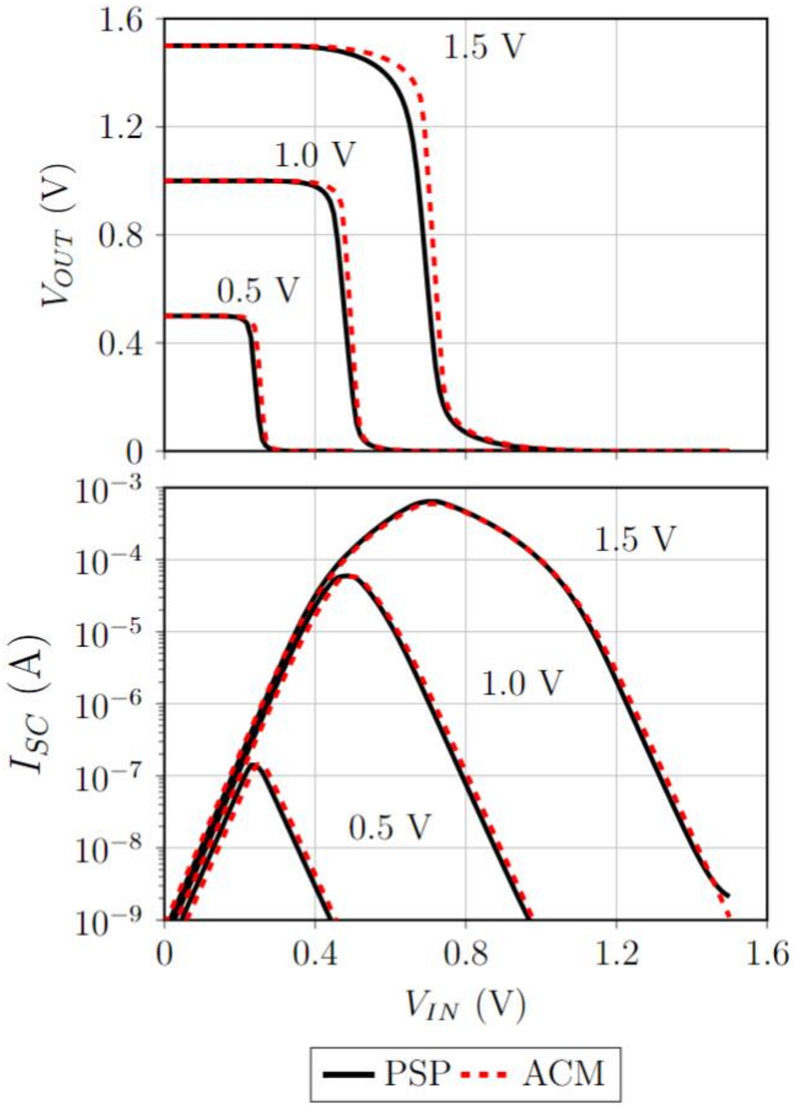
Automatic parameter extraction – IHP @ Xschem



Also, it will be available for GF180 and SKY130

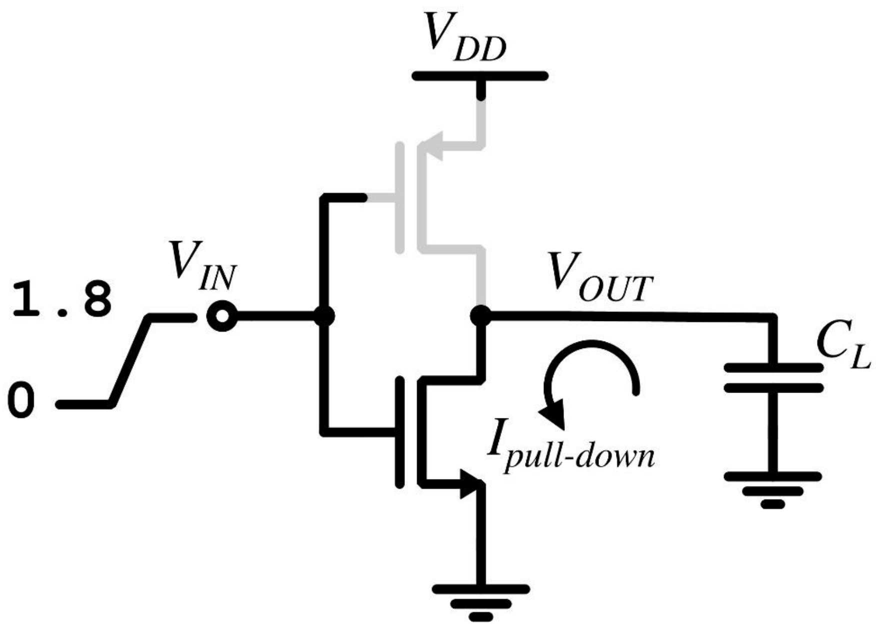
CMOS Inverter in 130 nm bulk
VTC and short-circuit current

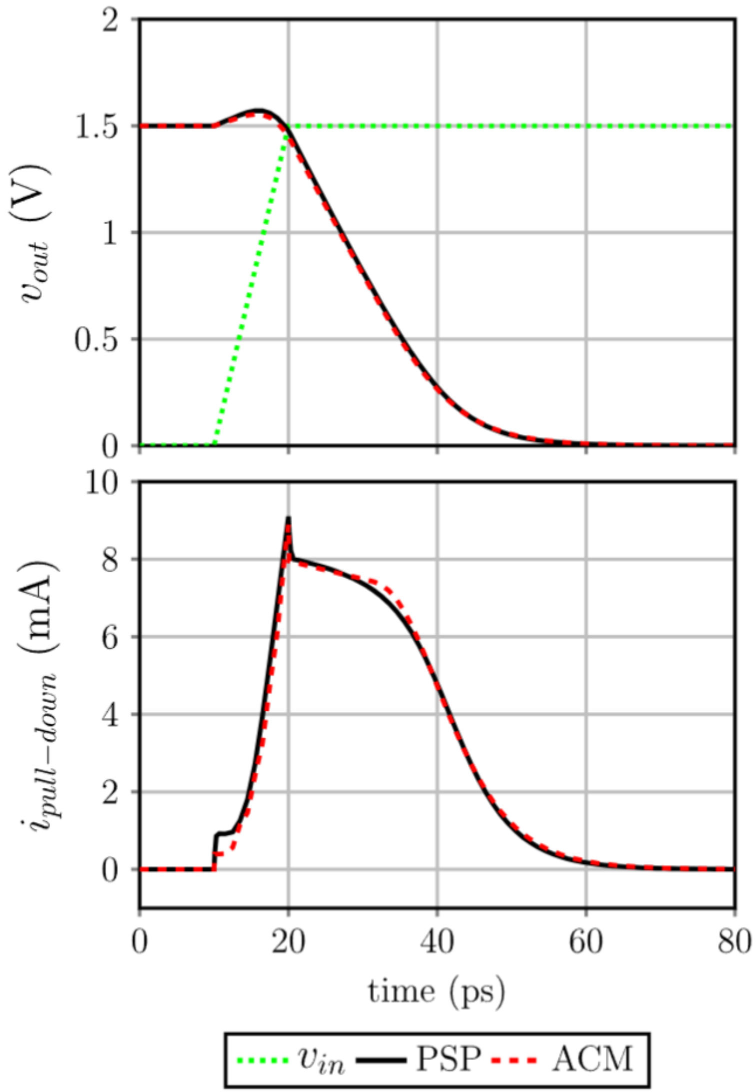




CMOS Inverter in 130 nm bulk

Output Voltage and pull-down current





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

Examples of PDKs and circuit simulators using the ACM model

XSCHEM

- GF180MCU
- IHP-SG13
- QucsStudio
- SkyWater130
- Spectre

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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); \
```

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 am Oder, Germany**
- **STIC-AmSud multinational program**
- **CAPES and CNPq agencies, Brazil**
- **CASS Tour France for the invitation**

Happening now:

ODIN

Chipathons:

IEEE SOLID-STATE CIRCUITS SOCIETY
IC Innovation

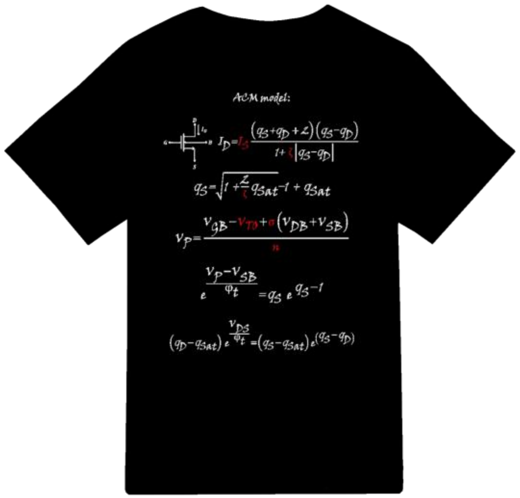
UNIC-CASS
Universalization of IC Design from IEEE CASS

What's next?

Live demo of the ACM2 @

ISCAS 2024

ACM2 merch



Main References

- C. M. Adornes, D. G. Alves Neto, M. C. Schneider and C. Galup-Montoro, "Bridging the Gap between Design and Simulation of Low-Voltage CMOS Circuits ," Journal of Low Power Electronics and Applications, vol. 12, issue 2, June 2022.
- 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.

- ACM2.0 Github: https://github.com/ACMmodel/MOSFET_model
- IHP Github : https://github.com/IHP-GmbH/IHP-Open-PDK

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