Part 3
Advanced Compact MOSFET Model: Parameter extraction

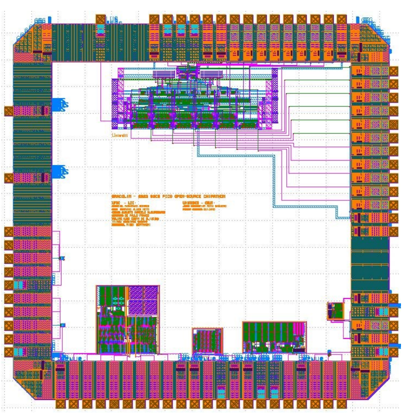
“Scan me”

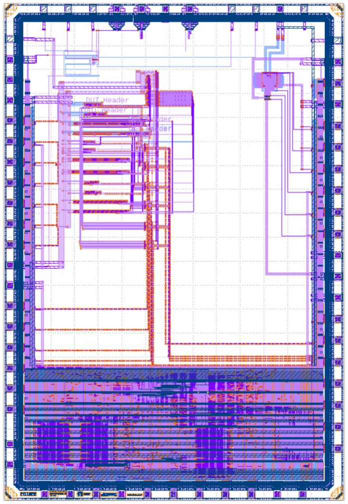
Deni Germano Alves Neto

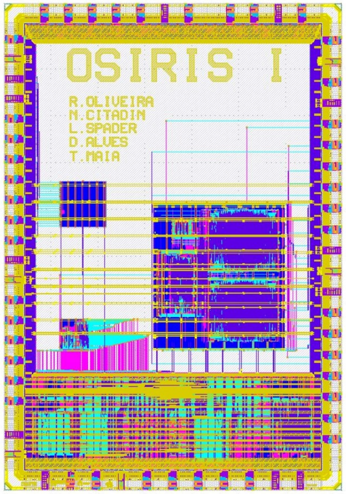
https://github.com/ACMmodel/MOSFET_model

About me

- Universidade Federal de Santa Catarina – UFSC - Brazil
- Undergrad and Masters in IC design - 2022
  - Subject : Ultra-Low-Voltage IC circuits $V_{DD} < 100\ mV$
    - Dissertation: Ultra-Low-Voltage Standard Cell Library
      - ACM for low voltage circuits
- Contact with open-source IC design :
  - Chipathon - SSCS 2021 : Analog-front-end for Biosignals – AFEbio
  - Chipathon-SSCS & UNIC-CASS 2023/2024 – Analog/Digital IC design
- Start PhD in 2023 : MOSFET Modeling – ACM2
- Joint PhD between UFSC and
- UGA - Grenoble INP
  - TIMA (Currently based)
  - RFIC design







Outline

- ACM2 : Parameter Extraction
  - 3-DC-parameter model
    - VT0, IS and n
  - Transconductances in Saturation
    - Sigma & Zeta
  - DC and small-signals characteristics
  - Example: Inverter CMOS
- Overview of Open-source environment
  - Automatic parameter extraction

ACM2: A simple 5-DC-parameter MOSFET model

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

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

Used to calculate q_s

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

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

Used to calculate q_d

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

Specific current I_S ***(W,L)***	**Threshold voltage** V_{T0} ***(W,L)***	**Slope factor** n ***(W,L)***	**DIBL factor** σ ***(W,L)***	**V_{sat} effect** ζ ***(W,L)***

I_{S0}, V_{T0} and n extraction→ let's simplify and use only the 3-parameter model (no sat no DIBL)

DC equations

$$I_D = \boldsymbol{I_S} \frac{(q_s + q_d + 2)}{1 \cancel{+ \zeta(q_s - q_d)}}(q_s - q_d) \qquad \text{where} \qquad \boldsymbol{I_S} = \mu C_{ox} \boldsymbol{n} \frac{\phi_t^2}{2} \frac{W}{L} = I_{SH} \frac{W}{L}$$

$$\frac{V_{DS}}{\phi_t} = q_s - q_D + \ln\left(\frac{q_S \cancel{- q_{Dsat}}}{q_D \cancel{- q_{Dsat}}}\right)$$

No saturation effect → no ζ,no q_{Dsat}

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

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

No DIBL effect → no $\boldsymbol{\sigma}$

Remember that:

$$I_D = \boldsymbol{I_S}[i_f - i_r] \qquad \text{with} \qquad \begin{cases} q_s = \sqrt{1 + i_f} - 1 & \text{for forward current} \\ q_D = \sqrt{1 + i_r} - 1 & \text{for reverse current} \end{cases}$$

Then we re-write:

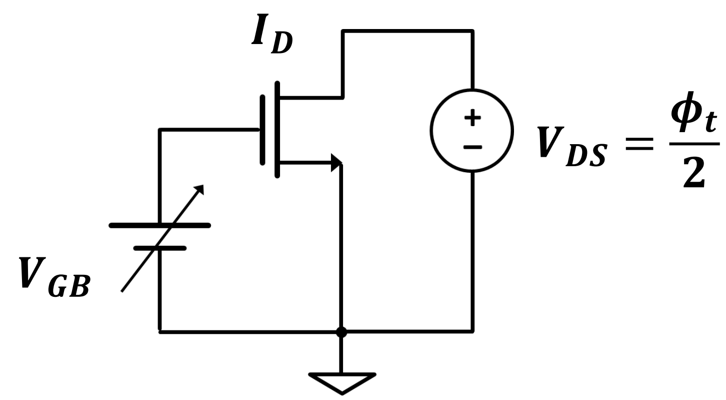
$$\frac{V_{DS}}{\phi_t} = \sqrt{1 + i_f} - \sqrt{1 + i_r} + \ln\left(\frac{\sqrt{1 + i_f} - 1}{\sqrt{1 + i_r} - 1}\right) \qquad \frac{V_P - V_{SB}}{\phi_t} = \sqrt{1 + i_f} - 2 + \ln\left(\sqrt{1 + i_f} - 1\right)$$

I_{S0}, V_{T0} and n extraction→ let's simplify and use only the 3-parameter model (no sat no DIBL)

From DC equations

If we choose $i_f = 3 \leftarrow\rightarrow q_S = 1 \leftarrow\rightarrow V_P = 0 \leftarrow\rightarrow V_{GB} = \boldsymbol{V_{T0}}$

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



If we add that we want to work at $V_{DS} = \phi_t/2$

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

Then $i_r = 2.12$ and $I_D = \boldsymbol{I_{S0}}[i_f - i_r] = 0.88\ \boldsymbol{I_{S0}}$

Consequence on small signal equations for $i_f = 3$ and $V_{DS} = \phi_t/2$

$$\frac{g_m}{I_D} = \frac{1}{\boldsymbol{n}\phi_t} \cdot \frac{2}{\left(\sqrt{1+i_f} + \sqrt{1+i_r}\right)} = \frac{0.531}{\boldsymbol{n}\phi_t}$$

Meanwhile $$\left.\frac{g_m}{I_D}\right|_{max} = \frac{1}{\boldsymbol{n}\phi_t} \qquad i_f(i_r) \approx 0$$

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 $i_f = 3$ $\Rightarrow$ $RHS = 0$ $\Rightarrow$ $V_{GB} = \boldsymbol{V_{T0}}$

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

DC eqs

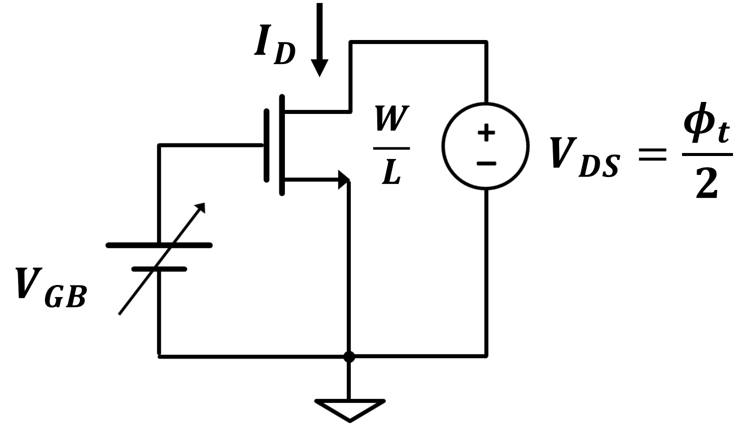
$$g_{ms(d)} = \frac{2I_S}{\phi_t}\left(\sqrt{1+i_{f(r)}} - 1\right) \Rightarrow \frac{W}{L} = \frac{g_{ms(d)}\phi_t}{2I_{SH}\left(\sqrt{1+i_{f(r)}} - 1\right)}$$

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

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 $i_f = 3$

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

$\boxed{\text{Thus}: i_r = 2.12}$

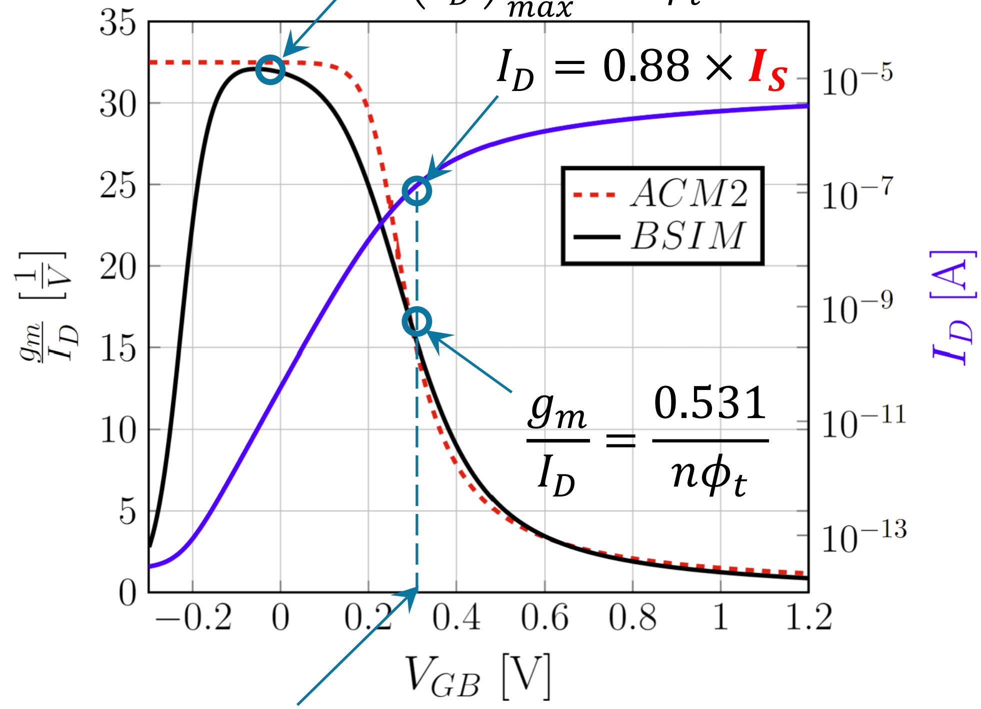
$$\frac{g_m}{I_D} = \frac{d(\ln I_D)}{dV_G} = \frac{2}{n\phi_t\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)}$$

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

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

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

$$\left(\frac{g_m}{I_D}\right)_{max} \cong \frac{1}{n\phi_t}$$



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ACM2 : Transconductances in saturation

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

Definitions $\begin{cases} g_m \triangleq \frac{\partial I_{Dsat}}{\partial V_G} \quad g_d \triangleq \frac{\partial I_{Dsat}}{\partial V_D} \quad g_{msat3} \triangleq \frac{\partial^3 I_{Dsat}}{\partial V_G^3} \end{cases}$

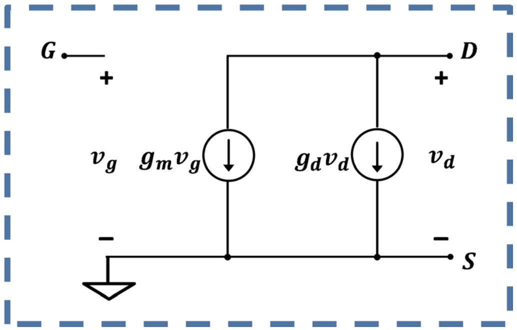
Transconductances in terms of q_s:

$$g_{msat} = \frac{2I_S}{n\phi_t} \frac{q_s}{1 + \zeta(q_s + 1)} \qquad g_{dsat} = \sigma \frac{2I_S}{n\phi_t} \frac{q_s}{1 + \zeta(q_s + 1)} \Rightarrow g_{dsat} = \sigma g_{msat}$$

$$g_{msat3} = \frac{16I_S}{(n\phi_t)^3} \frac{q_s}{(q_s + 1)^3} \frac{2 - 2\zeta q_s - 3\zeta q_s^2}{(\zeta q_s + 2)^4}$$

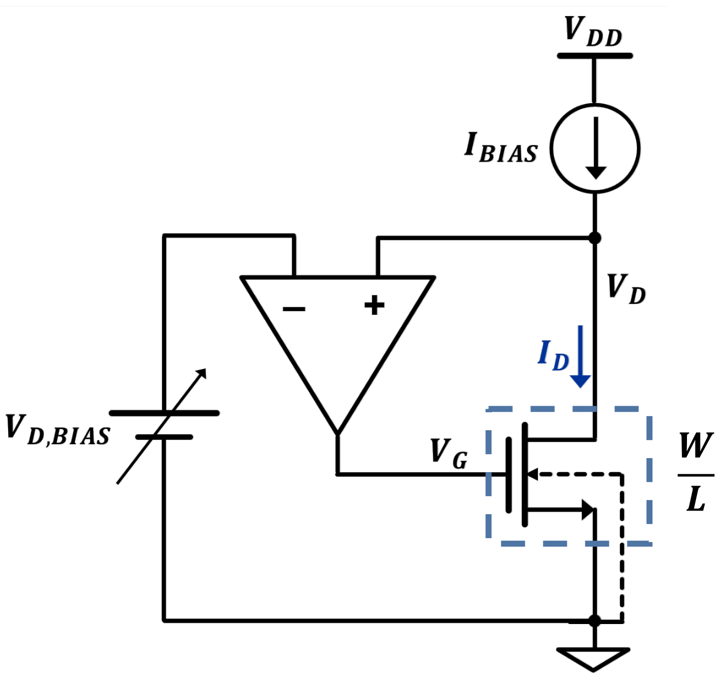
Extraction of σ

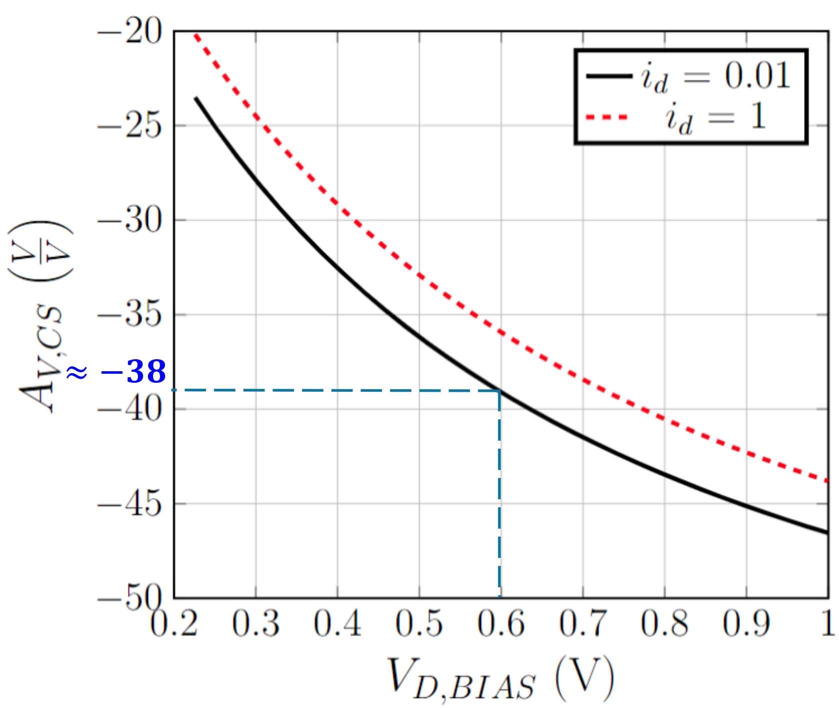
Common-Source Intrinsic-Gain method



In saturation : $g_{dsat} = \boldsymbol{\sigma} g_{msat}$

$$A_{V,CS} = \frac{\Delta v_D}{\Delta v_G} = -\frac{g_{msat}}{g_{dsat}} = \frac{\frac{\partial I_{Dsat}}{\partial V_G}}{\frac{\partial I_{Dsat}}{\partial V_D}} = -\frac{\frac{2I_S}{n\phi_t}\frac{q_s}{1+\zeta(q_s+1)}}{\sigma\frac{2I_S}{n\phi_t}\frac{q_s}{1+\zeta(q_s+1)}} = -\frac{1}{\sigma}$$





Example:

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

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

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

ζ extraction

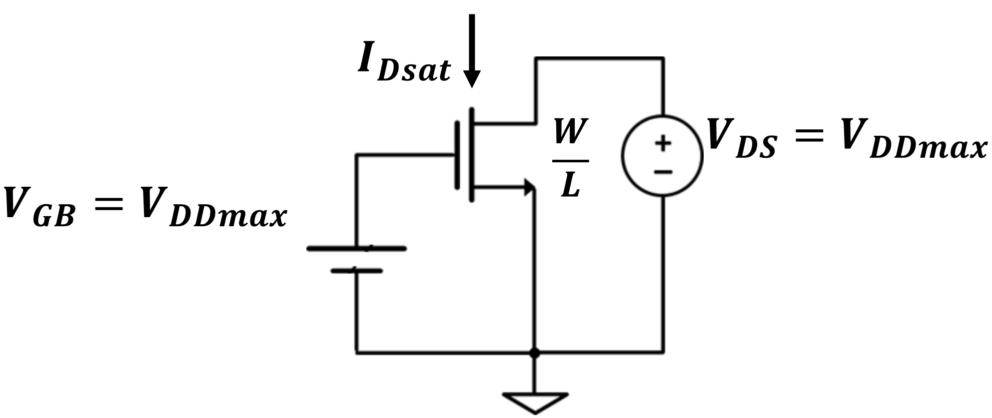
$$i_{dsat} = \frac{2}{\zeta} q_{dsat} \qquad q_s = \sqrt{1+\frac{2}{\zeta}q_{dsat}} - 1 + q_{dsat}$$

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

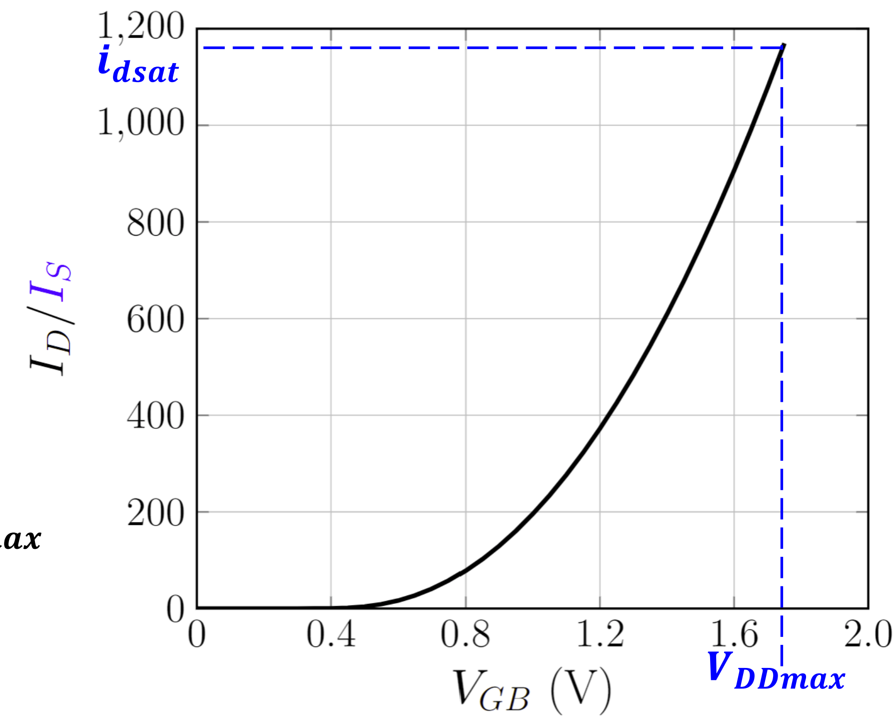
- q_s calculated using parameters (V_{T0}, n, σ) and UCCM.

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

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



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



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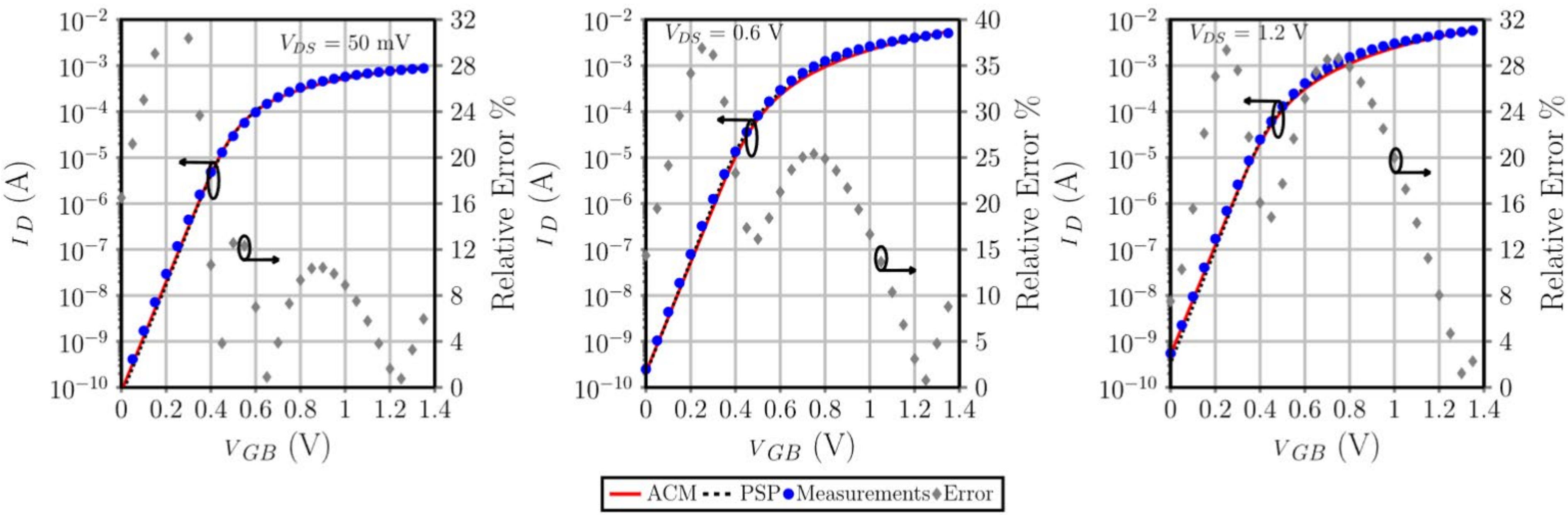
ACM2[1] vs PSP – 130 nm SiGe IHP[2]

$I_D \ vs \ V_{GB}$

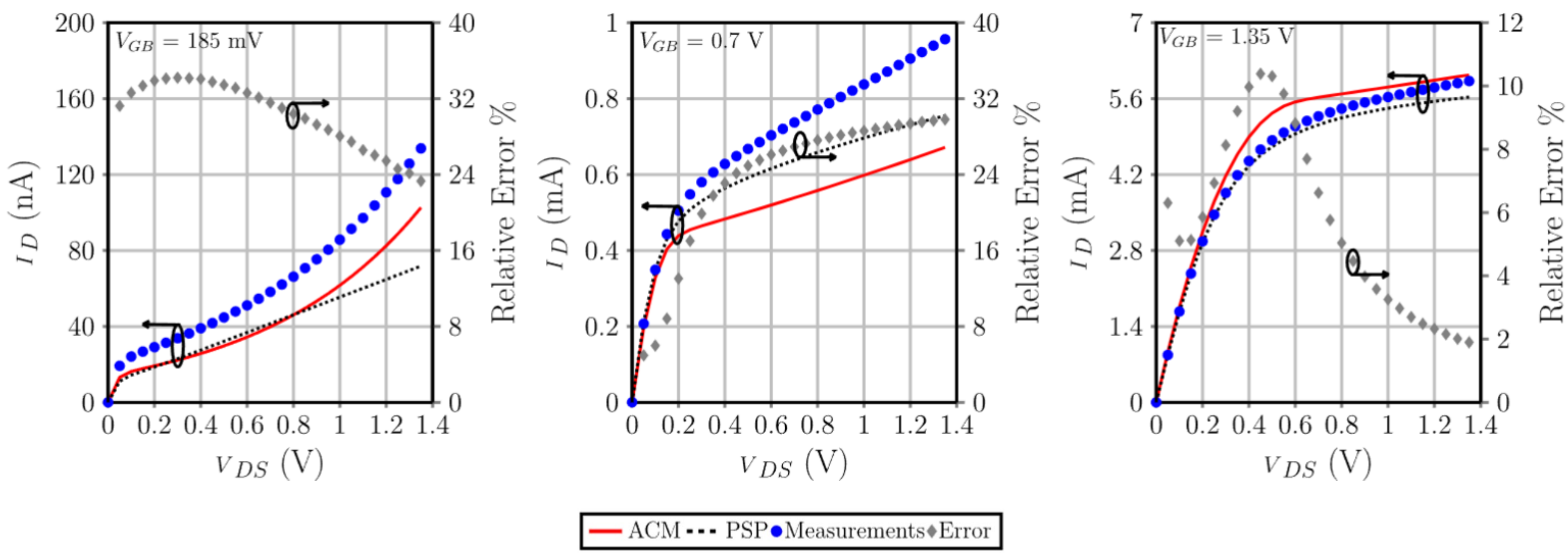


Characteristics of a LVT NMOS bulk transistor with W /L = 10µm/ 120 nm.

[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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[1] ACM2 : implemented in verilog-A, compiled by OPENVAF, simulated in Ngspice

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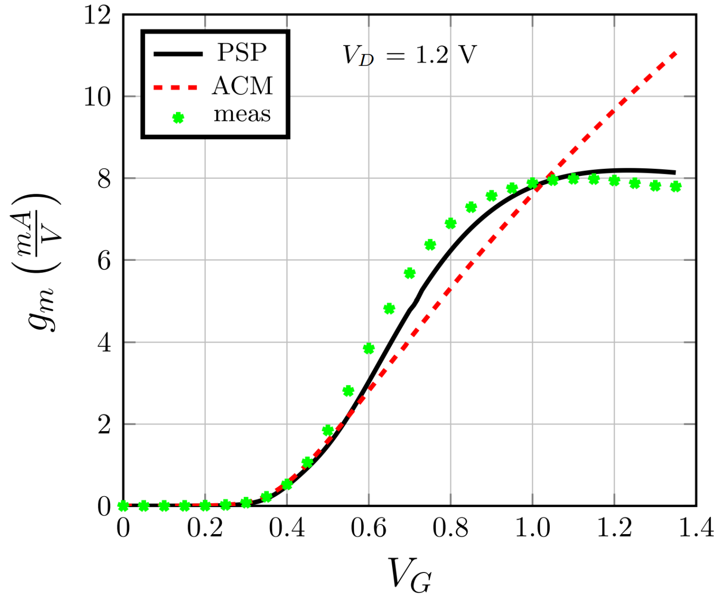
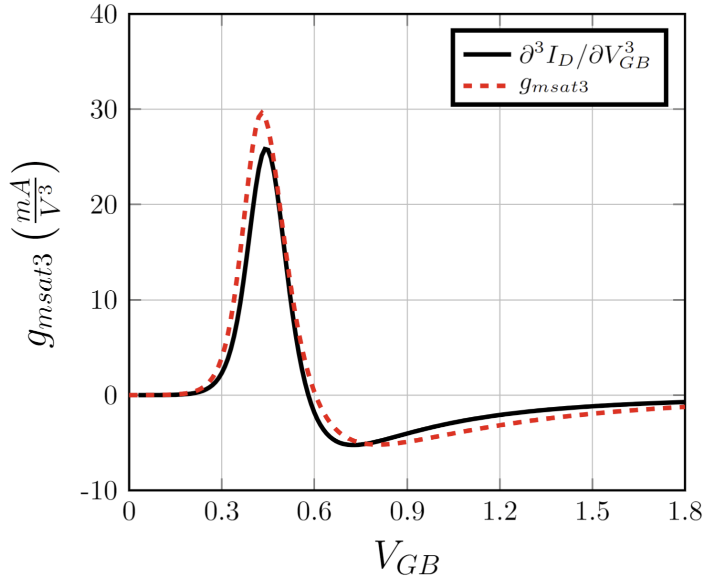
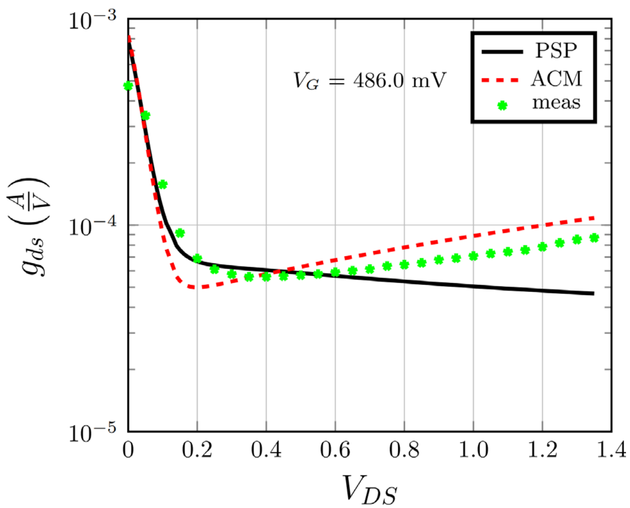
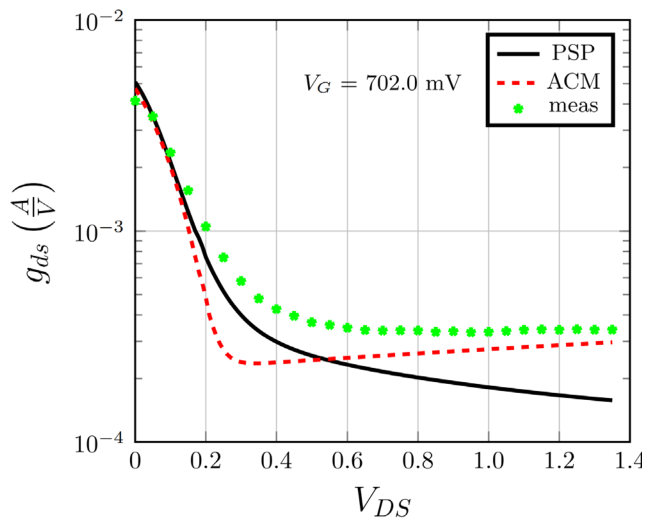
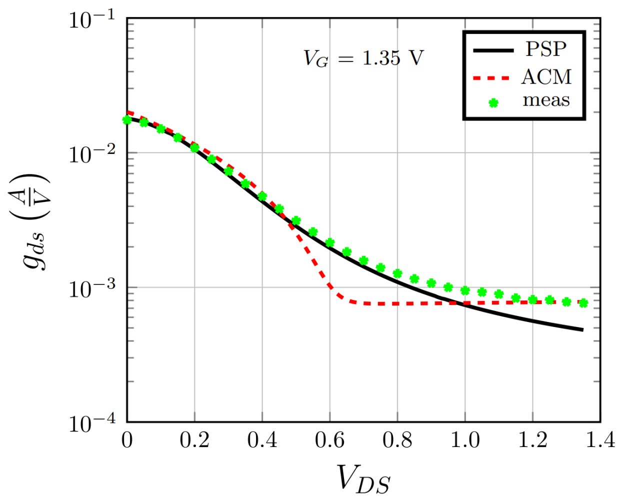
5PM-ACM2 : Transconductance gm, gm3 and gds



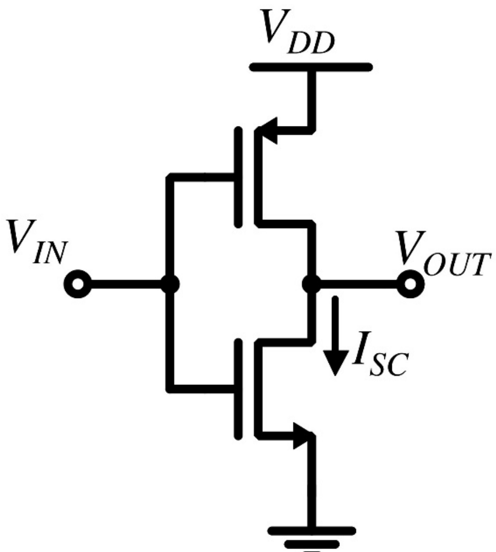


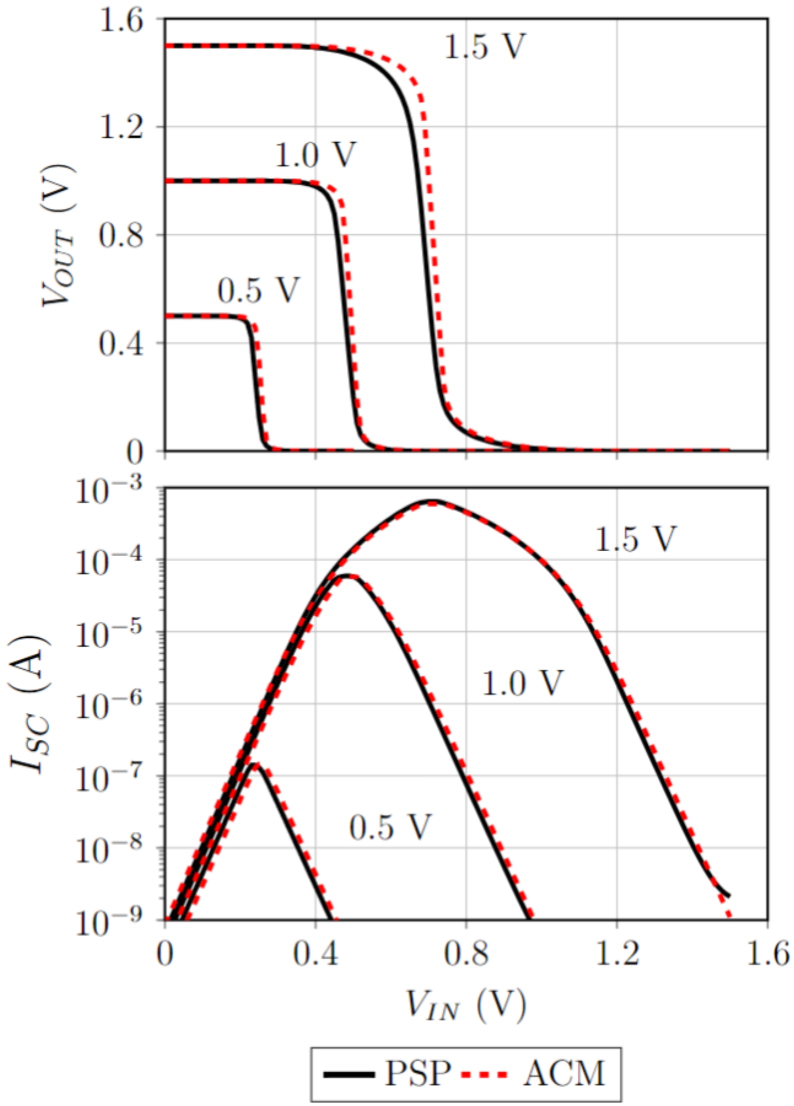






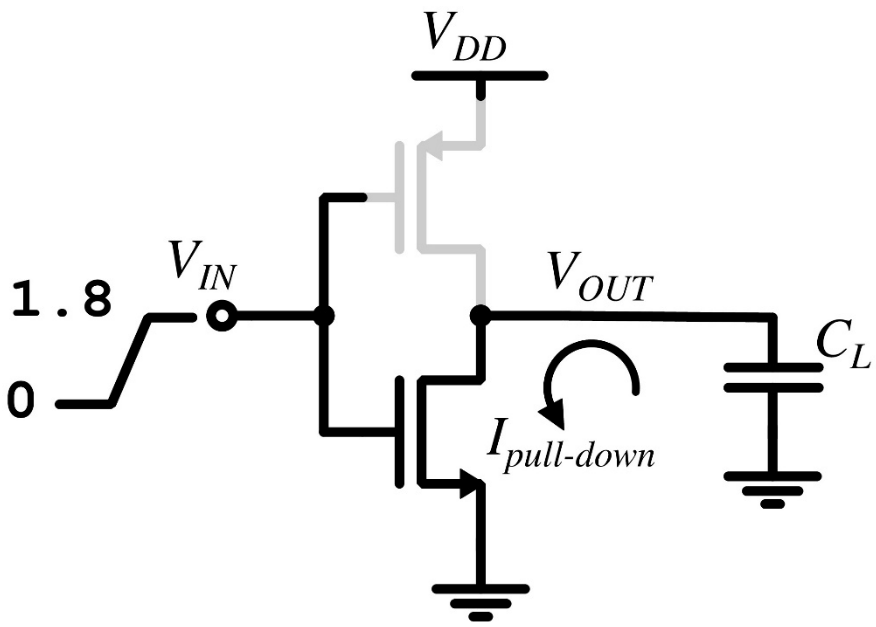
CMOS Inverter in 130 nm bulk
VTC and short-circuit current

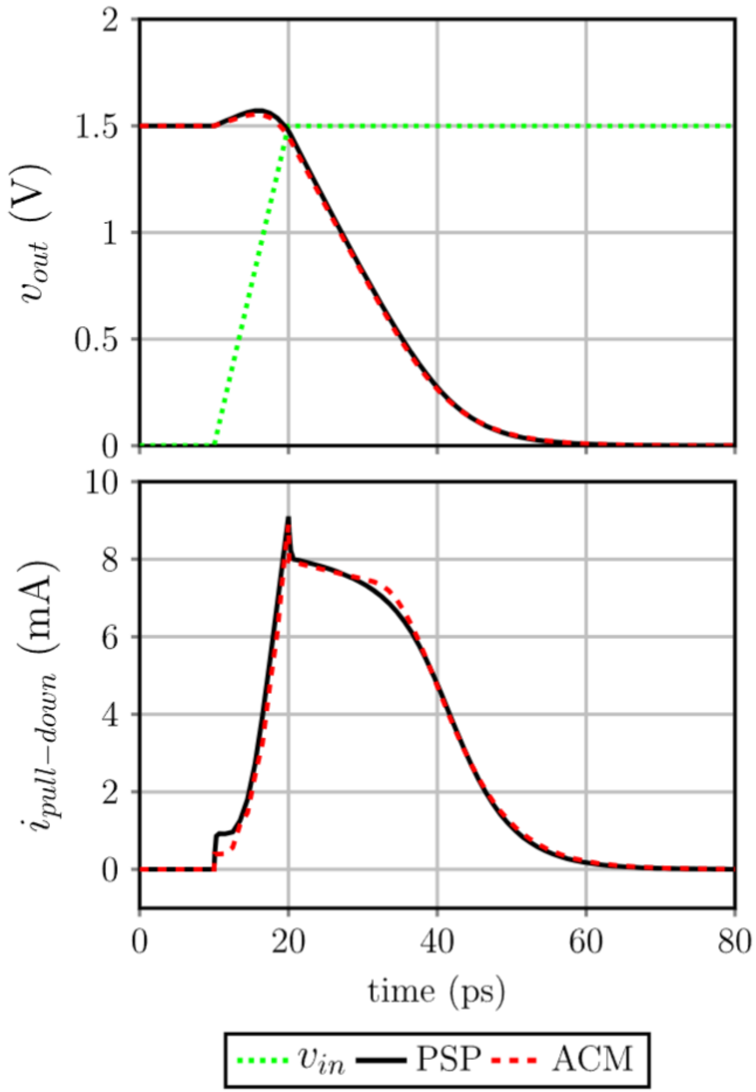




CMOS Inverter in 130 nm bulk

Output Voltage and pull-down current





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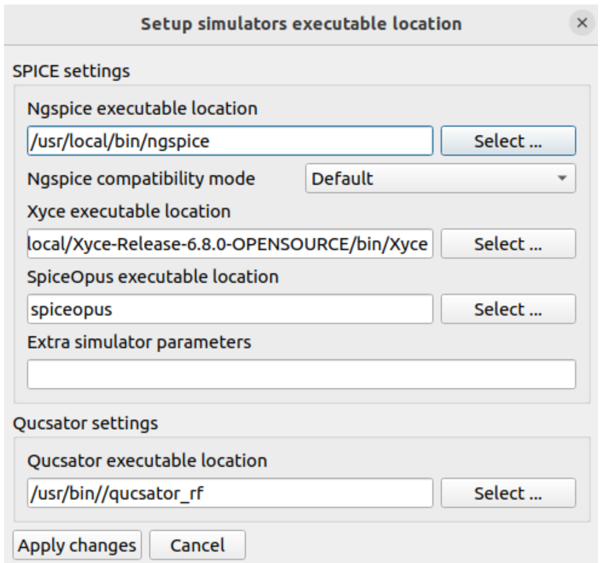
Qucs-S: Quite universal circuit simulator with SPICE

Simulation setup:


Setup simulators executable location

SPICE settings

Ngspice executable location

/usr/local/bin/ngspice | Select ...

Ngspice compatibility mode | Default

Xyce executable location

local/Xyce-Release-6.8.0-OPENSOURCE/bin/Xyce | Select ...

SpiceOpus executable location

spiceopus | Select ...

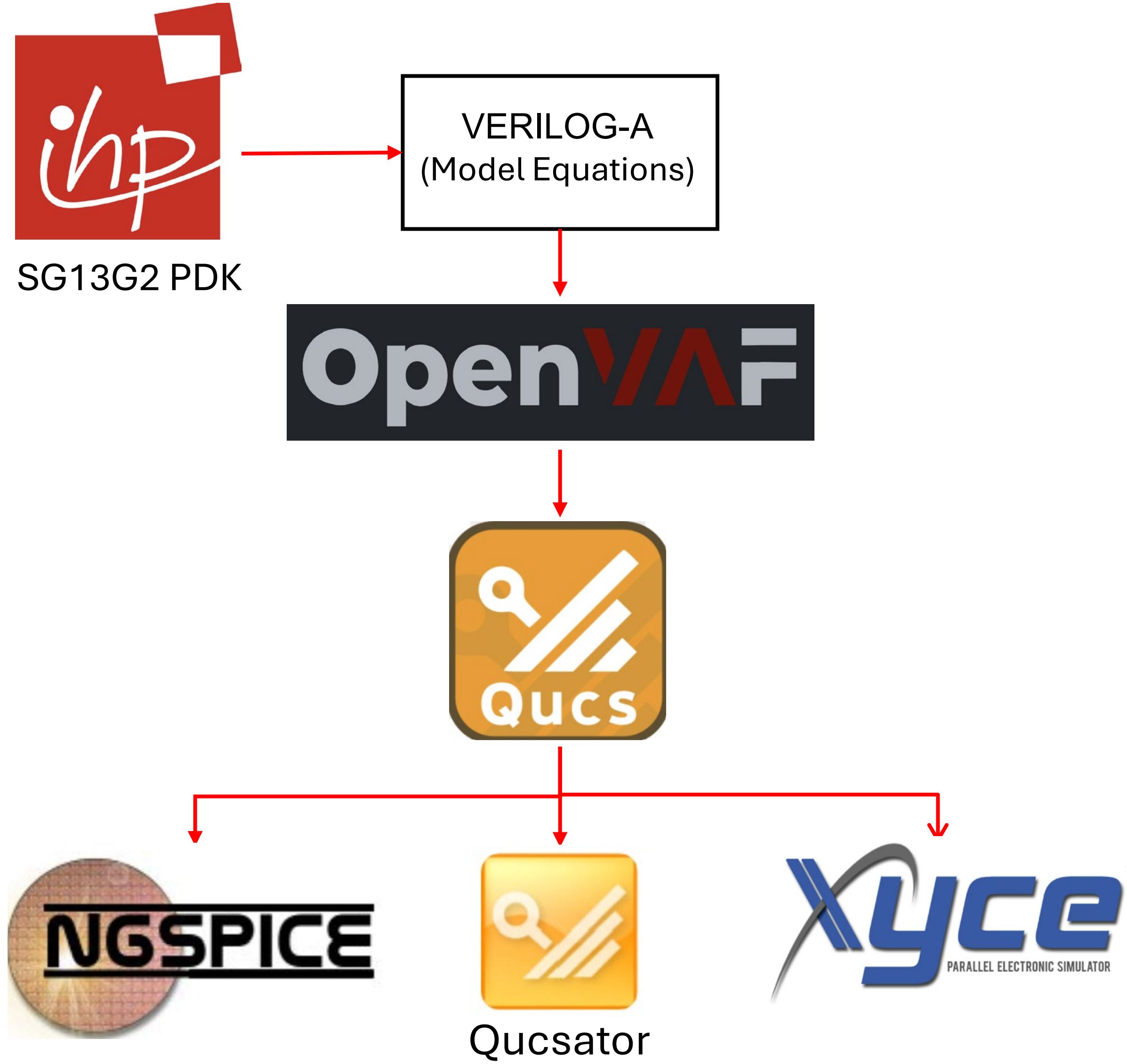
Extra simulator parameters

Qucsator settings

Qucsator executable location

/usr/bin//qucsator_rf | Select ...

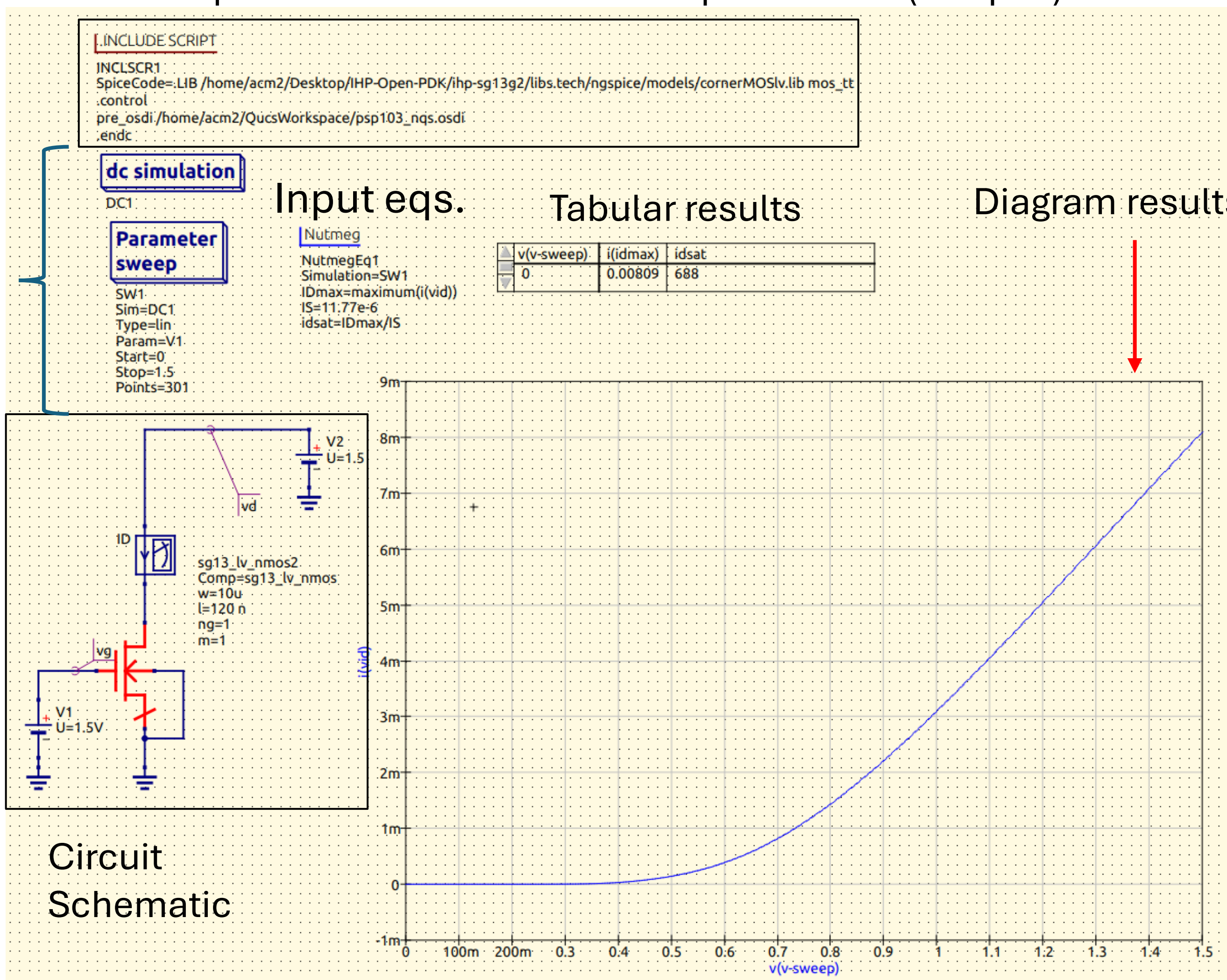
Apply changes | Cancel



Qucs-S: Quite universal circuit simulator with SPICE

Device path for the MOS model and parameters (IHP pdk)

Simulations Control



- Ngspice simulations:
  - DC
  - AC
  - TRAN
  - S-parameters
  - Noise
  - Fourier

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

“Scan me”

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); \
```

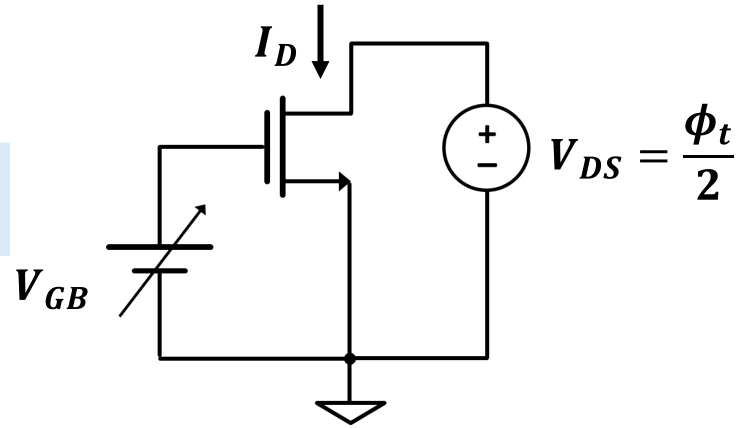
Examples of PDKs and circuit simulators using the ACM model

NGSPICE & XSCHEM → GF180MCU, IHP-SG13, SkyWater130

Qucs → IHP-SG13

I_{S0}, V_{T0} and n extraction

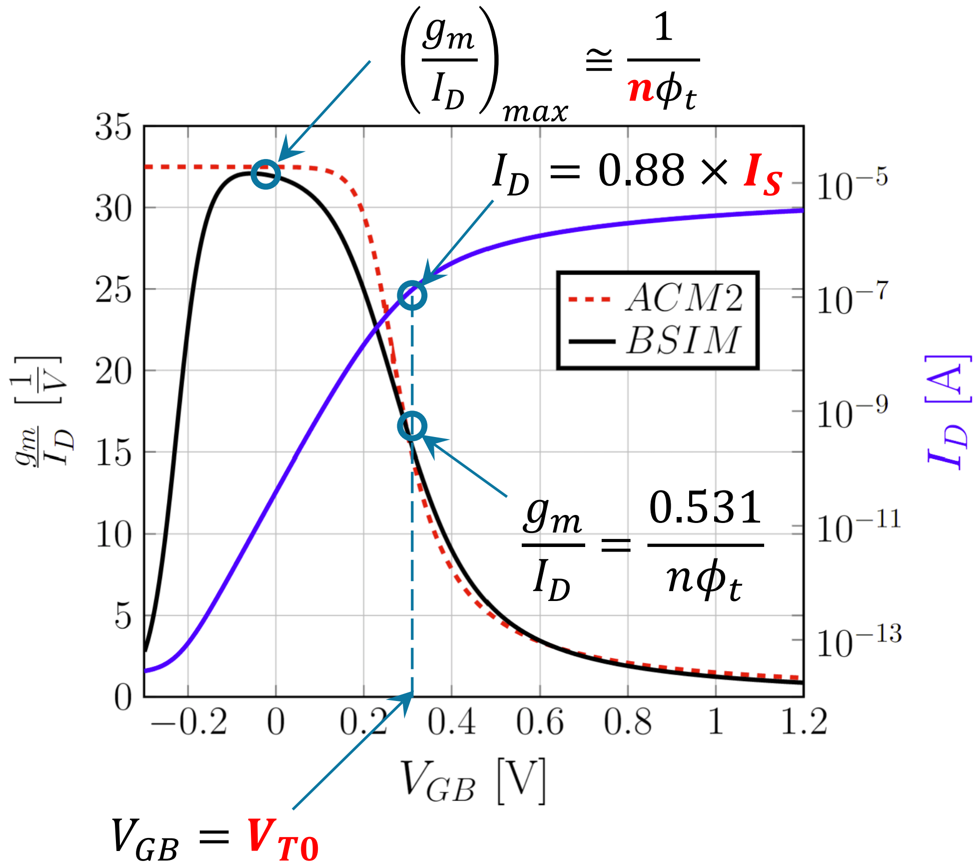
The g_m/I_D method



We identify the $\left.\frac{g_m}{I_D}\right|_{max}$ → n

We calculate $0.531 \left.\frac{g_m}{I_D}\right|_{max}$ → V_{T0}

We read the value of I_D → I_S



Practical part → Go to QuCS !

Let’s go to Qucs-S!

Useful links:

- Qucs-S oficial page: https://ra3xdh.github.io/
- Qucs-S iterative doc: https://qucs-s-help.readthedocs.io/
- Ngspice oficial page : https://ngspice.sourceforge.io/index.html
- Google Colab: ACM2 & LNA design:
  https://colab.research.google.com/drive/1s3PKF6pf3zIhlTj6jc-qhCLIcGfJ_UEE?usp=sharing

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

CAPES

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

SOIL
SOLIDIFY THE EUROPEAN FDSOI ECOSYSTEM ACCELERATING ITS INDUSTRIAL DEPLOYMENT

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References

- D. Germano Alves Neto et al., "Design-Oriented Single-Piece 5-DC-Parameter MOSFET Model," in IEEE Access, vol. 12, pp. 87420-87437, 2024.
- ACM2 Github: https://github.com/ACMmodel/MOSFET_model
- IHP Github : https://github.com/IHP-GmbH/IHP-Open-PDK

"Scan me"

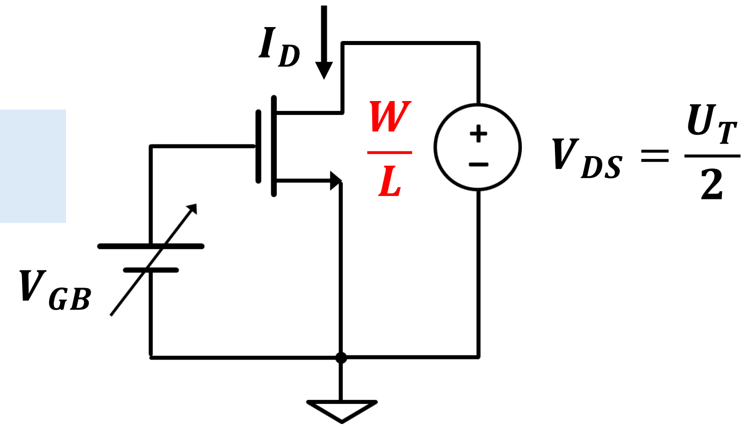
- **Available in Github:**
  - **DC model**
  - **Small-signal model**
  - **Dynamic model**
  - **Thermal &**

Flicker noise models (1/f)

Step-by-Step extraction

I_{S0}, V_{T0} and n extraction

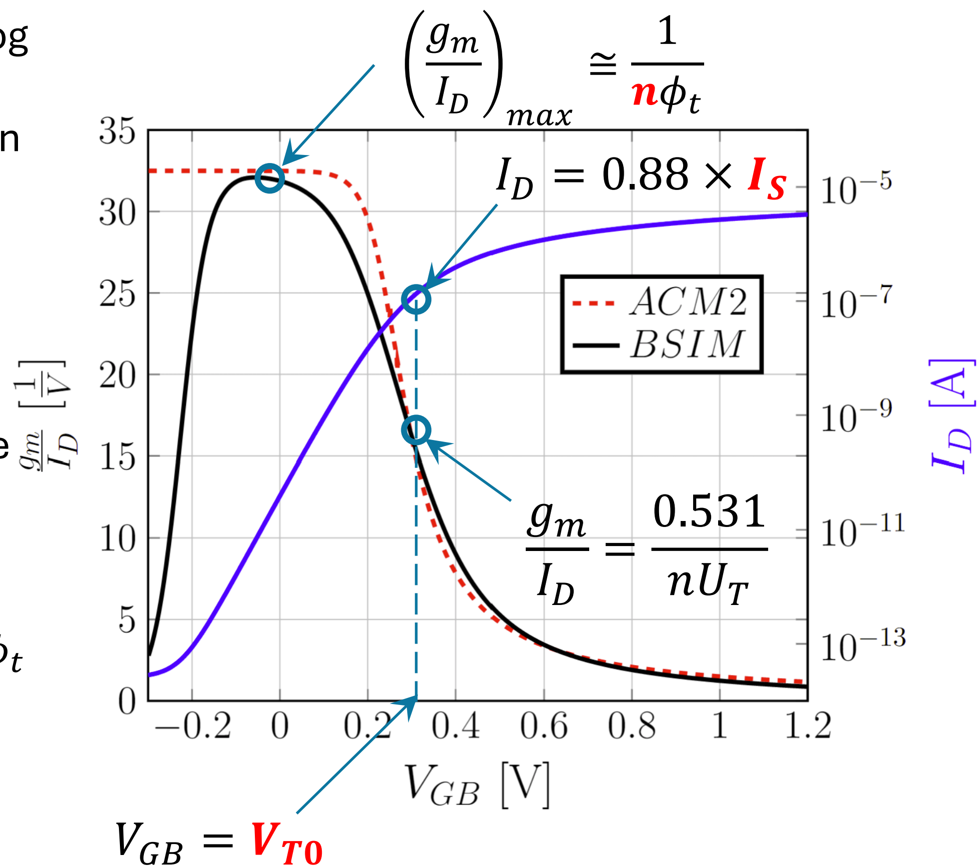
g_m/I_D method – Steps!



1. Assemble the circuit for extraction
2. Define the VDS value
3. Do a voltage sweep in VGB and measure the drain current ID
4. Put on the right side of the plot the ID in semilog y axis
5. Plot the gm/ID characteristics using equation in Qucs-s.

$$\frac{g_m}{I_D} = \frac{d(\ln I_D)}{dV_G}$$

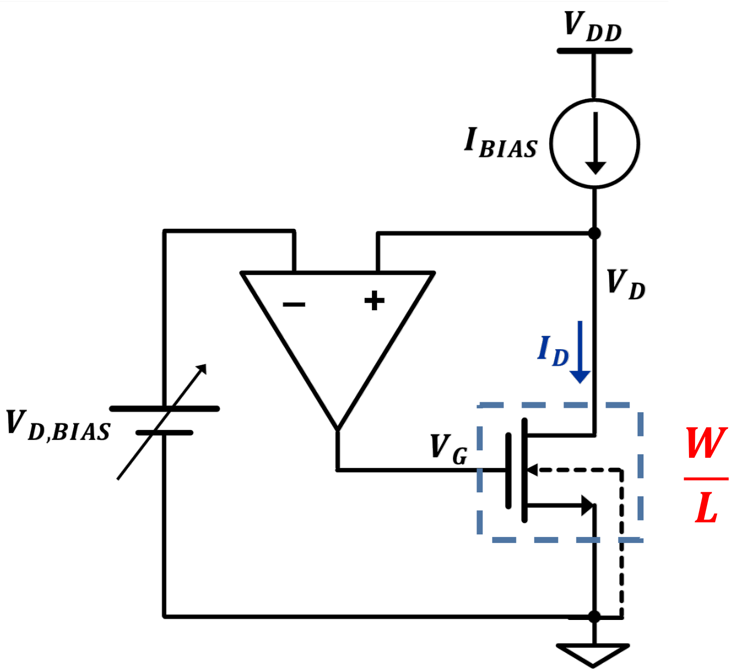
6. With a cursor measure the maximum of gm/ID
7. With gm/ID(max) multiply it by 0.531 to find the point in which VGB = VT0
8. IS is the same VGB value but in the ID curve divided by 0.88
9. n is extracted from the gm/ID(max) value and ϕ_t = 25.8 mV (room temperature)



σ extraction

Common-Source Intrinsic-Gain method - Steps!

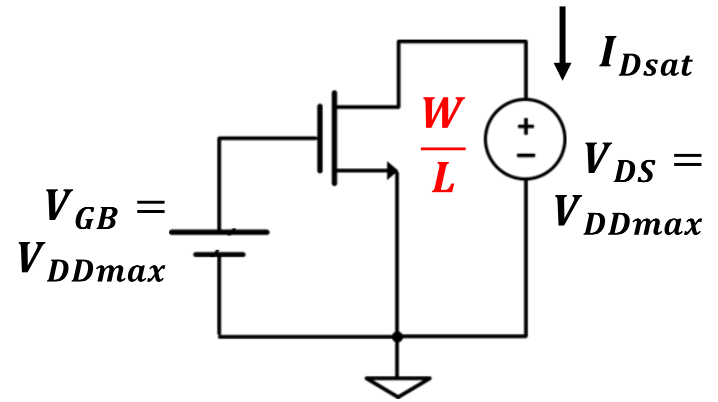
$$A_{V,CS} = \frac{\Delta v_D}{\Delta v_G} = -\frac{g_{msat}}{g_{dsat}} = -\frac{1}{\sigma}$$



1. Assemble the circuit for extraction
2. Define the IBIAS = 100 nA (weak inversion)
3. Use Qucs-S equations to calculate the derivate of vd and vg
4. Using equations set the equation for sigma
5. Do a voltage sweep in VD,BIAS from 0.2 V to 1 V
6. With a cursor measure the value for sigma at VD = VDDmax/3

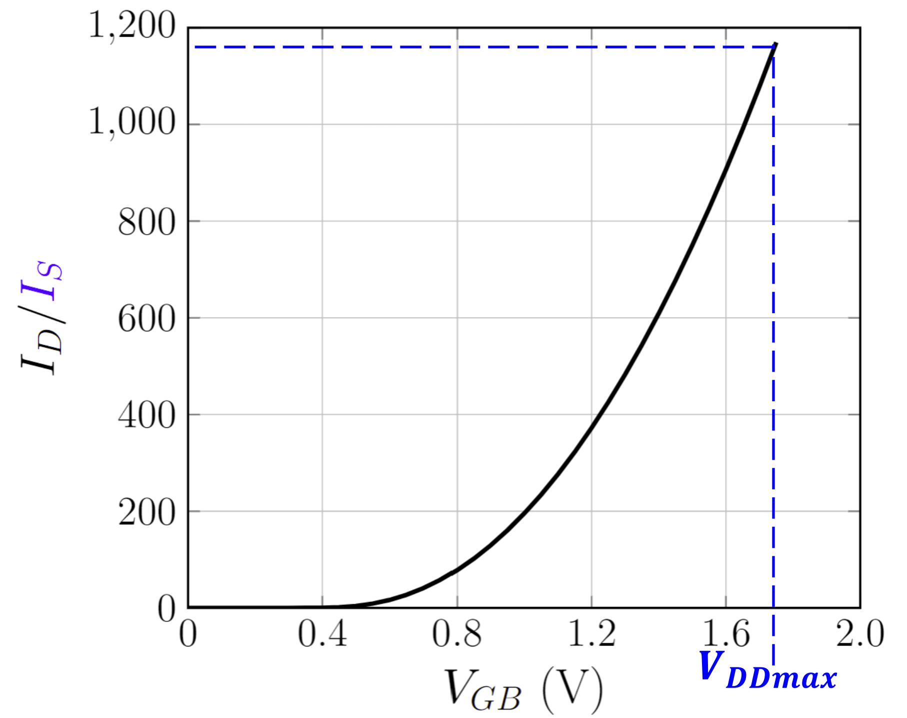
ζ extraction

Saturation method – Steps !



1. Assemble the circuit for extraction
2. Define $V_G = V_D = V_{DDmax}$ and $V_S = V_B = 0$ V
3. Using equations set the equation for $i_{dsat} = I_{Dsat}/I_{S0}$
4. Insert a table in Qucs-s to evaluate i_{dsat}

Google Colab: ACM2 & LNA design: https://colab.research.google.com/drive/1s3PKF6pf3zIhlTj6jc-qhCLIcGfJ_UEE?usp=sharing



5. Using the Colab, in the section Zeta extraction, we will insert the value of the appropriate idsat for the python code which calculate qs transcendant equation and then zeta!