Design and simulation of analog/RF circuits with the single-piece ACM2 MOSFET model

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IEEE ICECS 2024
31st IEEE International Conference on Electronics Circuits and Systems
Nancy, France | November 18-20, 2024

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18/11/2024

Part 1
Advanced Compact MOSFET Model: ACM2

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https://github.com/ACMmodel/MOSFET_model

18/11/2024

Outline

- **Introduction: ACM timeline**
- **ACM2 model**
- **Long-channel: I_D and g_m/I_D models**
- **Long-channel: MOS basic amplifier design**

ACM timeline

- **1993 φs model (SBMICRO, Campinas, Br)**
- **1995 Long-channel charge-based model (SSE, Nov.)**
- **1996 gm/ID model (SBMICRO, Aguas de Lindoia, Br)**
- **1997 Unified current control model (ISCAS, Hong Kong)**
- **1998 Most referenced ACM paper (JSSC, Oct.)**
- **2000 ACM model in SMASH simulator (CICC, Orlando)**
- **2021 4-parameter single-piece model (NorCAS, Oslo)**
- **2023 ACM2 in VERILOG-AMS (NEWCAS, Edinburgh)**

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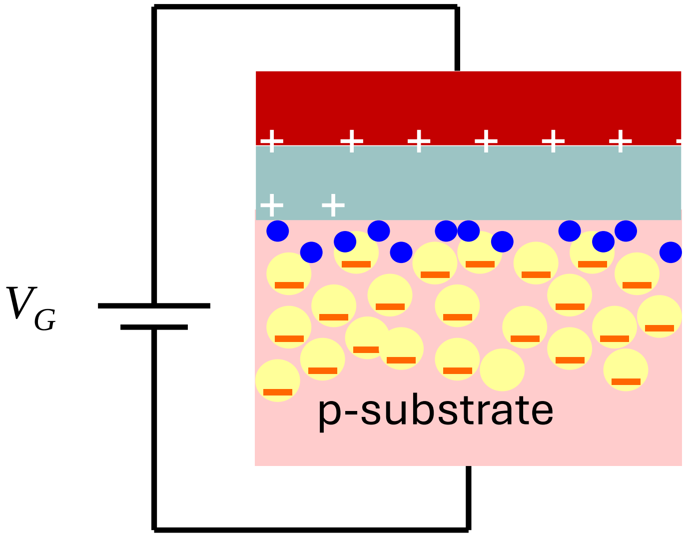
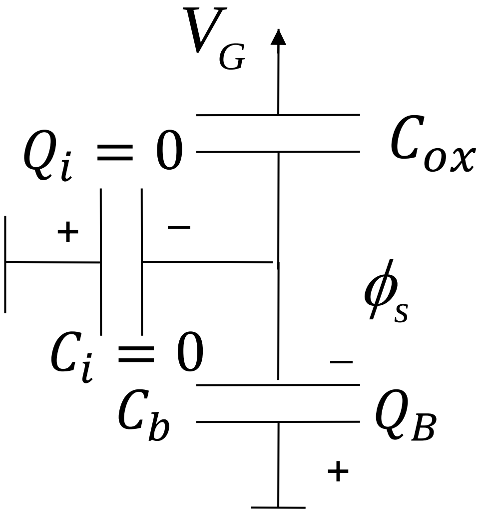
The capacitive model of the MOSFET





$$\frac{\Delta\phi_s}{\Delta V_G} = \frac{C_{ox}}{C_{ox} + C_b} = \frac{1}{n}$$

ϕ_s surface potential

C_{ox} oxide capacitance per unit area

C_b depletion capacitance per unit area

$$\phi_s = 2\phi_F + \frac{V_G - V_{T0}}{n} = 2\phi_F + V_P$$

Q_I carrier charge density

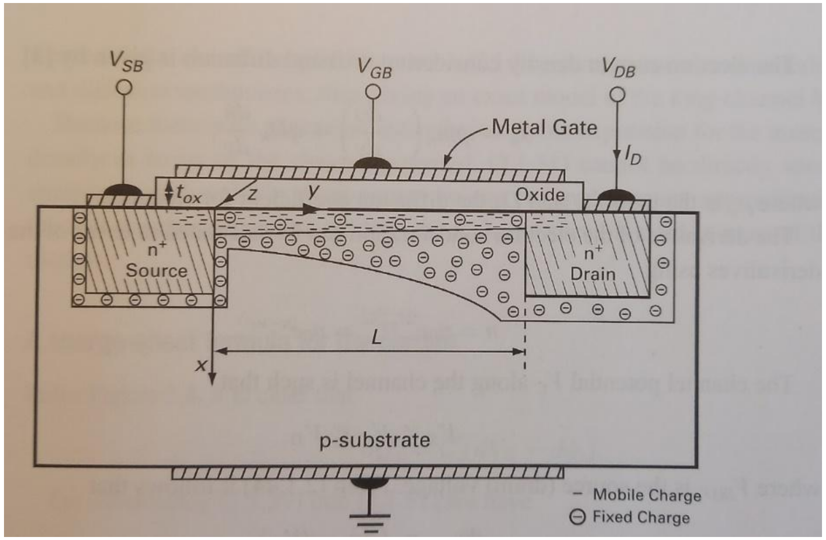
Drain current model: main simplifications

First approximation ACM2 $$dQ_I = nC_{ox}d\phi_s$$

Second approximation ACM2 $$I_D = \mu W\left(-Q_I\frac{d\phi_s}{dy} + \phi_t\frac{dQ_I}{dy}\right)$$

drift

Diffusion



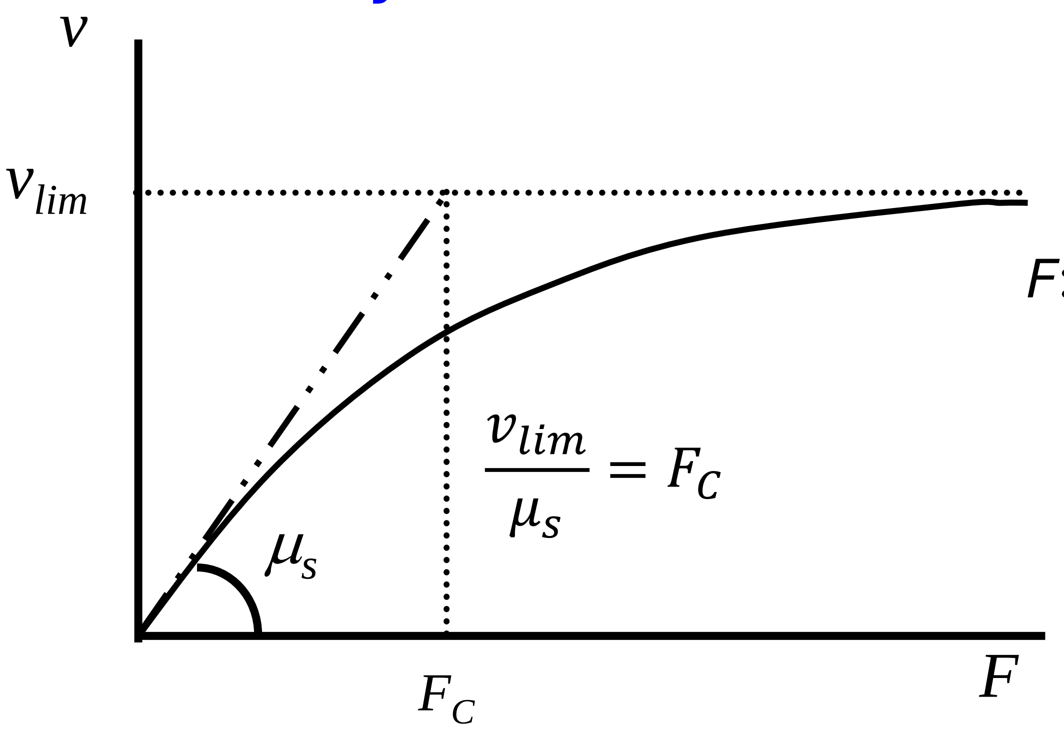
Q_I carrier charge density

W transistor width

μ carrier mobility

ϕ_t thermal voltage
26 mV @ 300K

Velocity saturation



$$\frac{v_{lim}}{\mu_s} = F_C$$

ϕ_S: surface potential

F: longitudinal electrical field

$$\frac{d\phi_S}{dy} = -F$$

Third approximation ACM2

$$\boxed{\mu = \frac{\mu_s}{1 + \frac{\mu_s}{v_{lim}} \frac{d\phi_S}{dy}}}$$

Allows analytical integration for I_D

ACM2 current law

From the 3 approximations normalized current vs. normalized charge densities at source and drain

$$i_D = \frac{(q_S + q_D + 2)}{1 + \zeta(q_S - q_D)}(q_S - q_D)$$

$$i_D = I_D / I_S$$

$$I_S = \frac{W}{L}\mu_s n C_{ox}\frac{\phi_t^2}{2}$$

normalization (specific) current

$$q_{S(D)} = Q_{S(D)}/(-nC_{ox}\phi_t)$$

$-nC_{ox}\phi_t$ thermal charge

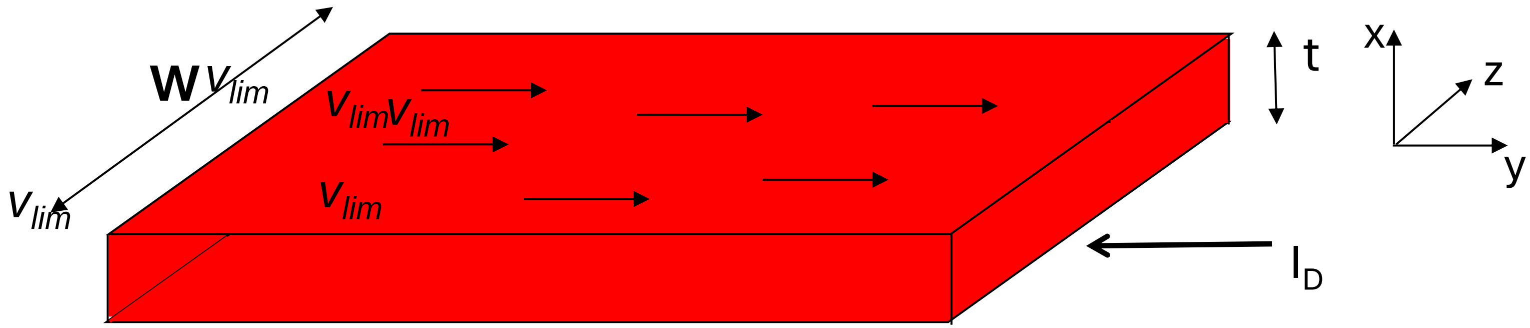
$SI: q_{S(D)} >> 1 \quad WI: q_{S(D)} << 1$

Short-channel parameter ζ :

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

ratio of diffusion-related velocity to saturation velocity

Physics-based saturation



Saturation current due to saturation velocity of the carriers

$$\boxed{I_{Dsat} = -W Q_{Dsat}\, v_{lim}}$$

Q_{Dsat} is the saturation inversion charge per unit area

or, using normalized variables

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

"Carrier velocity approaches v_{sat}, but never reaches v_{sat}"
Y.Taur TED March 2019

Physics-based saturation: design model

$$i_{Dsat} = \frac{2}{\zeta} q_{dsat} \qquad i_{Dsat} = \frac{(q_S + q_{Dsat} + 2)}{1 + \zeta(q_S - q_{Dsat})}(q_S - q_{Dsat})$$

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

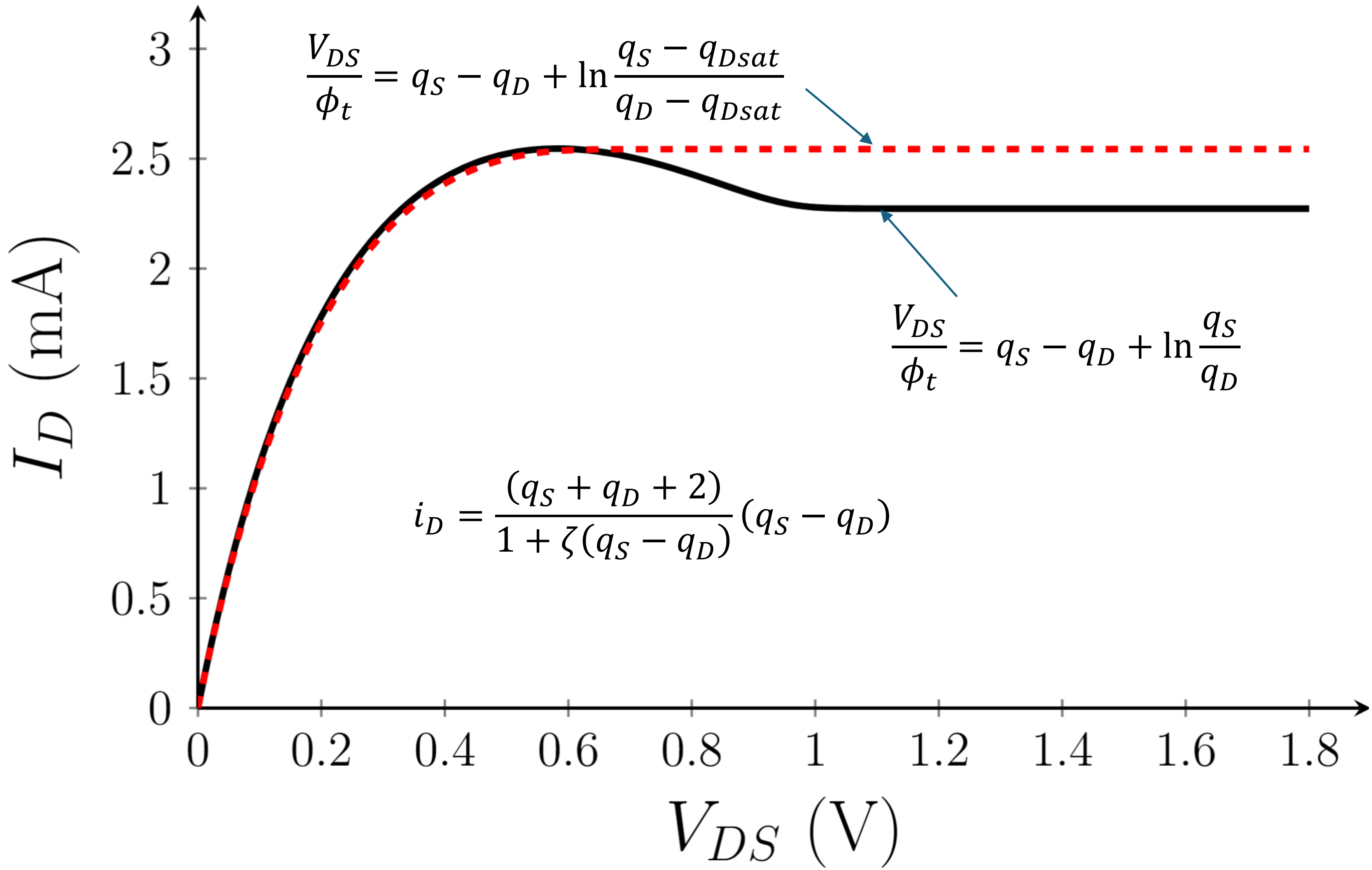
or equivalently

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

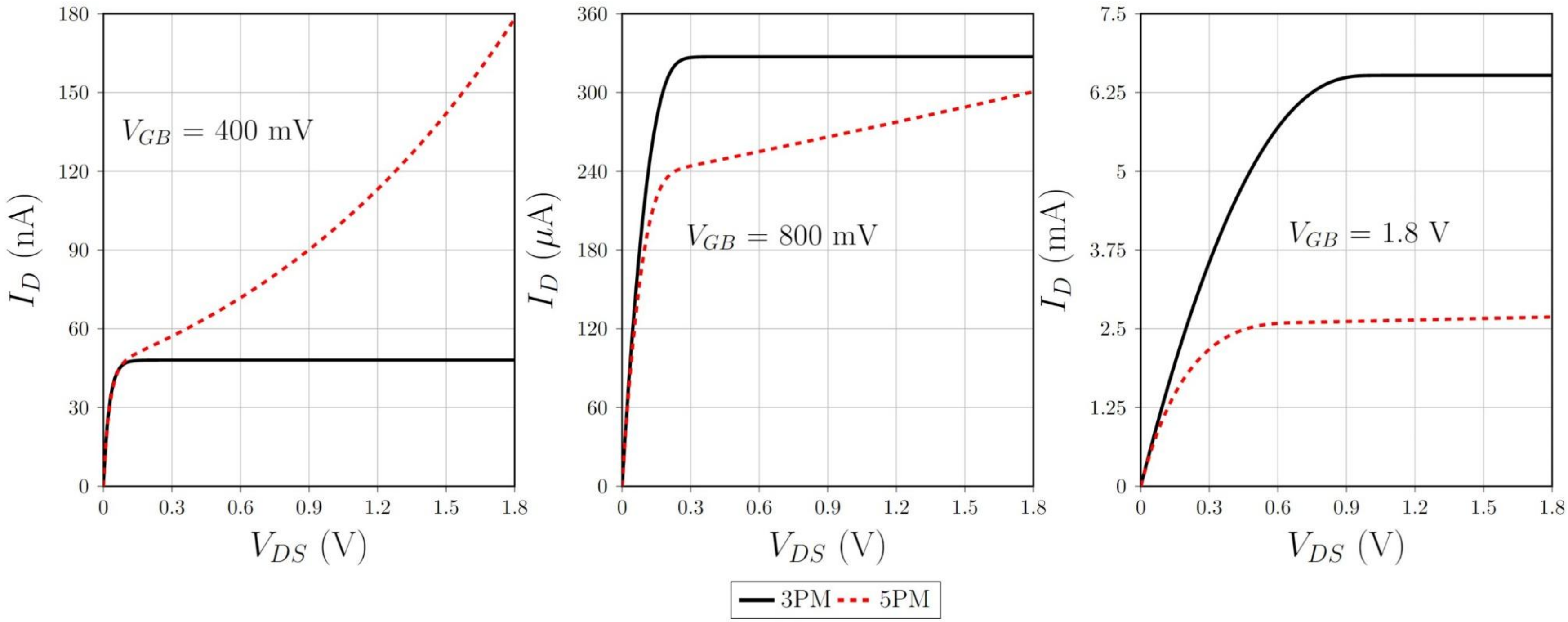
Unified Charge Control Model including the effect of velocity saturation

$$\frac{V_P - V_{SB}}{\phi_t} = q_S - 1 + \ln q_S \qquad \frac{V_{DS}}{\phi_t} = q_S - q_D + \ln \frac{q_S - q_{Dsat}}{q_D - q_{Dsat}}$$

Effect of the maximum of $i_D(q_D)$ on the output characteristic $i_D(v_D)$



Output characteristics including DIBL and v_{sat}



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

Transisto r	W/L $(\mu m/\mu m)$	V_{T0} (mV)	I_S (μA)	n	σ	ζ
NMOS2V	$\mathbf{5/0.18}$	528	5.52	1.37	0.025	0.056

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Unified Current Control Model (UICM)-I

$$\boxed{I_D = I_S[(q_S^2 + 2q_S) - (q_D^2 + 2q_D)]} \quad \text{(A)}$$

(A) can also be written as

$$\boxed{I_D = I_F - I_R = I_S\left[i_f - i_r\right]} \quad \text{(B)}$$

$\boxed{I_F, I_R}$: forward and reverse currents

$\boxed{i_{f(r)} = q_{S(D)}^2 + 2q_{S(D)}}$: forward (reverse) inversion coefficients

Unified Current Control Model (UICM)-II

$$\boxed{i_{f(r)} = q_{S(D)}^2 + 2q_{S(D)}}$$

$$\boxed{q_{S(D)} = \sqrt{1 + i_{f(r)}} - 1}$$

Normalized UCCM

$$\boxed{\frac{V_P - V_{S(D)B}}{\varphi_t} = q_{S(D)} - 1 + \ln q_{S(D)}}$$

Normalized UICM

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

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

g_m/I_D

$$g_{ms(d)} = \frac{2I_S}{\phi_t}\left(\sqrt{1+i_{f(r)}}-1\right) = \frac{W}{L}\mu C_{ox} n\phi_t\left(\sqrt{1+i_{f(r)}}-1\right)$$

$$g_m = \frac{g_{ms}-g_{md}}{n}$$

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

For V_{DS}/ϕ_t<<1 we have $i_f \cong i_r$

$$\boxed{\frac{g_m}{I_D} \cong \frac{1}{n\phi_t\sqrt{1+i_f}}}$$

In saturation $i_f >> i_r$

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

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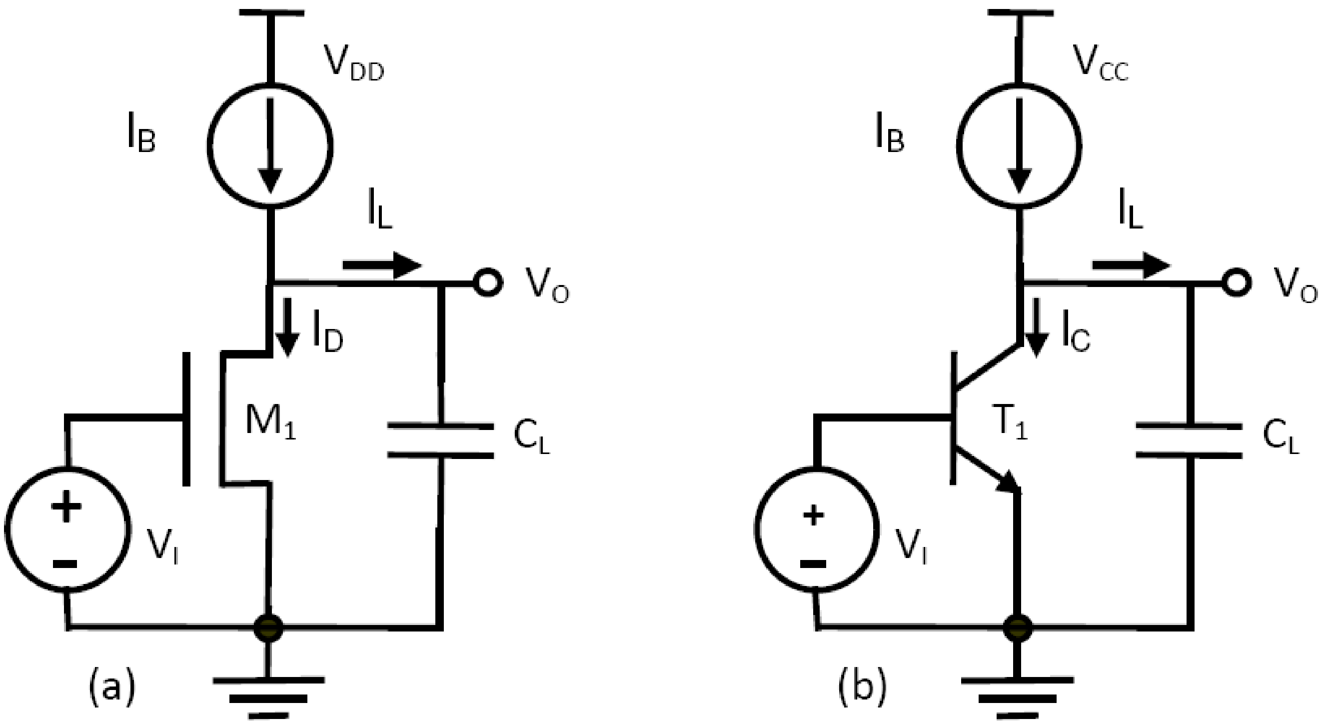
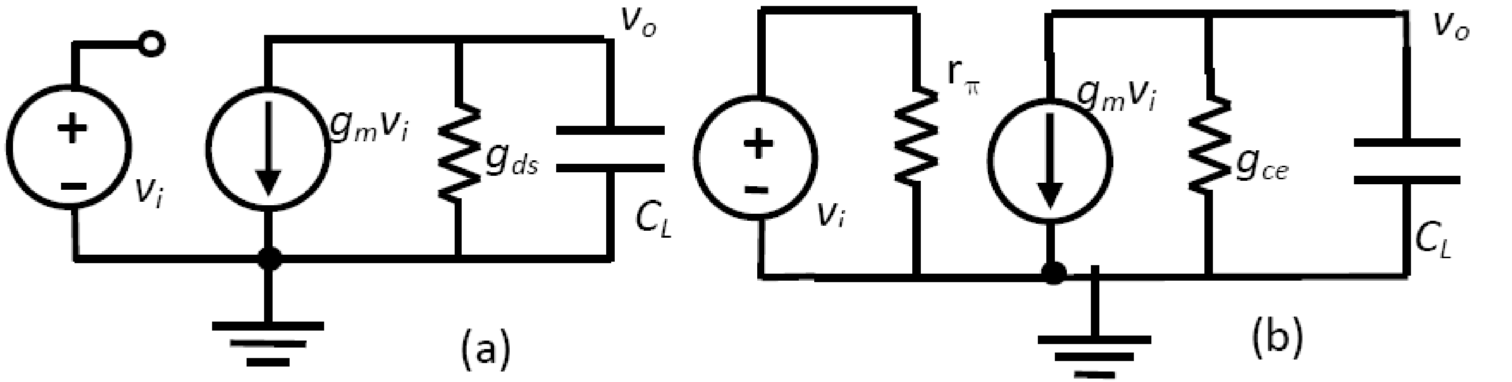
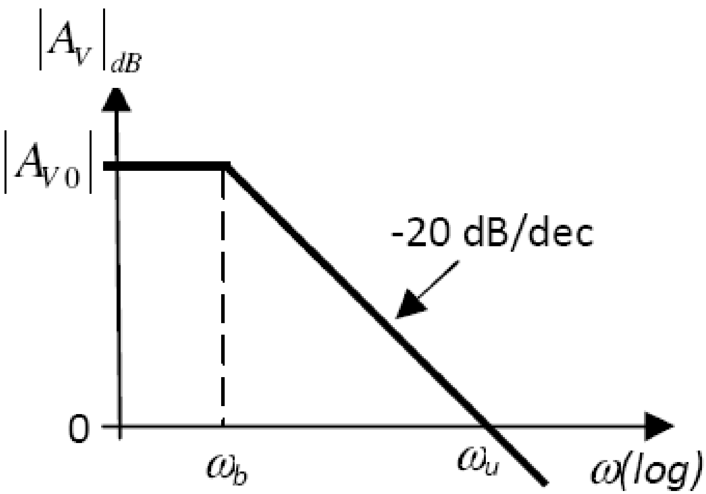
Intrinsic gain stages: common-source and common-emitter amplifiers



Small-signal circuit and frequency response of the CS and CE amplifiers





$$v_o \cong -\frac{g_m}{j\omega C_L} v_i; \qquad \omega >> \omega_b$$

$$\boxed{\omega_u = \frac{g_m}{C_L}}$$

Design of the CE and CS amplifiers

$$\left|A_v\left(\omega_u\right)\right| = 1 \qquad g_m = \omega_u C_L = 2\pi \cdot GB \cdot C_L$$

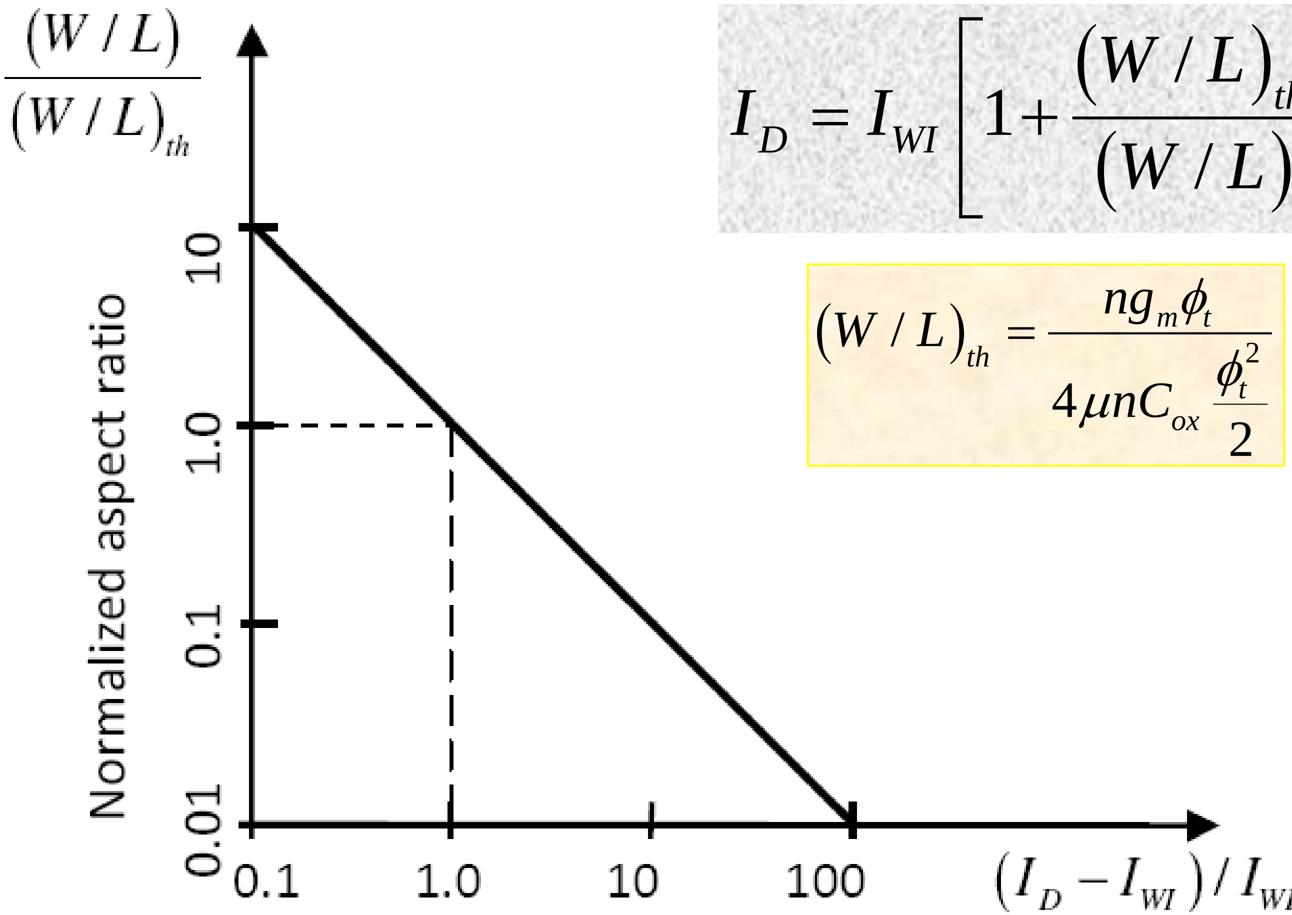
BJT in the direct active region

$$I_C = I_S e^{V_{BE}/\phi_t} \Rightarrow I_C = g_m \phi_t = 2\pi \cdot GB \cdot C_L \cdot \phi_t$$

MOSFET in saturation

$$I_D = n g_m \phi_t \frac{\left(\sqrt{1+i_f}+1\right)}{2} = n g_m \phi_t \left[1 + \frac{g_m}{2\mu C_{ox}\phi_t (W/L)}\right]$$

Aspect ratio vs. current excess in MOSFET design



$$I_D = I_{WI}\left[1 + \frac{(W/L)_{th}}{(W/L)}\right]$$

$$(W/L)_{th} = \frac{n g_m \phi_t}{4\mu n C_{ox}\frac{\phi_t^2}{2}}$$

Part 2
Advanced Compact MOSFET Model: Parameter extraction

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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 (4PM) 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 2023/2024 – Analog IC design
  - Live demonstration of the ACM2 at ISCAS 2024 with the open-source tools (XSCHEM+Ngspice)

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  - VT0, IS and n
  - Sigma
  - Zeta
- Introduction to Qucs-S
  - 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)***

5PM-ACM2 : Transconductances in saturation

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

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:

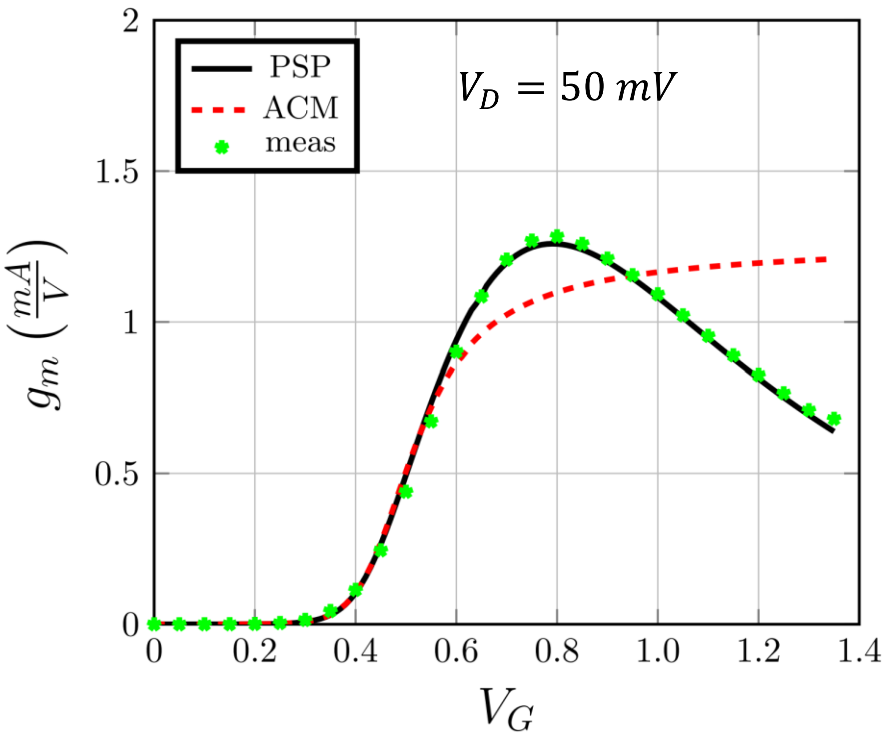
$$g_{msat} = \frac{2I_S}{n\phi_t} \frac{q_s}{1 + \zeta(q_s + 1)}$$

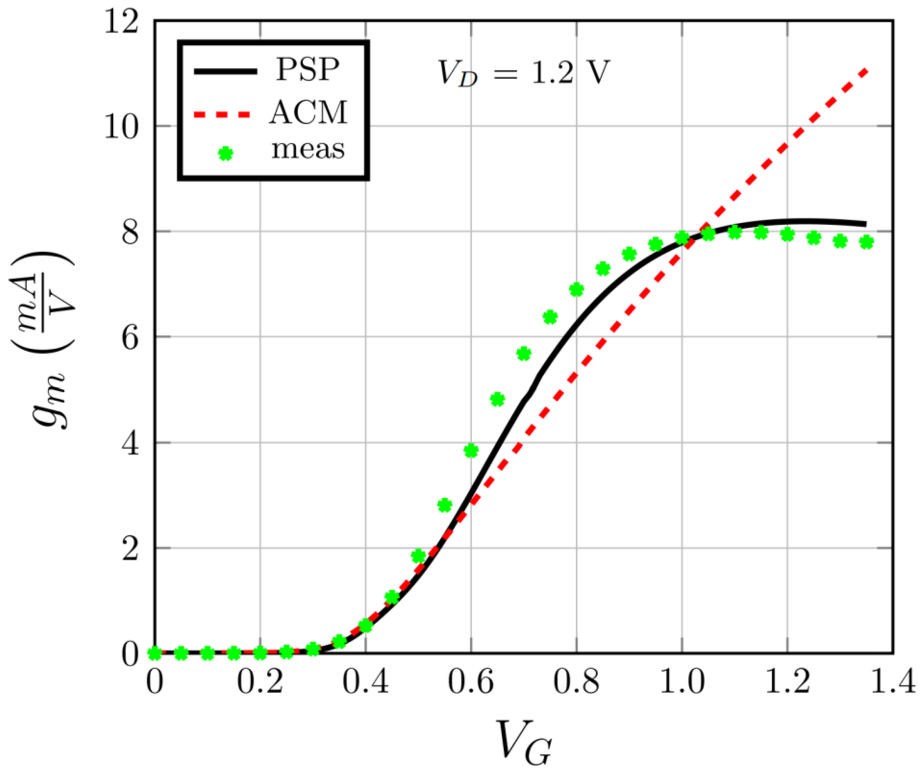
$$g_{dsat} = \sigma \frac{2I_S}{n\phi_t} \frac{q_s}{1 + \zeta(q_s + 1)}$$

$$\Rightarrow \quad g_{dsat} = \sigma g_{msat}$$

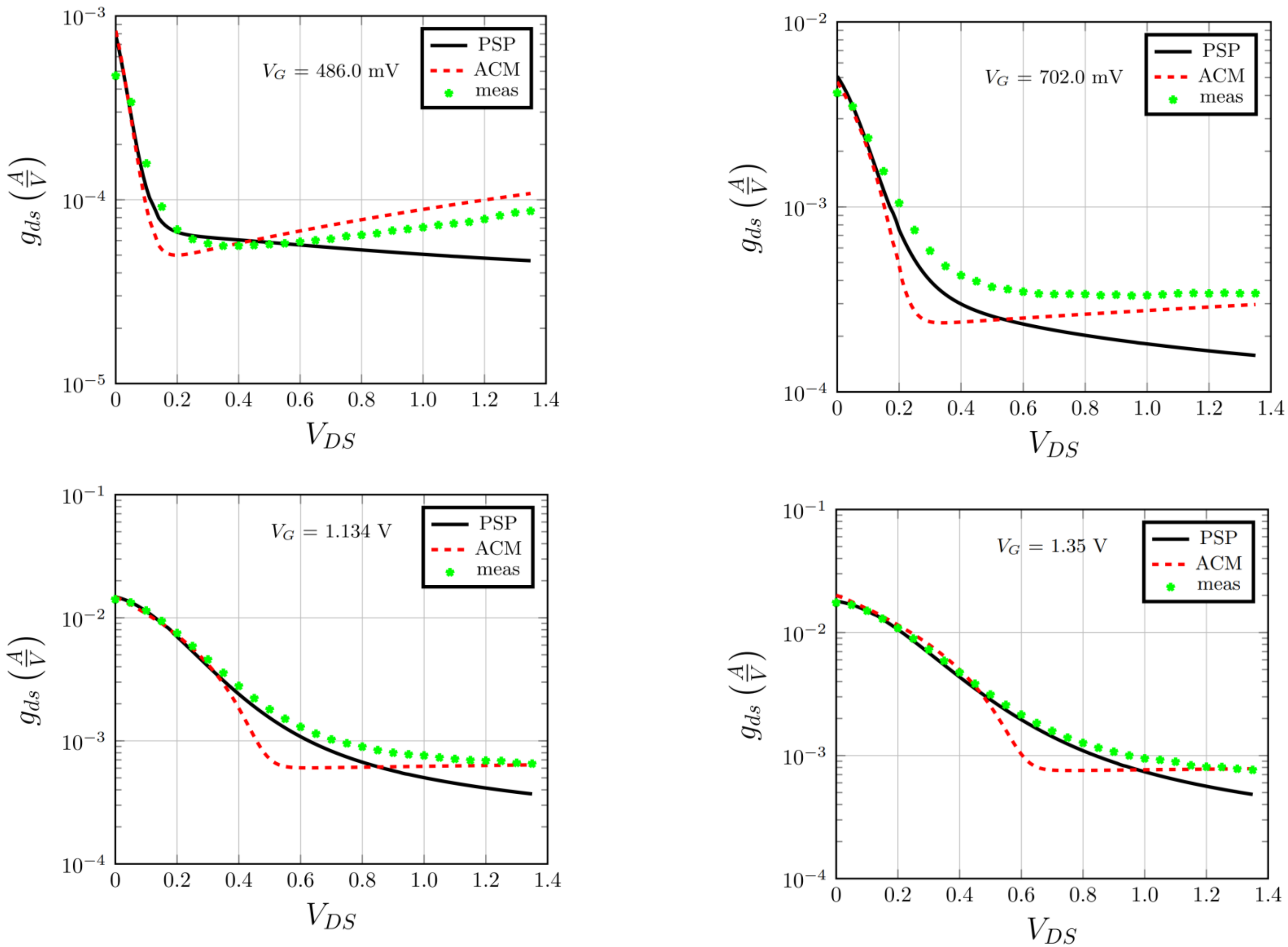
$$g_{msat3} = \frac{16I_S}{(n\phi_t)^3} \frac{q_s}{(q_s + 1)^3} \frac{2 - 2\zeta q_s - 3\zeta q_s^2}{(\zeta q_s + 2)^4}$$

5PM-ACM2 : Transconductance gm



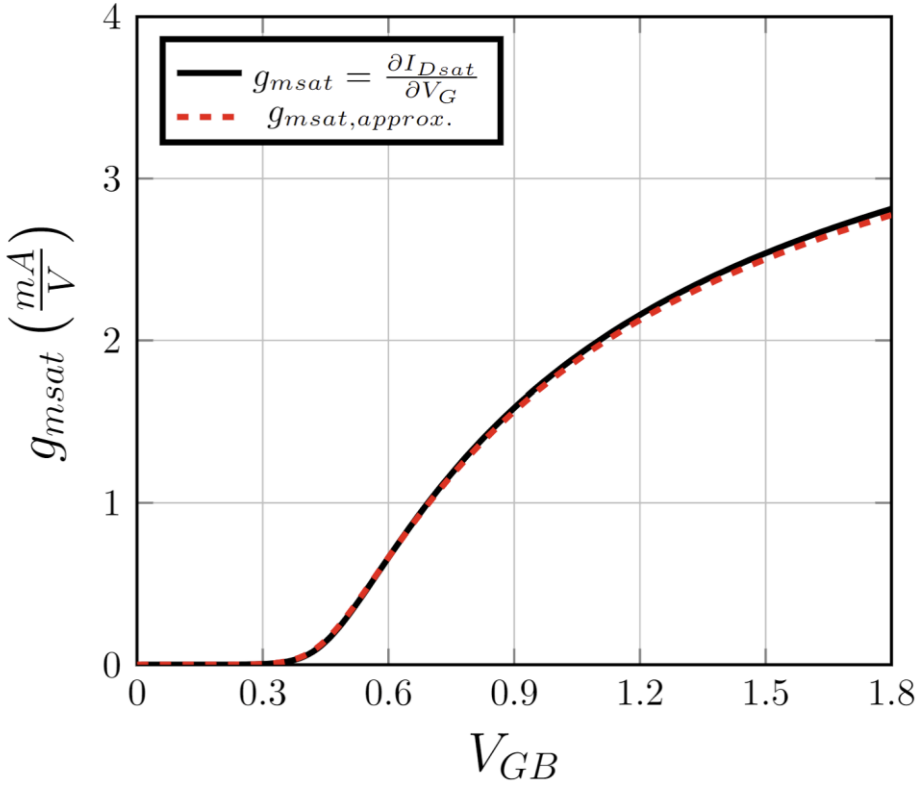


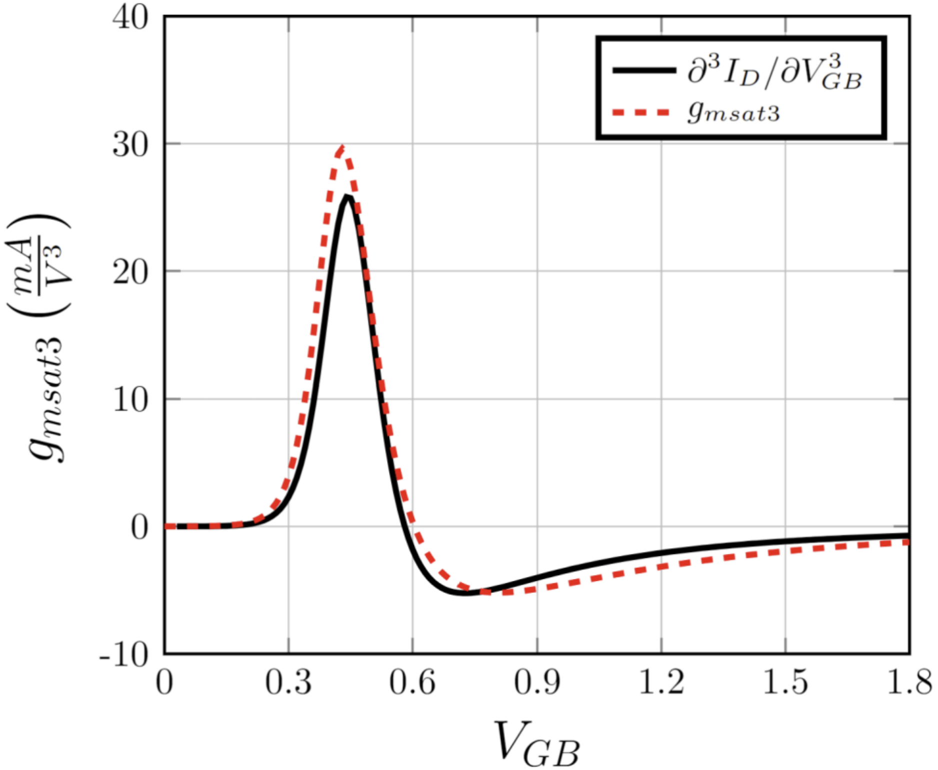
5PM-ACM2 : gds -Transconductances



5PM-ACM2 : Transconductance gmsat3

$$V_D = 1.8\ V$$





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3PM-ACM model in a nutshell

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

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

If we choose $i_f = 3$ ➡ $RHS = 0$ ➡ $V_{GB} = \boldsymbol{V_{T0}}$

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

DC eqs

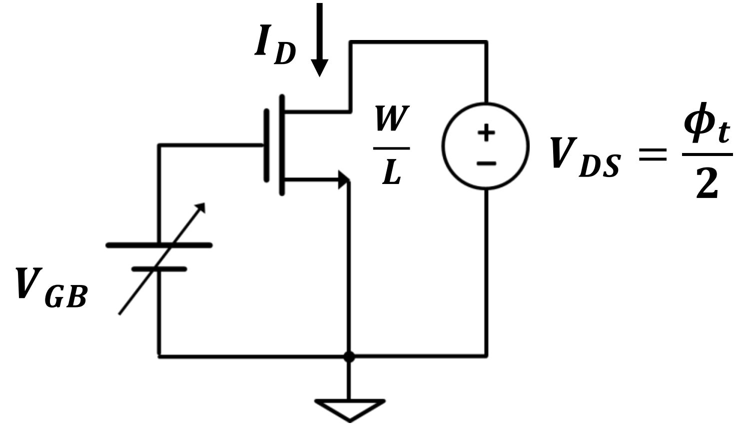
$$g_{ms(d)} = \frac{2I_S}{\phi_t}\left(\sqrt{1+i_{f(r)}} - 1\right) \Rightarrow \frac{W}{L} = \frac{g_{ms(d)}\phi_t}{2I_{SH}\left(\sqrt{1+i_{f(r)}} - 1\right)}$$

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

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 : $i_r = 2.12$

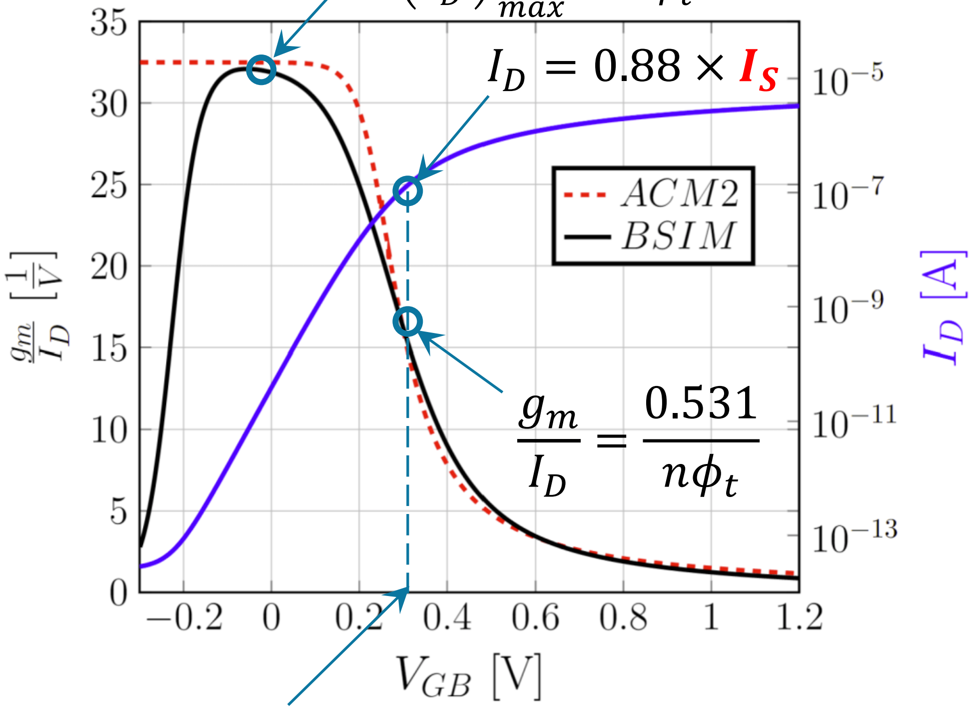
$$\frac{g_m}{I_D} = \frac{d(\ln I_D)}{dV_G} = \frac{2}{n\phi_t\left(\sqrt{1+i_f}+\sqrt{1+i_r}\right)}$$

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

$$I_D = I_S\left(i_f - i_r\right)$$

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

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



$V_{GB} = V_{T0}$

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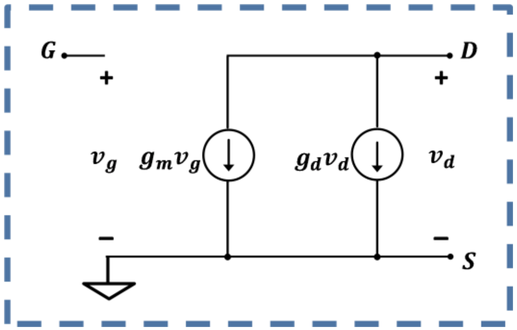
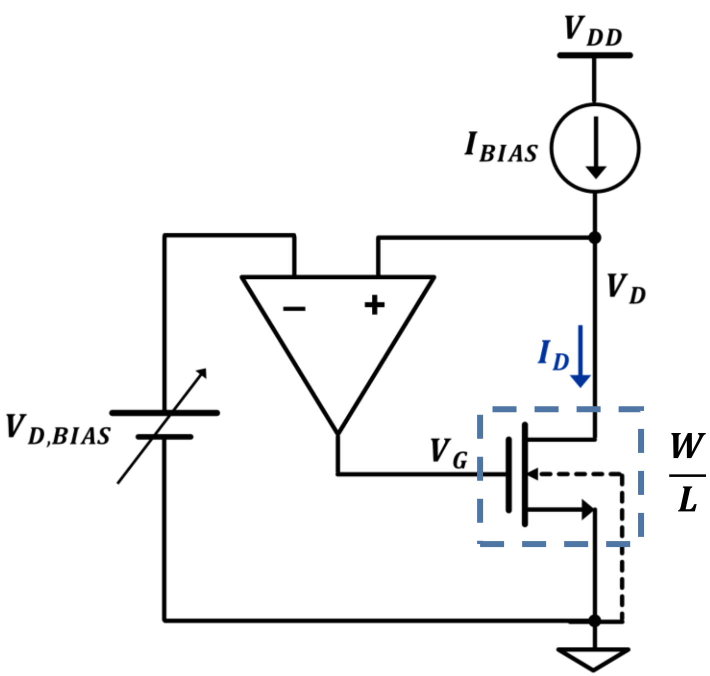
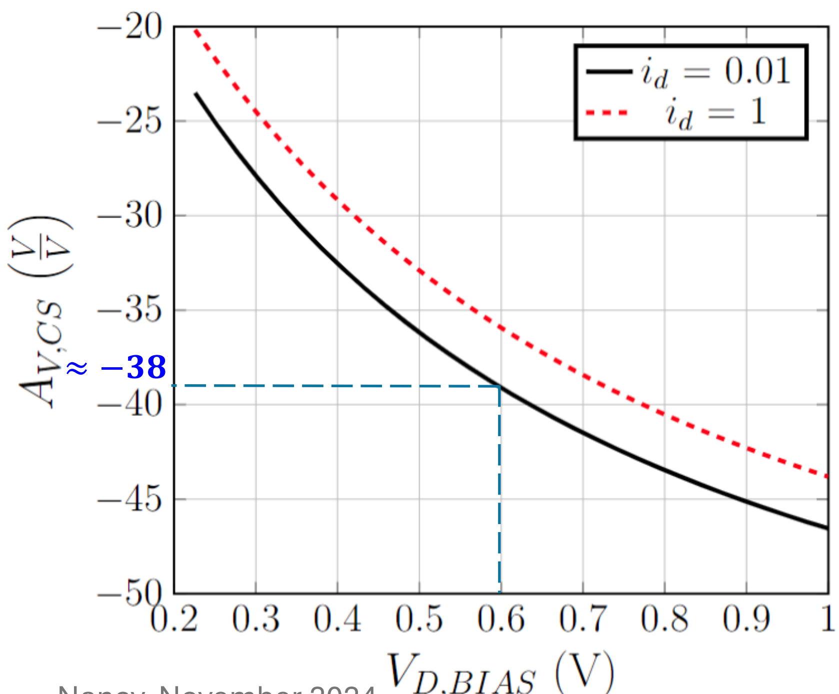
Extraction of σ

Common-Source Intrinsic-Gain method



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





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

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

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

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ζ extraction

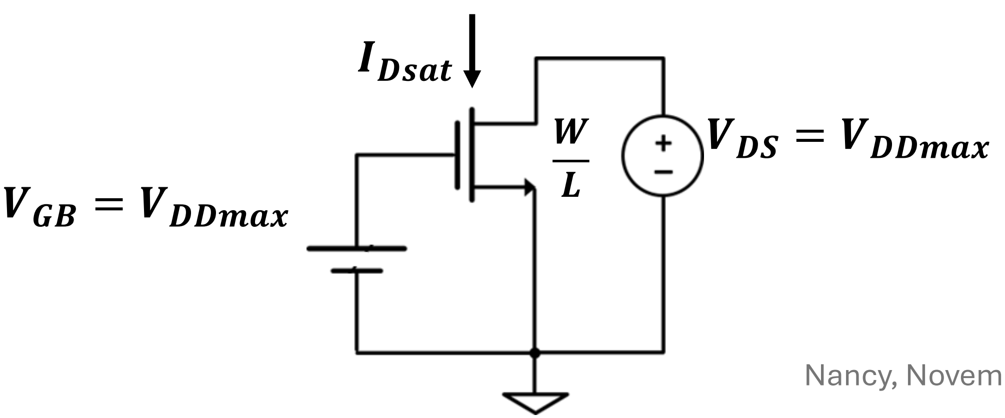
$$i_{dsat} = \frac{2}{\zeta} q_{dsat} \qquad q_s = \sqrt{1 + \frac{2}{\zeta} q_{dsat}} - 1 + q_{dsat}$$

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

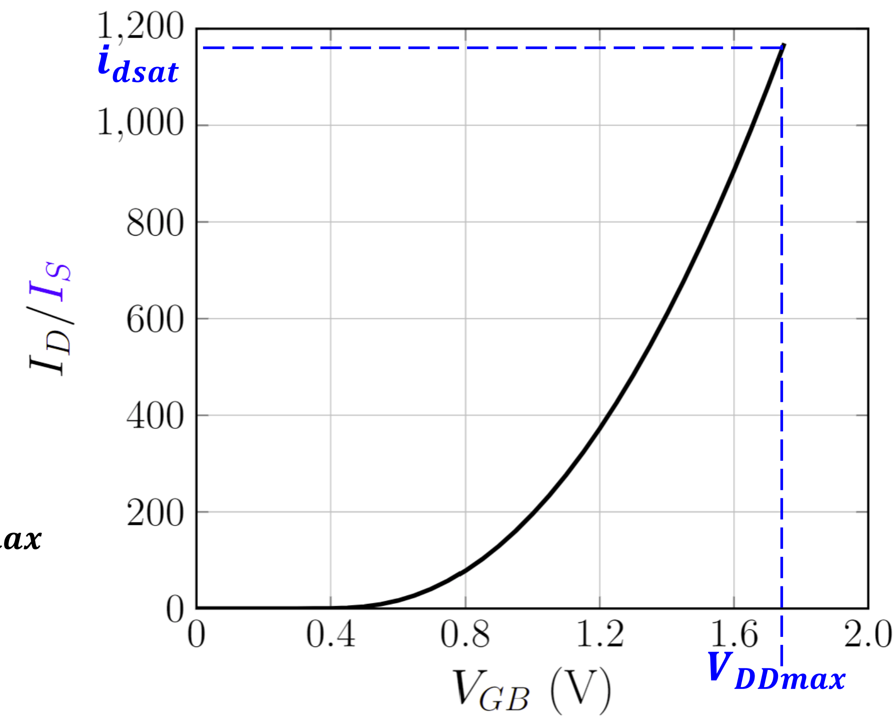
- q_s calculated using parameters ($\boldsymbol{V_{T0}}$, $\boldsymbol{n}$, $\boldsymbol{\sigma}$) and UCCM.

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

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



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



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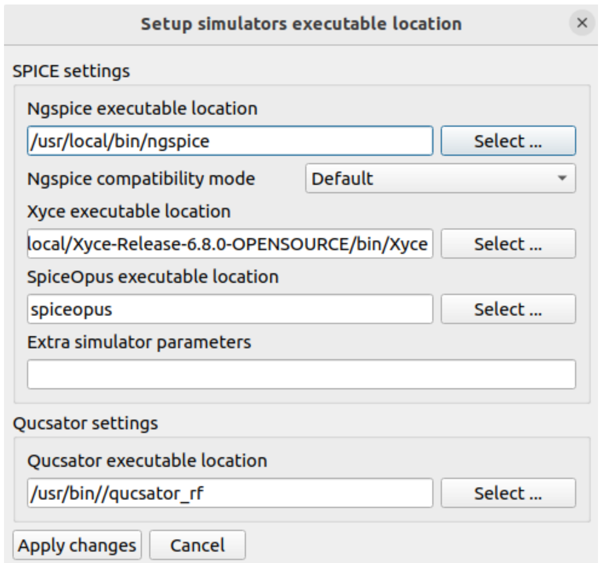
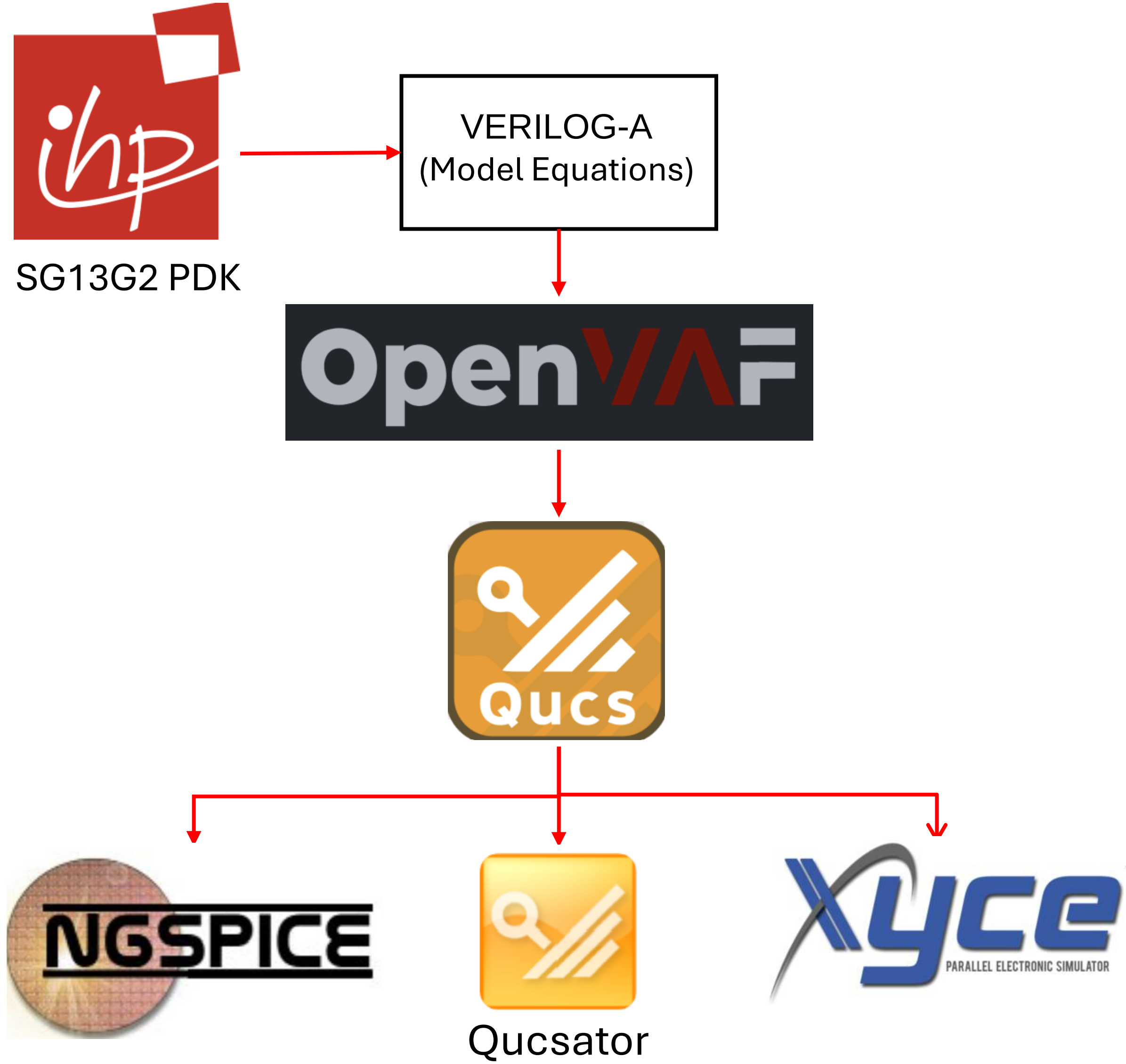
Qucs-S: Quite universal circuit simulator with SPICE

Simulation setup:



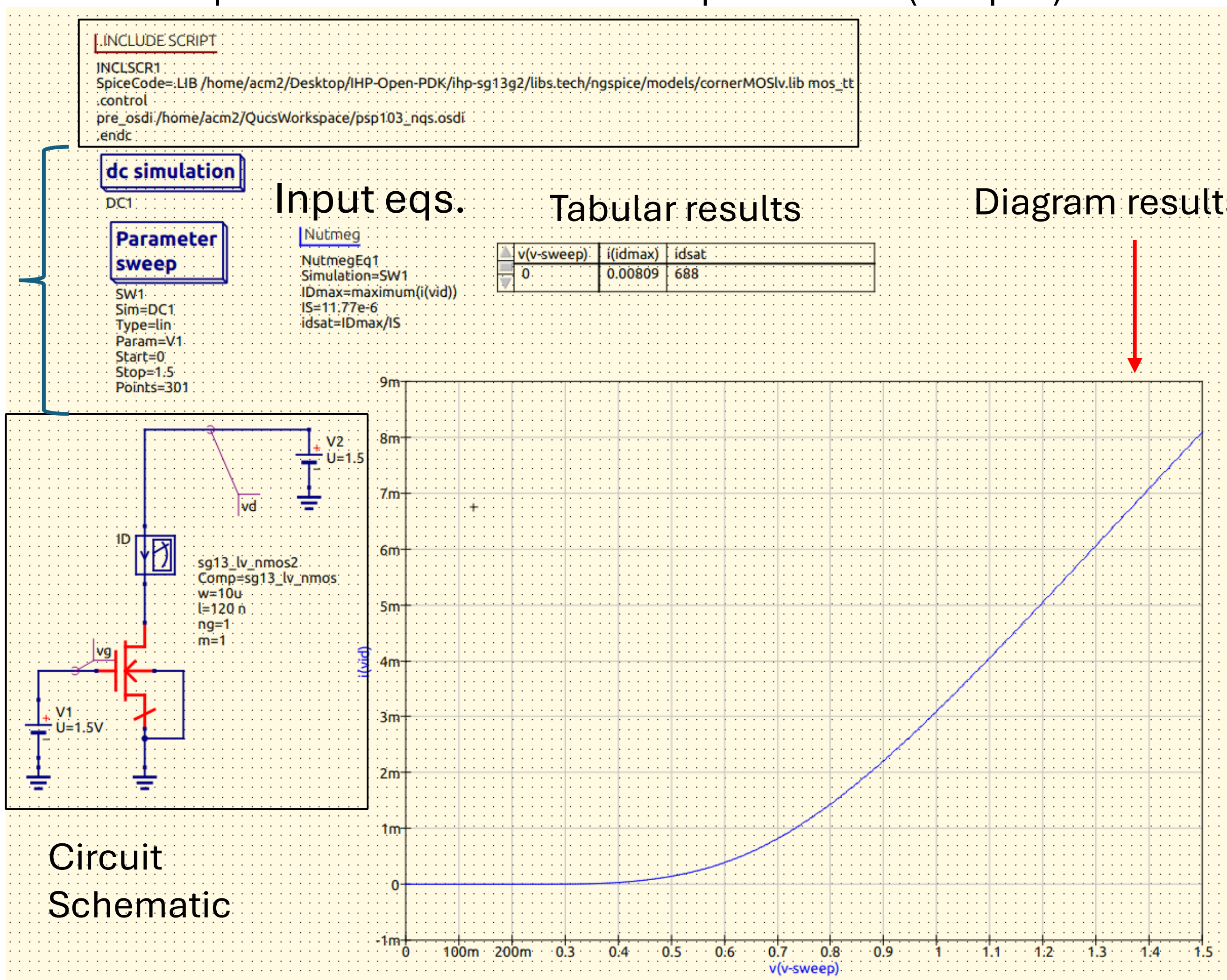


Qucs-S: Quite universal circuit simulator with SPICE

Simulations Control

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

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



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

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

Part 3
Advanced Compact MOSFET Model: Design Methodology-Application to Low Noise Amplifier

"Scan me"

IEEE ICECS 2024
31st IEEE International Conference on Electronics Circuits and Systems
Nancy, France | November 18-20, 2024

Sylvain Bourdel

https://github.com/ACMmodel/MOSFET_model

18/11/2024

Agenda

- Overview of Design Methods for RFIC
- LNA Design Considerations
- Resistive Feedback LNA
- What we need in ACM-2
- Inversion Level Based Method for R-Feedback LNA with ACM-2

Agenda

- Overview of Design Methods for RFIC
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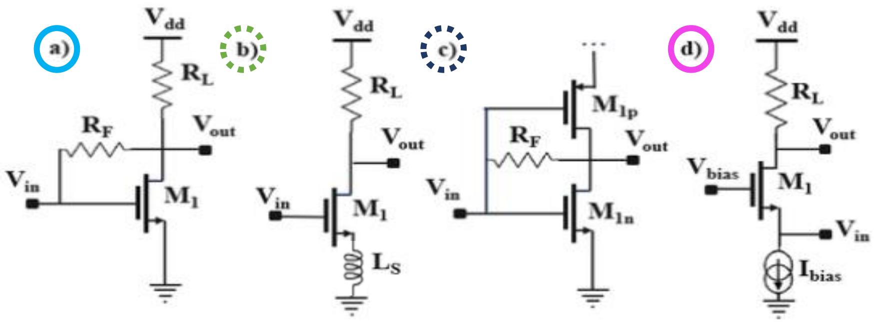
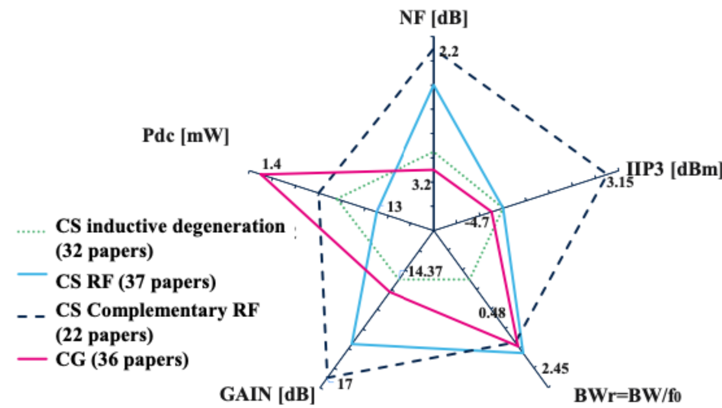
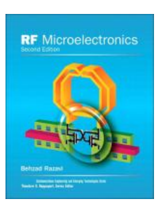
Overview of Design Methods for RFIC General Principle

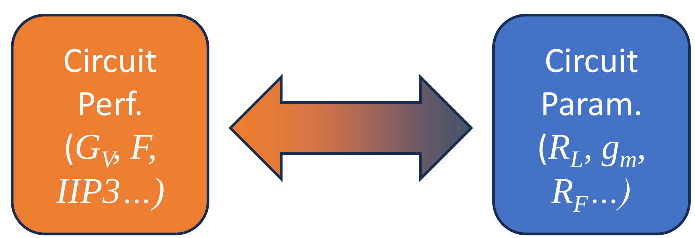
- 1st Step: Architecture Choice





- 2nd Step: Circuit Analysis

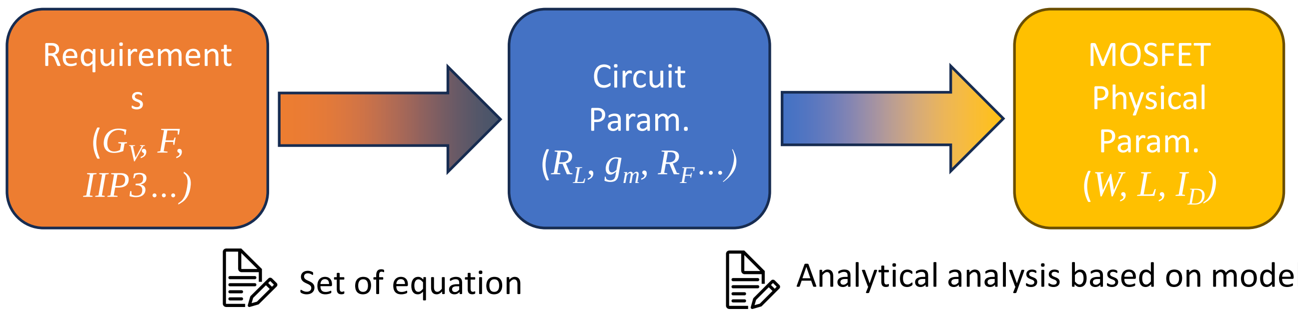




$$|G_T| = |G_v|Q_{IN} = \frac{(G_m R_F - 1)R_O}{(R_O + R_F)}\sqrt{1 + Q_P^2}$$

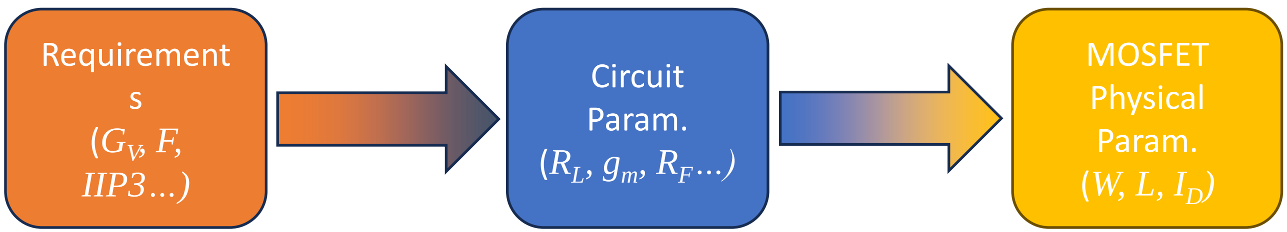
Overview of Design Methods for RFIC General Principle

- 3rd Step: Circuit Sizing



Overview of Design Methods for RFIC General Principle

- 3^{rd} Step: Circuit Sizing



Set of equation

Analytical analysis based on model

Region based model

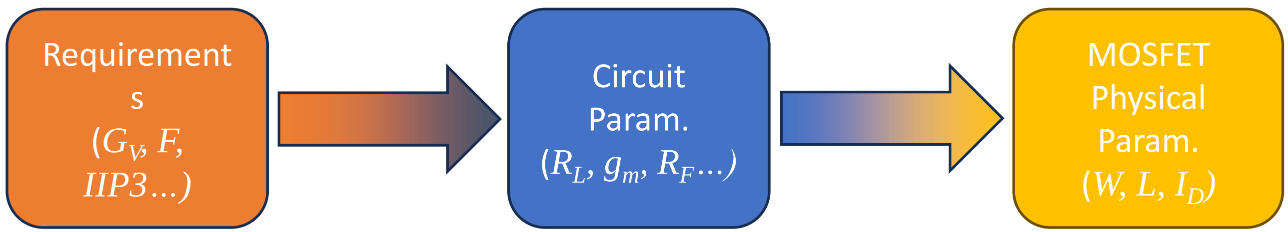
sat. $$I_d = 2.K_n \frac{W}{L}\left[\left(V_{gs} - V_t\right)V_{ds} - \frac{V_{ds}^2}{2}\right]$$

lin. $$I_d = K_n \frac{W}{L}\left(V_{gs} - V_t\right)^2\left(1 + \frac{k_{en}}{L}V_{ds}\right)$$

PROS: simple
CONS: Inaccurate with short channel MOS

Overview of Design Methods for RFIC General Principle

- 3^{rd} Step: Circuit Sizing



Set of equation

Analytical analysis based on model

Electrical simulation based on model

BSIM3 / UTSOI compact model

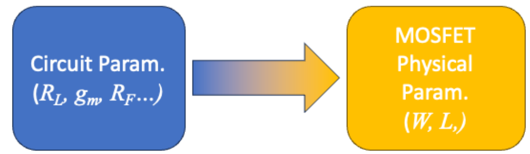
PROS: Accurate

Direct relationship between requirements and physical parameters

CONS: Increases the gap between Physic and design

Overview of Design Methods for RFIC New Trends

- Issue in the sizing step



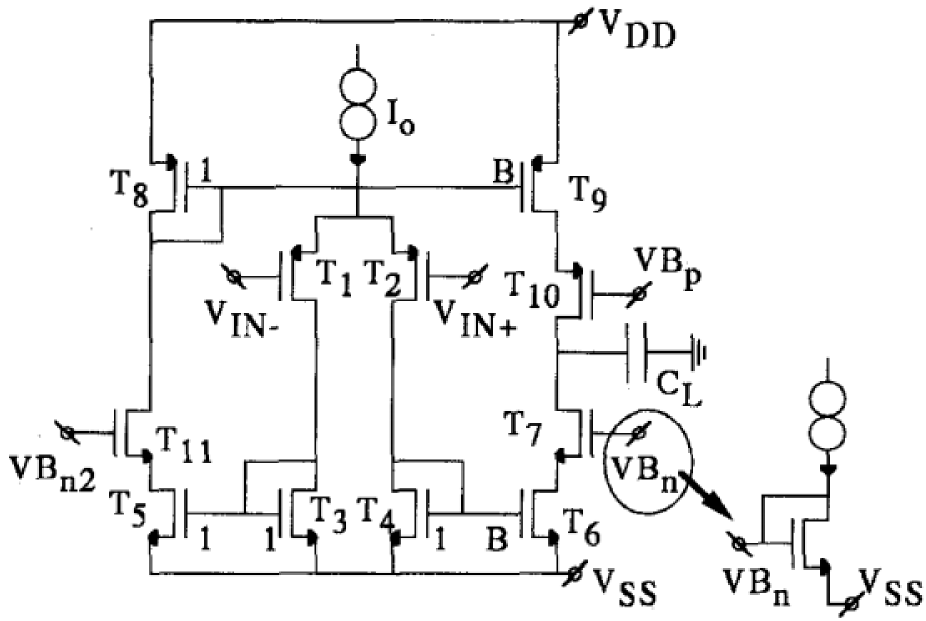
  - How to maintain simplicity **and** accuracy with the scaling and especially Short Channel Effects (SCE) at the sizing step.

- g_m/Id design approaches
  - LUT based
  - ACM or EKV based

Overview of Design Methods for RFIC
g_m/Id approach based on LUT

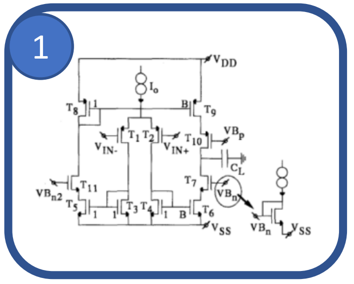
General Principle [Silveira, Flandre, Jespers – JSSC 1996]

- For a given structure

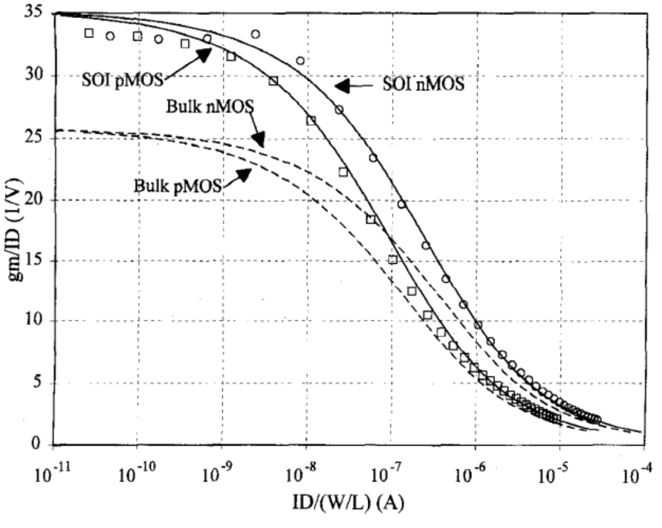


Overview of Design Methods for RFIC
g_m/Id approach based on LUT

General Principle



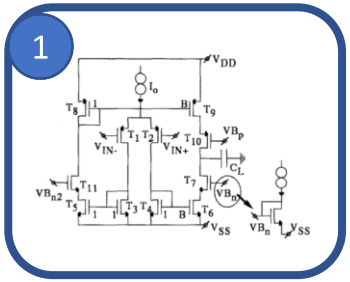
- For a given structure
- Methods are based on
  - $\Rightarrow$ Extraction of MOS parameters (LUT)
    - $I_D/(W/L)$ vs g_m/I_D
    - g_m/I_D vs V_{gs0}

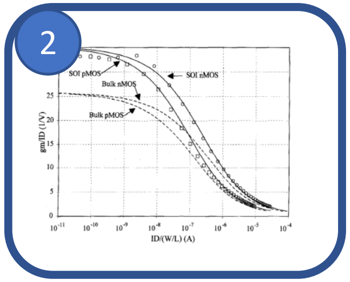


Overview of Design Methods for RFIC

g_m/Id approach based on LUT

General Principle





- For a given structure

- Methods are based on
  - ⇒ Extraction of MOS parameters (LUT)
    - $I_D/(W/L)$ vs g_m/I_D
    - g_m/I_D vs V_{gs0}
  - ⇒ Set of equations

$$SR = \frac{B \cdot I_{D1}}{C_L}$$

$$f_T = \frac{B \cdot g_{m1}}{2\Pi \cdot C_L} \qquad (5)$$

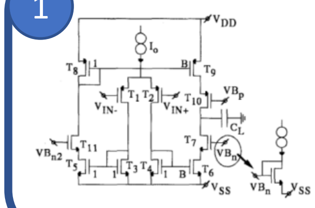
$$A_0 = \left(\frac{g_m}{I_D}\right)_1 \cdot \left(\frac{g_m}{I_D}\right)_2 \cdot \frac{1}{\frac{1}{V_{A6} \cdot V_{A7}} + \frac{1}{V_{A9} \cdot V_{A10}}} \qquad (4)$$

Overview of Design Methods for RFIC

g_m/Id approach based on LUT

General Principle

1



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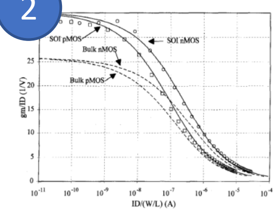


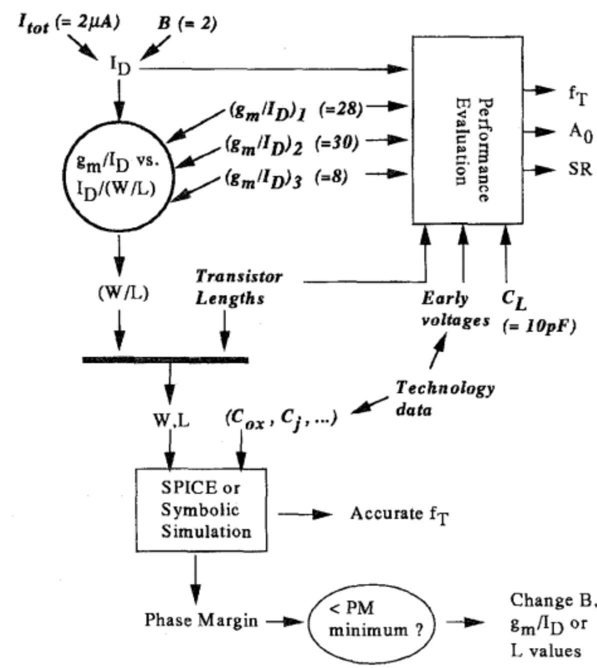
3

$$SR = \frac{B \cdot I_{D1}}{C_L}$$

$$f_T = \frac{B \cdot g_{m1}}{2\Pi \cdot C_L} \qquad (5)$$

$$A_0 = \left(\frac{g_m}{I_D}\right)_1 \cdot \left(\frac{g_m}{I_D}\right)_2 \cdot \frac{1}{\frac{1}{V_{A6} \cdot V_{A7}} + \frac{1}{V_{A9} \cdot V_{A10}}} \qquad (4)$$

- For a given structure
- Methods are based on
  - ⇒ Extraction of MOS parameters
    - $I_D/(W/L)$ vs g_m/I_D
    - g_m/I_D vs V_{gs0}
  - ⇒ Set of equations
- Methods helps the designers in sizing the structure
- Quite used in low frequency domain



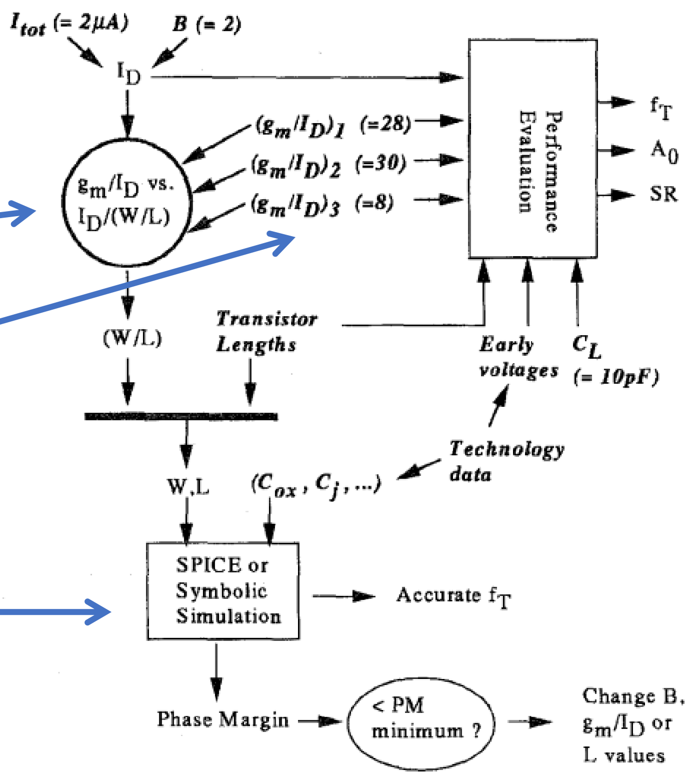
Overview of Design Methods for RFIC
g_m/Id approach based on LUT

LIMITATIONS ?

- Time Consuming
- Lakes of precision (parametric set of characteristics)

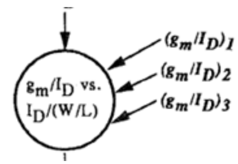
- Long optimization sequence

Need for a model based approach



All Region 3PM model

- EKV – [Enz, Krummenacher, Vittoz]
- ACM – [Schneider, Galup]



$$\frac{I_D}{(W/_L)} = i_f I_{S0}$$

- With a 3PM model we have :

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

$$V_P \cong \frac{V_G - V_{T0}}{n}$$

- PROS: The sizing is straightforward
- CONS: Inaccurate with SCE
  Non-linearities can't be captured
  gds effect can't be captured

Is it possible in RFIC ?

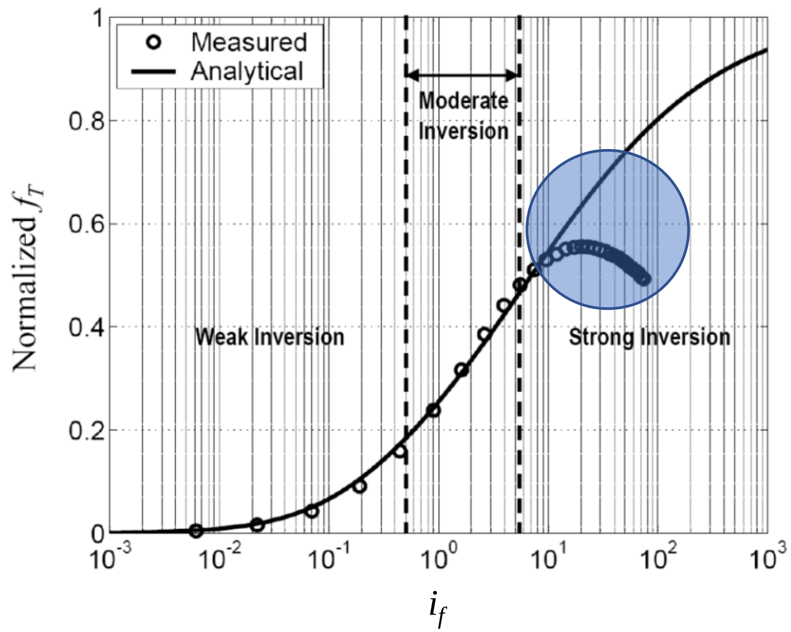
Overview of Design Methods for RFIC

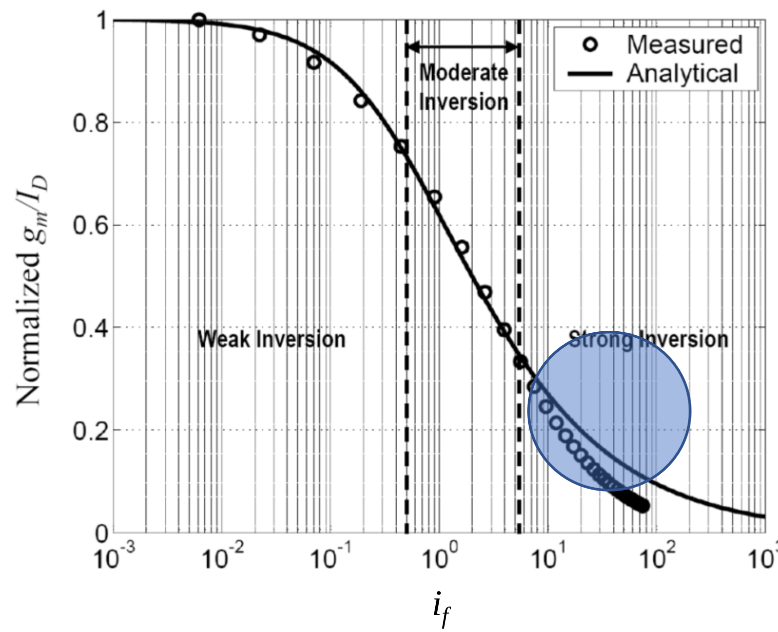
g_m/Id in RFIC design

Design Regions

Year 2000 (RF-180nm)

- f_t grows with i_f





Overview of Design Methods for RFIC

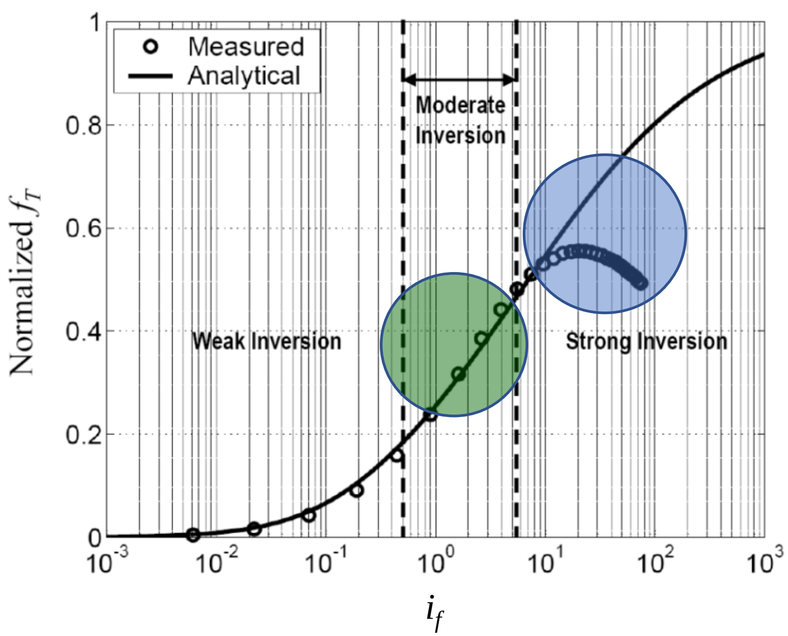
g_m/Id in RFIC design

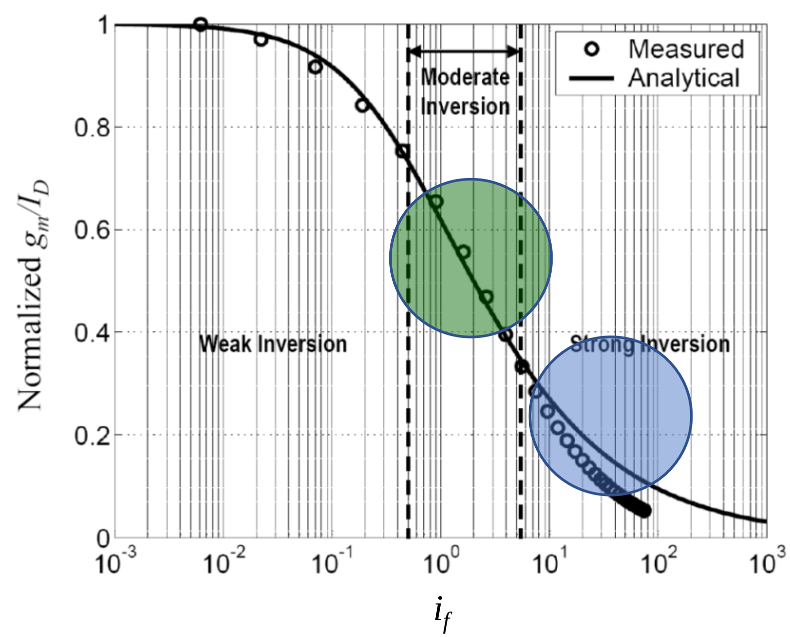
Design Regions

Year 2000 (RF-180nm)

Year 2016 (RF-22nm)

- f_t grows with i_f but g_m/I_D reduces with i_f





Overview of Design Methods for RFIC

g_m/Id in RFIC design

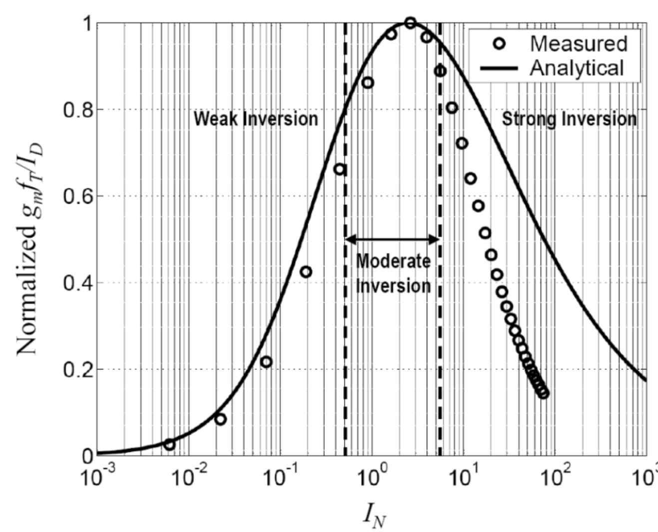
$g_m f_t / I_D$: A First Approach

- For RF design
- A FOM that maximize the gain bandwidth product

$$\frac{g_m f_T}{I_D}$$

- Gives the i_f that produces the best GBW product
- Not optimal :
  - the gain or the bandwidth might be oversized.
  - Do not depends on the topology

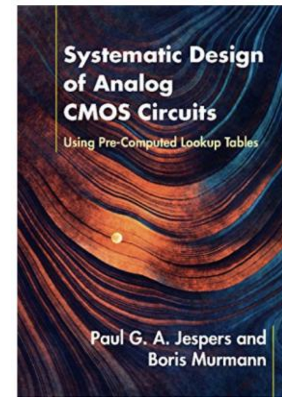
A. Shameli et P. Heydari, « Ultra-Low Power RFIC Design Using Moderately Inverted MOSFETs: An Analytical/Experimental Study », *RFCI*, 2004.



Overview of Design Methods for RFIC
g_m/Id in RFIC design

Circuit Sizing Based on LUT

- For a given Circuit
- Similar to the one introduced by Silveira, Flandre, Jespers in 1996
- Capacitance and noise effects can be captured in LUT for bandwidth and noise analysis
- Well known and well referenced
- But …
    - Still complicated
    - The gap between physics and design remains
    - No analytical relationships to size « by hand »



Circuit Sizing Based on ACM

- Equations can be derived for a given circuit
- Quasi analytical approach
    - R-F LNA designed with 3PM-ACM [Bourdel - ICECS 2019]
- Gds and gm3 (NL) are taken into account
    - R-F LNA designed with 7PM-ACM [Bouchoucha – ISCAS 2023]
    - CG LNA designed with 5PM-ACM2[Alves Neto – ACCESS 2024]

All Ressources accessible for free

https://github.com/ACMmodel/MOSFET_model

Agenda

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- LNA Design Considerations
- Resistive Feedback LNA
- What we need in ACM-2
- Inversion Level Based Method for R-Feedback LNA with ACM-2

LNA Design considerations

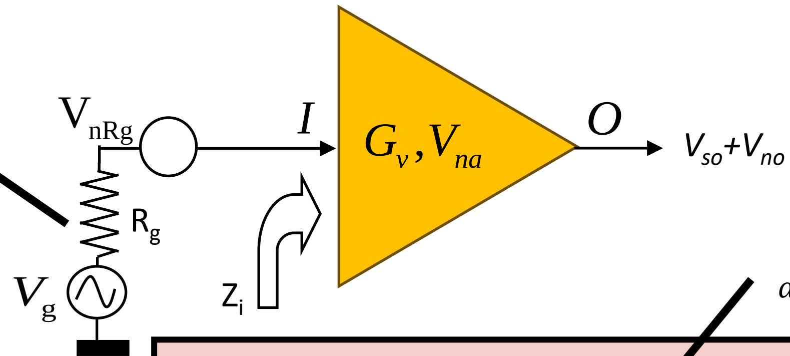
Noise Factor

- NF is the signal to noise ratio (SNR) degradation (Eq. 1)

$$\boxed{F = \frac{(S/N)_i}{(S/N)_o} \quad (1)}$$

$$\overline{v_{nRg}^2} = 4KTR_g$$

$$V_{RMS\_nRg} = \sqrt{4KTR_g \Delta f}$$



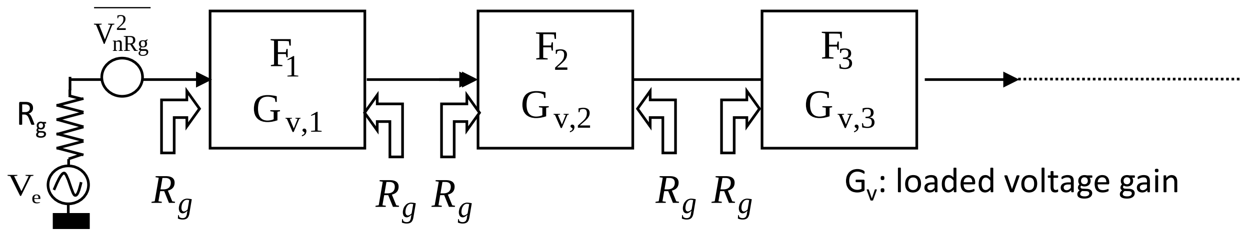
$$\alpha = \left\| \frac{Z_i}{Z_i + R_g} \right\|$$

$$F = \frac{V_{si}^2/V_{ni}^2}{V_{so}^2/V_{no}^2} = \frac{V_g^2/V_{nRg}^2}{V_{so}^2/V_{no}^2} = \frac{V_{no}^2}{\alpha^2 . G_v^2 . V_{nRg}^2} = \frac{\overline{v_{no}^2}}{\alpha^2 . G_v^2 . \overline{v_{nRg}^2}}$$

$$F = \frac{\textit{total output noise}}{\textit{total output noise of the ideal (no aditive noise) device}} \quad (2)$$

- NF also express the quantity of noise added by the stage regarding the noise delivered by the source (R_g) on Δf. (Eq. 2)

LNA Design considerations
Friss Formula



G_v: loaded voltage gain

$$F = F_1 + \frac{(F_2 - 1)}{G_{v,1}^2} + \frac{(F_3 - 1)}{G_{v,1}^2 . G_{v,2}^2} + \ldots\ldots$$

This formula is valid only for real impedances and in case of power matching: (Z_s=Z_e=R_g)

In RFIC, impedances are complex and never equal. This formula cannot be used as is. However, the following statements remain valid in RFIC.

The gain of the first stages reduces the NF of the following ones.

=> The receiver chain must start by amplifiers

=> The NF of the first stage must be as low as possible

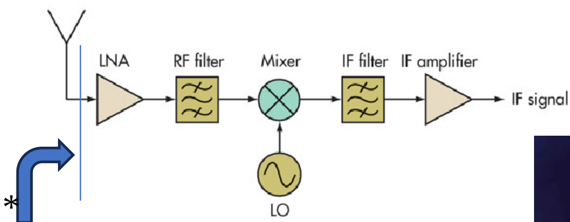
LNA

Note that lossy stages (G_v<1) increase the NF, especially when they are in front of the receiver chain ***(antenna filter, image rejection filter, antenna switch).***

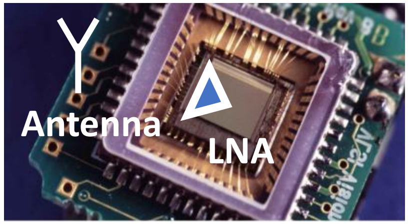
LNA Design considerations
Input patching

System point of vue

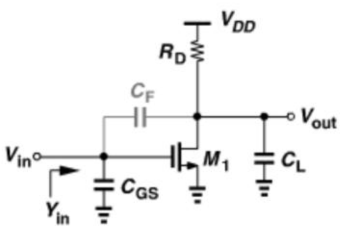
- LNA is the first device due to Friss formula
- Antenna is mainly 50 Ω.



$Z_{lna}=Z_g{}^*$



In CMOS
- Generally, the input impedance is capacitive Re (Y11) is very low
- For exemple : CS amplifier

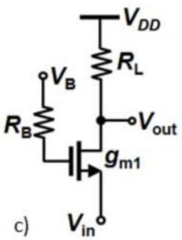


$$\Re(Y_{in}) = R_D \| 1/g_m$$

$$\Im(Y_{in}) = \frac{1}{C_{GS}C_F\omega}$$

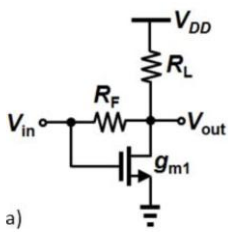
Common Structures

CG



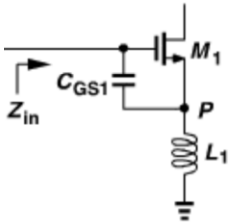
$$\Re(Z_{in}) = \frac{1}{g_{m1}}$$

R-Feedback



$$\Re(Z_{in}) = \frac{R_F}{1+|A_V|}$$

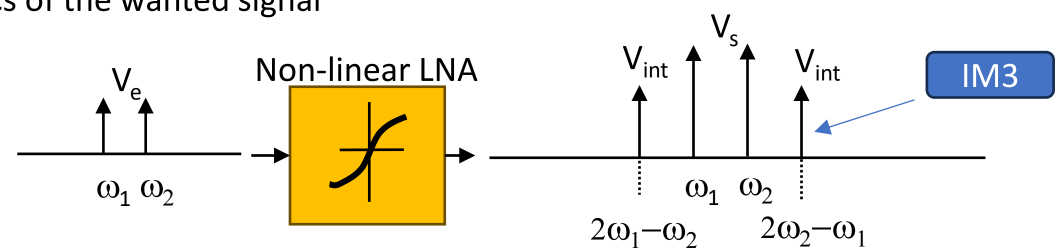
Inductive Degeneration

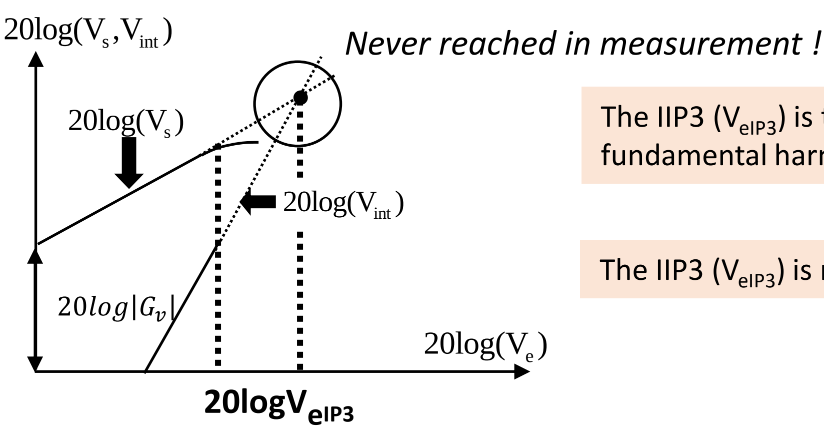


$$\Re(Z_{in}) = \frac{g_m L_1}{C_{GS}}$$

LNA Design considerations
Non-Linearities

ω_1 and ω_2 are 2 harmonics of the wanted signal





The IIP3 (V_{eIP3}) is the input signal level for which the output IM3 is equaling the fundamental harmonic (Vs) extrapolated from small signal (AC).

The IIP3 (V_{eIP3}) is related to the maximum power you can apply to your system

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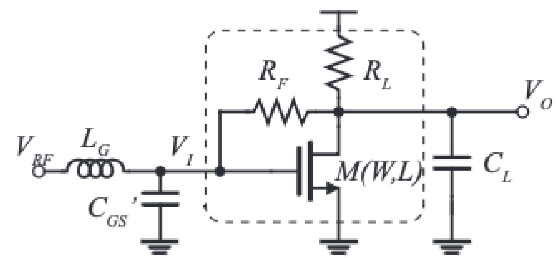
Resistive Feedback LNA

Topology

R-Feedback general considerations

- Simple
- Compact (No-inductors)
- Wideband
- RF allows to synthesize a real part in Zin
- LG and CGS' will help in cancelling the imaginary part while controlling Qin

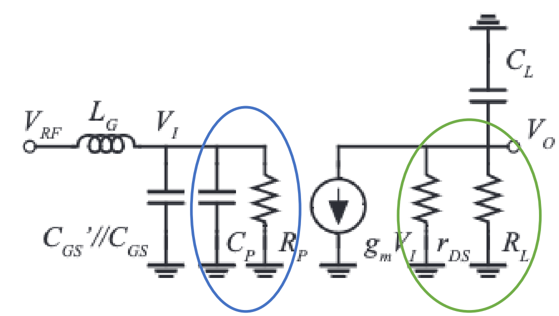


Input impedance

$$Z_{IN} = L_G s + \left(\frac{1}{(C_{GS} + C'_{GS})s} // Z_P \right)$$

$$\boxed{\Re(Zp) = R_P = \frac{R_O + R_F}{1 + G_m R_O},}$$

$$\boxed{C_P = \frac{R_O^2 C_L (G_m R_F - 1)}{(R_O + R_F)^2}}$$



$$\boxed{R_O = \frac{R_L r_{DS}}{R_L + r_{DS}}}$$

$$\Re(Z_{IN}) = R_S = \frac{R_P}{(1 + Q_P^2)} = 50\,\Omega \qquad Q_P = R_P C_T \omega_0 \qquad C_T = C_{GS} + C'_{GS} + C_P$$

$$\Im(Z_{IN}) = 0 = L_G s + \frac{Q_P^2}{C_T s (1 + Q_P)^2}$$

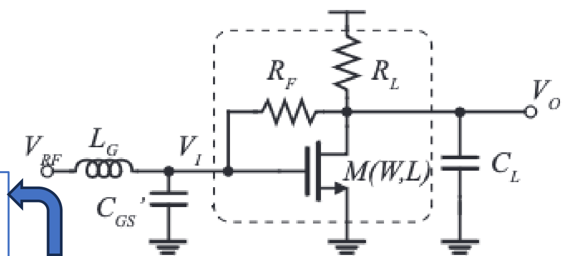
Resistive Feedback LNA
Topology

Voltage Gain

$$|G_T| = |G_v|Q_{IN} = \frac{(G_m R_F - 1)R_O}{(R_O + R_F)}\sqrt{1+Q_P^2}$$

$$Q_{IN} = V_I/V_{RF} = \sqrt{1+Q_P^2} = \sqrt{\frac{R_O + R_F}{R_S(1+G_m R_O)}}$$

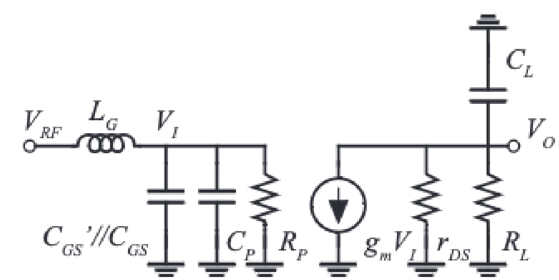
R_S
(the source resistance seen at the $50\ \Omega$ input)



Noise Figure

$$F = 1 + \frac{4\left(\frac{R_F}{Q_{IN}^2} + R_S\right)^2}{Q_{IN}^2 G_m R_S\left[\frac{R_F}{Q_{IN}^2} + R_S + \frac{G_m R_S R_F R_L)}{R_F + R_L}\right]^2}\left[\gamma + \frac{1}{G_m R_L} + \frac{\left(1 + \frac{Q_{IN}^2 G_m R_S R_F}{R_F + Q_{IN}^2 R_S}\right)^2}{G_m R_F}\right]$$

$$\left(F_{min} = 1 + \frac{(1+G_m\ )R_S{}^2 R_F}{R_S\,(1-G_m\ R_F)^2} + \frac{\gamma\, g_m\,(R_S+R_F)^2}{R_S\,(1-G_m\ R_F)^2} + \frac{(R_S+R_F)^2}{R_S\,R_L(1-G_m\ R_F)^2}\right)$$



IIP$_3$

$$V_{IIP3} = \frac{2}{Q_{IN}}\sqrt{\frac{2G_m}{G_{m3}}}$$

BW

$$f_c = \frac{R_O + R_F}{2\pi R_O R_F C_L}$$

Agenda

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What we need in ACM-2

Small signal parameters

Small signal (AC) parameters

- G_T, NF, IIP3 vs (G_m, G_{m3}, G_{DS})

$$g_m = \frac{\partial I_D}{\partial V_G} = \frac{I_S}{\phi_t} g_G = \frac{I_S}{n\phi_t} \frac{2(q_s - q_d) - i_d\,\zeta\left(\frac{q_s}{1+q_s} - \frac{q_d}{1+q_d}\right)}{1+\zeta\,(q_s - q_d)} \qquad g_{ds} = \frac{I_S}{\phi_t} g_D = \frac{I_S}{n\phi_t} \frac{2(q_s\sigma - q_d(\sigma - n)) - i_d\zeta\left(\sigma\frac{q_s}{1+q_s} - (\sigma - n)\frac{q_d}{1+q_d}\right)}{1+\zeta(q_s - q_d)}$$

$$g_{m3} = \frac{I_S}{(n\phi_t)^3}\left\{\frac{\frac{2q_s}{(1+q_s)^3} - \frac{2q_d}{(1+q_d)^3} - \zeta n^2 g_{G2}\left(\frac{q_s}{1+q_s} - \frac{q_d}{1+q_d}\right) - \zeta\left[2ng_G\left(\frac{q_s}{(1+q_s)^3} - \frac{q_d}{(1+q_d)^3}\right) + i_d\left(\frac{q_d(1-2q_d)}{(1+q_d)^5} - \frac{q_d(1-2q_d)}{(1+q_d)^5}\right)\right]}{1+\zeta\,(q_s - q_d)}\right\}$$

- Valid in all region (qs and qd shall be explored)
  - We consider only saturation
  - It reduces the exploration to only qs.

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

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

What we need in ACM-2
Small signal parameters

Large signal (DC) parameters

- To compute the final voltages

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

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

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

- Sometimes we'll use i_f in the code

$$i_d = i_f - i_r \quad \Longleftrightarrow \quad q_{S(D)} = \sqrt{1 + i_{f(r)}} - 1, \quad \Longleftrightarrow \quad i_d = \frac{(q_s + q_d + 2)}{1 + \zeta |q_s - q_d|}(q_s - q_d)$$

$$I_D = I_{SO}.i_d$$

$$I_{S0} = \mu C'_{ox} n \frac{(U_T)^2}{2} \frac{W}{L}$$

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Inversion Level Based Method for R-Feedback LNA with ACM-2

General Approach :

Requirements

- GT, NF, IIP3, IDC ← Possible Tradeoff
- fo, CL, BW ← No Tradeoff

Design parameters

- ACM parameters for a fixed L
- $V_{T0}, I_S, n, \sigma, \zeta$

Design Variables (parameters)

- W, qs are first order design variables (qs = inversion level sets the energy efficiency and the voltages)
- RL, RF are second order design variables

Approach :

- Explore the different tradeoff (the design space) on GT, NF, IIP3 and IDC by playing with W, qs.
- In saturation region (only qs is needed)

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

- Circuit equations depend on Gm and ACM depends on gm …

Where we introduce W in the design space

$$|G_T| = \frac{(G_mR_F-1)R_O}{(R_O+R_F)}\sqrt{\frac{R_O+R_F}{R_S(1+G_mR_O)}} \qquad G_{[m;DS]x} = \mu C'_{ox}\frac{(U_T)^{2-x}}{2}\frac{W}{L}g_{[m;DS]x}$$

$$I_{S0} = \mu C'_{ox}n\frac{(U_T)^2}{2}\frac{W}{L} \qquad I_{SL} = \frac{I_{S0}}{W} = \mu C'_{ox}n\frac{(U_T)^2}{2L}$$

Inversion Level Based Method for R-Feedback LNA with ACM-2

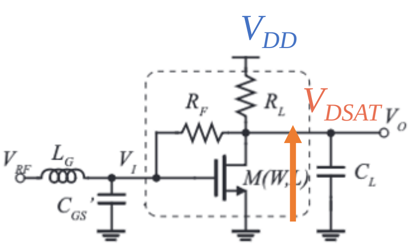
Reducing the variables :

Starting from : $|G_T| = \frac{(G_m R_F - 1)R_O}{(R_O + R_F)}\sqrt{\frac{R_O + R_F}{R_S(1+G_m R_O)}}$ $\quad G_T(G_m; R_0; R_F; R_S) = G_T(W; q_S; I_D; V_{DSAT}; V_{T0}; I_S; n; \sigma; \zeta; f_c; C_L)$

variables parameters

$$G_{[m;DS]x} = \mu C'_{ox}\frac{(U_T)^{2-x}}{2}\frac{W}{L}g_{[m;DS]x} \rightarrow g_{msat} = \frac{2I_S}{n\phi_t}\frac{q_s}{1+\zeta(q_s+1)} \Rightarrow \boxed{G_m(q_S; W)}$$

$$\rightarrow g_{dsat} = \frac{\sigma}{n}\frac{2I_S}{\phi_t}\frac{q_s}{1+\zeta(q_s+1)} \Rightarrow \boxed{G_{DS}(q_S; W)}$$



$$R_O = \frac{R_L r_{DS}}{R_L + r_{DS}} \rightarrow G_{DS}(q_S; W)$$

$$R_L(I_D) = \frac{V_{DD} - V_{DSAT}}{I_D} \rightarrow V_{DSAT} = \phi_t(\sqrt{1+i_f} + 3)$$

$$i_f = (1+q_s)^2$$

$$I_D = I_{SL} * W * i_f$$

$$\Rightarrow \boxed{R_0(q_S; W)}$$

$$R_F = \frac{R_0}{2\pi R_0 C_L f_c - 1} \Rightarrow \boxed{R_F(q_S; W)\Big|_{f_c}}$$

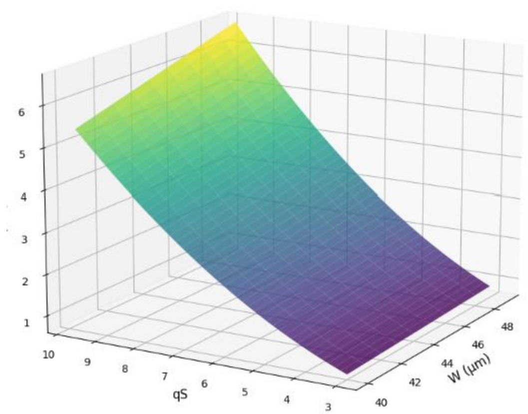
$$\left(f_c = \frac{R_O + R_F}{2\pi R_O R_F C_L}\right)$$

$$\Rightarrow \boxed{G_T(G_m; R_0; R_F; R_S) = G_T(W; q_S)}$$

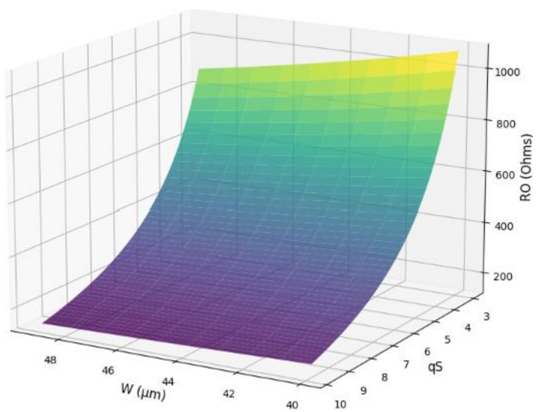
Inversion Level Based Method for R-Feedback LNA with ACM-2

Finally : $I_D(q_s;W)$; $R_F(q_s;W)$; $R_0(q_s;W)$; $G_T(q_s;W)$

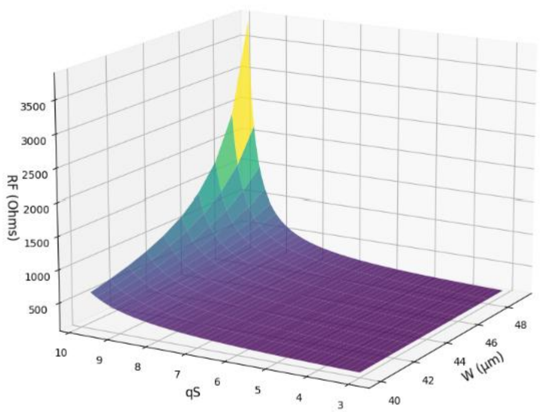
$I_D(q_s;W)$



$R_0(q_s;W)$



$R_F(q_s;W)$



Inversion Level Based Method for R-Feedback LNA with ACM-2

Computing GT, F and IIP3:

Finally : $|G_T| = \dfrac{(G_m R_F - 1) R_O}{(R_O + R_F)} \sqrt{\dfrac{R_O + R_F}{R_S(1 + G_m R_O)}}$

$\boxed{G_T(q_s; W)|_{f_c; C_L}}$

$$F = 1 + \frac{4\left(\frac{R_F}{Q_{IN}^2} + R_S\right)^2}{Q_{IN}^2 G_m R_S \left[\frac{R_F}{Q_{IN}^2} + R_S + \frac{G_m R_S R_F R_L)}{R_F + R_L}\right]^2} \left[\gamma + \frac{1}{G_m R_L} + \frac{\left(1 + \frac{Q_{IN}^2 G_m R_S R_F}{R_F + Q_{IN}^2 R_S}\right)^2}{G_m R_F}\right]$$

$\boxed{F(q_s; W)|_{f_c; C_L; R_S}}$

$$V_{IIP3} = \frac{2}{Q_{IN}} \sqrt{\frac{2 G_m}{G_{m3}}}$$

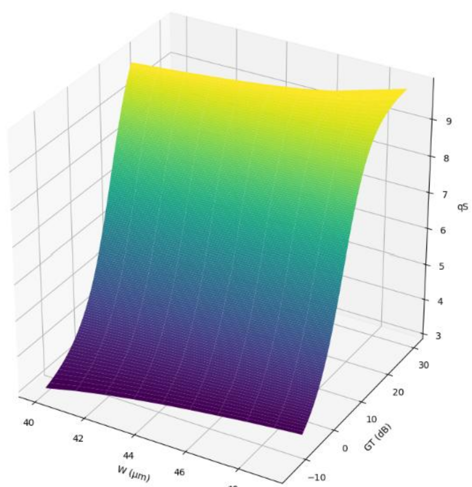
$\boxed{IIP_3(q_s; W)|_{f_c; C_L; R_S}}$

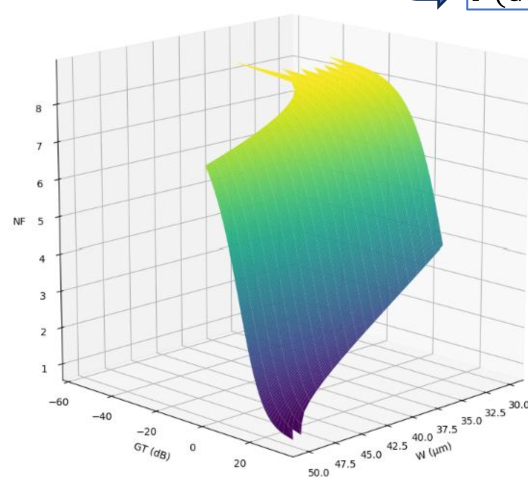
with $G_T(q_s; W)|_{f_c; C_L}$

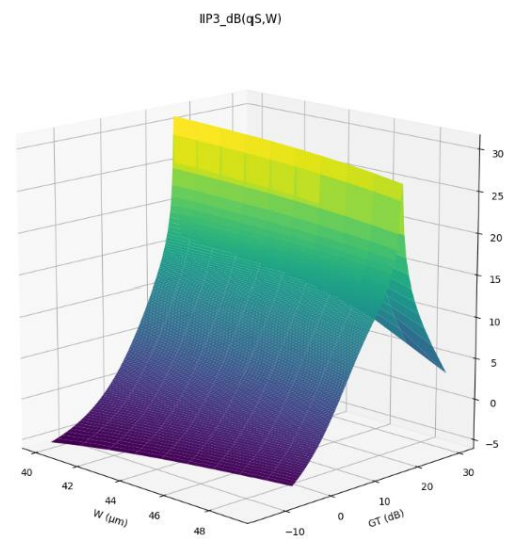
$\boxed{F(G_T; W)}$

Remember :

$$Q_{IN} = V_I / V_{RF} = \sqrt{1 + Q_P^2} = \sqrt{\frac{R_O + R_F}{R_S(1 + G_m R_O)}}$$







Inversion Level Based Method for R-Feedback LNA with ACM-2

Exploring the design space:

Setting GT (or NF, or IIP3) helps to build 2D plots.

For a particular G_T

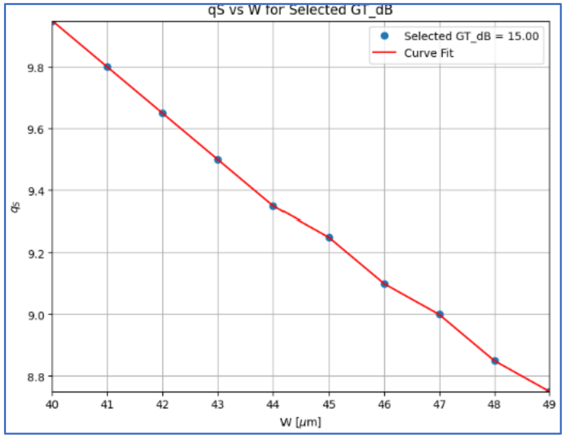
=> We get the relationship q_S<=>W

=> We plot $NF(W)$

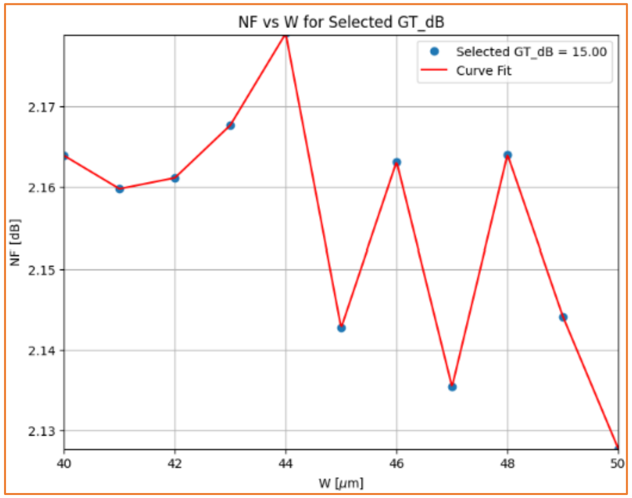
=> We plot $IIP3(W)$

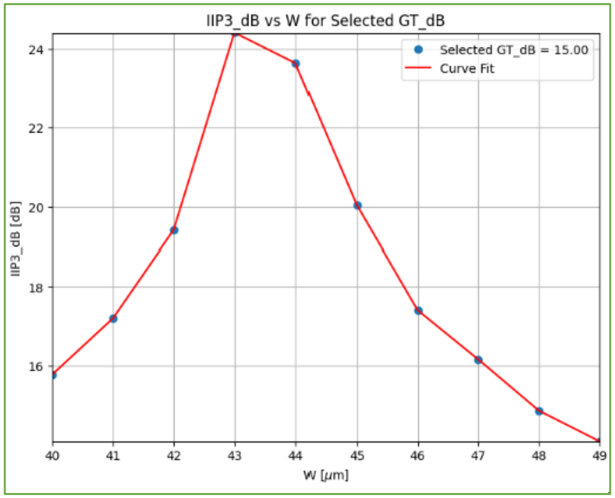
And We already have I_D

q_S



$W(\mu m)$





Inversion Level Based Method for R-Feedback LNA with ACM-2

Setting the final value:

- We choose W, that gives q_S for a given G_T.
- $(W;q_S)$ gives R_0, R_L, I_D, G_m, V_{DSAT} and V_G

Input Matching

- *With* R_0 , R_F , G_m => R_P $\quad \Re(Zp) = R_P = \dfrac{R_O + R_F}{1 + G_m R_O},$
- *With* R_S *and* R_P *calculate* Q_P $\quad \Re(Z_{IN}) = R_S = \dfrac{R_P}{(1 + Q_P^2)} = 50\ \Omega$
- *With* Q_P *calculate* C_T *and* C_{GS}' $\quad Q_P = R_P C_T \omega_0 \quad C_T = C_{GS} + C'_{GS} + C_P \quad C_P = \dfrac{R_O^2 C_L (G_m R_F - 1)}{(R_O + R_F)^2}$
- *With* C_T *calculate* L_G $\quad \Im(Z_{IN}) = 0 = L_G s + \dfrac{Q_P^2}{C_T s (1 + Q_P)^2}$

Validation

Now, let's simulate with a real PDK