Measurements, models and extractions

Rüdiger Follmann

Contents

Ways of modeling

→**Physical models**: Particle models or semiconductor equations

→**Table based models**: Bias dependentS-parameters are saved in a table

→**Mathematical models**: Transfer behavior is described by mathematical functions

→**Equivalent circuits**: Physical behavior is emulated by lumped elements

Ways of modeling

Linear models

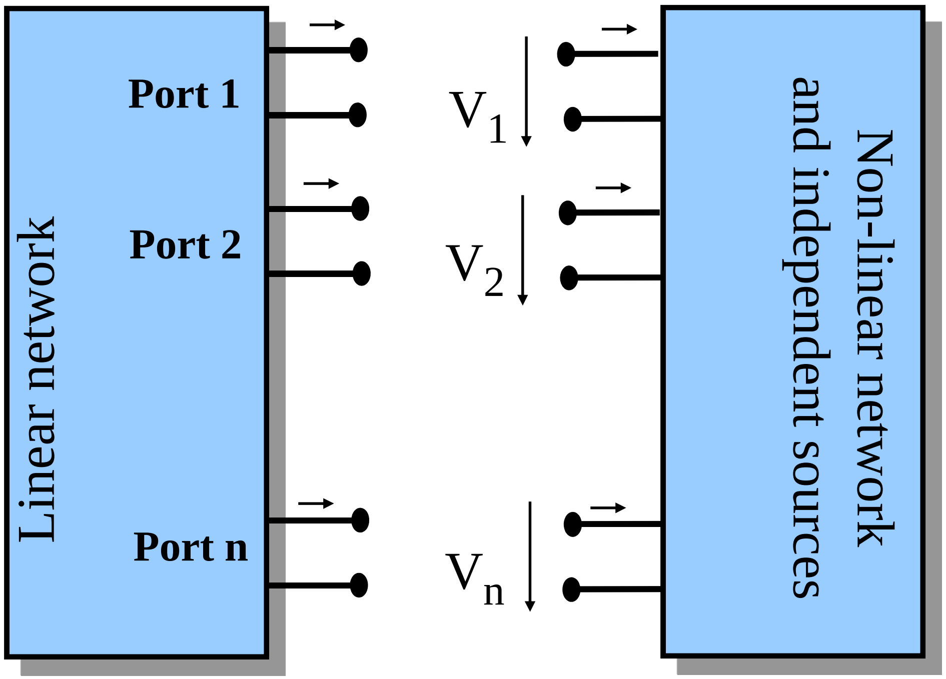
→Description of DC behavior

→Description of RF behavior, e.g. in dependence of bias point. Only small signal amplitudes close to bias point are allowed

Non-linear models

→Large signal amplitudes and change of bias point (Harmonic balance).

Harmonic balance



Only linear elements

Only non-linear elements

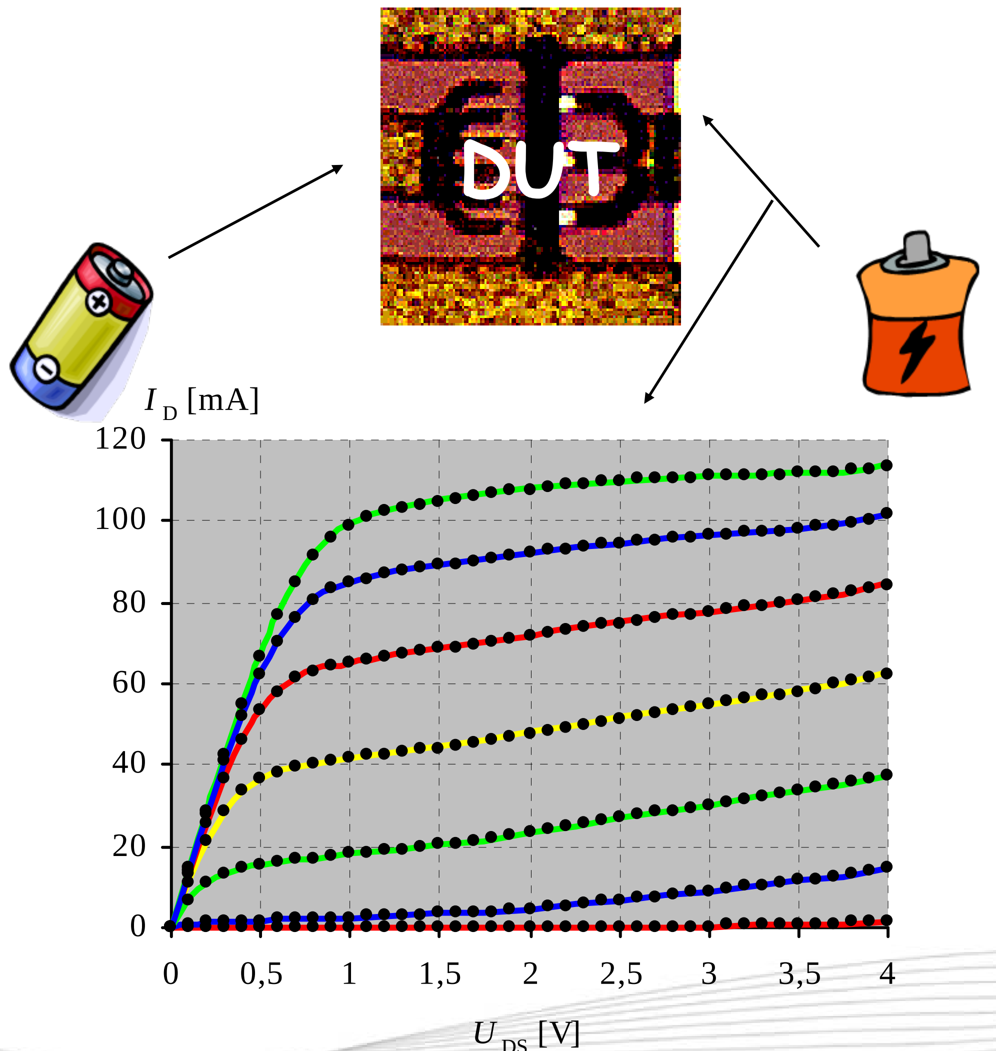
HB is a hybrid between time- and frequency domain calculations.
Non-linear part is calculated In time domain, linearer part in frequency domain

Voltages and currents at each port are balanced, until they are equal for both part of network.

DC measurements

Port 1
Input

Port 2
Output

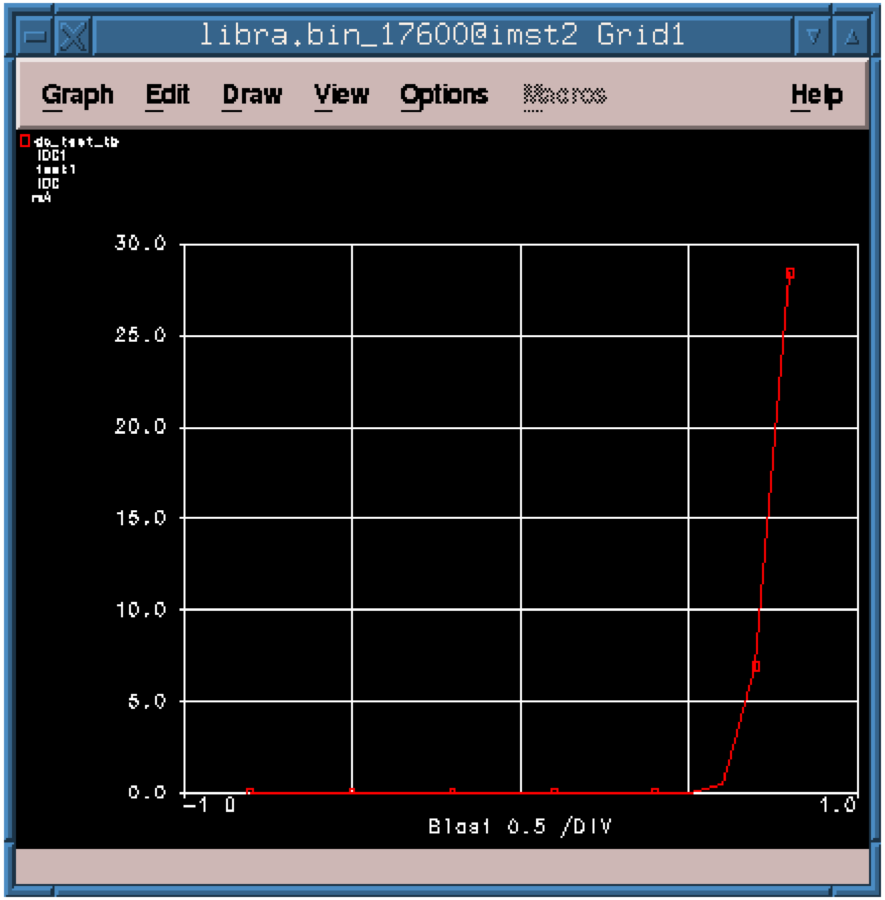


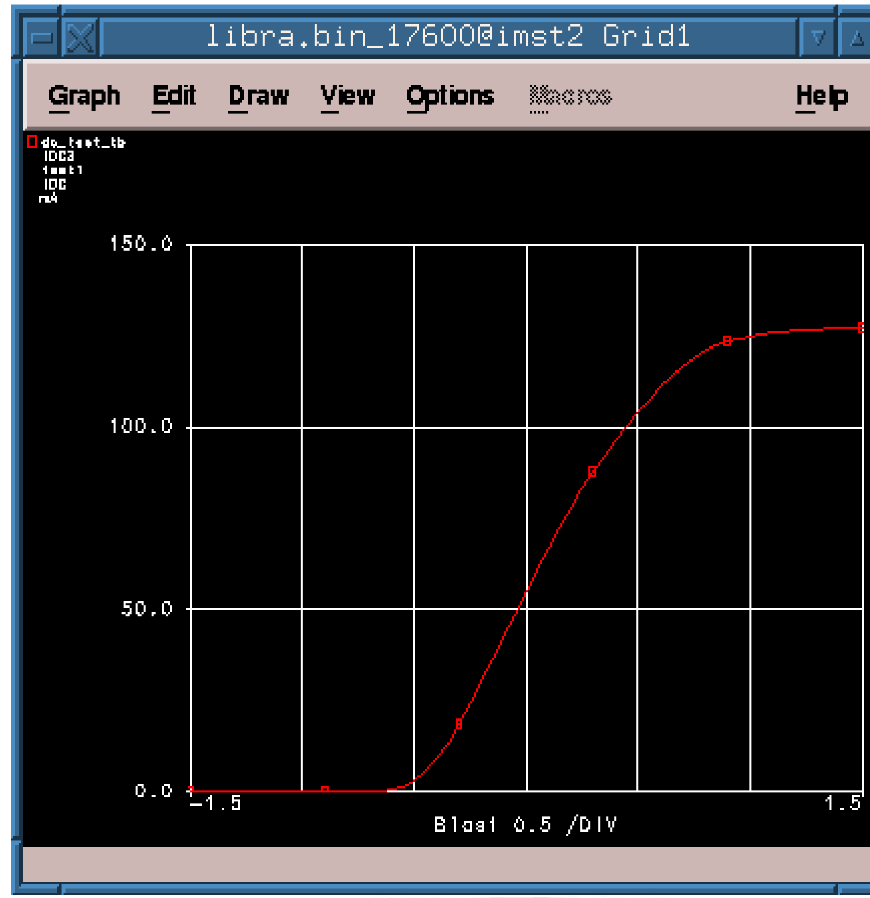
V_{GS}

V_{DS}

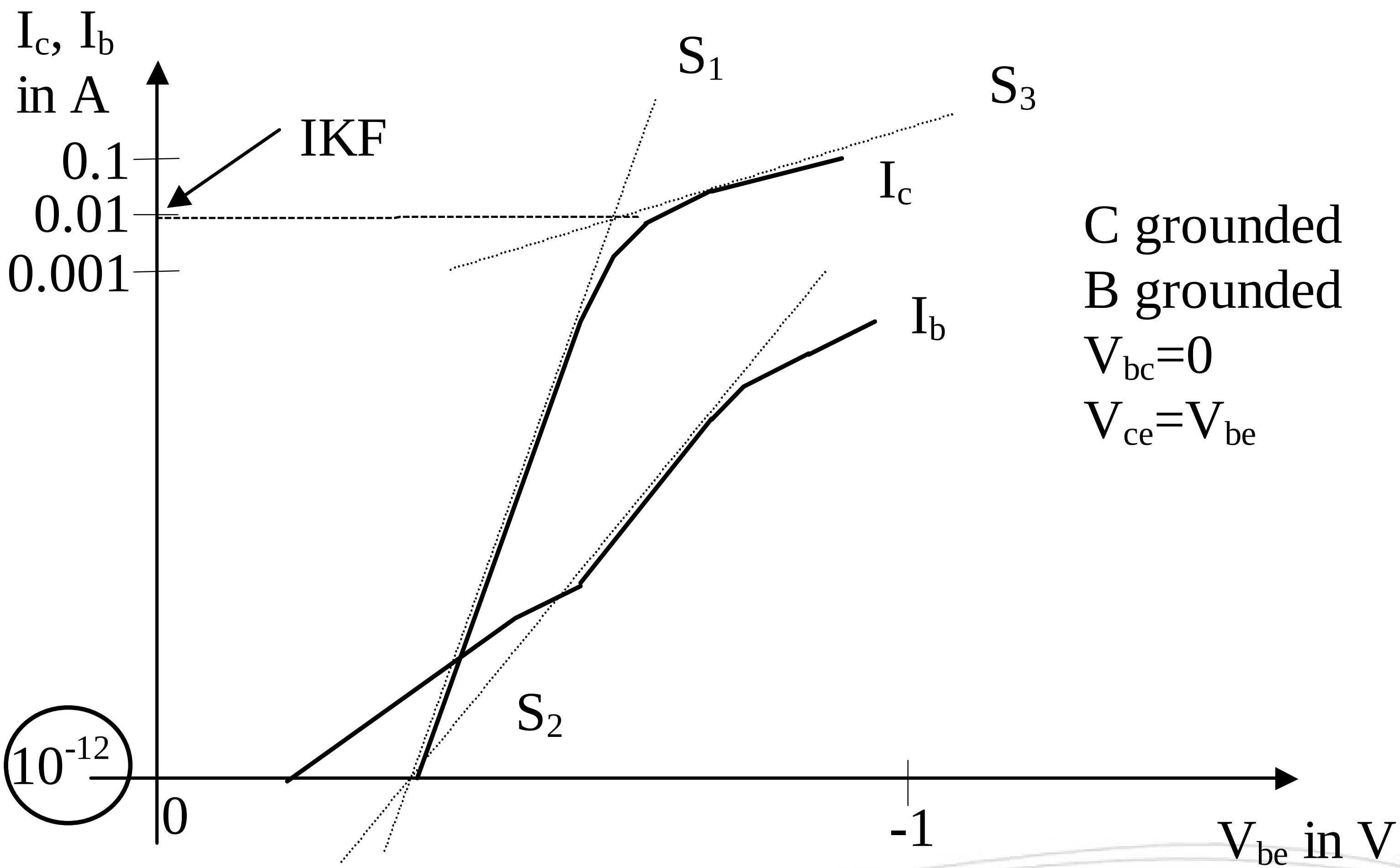
DC IV-curves

Transistor transfer curves





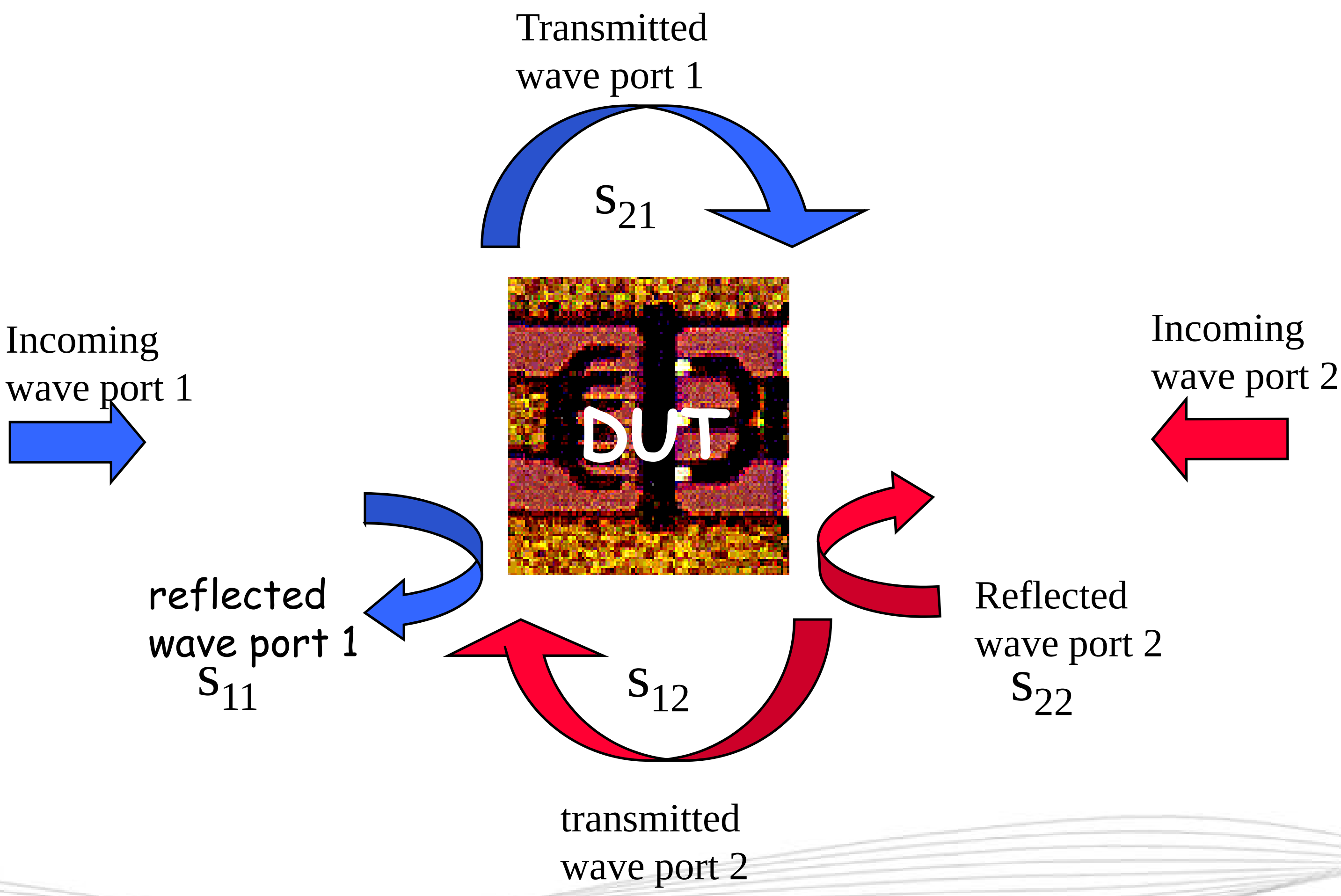
Gummel-Plots



C grounded
B grounded
$V_{bc}=0$
$V_{ce}=V_{be}$

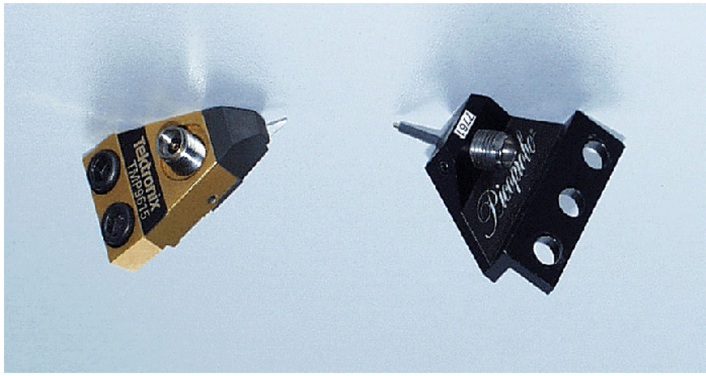
RF measurements

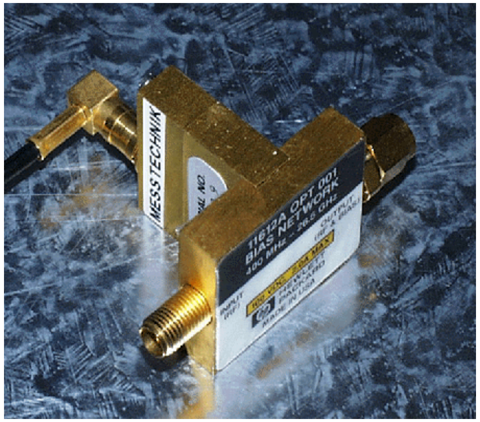
S-parameter measurements



RF measurements

S-parameter measurements





 Models Feb-09

Qualification

→Pinch-off of transistor device

→Enhancement or depletion mode

→Slope and IV curves

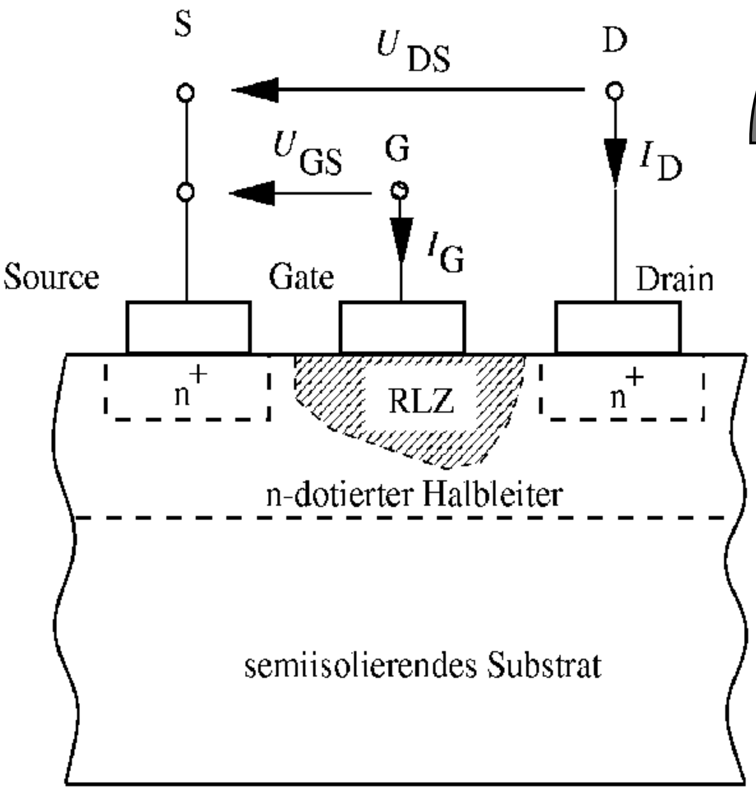
→Gate diode current

→amplification s_{21} and attenuation

→Compression behavior

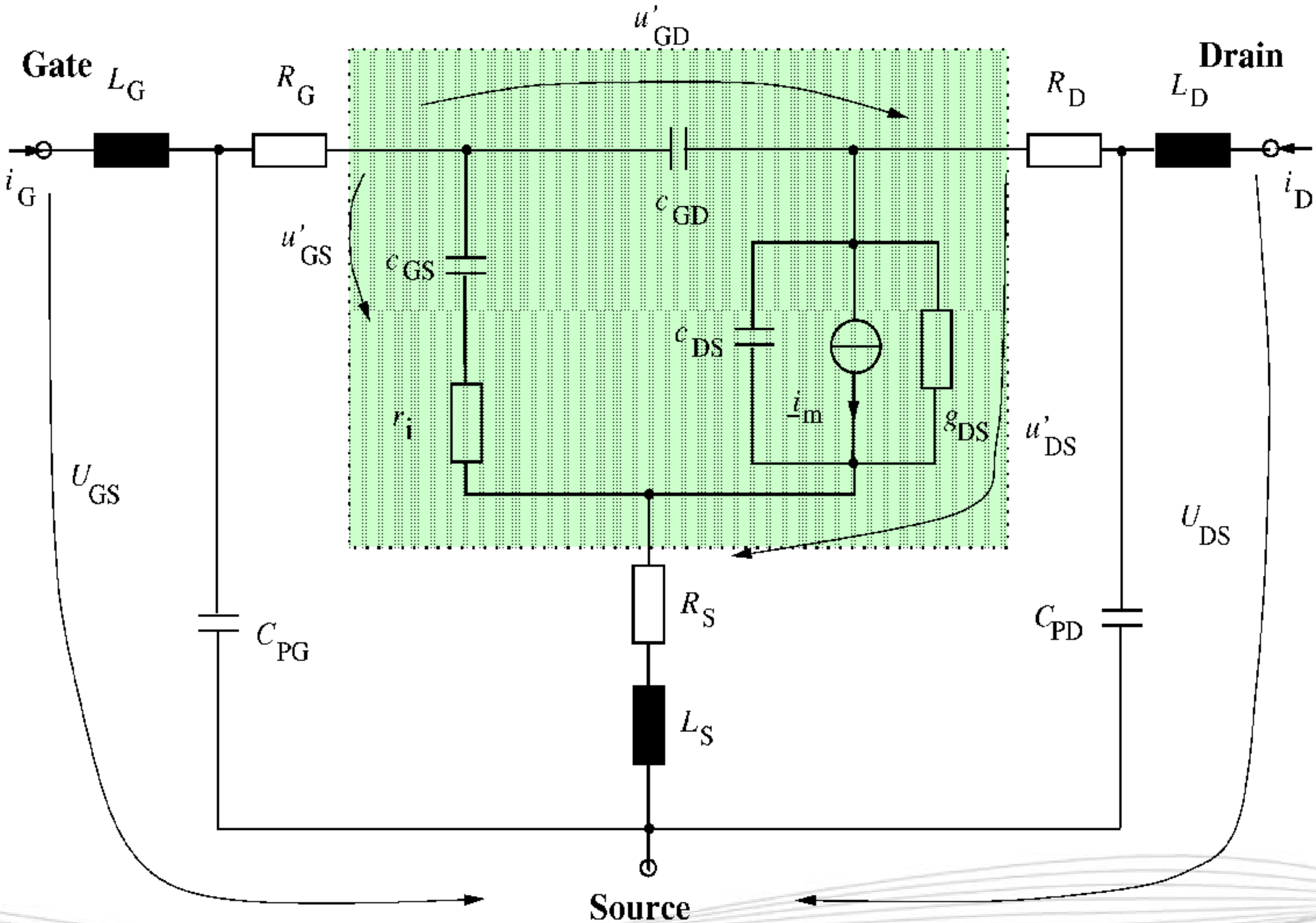
→Other s-parameters < 0 dB

Composition FET und equivalent circuit

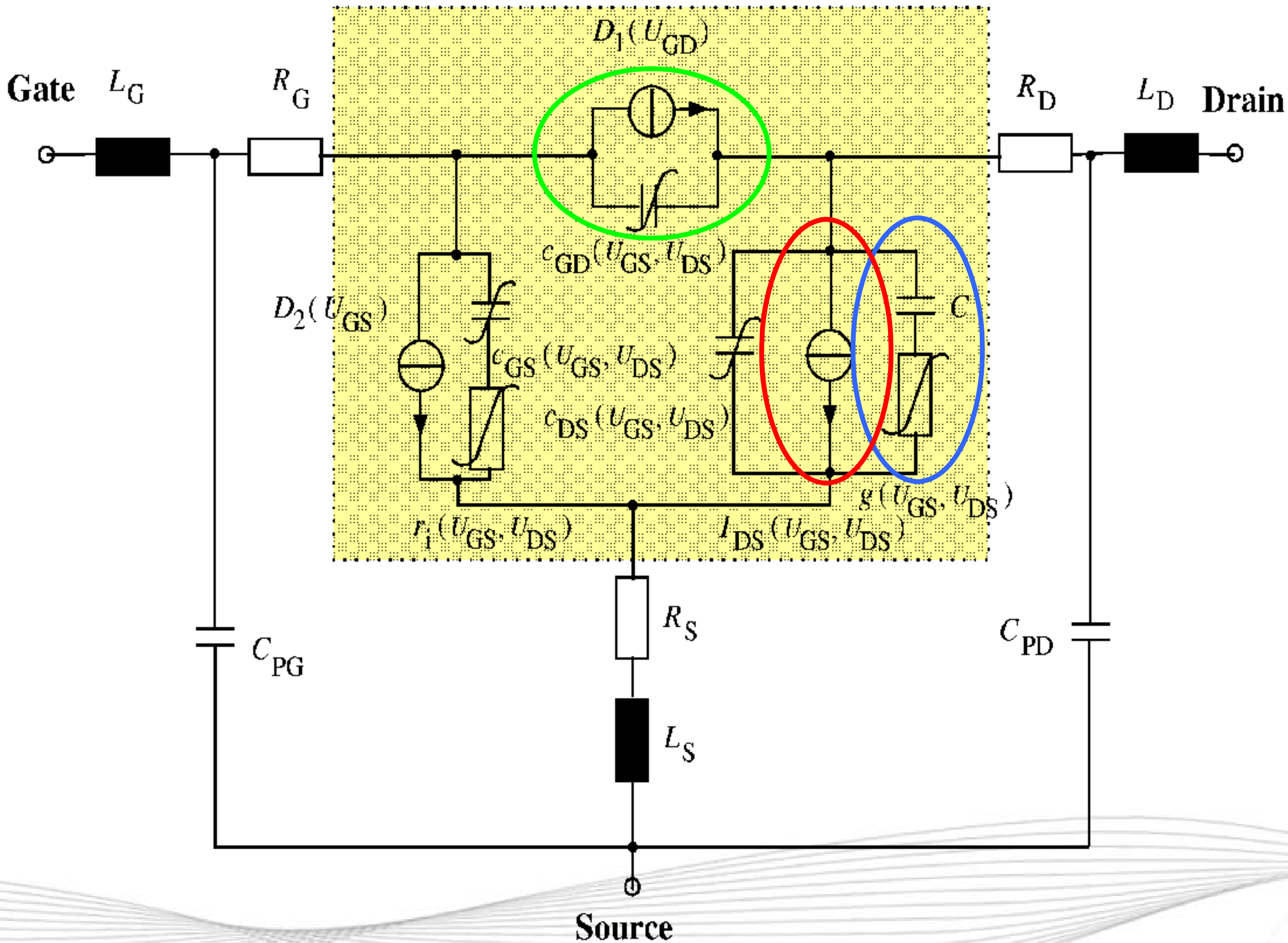


Das Bild kann nicht angezeigt werden. Dieser Computer verfügt möglicherweise über zu wenig Arbeitsspeicher, um das Bild zu öffnen, oder das Bild ist beschädigt. Starten Sie den Computer neu, und öffnen Sie dann erneut die Datei. Wenn weiterhin das rote x angezeigt wird, müssen Sie das Bild möglicherweise löschen und dann erneut einfügen.

Small signal equivalent circuit



Enhanced small signal equivalent circuit

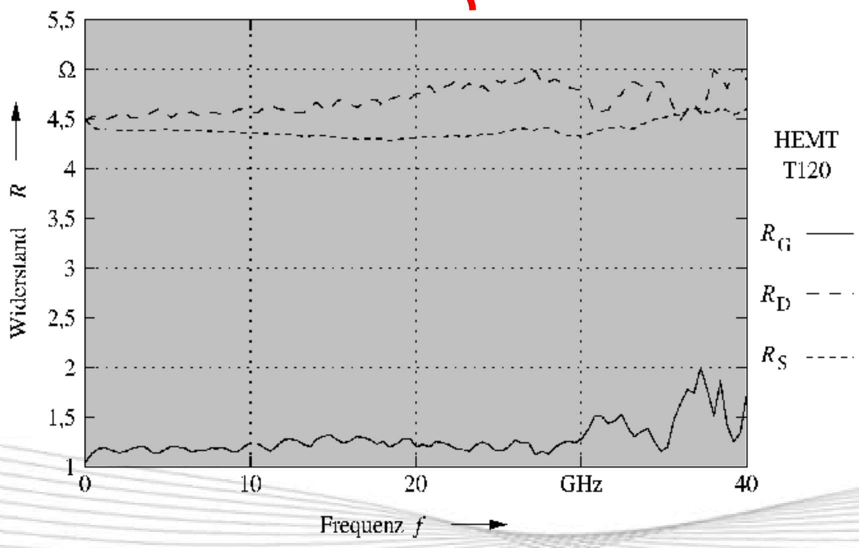


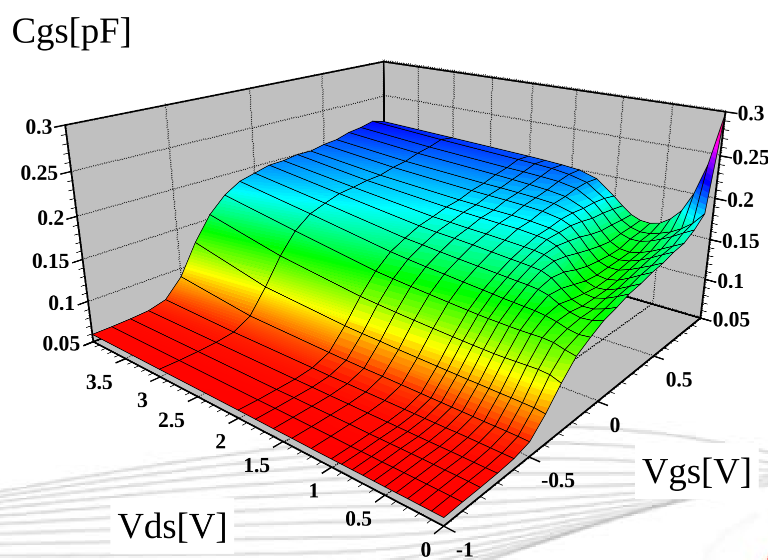
Parameter extraction

S-Parameter
IV curves → Extrinsic elements → Intrinsic elements →

$$R_S = \mathrm{Re}\{\underline{z}_{12}\}$$

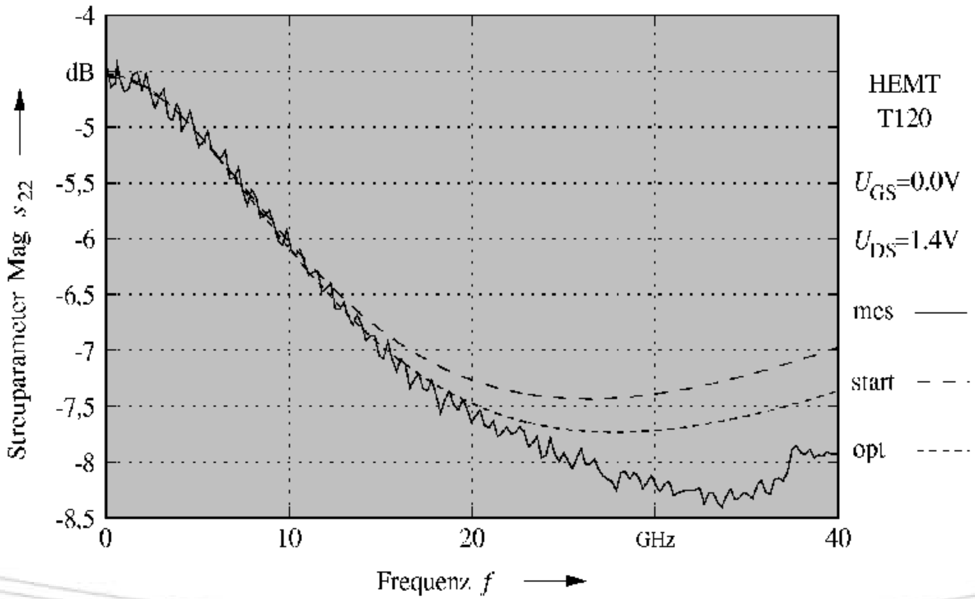
$$c_{GS}(V_{GS},V_{DS}) = \sum_{f=f_1}^{f_2} \frac{1}{\omega}\left(\mathrm{Im}\{\underline{y}_{11}(V_{GS},V_{DS})\} + \mathrm{Im}\{\underline{y}_{12}(V_{GS},V_{DS})\}\right) / \left(n_{f2} - n_{f1}\right)$$





Parameter extraction

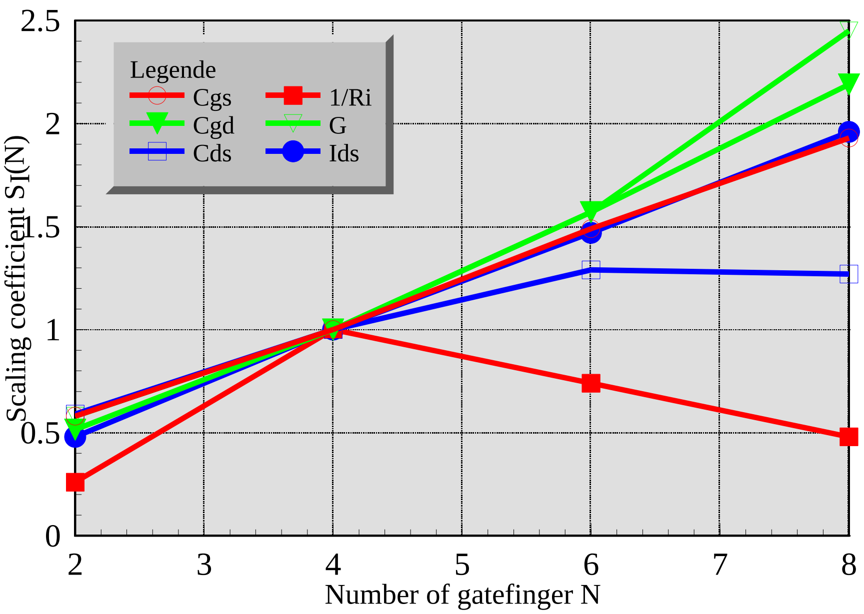
Optimization of intrinsic elements → Calcualtion of conductance *g* → De-embedding of voltages →

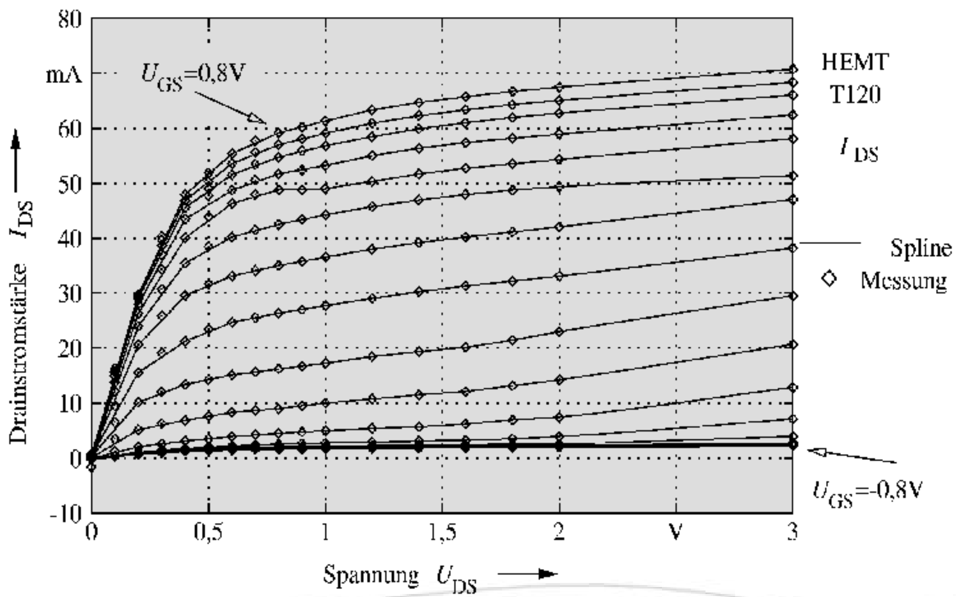


$$V'_{GS} = V_{GS} - I_{DS} R_S$$
$$V'_{DS} = V_{DS} - I_{DS}\left(R_D + R_S\right)$$

Parameterextraktion

Calculation of scaling and noise parameters → Description of intrinsic elements → Store the Simulation file





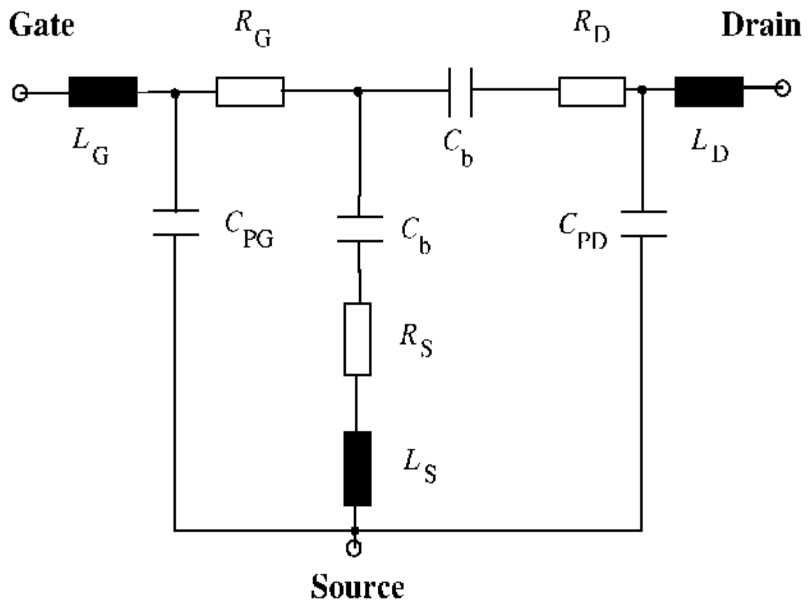
 Models Feb-09

Extraction of extrinsic elements

Extraction of capacitances

$$V_{GS} < V_p$$

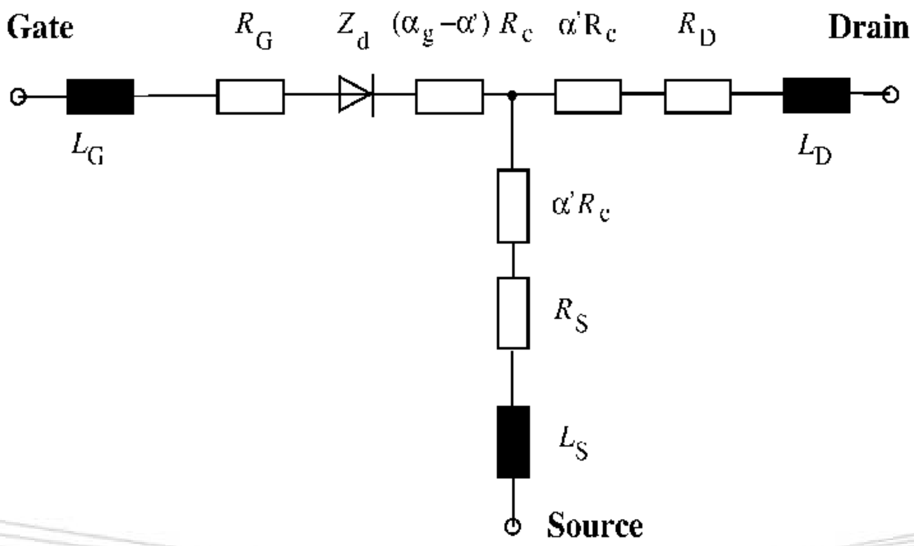
$$V_{DS} = 0\,\text{V}$$



Extraction of inductances and resistors

$$V_{GS} > 0\,\text{V}$$

$$V_{DS} = 0\,\text{V}$$



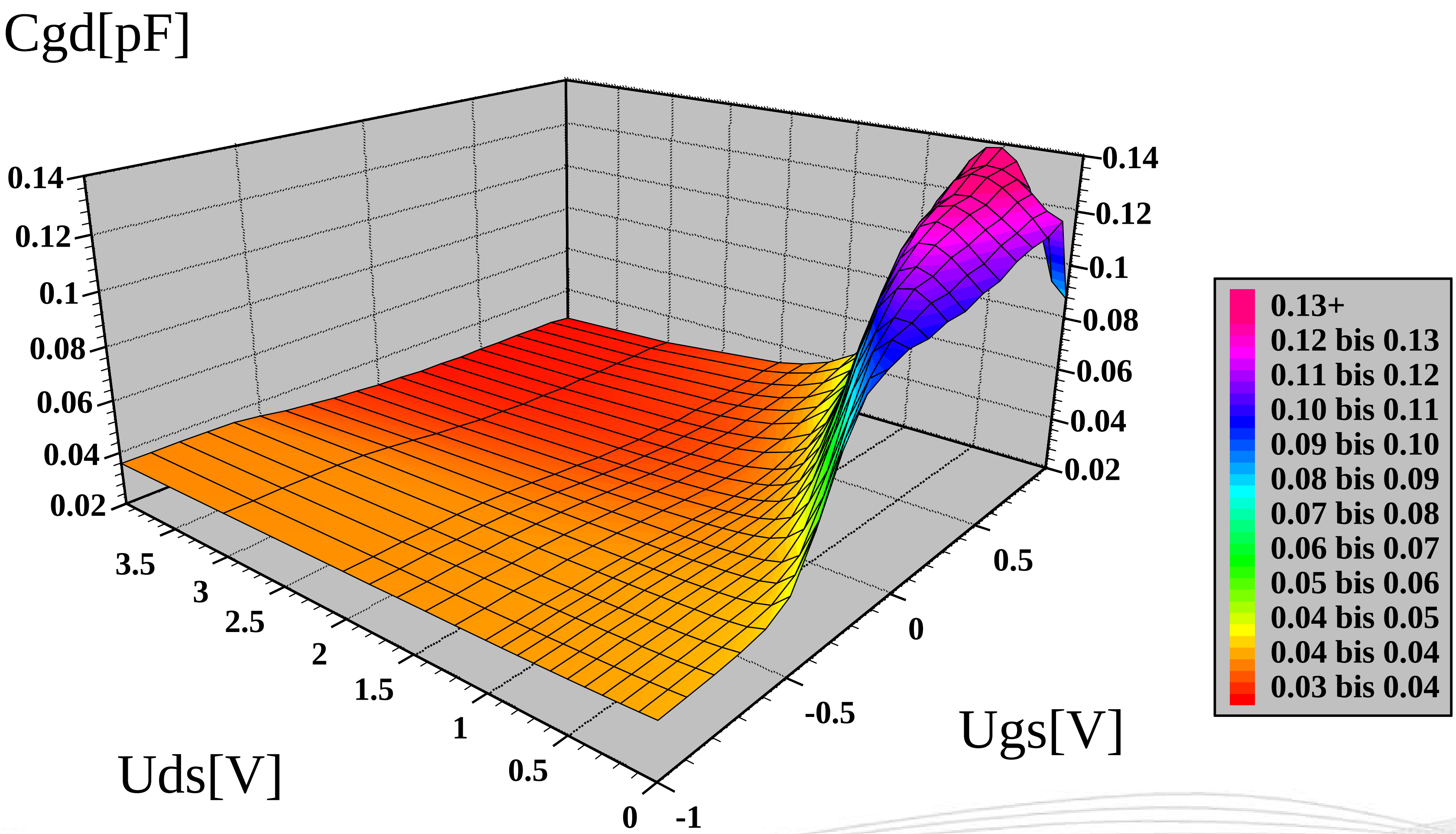
Extraction of intrinsic elements

$\underline{S} \rightarrow \underline{Z}$ ⇒
$$\begin{pmatrix} \underline{z}_{11} - j\omega L_G & \underline{z}_{12} \\ \underline{z}_{21} & \underline{z}_{22} - j\omega L_D \end{pmatrix}$$

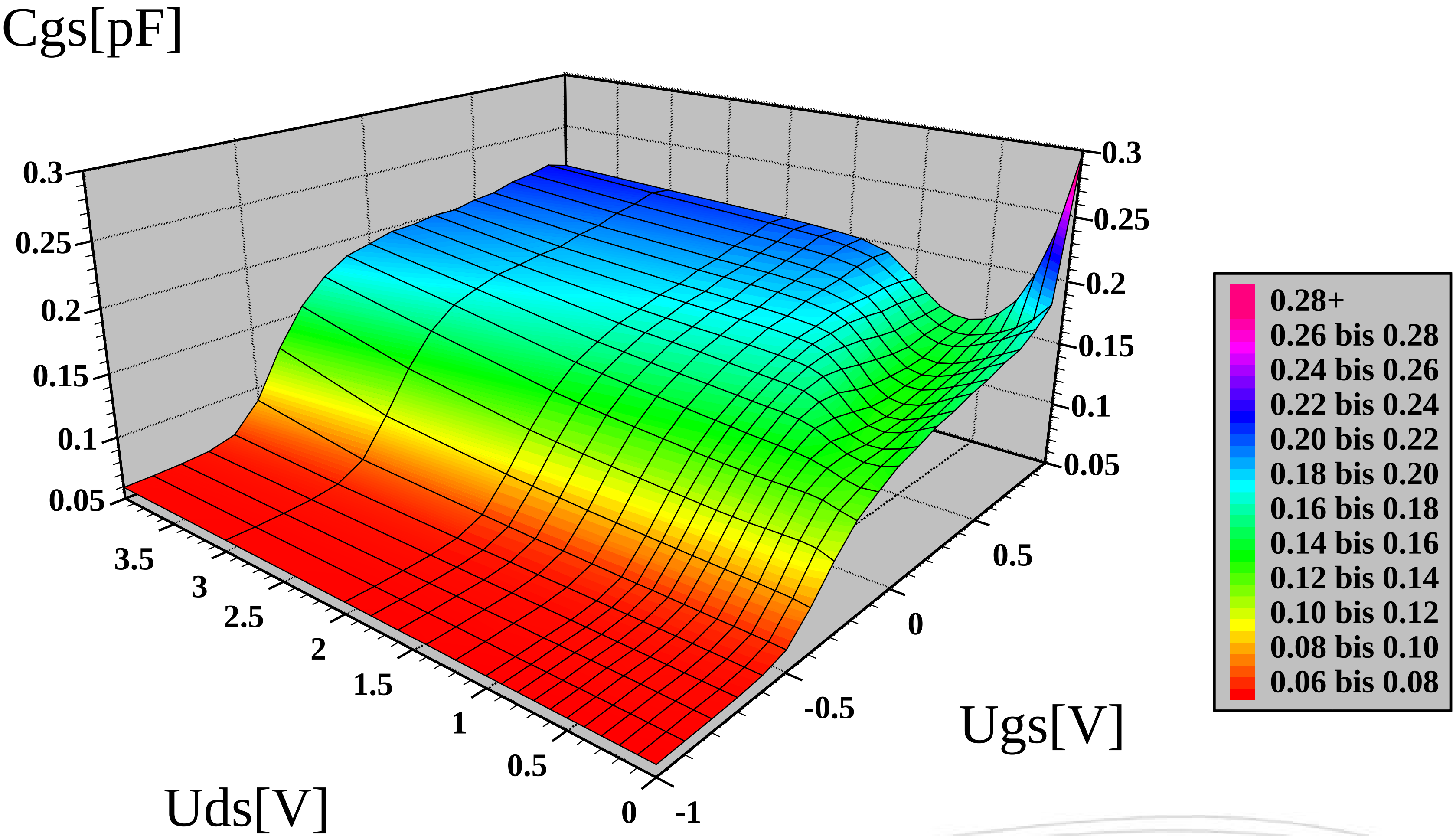
$\underline{Z} \rightarrow \underline{Y}$ ⇒
$$\begin{pmatrix} \underline{y}_{11} - j\omega C_{PG} & \underline{y}_{12} \\ \underline{y}_{21} & \underline{y}_{22} - j\omega C_{PD} \end{pmatrix}$$

$\underline{Y} \rightarrow \underline{Z}$ ⇒
$$\begin{pmatrix} \underline{z}_{11} - R_S - R_G - j\omega L_S & \underline{z}_{12} - R_S - j\omega L_S \\ \underline{z}_{21} - R_S - j\omega L_S & \underline{z}_{22} - R_S - R_D - j\omega L_S \end{pmatrix}$$

Extraction of intrinsic elements

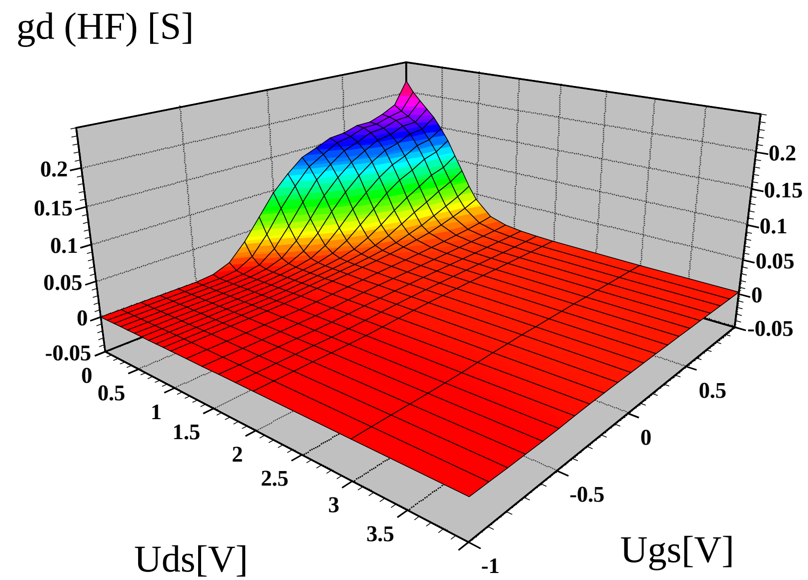


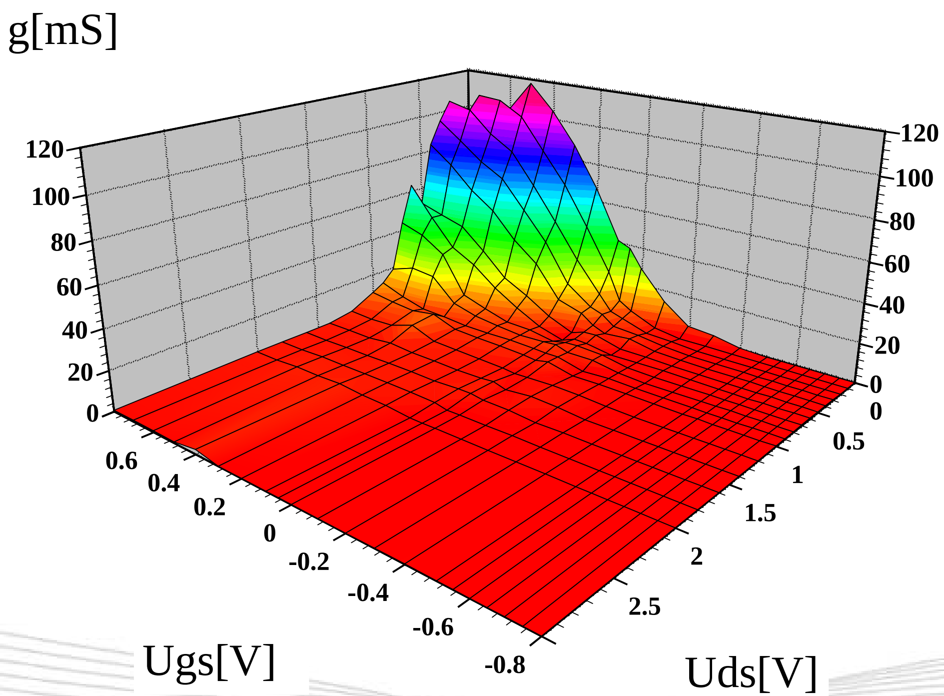
Extraction of intrinsic elements

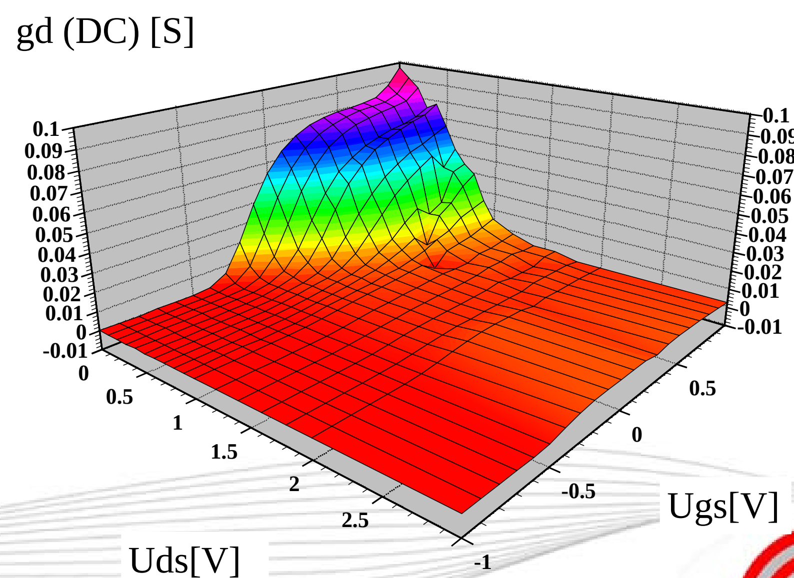


Calculation of output conductance

Extraction of output conductance *g* using optimizing process

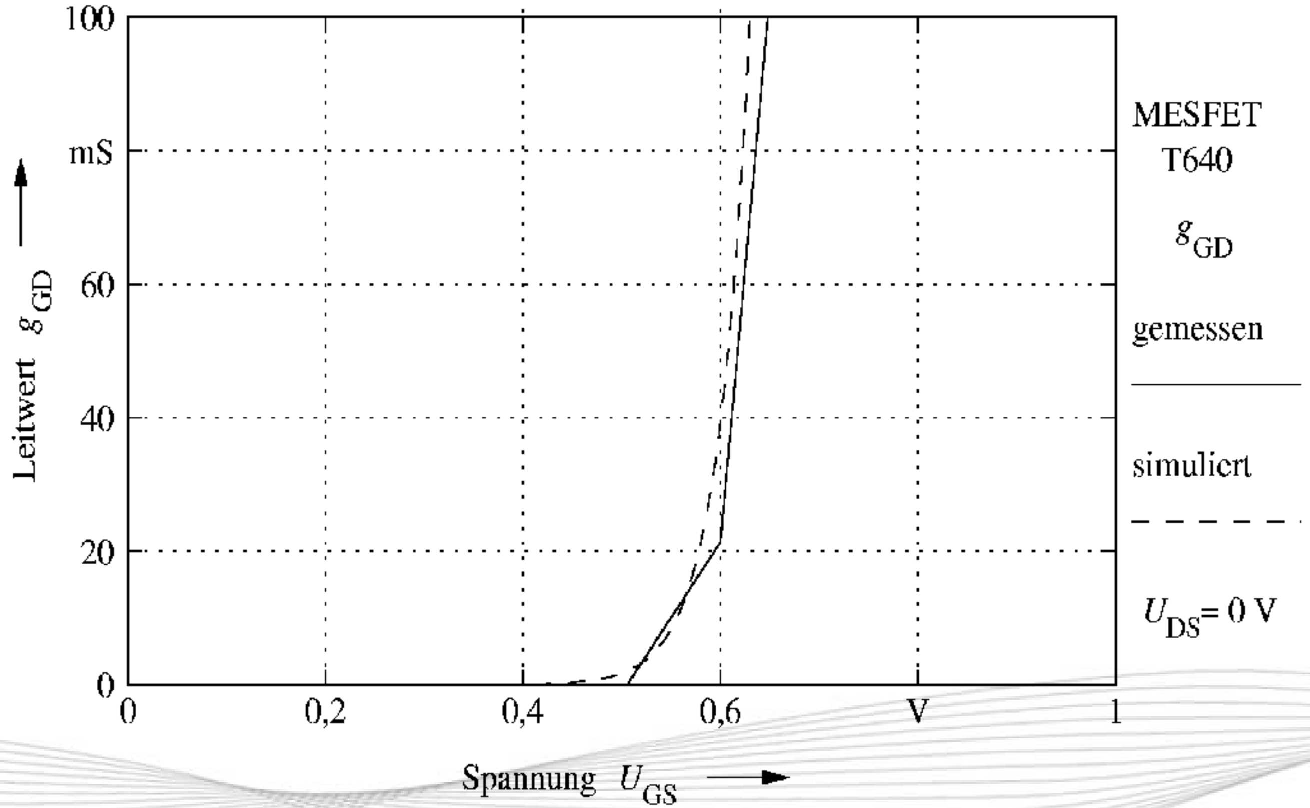






Extraction of Is and n

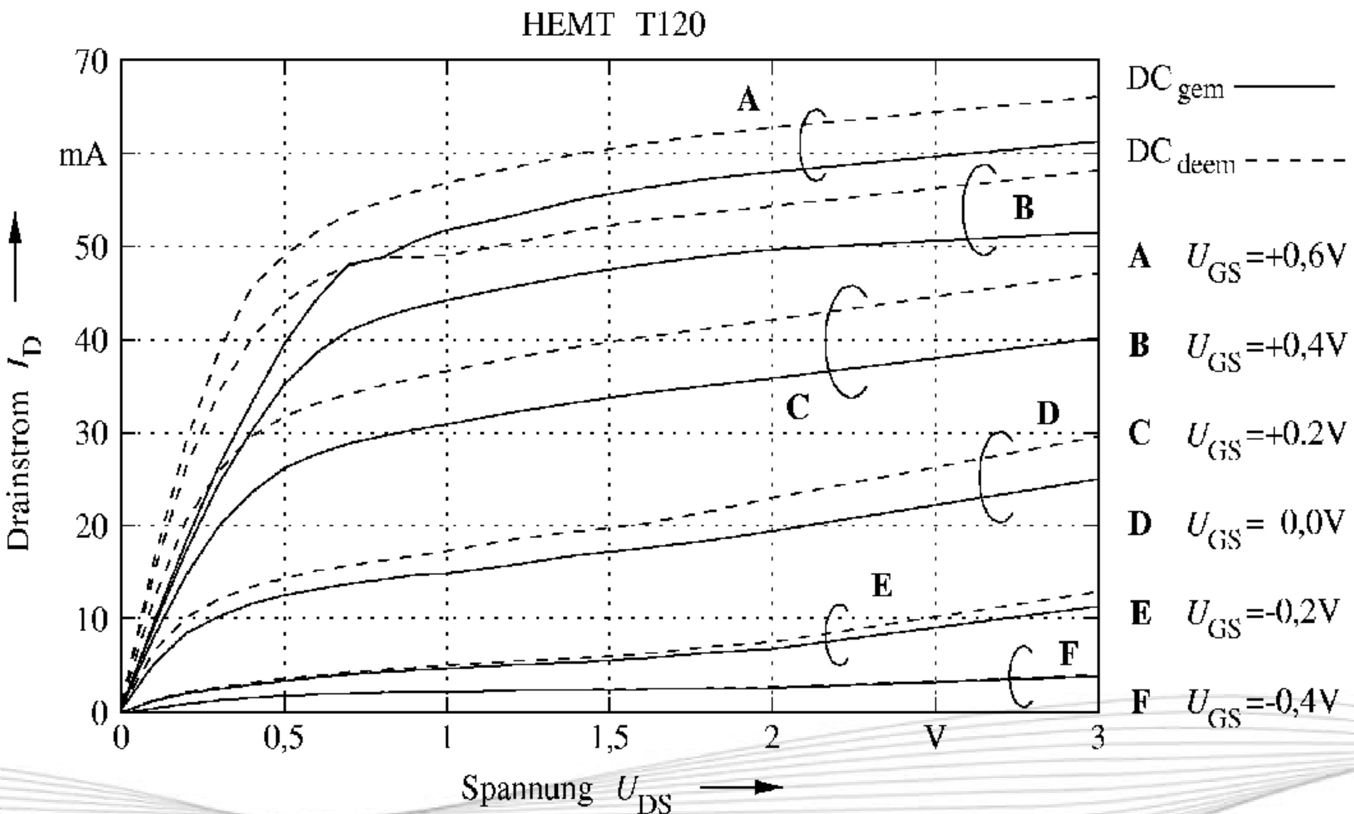
$$\mathrm{Re}\left\{\underline{y}_{12}\right\} = -\frac{\mathrm{d}I_{\mathrm{d1}}}{\mathrm{d}U_{\mathrm{GD}}} = -\frac{I_{\mathrm{S}}}{nU_{\mathrm{t}}}\exp\left(\frac{U_{\mathrm{GD}}}{nU_{\mathrm{t}}}\right)$$



 Models Feb-09

Outer and inner voltages

$$V'_{GS} = V_{GS} - I_{DS} R_S$$
$$V'_{DS} = V_{DS} - I_{DS}\left(R_D + R_S\right)$$



Description of intrinsic elements

$$c_{GS} = \begin{cases} k_h + k_g U_{DS} + x_{20} & U_{DS} > 0 \\ k_h + x_{20} & \text{sonst} \end{cases}$$

$$k_a = \begin{cases} x_0 (U_{GS} - x_1)^2 & U_{GS} \geq x_1 \\ 0 & \text{sonst} \end{cases}$$

$$k_b = x_2 \left(\tanh\left(x_3 (U_{GS} - x_{17}) \right) + 1 \right)$$

$$k_h = k_a \left(\exp\left(k_b (U_{DS} - k_c)^2 \right) \right) + k_d \left(\tanh\left(k_e (U_{DS} - k_f) \right) + 1 \right)$$

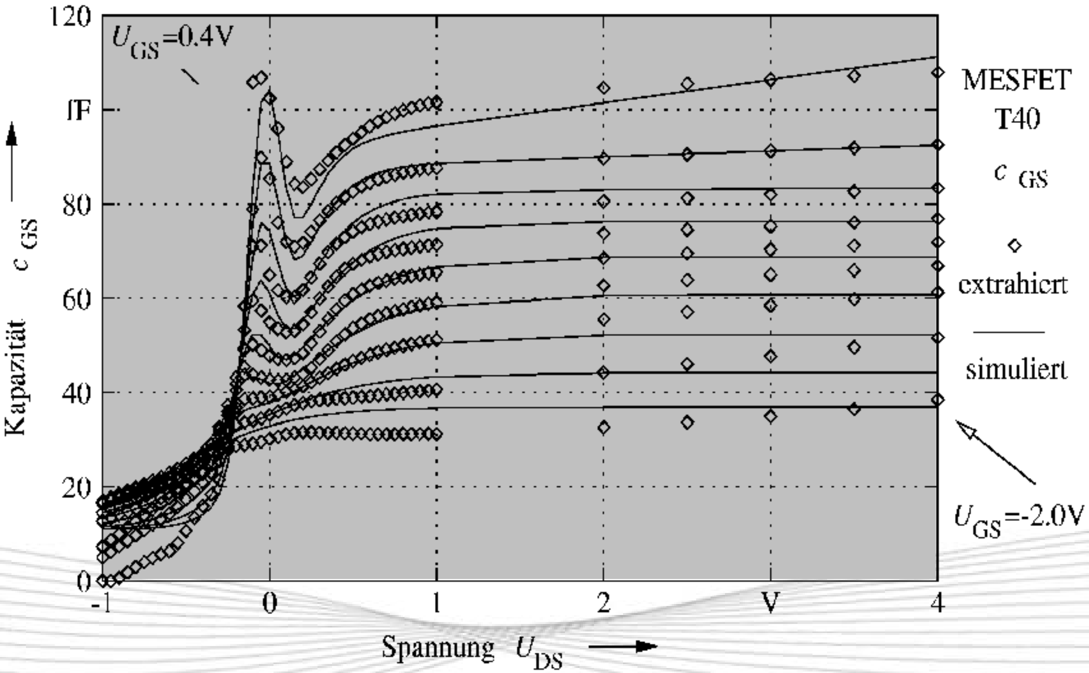
$$k_c = x_4 \exp\left(x_5 (U_{GS} - x_6)^2 \right)$$

$$k_d = x_7 \left(\tanh\left(x_{21} (U_{GS} - x_8) \right) + 1 \right)$$

$$k_e = x_9 (U_{GS} - x_{10})^2 + x_{11}$$

$$k_f = x_{12} \exp\left(x_{13} (U_{GS} - x_{14})^2 \right) + x_{18}$$

$$k_g = x_{15} \exp\left(x_{16} (U_{GS} - x_{19})^2 \right)$$



Large signal simulation

$$Q_1(u_1) = \int_{u_{10}}^{u_1} c(\tilde{u}_1)\mathrm{d}\tilde{u}_1$$

$$\Delta Q = \oint_{\partial\Omega} c(\tilde{u}_1)\mathrm{d}\tilde{u}_1 = 0$$

Defined charge cycle

$$Q_2(u_1,u_2) = \int_{u_{10}}^{u_1} c(\tilde{u}_1,u_2)\mathrm{d}\tilde{u}_1 + Q_1'(u_2)$$

Trans elements

$$C(u_1,u_2) = \sum_{i=0}^{n} c_i(u_1)T_i(u_2)$$

Complete gate current

$$i_\mathrm{G} = i_\mathrm{GS} + i_\mathrm{GD}$$

$$u_\mathrm{GS} = U_\mathrm{GS} + u_\mathrm{GS\sim} \Rightarrow \frac{\mathrm{d}u_\mathrm{GS}}{\mathrm{d}t} = \frac{\mathrm{d}u_\mathrm{GS\sim}}{\mathrm{d}t}$$

GS-part of gate current $i_\mathrm{GS} = \frac{\mathrm{d}Q_\mathrm{GS}}{\mathrm{d}t} = C'_\mathrm{GS}(u_\mathrm{GS},u_\mathrm{DS})\frac{\mathrm{d}u_\mathrm{GS}}{\mathrm{d}t}$

Large signal simulation

$$i_{GS} = C'_{GS}\left(U_{GS} + u_{GS\sim}, U_{DS} + u_{DS}\right)\frac{du_{GS\sim}}{dt}$$

Taylor-series

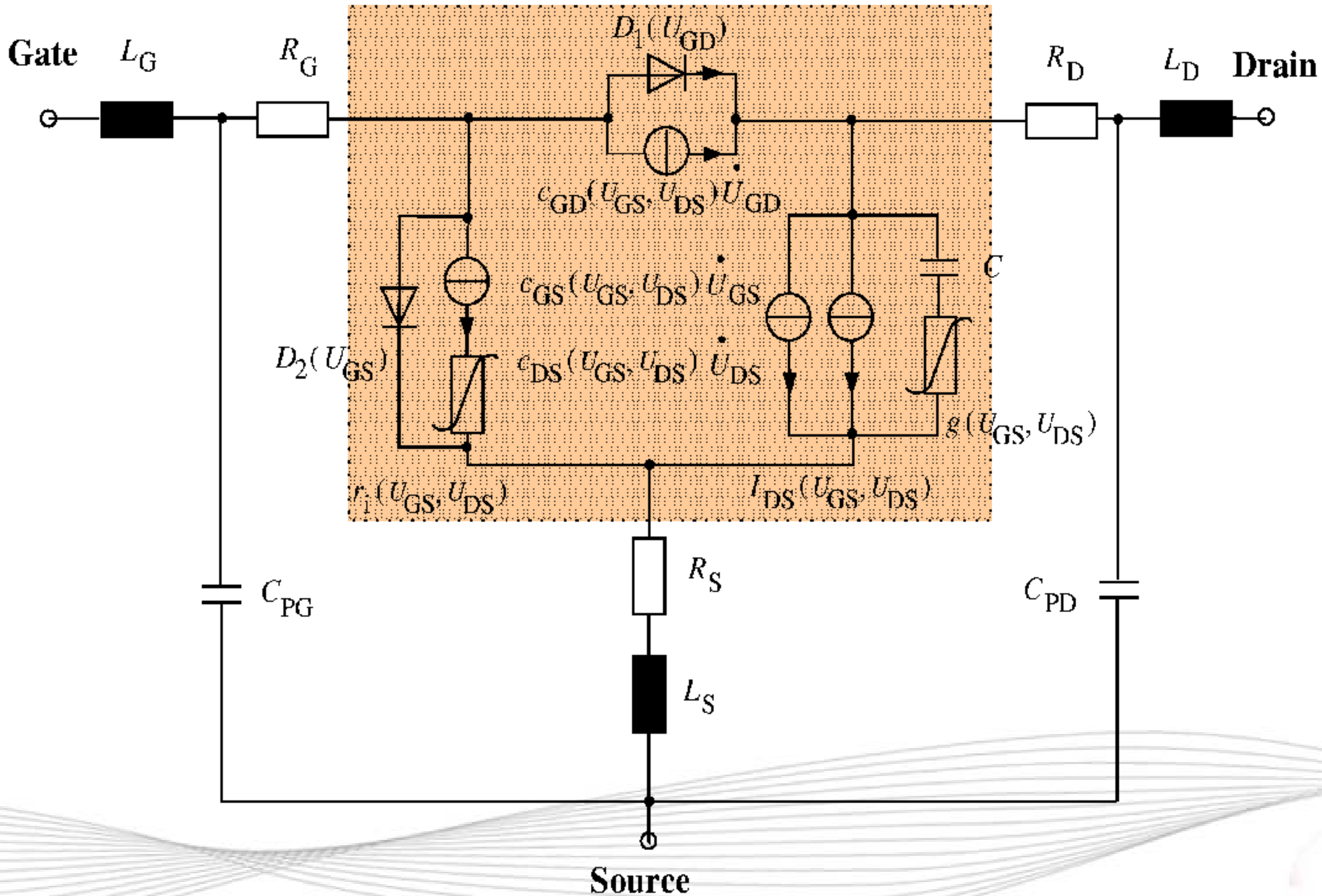
$$C'_{GS}\left(U_{GS} + u_{GS\sim}, U_{DS} + u_{DS\sim}\right) = C'_{GS}\left(U_{GS}, U_{DS}\right) + \left.\frac{\partial C'_{GS}\left(u_{GS}, u_{DS}\right)}{\partial u_{GS}}\right|_{\substack{u_{GS}=U_{GS}\\ u_{DS}=U_{DS}}} u_{GS\sim} + \left.\frac{\partial C'_{GS}\left(u_{GS}, u_{DS}\right)}{\partial u_{DS}}\right|_{\substack{u_{GS}=U_{GS}\\ u_{DS}=U_{DS}}} u_{DS\sim} + \ldots$$

GS-part of gate current

$$i_{GS} = c_{GS}\left(U_{GS}, U_{DS}\right)\frac{du_{GS}}{dt}$$

Large signal simulation

$$i_G = \frac{dQ(u_{GS}, u_{DS})}{dt} = \frac{\partial Q(u_{GS}, u_{GD})}{\partial u_{GS}} \frac{du_{GS}}{dt} + \frac{\partial Q(u_{GS}, u_{GD})}{\partial u_{GD}} \frac{du_{GD}}{dt}$$



Large signal simulation

Due to designation of 2 voltages of Vgs, Vds and Vgd, the third voltage is always defined!

Case 1: Gate charge is known

$$Q_G = au_{GS}^2 + bu_{GS}u_{DS} + au_{DS}^2$$

$$i_G = \frac{dQ(u_{GS}, u_{DS})}{dt} = \frac{\partial Q_G(u_{GS}, u_{GD})}{\partial u_{GS}} \frac{du_{GS}}{dt} + \frac{\partial Q_G(u_{GS}, u_{GD})}{\partial u_{GD}} \frac{du_{GD}}{dt}$$

$$u_{DS} = f\cos(\omega t) \qquad u_{GS} = e\sin(\omega t)$$

$$i_G = \omega(A\sin(2\omega t) + B\cos(2\omega t)) \qquad A = ae^2 - cf^2 \qquad B = bef$$

Pure capacitive gate current, no DC part

Large signal simulation

Case 2: The capacitances are known

$$c_{DS}(u_{GS}, u_{DS}) = \left.\frac{\partial Q_G}{du_{DS}}\right|_{u_{GS}=\text{const.}} = bu_{GS} + 2cu_{DS}$$

$$c_{GS}(u_{GS}, u_{DS}) = \left.\frac{\partial Q_G}{du_{GS}}\right|_{u_{DS}=\text{const.}} = 2au_{GS} + bu_{DS}$$

$$i_{GS} = \omega\left(C + D\sin(2\omega t) + C\cos(2\omega t)\right)$$

$$C = 0{,}5bef$$

$$D = ae^2$$

$$i_{GD} = \omega\left(-C + E\sin(2\omega t) + C\cos(2\omega t)\right)$$

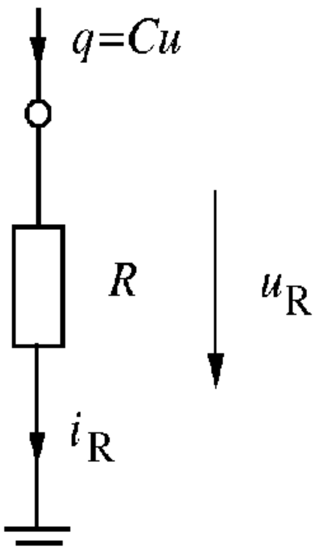
$$E = -cf^2$$

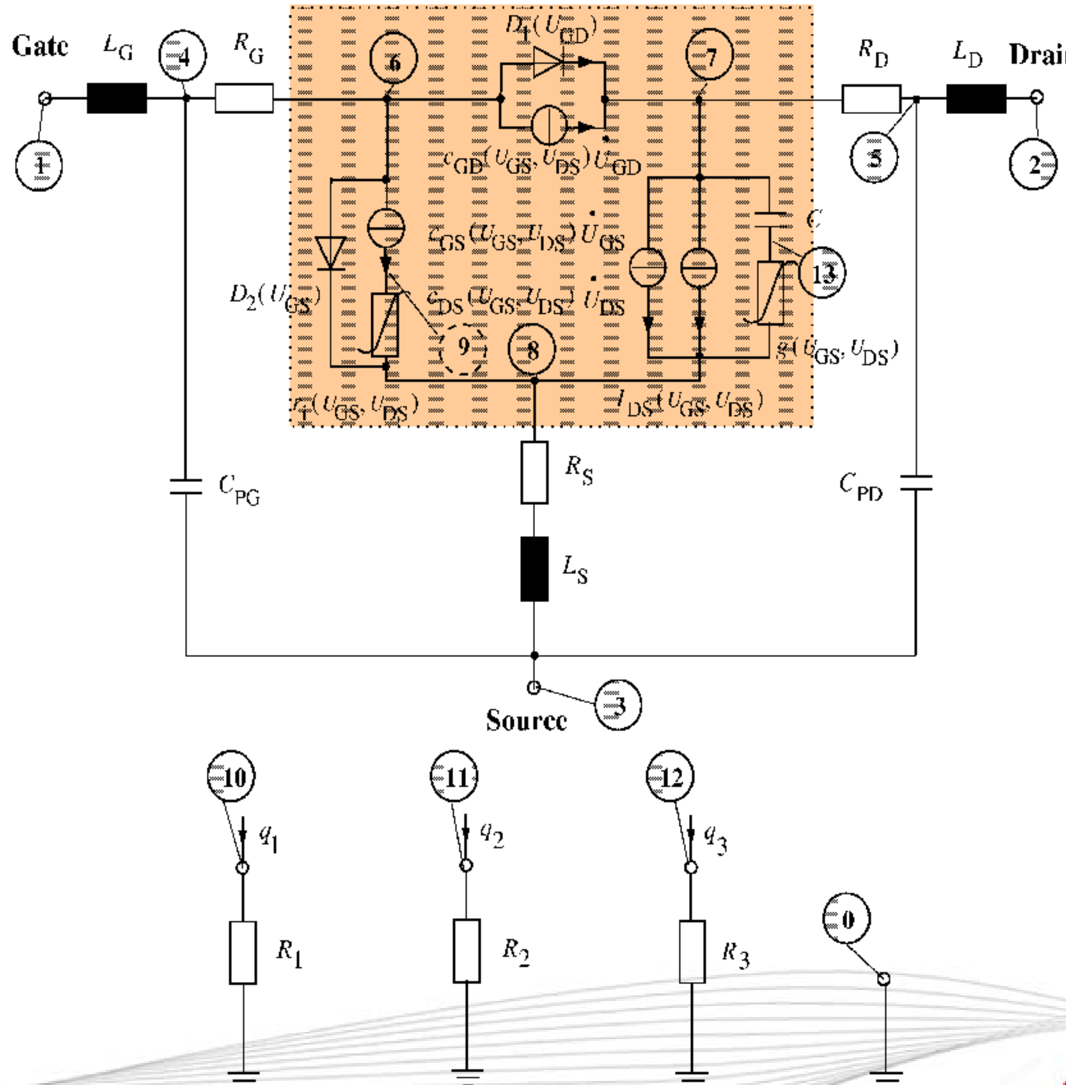
DC current parts, which compensate each other

Large signal simulation

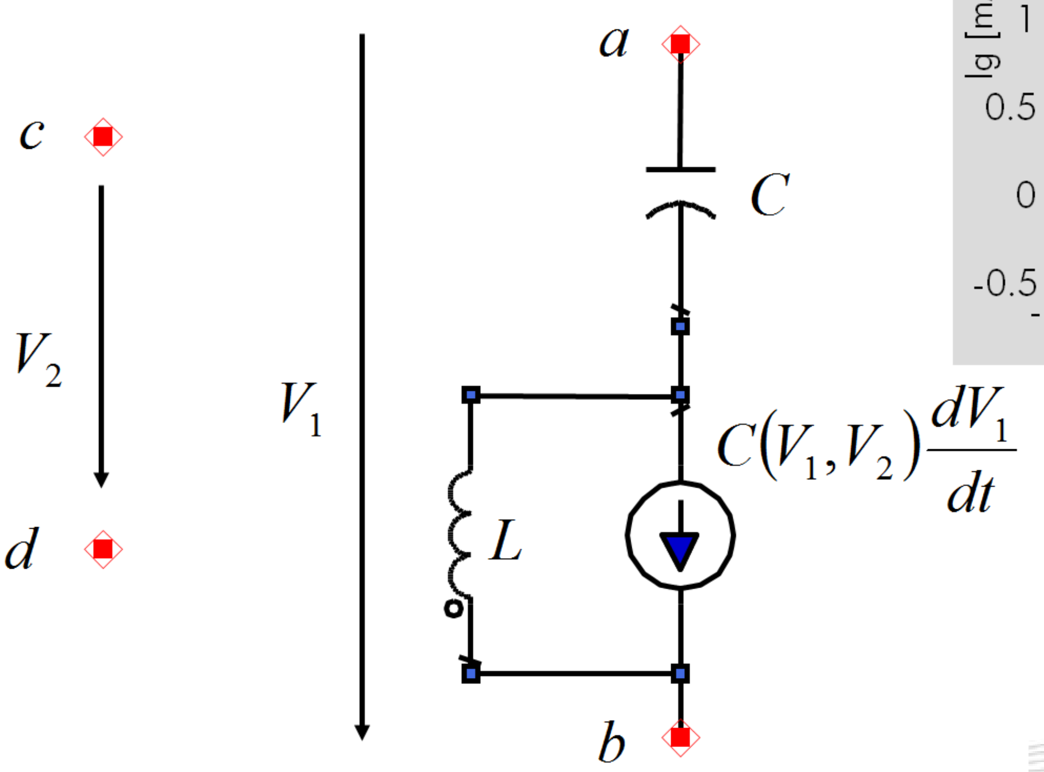
$$i_R = \dot{q} = C \cdot \dot{V}$$

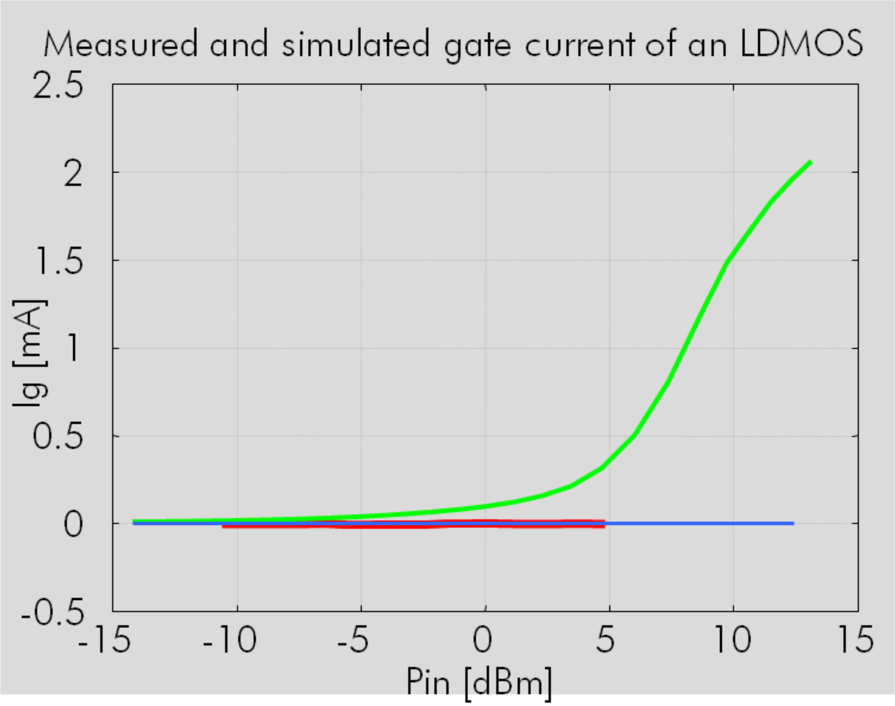
$$V_R = i_R R = CR \cdot \dot{V}$$





Example

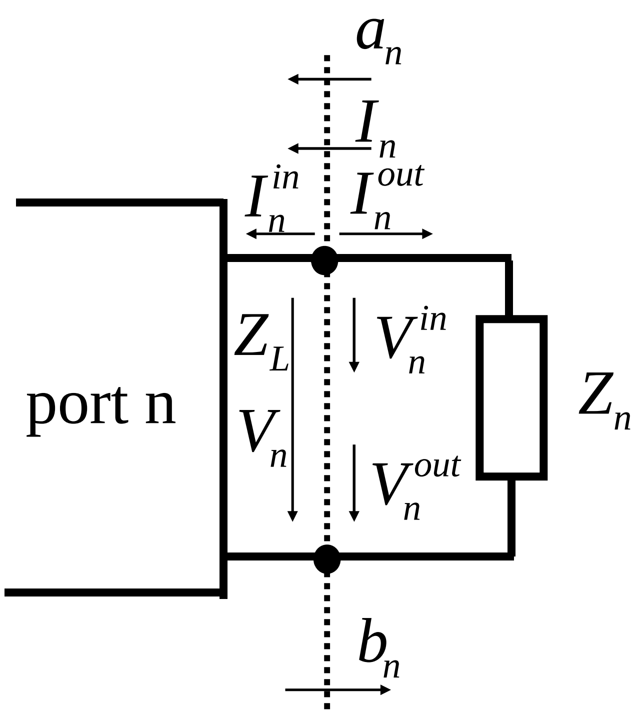




L, C large

Consistent implementation

Calculation of S-parameters using currents and voltages



Waves in an out of port n

$$a_n = \frac{V_n^{in}}{\sqrt{Z_{Ln}}} = I_n^{in}\sqrt{Z_{Ln}}$$

$$b_n = \frac{V_n^{out}}{\sqrt{Z_{Ln}}} = I_n^{out}\sqrt{Z_{Ln}}$$

Voltages and currents on the line

$$u_n = \frac{V_n}{\sqrt{Z_{Ln}}} = \frac{V_n^{in} + V_n^{out}}{\sqrt{Z_{Ln}}} = a_n + b_n$$

$$i_n = I_n\sqrt{Z_{Ln}} = \left(I_n^{in} - I_n^{out}\right)\sqrt{Z_{Ln}} = a_n - b_n$$

$$\Rightarrow \quad a_n = \frac{1}{2}(u_n + i_n) \qquad b_n = \frac{1}{2}(u_n - i_n) \quad \Rightarrow$$

S-Matrix

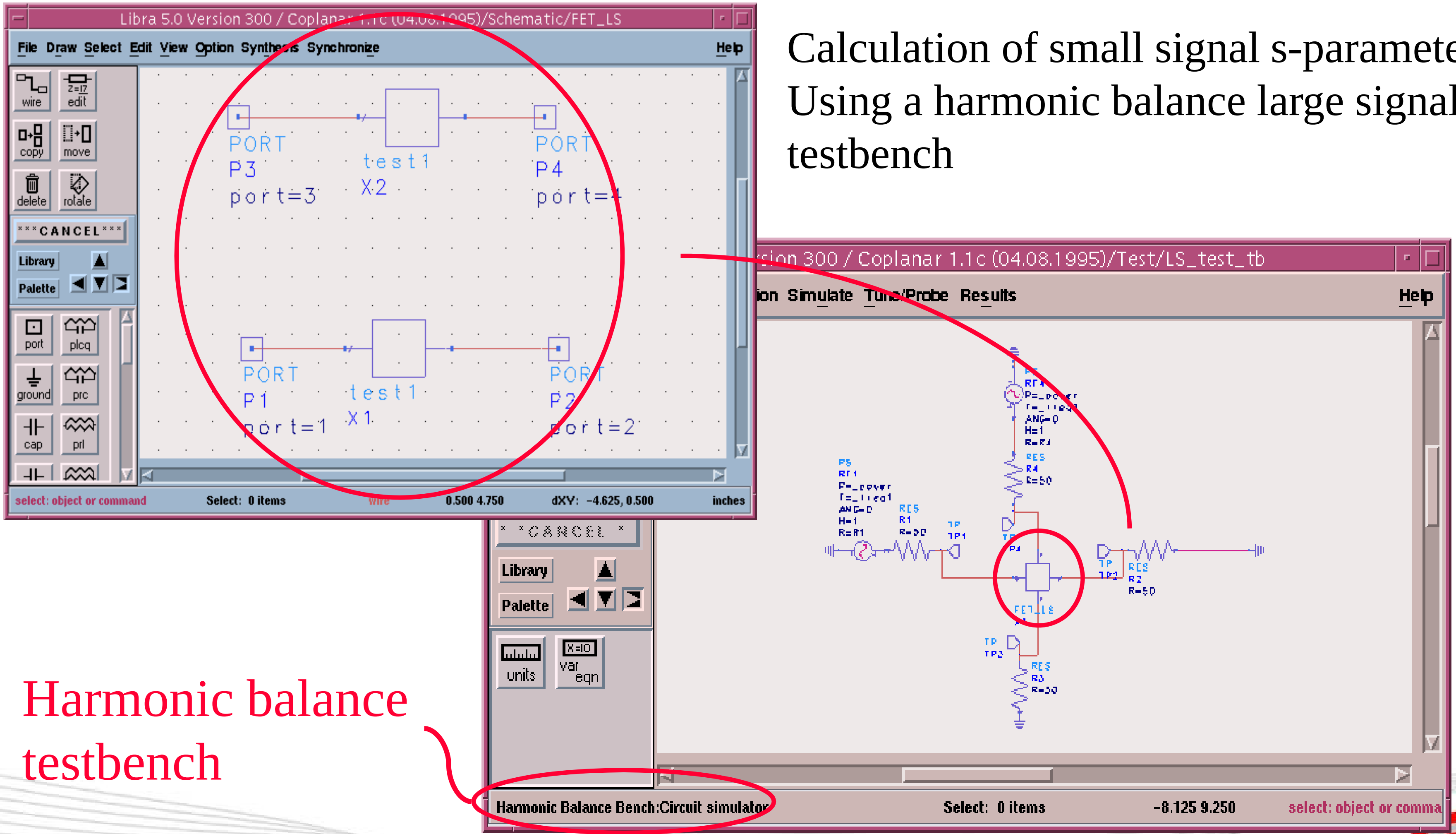
$$\|b\| = \|s\| \cdot \|a\|$$

Example

$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$

$$s_{11,dB} = 20 \cdot \log \frac{u_1 - i_1}{u_1 + i_1}$$

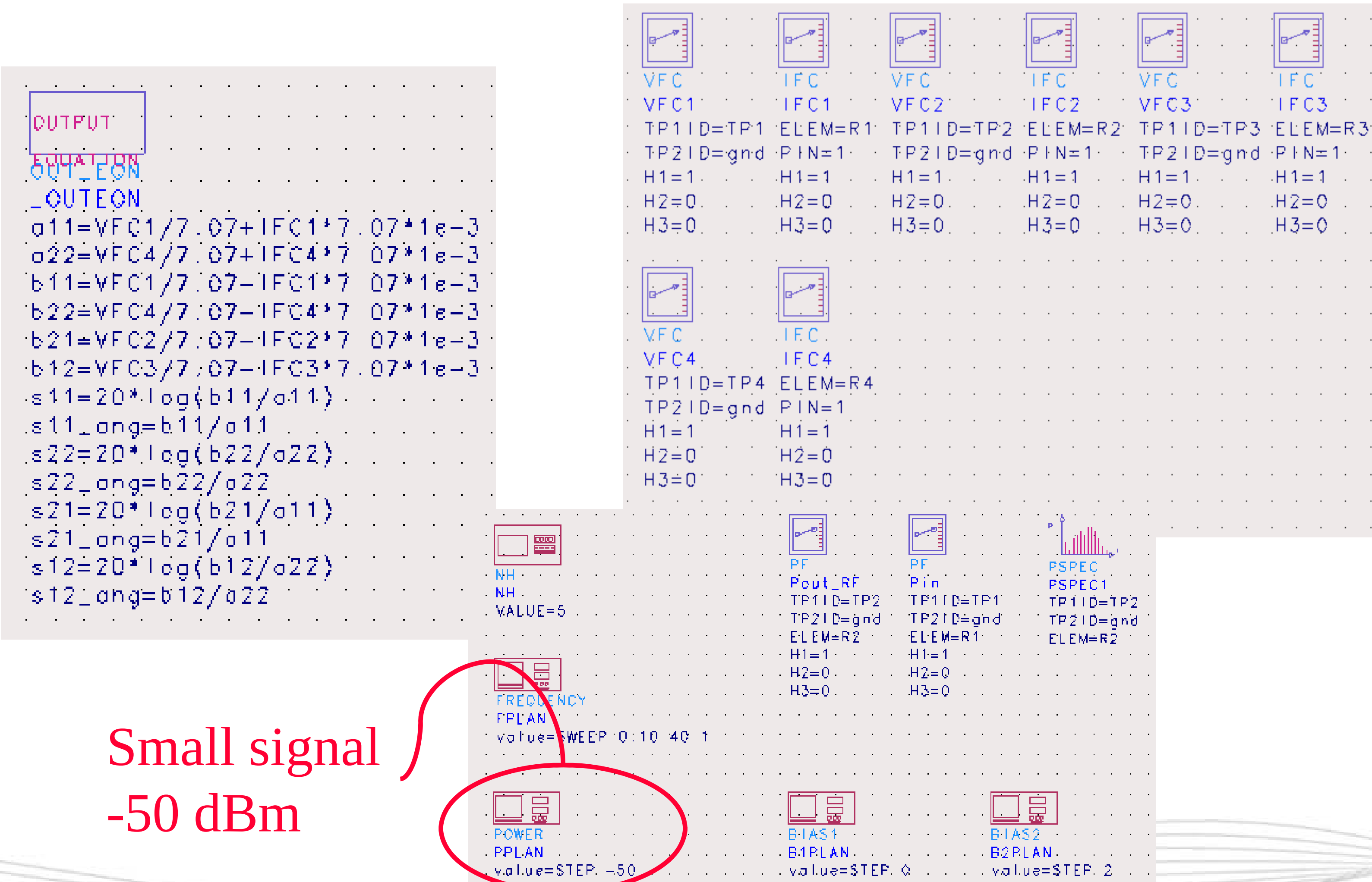
Consistent implementation



Calculation of small signal s-parameters
Using a harmonic balance large signal testbench

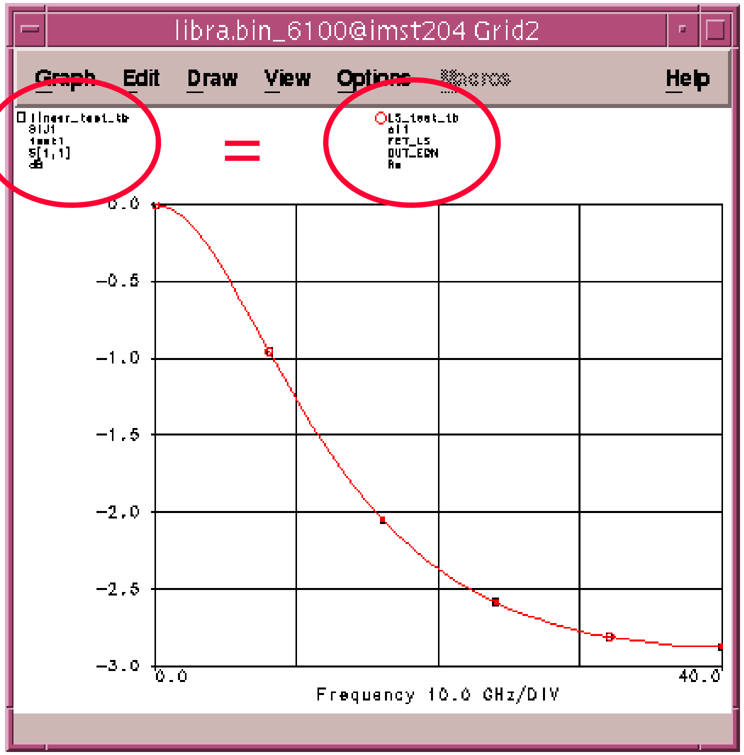
Harmonic balance testbench

Consistent implementation



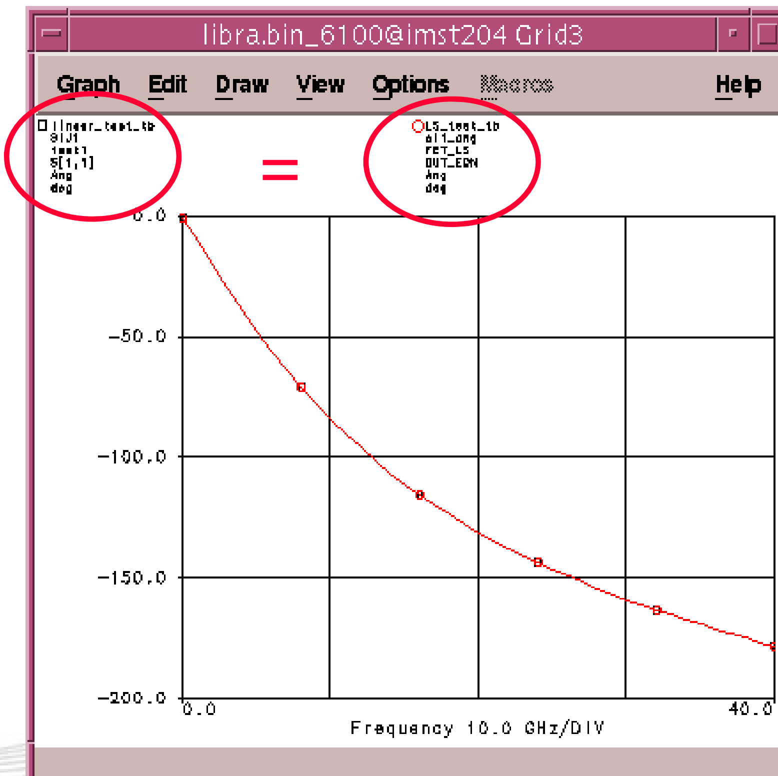
Small signal
-50 dBm

Consistent implementation



Mag(s_{11}), simulated using Small signal and HB testbench for very low input power (-50 dBm)

Phase(s_{11}), simulated using Small signal and HB testbench for very low input power (-50 dBm)



Needful things

Linearize exp functions

$$f(x) = \begin{cases} \exp(x) & x \le x_0 \\ mx + b & x > x_0 \end{cases}$$

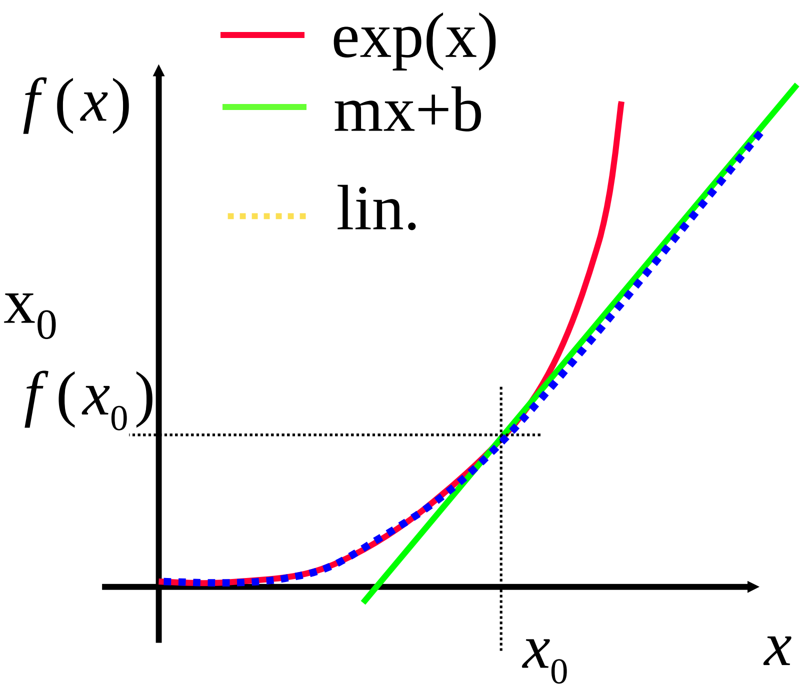
Function must be continuous at x_0

$$f_1(x_0) = f_2(x_0) \qquad \left.\frac{df_1}{dx}\right|_{x_0} = \left.\frac{df_2}{dx}\right|_{x_0}$$

$$\Rightarrow \quad \exp(x_0) = mx_0 + b$$

$$m = \exp(x_0)$$

$$\Rightarrow \quad b = \exp(x_0)(1 - x_0) \Rightarrow f_2(x) = \exp(x_0)(x + 1 - x_0)$$



Noise sources

Thermal noise

$$\langle i_{th}^2 \rangle = \frac{4kT_0}{R}\Delta f$$

Popcorn (burst)-noise

$$\langle i_{burst}^2 \rangle = KB \frac{I_D^{CF}}{1 + \left(\frac{f}{f_{CF}}\right)^2}\Delta f$$

Shot-noise

$$\langle i_{shot}^2 \rangle = 2qI_D\Delta f$$

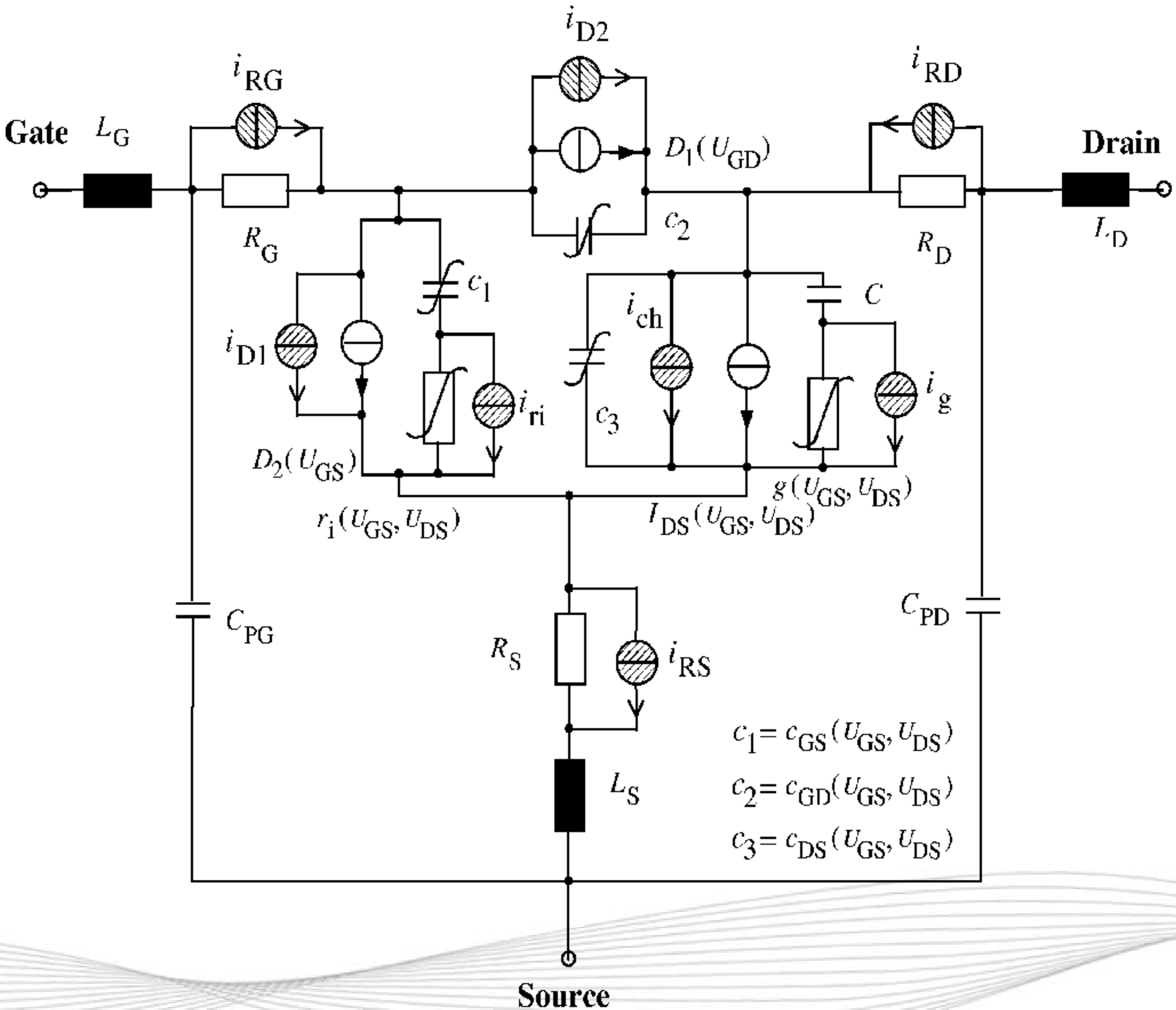
Channel noise

$$\langle i_c^2 \rangle = \frac{8kTg_m}{3}\Delta f$$

1/f (flicker)-noise

$$\langle i_{1/f}^2 \rangle = KF \frac{I_D^{AF}}{f^{FFE}}\Delta f$$

Noise equivalent ciruit



Noisy 2-ports

Transformation matrix

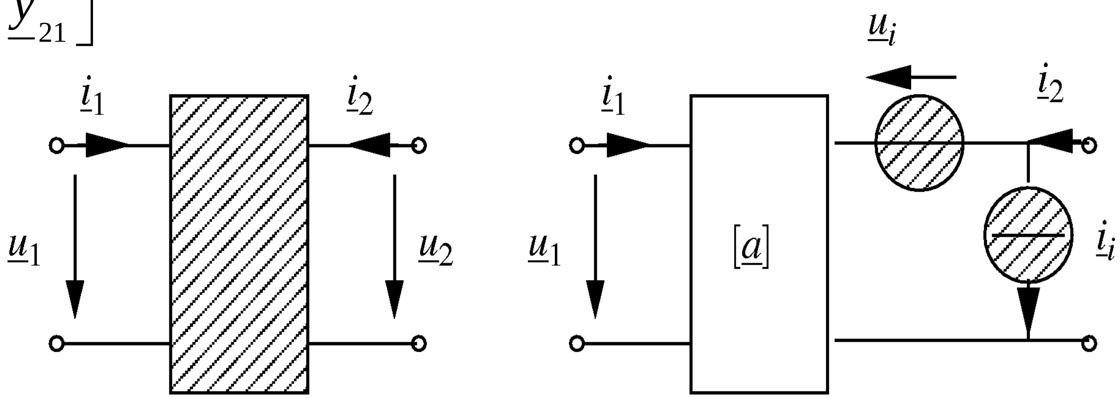
$$[\underline{T}]^{(y \to a)} = \begin{bmatrix} 0 & -\dfrac{1}{\underline{y}_{21}} \\ 1 & -\dfrac{\underline{y}_{11}}{\underline{y}_{21}} \end{bmatrix}$$

Noise matrix

input, output

$$\begin{bmatrix} \underline{v}_i^{(a)} \\ \underline{i}_o^{(a)} \end{bmatrix} = [\underline{T}]^{(y \to a)} \begin{bmatrix} \underline{i}_i^{(y)} \\ \underline{i}_o^{(y)} \end{bmatrix}$$

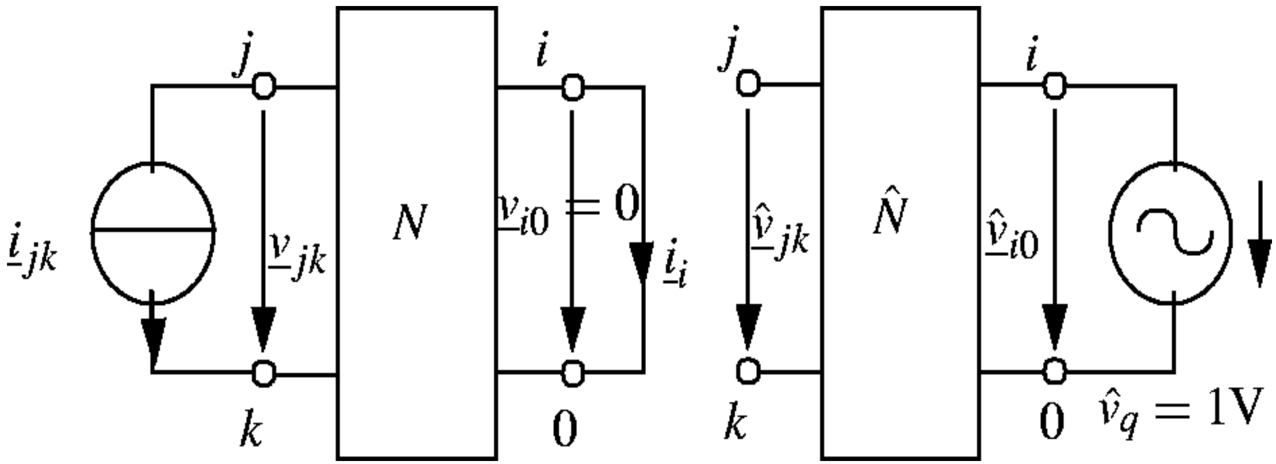
Transformation of noise sources.



Correlation matrix, calculation of noise power

$$[\underline{C}]^{(a)} = \frac{1}{4kT\Delta f} \left(\begin{bmatrix} \underline{v}_i \\ \underline{i}_i \end{bmatrix} \begin{bmatrix} \underline{v}_i^* & \underline{i}_i^* \end{bmatrix} \right)$$

Separation of noise sources



Calculation of transformation fucntion

Network N
Y-Matrix

Adjoint network
transposed Y-Matrix

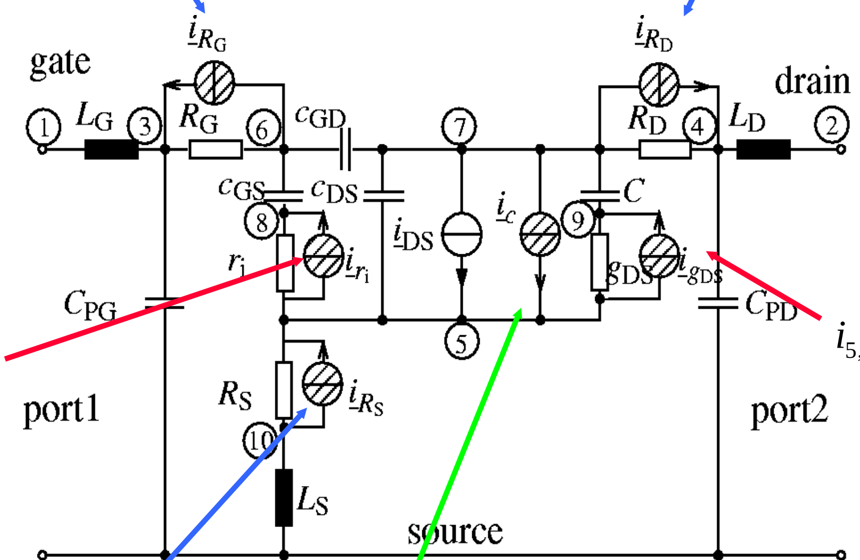
Current transforming function

$$\alpha_{i,jk} = \frac{i_i}{i_{jk}} = -\frac{\hat{v}_{jk}}{\hat{v}_q}$$

FET example

$$i_{6,3} = \sqrt{\frac{1}{R_G}} \qquad i_{7,4} = \sqrt{\frac{1}{R_D}}$$

$$i_{5,8} = \sqrt{\frac{1}{r_i}} \qquad i_{5,9} = \sqrt{g_{DS}}$$



TOPAS equivalent circuit.

$$i_{10,5} = \sqrt{\frac{1}{R_S}} \qquad i_{7,5} = \sqrt{g_{i_C}}$$

Noise current matrix

$$[i_N] = \sqrt{4kT\Delta f}\cdot\begin{pmatrix} 0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&i_{5,8}&i_{5,9}&0\\ 0&0&i_{6,3}&0&0&0&0&0&0&0\\ 0&0&0&i_{7,4}&i_{7,5}&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&i_{10,5}&0&0&0&0&0 \end{pmatrix}$$

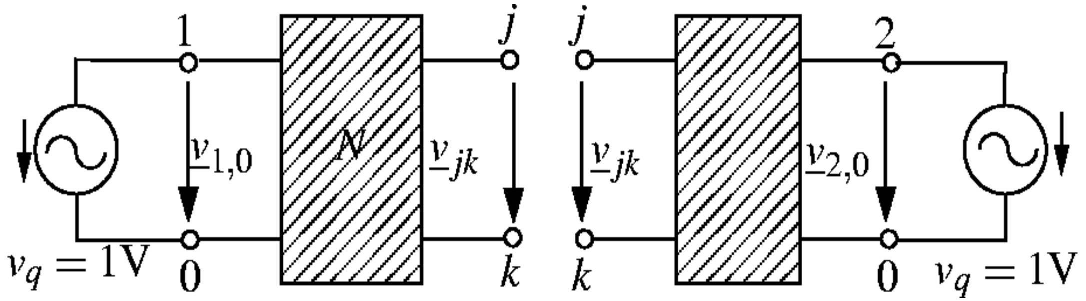
Channel noise

$$g_{i_C} = \frac{T_{sim}}{T_0}\frac{2}{3}g_m + k_f\frac{I_c^{af}}{f^b 4kT_0}$$

1/f-noise

Tellegen Thoerem

Y-Matrix → Z-Matrix → Y_{2x2}-Matrix → $[\underline{y}_{\mathrm{T}}] = [\underline{y}]^{\mathrm{T}}$



Tellegen Theorem for noisy n-ports

Adjoined network for calculation of transformation function

$$i_{\mathrm{Q}_1} = v_{\mathrm{q}} \cdot \underline{y}_{\mathrm{T},2\times2_{1,1}} \quad \text{and} \quad i_{\mathrm{Q}_2} = v_{\mathrm{q}} \cdot \underline{y}_{\mathrm{T},2\times2_{2,2}}$$

Tellegen Theorem

$$\begin{bmatrix} i_{Q1} \\ \vdots \\ i_{Q10} \end{bmatrix} = \begin{bmatrix} y_{T1,1} & \cdots & y_{T1,10} \\ \vdots & \ddots & \vdots \\ y_{T10,1} & \cdots & y_{T10,10} \end{bmatrix} \begin{bmatrix} v_1 \\ \vdots \\ v_{10} \end{bmatrix}$$

Solving the equation system for the voltagesusing the Gaussian algorithm

⇓

Voltage transformation factor

⇓

One single noise source at Eingang, one at output ⇒ $[T]^{(y \to a)} = \begin{bmatrix} 0 & -\frac{1}{\underline{y}_{2\times2_{21}}} \\ 1 & -\frac{\underline{y}_{2\times2_{11}}}{\underline{y}_{2\times2_{21}}} \end{bmatrix}$ ⇒ 1 current source, 1 voltage source at output

Correlation matrix

$$F = 1 - \frac{T_{\mathrm{sim}}}{T_{\mathrm{o}}} \frac{\left|\underline{y}_{\mathrm{G}}\right|^2 C_{11}^{(a)} + C_{22}^{(a)} + 2\Re\left\{\underline{y}_{\mathrm{G}} \underline{C}_{12}^{a}\right\}}{g_{\mathrm{G}}}$$

$$R_{\mathrm{n}} = \frac{T_{\mathrm{sim}}}{\mathrm{T}_0} C_{11}^{a}$$

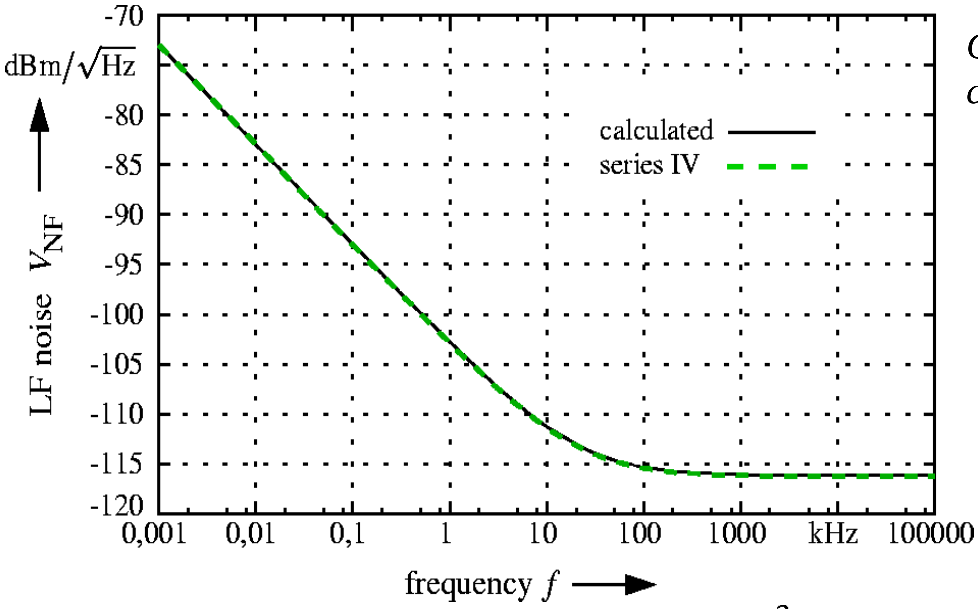
Korrelationsmatrix

$$\left[\underline{C}\right]^{(a)} = \left[T\right]^{(y\to a)} \left[\underline{C}\right]^{(y)} \left[T\right]^{(y\to a)+}$$

$$V_{\mathrm{NF}}\left[\mathrm{dBm}/\sqrt{\mathrm{Hz}}\right] = 20\log\left(\sqrt{\frac{T_{\mathrm{sim}}}{\mathrm{T}_0} \cdot i_0 i_0^{*} \frac{50\Omega}{50\Omega\Re\left(\underline{y}_{2\times2_{22}}\right)+1}} \cdot 1000\right)$$

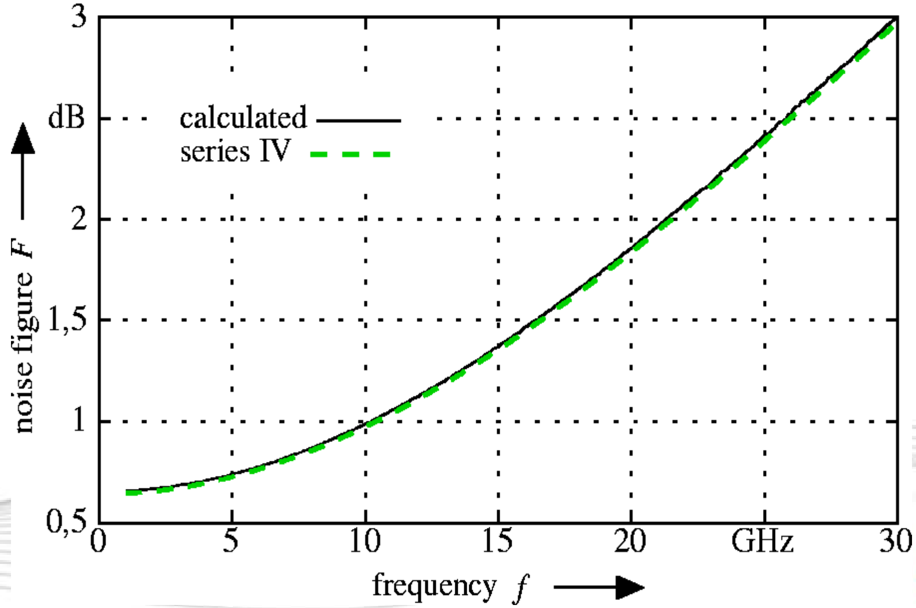
$$\Gamma_{G_{\mathrm{opt}}} = \frac{1 - \underline{y}_{G_{\mathrm{opt}}} Z_0}{1 + \underline{y}_{G_{\mathrm{opt}}} Z_0}$$

Verifications

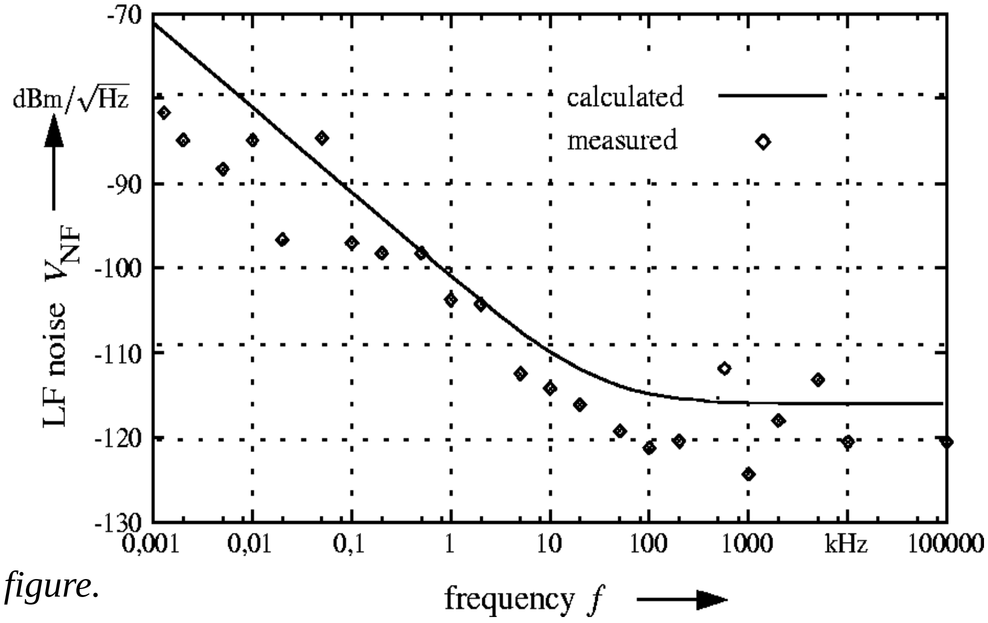


Calculation of 1/f noise..Simulation in comparison to calcualtion using the porposed algorithm.

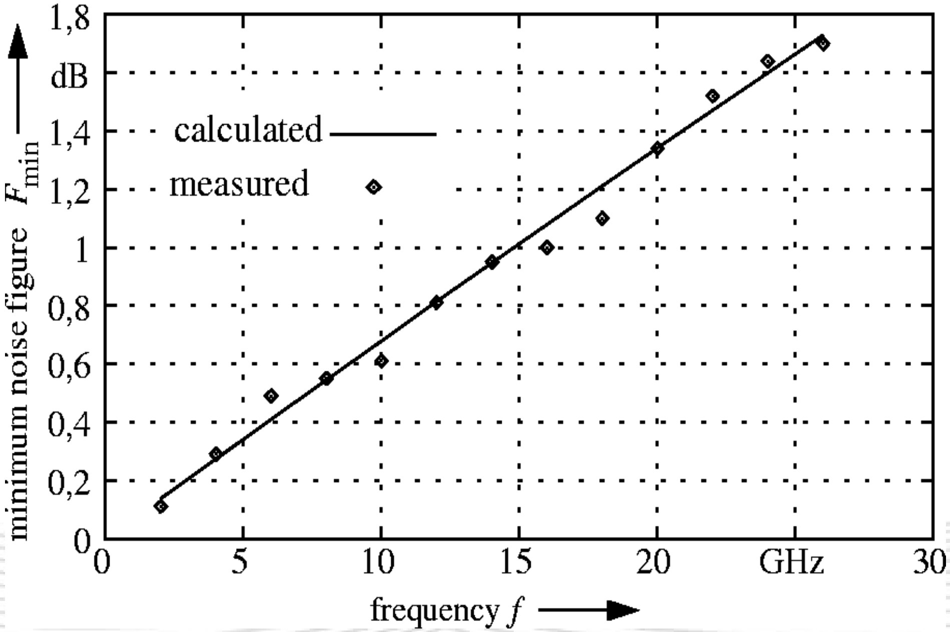
Calcualtion of noise figure NF. Comparison of simulation and calculation.



Verifications

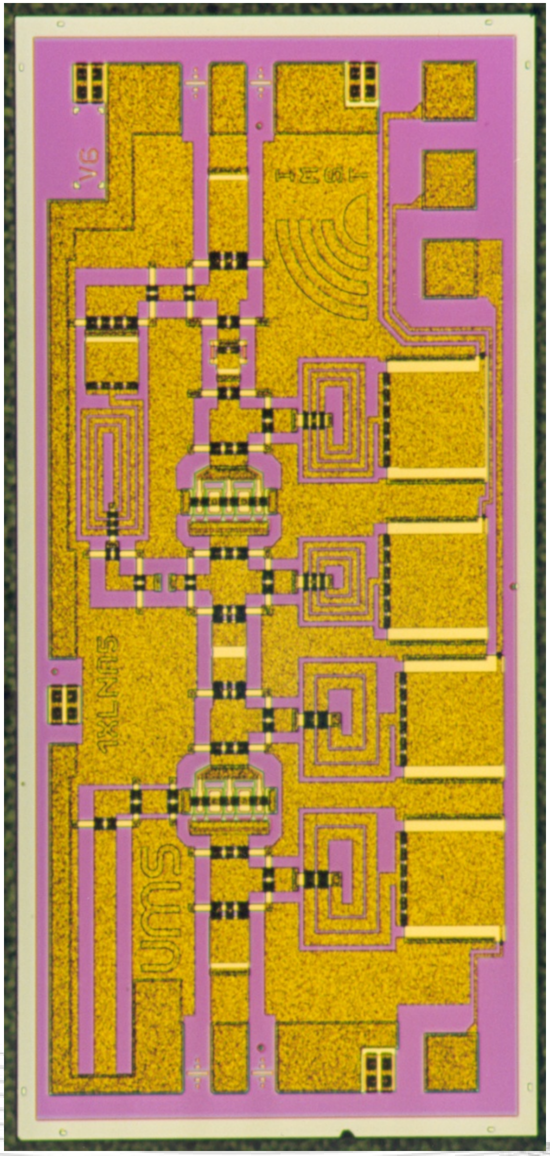


Simulation and measurement of minimum noise figure.

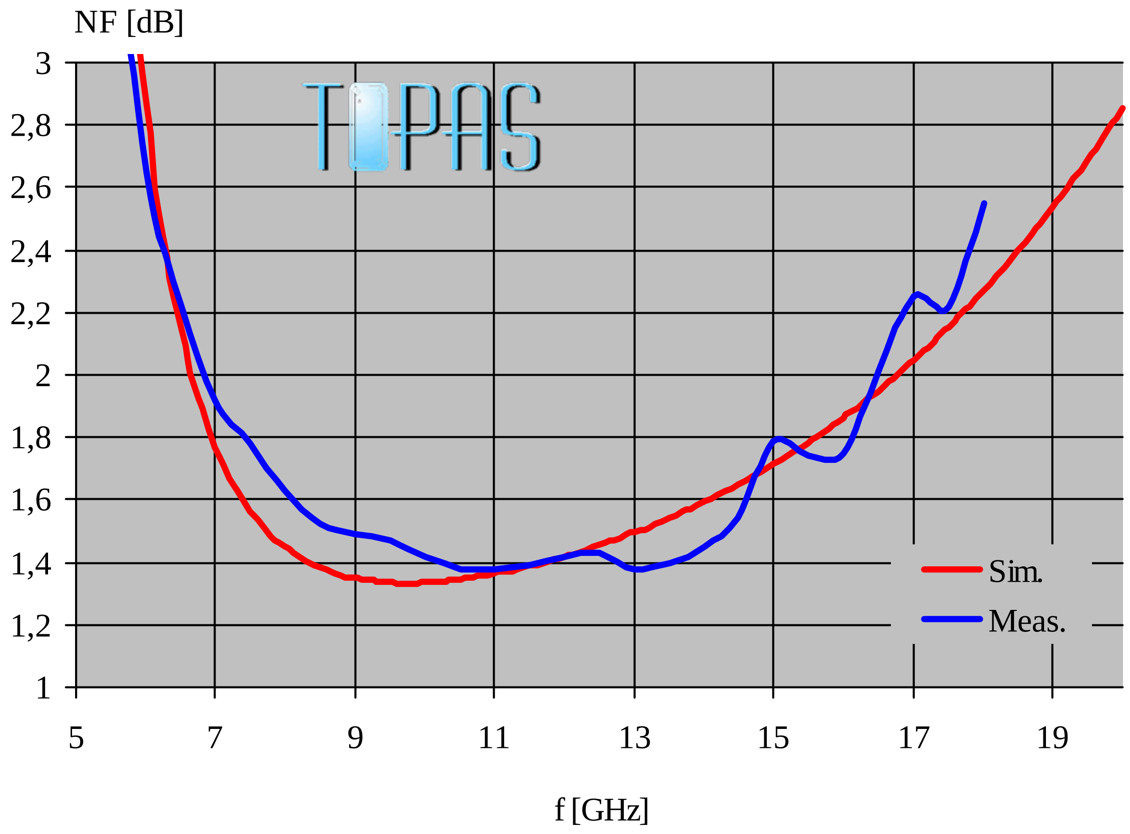


Simulation and measurement of 1/noise.

Verifications



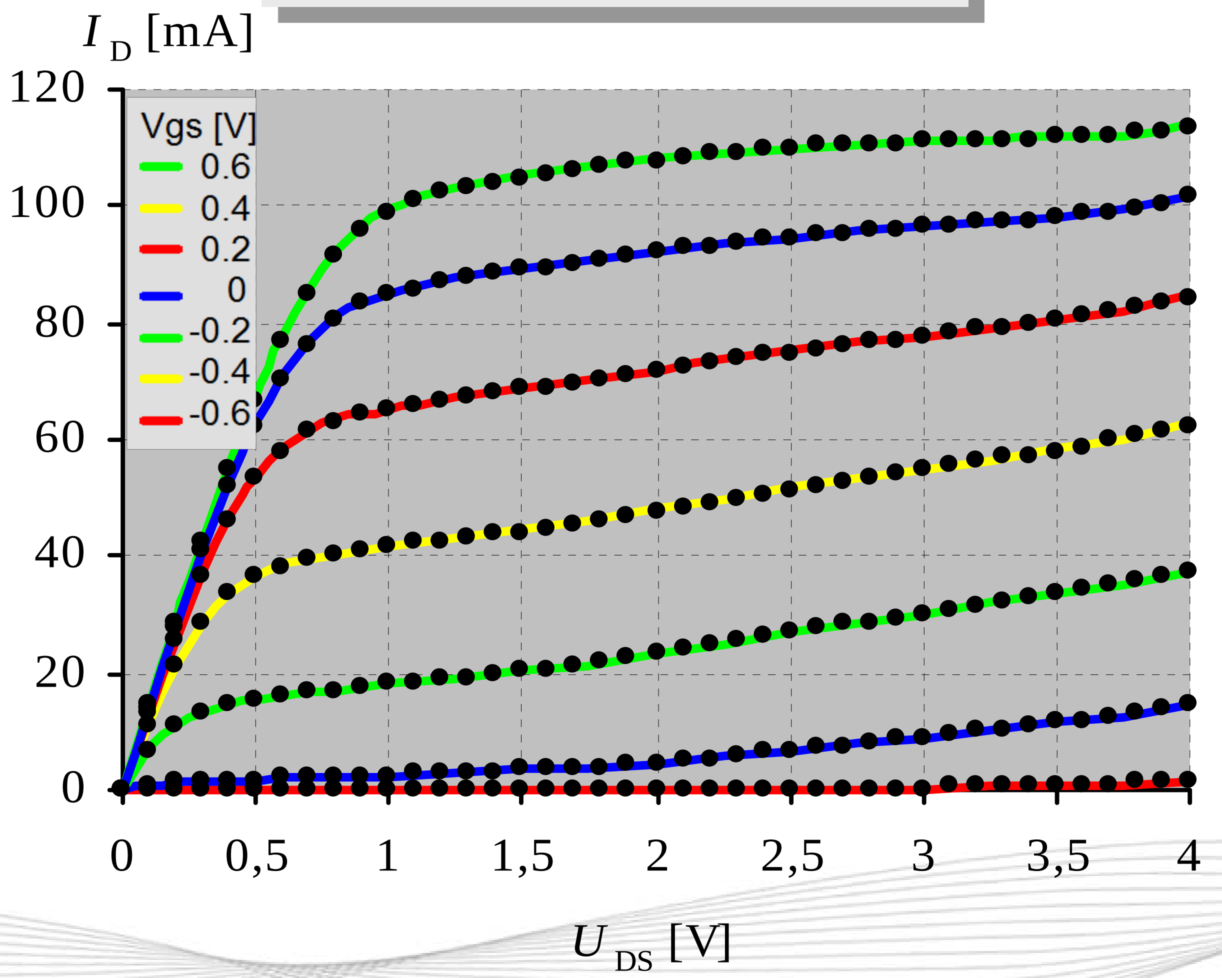
Realized LNA



Minimum noise figure, simulation versus measurement.

Verfications

UMS 4x50 µm
HEMT



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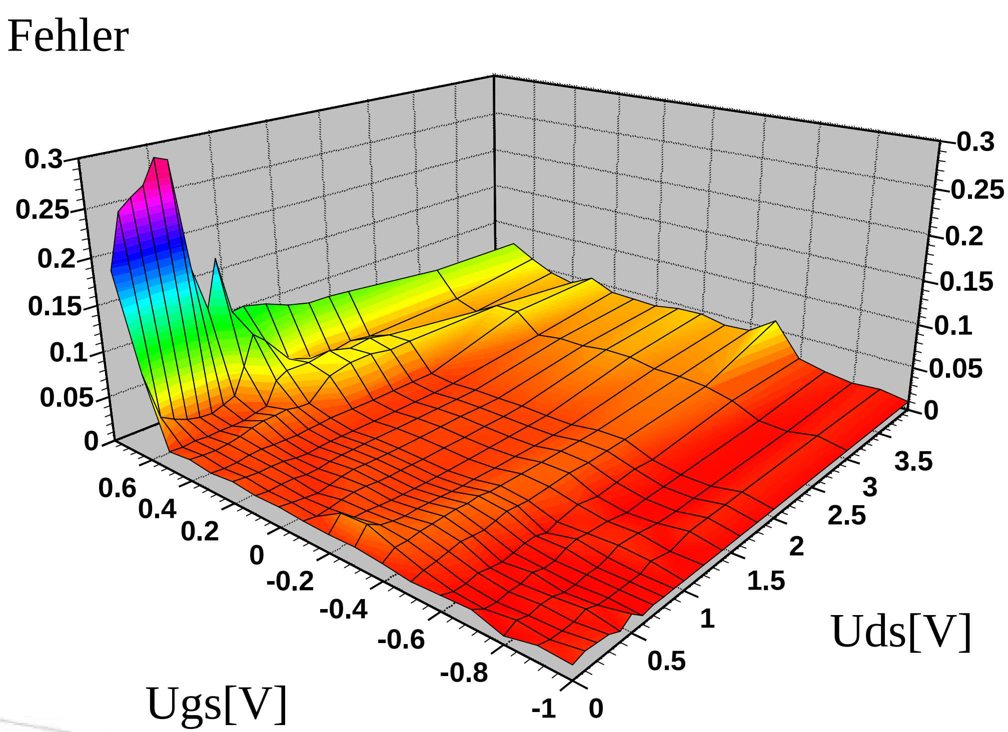
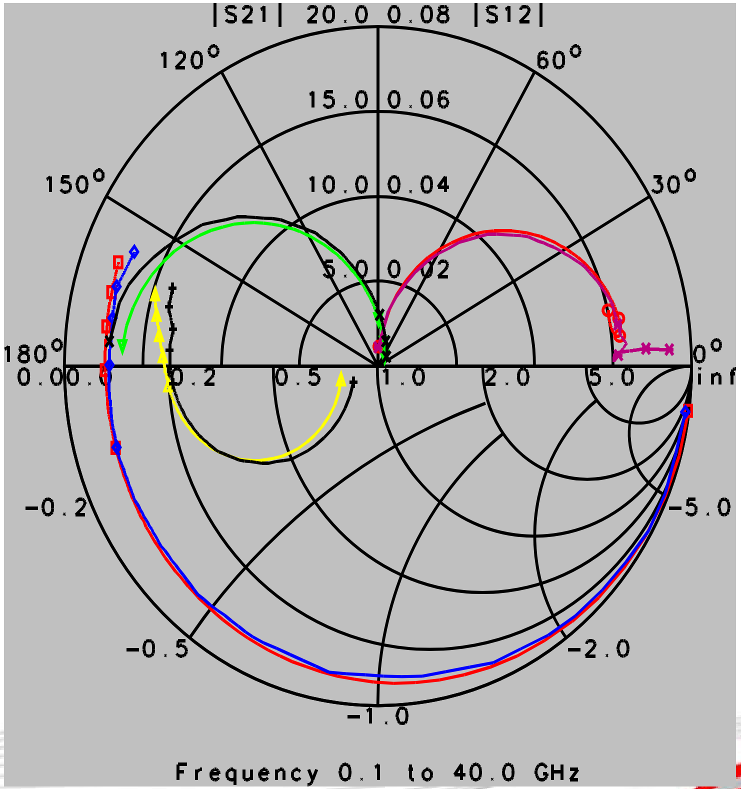
Verifications

Deviations
6x20 μm HEMT

4x50 μm ⇗ 8x75 μm
V_{GS} = 0 V, V_{DS} = 2 V

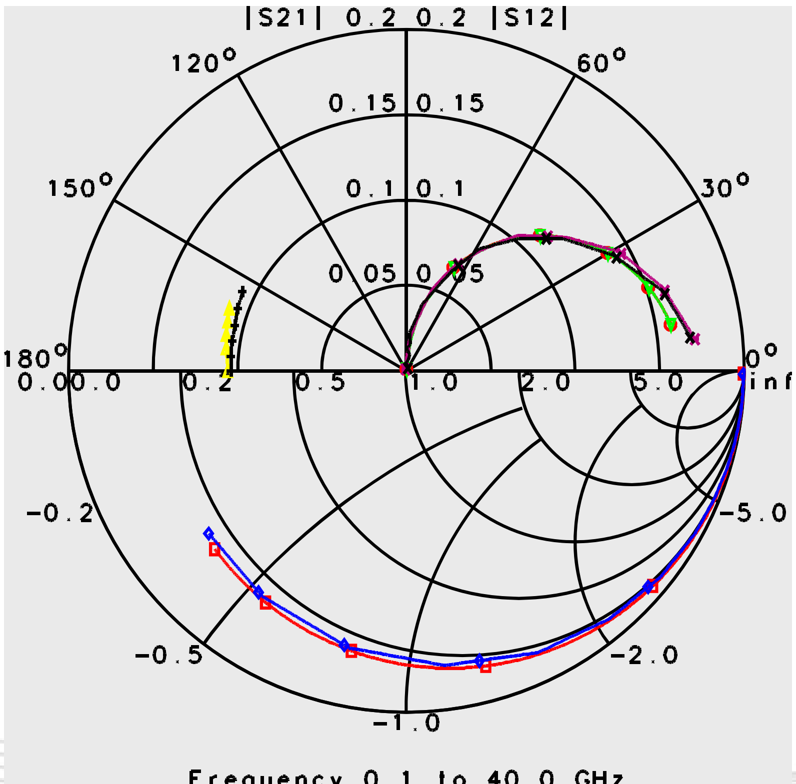


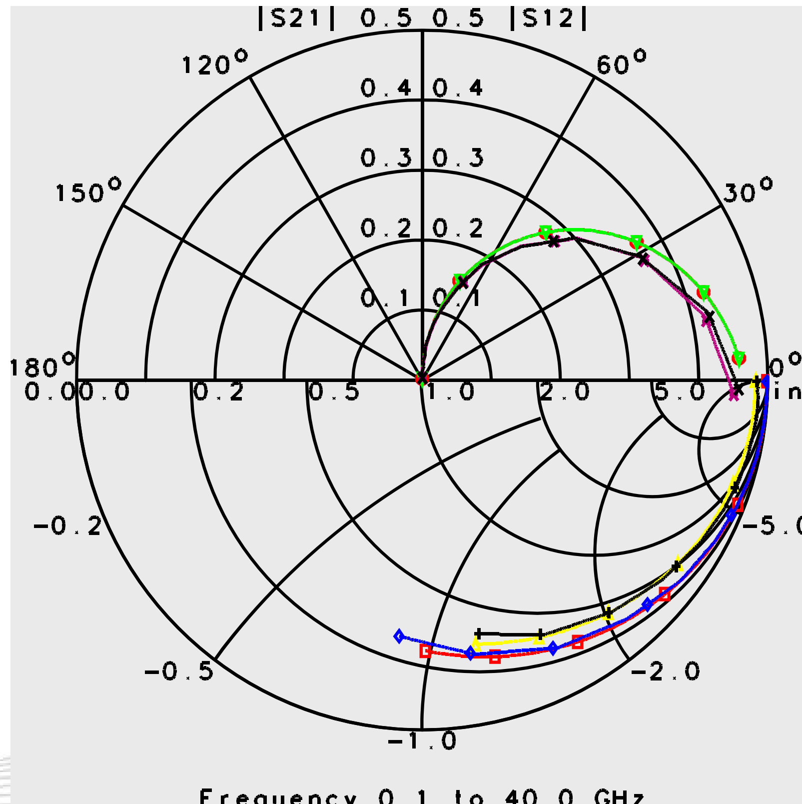


Verifications

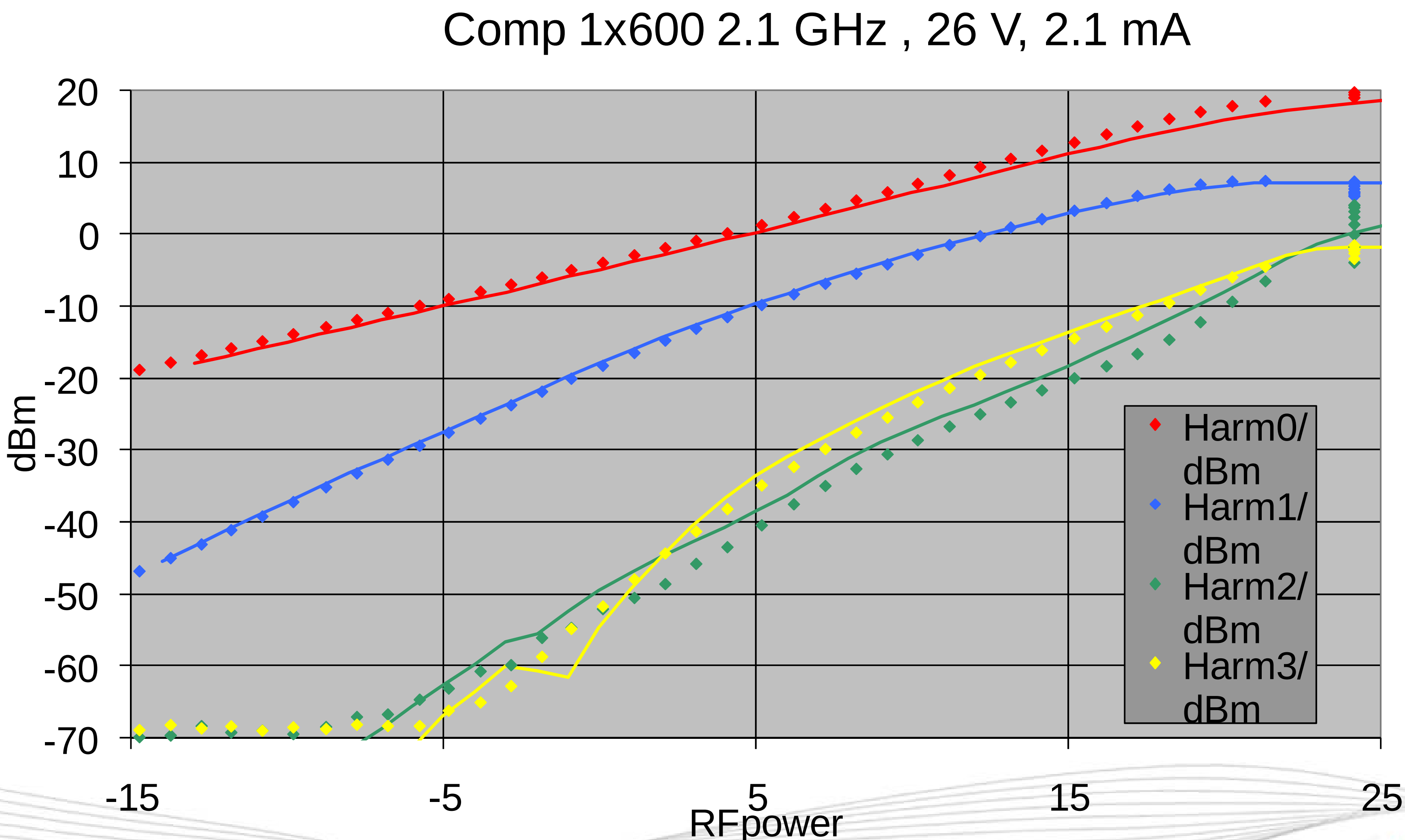
4x50 µm ⇗ 2x40 µm
$V_{GS} = 0$ V, $V_{DS} = 0$ V

4x50 µm ⇗ 2x40 µm
$V_{GS} = -0.8$ V, $V_{DS} = 2$ V

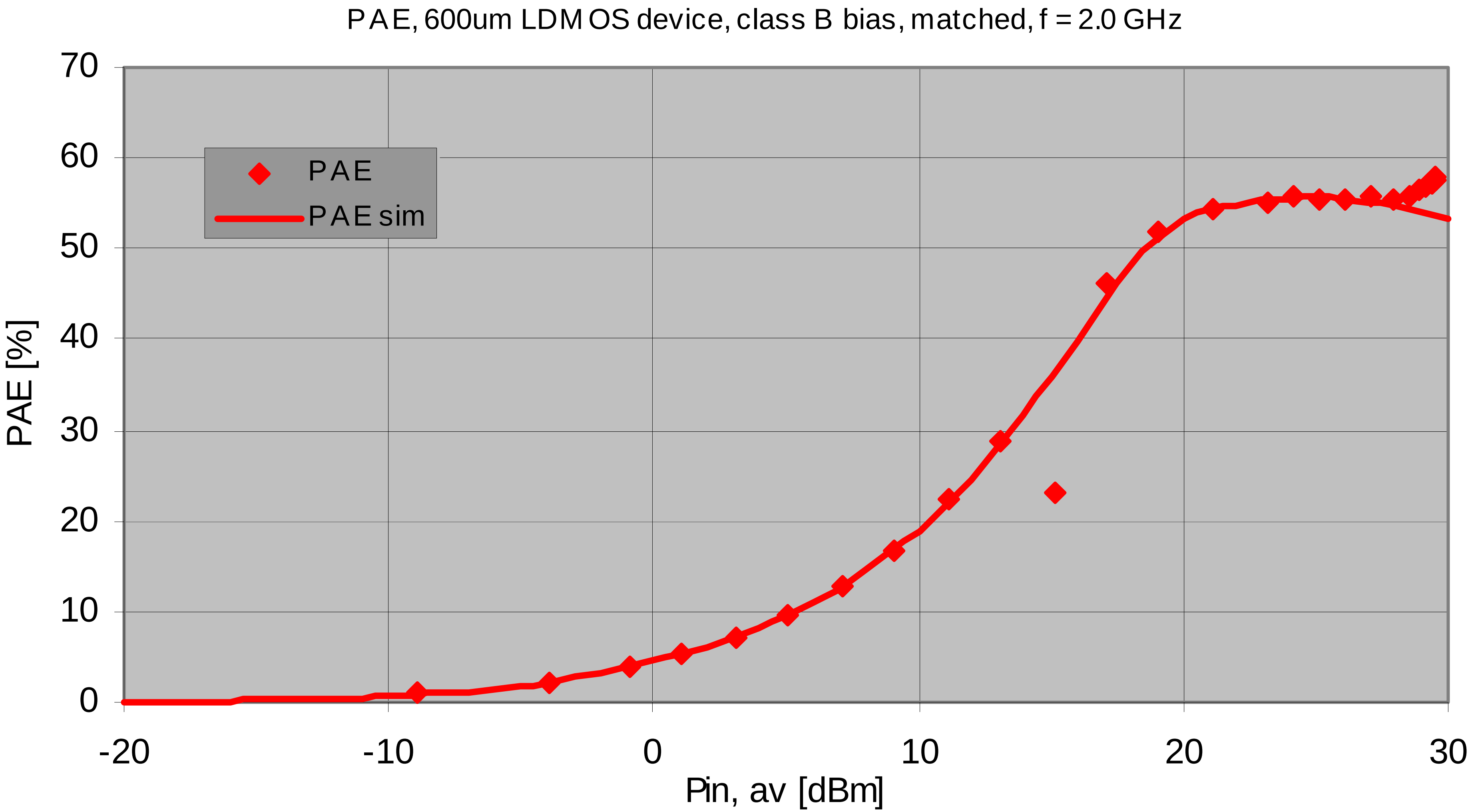




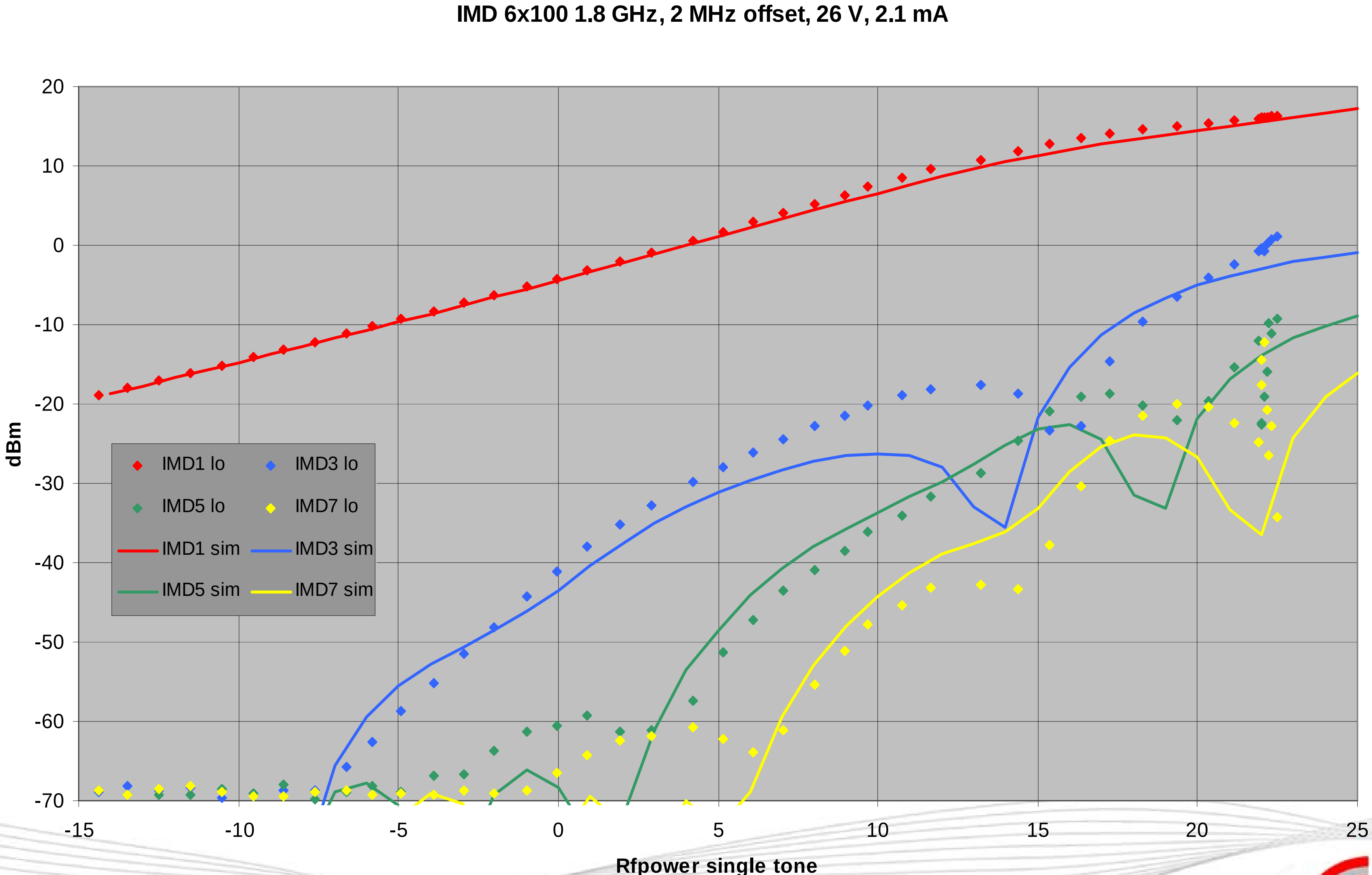
Verifications



Verifications

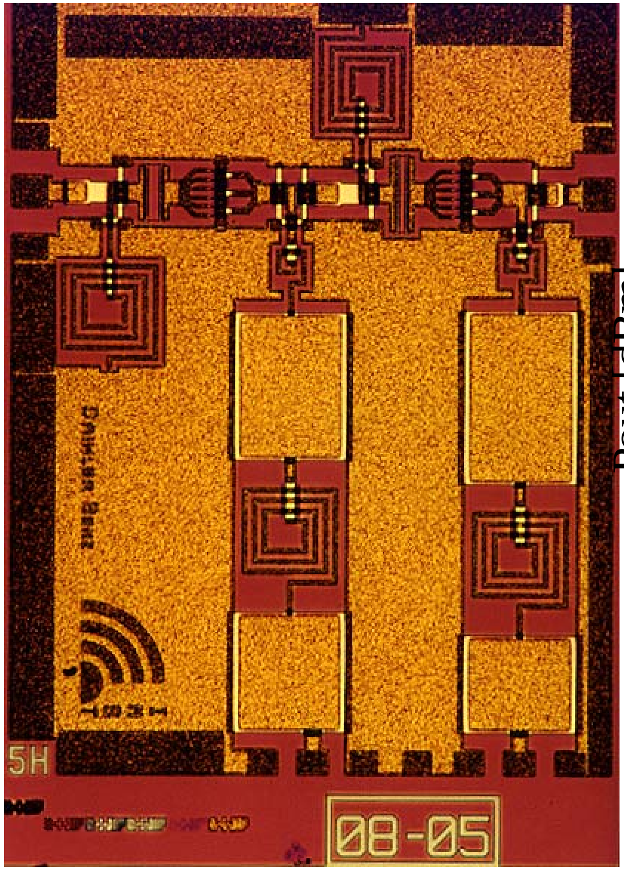


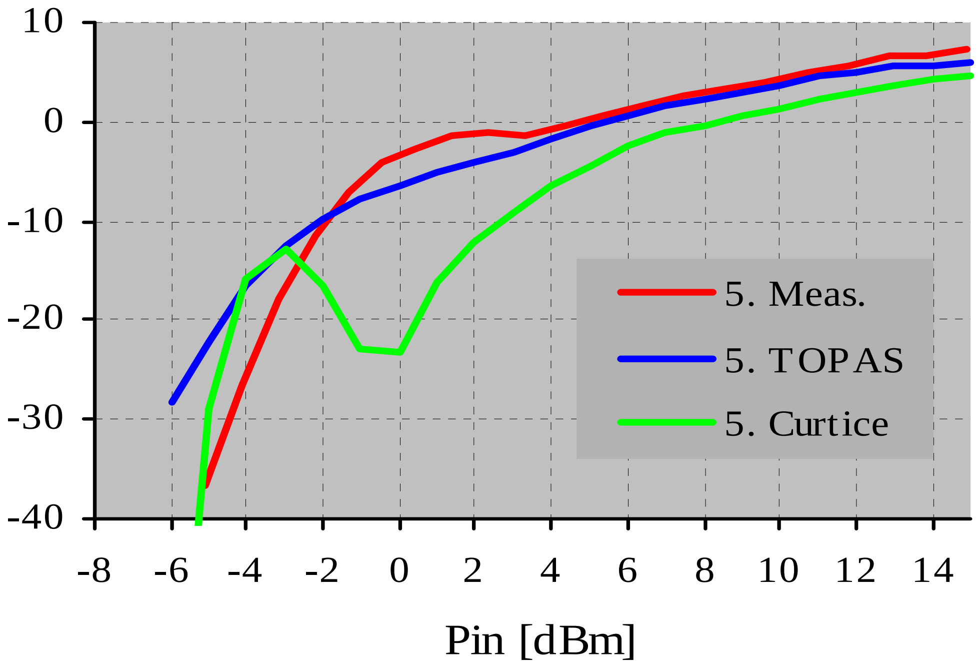
Verifications



Verifications

Times 5 multiplier





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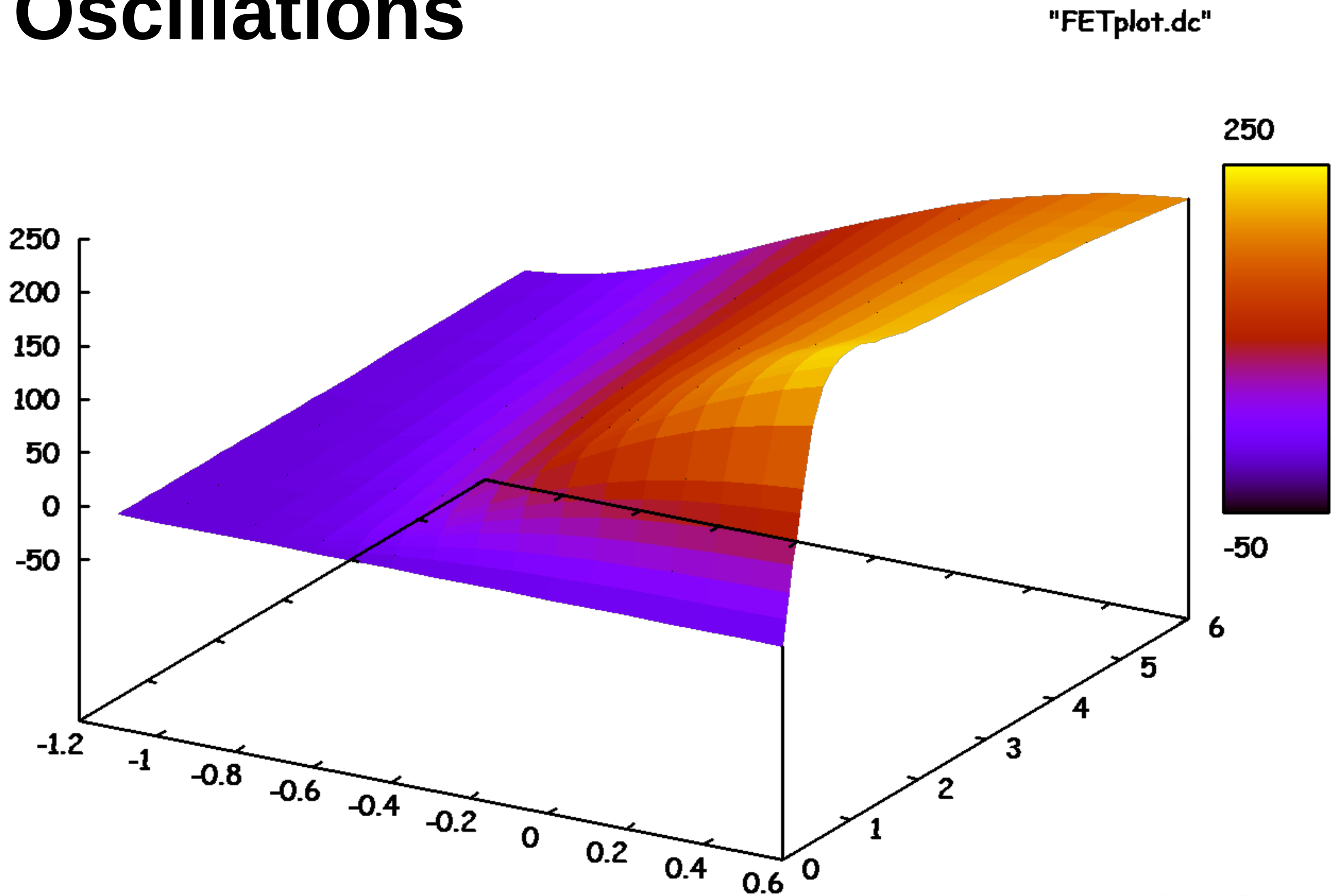
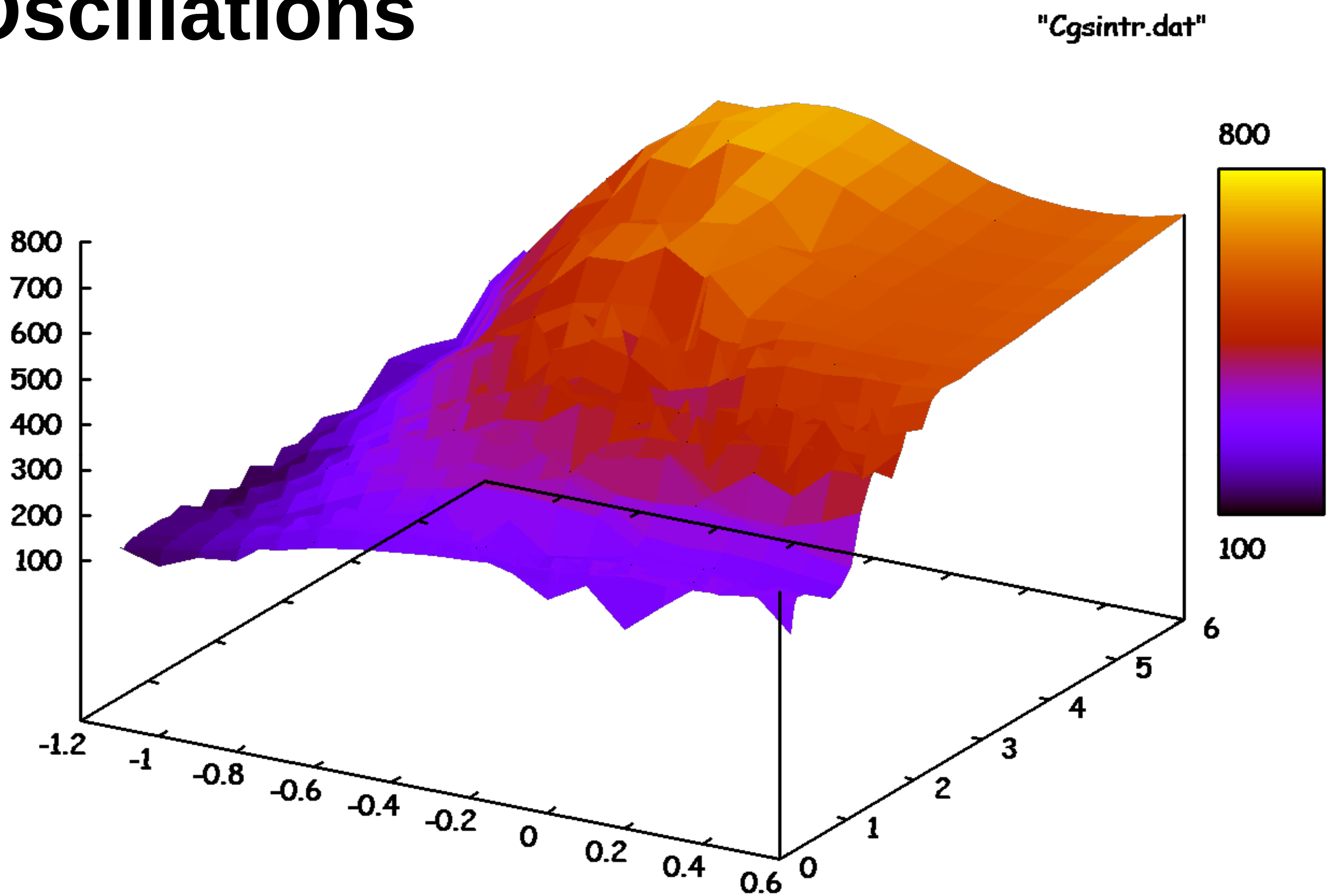
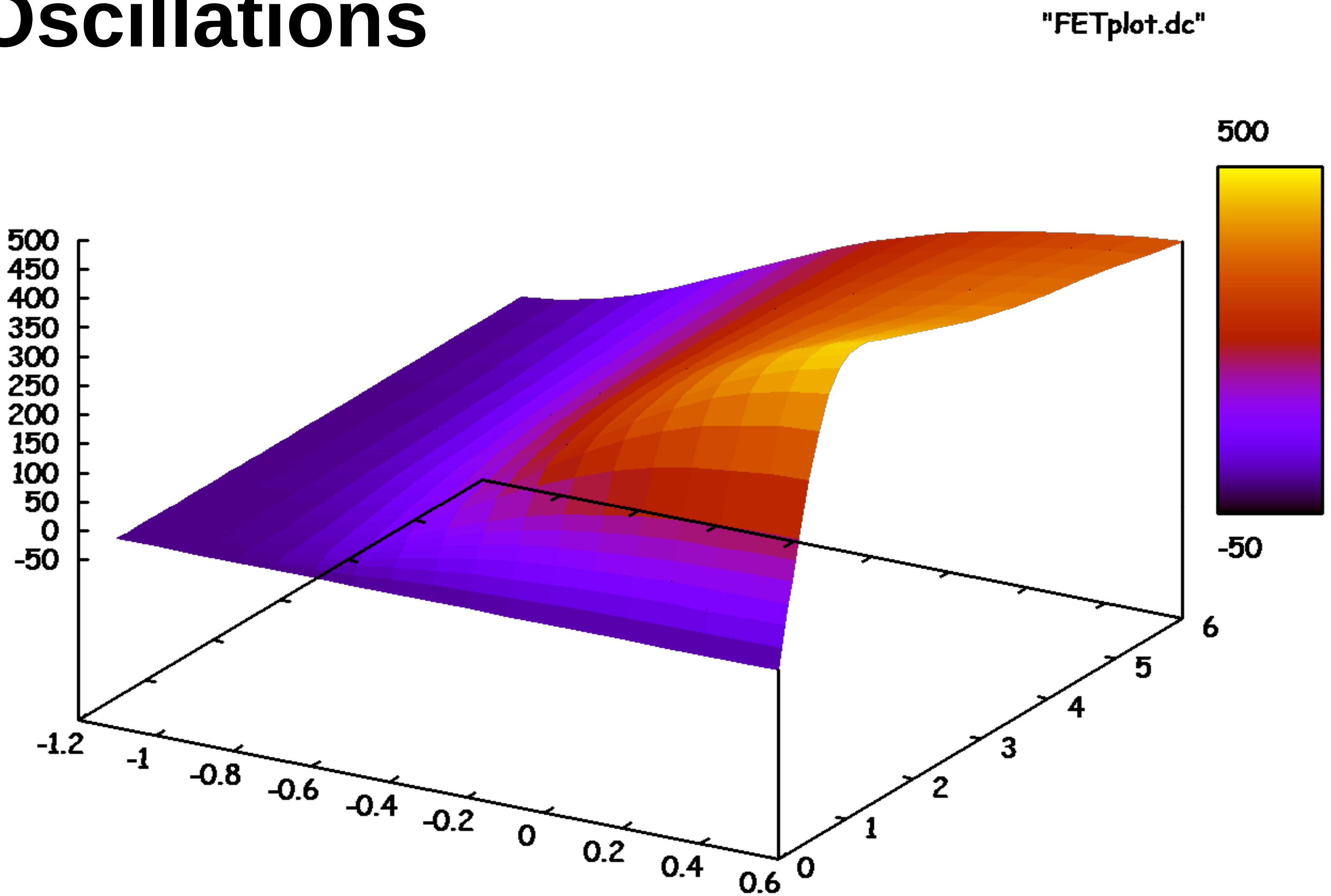
Oscillations



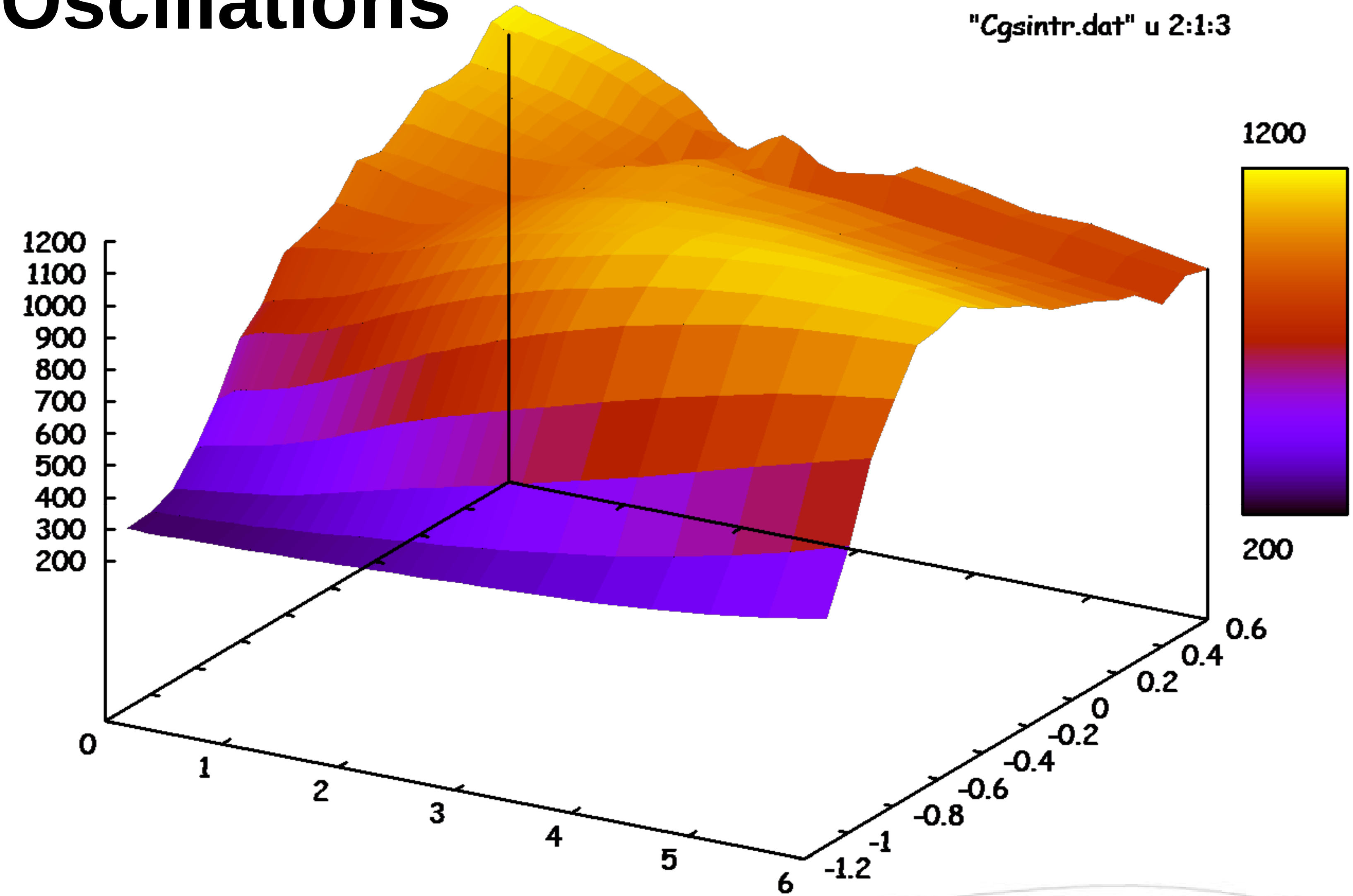
Oscillations



Oscillations



Oscillations



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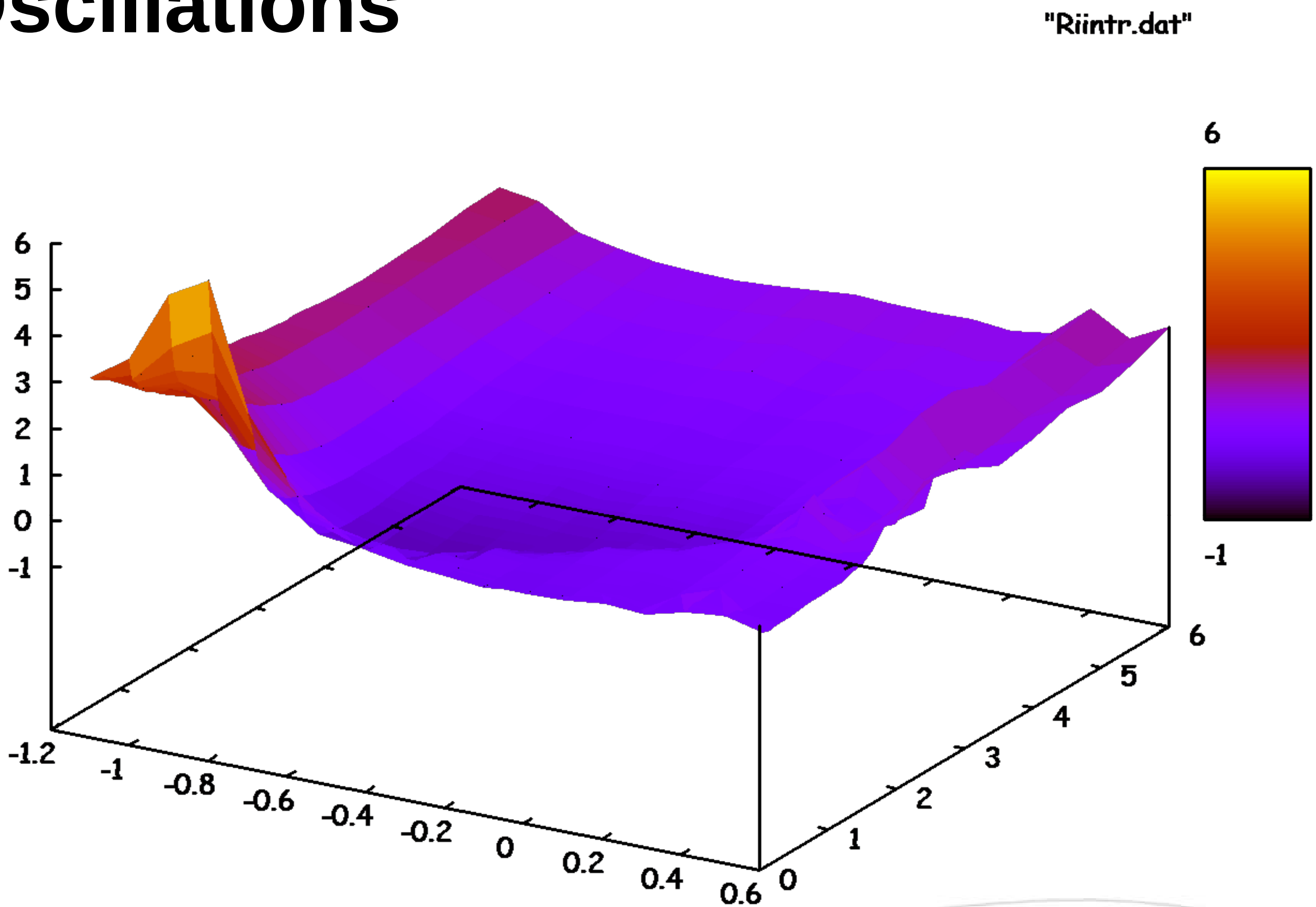
Oscillations



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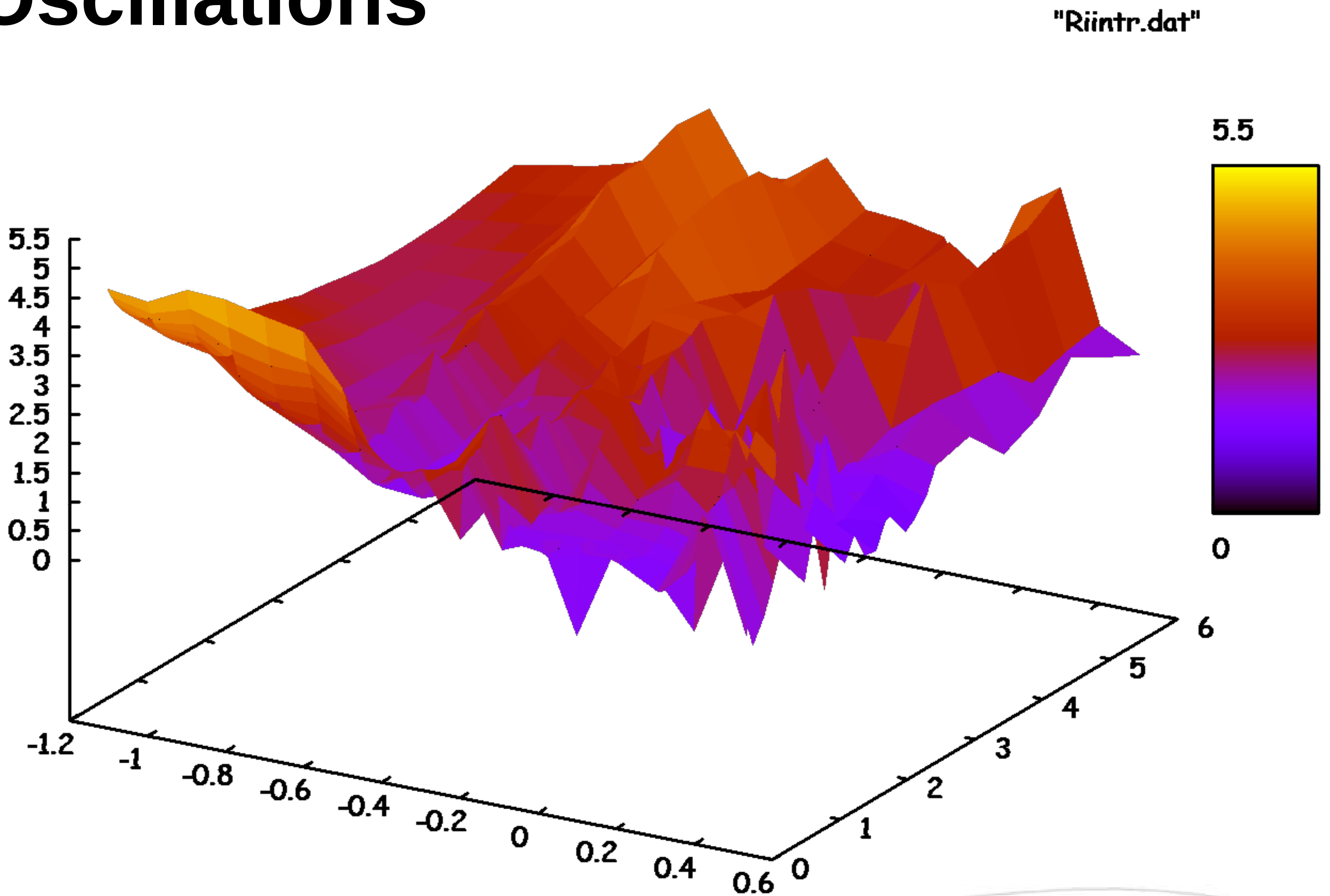
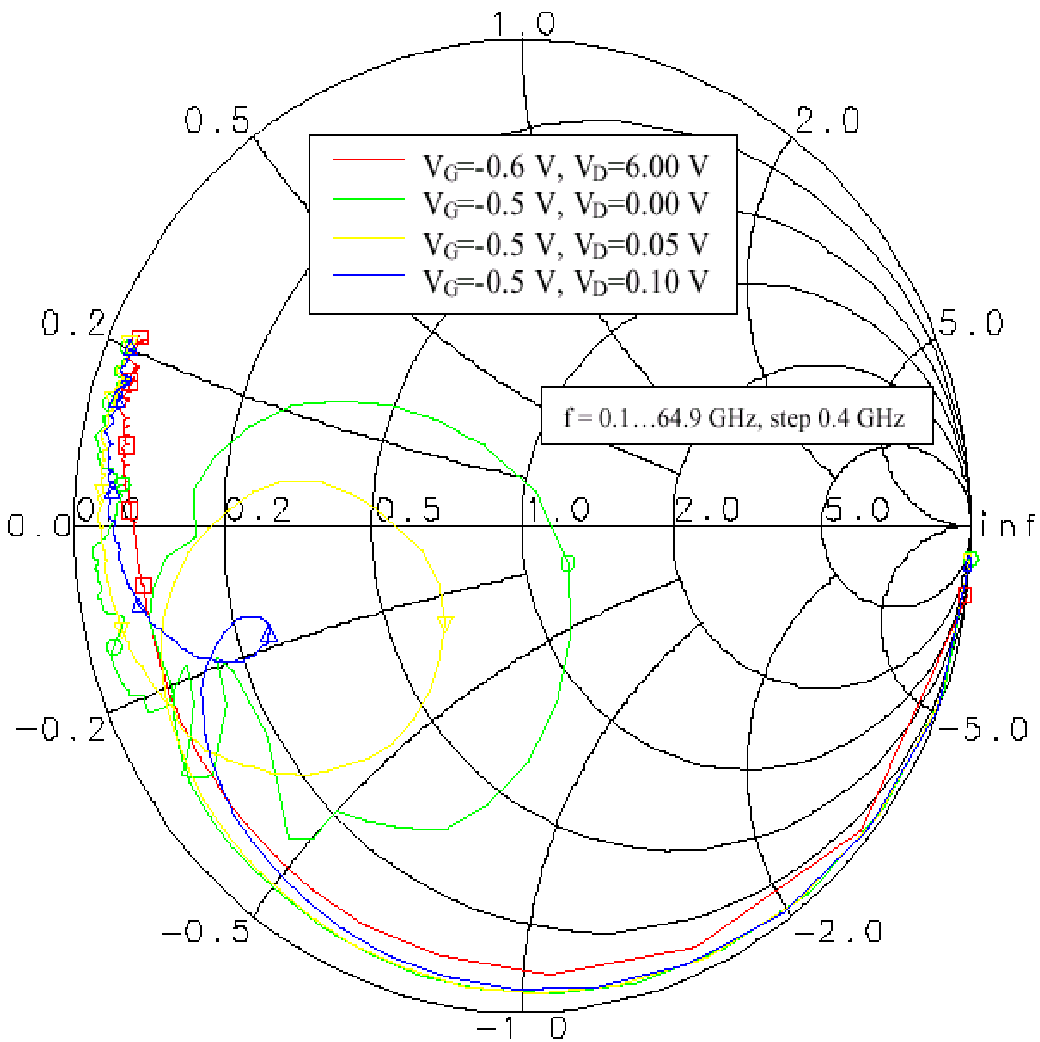
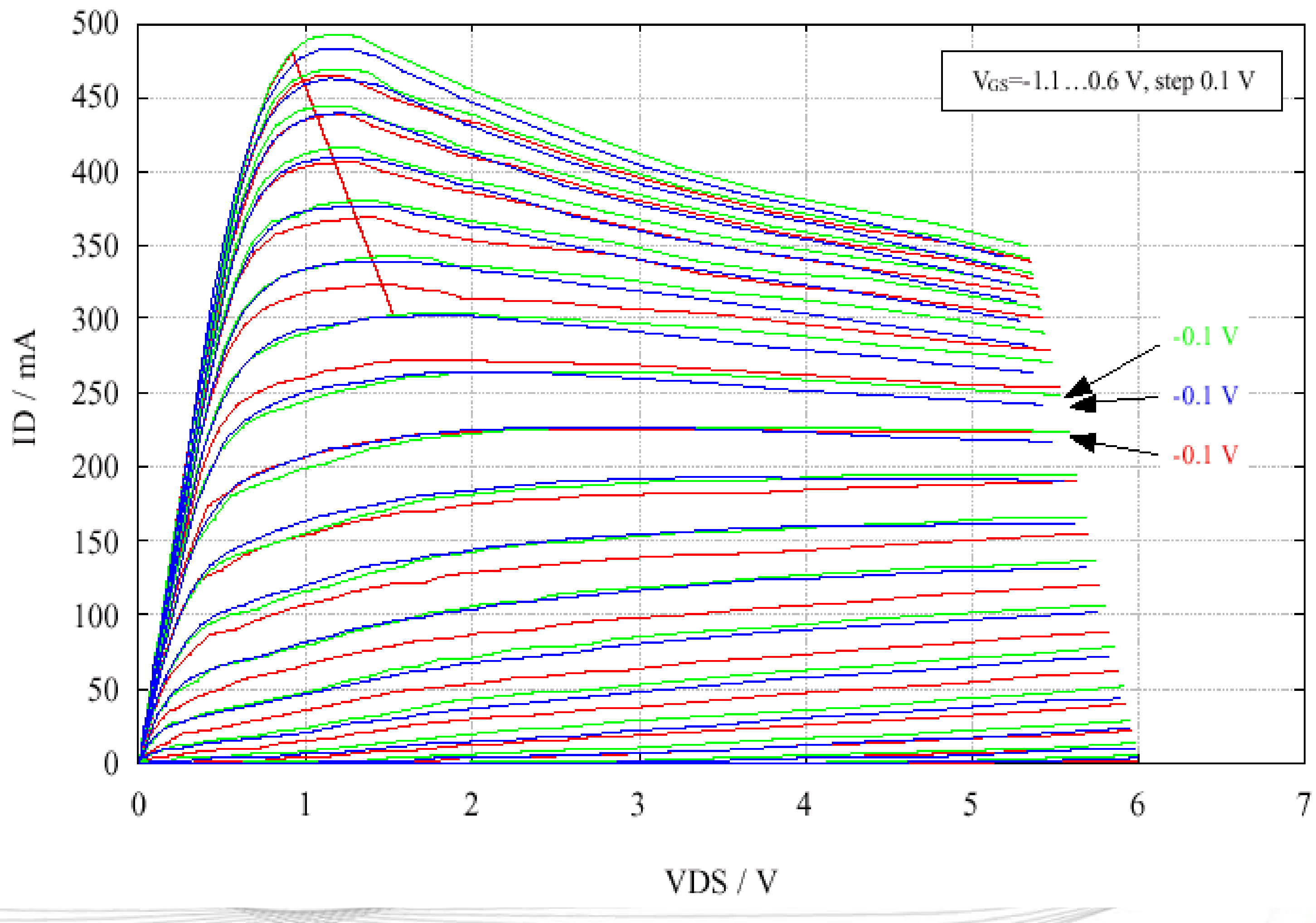
Oscillations



Switching problems



Burn-in effects



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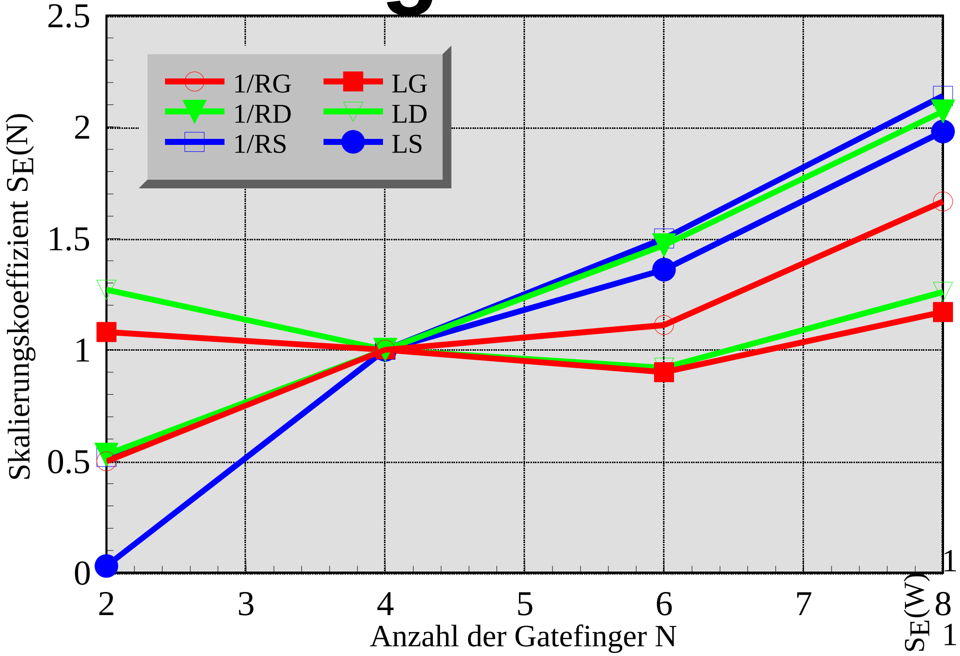
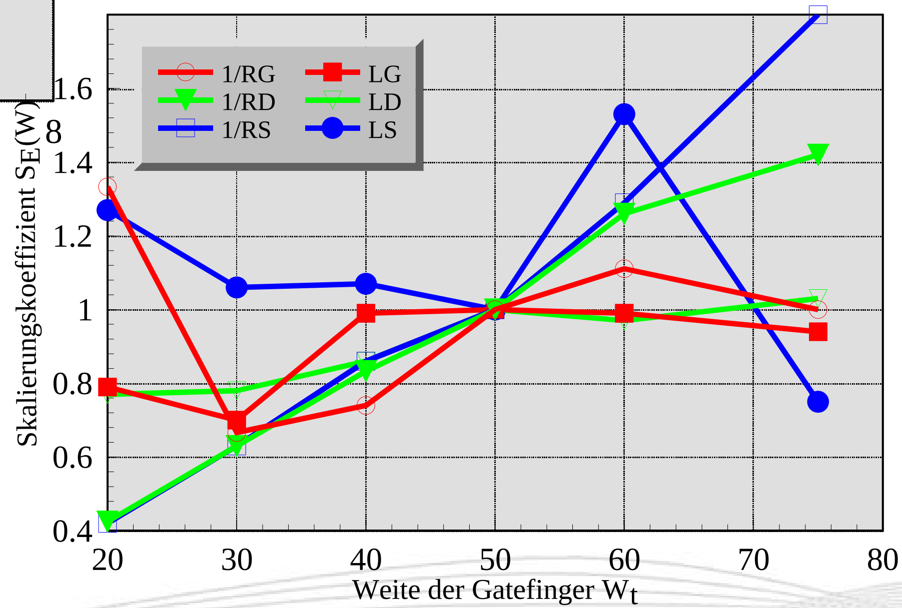
Scaling of extrinsic elements



Variation of gate finger width



Variation of gate finger number

Scaling of extrinsic elements

$$S_E(N) = a_{EN} \cdot N + b_{EN}$$

$$S_E(W_t) = a_{EW} \cdot W_t + b_{EW}$$

$$S_E(N, W_t) = S_E(N) \cdot S_E(W_t)$$

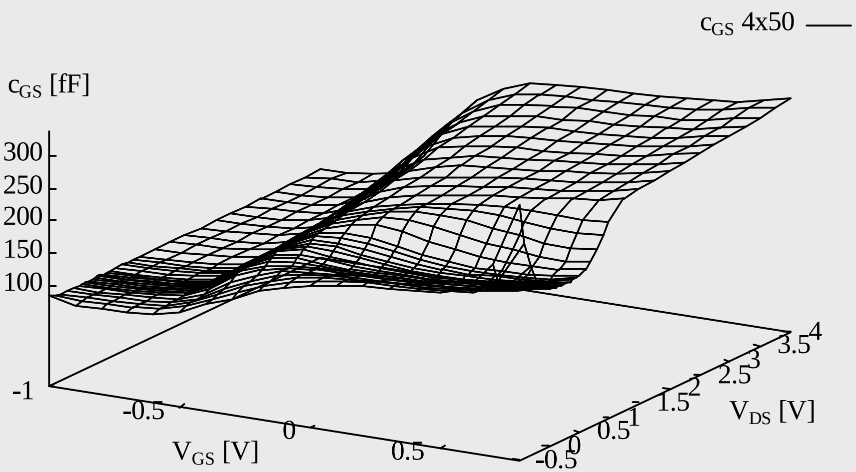
$S_E(N)$	$S_E(W)$	a_{EN}	b_{EN}	a_{EW}	b_{EW}
GG	GG	0.18	0.17	0.0	0.98
GD	GD	0.25	0.0	0.019	0.076
GS	GS	0.27	-0.04	0.024	-0.11
1/LG	LG	0.0	0.993	0.004	0.713
1/LD	LD	0.0	0.895	0.005	0.67
LS	1/LS	0.31	-0.46	0.006	0.68

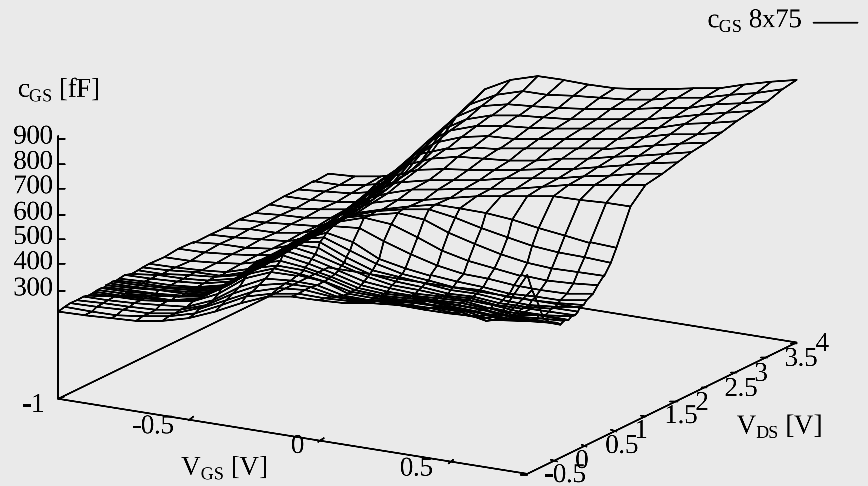
IMST

Scaling of intrinsic elements

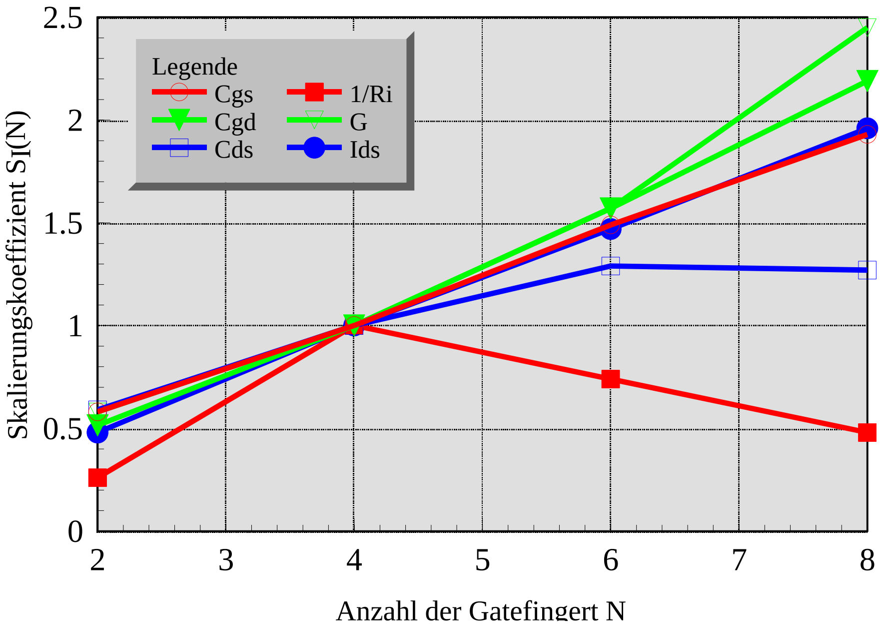
$$c_{old} = \frac{8x75\mu m}{4x50\mu m} = 3$$

$$c = \frac{\sum_{V_{gs},V_{ds}} \frac{G_x(V_{GS},V_{DS})}{G_{ref}(V_{GS},V_{DS})}}{n_{V_{GS},V_{DS}}}$$



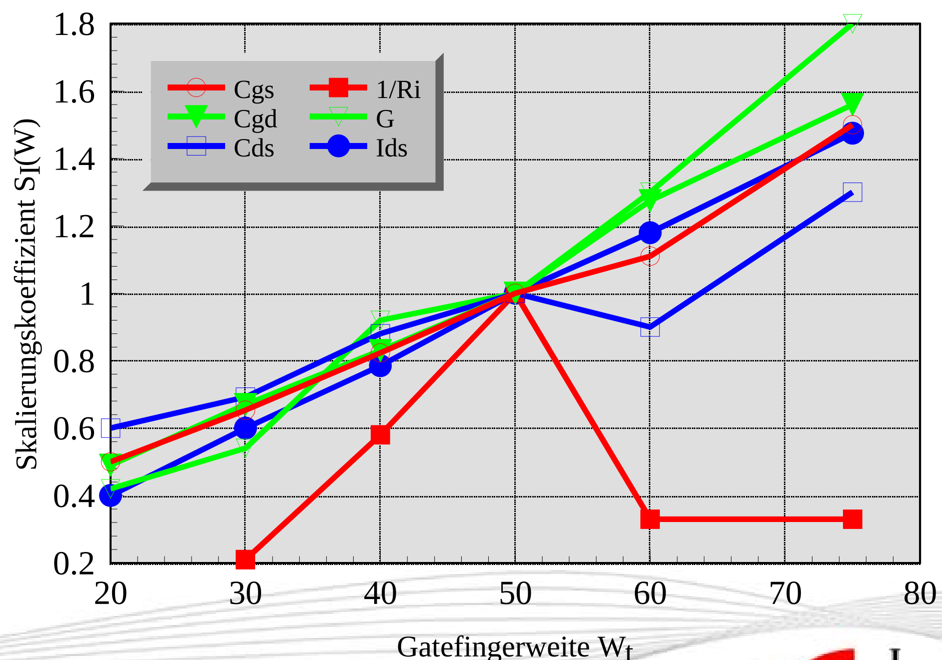


Scaling of intrinsic elements



Variation of gate finger number

Variation of gate finger width



Scaling of intrinsic elements

$$S_I(N) = a_{IN} \cdot N + b_{IN}$$

$$S_I(W) = a_{IWt} \cdot W + b_{IWt}$$

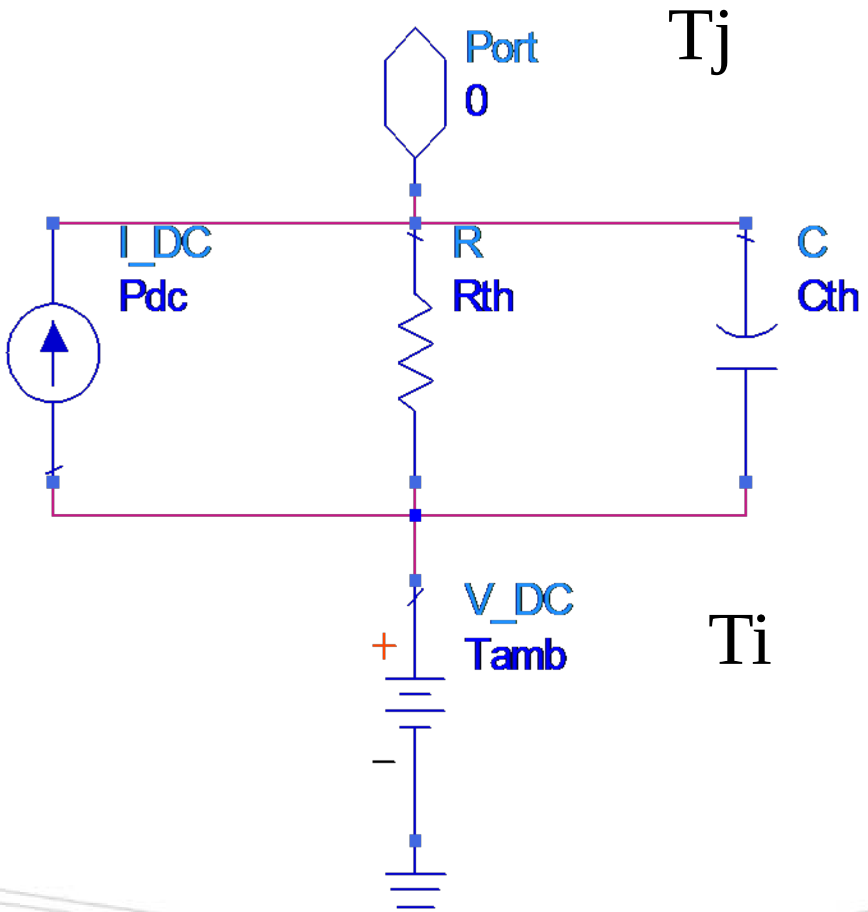
$$S_I(N,W) = S_I(N) \cdot S_I(W)$$

$S_I(N)$	$S_I(W)$	a_{IN}	b_{IN}	a_{IW}	b_{IW}
Cgs	Cgs	0.22	0.116	0.018	0.129
Cgd	Cgd	0.28	-0.08	0.019	0.077
Cds	Cds	0.12	0.459	0.011	0.371
Gi	Gi	0.02	0.52	-0.06	3.878
G	G	0.31	-0.14	0.025	-0.15
Id	Id	0.25	0.0	0.02	0.01

$$c_{new} = S_I(N = 4 \rightarrow N = 8) \cdot S_I(W_t = 50 \rightarrow W_t = 75)$$

$$1.93 \cdot 1.49 = 2.88$$

Thermal model



$$C_{TH}\frac{d\Delta T}{dt}=P-\frac{\Delta T}{R_{TH}}$$

$$P=I_D V_{DS}$$

$$I_D=\frac{V_{Rd1}-V_{Rd2}}{R_D\left(V_{GS},V_{DS}\right)}$$

4D spline interpolation

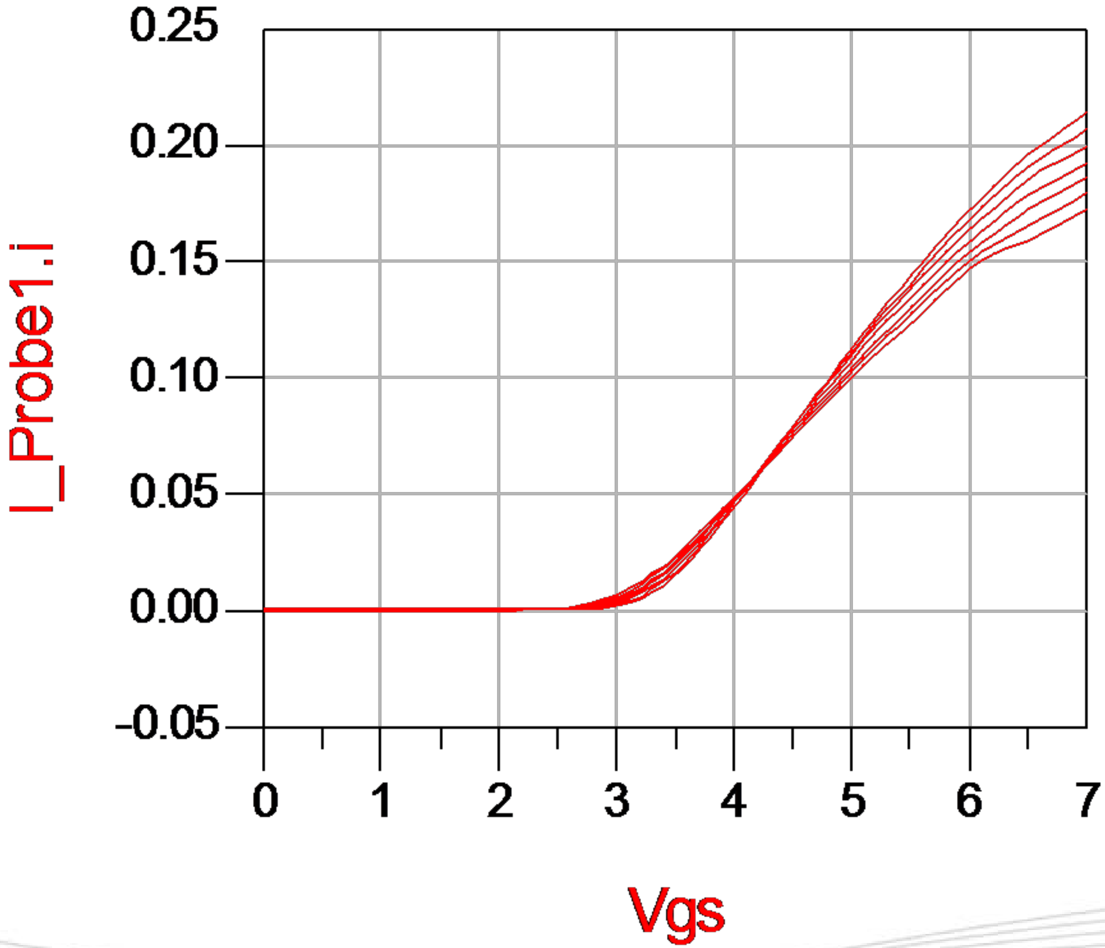
- Accurate description of $I_D(V_{GS}, V_{DS}, \text{Tjunc})$

$$f(\vec{x}) = \sum_{i=0}^{3}\sum_{j=0}^{3}\sum_{k=0}^{3} a_{ijk} x_1^i x_2^j x_3^k$$

- 64 unknown values, 8 points at same time

$$f, \frac{\partial f}{\partial x_i}, \left.\frac{\partial^2 f}{\partial x_i \partial x_j}\right|_{i \neq j}, \frac{\partial^3 f}{\partial x_1 \partial x_2 \partial x_3}$$

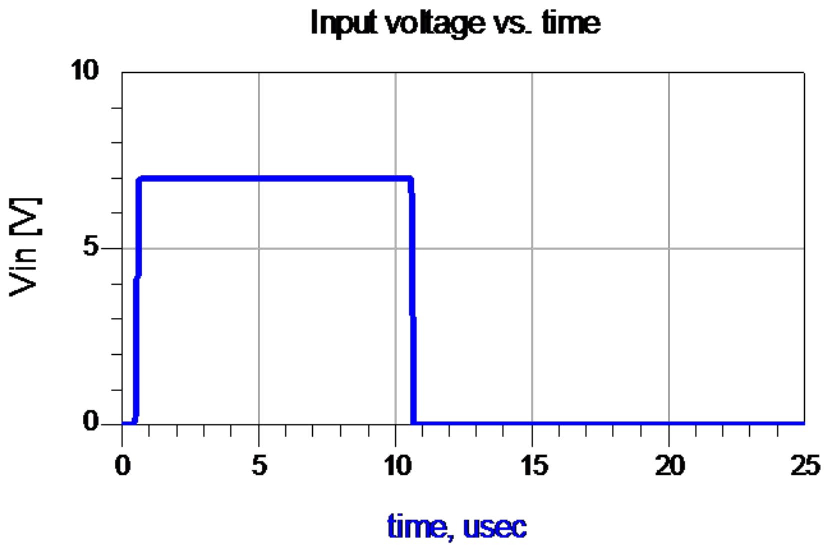
DC verification (LDMOS example)

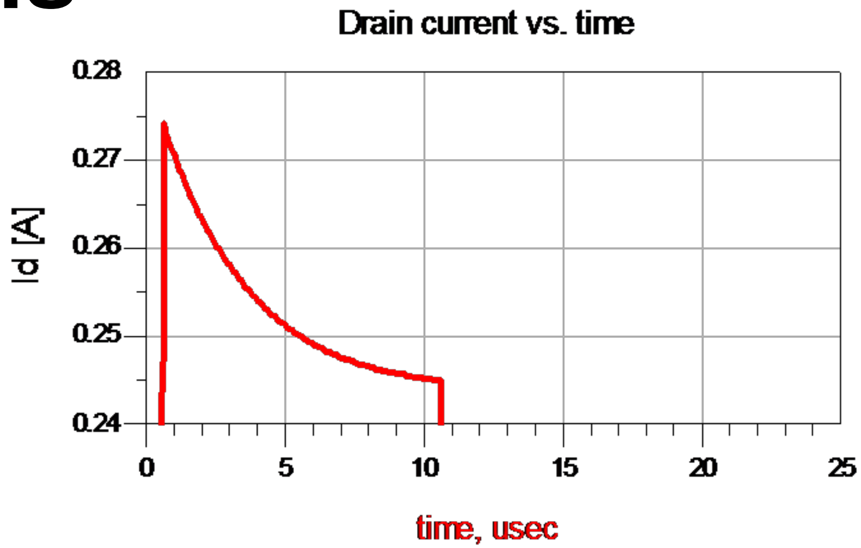


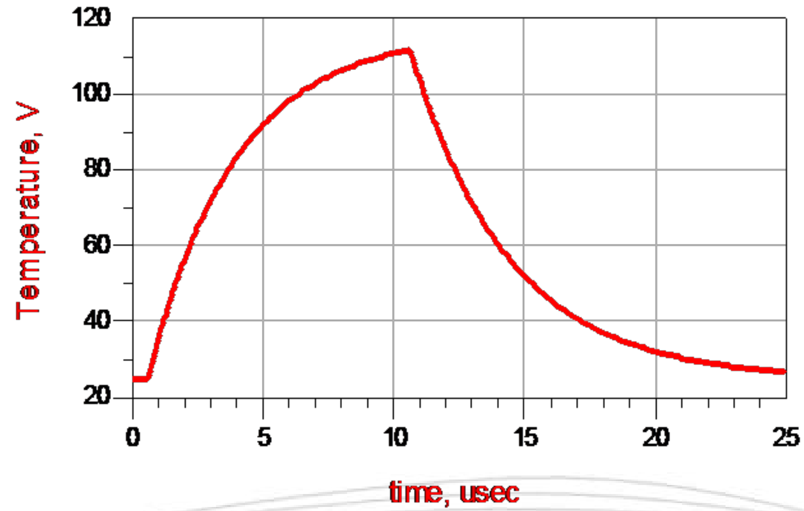
→Intersection in one point

7x100 µm device

Transient analysis







Rth/Cth extraction

→Compare pulsed and CW currents at different temperatures

$$R_{TH} = \frac{T - T_{amb}}{V_{DS} I_{DS}}$$

→Cth: Monitor current versus time

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Thank you for you attention

→ Any questions?