NON-LINEAR CHARACTERISATION AND MODELLING OF CMOS

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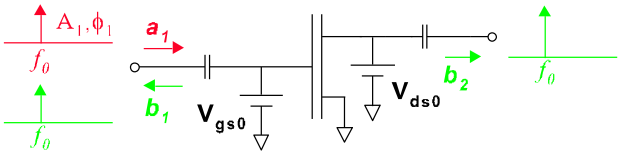
Outline

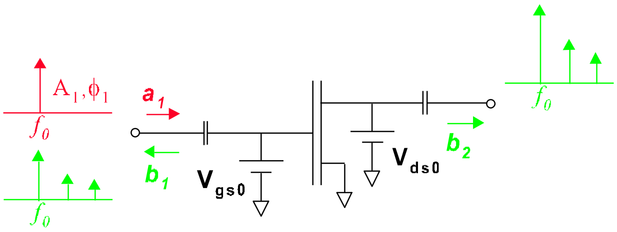
- Introduction
  - non-linear CMOS models
  - non-linear network measurement system (NNMS)
- *Verification* of non-linear CMOS models
  - single- and multi-tone excitation at 50 Ω load
  - two-tone excitation with small frequency offset (= intermodulation testing) combined with loadpull
- NNMS based non-linear device *modelling*
  - device's state-functions obtained by *optimisation*
  - direct *extraction* of the device's state functions
- Conclusions

Measurement techniques

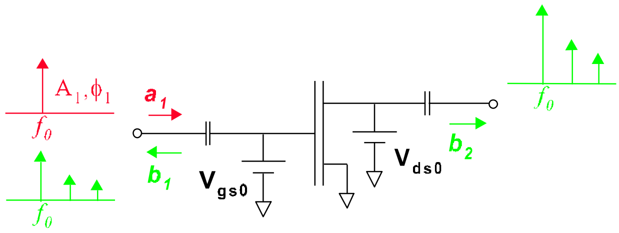
Vector Network Analyzer (VNA)

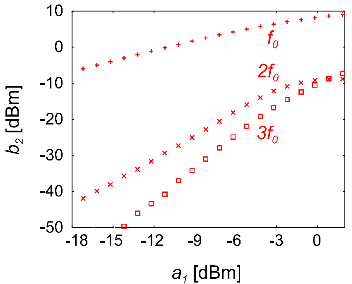


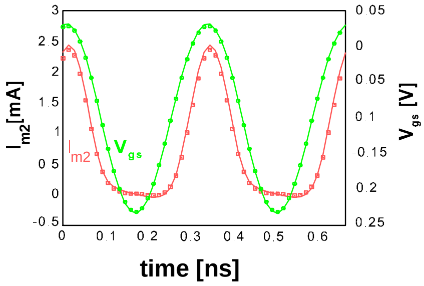
Non-linear Network Measurement System (NNMS)

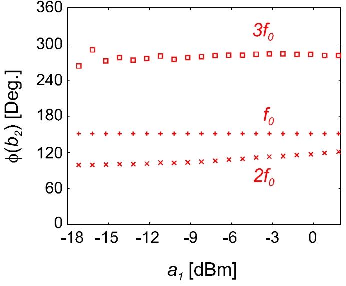


Vectorial large-signal measurements



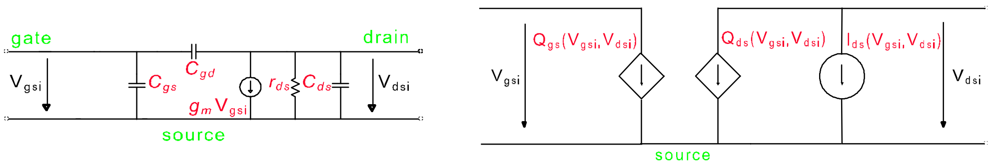






Non-linear CMOS modelling techniques

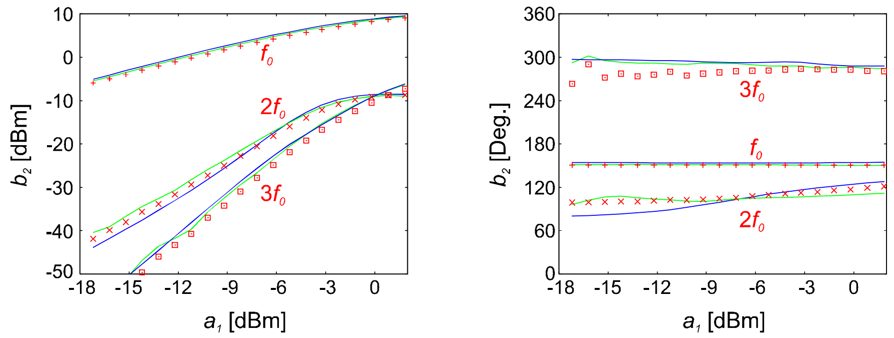
intrinsic quasi-static



linear ⇔ non-linear

- **Compact models:**
  - **state-functions represented by *analytical function***
  - **based on DC, low-frequency C-V and possibly HF S-par. meas.**
- **Table-based models:**
  - ***tabulated* state-functions**
  - **based on HF S-par. and possibly DC meas.**

CMOS non-linear model verification: single-tone excitation

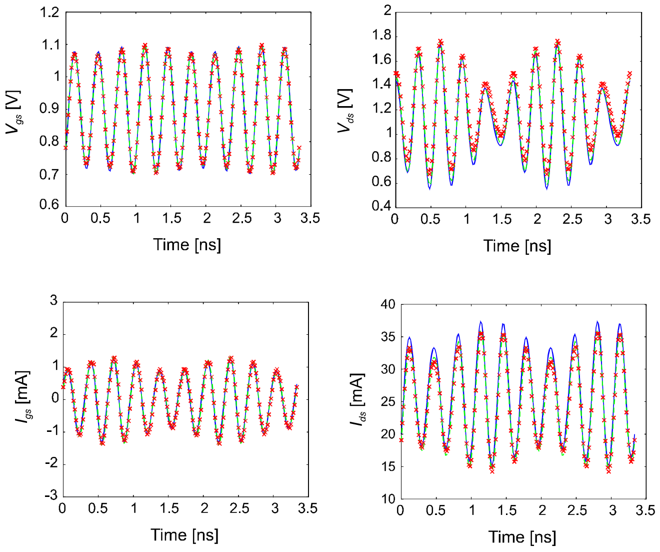


meas **table-based model** **BSIM3 model**

0.18 µm, 146 µm Si nMOSFET

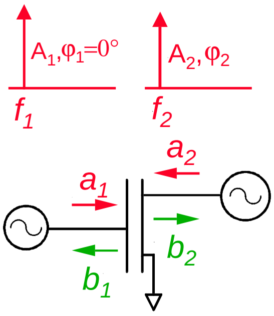
f_0=3.6 GHz - V_{gsDC}= 0.6 V - V_{dsDC}= 1.2 V

CMOS non-linear model verification: two-tone excitation



meas **table-based model** **BSIM3 model**

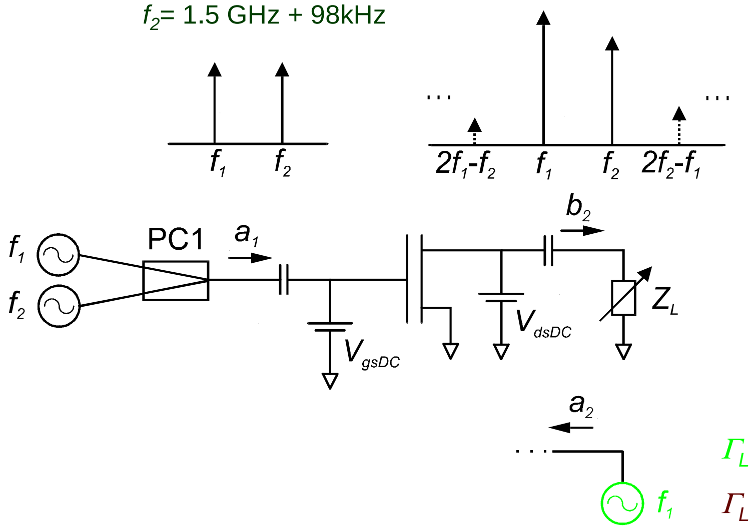
two-tone example



0.18 µm x 146 µm nMOST
V_{gsDC}= 0.9 V, V_{dsDC}= 1.2 V
f_1= 3 GHz, a_1 = -10 dBm
f_2= 3.6 GHz, a_2 = -7 dBm
$\phi(a_2)$-$\phi(a_1)$= 37°

Measurement configuration

f_1= 1.5 GHz - 98kHz
f_2= 1.5 GHz + 98kHz



loadpull

passive
ô
active

$\Gamma_{L,f1} = a_{2,f1}/b_{2,f1}$

$\Gamma_{L,fi} \approx 0$

CMOS non-linear model verification: IM3 & loadpull

Class A

	Meas. [dBm]	BSIM3 model [dBm]	table-based model [dBm]	Meas. [°]	BSIM3 model [°]	table-based model [°]
$b_{2,f1}$	3.1	4.1	3.9	31	34	32
$b_{2,f2}$	3.4	4.3	4.2	41	45	42
$b_{2,2f1-f2}$	-20.7	-20.3	-20.3	-156	-156	-157
$b_{2,2f2-f1}$	-19.5	-19.6	-19.5	-148	-135	-134

$Z_{L,f1}$= 36-j1, $Z_{L,f2}$= 66-j2

$|a_{1,f1}|=|a_{1,f2}|$= -7.3 dBm

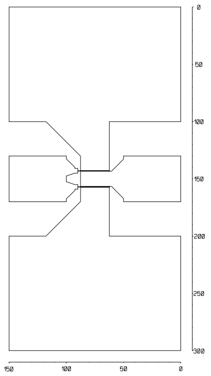
V_{gsDC}= 0.9 V, V_{dsDC}=1.2 V

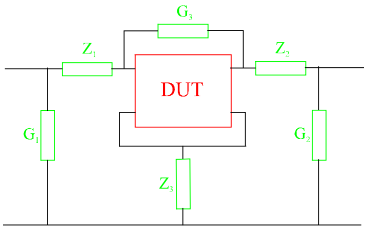
0.2 µm x 146 µm nMOSFET

De-embedding of access transmission lines

De-embedding of pad interconnections:

H. Cho and D. Burk, “A **three-step method** for the de-embedding of high-frequency S-parameter measurements”, IEEE Trans. Electron Devices, pp. 1371-1375, 1991

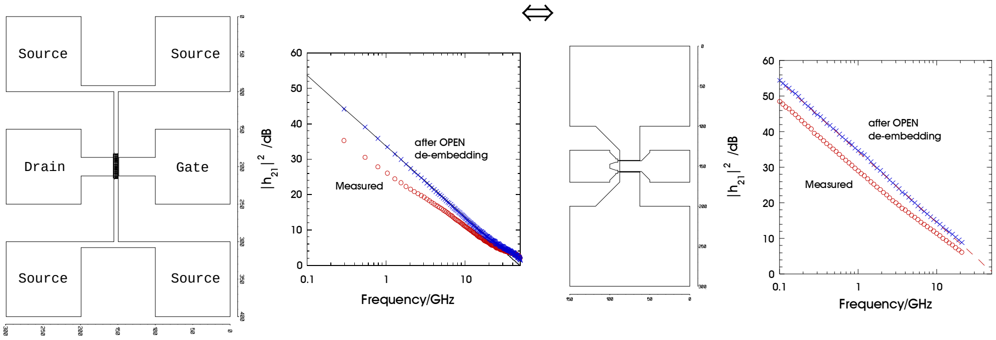




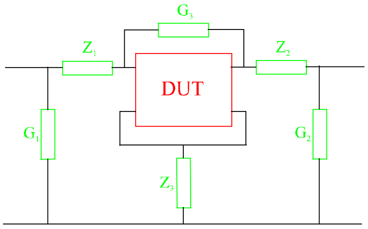
Measurement results — f_T

f_T should be extracted at low frequencies after de-embedding with (at least) an open structure

- **Measured $|h_{21}|^2$ not necessarily -20dB/dec**
- **Transistor-layout influences measured $|h_{21}|^2$**
- **$|h_{21}|^2$ after de-embedding shows -20dB/dec, as expected**



Importance of interconnections



$Z_{L,f1}$= 36-j1, $Z_{L,f2}$ = 66-j2

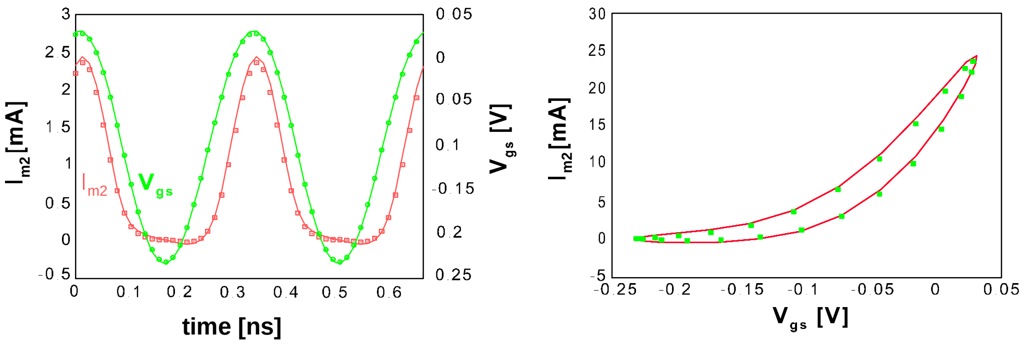
$|a_{1,f1}|=|a_{1,f2}|$= -7.3 dBm

V_{gsDC}= 0.9 V, V_{dsDC}=1.2 V

0.2 µm x 146 µm nMOSFET

	Meas. [dBm]	BSIM3 model incl. interc. [dBm]	BSIM3 model excl. interc. [dBm]	Meas. [°]	BSIM3 model incl. interc. [°]	BSIM3 model excl. interc. [°]
$b_{2,f1}$	3.1	4.1	4.7	31	34	42
$b_{2,f2}$	3.4	4.3	4.9	41	45	54
$b_{2,2f1-f2}$	-20.7	-20.3	-19	-156	-156	-146
$b_{2,2f2-f1}$	-19.5	-19.6	-18.2	-148	-135	-124

Non-linear model verification



Capacitive effects ð time shift between V_{gs} and I_{m2} waveforms
ð (I_{m2}, V_{gs}) trace shows hysteresis

0.2 µm, 100 µm GaAs PHEMT (but similar behaviour for CMOS)
V_{dsDC}=2 V - I_{ds}=3 mA/mm - f_0=3 GHz - P_{in}= -13.5 dBm

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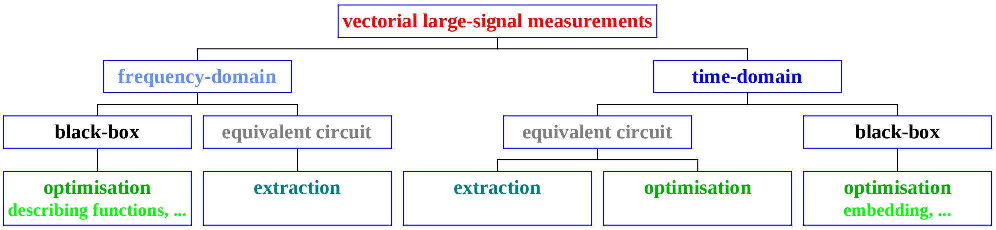
Overview of different modelling techniques


vectorial large-signal measurements

frequency-domain
- black-box
  - optimisation
describing functions, ...
- equivalent circuit
  - extraction

time-domain
- equivalent circuit
  - extraction
  - optimisation
- black-box
  - optimisation
embedding, ...

Device’s state functions by optimisation

Empirical & compact transistor models

- = state-functions are represented by analytical expression

  $Q_{gs}(V_{gsi},V_{dsi}),\ I_{ds}(V_{gsi},V_{dsi}),\ Q_{ds}(V_{gsi},V_{dsi})$

- often preferred by foundries due to limited number of parameters compared to table-based models

- technology dependent:
  - CMOS: e.g., BSIM3v3 model
  - HEMT: e.g., Chalmers model

- complexity analytical expression is often a compromise between number of parameters and accuracy over broad bias and frequency range

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Device’s state functions by optimisation

Parameter estimation by optimisation towards measurements:

- classical approach:

  DC - C-V - S-parameters - amplitude spectral measurements at output
  - (-) several measurement systems: DC, VNA, spectrum analyser, ...
  - (-) consistent optimisation requires adequate software

- novel approach:

  only vectorial large-signal measurements at input and output
  - 1 measurement system (NNMS) & 1 HB simulator with an optimiser

  ð fast and accurate generation of device models under *real* operating conditions

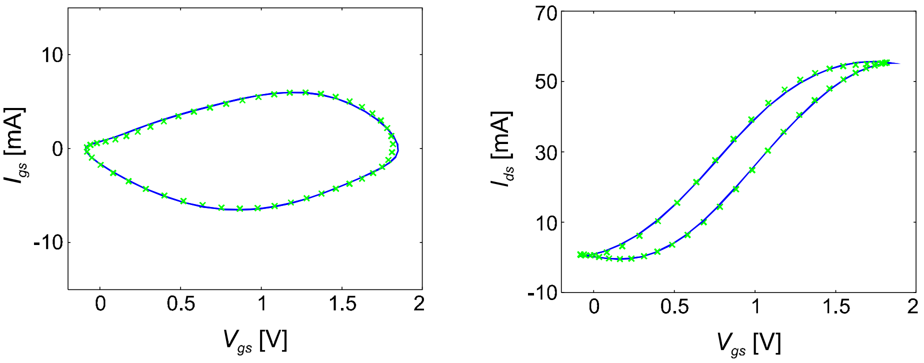
Empirical transistor model parameter estimation

empirical model: e.g., Chalmers model:

0.18 µm x 146 µm Si *nMOSFET* operated at class A (V_{gsDC}= 0.9 V - V_{dsDC} = 1.8 V)

NNMS measurements at f_0 = 3.6 GHz & varying P_{in}

results @ P_{in}= 3.8 dBm:



Conclusions

NNMS & non-linear MOSFET modelling:

- importance of *de-embedding* access transmission lines
- extended non-linear model *verification*
  - complex spectra / time-domain waveforms
  - at realistic operating conditions, e.g., intermodulation & loadpull
- *model building* directly based on large-signal measurements
  - state-functions obtained by *optimisation*
    - » applicable to empirical/compact device models & neural networks
    - » preferably used to model device for specific applications
  - direct *extraction* of state-functions
    - » preferably used to obtain ‘general’ model for device

Literature

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[2] E. Vandamme *et al.*, “Reliable extraction of RF figures-of-merit for MOSFETs”, 29th European Solid-State Device Research Conference, 1999, pp. 660-663.

[3] D. Schreurs *et al.*, “Easy and accurate empirical transistor model parameter estimation from vectorial large-signal measurements”, IEEE Int. Microwave Symp. Digest, 1999, pp. 753-756.

[4] D. Schreurs *et al.* , “Large-signal modelling and measuring go hand-in-hand: accurate alternatives to indirect S-parameter methods”, International Journal of RF and Microwave Computer-Aided Engineering 10 (2000), pp. 6-18.

[5] D. Schreurs *et al.*, “Evaluation of non-linear modelling techniques for MOSFETs based on vectorial large-signal measurements”, IEEE International Symposium on Circuits and Systems, 2000, pp. II-429 - II-432.

[6] D. Schreurs *et al.*, “Verification of non-linear MOSFET models by intermodulation measurements under loadpull conditions”, 55th Automatic RF Techniques Group Conference, June 2000, pp. 58-62.

[7] D. Schreurs *et al.*, “Development and verification of a non-linear look-up table model for MOSFETs”, European Gallium Arsenide and related III-V compounds Applications Symposium, 2000, pp. 109-112.

[8] E. Vandamme *et al.*, “Impact of probe-to-pad contact degradation on the high frequency characteristics of RF MOSFETs and guidelines to avoid it”, International Journal of RF and Microwave Computer Aided Engineering, publication scheduled for 2001.

[9] E. Vandamme *et al.*, “Improved three-step de-embedding method to accurately account for the influence of pad parasitics in silicon RF test-structures”, IEEE Transactions on Electron Devices, publication scheduled for 2001.