Enabling CNTFET-based analog high-frequency circuit design with CCAM

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CNTFET technology status for analog HF applications[1]

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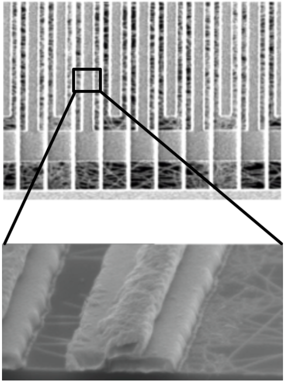
[1] M. Schröter, M. Claus, et al., "Carbon nanotube FET technology for radio-frequency electronics: State-of-the-art overview (invited)", IEEE Journal of the Electron Devices Society, 1(1), pp. 9–20, 2013.

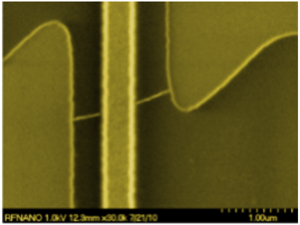
CNTFET technology overview

Multi-tube CNTFETs

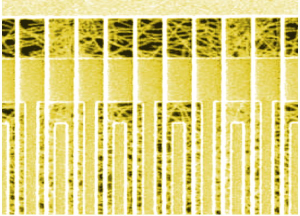


- high current, high power application (1000–3000 parallel tubes)
- scale with tube density, finger number and width to desired applications
- relaxed constraints for technology (800 nm channel length)
- parasitic metallic tubes in the channel (20%-30%)
- first prototyp technologies available ($f_{\mathrm{T,peak}} \approx 10\,\mathrm{GHz}$, $G_{\mathrm{power}} > 10\,\mathrm{dB}$)

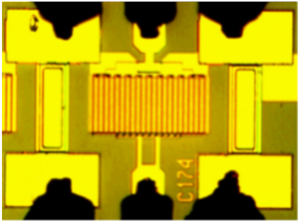
Status of HF CNTFET technology I



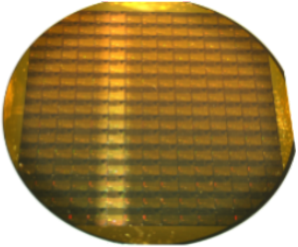
Single-tube CNTFET



Multi-tube Multi-finger CNTFET

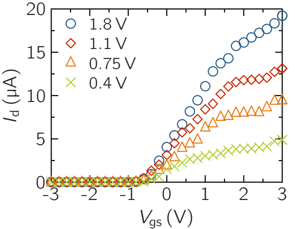


HF CNTFET in GSG configuration

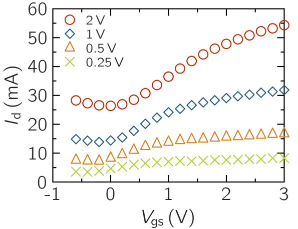


100 mm wafer

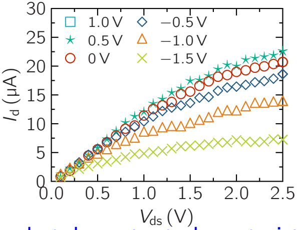
Status of HF CNTFET technology II



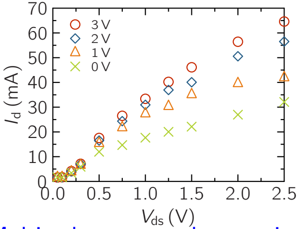
Single tube transfer characteristic



Multi tube transfer characteristic

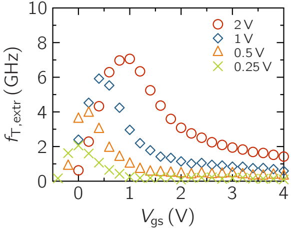


Single tube output characteristic

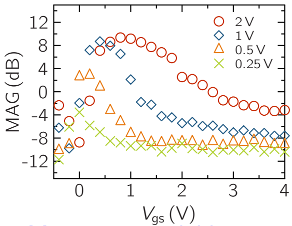


Multi tube output characteristic

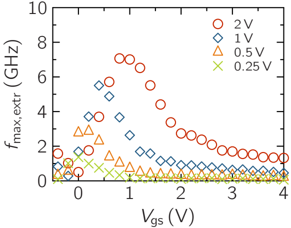
Status of HF CNTFET technology III



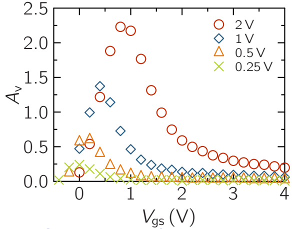
Transit frequency of HF CNTFET



Maximum available gain



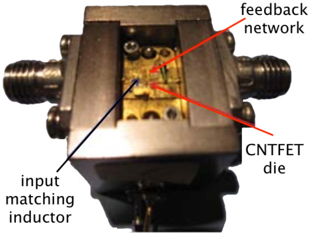
Maximum oscillation frequency

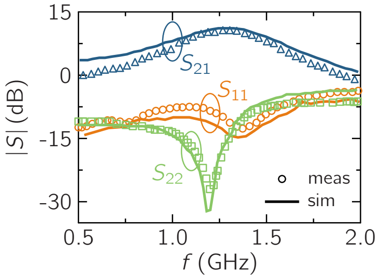


Intrinsic voltage gain

Circuit results - L-band RF amplifier

- First CNT-based single-stage L-band RF amplifier[2]
- 11 dB linear gain with 10 dB input/output return loss at 1.3 GHz





- Good comparison between experimental results and model

[2] M. Eron, S. Lin, D. Wang, M. Schröter, P. Kempf, "An L-band carbon nanotube transistor amplifier", Electronics Letters, vol. 47, no. 4, pp. 265-266, 2012.

CCAM – A compact model for HF CNTFETs[3,4]

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[3] M. Claus, ..., M. Schröter, "Critical review of cntfet compact models", in NSTI-Nanotech (Workshop on Compact modeling), Vol. 2, 2012.

[4] M. Schröter, ..., M. Claus, "A semi-physical large-signal compact carbon nanotube fet model for analog rf applications", IEEE Transactions on Electron Devices, Vol. 62(1), 2015.

Compact models for HF CNTFETs I

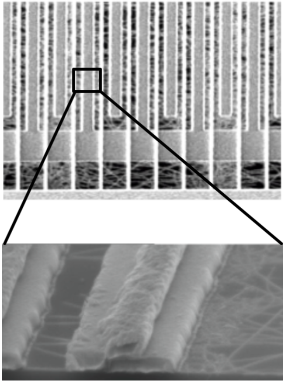
State-of-the-art of CNTFET compact models

- main focus on digital applications ("beyond CMOS")
  → nanoscale channel lengths
- models mostly restricted to single-tube CNTFETs and low voltages
- formulations focus mostly on describing DC behavior
- almost no experimental verification of model formulations

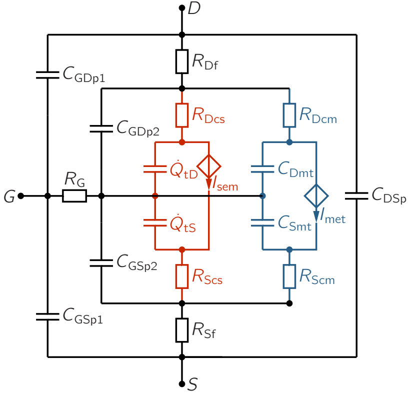
→ little emphasis on multi-tube high-frequency (HF) analog applications

Compact models for HF CNTFETs II

- CM for MT CNTFETs includes: equivalent circuit for semiconducting tubes + metallic tubes + parasitic elements



Multi-tube CNTFET



Equivalent circuit

Compact modeling issues I

Trap modeling

- In wafer-scale processes it is still challenging to get devices free of traps.
- For early applications: compact models for circuit design needed with which the trap-affected circuit behavior can be predicted
- Trap model can help to define measurement conditions to characterize trap-free device behavior which is needed for technology evaluation and modeling purposes
- Model helps to understand experimental observation such as the apparent linearity of CNTFETs

Compact modeling issues II

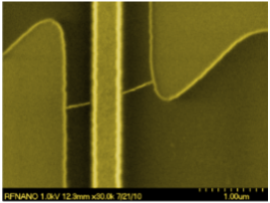
- All fabricated transistors have Schottky-like barriers (SB) between metal contacts and CNT

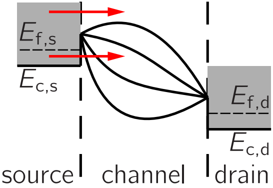
→ compact modeling very difficult

→ no feasible physics-based approach (for current and charge) is known

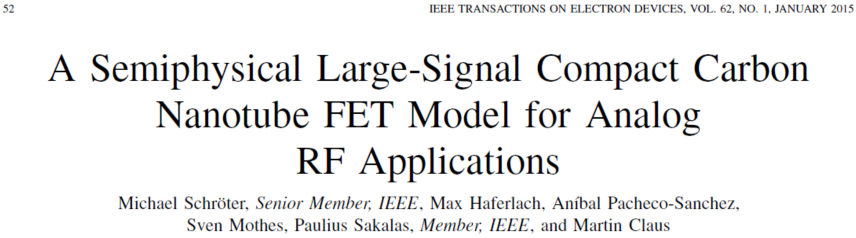
→ almost all existing compact models do not consider SB properly (compared to experiments)

Two parallel approaches in our group: semi-physics based (CCAM) and physics-based (TCAM) compact model





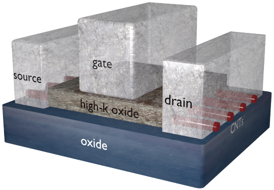
Compact model: CCAM

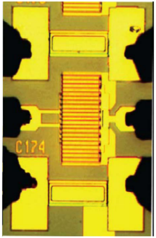


52 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 62, NO. 1, JANUARY 2015

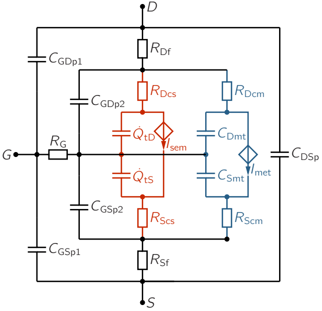
A Semiphysical Large-Signal Compact Carbon Nanotube FET Model for Analog RF Applications

Michael Schröter, *Senior Member, IEEE*, Max Haferlach, Aníbal Pacheco-Sanchez,
Sven Mothes, Paulius Sakalas, *Member, IEEE*, and Martin Claus





Compact model: CCAM



Equivalent circuit

CCAM Features

- bias-dependent formulation for internal elements (i. e. large signal model)
- temperature and geometry dependence for all equivalent circuit elements
- access to technology parameters e. g. fraction of metallic tubes
- noise and trap model

- CCAM has been implemented in Matlab and Verilog-A, making it widely available across circuit simulators[5]

[5] M. Schröter et al., CCAM Compact Carbon Nanotube Field-Effect Transistor Model, nanoHUB, doi:10.4231 / D34F1MK28, 2015.

CCAM equations (not showing all)

- Drain current:

$$I_{\mathrm{sem}} = I_{\mathrm{DS0}} f_{\mathrm{GS}} f_{\mathrm{DS}}$$

- GS dependence:

$$f_{\mathrm{GS}} = \left(\frac{u_{\mathrm{GS}} + \sqrt{u_{\mathrm{gs}}^2 + a_{\mathrm{thg}}}}{1 + \sqrt{1 + a_{\mathrm{thg}}}} \right)^2 \left(1 + 2 \frac{1 + u_{\mathrm{GS}}}{\sqrt{u_{\mathrm{GS}}^2 + a_{\mathrm{thg}}}} \right)$$

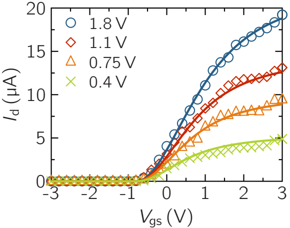
with $u_{\mathrm{GS}} = 1 - V_{\mathrm{thg0}} / v_{\mathrm{gt}}, \; v_{\mathrm{gt}} = V_{\mathrm{GS}} - V_{\mathrm{fb}}$

- DS dependece (simple form for scattering):

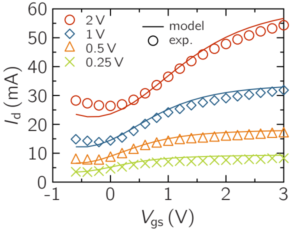
$$f_{\mathrm{DS}} = u_{\mathrm{DS}} \left(1 + |u_{\mathrm{DS}}|^{\beta} \right)^{-1/\beta}$$

- Similar smoothing functions for the charge

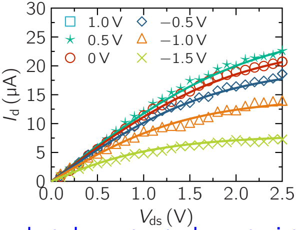
Experimental verification I



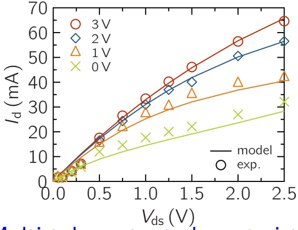
Single tube transfer characteristic



Multi tube transfer characteristic

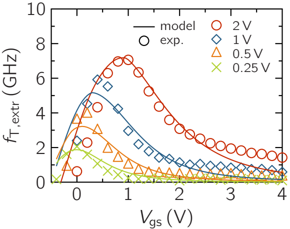


Single tube output characteristic

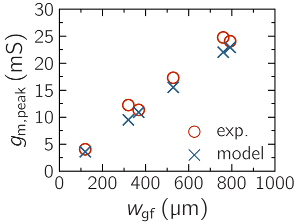


Multi tube output characteristic

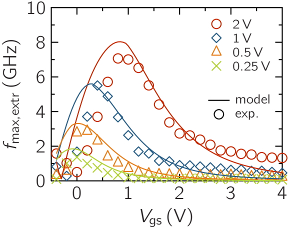
Experimental verification II



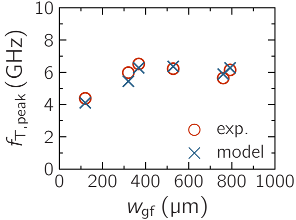
Transit frequency of HF CNTFET



Scaling of peak g_m with gate width



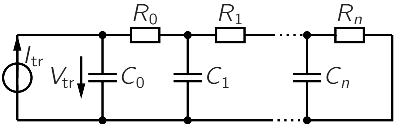
Maximum oscillation frequency



Scaling of peak f_T with gate width

Modeling of trap effects

- Empirical trap model included in CCAM[6]
- Electron capturing in traps and the resulted tube shielding is modeled as a threshold voltage shift $I_d = f(V_{GS} - V_{tr})$
- Dynamics of capture and emission modeled with RC network



- Empirical model for trap current $I_{tr} = \alpha V_{GS} + \beta V_{ds} + \gamma$ fitted to step response measurements
- Model parameters of intrinsic part adjusted to pulsed measurements

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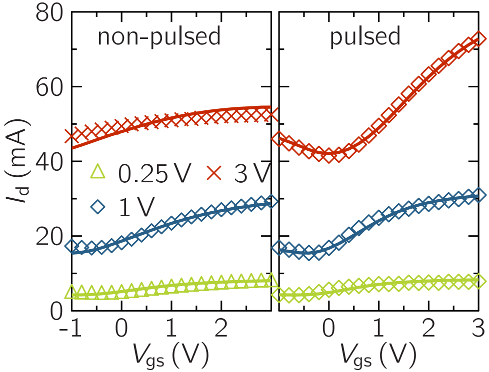
[6] M. Haferlach M. Claus, A.Pacheco, et al., Nanotech, Workshop on Compact Modeling (WCM), 2014.

Comparison with experimental data

- Non-pulsed mode: charges are trapped and shield tube potential from the external voltages
  - for high V_{GS} and V_{DS} tube potential and current stay almost constant
- Pulsed mode: measurement cycles too fast for trapping processes
  - tube potential directly follows external voltages



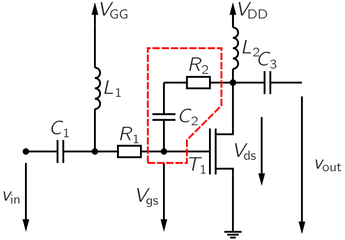
Transfer characteristics
symbols – exp. results, lines – model

→ CM predicts non-pulsed and pulsed behavior
(with one single parameter set for non-pulsed and pulsed mode)

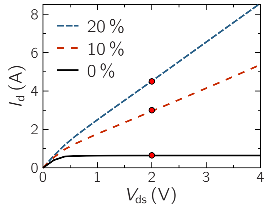
Benchmark circuit design studies

Circuit results - Power amplifier[7]

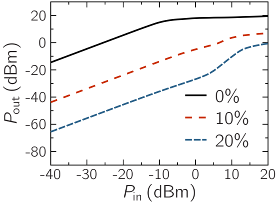
- Class-A power amplifier designed at $V_{\text{gs}} = 0.5\,\text{V}$ (low saturation voltage) and $V_{\text{ds}} = 2\,\text{V}$ for 2 GHz applications
- 150 similar devices are connected in parallel to have an output power of 16 dBm



PA circuit with matching and stabilization subcircuits



Output characteristic for various m_{frac}



Output power vs input power for various m_{frac}

- Power gain only for less than 10 % metallic tube fraction

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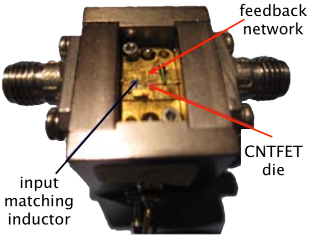
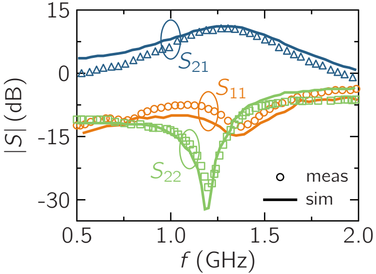
[7] M. Claus, et al., "High-frequency benchmark circuit design for a sub 50 nm cntfet technology", IMOC 2013

Circuit results - L-band RF amplifier[2]

- First CNT-based single-stage L-band RF amplifier
- 11 dB linear gain with 10 dB input/output return loss at 1.3 GHz





- Good comparison between experimental results and model[4]

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[2] M. Eron, ..., M. Schröter, "An L-band carbon nanotube transistor amplifier", Electronics Letters, Vol. 47(4), 2012.

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Conclusions

- CNTFET technology is suitable for HF applications.
- CCAM shows an excellent agreement with DC as well as with bias and frequency dependent AC data of fabricated SB CNTFETs
- Trap model included in CCAM to predict the impact of traps on circuit behavior
  - CCAM predicts non-pulsed and pulsed behavior
  - Temperature dependence to be published soon
- CNTFET circuit design is ongoing
  - CCAM is used to optimization and projection
  - Discrete circuit design by means of the CCAM model
- CCAM available at nanoHUB (doi:10.4231 / D34F1MK28, 2015)