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EKV MOS Transistor Modelling & RF Application

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- ☞Part I: Charge-based DC, AC and Noise Modelling
- ☞Part II: RF Application

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PART I: Charge-based DC, AC and Noise Modelling

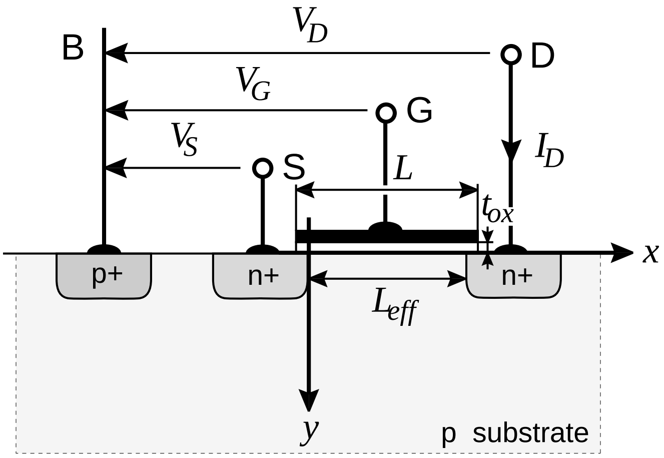
- ☞***Introduction: EKV v2.6***
- ☞***Charge-based Static Model***
- ☞***Quasi-static Charge & Transcapacitances Model***
- ☞***NQS Model***
- ☞***Noise Model***
- ☞***Mobility Model & Short-Channel Effects***

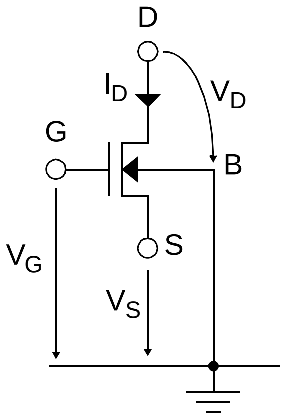
Introduction: EKV v2.6 MOS Transistor (MOST) Model

- Motivation:
  - ✔*RF circuit design requires **complete MOST model from DC to RF,** including noise.*
  - ✔*All current levels need to be well modelled, in particular also **moderate inversion.***
- EKV v2.6 in summary:
  - ✔*A **physics-based** compact MOST model in the **public domain.***
  - ✔*Dedicated to **analog circuit simulation** for submicron CMOS.*
  - ✔*Includes **weak-moderate-strong inversion modelling**, doping & mobility effects, short-channel effects, geometry- and bias-dependent matching.*
  - ✔*Small number of intrinsic model parameters:*

    EKV v2.6: < 20, BSIM3v3: > 65, MM9: > 55

Charge-based Static Model

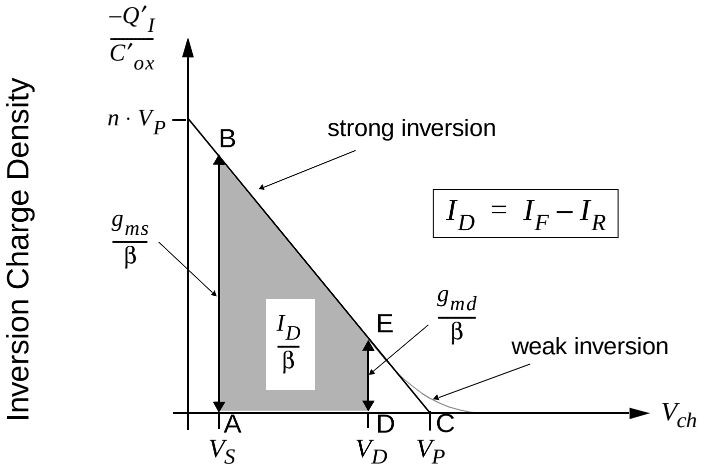




- Bulk-reference, symmetric model structure.
- Drain current expression including drift and diffusion:

$$I_D = W \cdot \mu \cdot (-Q'_I) \cdot \frac{dV_{ch}}{dx} \qquad (1)$$

Charge-based Static Model



$$\beta = \mu \cdot C'_{ox} \cdot \frac{W_{eff}}{L_{eff}}$$

- Integration of Q'_I from source to drain:

$$I_D = \beta \int_{V_S}^{V_D} \left(\frac{-Q'_I}{C'_{ox}}\right) \cdot dV_{ch} = \underbrace{\beta \int_{V_S}^{\infty} \left(\frac{-Q'_I}{C'_{ox}}\right) \cdot dV_{ch}}_{I_F(V_P - V_S)} - \underbrace{\beta \int_{\infty}^{V_D} \left(\frac{-Q'_I}{C'_{ox}}\right) \cdot dV_{ch}}_{I_R(V_P - V_D)} \tag{2}$$

Drain Current Normalization and Pinch-off Voltage

- Current normalization using the **Specific current** I_S:

$$I_D = I_F - I_R = I_S \cdot (i_f - i_r) = 2n\beta U_T^2 \cdot (i_f - i_r) \tag{3}$$

- **Pinch-off voltage** V_P accounts for...

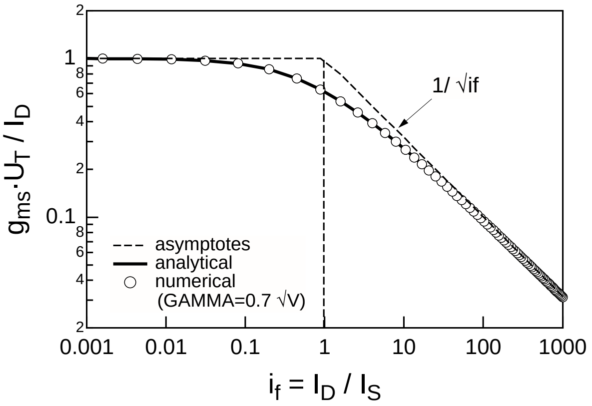
✔***threshold voltage*** V_{TO} *and* ***substrate effect*** $\gamma = (\sqrt{2q\varepsilon_s N_{sub}})/C'_{ox}$

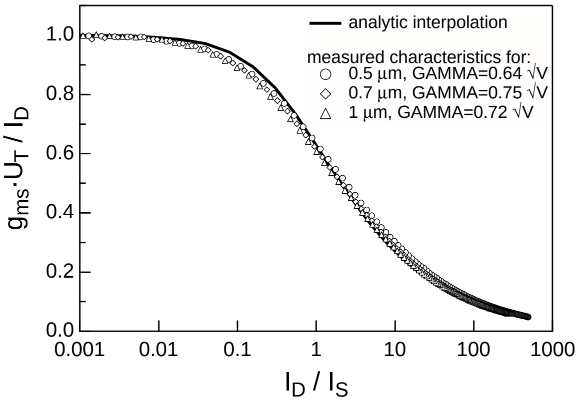
$$V_P = V_G - V_{TO} - \gamma \cdot \left[\sqrt{V_G - V_{TO} + \left(\sqrt{\Psi_0} + \frac{\gamma}{2}\right)^2} - \left(\sqrt{\Psi_0} + \frac{\gamma}{2}\right)\right] \tag{4}$$

- **Slope factor** n:

$$n = \left[\frac{\partial V_P}{\partial V_G}\right]^{-1} = 1 + \frac{\gamma}{2\sqrt{\Psi_0 + V_P}} \tag{5}$$

Charge-based Static Model

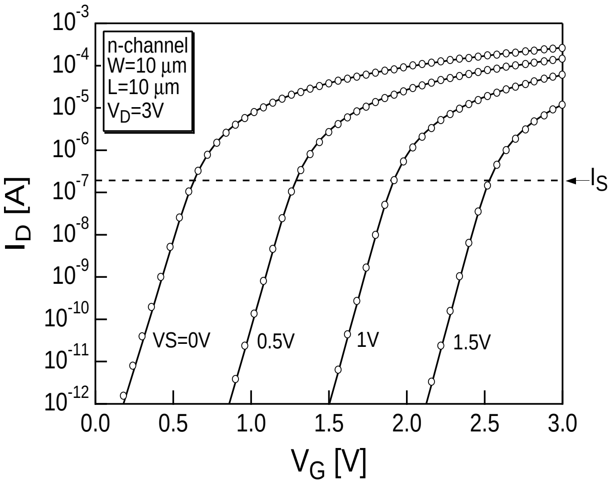


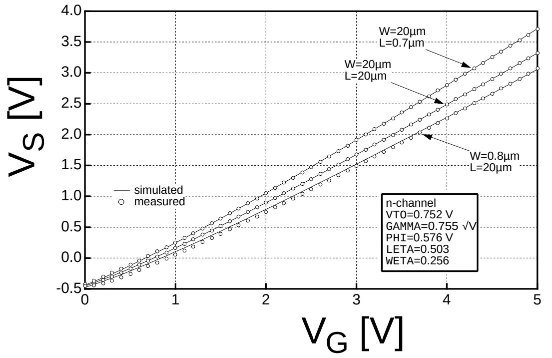


☞ Normalized transconductance-to-current ratio $g_{ms} \cdot U_T / I_D$ vs. normalized current I_D / I_S from weak through moderate to strong inversion.

- ✔*Comparison with numerical solution of the Poisson equation.*
- ✔*Comparison with three different CMOS processes (long-channel devices in saturation).*
- ✔*Almost technology independent!*

Drain Current and Pinch-off Voltage



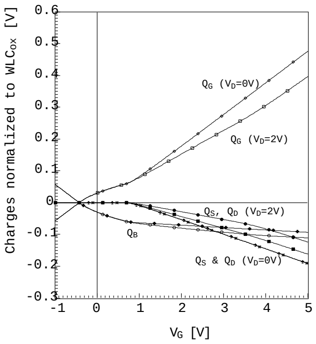


☞ Valid from weak to strong inversion, and from linear to saturation.

☞ Accuracy of weak inversion slope and substrate effect.

- ✔*no additional parameters used for adapting weak inversion slope*

Quasistatic Charge- & Transcapacitances Model



$$C_{OX} = C'_{ox} \cdot W \cdot L$$

☞ Node charges: integration of inversion charge density along channel:

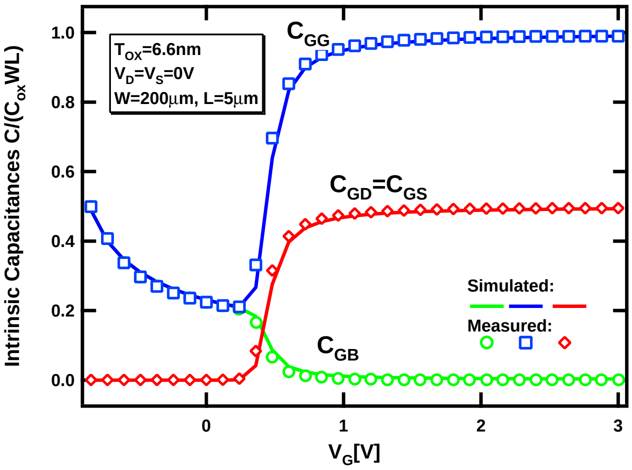
$$Q_I = W \cdot \int_0^L Q_I'(x) \cdot dx \qquad Q_D = W \cdot \int_0^L \frac{x}{L} \cdot Q_I'(x) \cdot dx \qquad Q_S = Q_I - Q_D \tag{6}$$

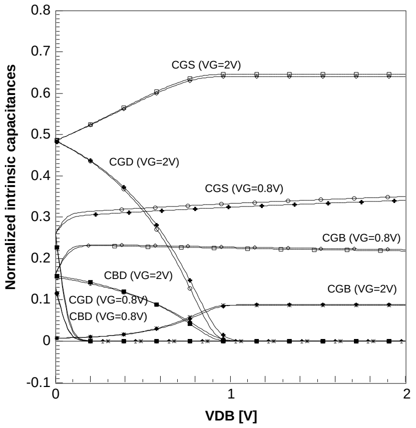
$$Q_B = -\gamma \cdot C_{OX} \cdot \sqrt{V_P + \Psi_0} - \left(\frac{n-1}{n} \cdot Q_I\right) \qquad Q_G = -Q_I - Q_B - Q_{ox} \tag{7}$$

✔*Drain and source charges are obtained using Ward's charge partitioning scheme.*

✔*Single equation expressions are used from weak to strong inversion.*

(Trans-)Capacitances Model





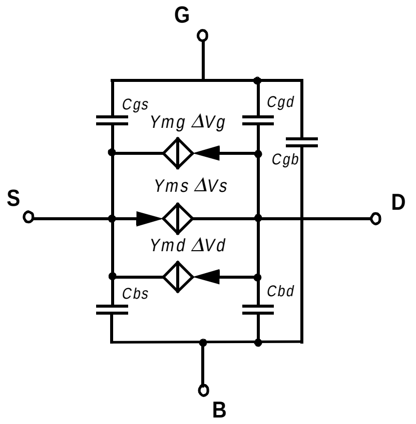
☞ Transcapacitances: derivation with respect to the terminal voltage:

$$C_{MN} = \pm\frac{\partial}{\partial V_N}(Q_M) \qquad M, N = G, D, S, B \tag{8}$$

✔*Accurate capacitances through all inversion levels.*

✔*Symmetric C_{GS} and C_{GD} at V_D=V_S=0.*

Intrinsic MOST - Small Signal Equivalent



Transcapacitances are not shown

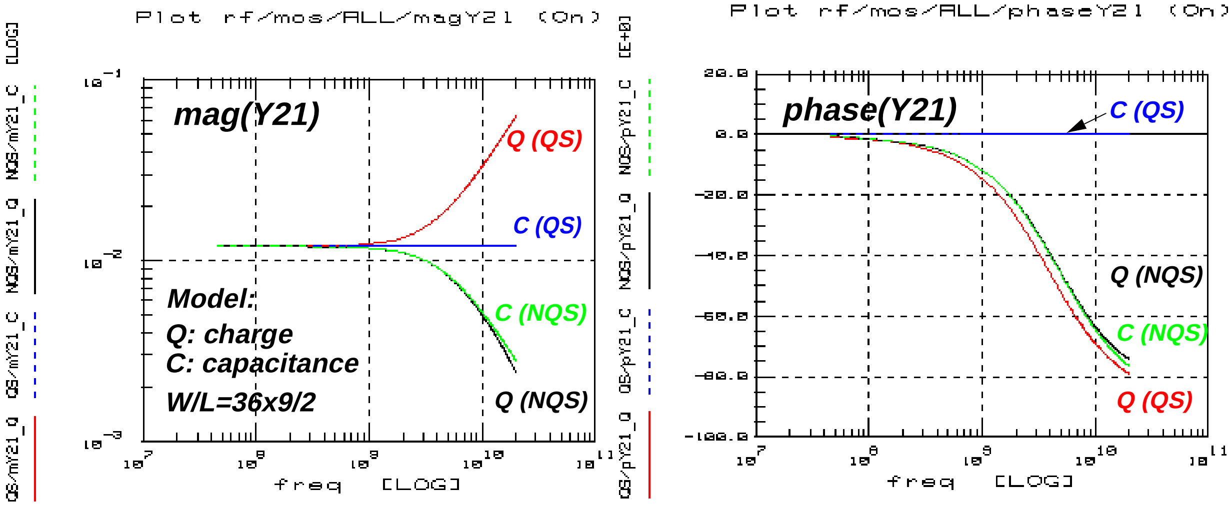
Distributed time constant accounting for “transmission line effect”

✔*First-order model for the transadmittances using bias-dependent time constant* τ*:*

$$Y_{m(g,d,s)} \equiv \frac{\partial i_d}{\partial v_{(g,d,s)}} = \frac{g_{m(g,d,s)}}{1+s\cdot\tau} \qquad with \quad \tau = \tau_0 \cdot f(i_f, i_r) \tag{9}$$

$$\tau_0 = \frac{L^2}{2\cdot\mu\cdot U_T} \tag{10}$$

Non-Quasistatic Model

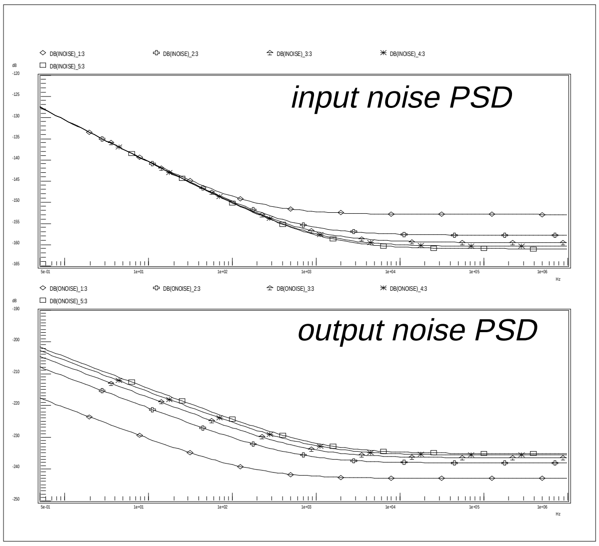


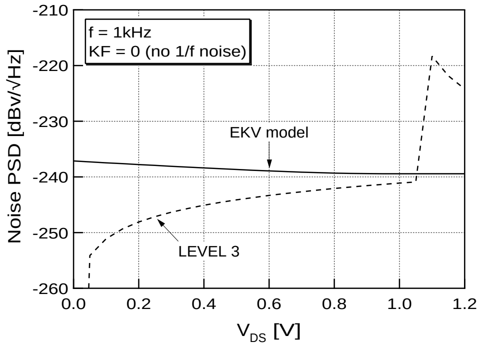
☞ Intrinsic MOST: effect of QS/NQS models on charges-trans-capacitances- and capacitances-only models.

✔*Y21 Phase prediction is similar for all models except C-only QS model.*

✔*Y21 Magnitude prediction is incorrect for Q (QS) and C (QS) models.*

Noise Model



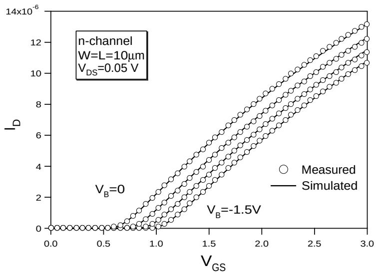


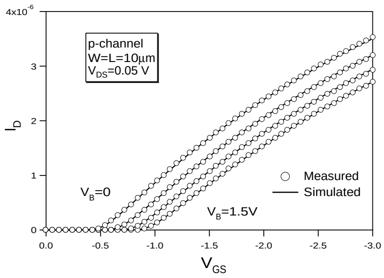
- Thermal noise is proportional to total inversion charge Q_I.

  ✔*Valid for all inversion levels, and from linear to saturation.*

- 1/f noise modelling included.

Mobility Model





EKV v2.6 for 0.5um CMOS (NMOS, PMOS)

- Field- and position-dependent mobility:

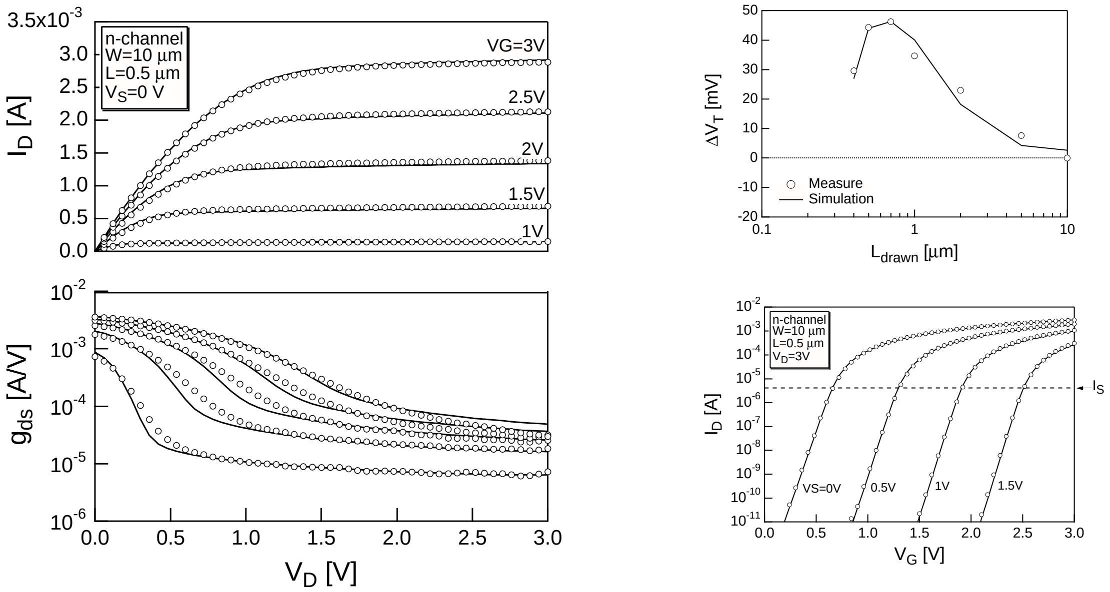
$$\mu(x) = \frac{\mu_0'}{1 + \dfrac{E_{eff}(x)}{\mathtt{E0}}} \qquad \text{where:} \qquad E_{eff}(x) = \frac{Q'_B(x) + \eta \cdot Q'_{inv}(x)}{\varepsilon_0 \varepsilon_{si}} \tag{11}$$

- One parameter: `E0` vertical critical field in the oxide

  ✔$\eta = 1/2$ *for n-channel,* $\eta = 1/3$ *for p-channel)*

  ✔*No back-bias dependence needed due to inclusion of bulk charge.*

Short-channel Effects



- Includes short-channel effects (here: 0.5um CMOS)
  - ✔*Velocity saturation, Channel length modulation (CLM), 2D-charge sharing, RSCE*

Summary

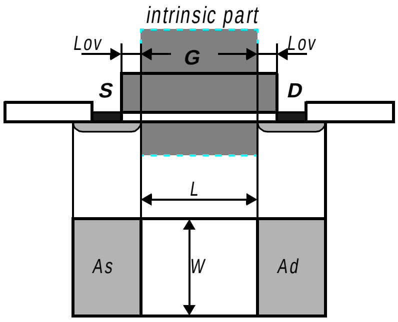
- EKV v2.6 MOST model is a charge-based compact model
  - ✔*Continuous, physics-based and valid for all bias conditions.*
  - ✔*Includes charge-based static and dynamic models, and noise.*
  - ✔*Non-quasistatic (NQS) model for small-signal.*
- Availability early ‘99:
  - ✔*Eldo, SmartSpice, Saber, Spectre, HSpice, PSpice, Aplac, Smash (check model versions).*
- EKV v2.6 on the web: *<http://legwww.epfl.ch/ekv/>*

PART II: RF Application of the EKV v2.6 MOST Model

- ☞ **Intrinsic MOST and Extrinsic Parasitic Elements**
- ☞ **RF Test Structure**
- ☞ **Simulation and Measurement Environment**
- ☞ **DC Measurements and Simulations**
- ☞ **RF Measurements and Simulations**

Intrinsic MOST and Extrinsic Parasitic Elements

Structure of the MOST



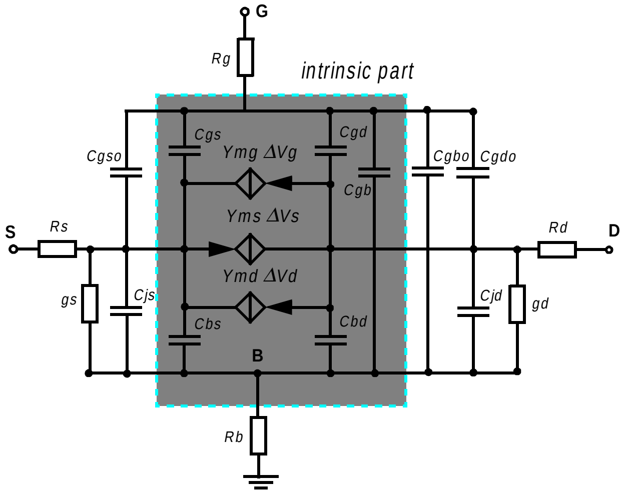
$C_{js(d)} = A_{s(d)} * C_j + P_{s(d)} * C_{jsw}$

$C_{ov} = W * L_{ov} * C_{ox}$

P_s, P_d - perimeter

A_s, A_d - area

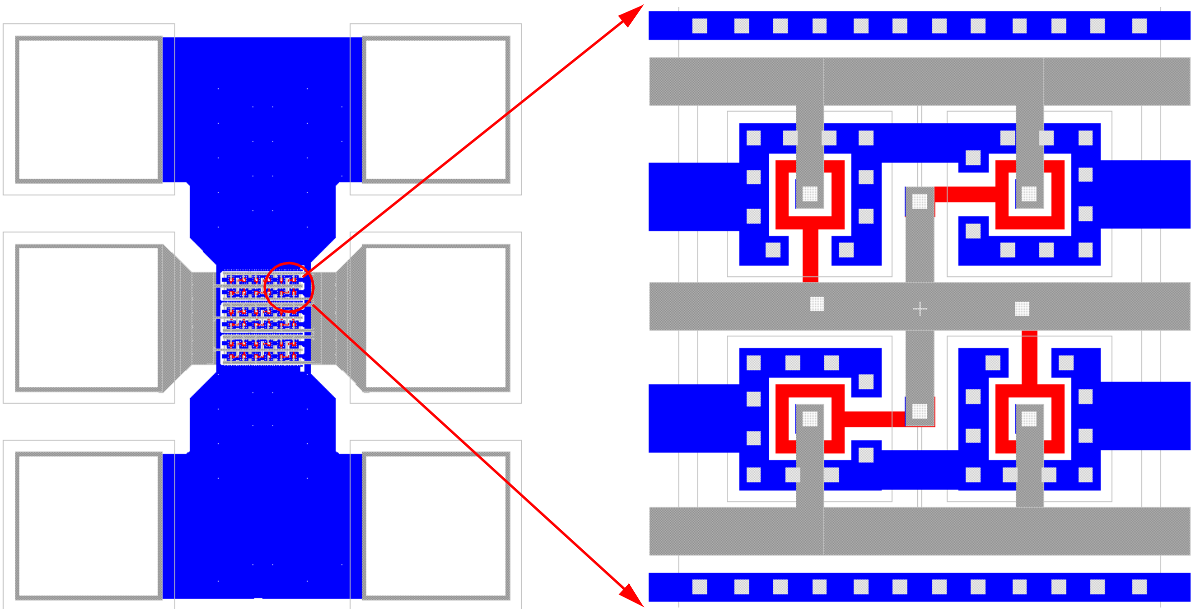
Corresponding small-signal EKV model



Simulation and Measurement Environment

- Measurements:
  - ✔*HP8510 and HP 8719 Network Analyzers*
  - ✔*HP4145 and HP4156 DC Parameter Analyzers*
  - ✔*Cascade HF Probe Station*
  - ✔*Ground-Signal-Ground (GSG) probes*
- Test Devices:
  - ✔*RF MOS transistor matrix with 36 parallel devices in GSG pad frame*
  - ✔*Geometry of single circular MOST: L = 0.5 um, W = 9.2um*
  - ✔*OPEN pad frame for de-embedding thru Y parameters*
- Parameter Extraction and Simulation:
  - ✔*IC-CAP 5*
  - ✔*ELDO v4.6 with EKV v2.6 (*LEVEL=44*)*

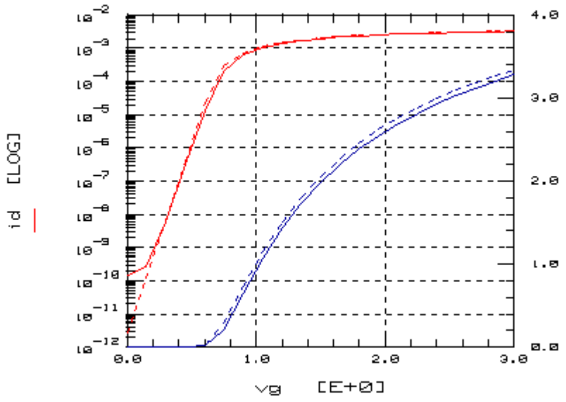
RF Test Structure



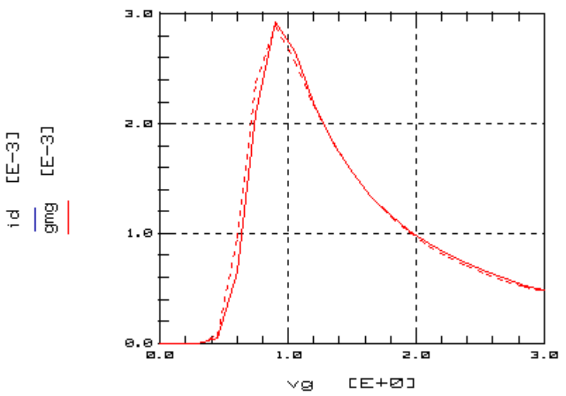
courtesy A.-S. Porret

- The GSG pad frame and matrix of the RF MOSTs
  - ✔*Minimized extrinsic drain capacitance using circular layout*

DC Measurements and Simulations



I_D vs. V_G

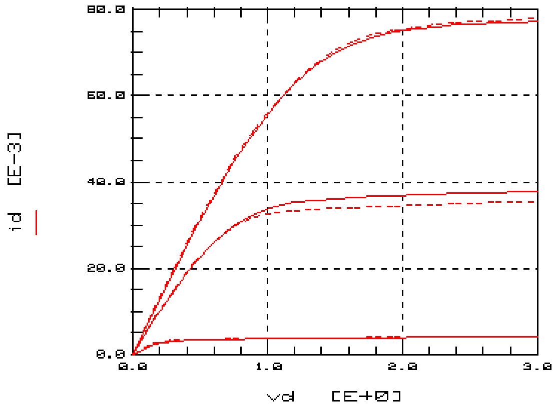


g_m vs. V_G

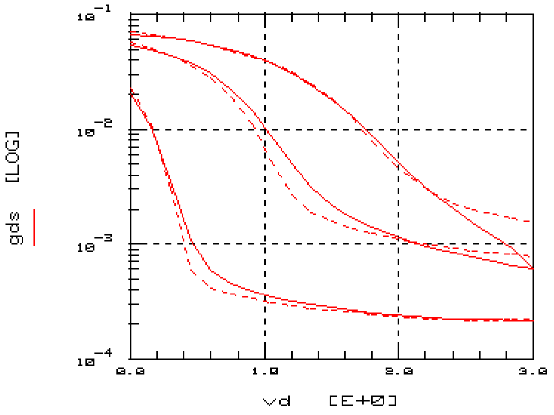
☞ Transfer current and conductance characteristics

✔ *VD = 50mV*

DC Measurements and Simulations



I_D vs. V_D

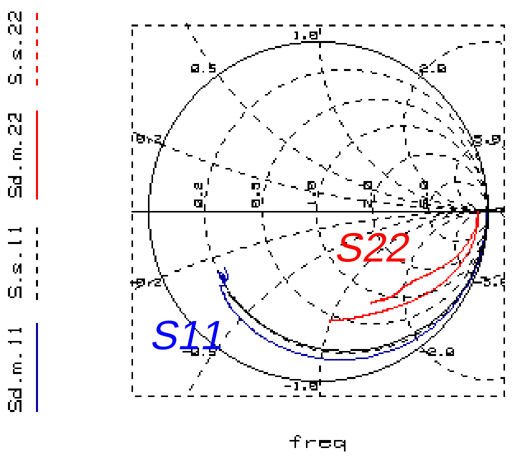


g_{ds} vs. V_D

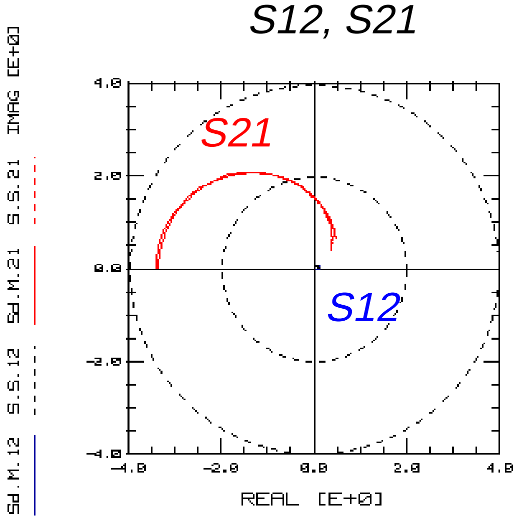
☞ Output current and conductance characteristics

RF Measurements and Simulations

S11, S22



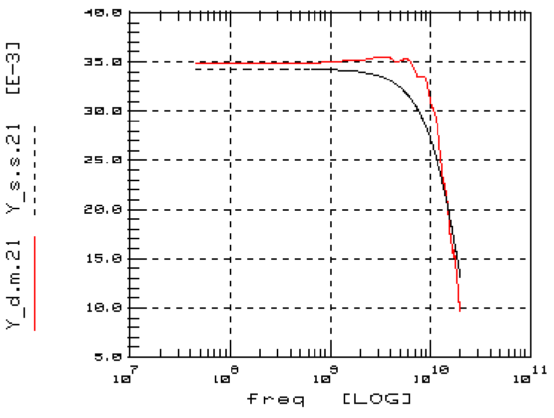
S12, S21



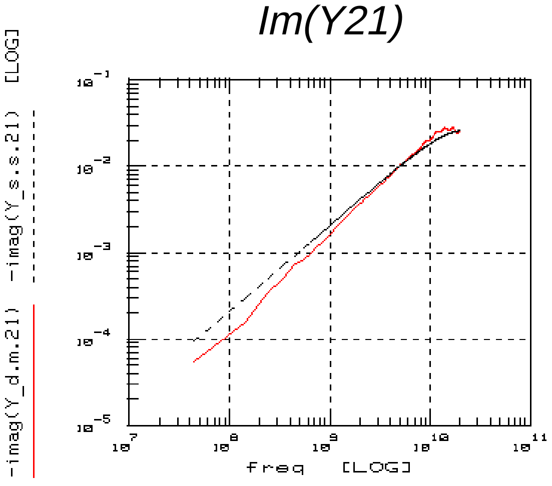
- Measured de-embedded and simulated S-parameters
  - ✔*Frequency sweep 45MHz - 20 GHz*
  - ✔*DC bias ID=18mA @ VG = 1.5 V VD = 3.0V*

RF Measurements and Simulations

Re(Y21)

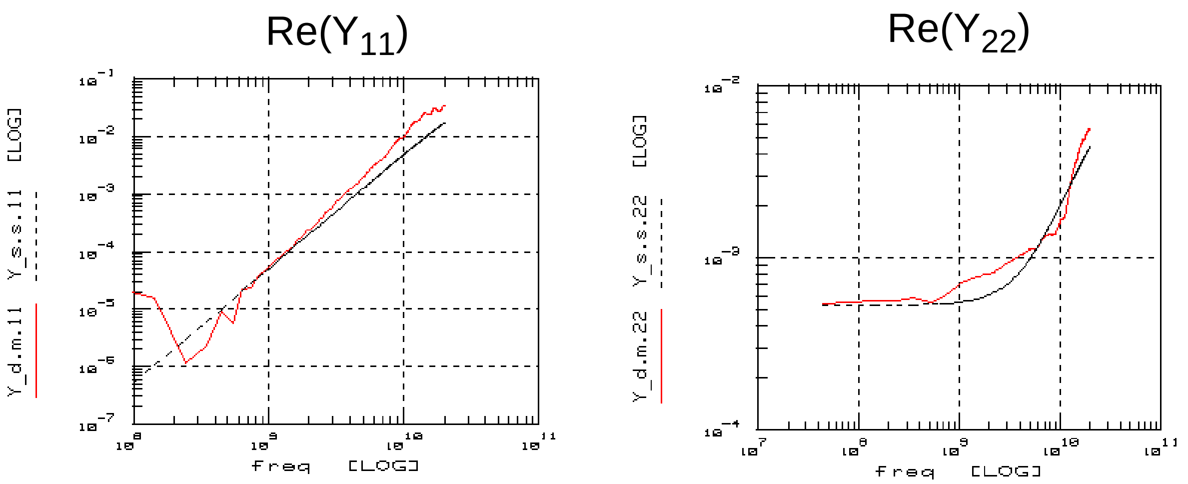


Im(Y21)



- Real and Imaginary parts of the forward admittance Y_{21}

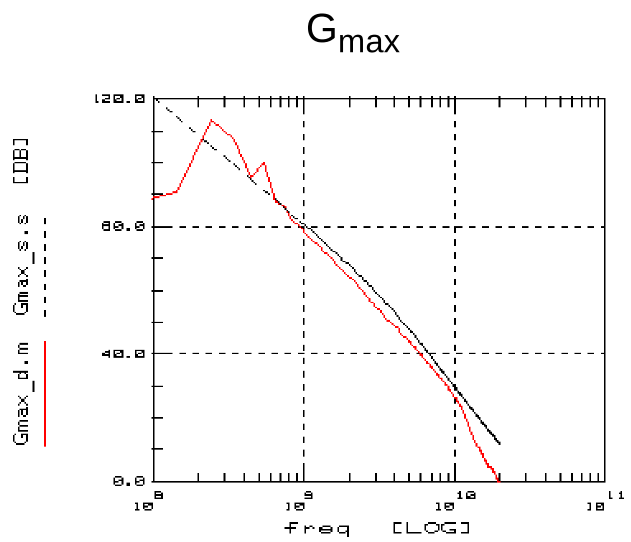
RF Measurements and Simulations


Re(Y_{11})

Re(Y_{22})

☞ Real parts of the input and output admittances Y_{11} , Y_{22}

RF Measurements and Simulations


G_{max}

☞ Maximum power gain G_{max}

Summary

☞ Application of the physics-based EKV v2.6 MOST model for RF simulation has been presented

- ✔ *DC parameter set was verified on the RF MOST test structure measurements*
- ✔ *The small-signal characteristics were corrected for interconnections and bond pads parasitics*
- ✔ *Effective gate and bulk (substrate) resistances were introduced to allow proper small signal simulation*
- ✔ *Simulated small-signal S- and Y- parameters match on-the-wafers measurements over wide range of frequencies (45MHz - 20GHz)*