ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

The EKV Model Parameter Extraction Based on its IC-CAP USERC Implementation

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- The EKV v2.6 Model
- Userc Implementation in IC-CAP
- Parameter Extraction Methodology
  - ✔ *DC sequence*
  - ✔ *CV modeling example*
- Summary

EKV v2.6 MOSFET Model

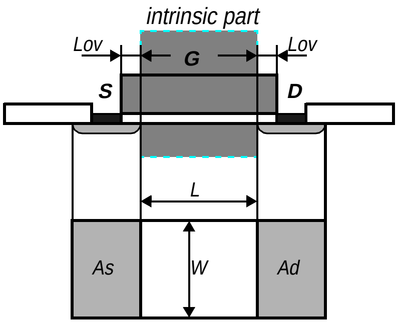
- EKV v2.6 in summary:
  - ✔ *a **physics based** MOST model in the **public domain.***
  - ✔ *dedicated to **analog circuit simulation** for submicron CMOS.*
  - ✔ *has < 20 intrinsic model parameters.*
  - ✔ *used in industrial and academic design groups.*
- EKV v2.6 available in major commercial circuit simulators:
  - ✔ *Antrim-AMS, Aplac, Eldo-Accusim, PSpice, Saber, SmartSpice, Smash, Spectre, Star-HSpice*
  - ✔ *on-going implementations:*

    ADS (at LEG-EPFL), MacSpice, Spice3, T-Spice

    MINIMOS (TU Vienna), TRANZ-TRAN (TU Budapest)
- New: EKV model web site: <http://legwww.epfl.ch/ekv>

Intrinsic MOST and Extrinsic Parasitic Elements

Structure of the MOST



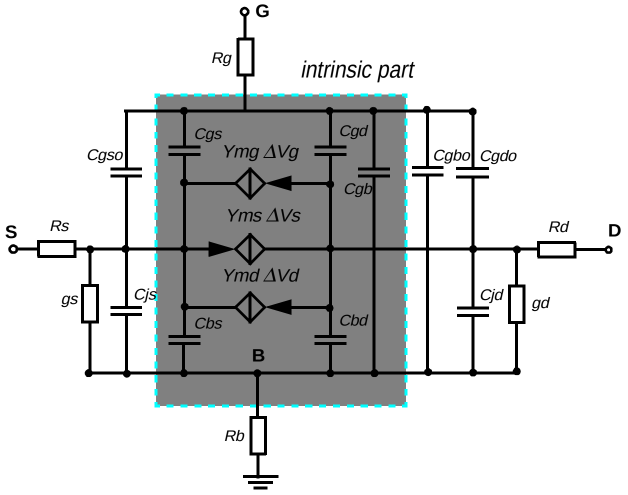
$C_{js(d)} = A_{s(d)} * C_j + P_{s(d)} * C_{jsw}$

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

P_s, P_d - perimeter

A_s, A_d - area

Corresponding small-signal EKV model



EKV v2.6 Modeled Effects

- ❒ Physics-based modeling of weak, moderate and strong inversion.
- ❒ Effects of substrate doping level, substrate effect.
- ❒ Vertical field dependent mobility.
- ❒ Common short-channel effects:
  - ✔*velocity saturation*
  - ✔*channel length modulation (CLM)*
  - ✔*two-dimensional bulk charge-sharing for short-and narrow-channel effects*
  - ✔*reverse short-channel effect (RSCE)*
  - ✔*substrate current effects on drain conductance*
- ❒ Short-distance matching for statistical circuit simulation.

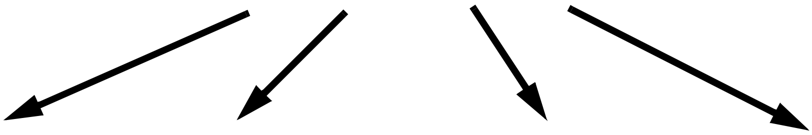
EKV v2.6 Model Structure

❒ Coherent model for static, dynamic and noise aspects.

✔ *physical model basis leads to accurate description of transconductance-to-current ratio at all current levels*

✔ *allows to derive all other model quantities in a coherent way*

Transconductance to current ratio $\frac{g_{ms} \cdot U_t}{I_D}$ $\quad g_{ms} \equiv -\frac{\partial I_D}{\partial V_S}$



Static Model	**Dynamic Model**	**Mobility Model**	**Noise Model**
$i_f\,(V),\ i_r\,(V)$	$Q_{I,G,D,S,B}\,(i_f,\ i_r)$	$\mu_S\,(Q_B, Q_I(i_f,\ i_r))$	$S_{Nth}\,(Q_I(i_f,\ i_r))$

✔ *common variable to the entire model:*
normalized currents i_f and i_r (forward and reverse)

EKV v2.6 Parameter Set

❒ *18 Intrinsic Model Parameters*

Purpose	NAME	DESCRIPTION	UNITS	EXAMPLE
Process parameters	COX	gate oxide capacitance per unit area	F/m^2	3.45E-3
	XJ	junction depth	m	0.15E-6
	DW	channel width correction	m	-0.05E-6
	DL	channel length correction	m	-0.1E-6
Doping & Mobility related parameters	VTO	long-channel threshold voltage	V	0.55
	GAMMA	body effect parameter	$\sqrt{V}$	0.7
	PHI	bulk Fermi potential (*2)	V	0.8
	KP	transconductance parameter	A/V^2	160E-6
	E0	vertical characteristic field for mobility reduction	V/m	80E6
	UCRIT	longitudinal critical field	V/m	4.0E6
Short- & narrow-channel effect parameters	LAMBDA	depletion length coefficient (channel length modulation)	-	0.3
	WETA	narrow-channel effect coefficient	-	0.1
	LETA	short-channel effect coefficient	-	0.3
	Q0	reverse short-channel effect peak charge density	$A \cdot s/m^2$	500E-6
	LK	reverse short-channel effect characteristic length	m	0.34E-6
Substrate current related parameters	IBA	first impact ionization coefficient	$1/m$	260E6
	IBB	second impact ionization coefficient	V/m	350E6
	IBN	saturation voltage factor for impact ionization	-	1.0

EKV v2.6 Parameter Set (cont.)

- Completed with 3 matching parameters

NAME	DESCRIPTION	UNITS	Example
AVTO	area related threshold voltage mismatch parameter	*Vm*	*- DEV=15E-9*
AKP	area related gain mismatch parameter	*m*	*- DEV=25E-9*
AGAMMA	area related body effect mismatch parameter	$\sqrt{Vm}$	*- DEV=10E-9*

- 4 temperature parameters

NAME	DESCRIPTION	UNITS	Example
TCV	threshold voltage temperature coefficient	*V/K*	*1.0E-3*
BEX	mobility temperature exponent	-	*-1.5*
UCEX	longitudinal critical field temperature exponent	-	*0.8*
IBBT	temperature coefficient for IBB	*1/K*	*9.0E-4*

- 2 noise parameters

NAME	DESCRIPTION	UNITS	Example
KF	flicker noise coefficient	-	*0*
AF	flicker noise exponent	-	*1*

EKV v2.6 Model and Userc Function

- Userc implementation of the EKV v2.6 model
  - ✔ *simulator independent*
  - ✔ *direct link to IC-CAP; very fast execution time*
  - ✔ *open environment for model evaluation and verification*
- EKV v2.6 userc function
  - ✔ *Inputs:*

    terminal voltages (V_d, V_s, V_b, V_g)
  - ✔ *Outputs:*

    all currents (I_d, I_s, I_b, I_g),

    conductances,

    capacitances (C_{gg}, C_{gd}, C_{gb}),

    charges.

EKV v2.6 Model and Userc Function (cont.)

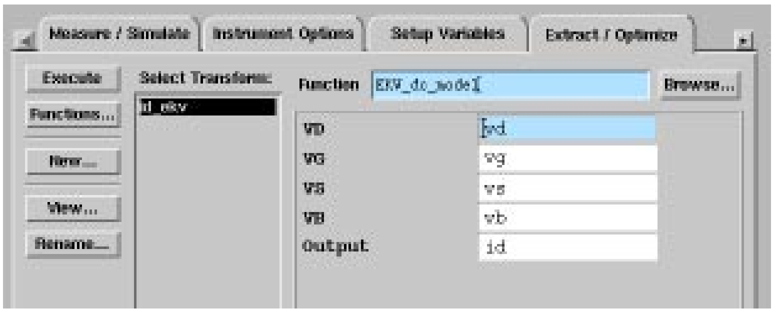
- Adding EKV v2.6 model to the function list

```
add_double_c_func2("EKV_dc_model", ekv26_dc_mod, 4, -1, 0, 1, FUNC_MAN, 0) ;
add_input_name("VD");
add_input_name("VG");
add_input_name("VS");
add_input_name("VB");
add_parameter_name("Output");
```

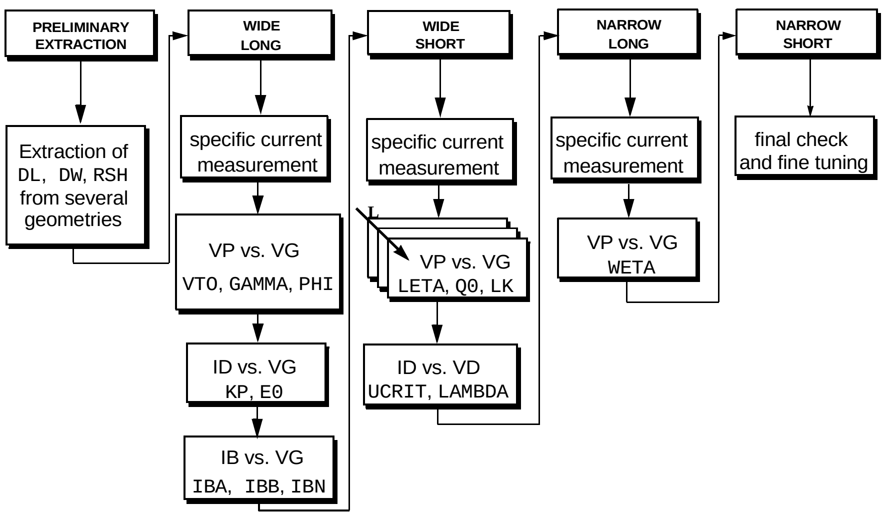
- Defining EKV v2.6 function

```
static int ekv26_dc_mod ( USERC_DECLS1 ) USERC_DECLS2
```

- IC-CAP user interface:



EKV v2.6 DC Parameter Extraction Methodology



- Sequential task: parameter extraction methodology established for EKV v2.6

  ✔ *performed from an array of transistors in the W/L plane.*

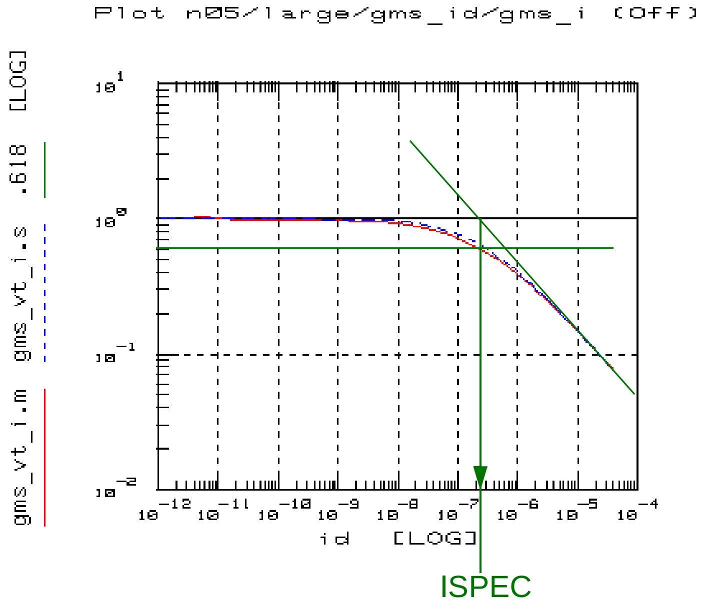
EKV v2.6 Specific Current Extraction

Transconductance-to-current ratio in saturation:

$$\frac{g_{ms} \cdot U_t}{I_D} = \frac{1}{\sqrt{\frac{1}{4} + \frac{I_D}{I_S}} + \frac{1}{2}}$$

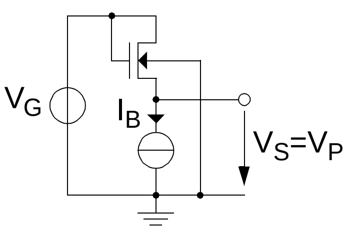
setting I_D/I_S to 1:

$$\frac{1}{\sqrt{\frac{1}{4} + 1} + \frac{1}{2}} = 0.618$$

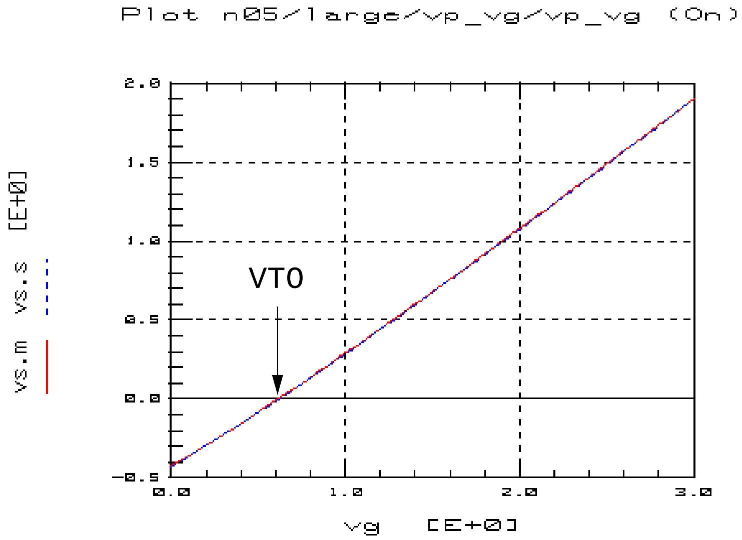


✔*Specific current I_S corresponds to intersection of strong & weak inversion asymptotes [5];*
not affected by: CLM, high field mobility reduction, S/D extrinsic resistances

Pinch-off Voltage Characteristic



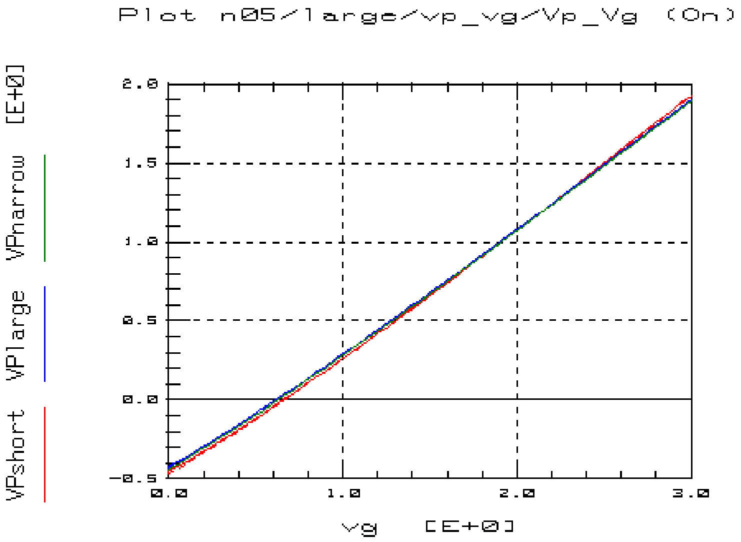
$$I_B \cong \frac{I_S}{2} = n \cdot \beta \cdot U_T^2$$



❒ Pinch-off voltage measurement at constant current ($I_S/2$)

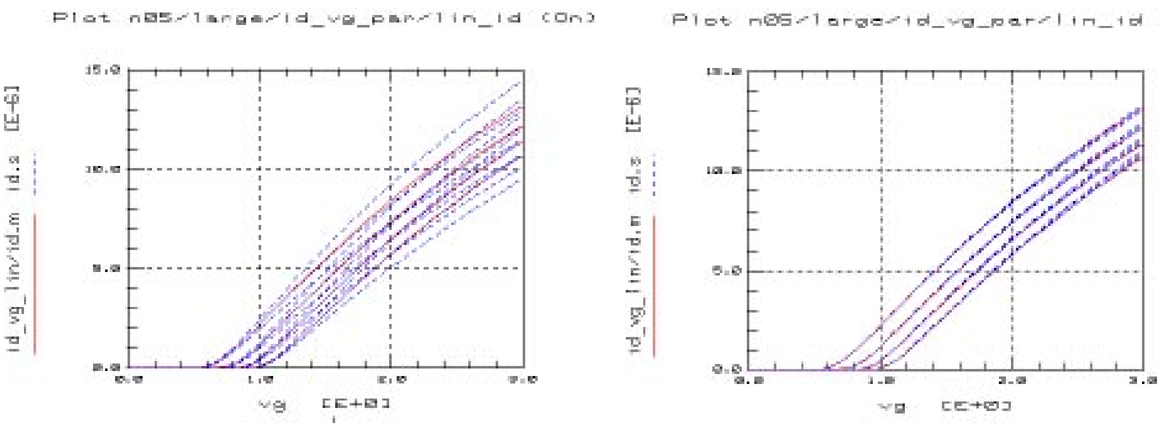
✔*Gate voltage V_G is swept and V_P=V_S is measured at the source for a transistor biased in moderate inversion and saturation [1,7]*

Short- and Narrow-Channel Effects on Vp-Vg



- ❐ Effects of short- and narrow-channels are analysed using the charge-sharing approach.
- ❐ Corresponding parameters: `LETA` and `WETA`.

Mobility Model

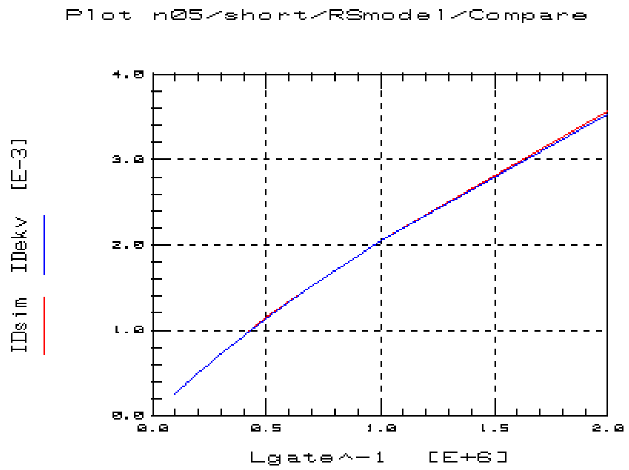


Influence of `KP` and `E0` on the transfer characteristics, respectively

- ❐ Good behaviour for mobility reduction for both channel types.
- ❐ Substrate effect is correctly accounted for.
- ❐ No back-bias dependence required.

Source/Drain Resistances

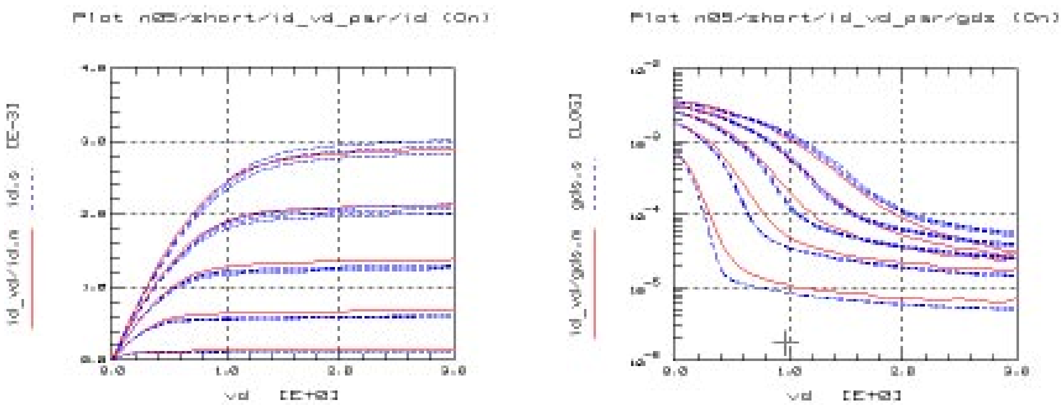
$$\frac{I_D}{I_{D0}} = \frac{g_m}{g_{m0}} = \frac{g_{ms}}{g_{ms0}} = \frac{g_d}{g_{d0}} \cong \frac{1}{1 + g_{ms0}R_S + g_{d0}R_D}$$



Drain current vs. gate length

- Series resistance accounted explicitly in drain current
  - ✔ *No extra nodes needed*
  - ✔ *Increased computation efficiency*
  - ✔ *S. Cserveny, IEEE Trans. Electron Devices, ED-37, no.11, 1990, pp.2413-2414.*

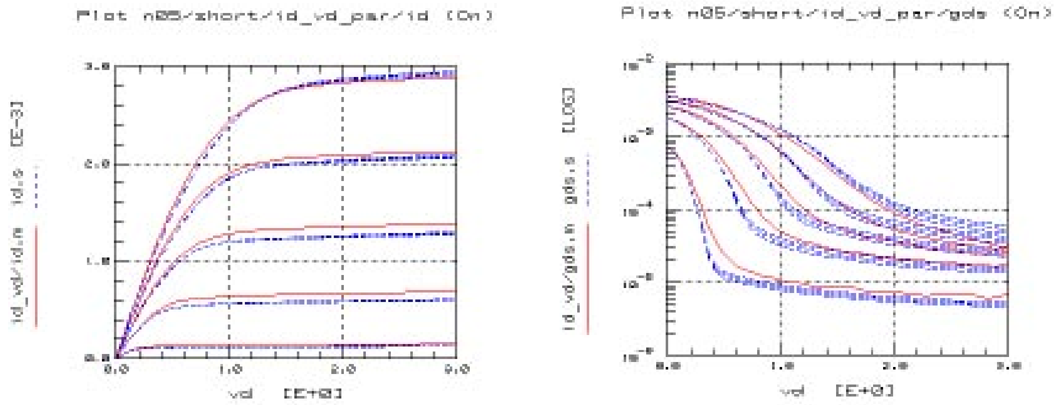
Velocity Saturation



Influence of `UCRIT` on the output characteristics

- A high lateral electric field in the channel causes the carrier velocity to saturate and limits the drain current.
- Parameter `UCRIT` accounts for this effect.

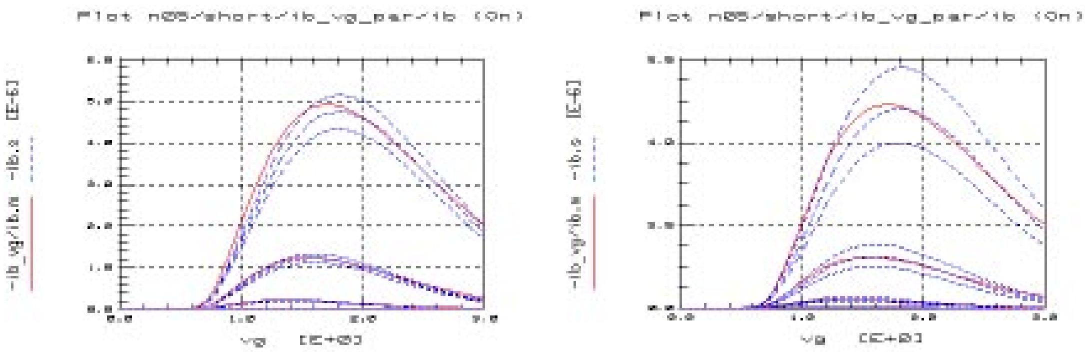
Channel-Length Modulation (CLM)



Influence of `LAMBDA` on the output characteristics

- The relative channel length reduction depends on the pinch-off point in the MOSFET channel near drain end.
- Depletion length coefficient (`LAMBDA`) models CLM effect.

Impact Ionization Current



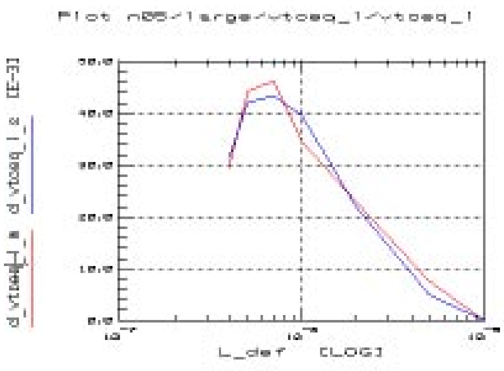
Influence of `IBA` and `IBB` on the substrate current, respectively

- The substrate current is treated as a component of the total extrinsic current:

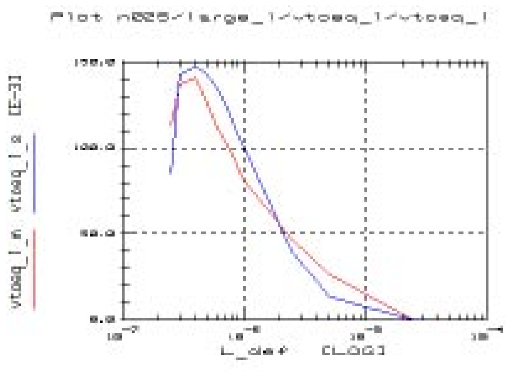
  ✔ $I_D = I_{DS} + I_{DB}$

- Substrate current affects the total extrinsic conductances, in particular drain conductance (g_{DS}).

Reverse Short Channel Effect (RSCE)



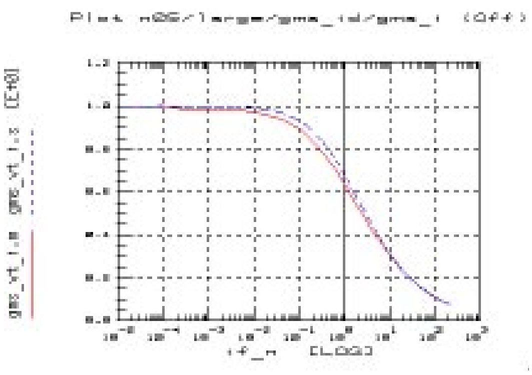
0.5um CMOS example



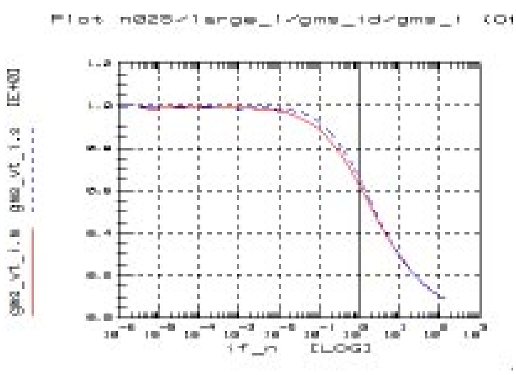
0.25um CMOS example

- Defect enhanced diffusion during fabrication leads to RSCE.
- RSCE is modeled as a change in the threshold voltage depending on L_{eff}
- Two model parameters `Q0` and `LK`.

Transconductance to Current Ratio



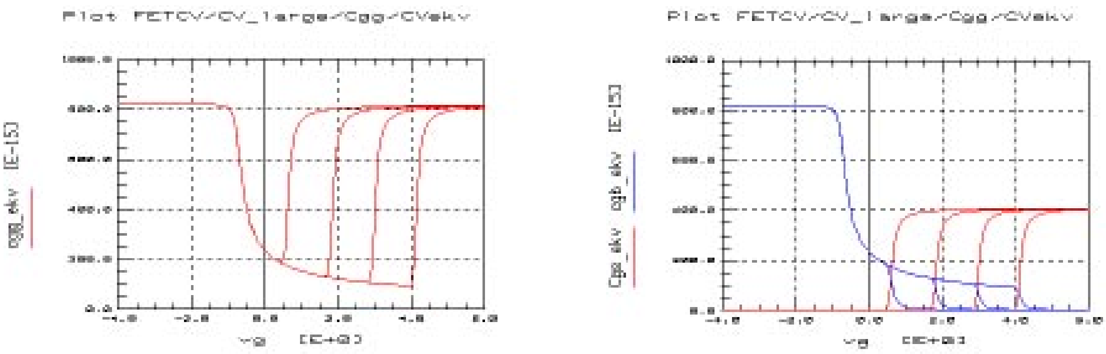
0.5um CMOS example



0.25um CMOS example

- Excellent match from weak through moderate to strong inversion regions.
- Measurement and simulation comparisons show that g_{ms}/i_D ratio is technology independent.

CV Modeling Example



CV characteristics (C_{gg}, C_{gs}, C_{gb}) of large MOSFET
as function of channel to bulk bias ($V_S = V_D$)

- ❒ Consistent model for all charges and capacitances (G,D,S,B).
- ❒ Capacitances are valid in all operating regions, continuous, and symmetrical at V_{DS}=0

Summary

- ❒ The EKV v2.6 model and related parameter extraction methodology have been developed at Electronics Lab of EPFL.
- ❒ Complete DC and CV EKV v2.6 model has been implemented as the IC-CAP userc function and offers:
  - ✔ *very fast execution time*
  - ✔ *perfect model development/verification environment*
  - ✔ *well suited for mixed mode (direct and optimization based) extraction as well as for statistical modeling tasks*
- ❒ Presented examples showed the EKV v2.6 model applications down to deep submicron technologies.

Parameter Extraction Service

- ❐ Parameter extraction service and design support are available through Smart Silicon Systems, Lausanne
- ❐ The EKV v2.6 parameter extraction kit for IC-CAP is under development
  - ✔ *modular structure:*
    - ✡ *measurement unit with mdm data base generator*
    - ✡ *general EKV v2.6 model extractor*
- ❐ Additional activities:
  - ✔ *RF modeling including S-parameter characterization*
  - ✔ *1/f noise characterization*
- ❐ Contact: modeling@smartsilicon.ch

References

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