

MOSFET SIMULATION USING MATLAB IMPLEMENTATION OF THE EKV MODEL

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The paper presents an implementation of EKV MOST model in Matlab environment. Parameter extraction and fitting procedures are briefly sketched. Open source modules for transistor characteristics and additional functions for parameter extraction and fitting are included in a Matlab toolbox. Model parameters are user defined to provide flexibility of design process. The accuracy of simulation results is ensured by using Labert's W interpolation function in the single expression for the drain current. Validation against conventional BSIM3v3 model for a 0.35 μm CMOS technology is performed.

Keywords: MOS transistor, open source model, EKV model, Matlab.

1. INTRODUCTION

Matlab [1] is a general-purpose mathematical computation package widely used in engineering, science and mathematics. It is quite useful for extraction and optimization of model parameters for device and circuit characterization and simulation. Accurate device modeling is at the core of correct design and analysis of electronic circuits especially analog ones.

The high speed of simulation within Matlab is essential to the optimization process. It is clear that the combined circuit and device optimization is capable of leading to real benefits in both device design and circuit use. Furthermore, the model codes are open source, providing direct access to model equations and parameters. Thus, parameters can be easily extracted and characteristics optimized for circuit design purposes.

In this context EKV MOST model is particularly suitable for implementation in Matlab as it provides accurate modeling with a small set of parameters. Some of these device parameters are also very useful in circuit calculations [2].

Although the majority of EKV parameters carry similar meanings to widely used SPICE ones and therefore could, as a first approximation, be used for design and simulation, better fit to experimental data can be obtained with parameters extracted for the model.

2. EKV MODEL FORMULATION

EKV model is described in detail in [4] and concise set of equations and parameters for extraction purposes are given in [5]-[7].

2.1. Static Model

In the EKV model the gate, source and drain voltages, V_G , V_S and V_D , are referred to the substrate in order to preserve the intrinsic symmetry of the device. Besides EKV proceeds from the pinch-off voltage V_P (rather than the threshold voltage V_{Th}). A constant current bias is used to measure the pinch-off voltage versus gate voltage characteristic in moderate inversion. This measure allows for an efficient and simple characterization method to be formulated for the most important model parameters as the threshold voltage, parameters accounting for mobility effects, short-channel effects, etc. The same principle applied for various geometries, including short- and narrow-channel devices, and forms the major part of the complete characterization methodology.

The EKV MOST model is hierarchically structured allowing both hand calculations and computer simulations including second order effects. The designer handles a concise parameter set (13 intrinsic parameters) to account for first and second order effects (see Tab.1): 10 physical parameters (COX, VTO, GAMMA, PHI, KP, THETA, UCRIT, XJ, DW, DL) and 3 second-order fitting coefficients (LAMBDA, WETA, LETA). equations of interest are presented below [8].

Table 1. Selected EKV parameters accounting for first and second order effects and their default values.

| Designation | Description |
|-----------------------------|-----------------------------------|
| COX 7E-4.[F/m] | Gate oxide capacitance |
| VTO 0.5 [V] | Nominal threshold voltage |
| GAMMA 1 [V ^{1/2}] | Body effect factor |
| PHI 0.7 [V] | Bulk Fermi potential (2x) |
| KP 5E-5 [A/V ²] | Transconductance parameter |
| THETA 0 [1/V] | Mobility reduction coefficient |
| UCRIT 2E6 [V/m] | Longitudinal critical field |
| XJ 1E-7 [m] | Junction depth |
| DL 0 [m] | Channel length correction |
| DW 0 [m] | Channel width correction |
| LAMBDA 0.5 [-] | Depletion length coefficient |
| LETA 0.1 [-] | Short channel effect coefficient |
| WETA 0.25 [-] | Narrow channel effect coefficient |

2.2. Pinch-off voltage

The pinch-off voltage V_P corresponds to the value of the channel potential for which the inversion charge becomes zero in a non-equilibrium situation. V_P depends only on the gate voltage and represents the voltage that should be applied to the channel (source and drain) to balance the effect of V_G . Hence, V_P can be directly related to V_G :

$$V_P = V_G' - \text{PHI} - \gamma' \left[\sqrt{V_G' + \left(\frac{\gamma'}{2}\right)^2} - \frac{\gamma'}{2} \right] \quad (1)$$

$$\text{where } V_G' = V_G - \text{VTO} - \text{PHI} + \text{GAMMA} \cdot \sqrt{\text{PHI}} \quad (2)$$

$$\gamma' = \text{GAMMA} - \frac{\varepsilon_0 \varepsilon_{Si}}{\text{COX}} \left[\frac{\text{LETA}}{L + \text{DL}} \sqrt{\text{PHI} + V_D} + \left(\frac{\text{LETA}}{L + \text{DL}} - 3 \frac{\text{WETA}}{W + \text{DW}} \right) \sqrt{\text{PHI} + V_S} \right] \quad (3)$$

The modified body effect factor γ' (3) accounts for short- and narrow-channel effects. For large device geometries $\gamma' = \text{GAMMA}$ (note that GAMMA is the body effect factor, i.e. $\text{GAMMA} \equiv \gamma = \sqrt{2q\varepsilon_{Si}N_{SUB}/C_{ox}}$) and if uniform doping in the channel is assumed then V_P is a function only of the gate voltage and the three parameters VTO , GAMMA and PHI .

2.3. Drain current

The drain current I_D , is expressed as

$$I_D = I_F - I_R \quad (4)$$

where I_F is the forward component of the current (independent of V_D) and I_R is the reverse component of the current (independent of V_S). The currents are obtained by integrating the inversion charge along the channel. In weak inversion (WI) and in strong inversion (SI)

$$I_{F(R)} = \exp\left(\frac{V_G - \text{VTO} - nV_{S(D)}}{nU_T}\right) \quad (\text{WI}) \quad (5)$$

$$I_{F(R)} = \left(\frac{V_G - \text{VTO} - nV_{S(D)}}{2nU_T}\right)^2 \quad (\text{SI}) \quad (6)$$

with the thermodynamic voltage $U_T = kT/q$ (0.026 V at 300° K).

The EKV model is based on inversion charge linearization, which is given by the following interpolation function [4]:

$$q_{IF(R)} = \sqrt{\frac{1}{4} + I_{F(R)}} - \frac{1}{2} \quad (7)$$

For computational purposes equations (5) and (6) are combined with mathematical transformations into a single expression $I_{F(R)} = I_S (q_{IF(R)}^2 + q_{IF(R)})$

$$I_{F(R)} = I_S \cdot \left\{ \ln \left[1 + \exp\left(\frac{V_G - \text{VTO} - nV_{S(D)}}{2nU_T}\right) \right] \right\}^2 \quad (8)$$

$$\text{where the specific current being } I_S \equiv 2n\beta U_T^2 \quad (9)$$

In (9) $\beta = \mu C'_{ox} (W_{eff}/L_{eff})$ is the transfer parameter.

The simple mobility reduction (transconductance) model uses parameter THETA :

$$\beta = \text{KP} \frac{W_{eff}}{L_{eff}} \frac{1}{1 + \text{THETA} \cdot V_P} \quad (10)$$

where $KP = \mu C'_{ox}$. (Note that default value for THETA is 0, Tab.1.)

Other parameter of interest is the slope factor n of the V_G vs. V_P characteristic with V_P , defined as the value of the channel potential for which the inversion charge becomes zero at a given V_G (non-equilibrium case) [5]. The slope factor n is defined as $n \equiv \{dV_P/dV_G\}^{-1}$ and is linked to the weak inversion slope [6]:

$$n = 1 + \frac{\text{GAMMA}}{2\sqrt{V_P + \text{PHI} + 4U_T}} \quad (11)$$

2.4. Effective channel lengths

The MOSFET effective channel length L_{eff} is a very useful parameter for circuit design and simulation as well as for technology characterization. Although related to the metallurgical length, shorter than the mask length owing to lateral diffusion, the effective channel length is rather an electrical parameter to which drain current is inversely proportional [2]. Its determination is strongly correlated with the measurement and modeling of the I - V characteristics. In EKV, the following equations are used to calculate the effective length and width:

$$L_{eff} = L + DL \quad , \quad W_{eff} = W + DW \quad (12)$$

3. PARAMETER EXTRACTION

Table 2. Extraction sequence specifying device sizes, measured characteristics, modes (SI–strong, MI–moderate, WI–weak inversion, co.–conduction, sat.–saturation).

| Size | Characteristic | Mode | Parameter |
|-----------------|---|------------------------------------|------------------------------------|
| matrix W/L | ID vs. VG gmg vs. VG | WI | DL, DW |
| wide/long | ID vs. VS VP vs. VG ID vs. VG | SI sat MI sat SI sat.@VS | IS VTO, GAMMA, PHI KP, THETA |
| wide/short | ID vs. VS VP vs. VG ID vs. VD | SI sat MI sat SI co.-sat. | IS LETA LABMDA |
| narrow/ long | ID vs. VS VP vs. VG | SI sat MI sat | IS WETA |

Model parameters such as gate capacitance COX, the junction depth XJ, and longitudinal critical field UCRIT are assumed to be known from the technology datasheet. Rest of the data is taken from experiment and subsequent fitting.

Experiments might be performed either via measurements or via simulation based on already calibrated model (e.g. BSIM).

The steps to follow are: “measurement” (in our case simulation) of V_P , determination of I_S , extraction of VTO, GAMMA, PHI, KP, THETA, DL and DW.

The extraction procedure goes through the following steps listed in Tab. 2.

4. MODEL IMPLEMENTATION

Above listed equations are coded into a set of m-files to obtain the device characteristics of interest: output characteristic (I_D vs. $V_D @ V_G$), transfer characteristic ($I_D/\sqrt{I_D}$ vs. $V_G @ V_S$), transconductance (g_m vs. $V_D @ V_G$).

The proposed model implementation works with user defined parameters (Fig. 1).

The accuracy of results given by generalized equation (8) determines the overall better coincidence between the experimental and theoretical data. That is why (7) is programmed with the use of Lambert's W interpolation function

$$q_{IF(R)} = \frac{n}{2.29} \text{LambertW} \left[\exp \left(\frac{V_G - V_{TO} - nV_{S(D)}}{nU_T} \right) \right] \quad (13)$$

to embed the following code

```
Qif=(nc./2.29).*lambertw(exp((VGTO-...
nc.*VS)./nt));
Qir=(nc./2.29).*lambertw(exp((VGTO-...
nc.*VD)./nt));

IF = IS.*(Qif.^2+Qif);
IR = IS.*(Qir.^2+Qir);

ID = IF - IR;
```

5. RESULTS

We have included our m-files in a toolbox named "EKV MOST". The basic modules are EKV_out (for output characteristics), EKV_trans (for transfer characteristics), and EKV_gm (for transconductances). Our toolbox also contains additional modules for extraction and fitting EKV parameters.

On the figures below, EKV_out and EKV_trans results are shown that are validated versus BSIM3v3 PSpice model for AMS 0.35 μm CMOS technology. The plots demonstrate a very close match between simulation results of our Matlab open source EKV and the conventional BSIM3v3 Pspice models.

6. CONCLUSION

This paper describes a Matlab implementation of the EKV model. Modules for output characteristics, for transfer characteristics, and for transconductances are programmed in m-files. Very good accuracy is achieved by using LambertW function. The program code is open source giving the designer a direct access to model equations and parameters.

Figure 1. Input Parameters.

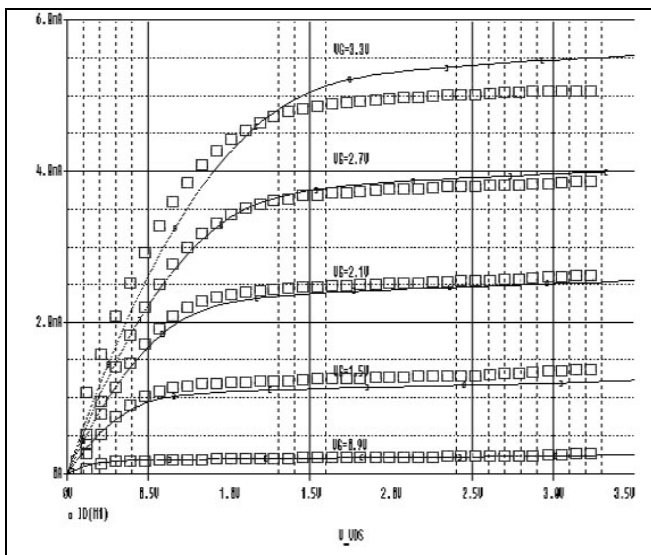


Figure 2. Output characteristics I_D vs. V_D @ $V_S = 0$ of a short channel device ($W=10\mu\text{m}$, $L=0.35\mu\text{m}$). (– - BSIM3v3 PSpice simulation; \square - Matlab EKV model).

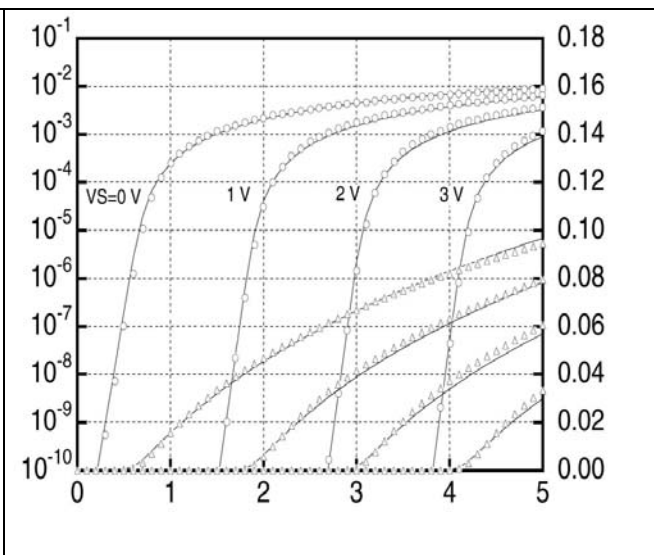


Figure 3. Transfer characteristics I_D vs. V_G @ V_S of a short channel device ($W=10\mu\text{m}$, $L=0.35\mu\text{m}$). (– - BSIM3v3 PSpice simulation; \circ - I_D vs. V_G and \triangle - $\sqrt{I_D}$ vs. V_G model).

7. REFERENCE

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