CMOS

Digital Integrated Circuits

Analysis and Design

Chapter 4

Modeling of MOS Transistors Using SPICE

Introduction

- The SPICE software that was distributed by UC Berkeley beginning in the late 1970s had three built-in MOSFET models
  - LEVEL1(MOS1) is a described y a square-law current-voltage characteristics
  - LEVEL2 (MOS2) is a detailed analytical MOSFET model
  - LEVEL 3 (MOS3) is a semi-empirical model
    - Both MOS2 and MOS3 include second-order effects
      - The short channel threshold voltage, subthreshold conduction, scattering-limited velocity saturation, and charge-controlled capacitances
  - The BSIM3 version
    - More accurate characterization sub-micron MOSFET characteristics

Basic concept

- The equivalent circuit structure of the NMOS LEVEL 1 model

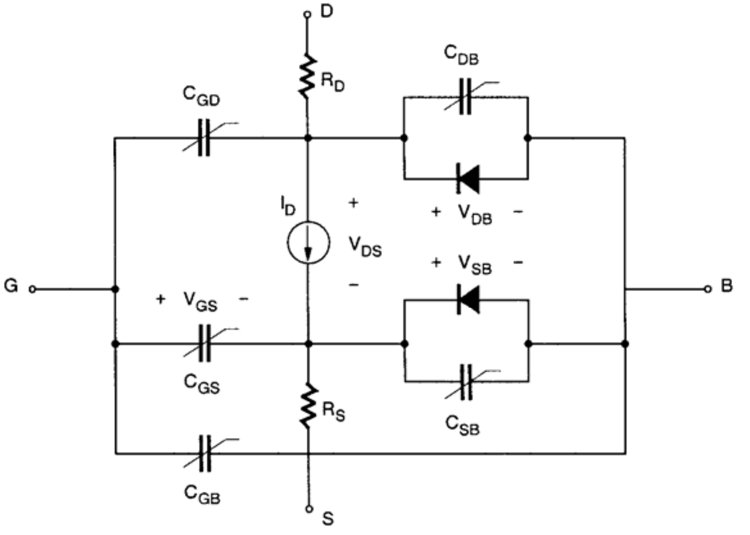

Figure 4.1 Equivalent circuit structure of the LEVEL 1 MOSFET model in SPICE.

The LEVEL 1 model equation

Linear region

$$I_D = \frac{k'}{2} \cdot \frac{W}{L_{eff}} \cdot \left[2 \cdot (V_{GS} - V_T) V_{DS} - V_{DS}^2\right] \cdot (1 + \lambda \cdot V_{DS}) \; for \;\; V_{GS} \geq V_T$$

$$and \; V_{DS} < V_{GS} - V_T$$

Saturation region

$$I_D = \frac{k'}{2} \cdot \frac{W}{L_{eff}} \cdot (V_{GS} - V_T)^2 \cdot (1 + \lambda \cdot V_{DS}) \; for \;\; V_{GS} \geq V_T$$

$$and \; V_{DS} \geq V_{GS} - V_T$$

The threshold voltage

$$V_T = V_{T0} + \gamma \cdot \left(\sqrt{|2\phi_F| + V_{SB}} - \sqrt{|2\phi_F|}\right)$$

$$L_{eff} = L - 2 \cdot L_D$$

$$k' = \mu \cdot C_{ox} \text{ where } C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$\gamma = \frac{\sqrt{2 \cdot \varepsilon_{Si} \cdot q \cdot N_A}}{C_{ox}}$$

$$2\phi_F = 2 \frac{kT}{q} \cdot \ln\left(\frac{n_i}{N_A}\right)$$

- $K' = 27.6 \mu A/V^2$ KP=27.6U
- $V_{T0} = 1.0V$ VTO=1
- $\gamma = 0.53 V^{1/2}$ GAMMA=0.53
- $2\phi F = -0.58$ PHI=0.58
- $\lambda = 0$ LAMBDA=0
- $\mu_n = 800 cm^2/Vs$ UO=800
- $t_{ox} = 100nm$ TOX=100E-9
- $N_A = 10^{15} cm^{-3}$ NSUB=1E15
- $L_D = 0.8 \mu m$ LD=0.8E-6

Variation of the drain current with model parameter

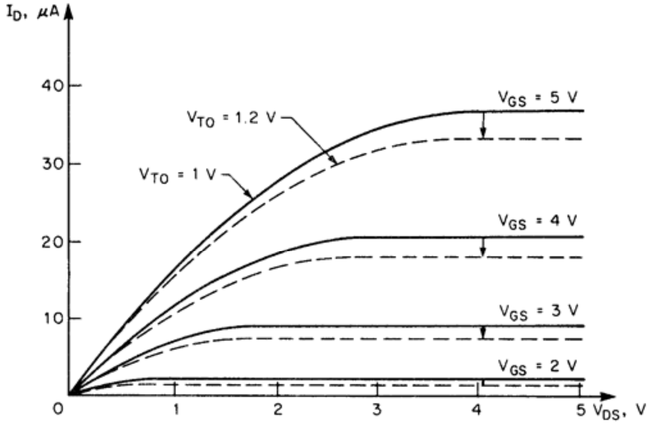

Figure 4.2 Variation of the drain current with model parameter VTO, for the LEVEL 1 model.

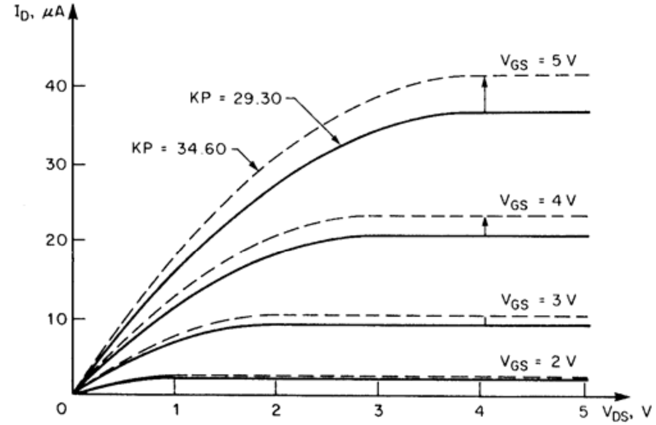

Figure 4.3 Variation of the drain current with model parameter KP, for the LEVEL 1 model.

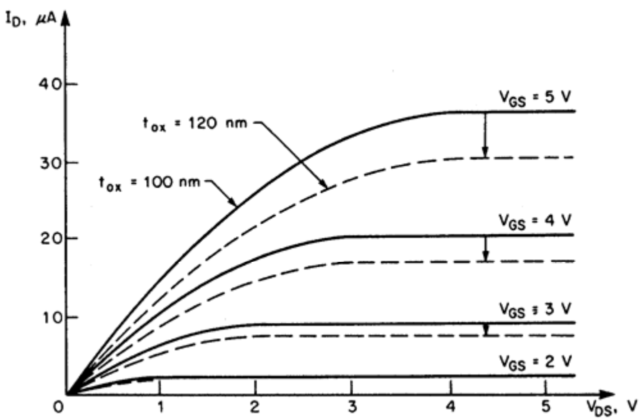

Figure 4.4 Variation of the drain current with model parameter TOX, for the LEVEL 1 model.

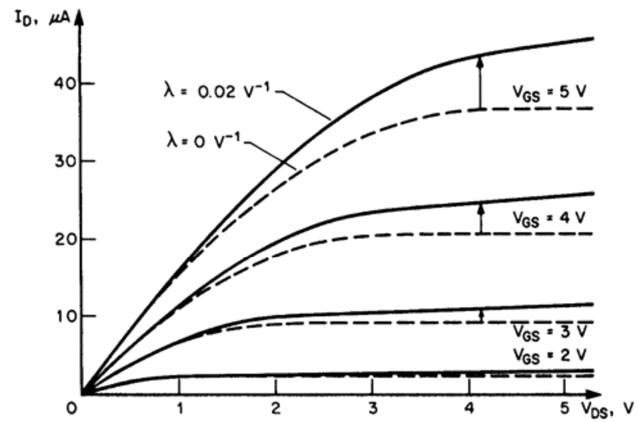

Figure 4.5 Variation of the drain current with parameter LAMBDA, for the LEVEL 1 model.

The LEVEL 2 model equation

$$I_D = \frac{k'}{(1-\lambda \cdot V_{DS})} \cdot \frac{W}{L_{eff}} \cdot \left\{ \left(V_{GS} - V_{FB} - |2\phi_F| - \frac{V_{DS}}{2} \right) \cdot V_{DS} - \frac{2}{3} \cdot \gamma \cdot \left[\left(V_{DS} - V_{BS} + |2\phi_F| \right)^{3/2} - \left(-V_{BS} + |2\phi_F| \right)^{3/2} \right] \right\}$$

The saturation voltage

$$V_{DSAT} = V_{GS} - V_{FB} - |2\phi_F| + \gamma^2 \cdot \left(1 - \sqrt{1 + \frac{2}{\gamma^2} \cdot (V_{GS} - V_{FB})} \right)$$

The saturation mode current

$$I_D = I_{Dsat} \cdot \frac{1}{(1\text{-}\lambda \cdot V_{DS})}$$

The zero bias threshold voltage

$$V_{T0} = \Phi_{GC} - \frac{q \cdot N_{ss}}{C_{ox}} + |2\phi_F| + \gamma \sqrt{|2\phi_F|}$$

- In the current equation above, the surface carrier mobility has been assumed constant, and its variation with applied terminal voltages has been neglected
- In reality, the surface mobility decreases with the increasing gate voltage
  - Due to the scattering of carriers in the channel
  - $$k'_{(new)} = k' \cdot \left(\frac{\varepsilon_{Si}}{\varepsilon_{ox}} \cdot \frac{t_{oc} \cdot U_c}{(V_{GS} - V_T - U_t \cdot V_{DS})} \right)^{Ue}$$

    U_c is the gate-to-channel critical field

    U_t is the contribution of the drain voltage to the gate-to-channel field

    U_e is the exponential fitting parameter

variation of channel length in saturation mode

$$L'_{eff} = L_{eff} - \Delta L$$

$$\Delta L = \sqrt{\frac{2 \cdot \varepsilon_{Si}}{q \cdot N_A}} \cdot \left[\frac{V_{DS} - V_{DSAT}}{4} + \sqrt{1 + \left(\frac{V_{DS} - V_{DSAT}}{4} \right)^2} \right]$$

The empirical channel length shortening coefficient

$$\lambda = \frac{\Delta L}{L_{eff} \cdot V_{DS}}$$

The slope of the I_D-V_{DS} vurve is saturation can be adjusted and fitted to experimental data by changing the substrate doping parameter N_A

In this case, however, other N_A - dependent electrical parameters such as $2\phi_F$ and γ must be specified separately in the .MODEL statement

Saturation of carrier velocity

- The calculation of the saturation voltage V_{DSAT} is based on the assumption
  - The channel charge near the drain becomes equal to zero when the device enters saturation
  - This hypothesis is actually incorrect
    - Since a minimum charge concentration greater than zero must exist in the channel, due to the carriers that sustain the saturation current
    - The minimum concentration depends on the speed of the carriers
    - The inversion layer charge at the channel-end is found as
      - $$Q_{inv} = \frac{I_{Dsat}}{W \cdot v_{\max}}$$

        $$\Delta L = X_D \cdot \sqrt{\left(\frac{X_D \cdot v_{\max}}{2 \cdot \mu}\right)^2 + V_{DS} - V_{DSAT}} - \frac{X_D^2 \cdot v_{\max}}{2 \cdot \mu}$$

        $$X_D = \sqrt{\frac{2 \cdot \varepsilon_{Si}}{q \cdot N_A \cdot N_{eff}}}$$
      - The parameter N_{eff} is used as a fitting parameter

Subthreshold conduction

- For $V_{GS}<V_T$, there is a channel current even when the surface is not in strong inversion
- This subthreshold current
  - Due mainly to diffusion between and the channel
  - Becoming an increasing concern for deep-sub-micron designs
- The model implemented in SPICE introduces an exponential, semi-empirical dependence of the drain current on V_{GS} in the *weak inversion region*
  -

$$I_D(\text{weak inversion}) = I_{on} \cdot e^{(V_{GS}-V_{on})\cdot\left(\frac{q}{nkT}\right)}$$

I_{on} is the current in strong inversion for $V_{GS} = V_{on}$

the voltage V_{on} is found as

$$V_{on} = V_T + \frac{nkT}{q} \quad where\ n = 1 + \frac{q \cdot N_{FS}}{C_{ox}} + \frac{C_d}{C_{ox}}$$

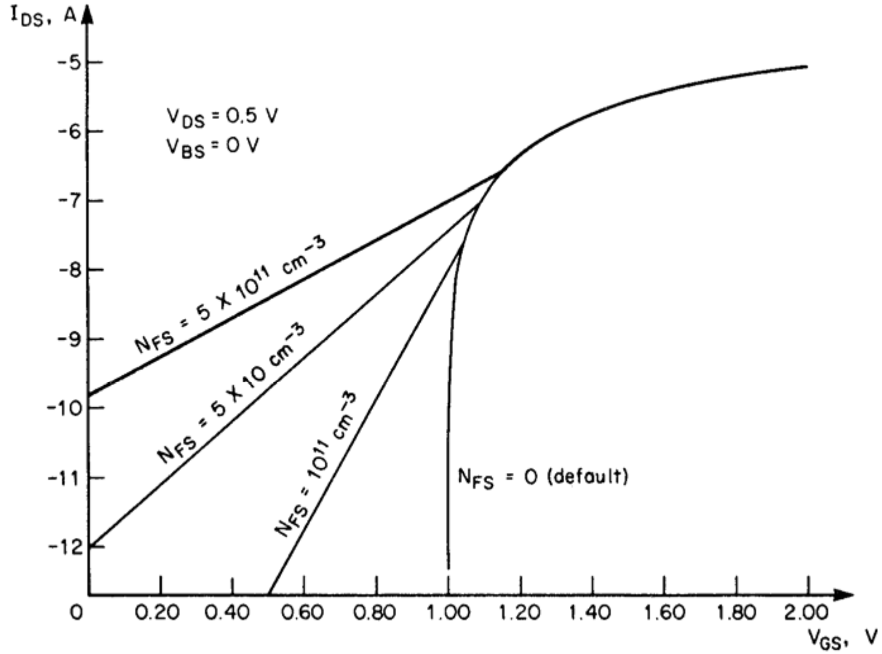

Figure 4.7 Variation of the drain current in the weak inversion region, as a function of the gate voltage and for different values of the parameter N_{FS}, in the LEVEL 2 model. *(Copyright © 1988 by McGraw-Hill, Inc.)*

The parameter N_{FS} is defined as the number of fast superficial states and is used as a fitting parameter that determines the slope of the subthreshold current - voltage characteristics

C_d : is the depletion capacitance

This model introduces a discontinuity for $V_{GS} = V_{on}$, therefore, the simulation of the transition region between weak and strong inversion is not very precise

The LEVEL 3 model equations

- The LEVEL 3 model has been developed for simulation of short channel MOS transistor
  - Quite precisely for channel lengths down to 2μm
  - The current-voltage equation in the linear region has been simplified with a Taylor series expansion
  - The majority of the LEVEL 3 model equations are empirical
    - To improve the accuracy of the model
    - To limit the complexity of the calculation

$$I_D = \mu_s \cdot C_{ox} \cdot \frac{W}{L_{eff}} \cdot \left(V_{GS} - V_T - \frac{1+F_B}{2} \cdot V_{DS} \right) \cdot V_{DS}$$

$$where\ F_B = \frac{\gamma \cdot F_s}{4 \cdot \sqrt{|2\phi_F| + V_{SB}}} + F_n$$

The empirical parameter F_B express the dependence of the bulk depletion charge

The V_T. F_s, and μ_s are influenced by the short - channel effects

The F_n is influenced by the narrow - channel effects

$$\mu_s = \frac{\mu}{1 + \theta \cdot (V_{GS}\text{-}V_T)}$$

The decrease in the effective mobility with the average lateral electrical field

$$\mu_{eff} = \frac{\mu_s}{1 + \mu_s \cdot \dfrac{V_{DS}}{v_{\max} \cdot L_{eff}}}$$

State-of-art MOSFET models

- BSIM-Berkeley short-channel IGFET model
  - The model is analytically simple and is based on a small number of parameters, which are normally extracted from experimental data
  - Accuracy and d\efficiency
  - Widely used by many companies and silicon foundries
- EKV (Enz-Krummenacher-Vittoz) transistor model
  - Previous models considering
    - The strong-inversion region of operation separately from the weak-inversion region
    - Causing serous problems in the modeling of transistors at very low voltages as in many cases involving deep sub-micron CMOS technology
  - Attempting to solve this problem by
    - Using a unified view of the transistor operating regions
    - Avoiding the use of disjoint equations in strong and weak inversion

Gate oxide capacitance

- SPICE uses a simple gate oxide capacitance model that represents the charge storage effect by three nonlinear two-terminal capacitor: C_{GB}, C_{GS} and C_{GD}
- The geometry information required for the calculation of gate oxide capacitance are:
  - Gate oxide thickness TOX
  - Channel width W
  - Channel length L
  - Lateral diffusion LD
- The capacitances CGBO, CGSO, and CGDO, which are specified in the .MODEL statement, are the overlap capacitances between the gate and the other terminals outside the channel region
- If the parameter XQC is specified in the .MODEL statement
  - SPICE uses a simplified version of the charge-controlled capacitance model proposed by Ward

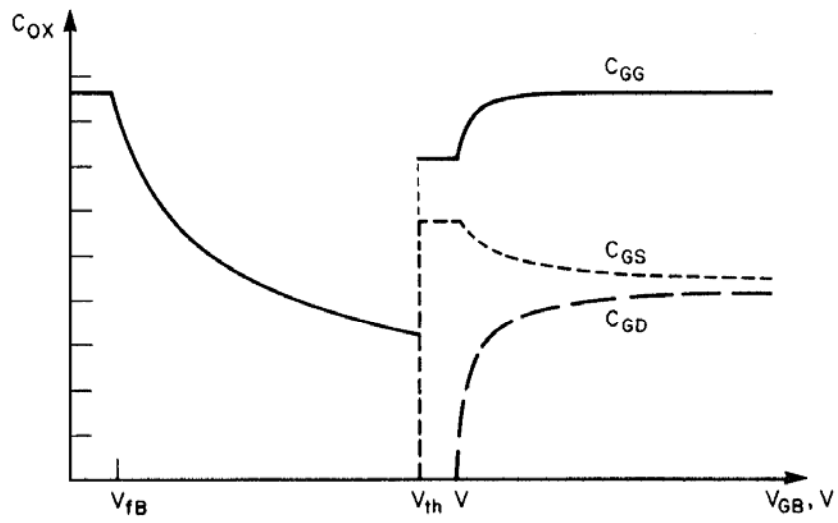

Figure 4.8 Oxide capacitances as functions of the gate-to-substrate voltage, according to Ward's capacitance model.
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Junction capacitance

$$C_{SB} = \frac{C_j \cdot AS}{\left(1 - \frac{V_{BS}}{\phi_0}\right)^{M_j}} + \frac{C_{jsw} \cdot PS}{\left(1 - \frac{V_{BS}}{\phi_0}\right)^{M_{jsw}}}$$

$$C_{DB} = \frac{C_j \cdot AD}{\left(1 - \frac{V_{BD}}{\phi_0}\right)^{M_j}} + \frac{C_{jsw} \cdot PD}{\left(1 - \frac{V_{BD}}{\phi_0}\right)^{M_{jsw}}}$$

C_j : the zero-bias depletion capacitance per unit area at the bottom of the junction

C_{jsw} : the zero-bias depletion capzcitance per unit length at the sidewall junctions

$C_{jsw} \cong \sqrt{10} \cdot C_j \cdot x_j$

AS and AD are the source and the drain areas

PS and PD are the source and the drain perimeters

M_j and M_{jsw} denote the junction grading coefficients for the bottom and the sidewalls junctions

Default values are $M_j = 0.5$ and $M_{jsw} = 0.33$

Comparison of the SPICE MOSFET models

- The LEVEL 1 model
  - Not very precise
  - Quick and rough estimate of the circuit performance without much accuracy
- THE LEVEL 2 model
  - Require a larger time
  - May occasionally cause convergence problems in the Newton-Raphson algorithm used in SPICE
- THE LEVEL 3 model
  - The CPU time needed for model evaluation is less and the number of iterations are significantly fewer for the LEVEL three model
  - Disadvantage
    - The complexity of calculating some of its parameters