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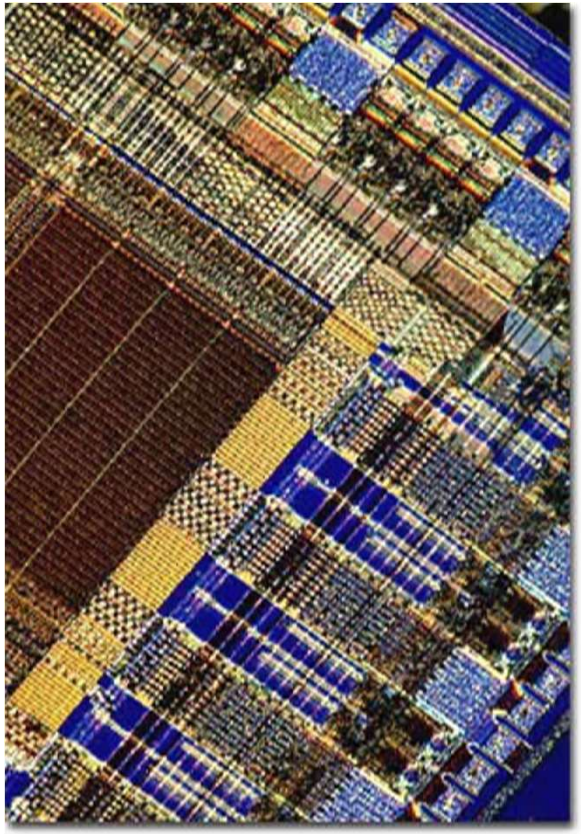

Chapter 4
Modeling of MOS Transistors Using SPICE

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HW#2 (issued on Jan. 17, 2019)

1. Prob. 3.1 (textbook)
2. Prob. 3.6
3. Prob. 3.7
4. Prob. 3.10
5. Prob. 3.14

Introduction(1)

- SPICE – Simulation Program with Integrated Circuit Emphasis
- SPICE is used very widely both in the microelectronics industry and in educational institutions
- The physical aspects of various MOSFET models used in SPICE will be described in this chapter

Introduction(2)

- The origin SPICE (UC Berkeley 1970s) has 3 built-in MOSFET models:
  - LEVEL 1 (MOS1) square-law current-voltage characteristic
  - LEVEL 2 (MOS2) analytical MOSFET
  - LEVEL 3 (MOS3) semi-empirical model
- The level of the MOSFET model is declared on the .MODEL statement
- Example:

```
M1  3  1  0  0  NMOD   L=1U   W=10U   AD=120P   PD=42U
MDEV32  14  9  12  5  PMOD   L=1.2U  W=20U
.MODEL NMOD NMOS (LEVEL=1 VTO=1.4 KP=4.5E-5 CBD=5PF CBS=2PF)
.MODEL PMOD PMOS          (VTO=-2  KP=3.0E-5  LAMBDA=0.02  GAMMA=0.4
+ CBD=4PF  CBS=2PF  RD=5  RS=3  CGDO=1PF
+ CGSO=1PF  CGBO=1PF)
```

Basic Concepts(1)

- I_D determines the steady-state current-voltage the device's behavior
- R_D and R_S are the parasitic source and drain resistances

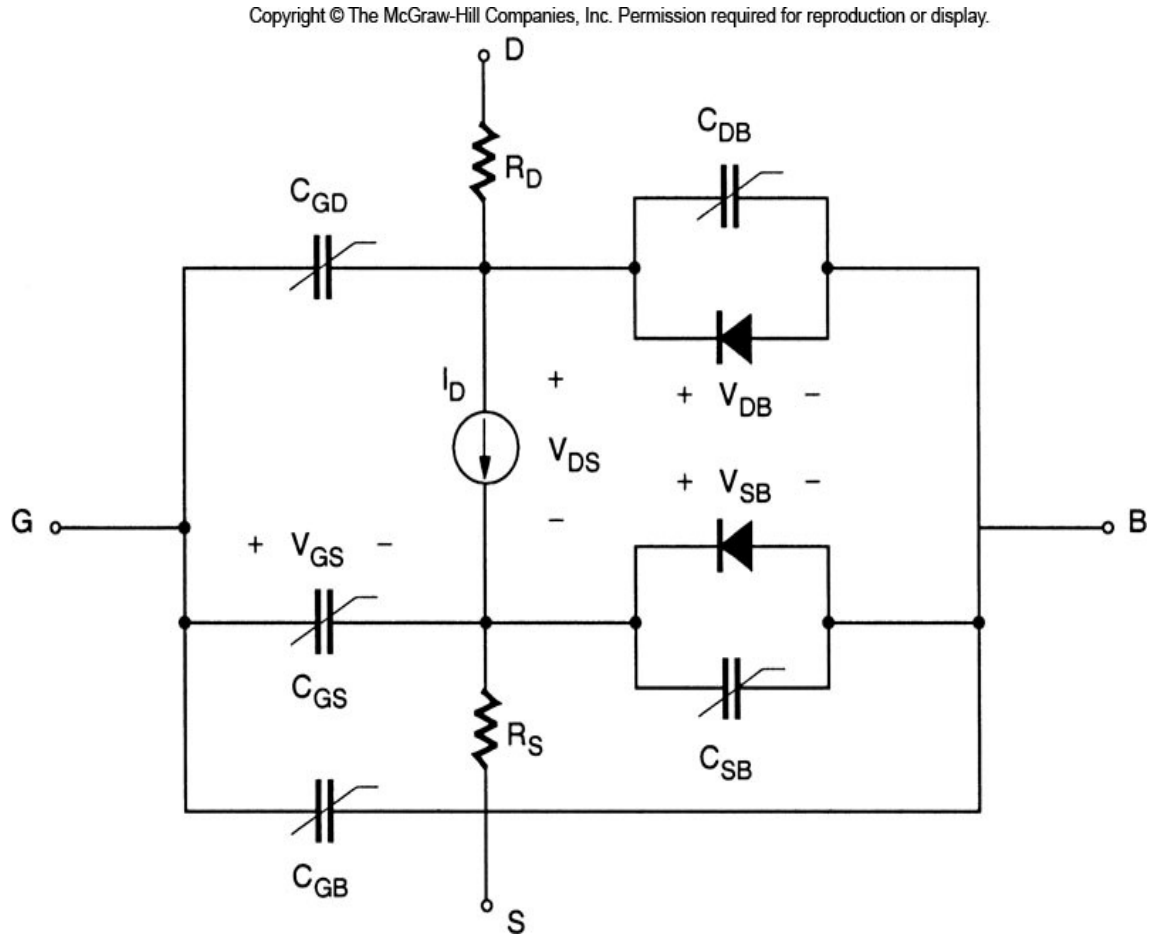


Figure 4.1. Equivalent circuit structure of the LEVEL 1 MOSFET

Basic Concept(2)

- W: Channel width
- L: nominal channel length
- L_{eff} the distance on the surface between the two diffusion regions
- L_D lateral diffusion coefficient

The LEVEL 1 Model Equations(1)

- Linear Region

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

$$\text{and} \quad V_{DS} < V_{GS} - V_T$$

- Saturation Region

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

$$\text{and} \quad V_{DS} \geq V_{GS} - V_T$$

- where:

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

The LEVEL 1 Model Equation(2)

- The effect channel length:

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

- Other parameters:

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

$$\gamma = \frac{\sqrt{2 \cdot \varepsilon_{Si} \cdot q \cdot N_A}}{C_{ox}} \qquad 2\phi_F = 2\frac{kT}{q} \cdot \ln\left(\frac{n_i}{N_A}\right)$$

The LEVEL 1 Model Equation(3)

- Example simulation parameters

$k' = 98.2\ \mu A/V2$	**KP = 98.2 U**
$VT0 = 0.53\ V$	**VTO = 0.53**
$\gamma = 0.574\ V1/2$	**GAMMA = 0.574**
$2\Phi F = -1.02$	**PHI = 1.02**
$\lambda = 0$	**LAMBDA = 0**

- Corresponding parameters

$\mu n = 44.7\ cm2/V\cdot s$	**UO = 44.7**
$tox = 1.6\ nm$	**TOX = 1.60E-9**
$NA = 4.80 \times 1018\ cm\text{-}3$	**NSUB = 4.80E18**
$LD = 10\ nm$	**LD = 1.00E-8**

The LEVEL 1 Model Equation(4)

- Drain current with VTO

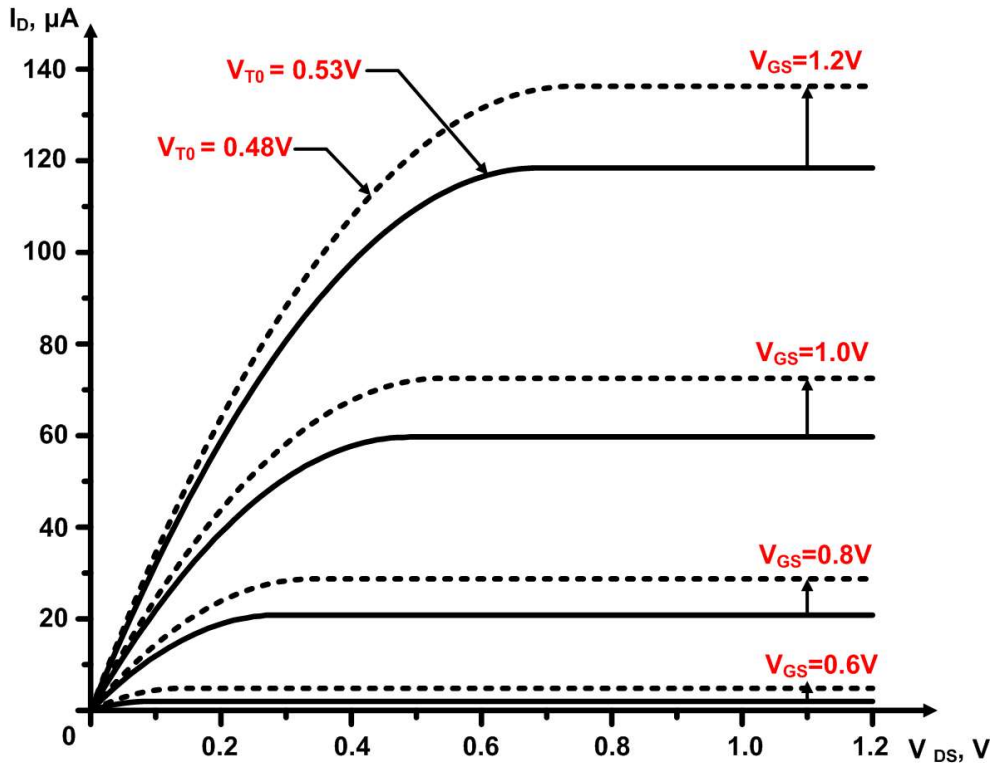


Figure 4.2. Variation of the drain current with model parameter VTO, for the LEVEL1 model

The LEVEL 1 Model Equation(5)

- Drain current with KP

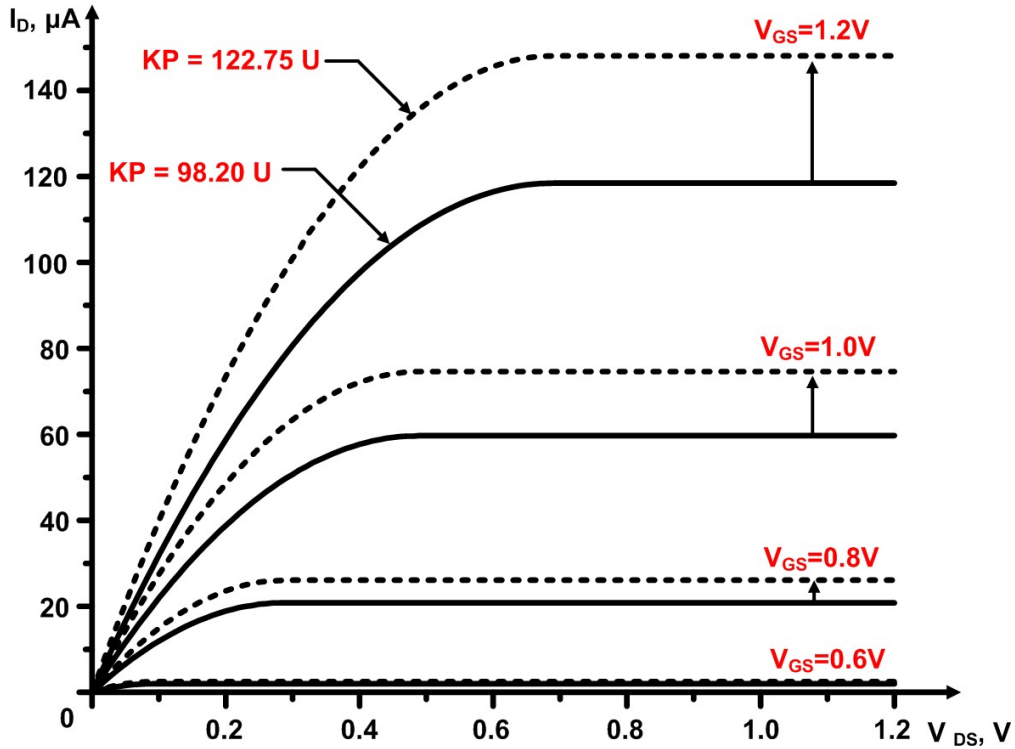


Figure 4.3. Variation of the drain current with model parameter KP, for the LEVEL1 model

The LEVEL 1 Model Equation(6)

- Drain current with TOX

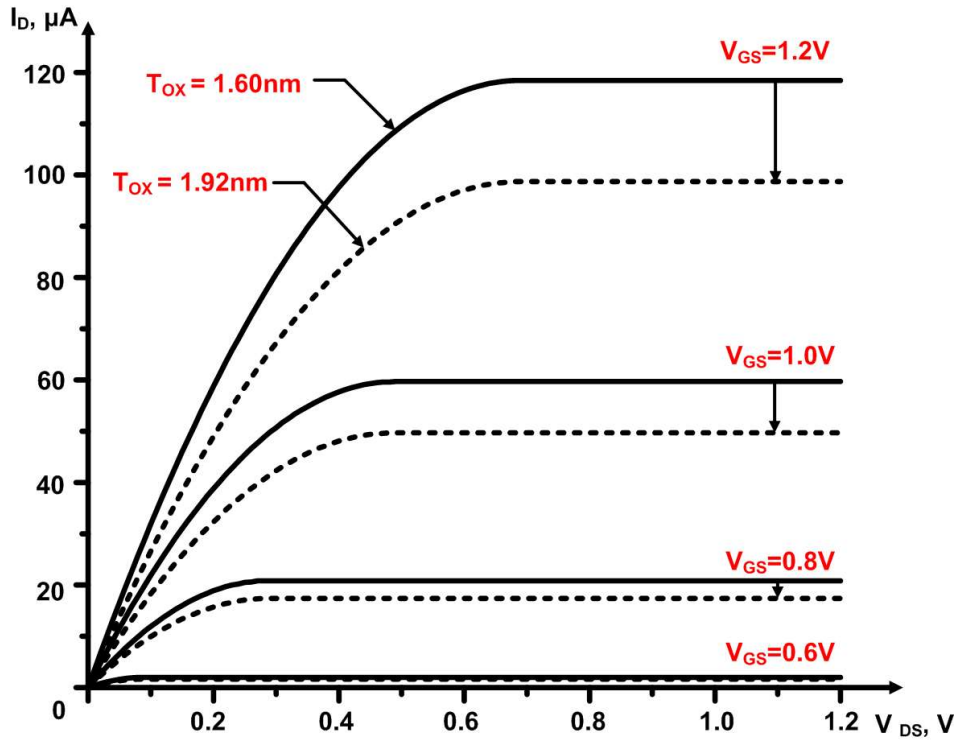


Figure 4.4. Variation of the drain current with model parameter TOX, for the LEVEL1 model

The LEVEL 1 Model Equation(7)

- Drain current with LAMBDA

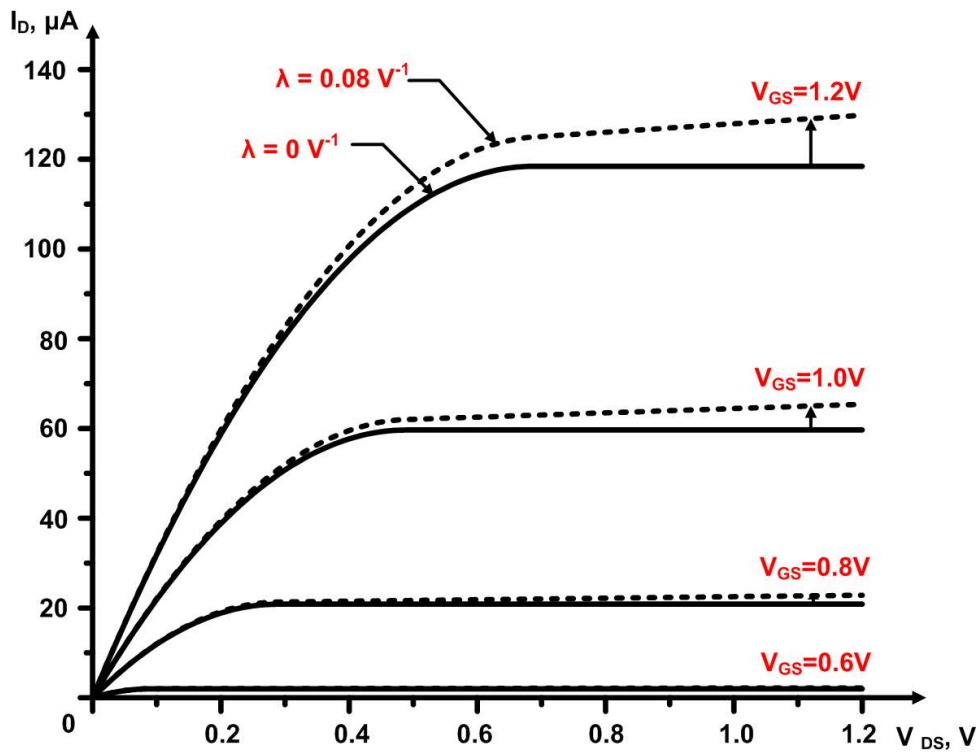


Figure 4.5. Variation of the drain current with parameter LAMBDA, for the LEVEL1 model

The LEVEL 2 Model Equation(1)

- Drain current in term of bulk charge

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

V_{FB} denotes the *flat-band* voltage of the MOSFET

- Saturation voltage – the channel charge at the drain end becomes zero

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

The LEVEL 2 Model Equation(2)

- Saturation mode current:

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

where IDsat is calculated from 4.9 using saturation condition

- The zero-bias threshold voltage:

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

Φ_{GC}: gate-to-channel work function difference

N_{ss}: fixed surface charge density

The LEVEL 2 Model Equation(3)

- Drain current with GAMMA

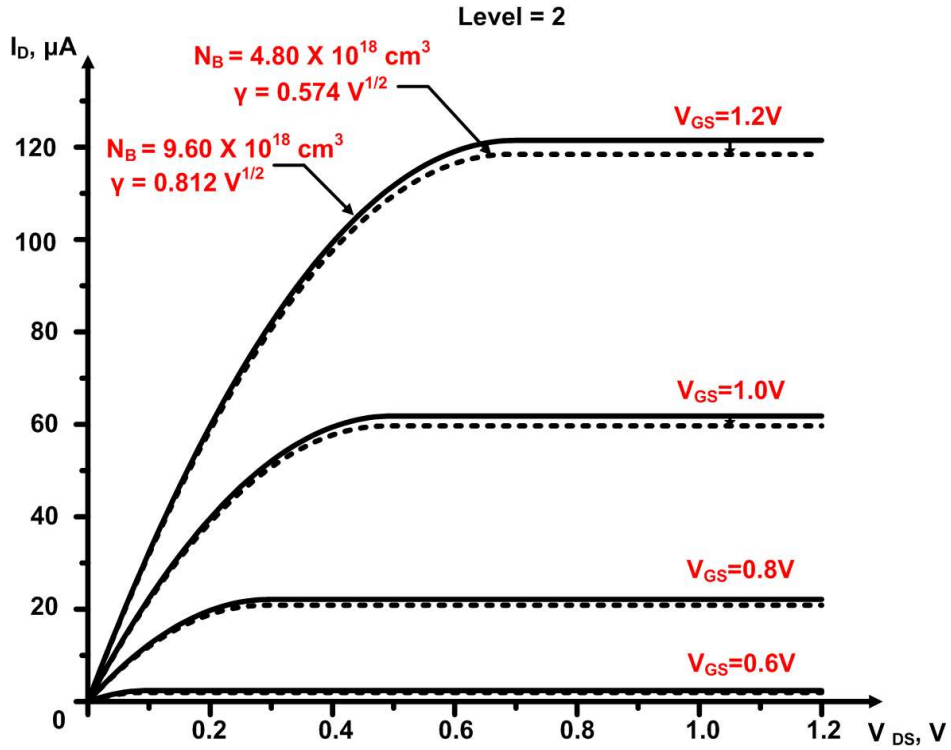


Figure 4.6. Variation of the drain current with parameter GAMMA, for the LEVEL2 model

The LEVEL 2 Model Equation(4)

- ***Variation of Mobility with Electric Field:*** to simulate the mobility variation, we use k′(new) instead of k′:

$$k'(new) = k' \cdot \left(\frac{\varepsilon_{Si}}{\varepsilon_{ox}} \cdot \frac{t_{oc} \cdot U_c}{(V_{GS} - V_T - U_t \cdot V_{DS})} \right)^{U_e}$$

U_c Gate-to-channel critical field

U_e Exponential fitting parameter

U_t Contribution of the drain voltage to gate-to-channel (value between 0 and 0.5)

The LEVEL 2 Model Equation(5)

- ***Variation of Channel Length in Saturation Mode:*** Channel length in saturation mode:

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

Where,

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

- Channel length shortening (not specified in the .MODEL)

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

The LEVEL 2 Model Equation(6)

- ***Saturation of Carrier Velocity:*** carriers in the channel approach maximum speed limit. In saturation mode, the inversion layer charge at the channel-end is:

$$Q_{inv} = \frac{I_{Dsat}}{W \cdot v_{max}}$$

$v_{\max}$ Maximum carrier speed

- Channel legnth shortening:

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

where, $$X_D = \sqrt{\frac{2 \cdot \varepsilon_{Si}}{q \cdot N_A \cdot N_{eff}}}$$

The LEVEL 2 Model Equation(7)

- ***Subthreshold Conduction:*** Because Vgs < VT, even when the surface is not in strong inversion, there is a channel current
- *Subthreshold current*: diffusion between the source and the channel
- Drain current in the *weak inversion region:*

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

I_{on}: current in strong inversion region

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

N_{FS} The number of fast superficial states

C_d The capacitance associated with the depletion region

The LEVEL 2 Model Equation(8)

- Drain current

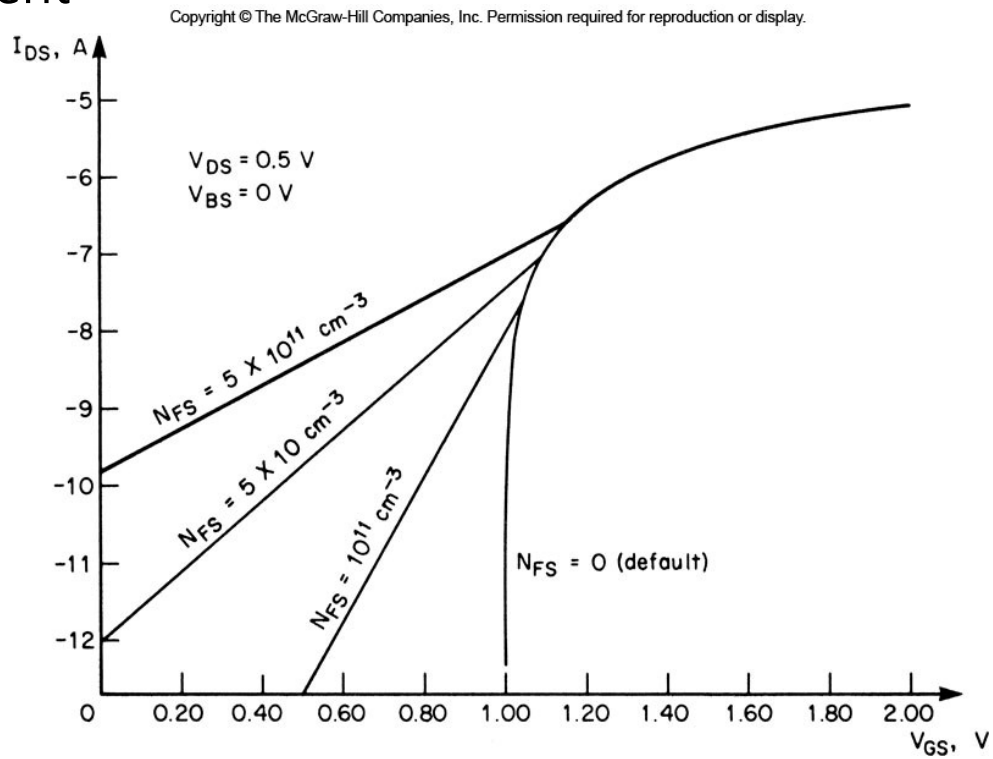


Figure 4.7. Variation of the drain current in the weak inversion region, as a function of the gate voltage and for different values of the parameter *NFS* , in the LEVEL 2 model

The LEVEL 3 Model Equation(1)

- LEVEL 3 equations are empirical
  - The accuracy improvement
  - The complexity of the calculation limitation
- The drain current in the linear region :

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

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

F_B The dependence of the bulk depletion charge of the MOSFET

The LEVEL 3 Model Equation(2)

- The surface mobility on the gate electric field:

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

- The effective mobility equation:

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

m_S Surface mobility

State-of-the Art MOSFET Models

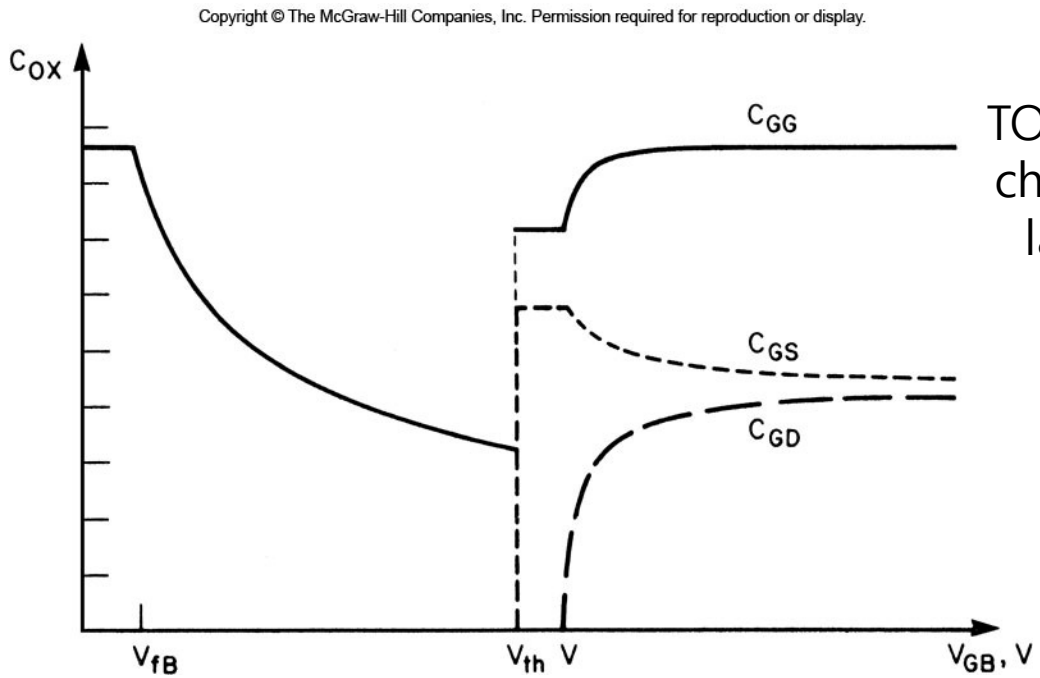
- BSIM – Berkeley Short-Channel IFGET Model or LEVEL 4 model
- BSIM becomes the most popular SPICE MOSFET models at present
- BSIM4 version is used by many companies with 0.13um CMOS fabrication processes

EKV Transistor Model

- EKV – Enz-Krummenacher-Vittoz
- EKV Model attempts to resolve the serious problems in the modeling of transistors operating at very low voltages. It uses unified view of the transistor operating regions, and avoids the use of disjoint equation in strong and weak inversion
- EKV model is accurate simulation tool for analog circuits and digital circuits operating near threshold voltage

Capacitance Model(1)

- Gate Oxide Capacitances: SPICE uses a simple gate oxide capacitance



TOX, channel width W, channel length L, and lateral diffusion LD are required

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

Capacitance Model(2)

- Junction Capacitances: SPICE uses simple pn-junction model to simulate the parasitic capacitances of the source and drain diffusion:

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

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

C_j :Zero-bias depletion capacitance per unit at the bottom junction of the drain and source

C_{jsw}: Zero-bias depletion capacitance per unit length at the sidewall junctions

Capacitance Model(3)

- For typical sidewall doping, we have:

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

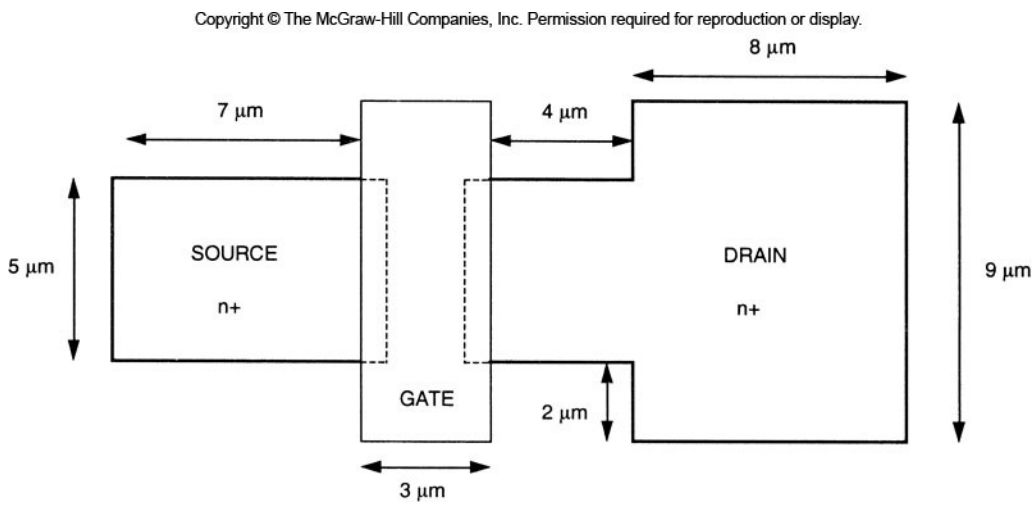
- AS and AD are the source and the drain areas
- PS and PD are the source and the drain perimeters
- M_j and M_{jsw} are the junction grading coefficients for the bottom and the sidewall junctions
- Default values:

$$M_j = 0.5$$

$$M_{jsw} = 0.33$$

Example 4.1(1)

- The top view of an n-channel MOSFET:



NA = 4.80 × 10^18 cm-3
NA (sidewall) = 1.51 × 10^15 cm-3
ND = 4.80 × 10^18 cm-3
xj = 0.032 μm
tox = 16 Å
Ld = 10 nm

- The zero-bias threshold voltage is measured as 0.53V
- and k′ = 98.2 uA/V^2
- λ=0.08

Example 4.1(2)

- The gate oxide capacitance per unit area:

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.51\times10^{-13}}{1.60\times10^{-7}} = 2.19\times10^{-6} F/cm^2$$

- The substrate bias coefficient(GAMMA):

$$\gamma = \frac{\sqrt{2\cdot q\cdot N_A\cdot\varepsilon_{Si}}}{C_{ox}} = \frac{\sqrt{2\cdot1.6\times10^{-19}\cdot4.80\times10^{18}\cdot1.04\times10^{-12}}}{2.19\times10^{-6}} = 0.577\mathrm{V}^{\frac{1}{2}}$$

- The surface inversion potential(PHI):

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

$$= \left|2\cdot0.026\,\mathrm{V}\cdot\ln\left(\frac{1.45\times10^{10}}{4.80\times10^{18}}\right)\right| = 1.02\mathrm{V}$$

Example 4.1(3)

- We can calculate:

$$\phi_0 = \frac{kT}{q} \cdot \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) = 0.026\,\mathrm{V} \cdot \ln\left(\frac{4.80\times10^{18} \cdot 4.80\times10^{18}}{2.10\times10^{20}}\right) = 1.02\,\mathrm{V}$$

$$\mathrm{C}_{j0} = \sqrt{\frac{\varepsilon_{Si} \cdot q}{2} \cdot \left(\frac{N_A \cdot N_D}{N_A + N_D}\right) \cdot \frac{1}{\phi_0}}$$

$$= \sqrt{\frac{1.04\times10^{-12}\,\mathrm{F/cm} \cdot 1.6\times10^{-19}\,C}{2} \cdot \left(\frac{4.80\times10^{18} \cdot 4.80\times10^{18}}{4.80\times10^{18} + 4.80\times10^{18}}\right) \cdot \frac{1}{1.02}}$$

$$= 4.42 \times 10^{-7}\ \mathrm{F/cm}^2$$

Example 4.1(4)

- And

$$C_{j0sw} = x_j \cdot \sqrt{\frac{\varepsilon_{Si} \cdot q}{2} \cdot \left(\frac{N_A(sw) \cdot N_D}{N_A(sw) + N_D} \right) \cdot \frac{1}{\phi_0}}$$

$$= 3.20 \times 10^{-6} \cdot \sqrt{\frac{1.04 \times 10^{-12}\,\text{F/cm} \cdot 1.6 \times 10^{-19}\,C}{2} \cdot \left(\frac{2.99 \times 10^{15} \cdot 4.80 \times 10^{18}}{2.99 \times 10^{15} + 4.80 \times 10^{18}} \right) \cdot \frac{1}{1.02}}$$

$$= 5.00 \times 10^{-14}\ \text{F/cm}$$

- We assume Mj = 0.5 and Mjsw = 0.33. We have:

$$C_{GSO} = C_{GDO} = C_{ox} \cdot L_D = 2.19 \times 10^{-6} \cdot 10 \times 10^{-7} = 2.19\,\text{pF/cm}$$

Example 4.1(5)

- SPICE statement:

```
M1 6 12 4 7 NM1 W=200N L=120N LD=10N  AS=0.058P PS=0.98U AD=0.1492P PD=1.7U
.MODEL   NM1   NMOS   (  VTO=0.53   KP=98.2U   LAMBDA=0.08   GAMMA=0.577
+                      PHI=1.02   PB=1.02   CJ=4.42E-3   CJSW=5.00E-10
+                      CGSO=2.19E-10   CGDO=2.19E-10   MJ=0.5   MJSW=0.33   )
```

Comparison of the SPICE MOSFET Models

- The LEVEL 1 model: usually not very precise because of GCA and small number of fitting parameters
  - Useful for a quick and rough estimate
- The LEVEL 2 model: can be used with differing complexities
  - By adding the related parameters
  - Requires a large amount of CPU time
  - Problem wit convergence

Comparison of the SPICE MOSFET Models

- LEVEL 2 AND LEVEL 3 comparison:

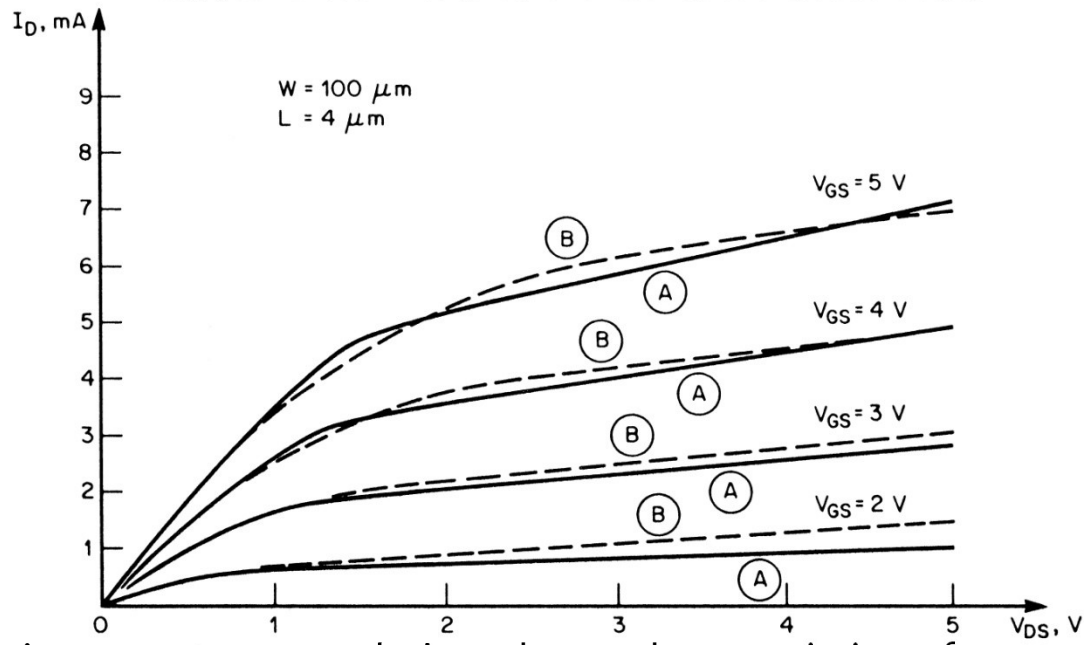


Figure 4.9. Drain current versus drain voltage characteristics of an n-channel MOSFET calculated with the LEVEL 2 model (A) and the LEVEL 3 model (B)
The parameters common for both models are : VTO = 0.53, XJ = 3.20E-8, LD = 1.0E-8.
The parameters of the LEVEL 2 model are : UO = 44.7, UCRIT = 2.0E7.
The parameters of the LEVEL 3 model are : UO = 47.5, THETA = 0.17.