**A**lexandria **U**niversity
**Faculty of Engineering**
*Electrical Engineering Department*

**ECE 336: Semiconductor Devices**
**Lab#4: MOSFET**

## Objectives

The purpose of this exercise is to analyze the properties of the MOSFET, understand the effect of each of the model parameters discussed in the exercise.
By the end of this exercise you should be able to:
1. Explain the effect of VT on the turn on of the MOSFET
2. Explain the effect of KP on the current of the MOSFET.
3. Explain the $2^{nd}$ order effects of the MOSFET device.

## Requirements and Deliverables

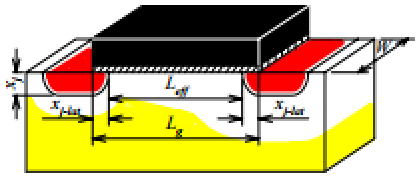
In this exercise you are required to use the MOSFET device in simulation to obtain its characteristic curves and analyze its various parameters.

You should deliver a technical report containing the following sections:

- A survey on the second order effects of MOSFET device ( channel length modulation, body effect, mobility degeneration… etc )
- Procedures: A description and snapshots of the lab procedures taken from your PC,
- Results: Numerical and graphical simulation results as requested
- Comments: Your conclusion about the results and your answers for the assignment questions.

## MOSFET Device model:

## GEOMETRICAL VARIABLES

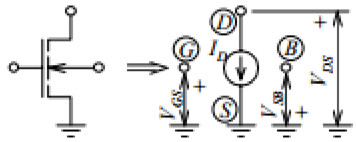


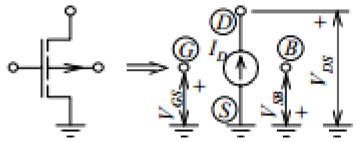

$L_{eff} = L_g - 2x_{j-lat}$ ($x_{j-lat}$ is a parameter; refer to Table 5.5)

| Symbol | SPICE Keyword | Variable Name | Default Value | Unit |
|---|---|---|---|---|
| $L_g$ | `L` | Gate length | $100 \times 10^{-6}$ | $m$ |
| $W$ | `W` | Channel width | $100 \times 10^{-6}$ | $m$ |

NOTE: $L$ and $W$ can also be specified as parameters

## STATIC LEVEL-3 MODEL




NMOS ($V_{Ts} = V_T + n_s kT/q$)
- sub-$V_T$: $V_{GS} \le V_{Ts}$
- triode: $V_{GS} > V_{Ts}$, and $0 < V_{DS} < V_{DSsat}$
- satur.: $V_{GS} > V_{Ts}$, and $V_{DS} \ge V_{DSsat} > 0$

PMOS ($V_{Ts} = V_T - n_s kT/q$)
- sub-$V_T$: $V_{GS} \ge V_{Ts}$
- triode: $V_{GS} < V_{Ts}$, and $0 > V_{DS} > V_{DSsat}$
- satur.: $V_{GS} < V_{Ts}$, and $V_{DS} \le V_{DSsat} < 0$

$$I_D = \begin{cases} f(V_{GS}) = \begin{cases} \beta\left[(V_{GS}-V_T)V_{DS} - (1+F_B)\frac{V_{DS}^2}{2}\right], & \text{triode region} \\ \frac{\beta}{2(1+F_B)}(V_{GS}-V_T)^2, & \text{satur. region } ^{(1)} \end{cases} \\ f(V_{GS}=V_{Ts}) \times e^{-qV_{subth}/n_s kT}, & \text{sub-}V_T \text{ region} \end{cases}$$

NMOS: $V_{subth} = V_{Ts} - V_{GS} \ge 0$

PMOS: $V_{subth} = V_{GS} - V_{Ts} \ge 0$

NMOS: $F_B = \frac{\gamma F_s}{2\sqrt{|2\phi_F| + V_{SB}}} + F_n$ (2)

PMOS: $F_B = \frac{\gamma F_s}{2\sqrt{|2\phi_F| - V_{SB}}} + F_n$ (2)

| | Principal Effects | Channel Related (Second-Order Effects) | Depletion Layer Related (Second-Order Effects) | All (Second-Order Effects) |
|---|---|---|---|---|
| $\beta$, $V_{DSsat}$ | Table A.5 | Table A.6 | Table A.5 | Table A.6 |
| $V_T$, $\lvert 2\phi_F \rvert$, $\gamma$, $F_s$, $F_n$, $n_s$ | Table A.5 | Table A.5 | Table A.7 | Table A.7 |

| *PRINCIPAL STATIC PARAMETERS* | | | | | |
|---|---|---|---|---|---|
| **Symbol** | **SPICE Keyword** | **Parameter Name** | **Typical Value** NMOS | PMOS | **Unit** |
| $KP$ (or | KP | Transconductance parameter * | $1.2 \times 10^{-4}$ | | $A/V^2$ |
| $\mu_0$ and | Uo | Low-field mobility † | 700 | | $cm^2/Vs$ |
| $t_{ox}$) | Tox | Gate-oxide thickness † | $20 \times 10^{-9}$ | | $m$ |
| $V_{T0}$ | Vto | Zero-bias threshold voltage | 1 | $-1$ | $V$ |
| $\lvert 2\phi_F \rvert$ | Phi | Surface potential in strong inversion | 0.70 | | $V$ |
| $\gamma$ | Gamma | Body-effect parameter | $> 0.3$ | | $V^{1/2}$ |

$\beta$, $V_T$, $V_{DSsat}$, $F_s$, $F_n$ and $n_s$ EQUATIONS

NMOS | PMOS

$$\beta = \begin{cases} \mathtt{KP}\frac{W}{L_{eff}}, & \text{if KP is specified} \\ \mu_0 \frac{\varepsilon_{ox}}{t_{ox}} \frac{W}{L_{eff}}, & \text{if KP is not specified} \end{cases}$$

$$L_{pinch} = 0 \quad (\mathtt{KAPPA=0})$$

$$V_T = \mathtt{Vto} + \mathtt{Gamma}\left(\sqrt{\mathtt{Phi} + V_{SB}} - \sqrt{\mathtt{Phi}}\right) \qquad V_T = \mathtt{Vto} - \mathtt{Gamma}\left(\sqrt{\mathtt{Phi} + V_{BS}} - \sqrt{\mathtt{Phi}}\right)$$

$$V_{DSsat} = \frac{V_{GS} - V_T}{1 + F_B}$$

$$F_s = 1 \quad (\mathtt{Xj=0})$$

$$F_n = 0 \quad (\mathtt{DELTA=0})$$

$$n_s = 1 + \frac{\gamma F_s(\mathtt{Phi} + |V_{SB}|)^{-1/2}}{2} \quad (\mathtt{NFS=0})$$

CONSTANT: $\varepsilon_{ox} = 3.9 \times 8.85 \times 10^{-12} F/m$

| CHANNEL RELATED STATIC PARAMETERS | | | | |
|---|---|---|---|---|
| **Symbol** | **SPICE Keyword** | **Parameter Name** | **Typical Value** | **Unit** |
| $KP$ (or | `KP` | Transconductance parameter * | $1.2 \times 10^{-4}$ | $A/V^2$ |
| $\mu_0$ and | `Uo` | Low-field mobility † | 700 | $cm^2/Vs$ |
| $t_{ox}$) | `Tox` | Gate-oxide thickness † | $20 \times 10^{-9}$ | $m$ |
| $\theta$ | `THETA` | Mobility modulation constant | 0.1 | - |
| $v_{max}$ | `Vmax` | Maximum drift velocity | $10^5$ | $m/s$ |
| $\kappa$ | `KAPPA` | Channel length modulation coefficient (needs `Nsub`) | 0.2 | - |
| $N_A$, $N_D$ | `Nsub` | Substrate doping concentration | $10^{15}$ | $cm^{-3}$ |

**$\beta$ and $V_{DSsat}$ EQUATIONS**

NMOS PMOS

$$\Rightarrow \quad \beta = \mu_{eff} \frac{\varepsilon_{ox}}{\texttt{Tox}} \frac{\texttt{W}}{L_{eff} - L_{pinch}}$$

$$\mu_{eff} = \frac{\mu_s}{1 + \mu_s \min(|V_{DS}|, |V_{DSsat}|)/(\texttt{Vmax} L_{eff})}$$

$$\mu_s = \frac{\mu_0}{1 + \texttt{THETA}|V_{GS} - V_T|}$$

$$\mu_0 = \texttt{KP}\frac{\texttt{Tox}}{\varepsilon_{ox}}, \text{ if } \texttt{KP} \text{ is specified; else } \mu_0 = \texttt{Uo}$$

$$L_{pinch} = \begin{cases} L_a = \sqrt{\texttt{KAPPA}\frac{2\varepsilon_s}{q\,\texttt{Nsub}}|V_{DS} - V_{DSsat}|}, & \text{if } \texttt{Vmax} \text{ is not specified}^{(1)} \\ \left[\left(\frac{\varepsilon_s}{q\,\texttt{Nsub}}\frac{V_{DSsat}}{L_{eff}}\right)^2 + L_a^2\right]^{1/2} - \frac{\varepsilon_s}{q\,\texttt{Nsub}}\frac{|V_{DSsat}|}{L_{eff}}, & \text{if } \texttt{Vmax} \text{ is specified} \end{cases}$$

$$\Rightarrow \quad V_{DSsat} = \begin{cases} \frac{V_{GS} - V_T}{1 + F_B}, & \text{if } \texttt{Vmax} \text{ is not specified}^{(1)} \\ V_{DSsat-corr}, & \text{if } \texttt{Vmax} \text{ is specified} \end{cases}$$

$$V_{DSsat-corr} = V_a + V_b - \sqrt{V_a^2 + V_b^2}\ ^{(2)} \qquad V_{DSsat-corr} = V_a - V_b + \sqrt{V_a^2 + V_b^2}\ ^{(2)}$$

$$V_a = \frac{V_{GS} - V_T}{1 + F_B}, \quad V_b = \frac{\texttt{Vmax} L_{eff}}{\mu_s}\ ^{(2)}$$

CONSTANT: $\varepsilon_{ox} = 3.9 \times 8.85 \times 10^{-12} F/m$

| DEPLETION-LAYER RELATED STATIC PARAMETERS | | | | |
|---|---|---|---|---|
| **Symbol** | **SPICE Keyword** | **Parameter Name** | **Typical Value** | **Unit** |
| $t_{ox}$ | `Tox` | Gate oxide thickness | $20 \times 10^{-9}$ | $m$ |
| $\eta$ | `ETA` | Static feedback | 0.7 | - |
| | | NOTE: This parameter can be used with $V_{T0}$, $2\|\phi_F\|$, and $\gamma$ . $t_{ox}$ should also be specified. | | |
| $N_A$, $N_D$ | `Nsub` | Substrate doping concentration | $10^{15}$ | $cm^{-3}$ |
| | | NOTE: This parameter has to be specified to include the parameters below. | | |
| $N_{oc}$ | `Nss` | Oxide-charge density (needs `Nsub`) | $10^{10}$ | $cm^{-2}$ |
| | `TPG` | Gate material type (needs `Nsub`) | | - |
| | | - same as drain/source: `TPG` $= 1$ | | |
| | | - opposite of D/S: `TPG` $= -1$ | | |
| | | - Al: `TPG=0` | | |
| $x_j$ | `Xj` | P–N junction depth (needs `Nsub`) | $0.5 \times 10^{-6}$ | $m$ |
| $x_{j-lat}$ | `Ld` | Lateral diffusion | $0.8 \times x_j$ | $m$ |
| $V_{bi}$ | `PB` | P–N junction built-in voltage (needs `Nsub`) | 0.8 | $V$ |
| $\delta$ | `DELTA` | Width effect on threshold voltage | 1.0 | - |
| | `NFS` | Subthreshold-current fitting parameter | $10^{11}$ | $cm^{-2}$ |

**$V_T$, $2|\phi_F|$, $\gamma$, $F_s$, $F_n$, and $n_s$ EQUATIONS**

| NMOS | PMOS |
| --- | --- |

$$C_{ox} = \varepsilon_{ox}/\texttt{Tox}$$

NMOS:

$$\Rightarrow \quad V_T = V_{T0} + \gamma F_s\left(\sqrt{|2\phi_F| + V_{SB}} - \sqrt{|2\phi_F|}\right) - \sigma_D V_{DS} + F_n(V_{SB} + 2\phi_F)$$

PMOS:

$$V_T = V_{T0} - \gamma F_s\left(\sqrt{|2\phi_F| + V_{BS}} - \sqrt{|2\phi_F|}\right) - \sigma_D V_{DS} - F_n(V_{BS} + |2\phi_F|)$$

NMOS:

$$V_{T0} = \phi_{ms} - \frac{q\,\texttt{Nss}}{C_{ox}} + |2\phi_F| + \gamma F_s\sqrt{|2\phi_F|}$$

PMOS:

$$V_{T0} = \phi_{ms} - \frac{q\,\texttt{Nss}}{C_{ox}} - |2\phi_F| - \gamma F_s\sqrt{|2\phi_F|}$$

NMOS:

$$\phi_{ms} = \begin{cases} -\frac{E_g}{2q} - |\phi_F|, & \text{if TPG} = 1 \\ \frac{E_g}{2q} - |\phi_F|, & \text{if TPG} = -1 \\ \phi_* - |\phi_F|, & \text{if TPG} = 0 \end{cases}$$

PMOS:

$$\phi_{ms} = \begin{cases} \frac{E_g}{2q} + |\phi_F|, & \text{if TPG} = 1 \\ \frac{-E_g}{2q} + |\phi_F|, & \text{if TPG} = -1 \\ \phi_* + |\phi_F|, & \text{if TPG} = 0 \end{cases}$$

$$\sigma_D = 8.15 \times 10^{-22}\texttt{ETA}/(C_{ox}L_{eff}^3) \quad ^{(1)}$$

$$\Rightarrow \quad \gamma = \frac{1}{C_{ox}}\sqrt{2\varepsilon_s q \texttt{Nsub}}$$

$$\Rightarrow \quad |2\phi_F| = 2\frac{kT}{q}\ln\frac{\texttt{Nsub}}{n_i}$$

$$\Rightarrow \quad F_s = 1 - \frac{\texttt{Xj}}{L_{eff}}\left(\frac{\texttt{Ld}+w_c}{\texttt{Xj}}\sqrt{1 - \frac{w_p}{\texttt{Xj}+w_p}} - \frac{\texttt{Ld}}{\texttt{Xj}}\right) \quad ^{(1)}$$

NMOS:

$$w_p = \sqrt{\frac{2\varepsilon_s}{q\,\texttt{Nsub}}(\texttt{PB} + V_{SB})}$$

PMOS:

$$w_p = \sqrt{\frac{2\varepsilon_s}{q\,\texttt{Nsub}}(\texttt{PB} + V_{BS})}$$

$$w_c = 0.0631353\texttt{Xj} + 0.8013929 w_p - 0.0111077 w_p^2/\texttt{Xj} \quad ^{(1)}$$

$$\Rightarrow \quad F_n = \texttt{DELTA}\ \varepsilon_s\pi/(4C_{ox}\texttt{W}) \quad ^{(1)}$$

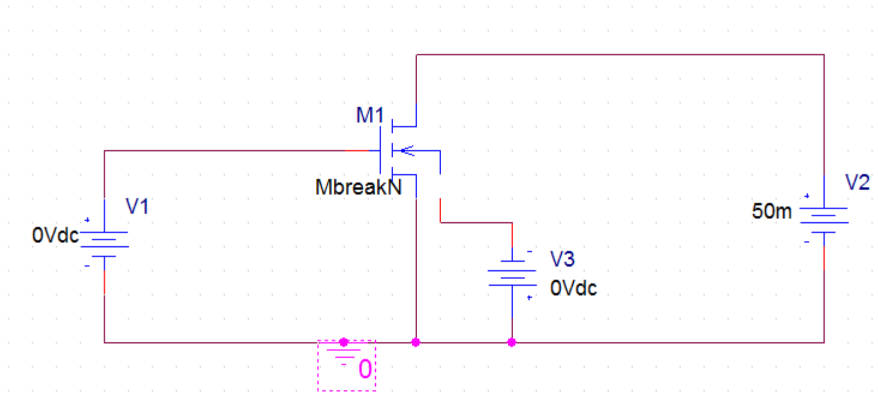
$$\Rightarrow \quad n_s = 1 + \frac{q\,\texttt{NFS}}{C_{ox}} + \frac{\gamma F_s(|2\phi_F| + |V_{SB}|)^{-1/2} - F_n}{2} \quad ^{(2)}$$

CONSTANTS:

| | | |
| --- | --- | --- |
| $\varepsilon_{ox} = 3.45 \times 10^{-11} F/m$ | $k = 8.62 \times 10^{-5} eV/K$ | $n_i = 1.4 \times 10^{10} cm^{-3}$ |
| $q = 1.6 \times 10^{-19} C$ | $\phi_* = \phi_m - 4.61V$ | $\varepsilon_s = 1.044 \times 10^{-10} F/m$ |

# Procedures:

1. Connect the circuit as shown in the figure, using the Mbreakn MOSFET model.




2. Edit the transistor model to `LEVEL=3 KP= 20E-6 VTO=0`.

3. Run DC sweep of V1 from 0 to 10V with 0.1V step and plot the drain current of the transistor, what is the region the transistor is operating in ?
4. Make `VTO=1` and repeat the previous step, explain the change in the output.
5. Make `KP=100E-6` and repeat step 3, explain the change in the output.
6. Set `GAMMA=0` and run DC sweep + parametric sweep on V3 ( bulk source voltage) from 0 to 5V with step 1V.
7. Set `GAMMA=0.6 PHI=0.75` and repeat step 6, explain why there was a change in this step not the first step ? what is the name of this phenomenon ?
8. Set GAMMA back to zero, and run **primary sweep on VDS** from 0V to 10V with 1V step and **parametric sweep on VGS from 0V to 8V with 2V step.**
9. Set `GAMMA=0.6 PHI=0.75` and repeat the step 8 and compare the saturation current levels ( what is the condition of saturation ? ) and exlain the results.
10. Run DC sweep on VGS from 0V to 10V with 1V step and run with it parametric sweep on the parameter `THETA = 0 0.1`, comment on the results.
11. Repeat step 8 and 9 but this time **change the parameter THETA (not gamma) to 0 and 0.1,** explain the results.