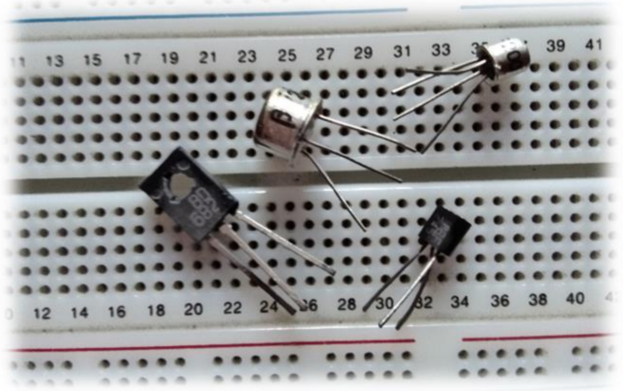
ELECTRONIC DEVICES

Assist. prof. Laura-Nicoleta IVANCIU, Ph.D.

C13 – MOSFET operation



Contents

Previously on ED (C11):

Transistors

= active semiconductor devices, with three terminals

- used to amplify or switch signals
- essential components of electronic circuits
- discrete or integrated

Operating principle:

The voltage applied between two terminals (command) controls the current through the third terminal

Symbols

Metal-oxide-semiconductor field effect transistors (MOSFETS)

n-channel enhancement-mode p-channel enhancement-mode

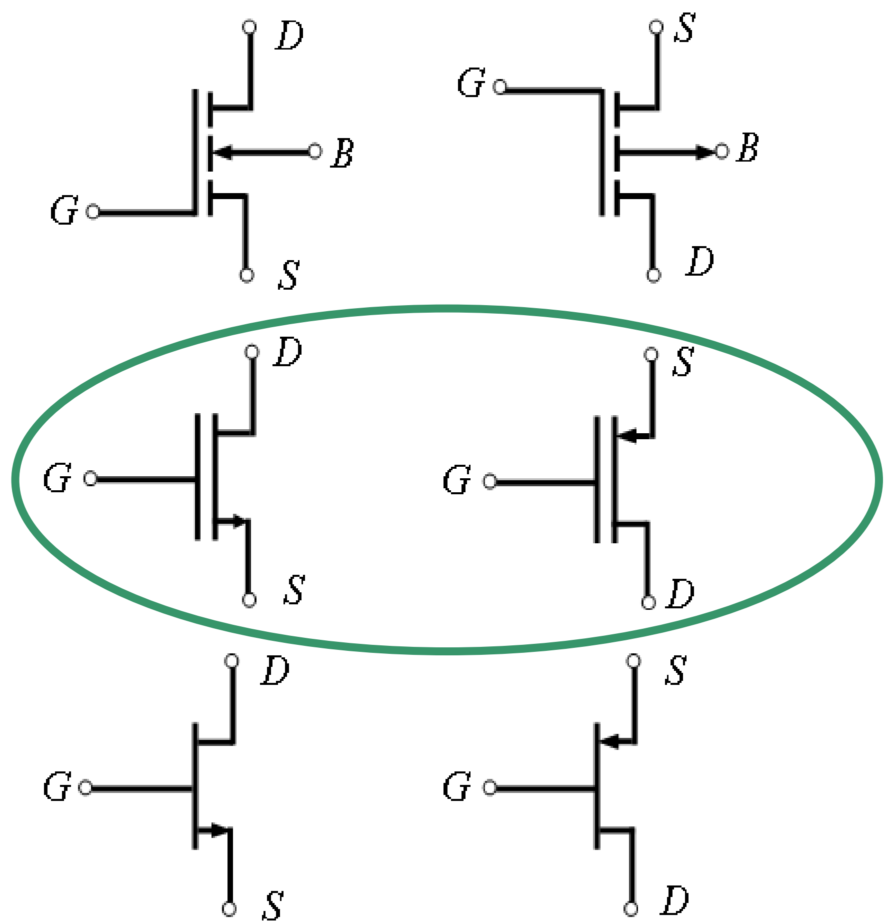
general symbols

(explicit body terminal B)

simplified symbols

(B internally connected to S)

other symbols



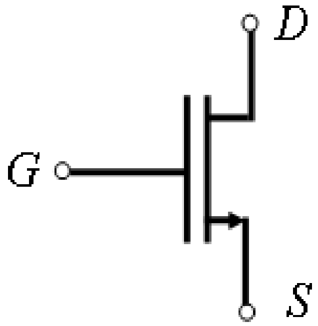
Symbols

Metal-oxide-semiconductor field effect transistors (MOSFETs)

D – drain (similar to C)
G – gate (similar to B)
S – source (similar to E)

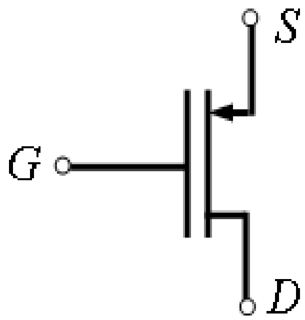
n-channel enhancement-mode

NMOS

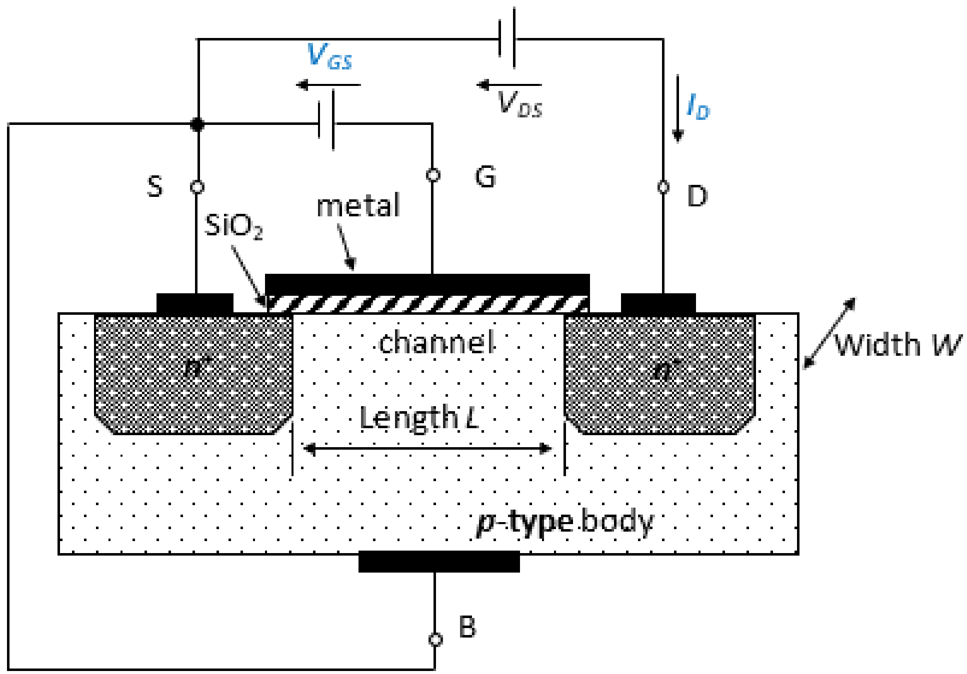


p-channel enhancement-mode

PMOS



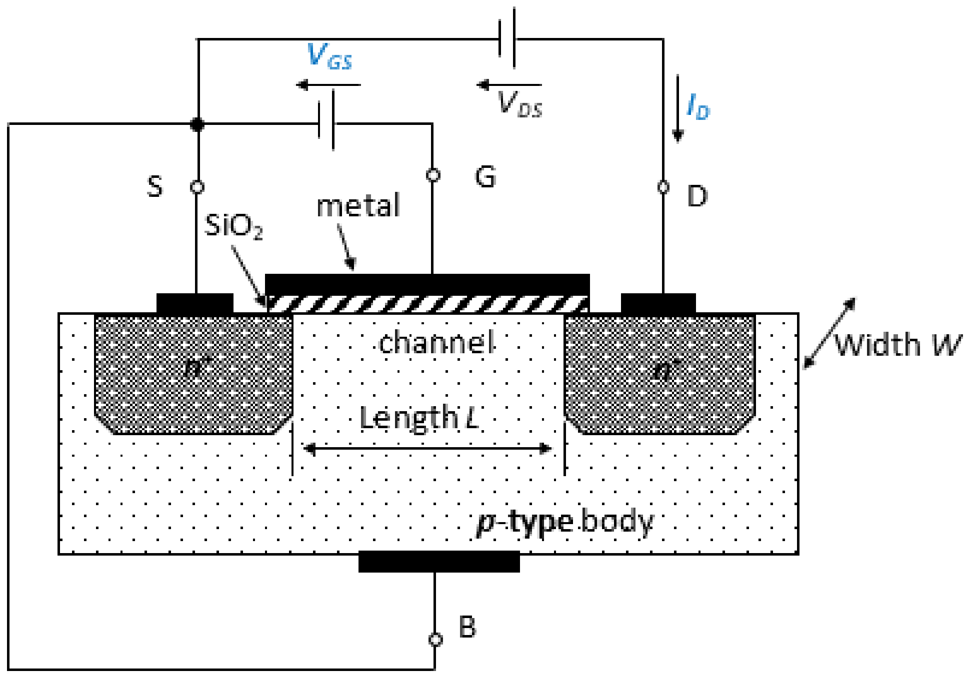
Structure and physical operation



Layers – metal, Silicon oxide (SiO_2) and a semiconductor substrate or body

- thickness of the oxide layer t_{ox} = 0.001 to 0.01 µm
- channel length L = 0.03 to 1 µm - distance between drain and source
- channel width W = 0.1 to 100 µm - how long the drain and the source regions are

Structure and physical operation

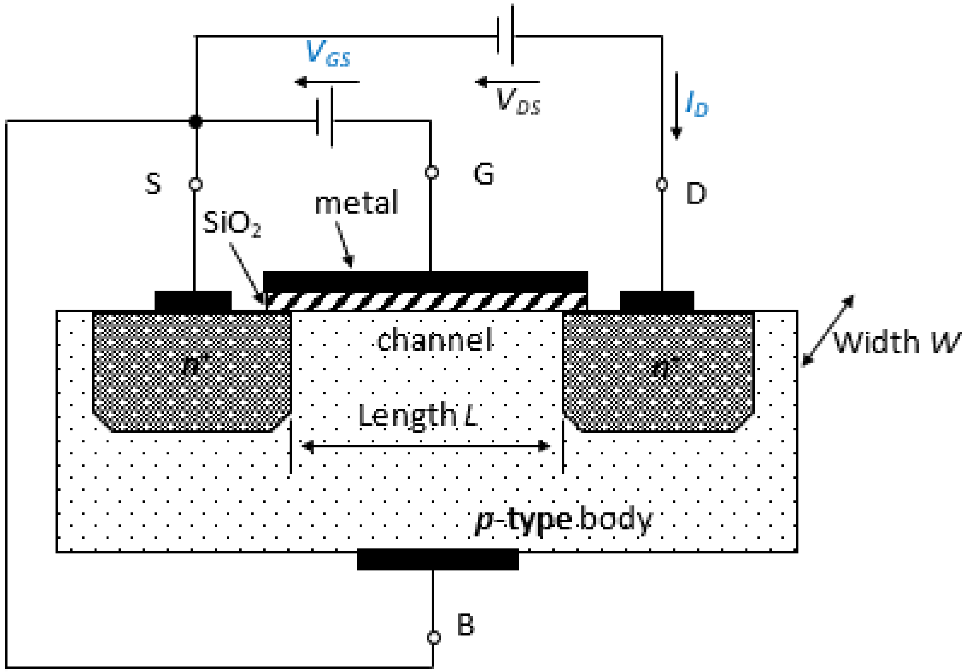


In order to have a drain-to-source current, two conditions must be fulfilled:

- creation of an *n-* type channel between the drain and source terminals
- existence of a positive potential difference between the drain and source to move the carriers

Structure and physical operation

OPTIONAL



V_{Th} – threshold voltage

$$V_{GS} < V_{Th}$$
$$V_{DS} = 0$$
$$I_D = 0$$

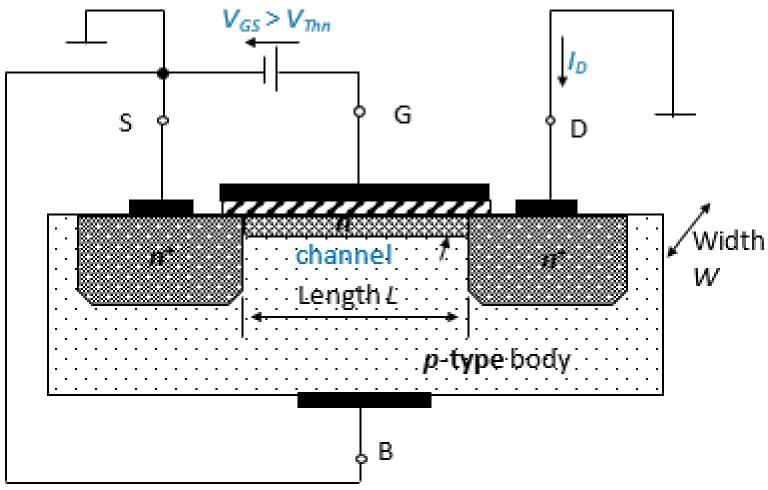
Operating region: cutoff (off)

No possibility for the current to flow from drain to source

No channel

Structure and physical operation

OPTIONAL



$$V_{GS} > V_{Th}$$
$$V_{DS} = 0$$
$$I_D = 0$$

Due to the electric field created by $V_{GB} > 0$ ($V_{GS} > 0$), the electrons in the substrate will be attracted and accumulated just under the oxide (gate region).

When V_{GS} is increased further, the electron concentration becomes larger than the hole concentration; this process is called population inversion.

Inversion creates a conducting n-channel between the drain and the source.

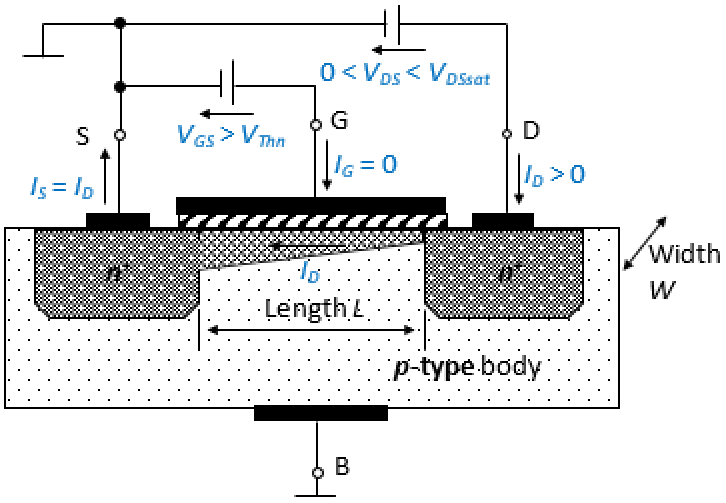
The gate voltage V_{GS} at which inversion produces an n concentration equal to the unbiased p concentration is called the threshold voltage V_{Th}.

Operating region: cutoff (off)

Channel is created, still no current

Structure and physical operation

OPTIONAL



$$V_{DSsat} = v_{GS} - V_{Th}$$

$$V_{GS} > V_{Th}$$
$$0 < V_{DS} < V_{DSsat}$$
$$I_D > 0$$

The current flows through the channel under the action of V_{DS} >0. The transistor operates in the linear (triode, extreme conduction) region - *exc*

The channel will become shallower at the drain end, because the electrons from the close vicinity of the drain region are attracted by the positive drain region.

$$I_D = \beta\left[2\left(V_{GS} - V_{Th}\right)V_{DS} - V_{DS}^2\right]$$

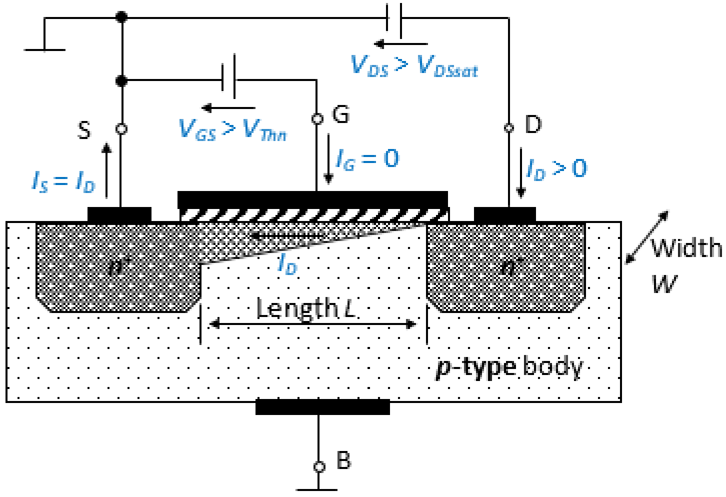
$$I_D = \frac{K}{2}\frac{W}{L}\left[2\left(V_{GS} - V_{Th}\right)V_{DS} - V_{DS}^2\right]$$

β – constructive parameter [$\mu A/V^2$]
K – transconductance parameter [$\mu A/V^2$]
W, L – physical dimensions of channel [μm]

The current depends linearly on V_{GS}, but also depends on V_{DS}.

Structure and physical operation

OPTIONAL



$V_{DS} > V_{DSsat}$

All the electrons from the close vicinity of the drain region are attracted by the more positive drain region.

The channel depth becomes zero at the drain end. The transistor is now in the pinch-off region or saturation region or active region (a_F)

I_D is almost independent of the V_{DS}. Conduction from the source to drain still occurs with current passing through the depletion region next to the drain.

$$V_{DSsat} = v_{GS} - V_{Th}$$

$$V_{GS} > V_{Th}$$
$$V_{DS} > V_{DSsat}$$
$$I_D > 0$$

$$I_D = \beta (V_{GS} - V_{Th})^2 \left(1 + \frac{V_{DS}}{V_A}\right) \cong \beta (V_{GS} - V_{Th})^2$$

$$I_D = \frac{K}{2} \frac{W}{L} (V_{GS} - V_{Th})^2 \left(1 + \frac{V_{DS}}{V_A}\right) \cong \frac{K}{2} \frac{W}{L} (V_{GS} - V_{Th})^2$$

The current depends non-linearly (quadratic) on V_{GS}

Structure and physical operation

➢ The current through MOSFET

$I_D = f(V_{GS}, V_{DS})$

Active region: $I_D = f(V_{GS}$ squared)

$$I_D = \beta \cdot (V_{GS} - V_{Thn})^2 \cdot (1 + \frac{V_{DS}}{V_A}) \approx \beta \cdot (V_{GS} - V_{Thn})^2$$

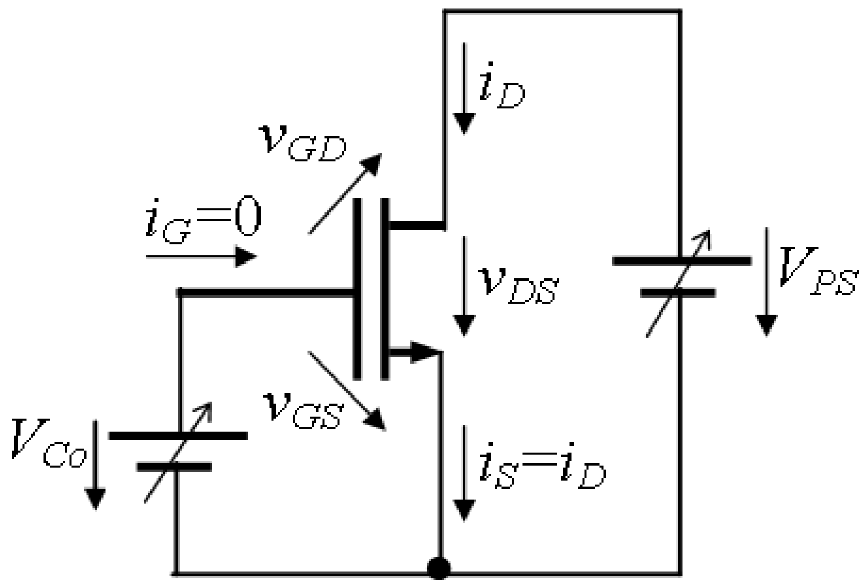
Linear region (exc): $I_D = f(V_{GS})$

$$I_D = \beta \cdot \left[2 \cdot (V_{GS} - V_{Thn}) \cdot V_{DS} - V_{DS}^2\right]$$

The current depends on

- V_{GS} - to create and enhance the conducting channel
- V_{DS} – to control the movement of the carriers (free electrons between D and S terminals)

- n-channel enhancement mode MOSFET



- Family of transfer characteristics

  $i_D(v_{GS}),\ v_{DS}$ as parameter

- Family of output characteristics

  $i_D(v_{DS}),\ v_{GS}$ as parameter

$$v_{GS}=v_{Co}$$
$$v_{DS}=V_{PS}$$

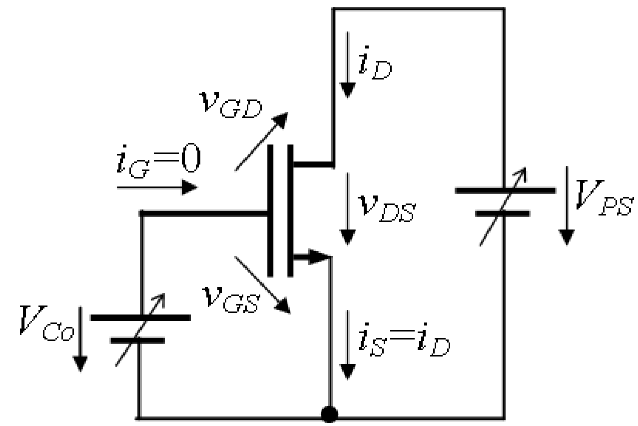
$$i_D+i_G=i_S$$
$$i_G=0$$
$$i_D=i_S$$

Transfer and output characteristics

➢ Transfer characteristics

$i_D(v_{GS}),\ v_{DS}$ as parameter

$V_{DSsat} = v_{GS} - V_{Th}$ drain-source saturation voltage



- Active (saturation) region (a_F)

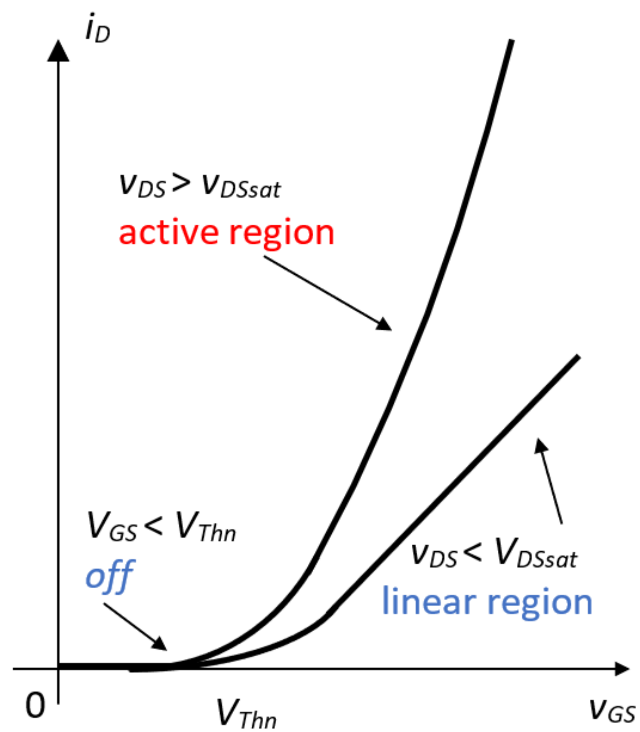
$v_{DS} > V_{DSsat}$ $$i_D = \beta(v_{GS} - V_{Th})^2$$

i_D – quadratic dependence on v_{GS}

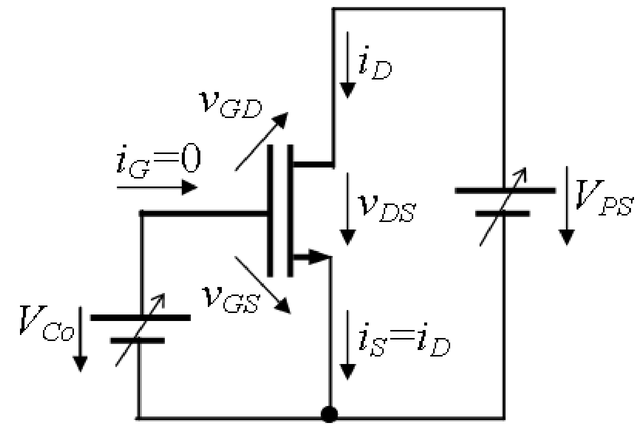
- Linear (triode) region (exc)

$v_{DS} < V_{DSsat}$ $$i_D = \beta[2(v_{GS} - V_{Th})v_{DS} - v_{DS}^2]$$

i_D – linear dependence on v_{GS}
- also influenced by the output voltage v_{DS}



Transfer and output characteristics



➢ Output characteristics

$i_D(v_{DS}),\ v_{GS}$ as parameter

$V_{DSsat} = v_{GS} - V_{Th}$ drain-source saturation voltage

- Active (saturation) region (a_F)

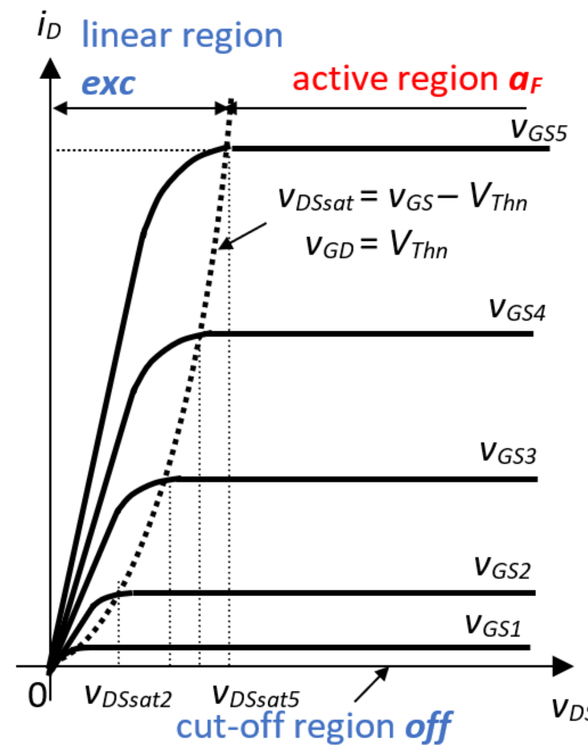
$v_{DS} > V_{DSsat}$ $i_D = \beta(v_{GS} - V_{Th})^2$

i_D – quadratic dependence on v_{GS}

- Linear (triode) region (exc)

$v_{DS} < V_{DSsat}$ $i_D = \beta[2(v_{GS} - V_{Th})v_{DS} - v_{DS}{}^2]$

i_D – linear dependence on v_{GS}
- also influenced by the output voltage v_{DS}



Operating regions

T – (off): $V_{GS} < V_{Th}$

$$i_D = 0$$

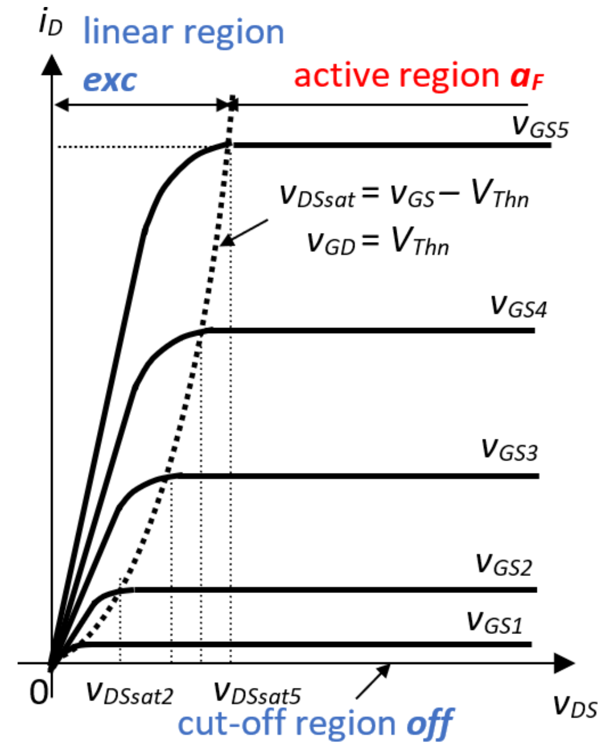
T – (a_F): $V_{Th} < V_{GS}$, $V_{DS} > V_{DSsat}$

$$i_D = \beta(v_{GS} - V_{Th})^2$$

Boundary (a_F) - (exc): $v_{DSsat} = v_{GS} - V_{Th}$

T – (exc): $V_{Th} < V_{GS}$, $V_{DS} < V_{DSsat}$

$$i_D = \beta[2(v_{GS} - V_{Th})v_{DS} - v_{DS}^{\ 2}]$$



Modes of use
- switching mode: (off) / (exc)
- as an amplifier: (a_F)
- voltage-controlled linear resistance (small v_{DS})

Operating regions

Linear region (exc):

$$i_D = \beta[2(v_{GS} - V_{Th})v_{DS} - v_{DS}^2]$$

Saturation (active) region (a_F):

$$i_D = \beta(v_{GS} - V_{Th})^2$$

β – parameter of the MOSFET - beta factor
- measured in $\mu A/V^2$, mA/V^2, A/V^2
- constructive parameter

For integrated transistors:

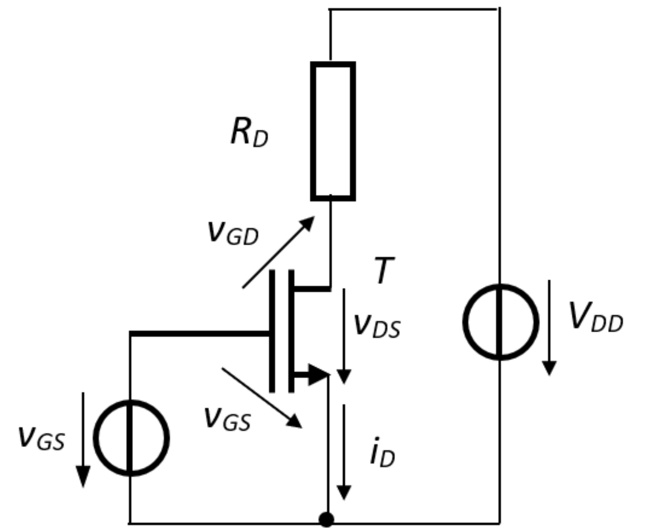
$$\beta = \frac{K}{2}\frac{W}{L}$$

$$i_D = \frac{K}{2}\frac{W}{L}\left(v_{GS} - V_{Th}\right)^2$$

In the active region

K – transconductance parameter [$\mu A/V^2$]
W - the width of the channel [μm]
L - the length of the channel [μm]

Example – 1



a) Determine the operating region of T for V_{DD} = 12 V, V_{Thn} = 1.4 V, β = 2 mA/V^2, R_D = 4 kΩ, and:

i) V_{GS} = 1 V;

ii) V_{GS} = 2 V;

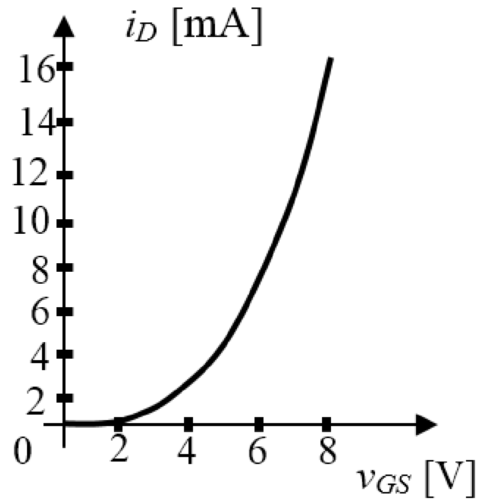
iii) V_{GS} = 6 V.

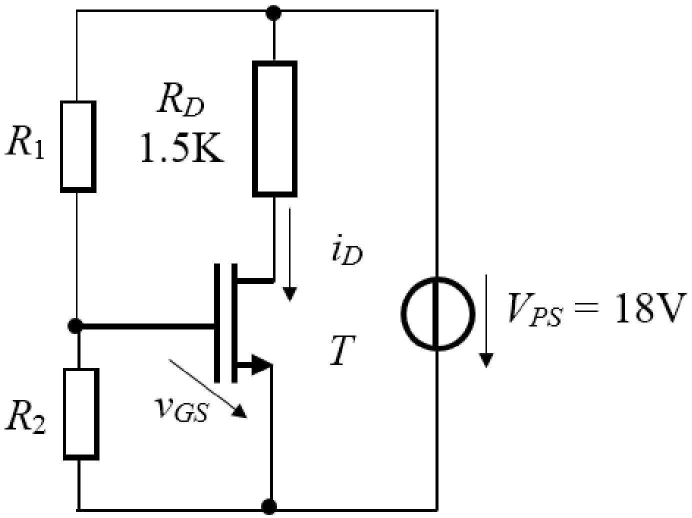
Compute I_D and V_{DS} for each of the above cases.

b) What is the minimum value of v_{GS} so that T stays in (exc)?

c) Propose a method to obtain V_{GS} = 2 V from V_{DD}. Size the newly added components.

Example - 2





a) Determine the operating region of the transistor for:

i) R_1 = 4.5 MΩ; R_2 = 0.5 MΩ;

ii) R_1 = 12 MΩ; R_2 = 6 MΩ;

b) What can be the range for R_1 with R_2 = 0.5 MΩ so that the transistor is (on)?

Summary

The MOSFET is no longer a random acronym, after digging into:

- Symbols
- Structure and physical operation
- Operating principle
- Transfer and output characteristics
- Operating regions
- Examples

Next week: Recap. Preparation for exam.