ELECTRONIC DEVICES

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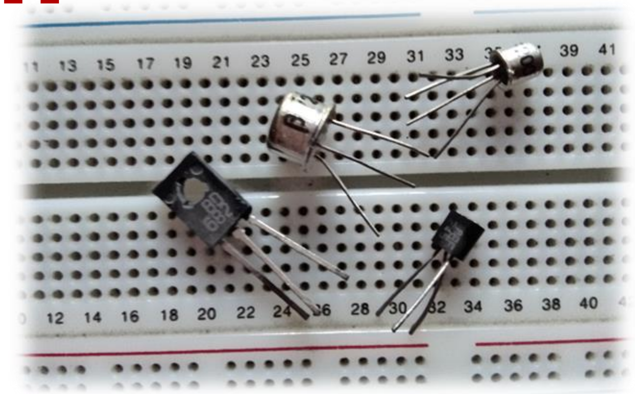
C13 – MOSFET operation



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-type

p-channel enhancement-type

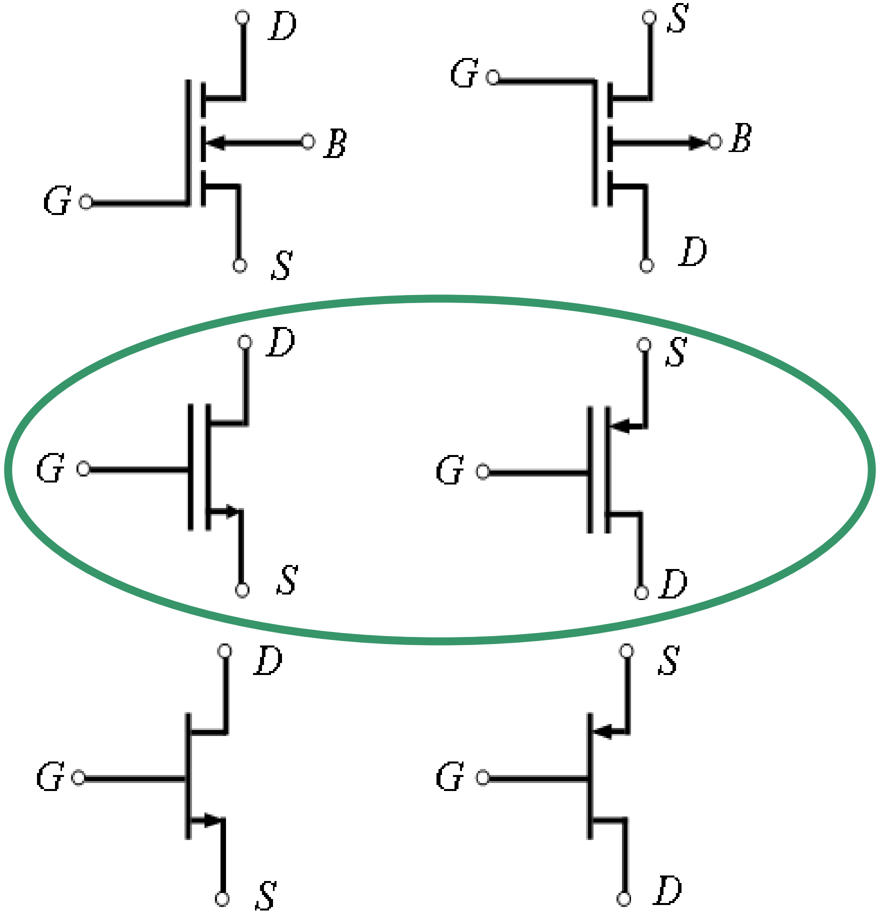
general symbols

(w/ B substrate terminal)

simplified symbols

(B internally connected to S)

other symbols

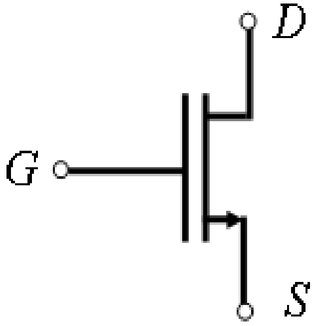


Symbols

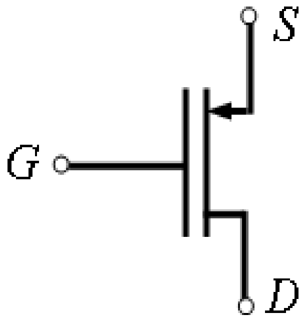
Metal-oxide-semiconductor field effect transistors (MOSFETS)

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

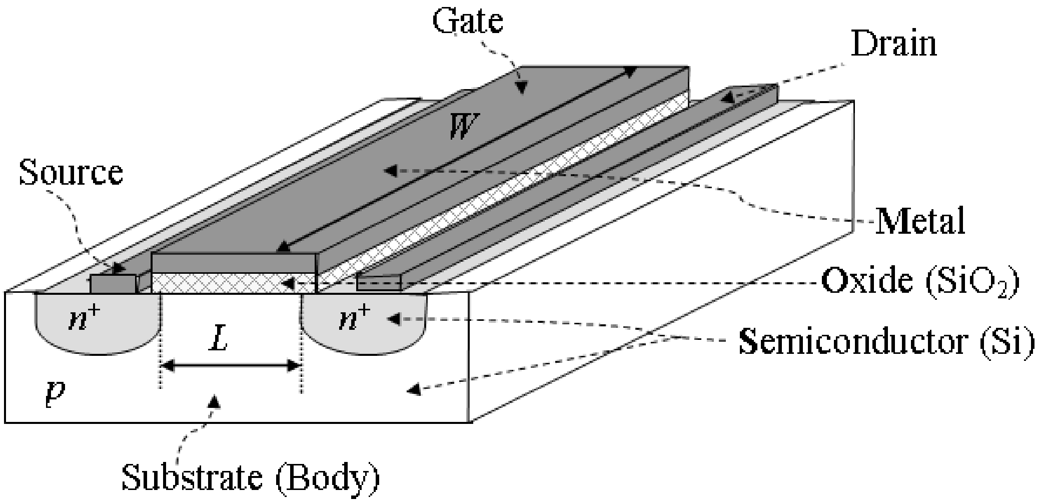
n-channel enhancement-type

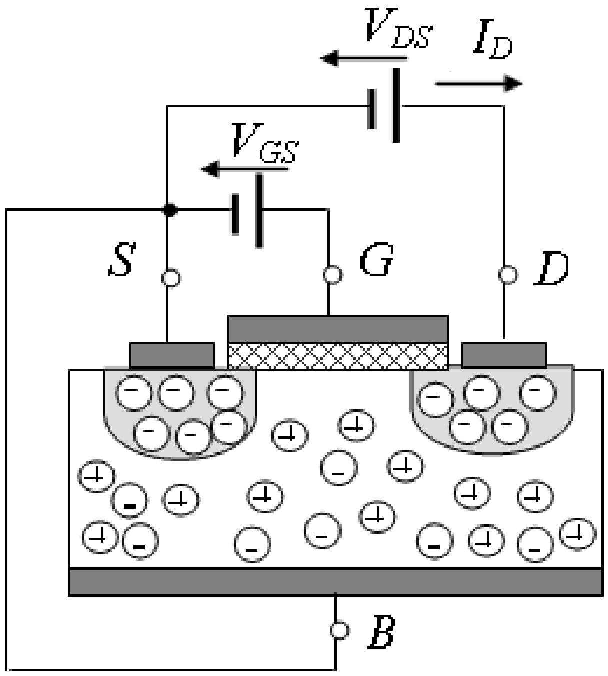


p-channel enhancement-type



Structure and physical operation

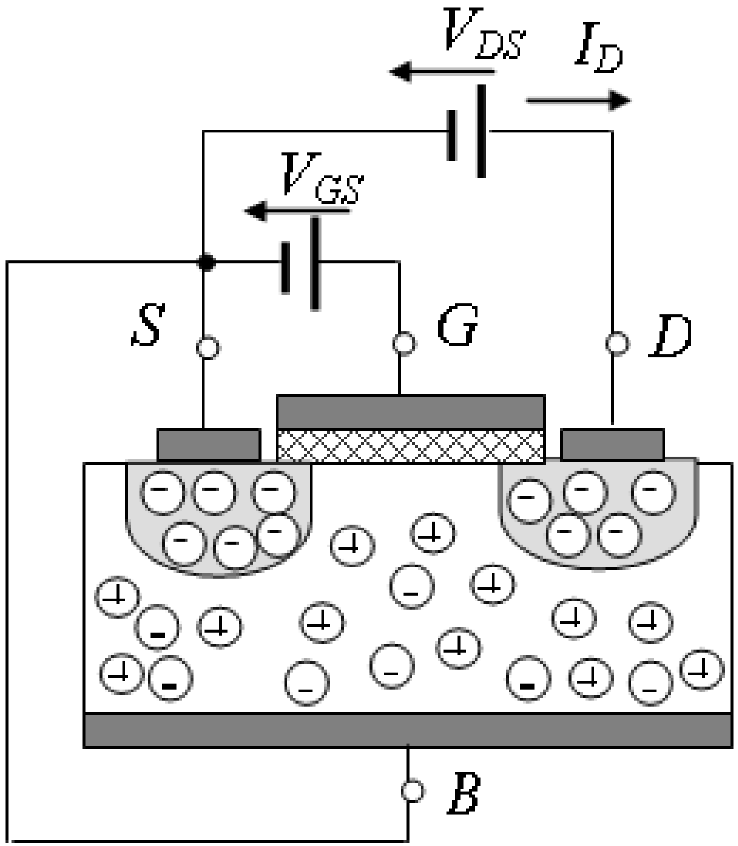




In order to have a drain-to-source current, two conditions must be fulfilled:

- 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

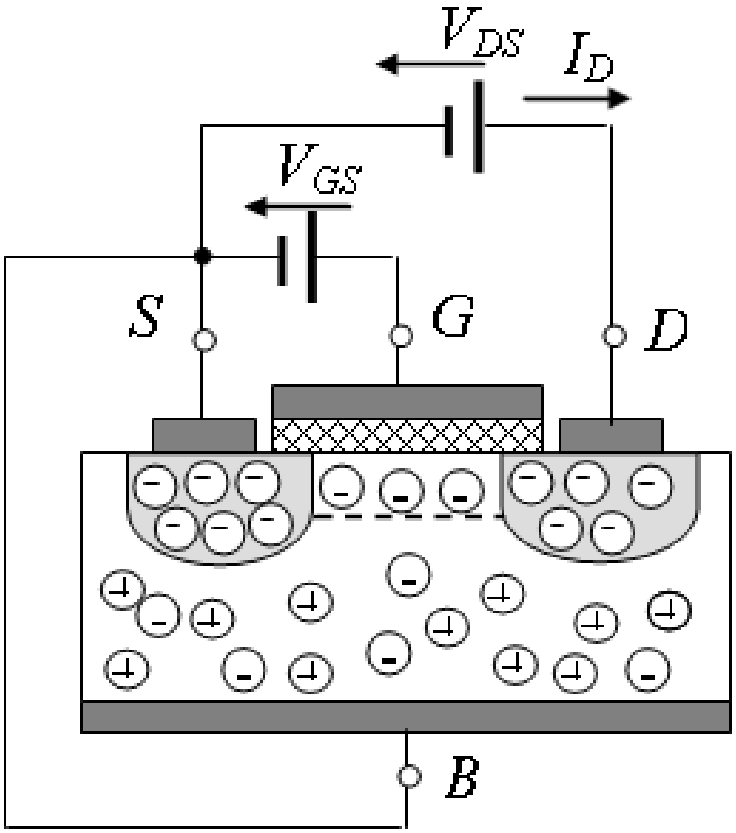
V_{Th} – threshold voltage

$$\boxed{\begin{array}{l} V_{GS} < V_{Th} \\ V_{DS} = 0 \\ I_D = 0 \end{array}}$$

No possibility for the current to flow from drain to source

No channel

Structure and physical operation



$$V_{GS} > V_{Th}$$

$$V_{DS} = 0$$

$$I_D = 0$$

OPTIONAL

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).

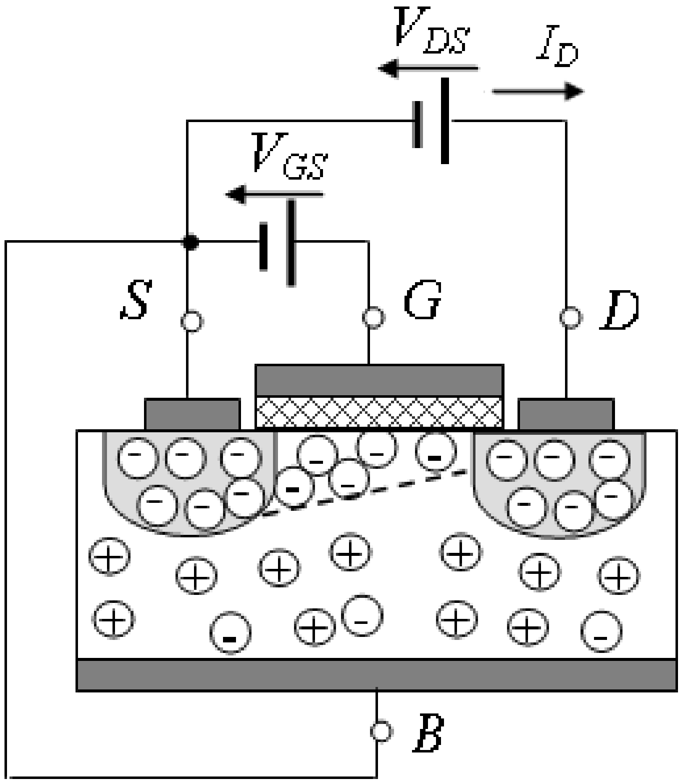
When V_{GS} is increased further, the electron concentration becomes larger than the hole concentration; this process is called population inversion.

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}.

Structure and physical operation

OPTIONAL



The current flows through the channel under the action of $V_{DS} > 0$. The transistor operates in the linear region.

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

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

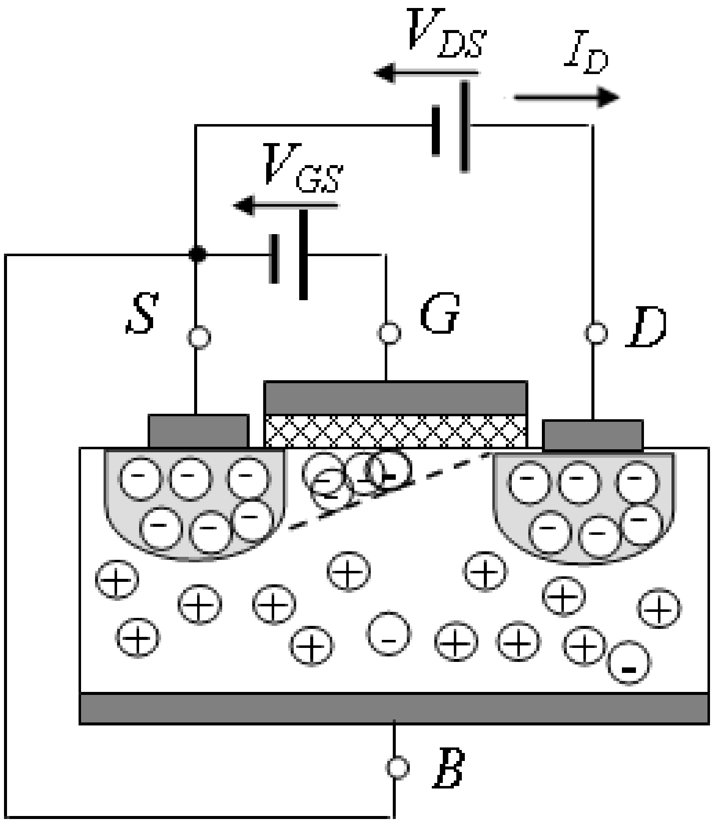
$$I_D = \frac{K}{2}\frac{W}{L}\left[2\left(V_{GS} - V_{Th}\right)V_{DS} - V_{DS}^2\right]$$

$$\boxed{\begin{array}{l} V_{GS} > V_{Th} \\ 0 < V_{DS} < V_{DSsat} \\ I_D > 0 \end{array}}$$

β – constructive parameter [μA/V²]
K – transconductance parameter [μA/V²]
W, L – physical dimensions of channel [μm]

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

Structure and physical operation



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

OPTIONAL

The V_{DS} voltage is greater than the V_{DSsat} voltage.

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.

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.

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

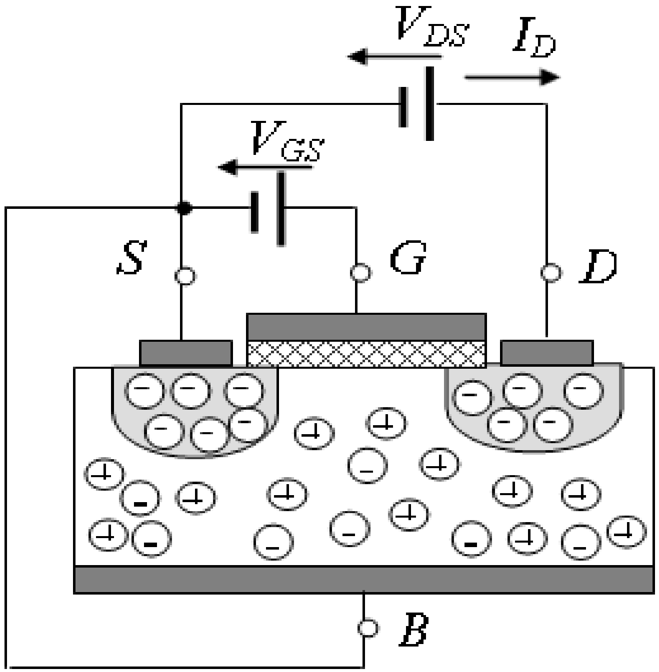
$$I_D = \frac{K}{2}\frac{W}{L}(V_{GS} - V_{Th})^2 \left(1 + \frac{V_{DS}}{V_A}\right) \cong \frac{K}{2}\frac{W}{L}(V_{GS} - V_{Th})^2$$

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

Structure and physical operation

➢ The current through MOSFET

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

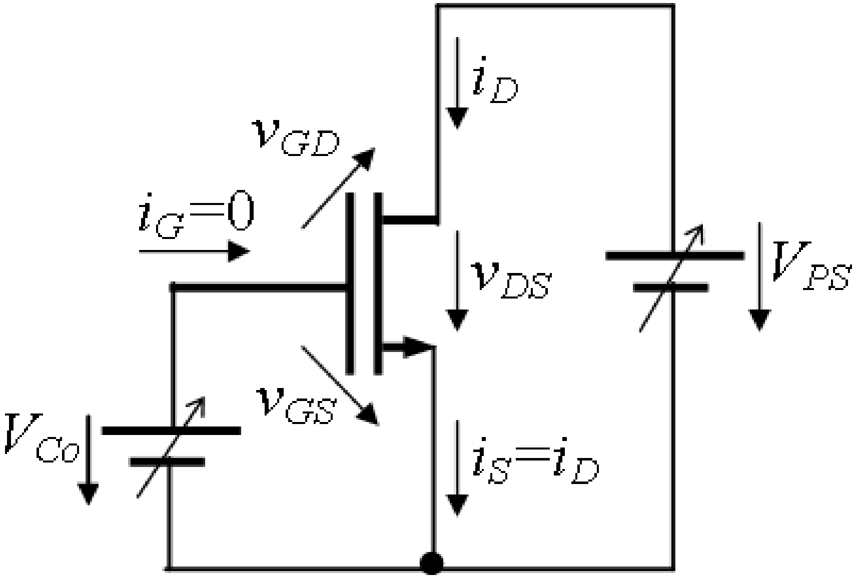


The current depends on

- V_{GS} - conducting channel building (enhancement)
- V_{DS} – controlled movement of the carriers (free electrons between D and S terminals)

Operating principle

- n-channel enhancement type 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

- Saturation region (a_F)

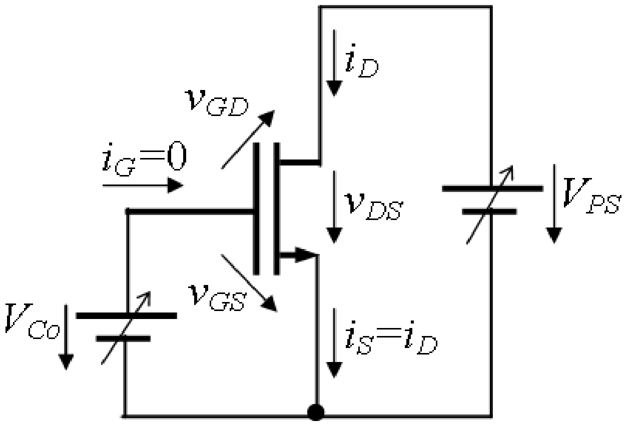
$$v_{DS} > V_{DSsat} \quad \boxed{i_D = \beta(v_{GS} - V_{Th})^2}$$

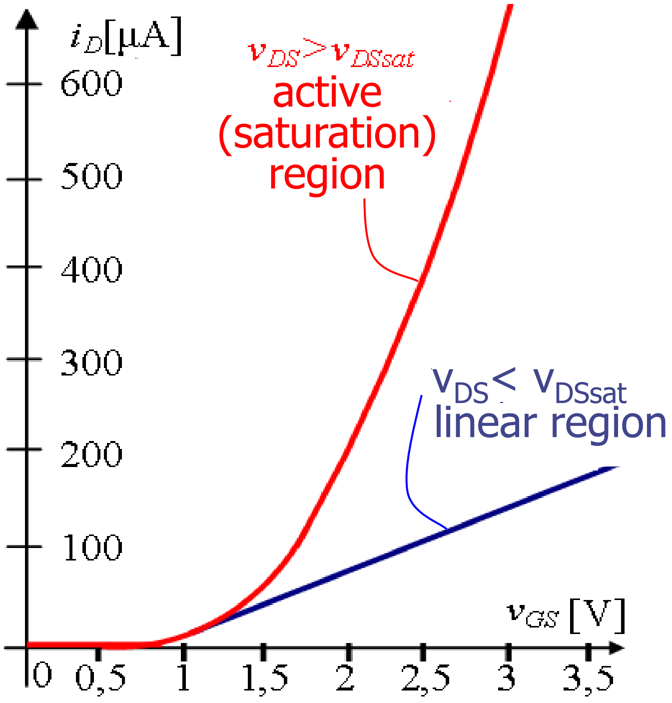
i_D – quadratic dependence on v_{GS}

- Linear region (exc)

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

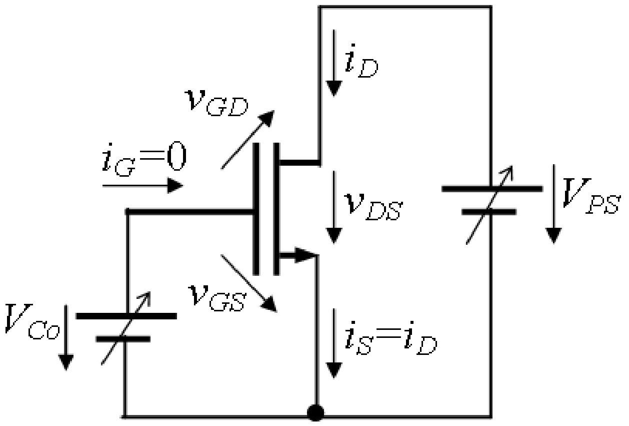
i_D – linear dependence on v_{GS}
- also influenced by the output voltage v_{DS}





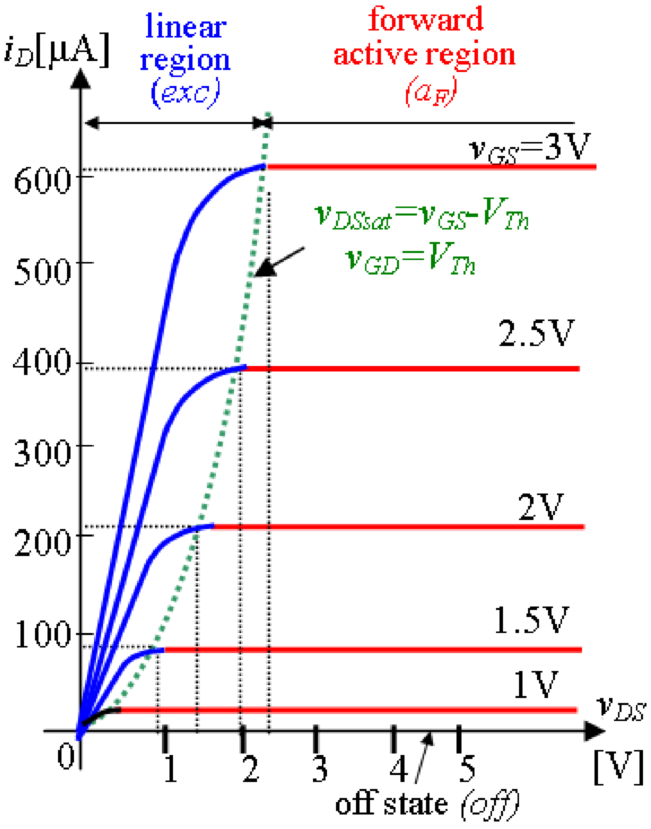
V_{Th}= 0.58 V, β = 104 μA/V²

Transfer and output characteristics



➢ Output characteristics

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



- Saturation region (a_F)

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

i_D – quadratic dependence on v_{GS}

- Linear region (exc)

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

i_D – linear dependence on v_{GS}

- also influenced by the output voltage v_{DS}

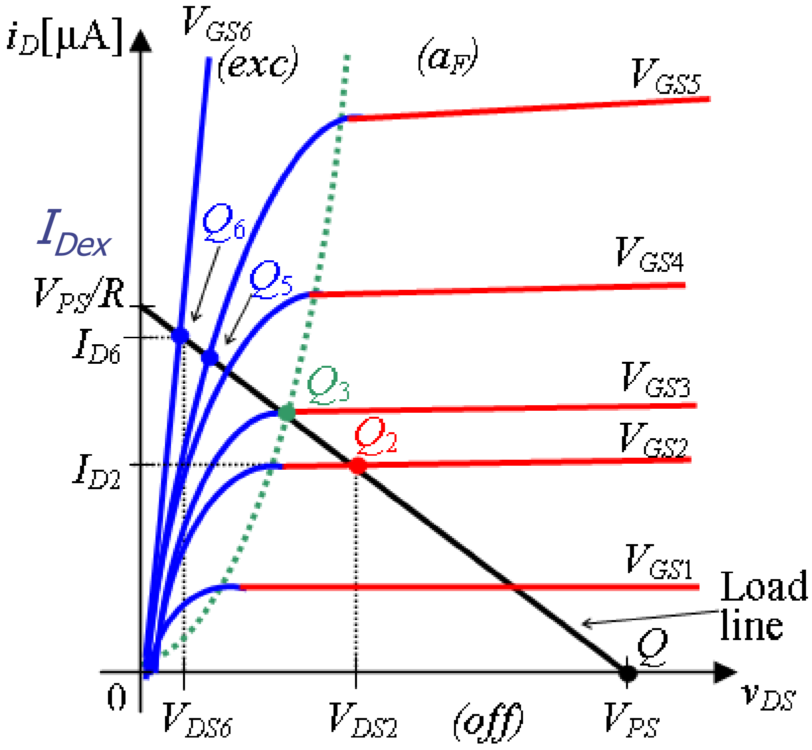
Quiescent point

Quiescent point Q = a point on the output characteristic $i_D(v_{DS})$ of MOSFET

- Q is defined by V_{DS} and I_D
- $Q(V_{DS}, I_D)$ is at the intersection between the load line and the output characteristic corresponding to v_{GS}

Load line:

$v_{DS} = V_{PS} - R_D\, i_D$



Operating regions

T – (off): $V_{GS} < V_{Th}$

$$i_D = 0$$

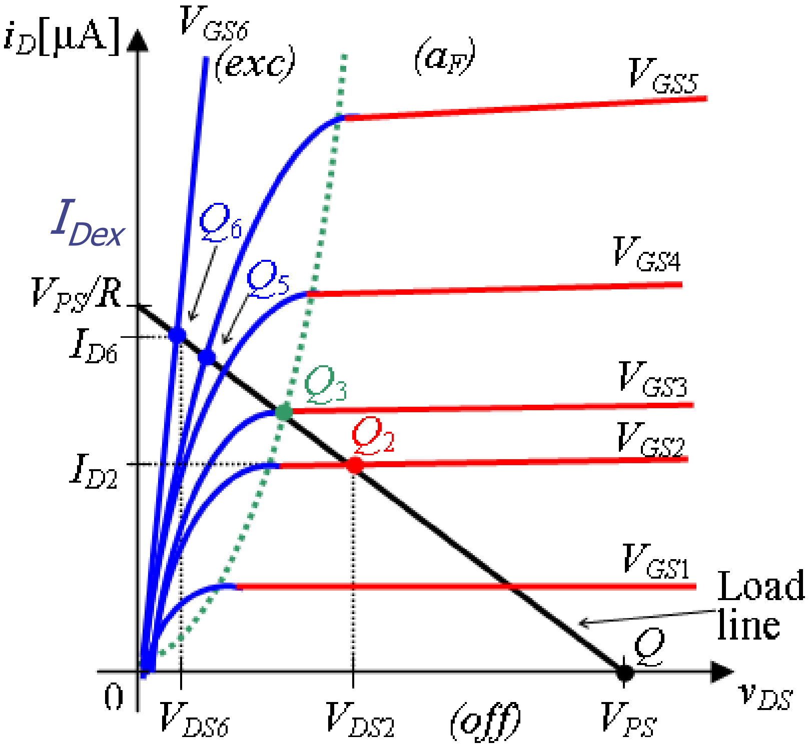
T – (a_F): $V_{Th} < V_{GS} < V_{GS3}$

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

Boundary (a_F) - (exc): $v_{DS,sat} = v_{GS} - V_{Th}$

T – (exc): $V_{GS} > V_{GS3}$

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



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 μA/V², mA/V², A/V²
- constructive parameter

For integrated transistors:

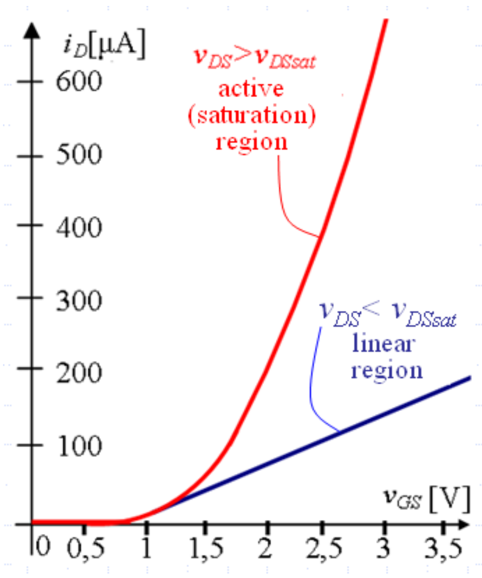
$$\beta = \frac{K}{2}\frac{W}{L}$$

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

In the active region

K – transconductance parameter [μA/V²]
W - the width of the channel [μm]
L - the length of the channel [μm]

Examples



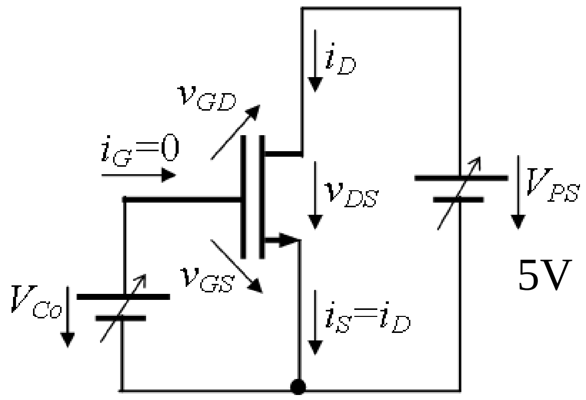
➢ Example - 1

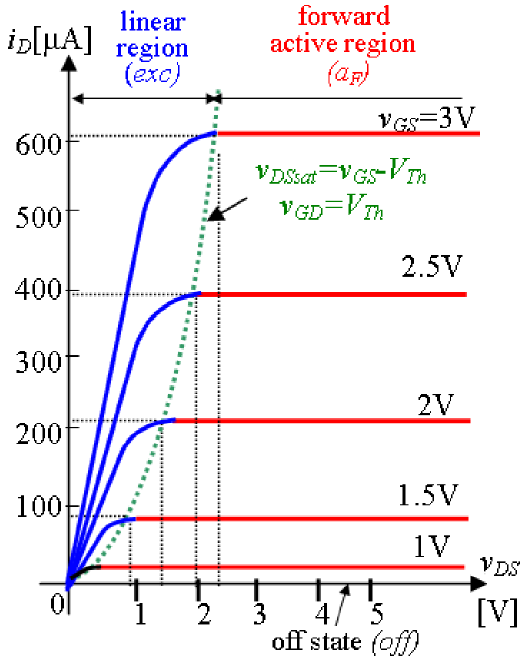
Compute the values of V_{GS}, I_D, V_{DS}, V_{GD}, V_{DSsat} for:

- i) $v_{Co} = 0.5$ V;
- ii) $v_{Co} = 2.5$ V;
- iii) $v_{Co} = 2.75$ V.

Place the quiescent points Q(V_{DS}, I_D) in the plan of output characteristics.

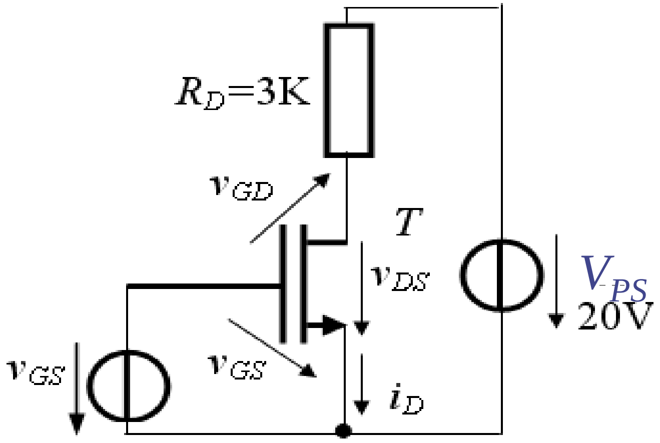
Find the operating regions of T.





Examples

➢ Example - 2



a) What is the operating region of T for:

- i) $v_{GS} = 0.8$ V;
- ii) $v_{GS} = 2.5$ V;
- iii) $v_{GS} = 4$ V.

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

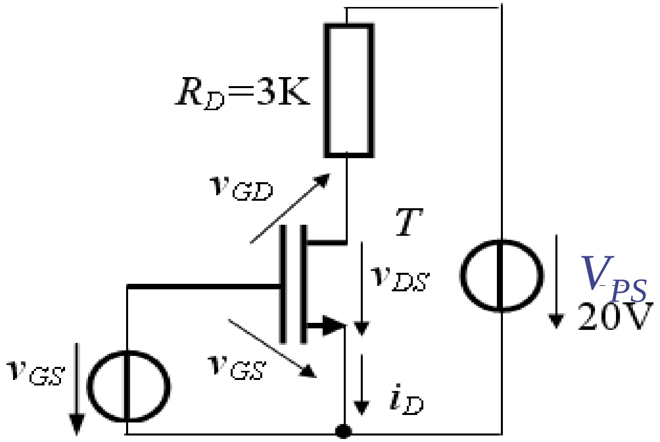
$B = 2\ \text{mA/V}^2$

$V_{Th} = 1$ V

Examples

Example - 2

Solution:



$B = 2\ mA/V^2$
$V_{Th} = 1\ V$

a)

i) Because $v_{GS} < V_{Th}$ => T - (off)

ii) $v_{GS} > V_{Th} \Rightarrow$ T is on, in (a_F) or in (exc)

- Assume T in (a_F), so that $i_D = \beta(v_{GS} – V_{Th})^2$
- Compute v_{DS}
- Compare v_{DS} with v_{DSsat} :

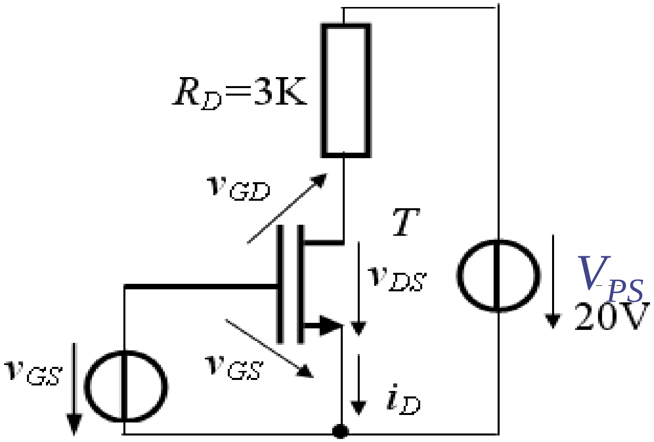
If $v_{DS} > v_{DSsat}$, the assumption was true, and T is in (a_F)
If $v_{DS} < v_{DSsat}$, the assumption was false, and T is in (exc)

Examples

Example - 2

Solution:

a) ii)



$B = 2\ mA/V^2$
$V_{Th} = 1\ V$

$i_D = 2(2.5 - 1)^2 = 4.5mA$

$v_{DS} = V_{PS} - R_D\ i_D$

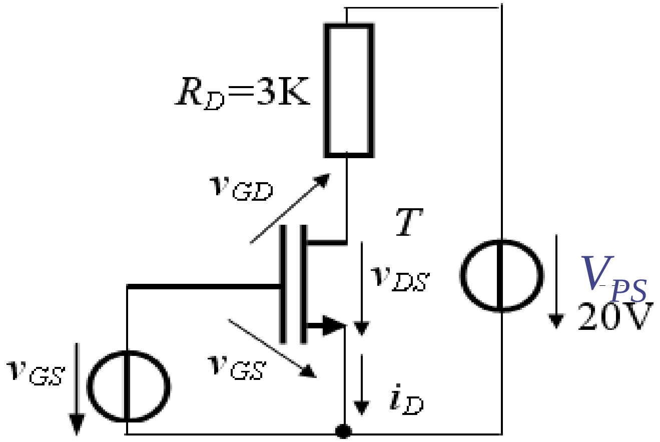
$v_{DS} = 20 - 3 \cdot 4.5 = 6.5\ V$

$v_{DS\ sat} = v_{GS} - V_{Th} = 2.5 - 1 = 1.5\ V$

$v_{DS} > v_{Dssat}$, T is in (a_F)

$v_{GD} = v_{GS} - v_{DS} = 2.5 - 6.5 = -4V < V_{Th}$

Examples



➢ Example - 2

Solution:

a) iii) $v_{GS} > V_{Th} \Rightarrow$ T is on, in (a_F) or in (exc)

- Assume T in (a_F), so that $i_D = \beta(v_{GS} - V_{Th})^2$

$$i_D = 2(4 - 1)^2 = 18 \text{ mA}$$

- Compute v_{DS} $\quad v_{DS} = 20 - 3 \cdot 18 = -34$ V
- Compare v_{DS} with v_{DSsat} :

$v_{DS\ sat} = v_{GS} - V_{Th} = 4 - 1 = 3$ V $\qquad v_{DS} < v_{DSsat}$, T is in (exc)

B = 2 mA/V^2
V_{Th} = 1 V

Alternative method: compare the value of i_D in (a_F) with i_{Dex}

$$i_{Dex} = \frac{V_{PS} - v_{DS,ex}}{R} \approx \frac{V_{PS}}{R} = \frac{20}{3} = 6.67\text{mA}$$

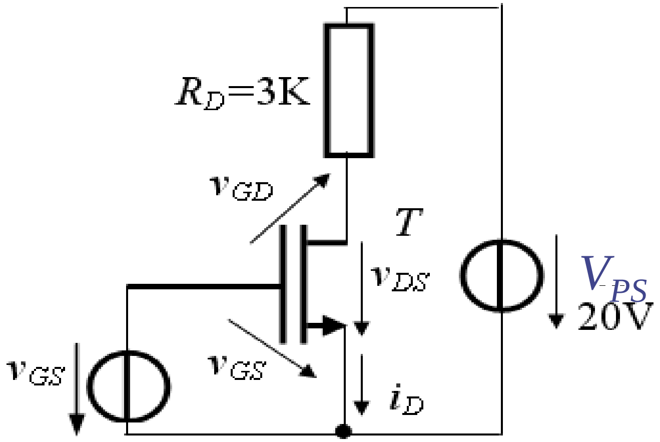
i_D = 18 mA > i_{Dex} = 6.67 mA $\Rightarrow$ T - (exc)

What is the actual value of i_D?

Examples

➢ Example - 2

Solution:



b) Minimum value of v_{GS} so that T stays in (exc)

$B = 2\ mA/V^2$
$V_{Th} = 1\ V$

The operating point of T is placed on the v_{DSsat} curve:

$v_{DSsat} = V_{PS} - Ri_D$

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

$V_{PS} - Ri_D = v_{GSmin} - V_{Th}$

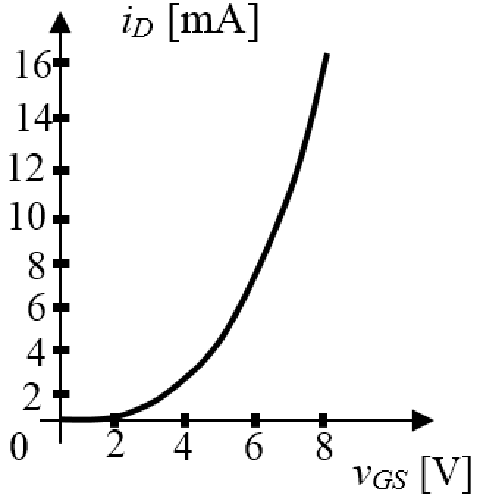
$i_D = \beta(v_{GSmin} - V_{Th})^2$

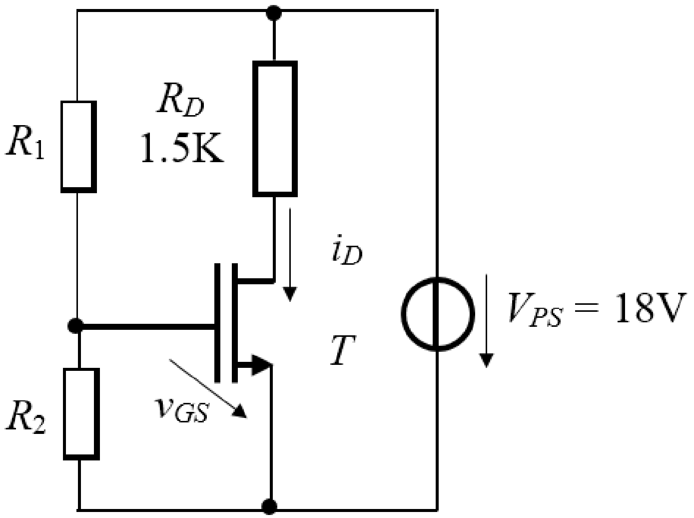
$R\ \beta(v_{GSmin} - V_{Th})^2 + (v_{GSmin} - V_{Th}) - V_{PS} = 0$

Two solutions for v_{GSmin}, choose the convenient one: $v_{GSmin} > V_{Th}$

$V_{GSmin} = 2.744\ V$

Example - 3





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
- Quiescent point
- Operating regions
- Examples

Next week: Recap. Preparation for exam.

To do: Homework 10