Universidad Carlos III de Madrid
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Session 13
Introduction to Field Effect Transistors (FET)

Electronic Components and Circuits

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Field Effect Transistors FET

OBJECTIVES

- To know the structure of the device and the transistor effect
- To know and distinguish different FET transistor types
- To understand the current-voltage characteristic of the device
- To identify the operating regions
  - Cut-off, Saturation, Ohm (triode)
- To analyze FET circuits basic cases in DC
- To know small-signal model for FET transistors

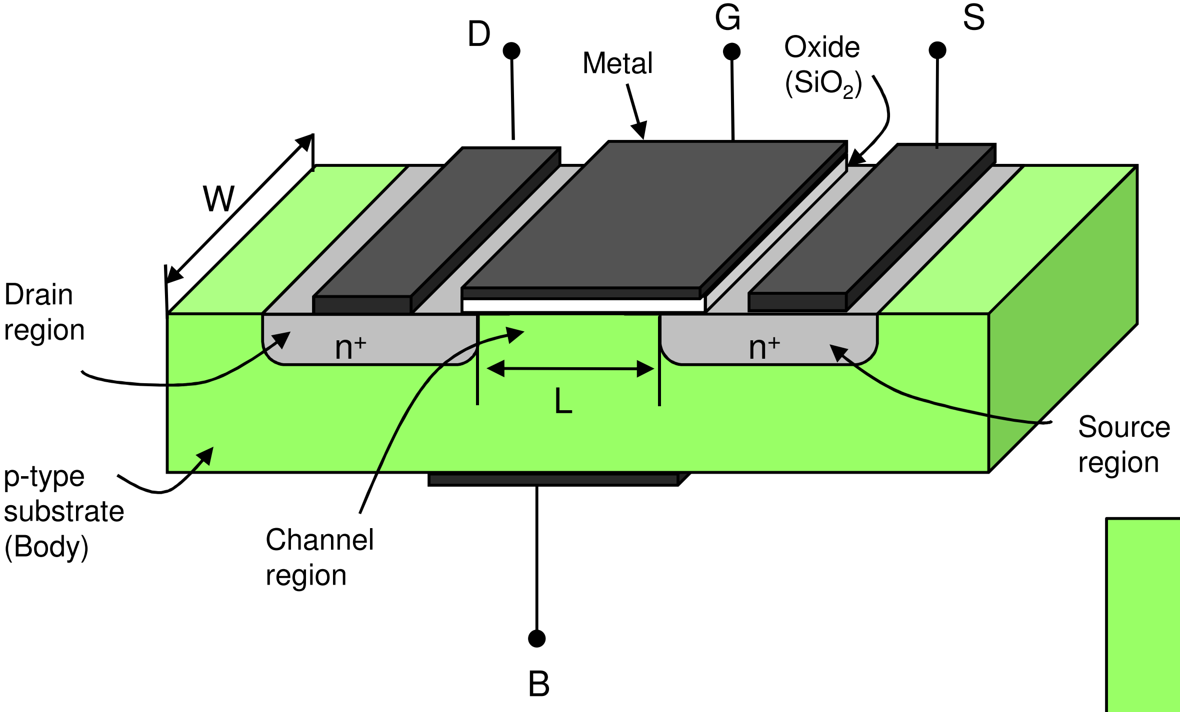
Field Effect Transistors (FET)

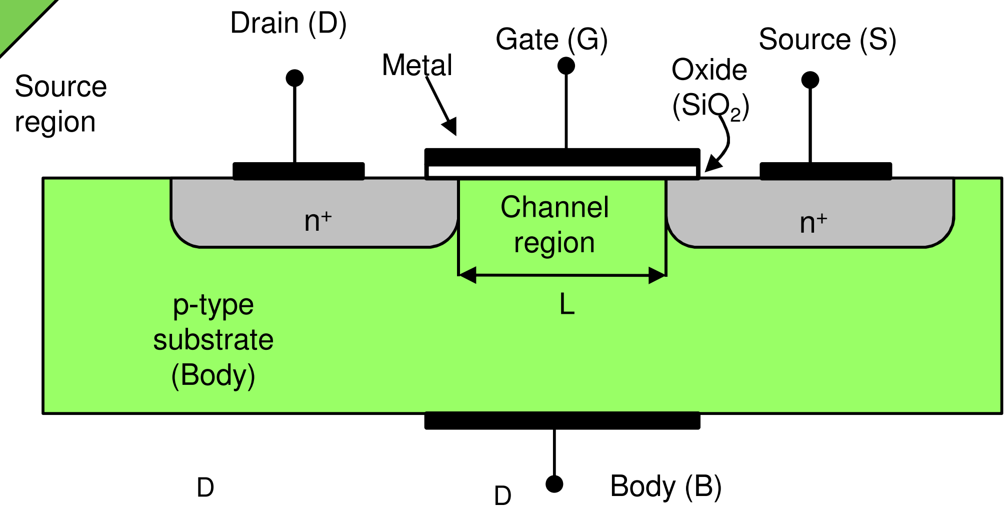
Types	Mode	Channel
MOSFET **(Metal-Oxide Semiconductor FET)**	**Enhancement/ Accumulation**	Channel N (or N-MOS) Channel P (or P-MOS)
	Depletion	Channel N (or N-MOS) Channel P (or P-MOS)
JFET **(Joint FET)**	**Junction**	Channel N Channel P

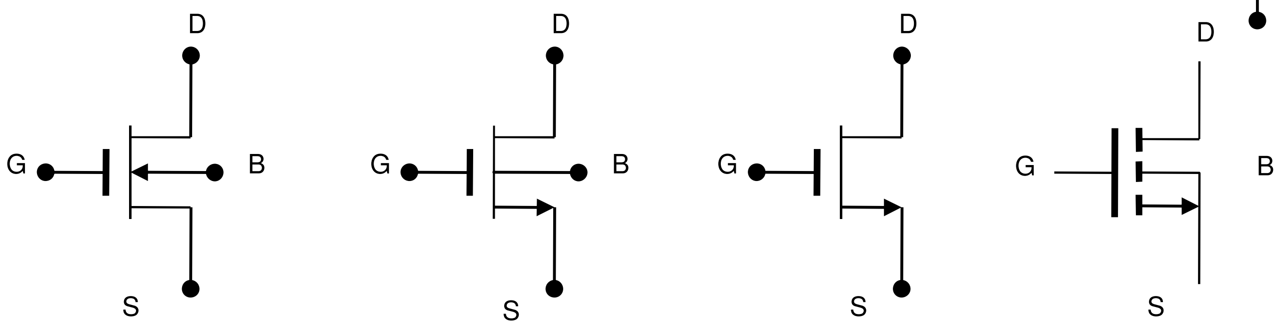
Basic characteristics

- Unipolar: only one carrier type (electrons in N-channel and holes in P-channel)
- Control of *Current (I)* through *Voltage* (V) (BJT devices control I through I)
- Three terminals:
  - Source (S): provides carriers
  - Gate (G): controls carriers flow
  - Drain (D): receives carriers

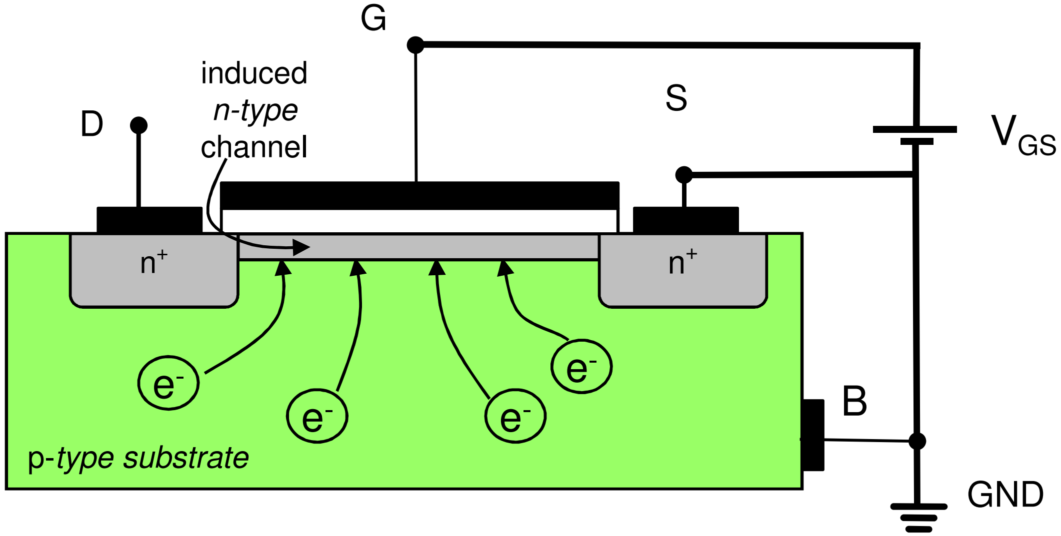
Structure of Channel-n Enhancement MOS Transistor

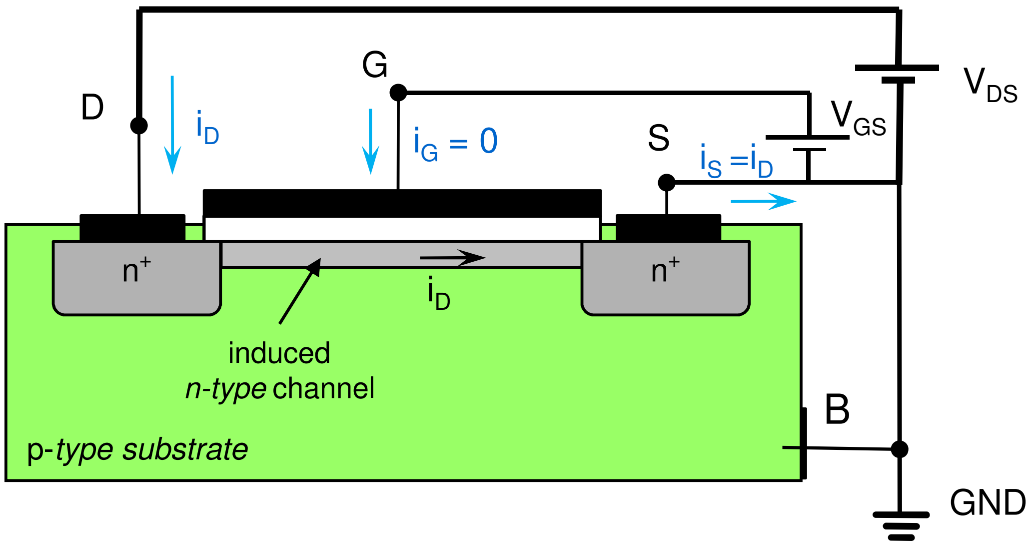




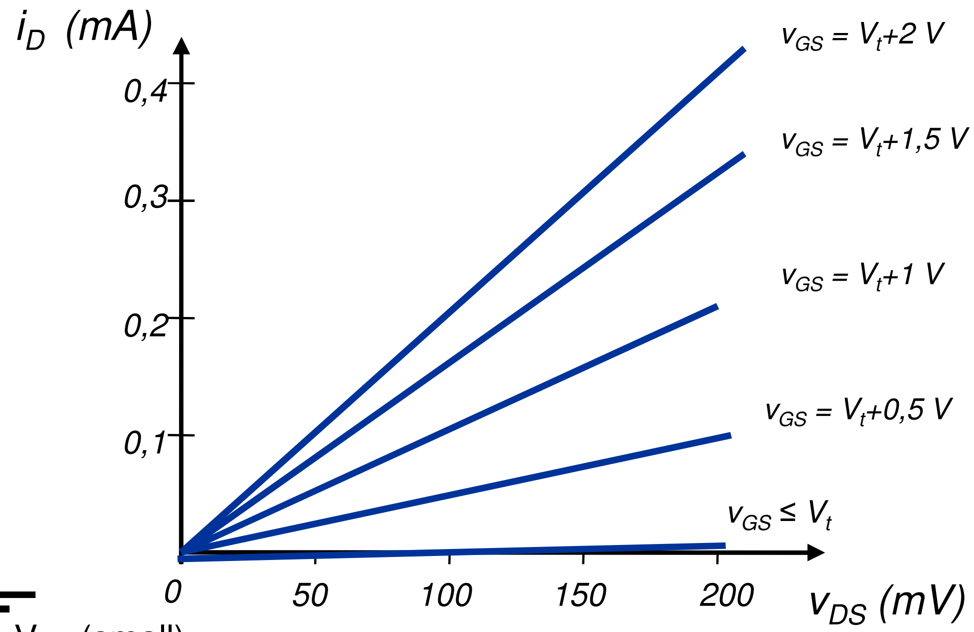


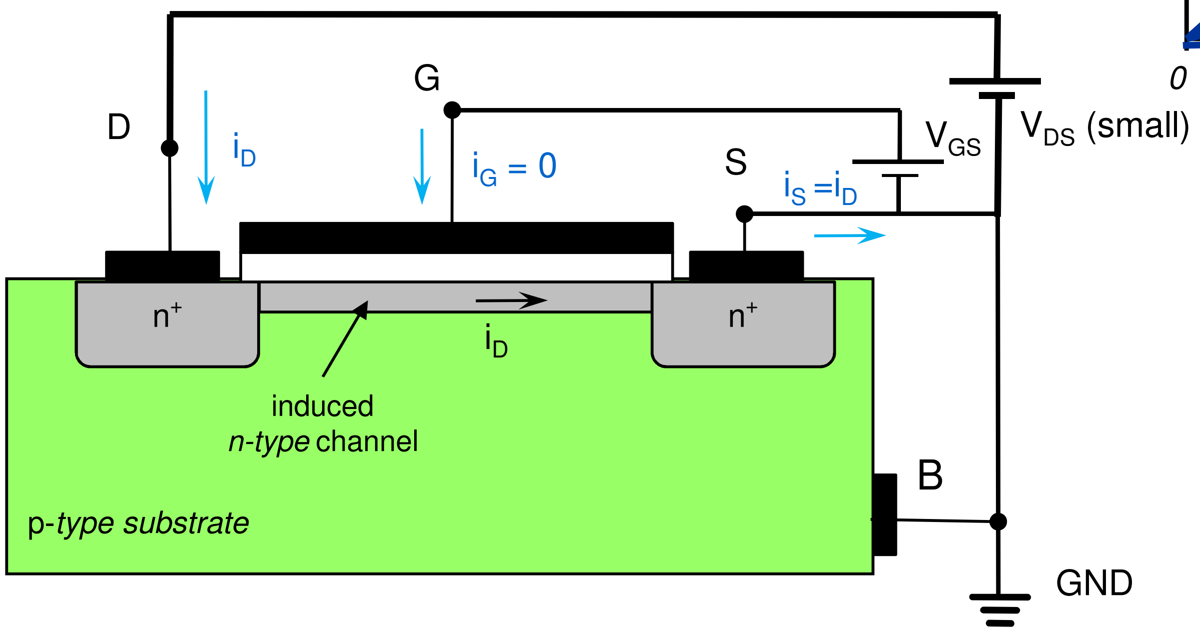
n-MOS Transistor Operation



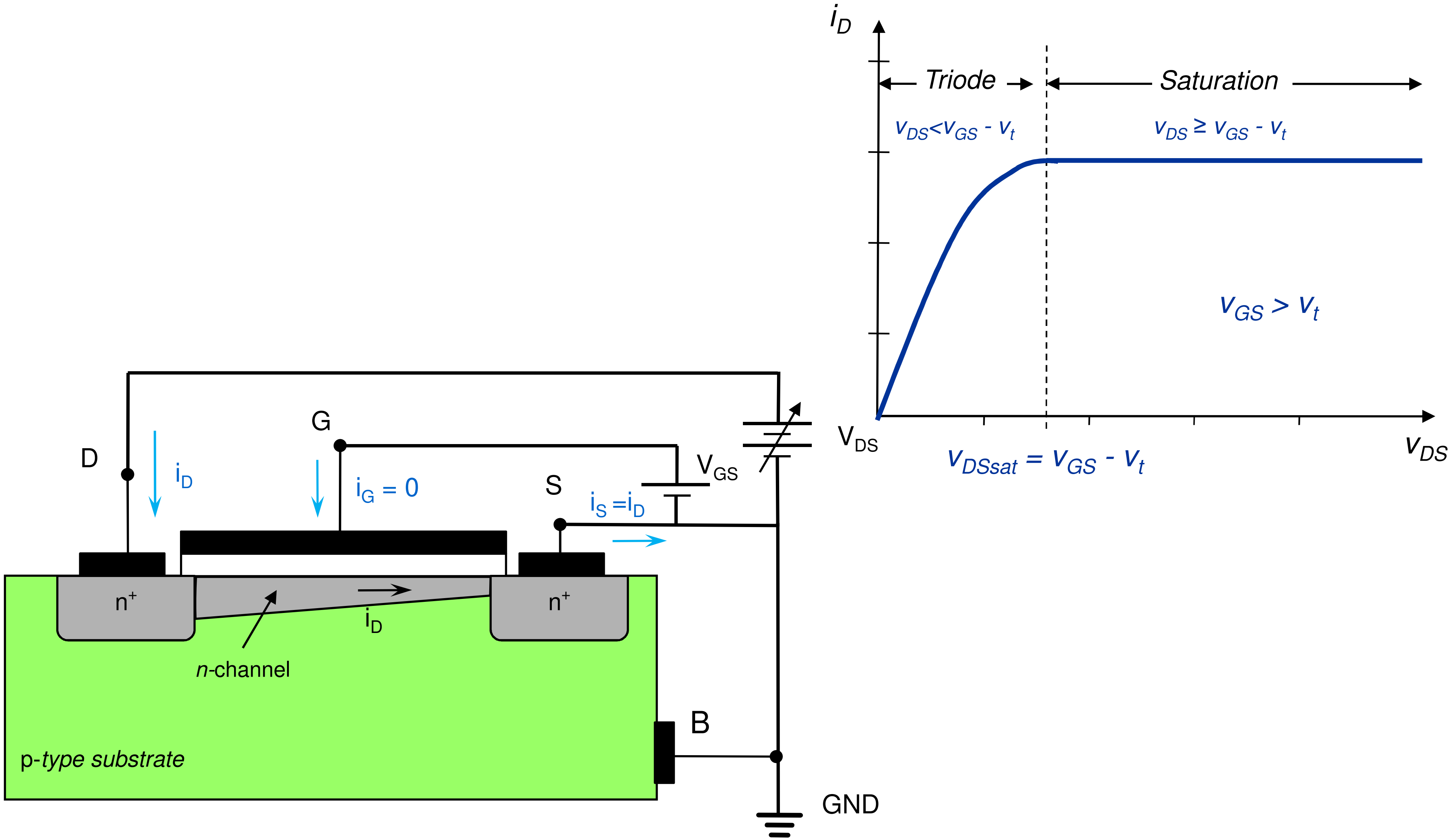


n-MOS Operation: Triode region

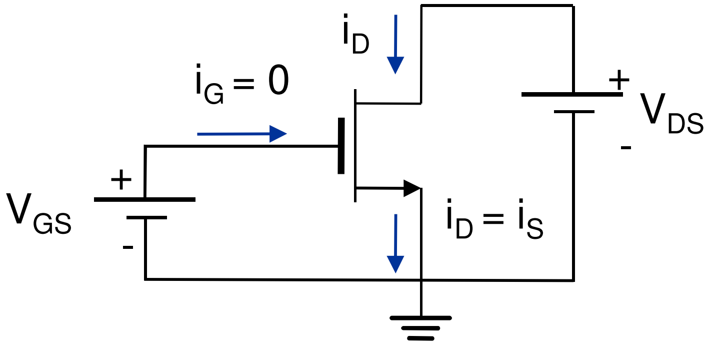


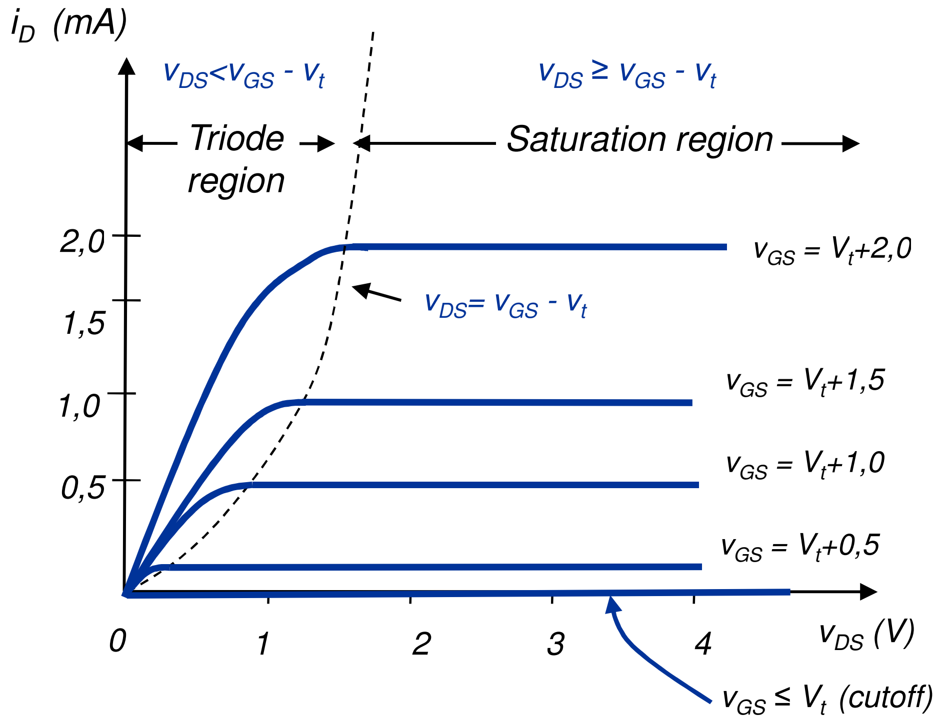


n-MOS Operation: Saturation region



Current-Voltage Characteristic





- Triode region

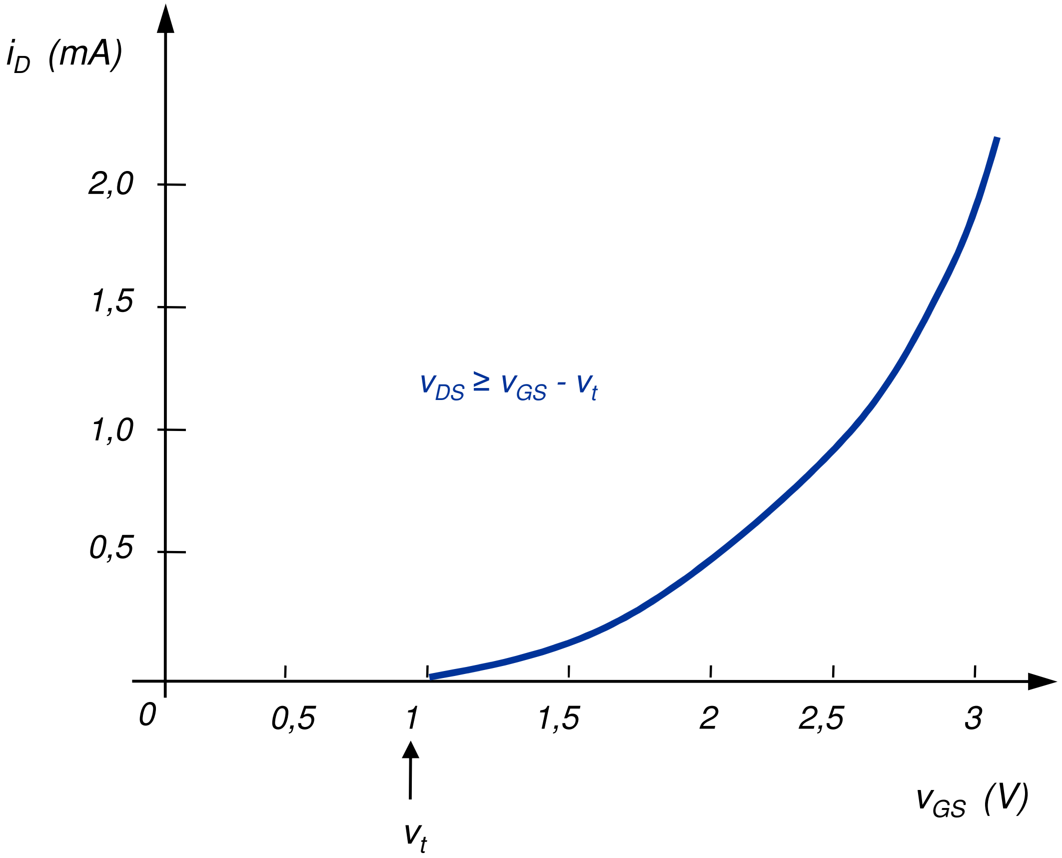
$$i_D = K\left[2(V_{GS} - V_t)V_{DS} - V_{DS}{}^2\right]$$

- Saturation region (I_D does not depend on V_{DS})

$$i_D = K(V_{GS} - V_t)^2$$

$$K = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}$$

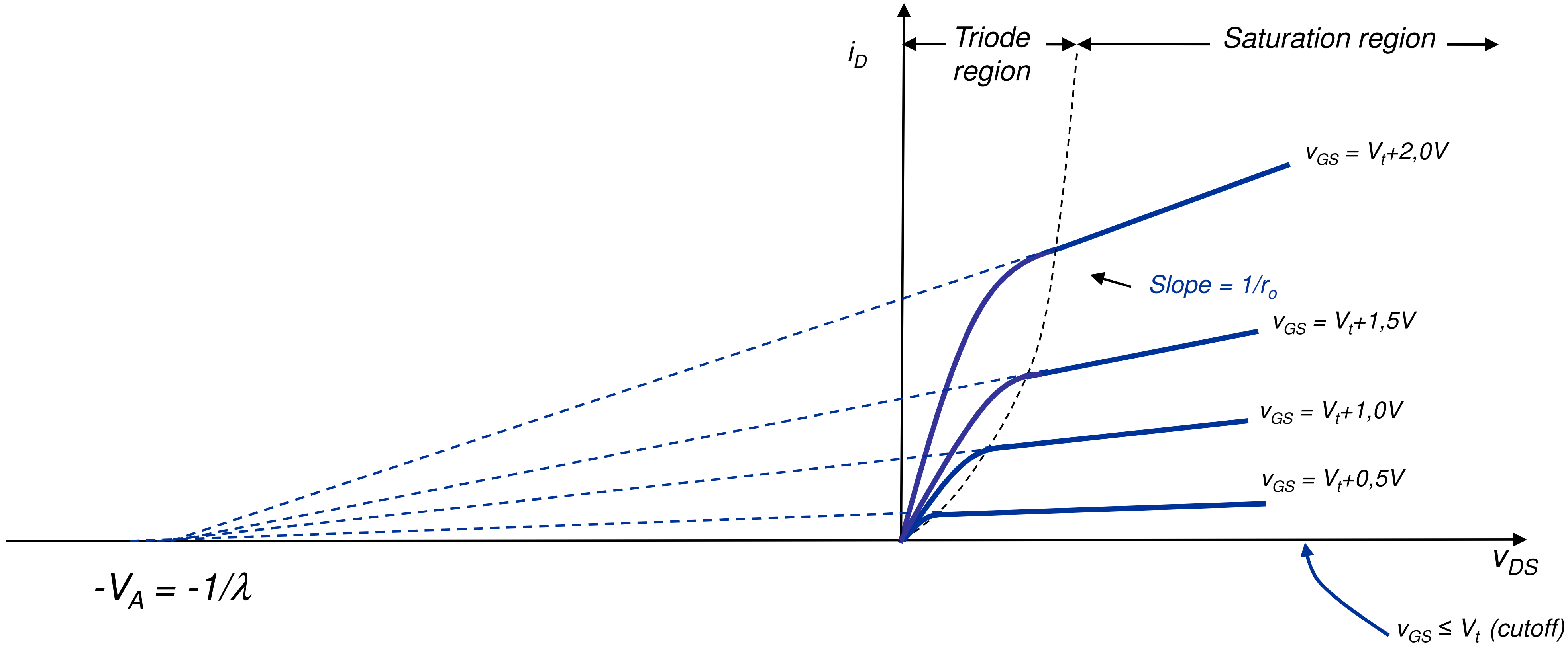
Output Characteristics: Saturation



- Saturation region (I_D does not depend on V_{DS})

$$i_D = K(V_{GS} - V_t)^2$$

Current-Voltage Characteristic

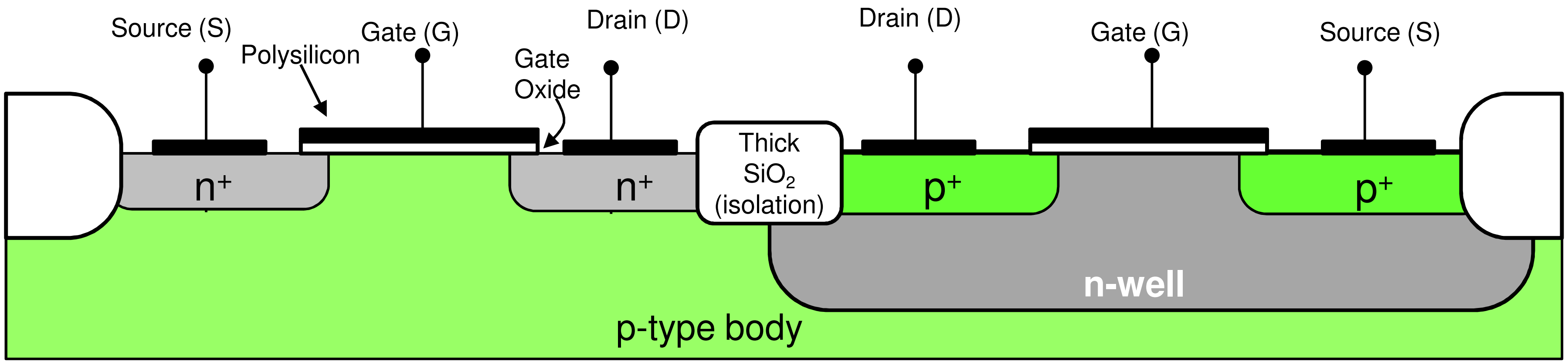


V_A is the channel modulation voltage, producing a similar effect to the Early voltage in BJT devices.

If we consider this effect then:

$$i_D = K(V_{GS} - V_t)^2(1 + \lambda V_{DS})$$

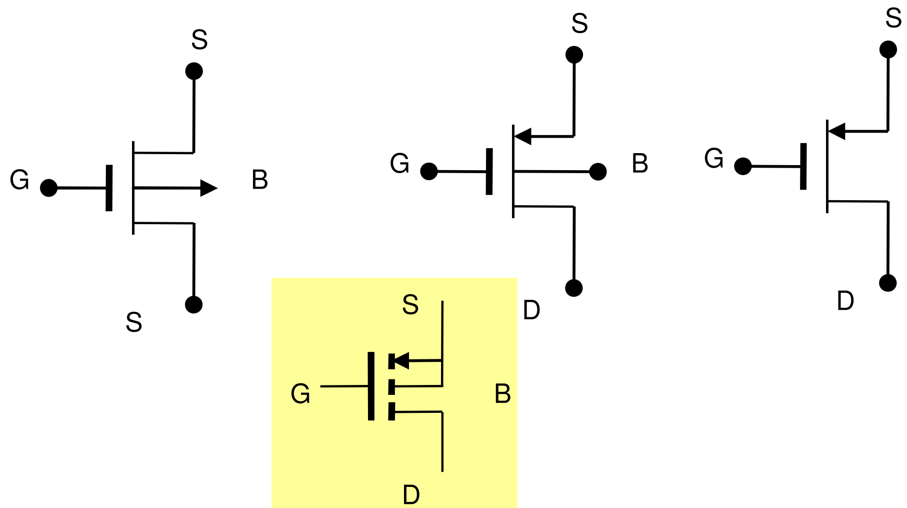
p-channel MOSFET (P-MOS)



In *enhancement p-mos* there is a channel if: $V_{GS} \leq V_t < 0$

$V_{DS} \geq V_{GS} - V_t$ triode region

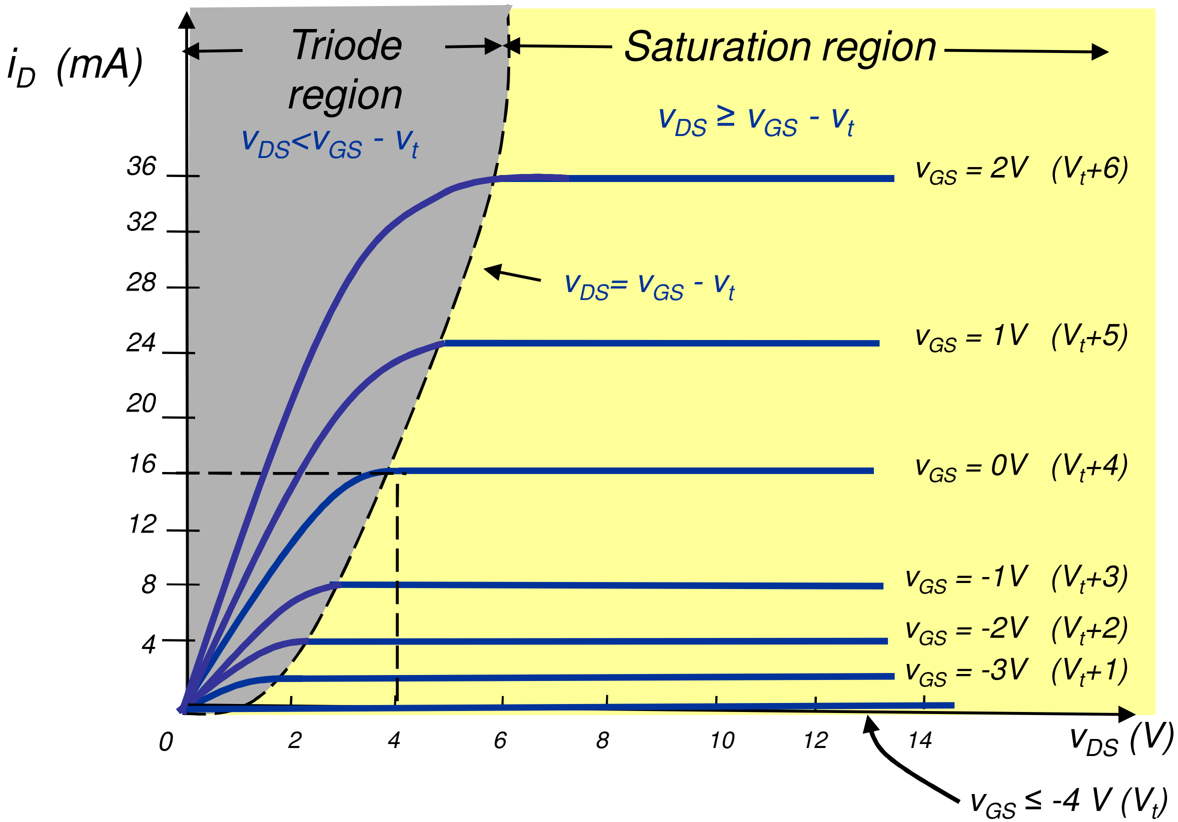
$V_{DS} \leq V_{GS} - V_t$ saturation region

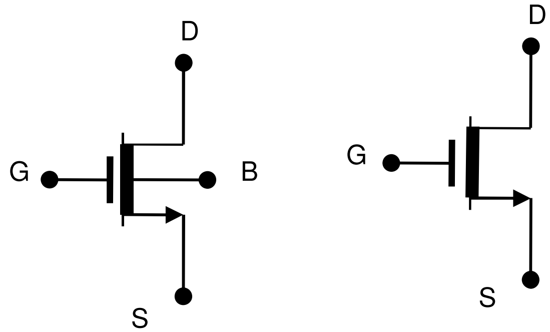


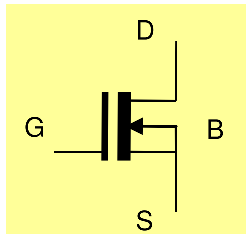
Depletion MOSFET

Equivalent behavior to enhancement MOSFET devices, except for

- Manufactured channel:
  - When $V_{GS}<0$ channel is reduced (e^- leave Gate region)
  - When $V_{GS} \le V_t < 0$ channel disappears (*cut-off* region)







Summary

- In *enhancement* n-MOS there is a channel if: $V_{GS} \geq V_t > 0$

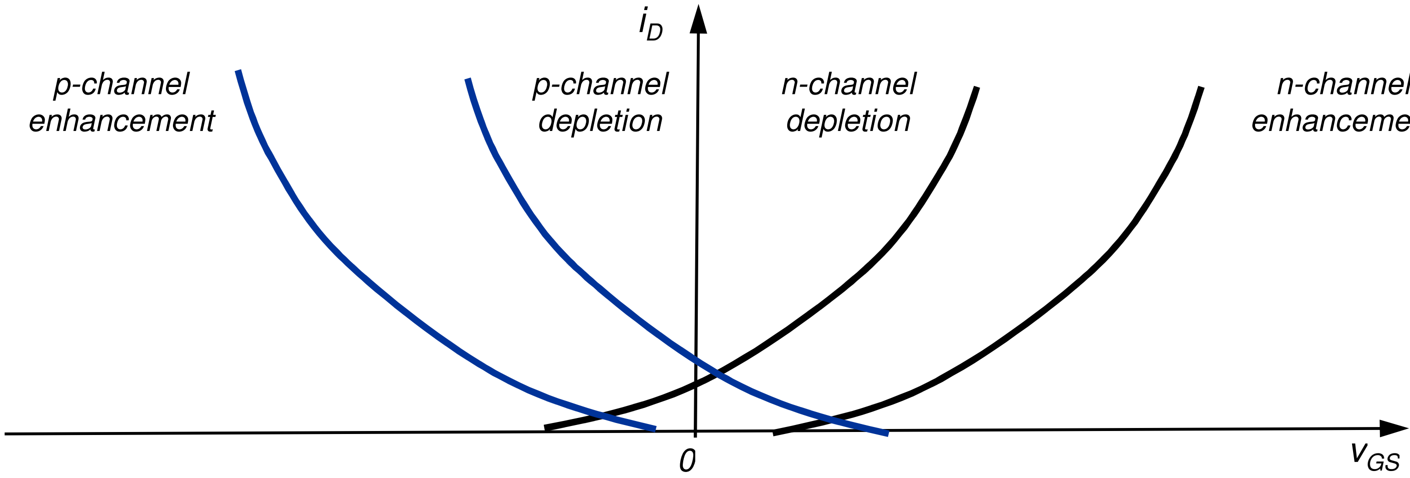
$V_{DS} \leq V_{GS} - V_t$ in triode region

$V_{DS} \geq V_{GS} - V_t$ in saturation region

- In *enhancement* p-MOS there is a channel if: $V_{GS} \leq V_t < 0$

$V_{DS} \geq V_{GS} - V_t$ in triode region

$V_{DS} \leq V_{GS} - V_t$ in saturation region



- In *depletion* n-MOS there is a channel if: $V_{GS} \geq V_t, \ V_t < 0$

$V_{DS} \leq V_{GS} - V_t$ in triode region

$V_{DS} \geq V_{GS} - V_t$ in saturation region

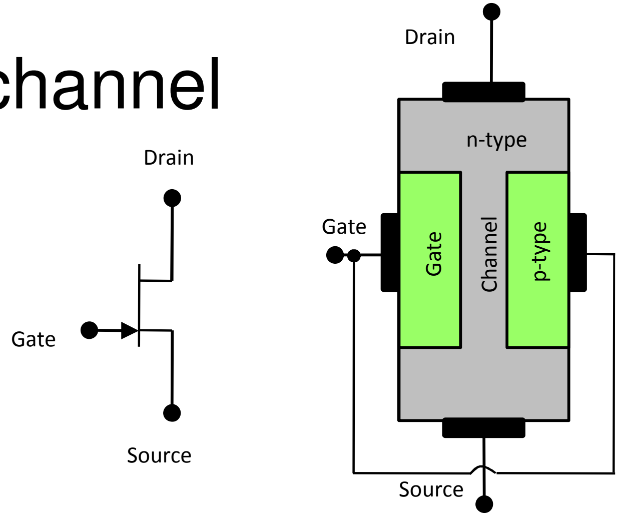
- In *depletion* p-MOS there is a channel if : $V_{GS} \leq V_t, \ V_t > 0$

$V_{DS} \geq V_{GS} - V_t$ in triode region

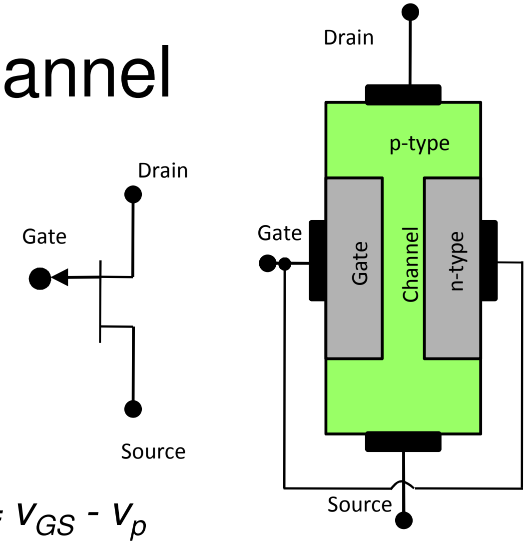
$V_{DS} \leq V_{GS} - V_t$ in saturation region

Junction Field Effect Transistor (JFET)

N channel

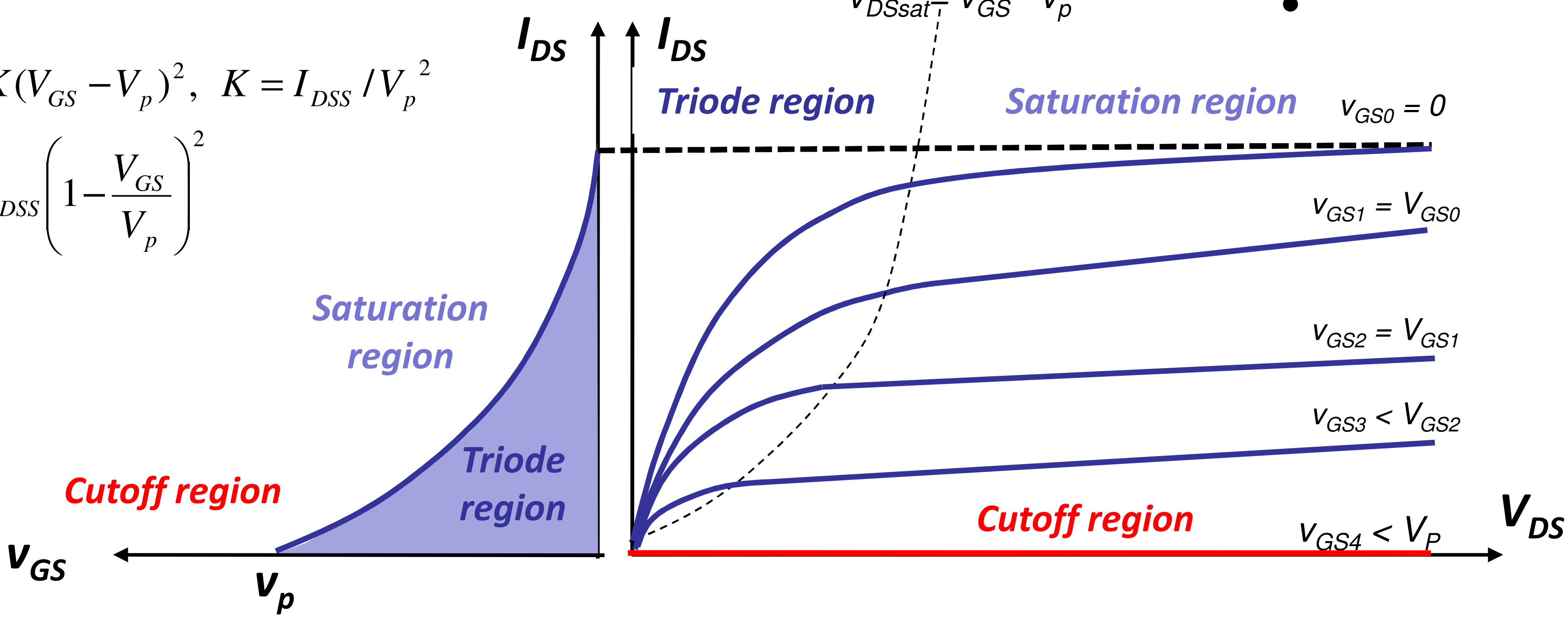


P channel

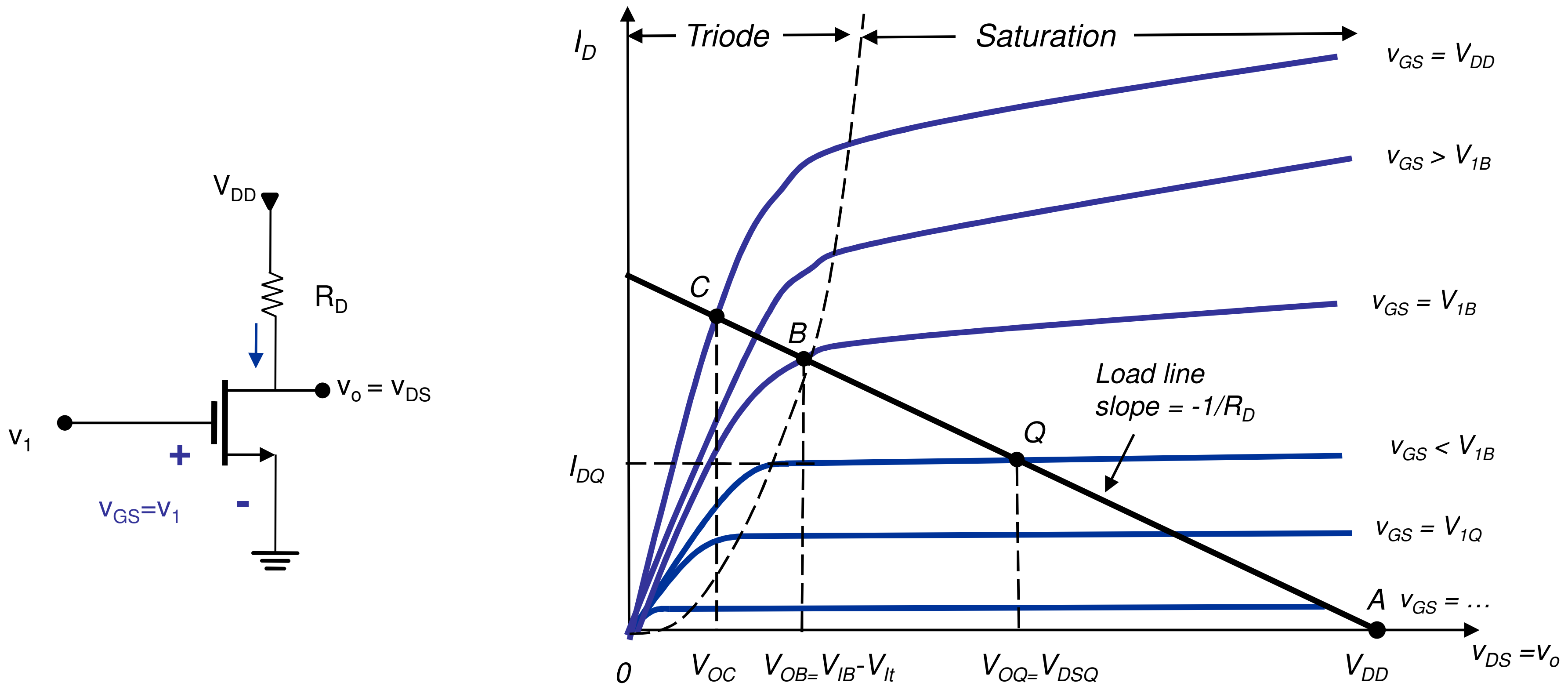


$$i_D = K(V_{GS} - V_p)^2, \quad K = I_{DSS} / V_p^{\,2}$$

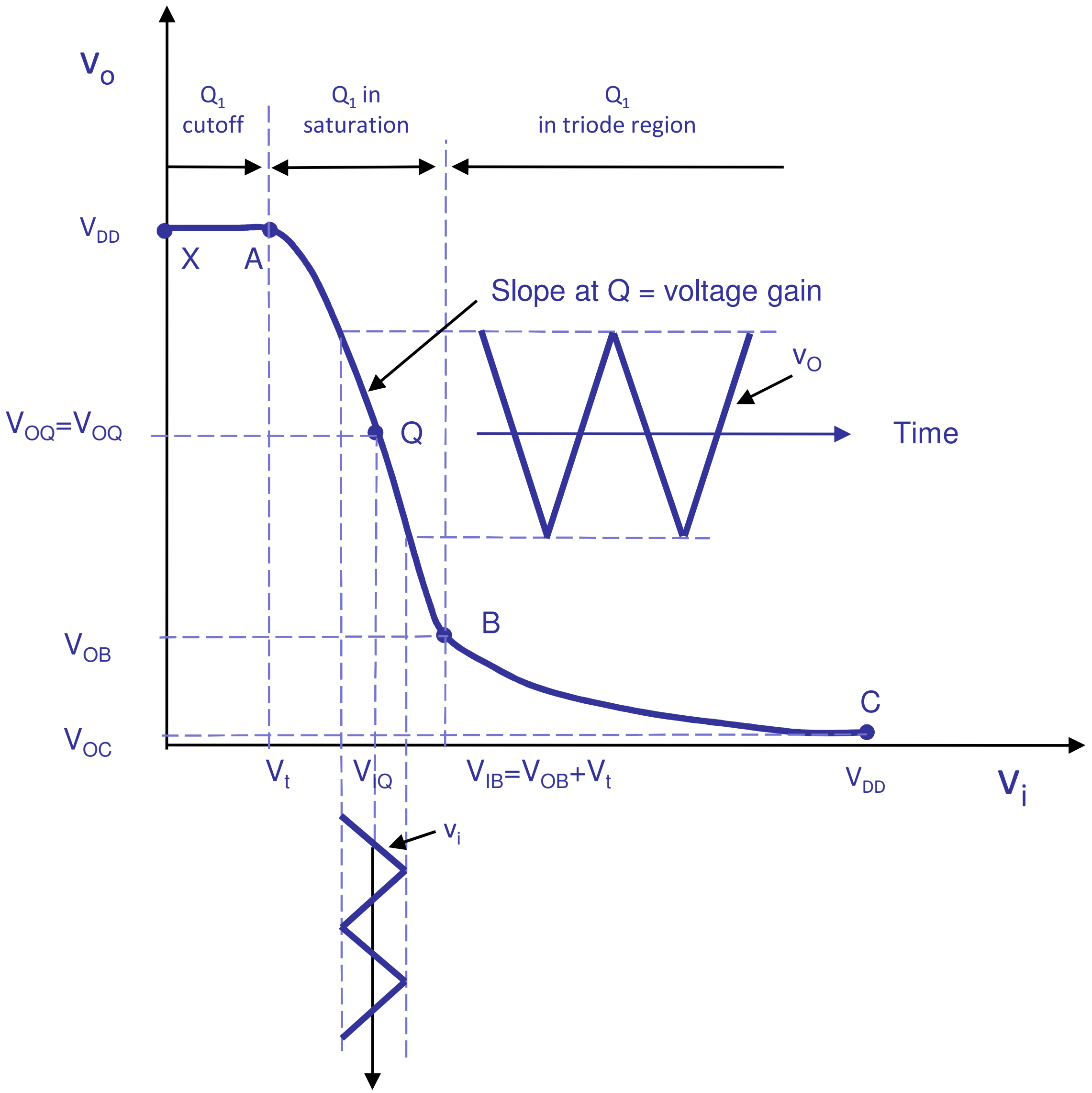
$$i_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_p}\right)^2$$



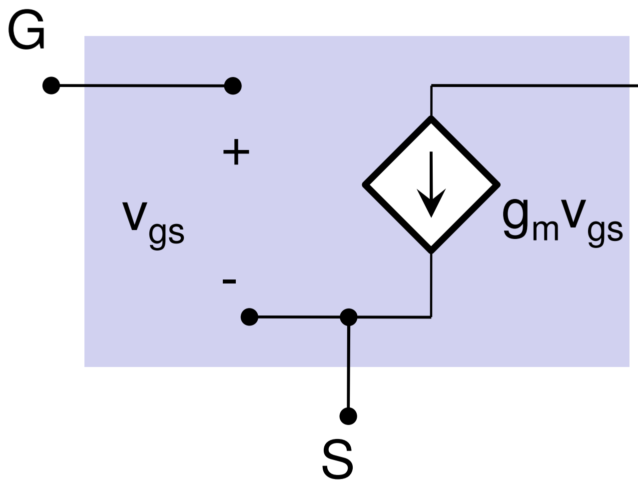
DC bias point: Load line

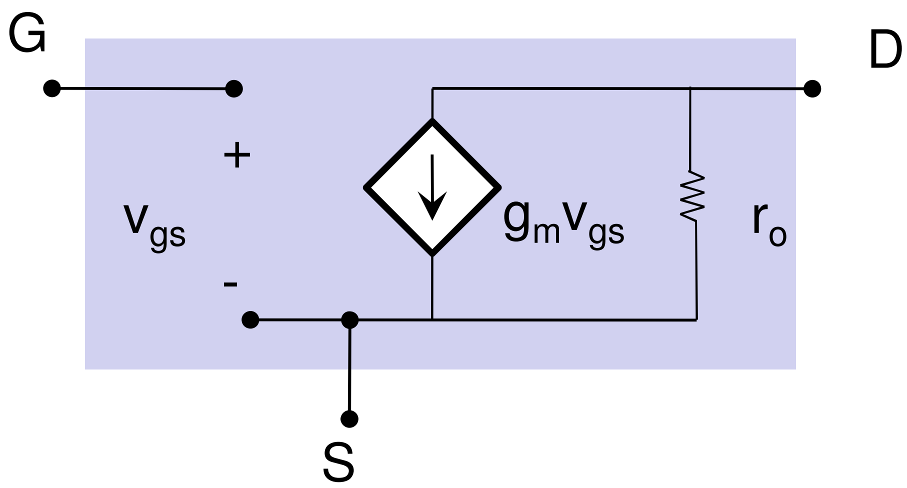


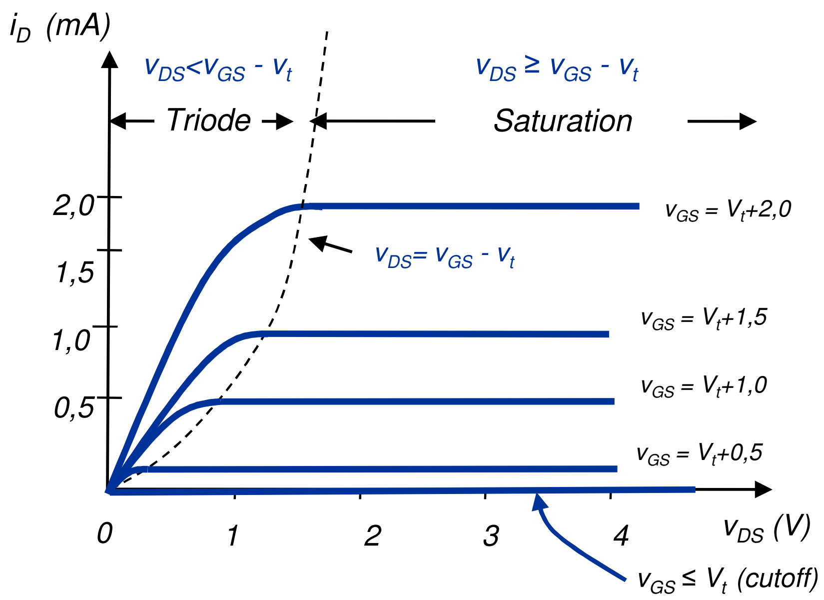
FET transistor as amplifier:

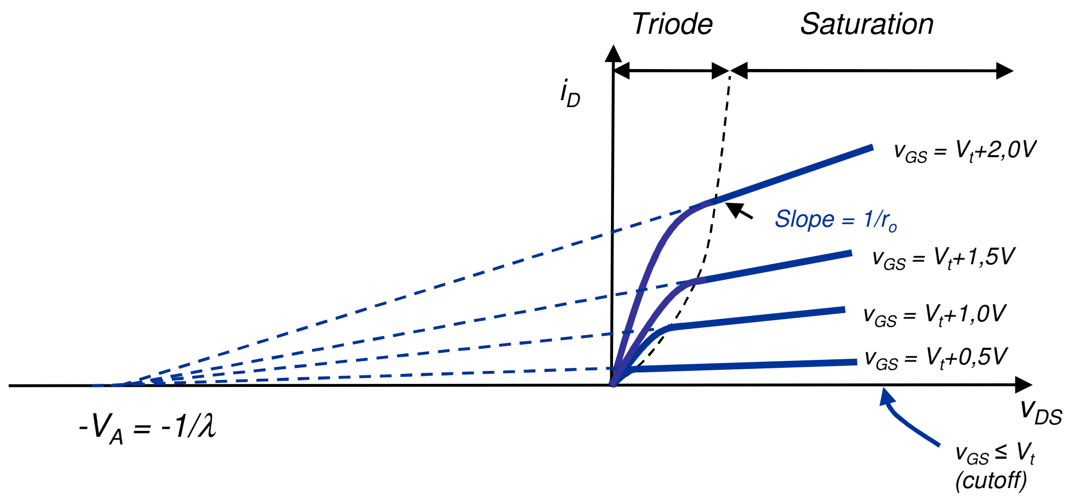


Small-signal model

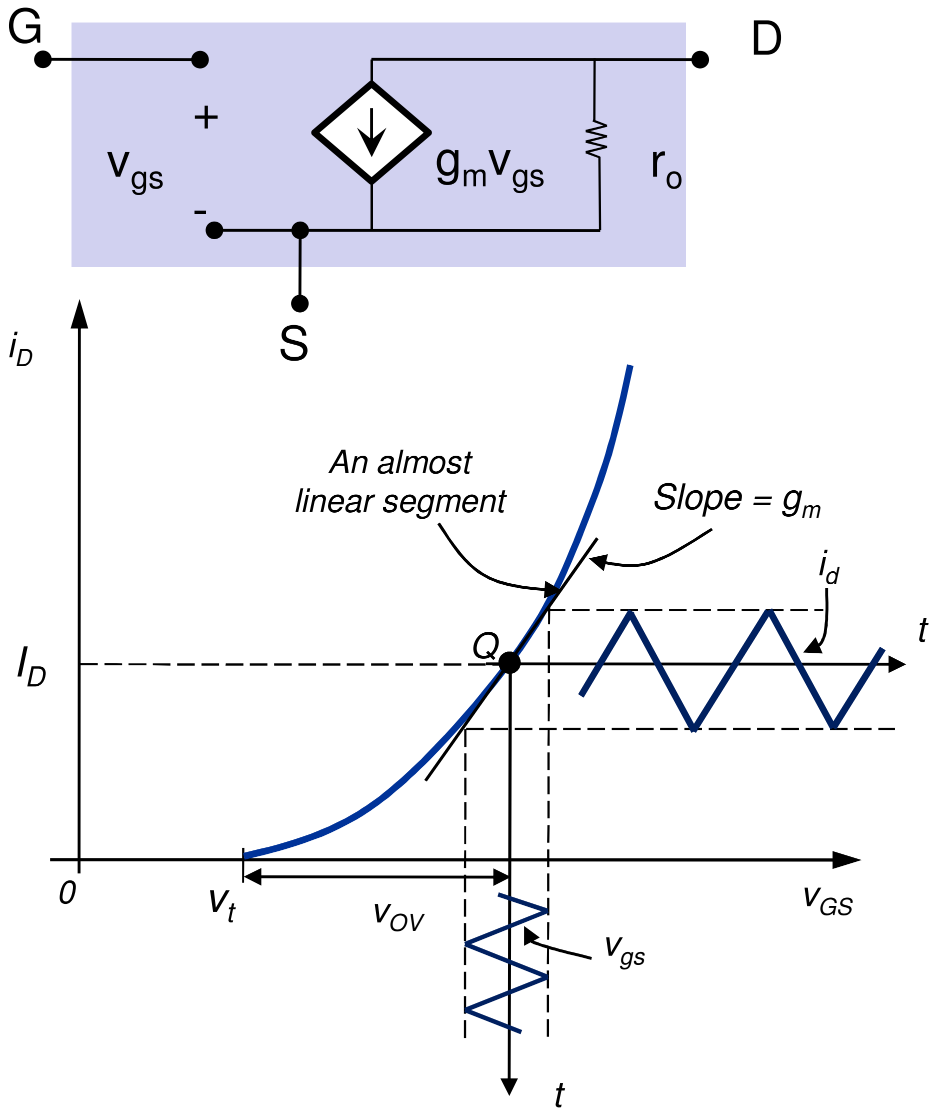








Small-signal parameters



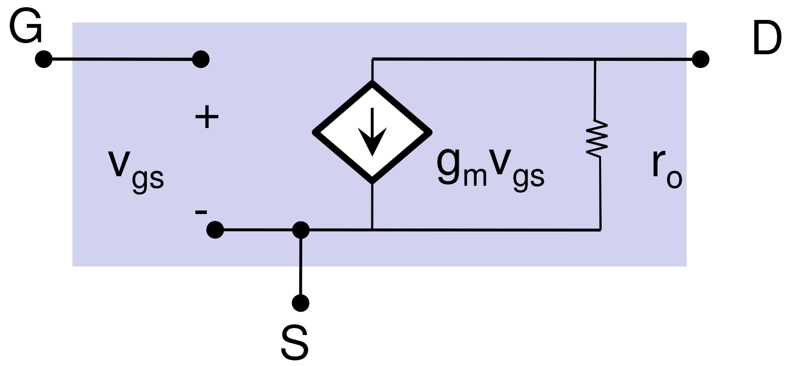
- In MOSFETs

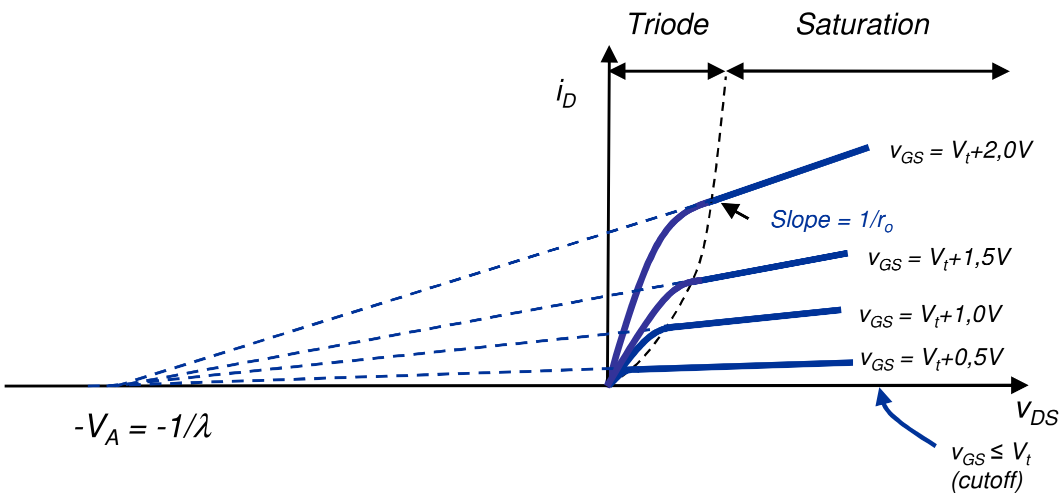
$$g_m = \left.\frac{\partial i_D}{\partial V_{GS}}\right|_{v_{ds}=V_{DSQ}} = 2K\,(V_{GS} - V_t)$$

- In JFETs

$$g_m = \left.\frac{\partial i_D}{\partial V_{GS}}\right|_{v_{ds}=V_{DSQ}} = -2\,\frac{I_{DSS}}{V_p}\left(1 - \frac{V_{GS}}{V_p}\right)$$

Small-signal parameters





$$\frac{1}{r_o} = \frac{\partial i_D}{\partial v_{DS}} \approx \lambda I_D = \frac{I_D}{V_A}$$

$$r_o = \frac{V_A}{I_D}$$

Exercise:
Operation regions. Saturation

EXAMPLE

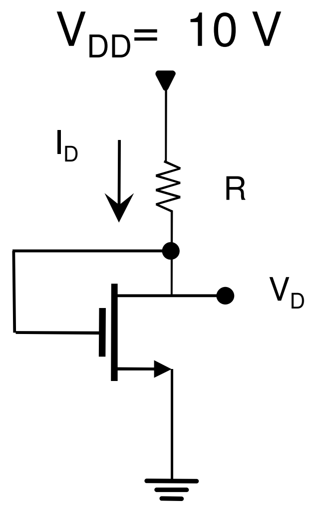
$|V_t| = 2$ V

L=10um

W=100um

λ=0

$\mu_n C_{ox} = 20uA/V^2$

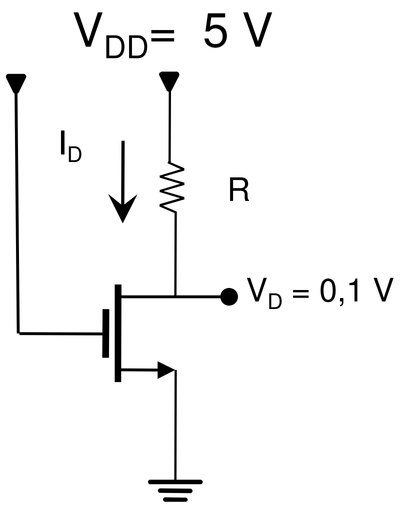


a) Design the circuit in order to obtain a I_D=0.4mA
b) Calculate the value of R and voltage V_D for that value of current

Exercise:
Operation regions. Triode region

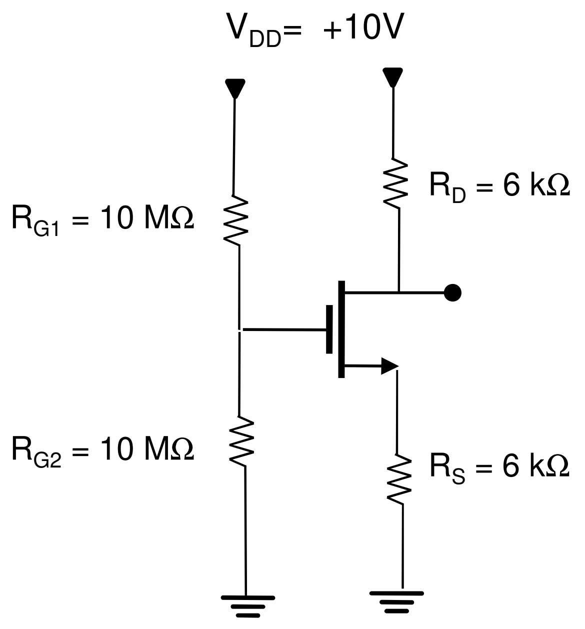
EXAMPLE

- V_{DD} = 5 V
- K = 0.5 mA/V^2
- $|V_t|$ = 1 V



a) Design the circuit for obtaining V_D=0.1V
b) Calculate the equivalent resistance of the transistor in this case

Proposed exercise



Example

- $K = 0.5\ mA/V^2$
- $|V_t| = 1\ V$

a) Analyse this circuit and calculate the voltage in every node and the current in every line

b) Obtain the equivalent small-signal circuit