AGH University of Science and Technology
im. Stanisława Staszica w Krakowie
Faculty of Computer Science, Electronics and Telecommunications
DEPARTMENT OF ELECTRONICS

ELECTRONIC DEVICES

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AMPLIFYING ELEMENTS

JUNCTION FIELD EFFECT TRANSISTOR - **JFET**

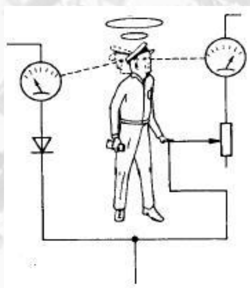
METAL-OXIDE-SEMICONDUCTOR
FIELD EFFECT TRANSISTOR - **MOSFET**

BIPOLAR JUNCTION TRANSISTOR - **BJT**

PRINCIPLE OF SIGNALS AMPLIFICATION

Transistors are electronic devices that fulfil many different functions, but amplification of signals is their main feature

In amplifier circuits transistors convert weak signals into higher power ones



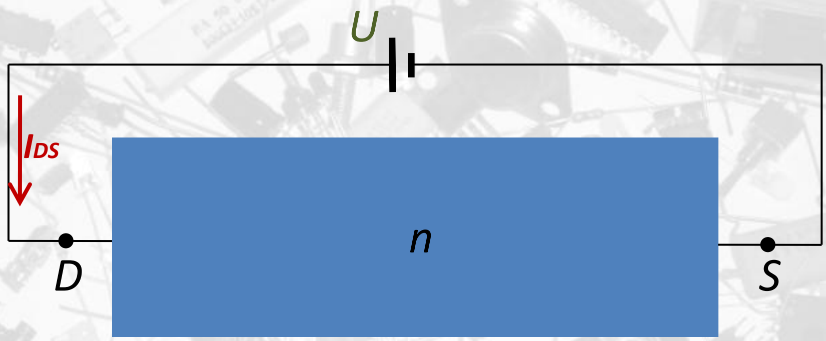
„transistor man"

Paul Horowitz *Sztuka Elektroniki*

JUNCTION FIELD EFFECT TRANSISTOR JFET

JUNCTION FIELD EFFECT TRANSISTOR

BASICS OF OPERATION

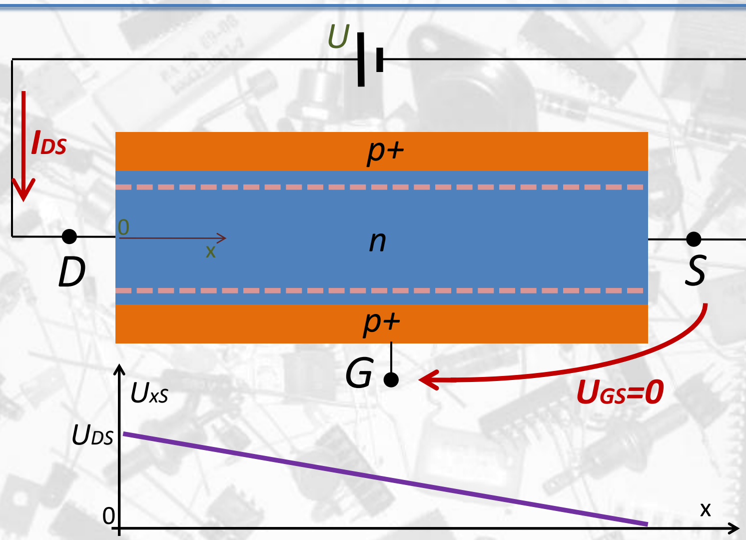


At U=const.: how can we change current I_D?

In JFET transistors, the majority carriers drift current is controlled by an applied external electric field

JUNCTION FIELD EFFECT TRANSISTOR

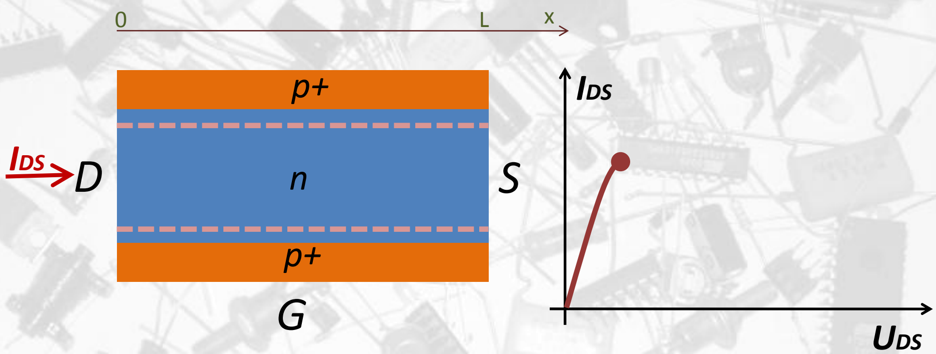
BASICS OF OPERATION



JUNCTION FIELD EFFECT TRANSISTOR

BASICS OF OPERATION

The shape of the depletion layer in the channel of junction field effect transistor at zero biased gate

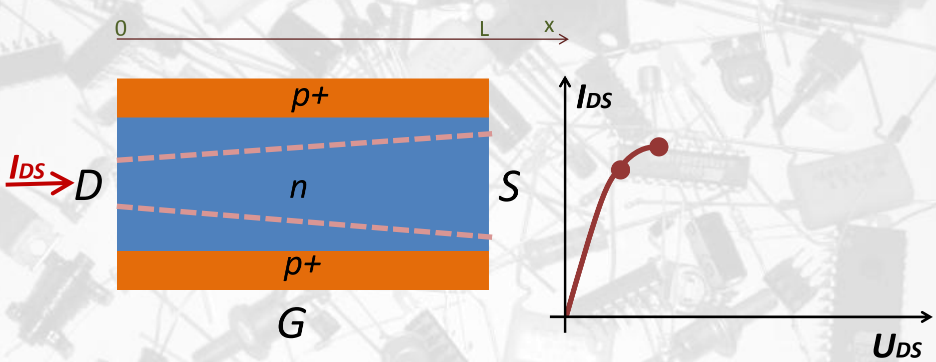


linear range

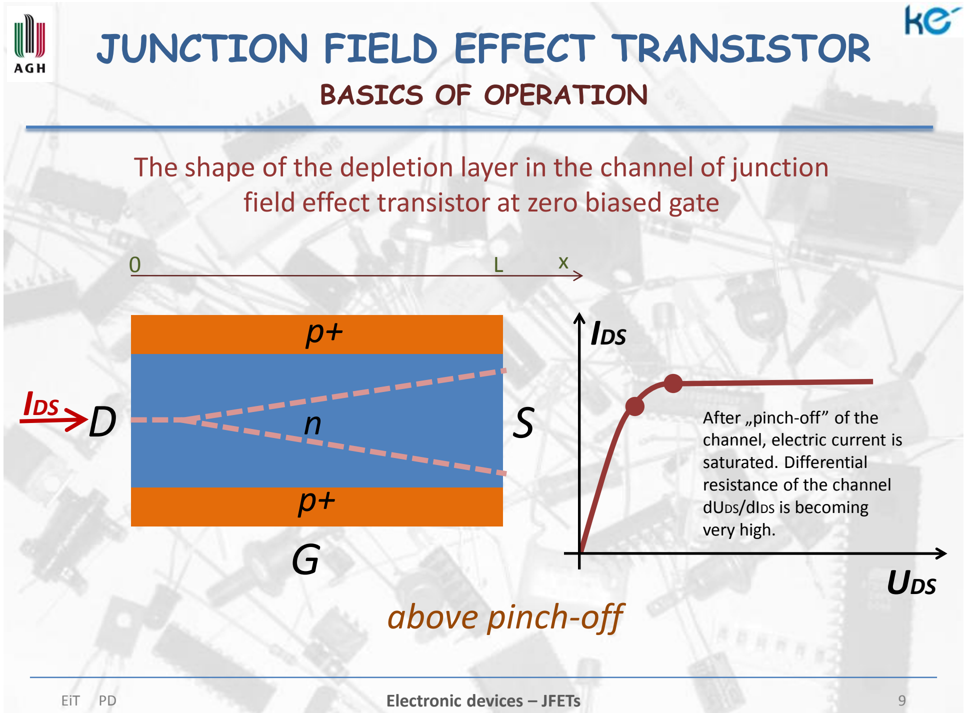
JUNCTION FIELD EFFECT TRANSISTOR

BASICS OF OPERATION

The shape of the depletion layer in the channel of junction field effect transistor at zero biased gate



near the pinch-off


JUNCTION FIELD EFFECT TRANSISTOR
BASICS OF OPERATION
The shape of the depletion layer in the channel of junction field effect transistor at zero biased gate
0
L
x
p+
n
p+
IDS
D
S
G
IDS
UDS
After „pinch-off” of the channel, electric current is saturated. Differential resistance of the channel dUDS/dIDS is becoming very high.
above pinch-off
EiT PD
Electronic devices – JFETs
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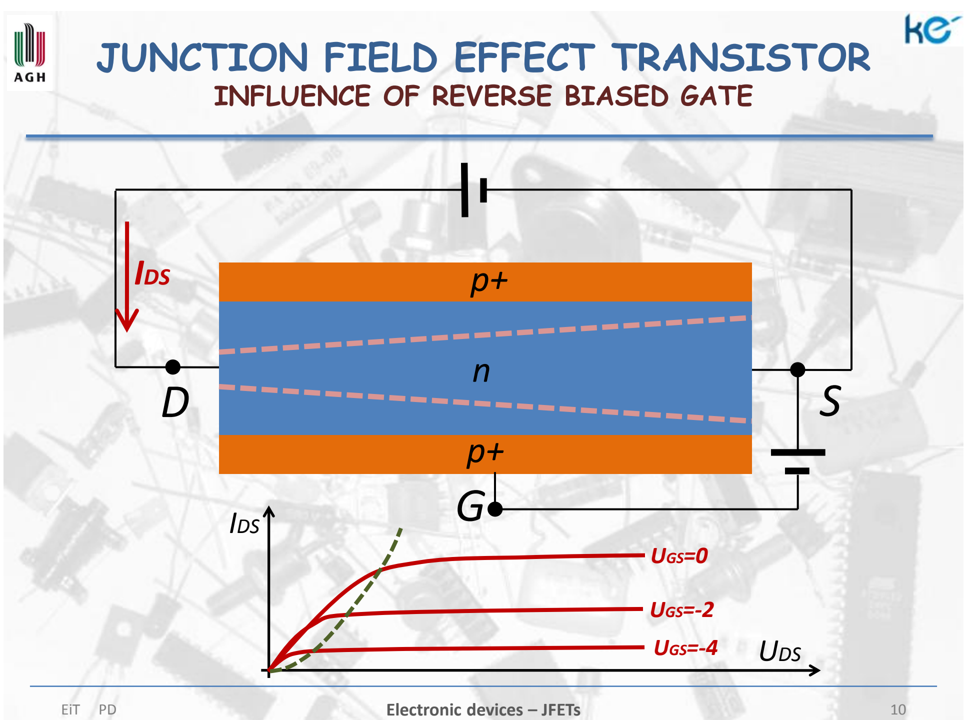
JUNCTION FIELD EFFECT TRANSISTOR
INFLUENCE OF REVERSE BIASED GATE
IDS
p+
n
p+
D
S
G
IDS
UGS=0
UGS=-2
UGS=-4
UDS
EiT PD
Electronic devices – JFETs
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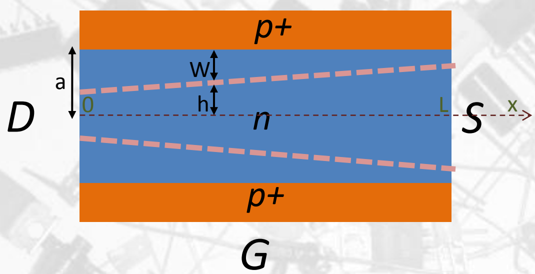
JUNCTION FIELD EFFECT TRANSISTOR
DETERMINATION OF THRESHOLD VOLTAGE

we estimate the width of the depletion layer at x=0, (due to dopant concentration we assume that depletion area spreads mainly in the direction n-channel):



$$W(x=0)=\left[\frac{2\varepsilon U_{GD}}{qN_D}\right]^{\frac{1}{2}}$$

Clamping of the channel (pinch-off) at the drain occurs when :

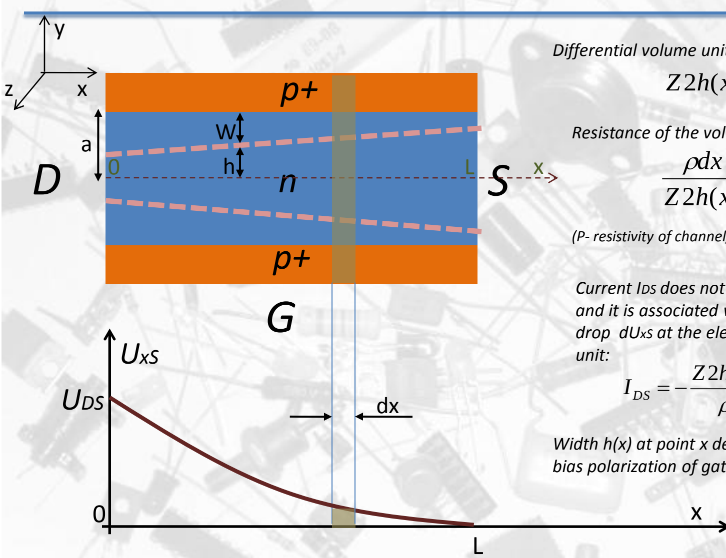
$$h(x=0)=a-W(x=0)=0$$

Therefore, W(x=0) = a. If you define a threshold voltage U_P, as a voltage U_{GD} at the clamping of channel, then:

$$\left[\frac{2\varepsilon U_P}{qN_D}\right]^{\frac{1}{2}}=a$$

$$U_P=\frac{qa^2N_D}{2\varepsilon}$$

JUNCTION FIELD EFFECT TRANSISTOR
DETERMINATION OF DRAIN CURRENT



Differential volume unit of the neutral channel part:

$$Z2h(x)dx$$

Resistance of the volume unit :

$$\frac{\rho dx}{Z2h(x)}$$

(Ρ- resistivity of channel, Z – thickness of channel)

Current I_{DS} does not change along the channel and it is associated with a differential voltage drop dU_{xS} at the elementary resistive volume unit:

$$I_{DS}=-\frac{Z2h(x)}{\rho}\frac{dU_{xS}}{dx}$$

Width h(x) at point x depends on the local reverse bias polarization of gate and channel $-U_{Gx}$

JUNCTION FIELD EFFECT TRANSISTOR
DETERMINATION OF DRAIN CURRENT

Width h(x) at x depends on locally reverse polarized gate and the channel $-U_{Gx}$

$$h(x) = a - W(x) = a - \left[\frac{2\varepsilon(-U_{Gx})}{qN_D}\right]^{\frac{1}{2}} = a\left[1 - \left(\frac{U_{xS} - U_{GS}}{U_P}\right)^{\frac{1}{2}}\right]$$

We take into account that: $U_{Gx} = U_{GS} - U_{xS}$ $\quad U_P = \frac{qa^2N_D}{2\varepsilon}$

After introduction to the equation describing I_{DS}, we get:

$$\frac{2Za}{\rho}\left[1 - \left(\frac{U_{xS} - U_{GS}}{U_P}\right)^{\frac{1}{2}}\right] dU_{xS} = -I_{DS}dx$$

After integration we obtain:

$$I_{DS} = G_0U_P\left[\frac{U_{DS}}{U_P} + \frac{2}{3}\left(-\frac{U_{GS}}{U_P}\right)^{\frac{3}{2}} - \frac{2}{3}\left(\frac{U_{DS} - U_{GS}}{U_P}\right)^{\frac{3}{2}}\right]$$

where $G_0 = \frac{2aZ}{\rho L}$ *is the channel conductance*

The above equation is valid until channel „pinch-off, when U_{DS}-U_{GS}=U_P

Derivations were based on: „Przyrządy półprzewodnikowe", Ben G. Streetman

JUNCTION FIELD EFFECT TRANSISTOR
DETERMINATION OF DRAIN CURRENT

Assuming that the saturation current remains the same as that one at the channel „pinch-off", we get:

$$I_{DSS} = G_0U_P\left[\frac{U_{GS}}{U_P} + \frac{2}{3}\left(-\frac{U_{GS}}{U_P}\right)^{\frac{3}{2}} + \frac{1}{3}\right]$$

For low voltages U_{DS}<U_{GS}-U_P, drain current linearly depends on the U_{DS} (linear operation range):

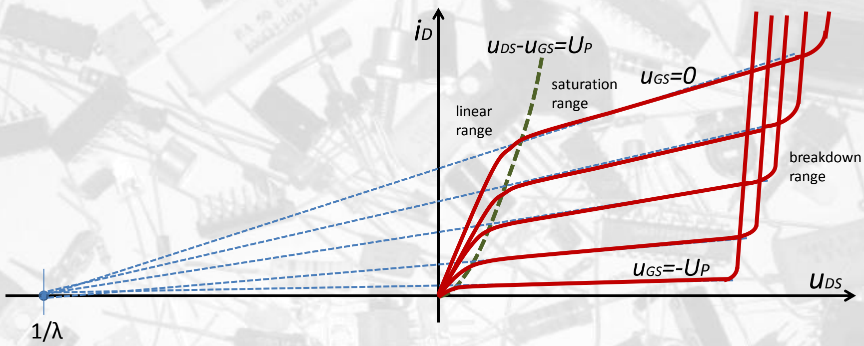
$$I_D = G_0\left(1 - \sqrt{\frac{U_{GS}}{U_P}}\right)U_{DS}$$

For voltages: U_{DS}>U_{GS}-U_P, transistor works „in saturation":

$$I_D = I_{DSS}\left(1 - \frac{U_{GS}}{U_P}\right)^2$$

JUNCTION FIELD EFFECT TRANSISTOR

REAL CHARACTERISTICS OF DRAIN CURRENT



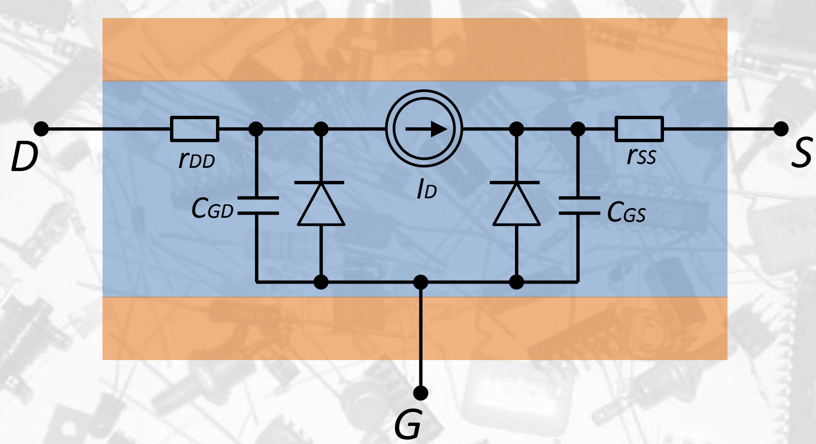
$$I_D = I_{DSS}\left(1-\frac{u_{GS}}{U_P}\right)^2 (1+\lambda u_{DS})$$

- the drain current in the saturation range, taking into account shortening of the channel

λ - channel length modulation factor :
it describes the reduction of the channel under the influence of the voltage U_{DS} and increasing I_D current

JUNCTION FIELD EFFECT TRANSISTOR

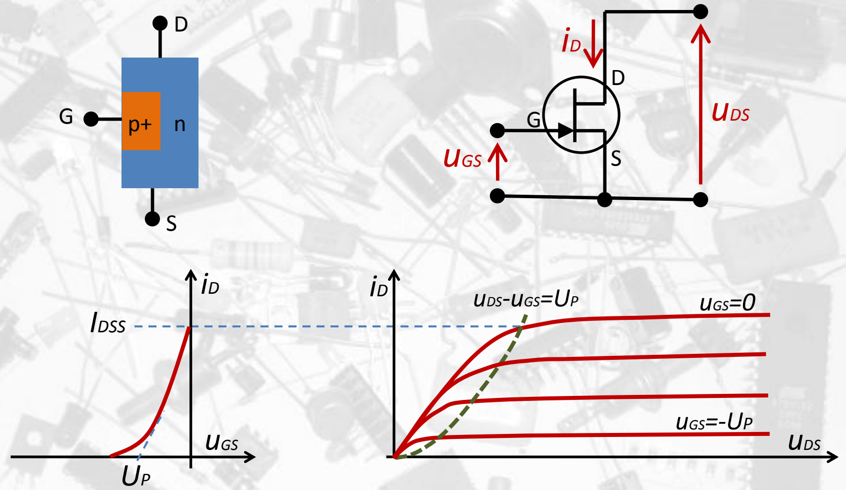
LARGE-SIGNAL MODEL



JUNCTION FIELD EFFECT TRANSISTOR

N-CHANNEL

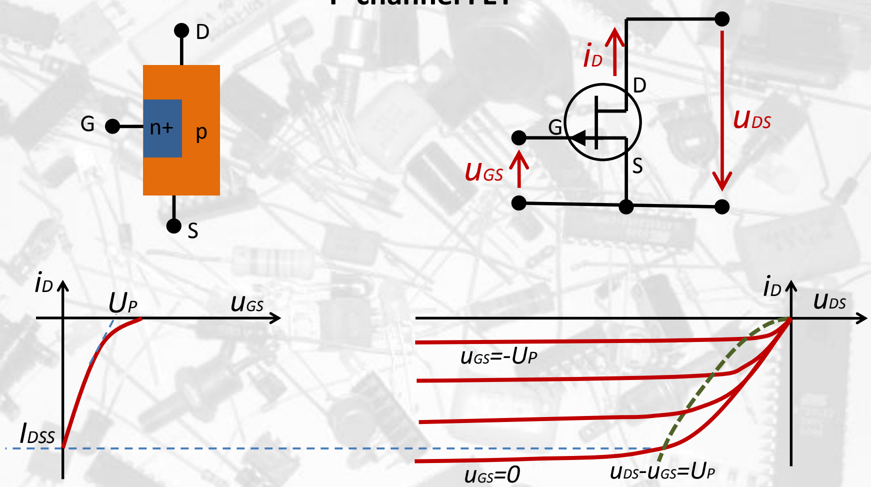
N-channel FET



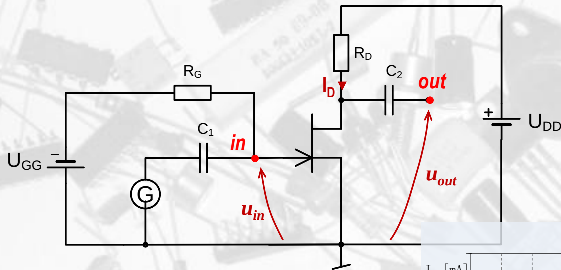
JUNCTION FIELD EFFECT TRANSISTOR

P-CHANNEL

P-channel FET



JUNCTION FIELD EFFECT TRANSISTOR
AMPLIFYING DEVICE – GRAPHIC INTERPRETATION



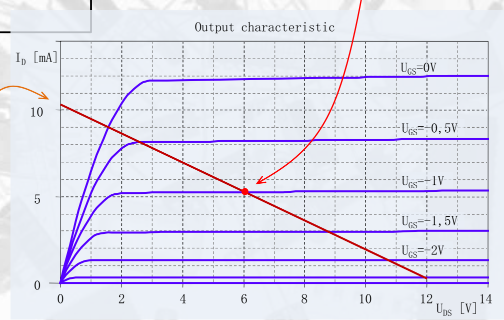
Operating point of a transistor – it is a point at output characteristic described by coordinates ($\mathbf{U_{DS}}$, $\mathbf{I_D}$)

For output circuit („ring”) we have:

$$U_{DS} + I_D R_D = U_{DD}$$

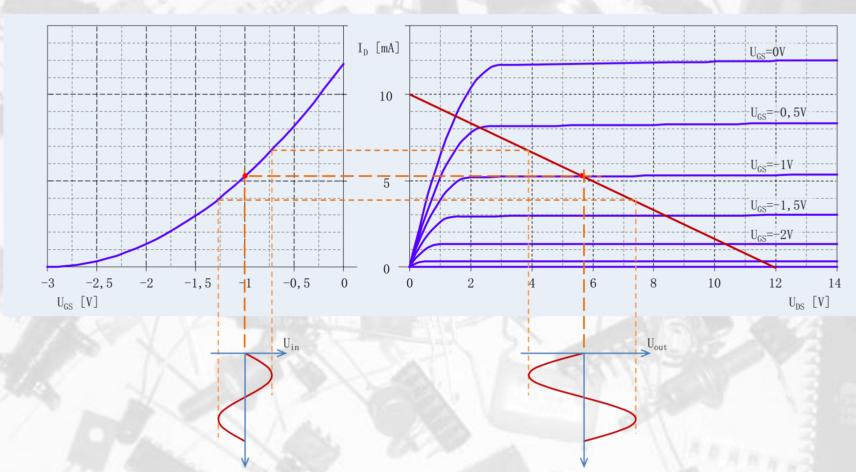
After transformation ($I_D = f(U_{DS})$):

$$I_D = -\frac{1}{R_D} U_{DS} + \frac{U_{DD}}{R_D}$$



JUNCTION FIELD EFFECT TRANSISTOR
AMPLIFYING DEVICE – GRAPHIC INTERPRETATION

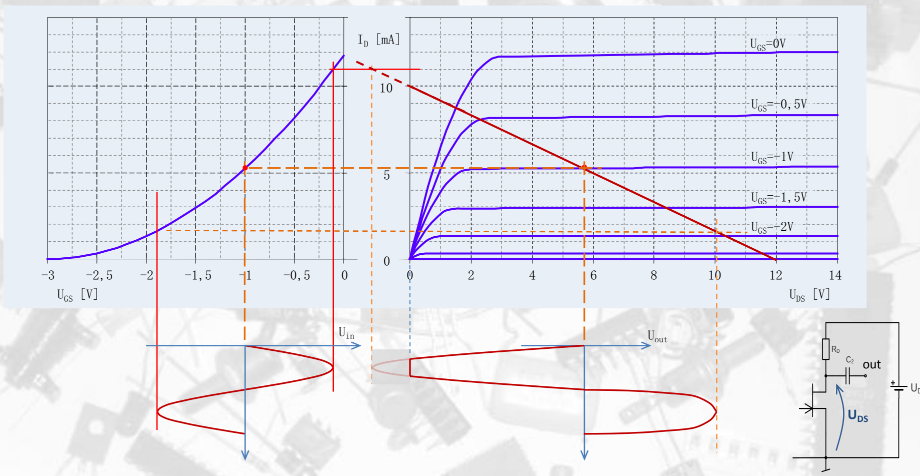
AMPLIFICATION



JUNCTION FIELD EFFECT TRANSISTOR

AMPLIFYING DEVICE – GRAPHIC INTERPRETATION

DISTORTION



JUNCTION FIELD EFFECT TRANSISTOR

AMPLIFYING DEVICE – ANALYTICAL DESCRIPTION

The saturation current is: $I_D = I_{DSS}\left(1-\frac{U_{GS}}{U_P}\right)^2$ (for simplification we neglect shortening of the channel) (1)

The total voltage at the gate $U_{GS}(t)$: $u_{GS} = U_{GS} + u_{gs}$ (2)

introducing (2) to (1): $i_D = I_{DSS}\left(1-\frac{u_{GS}}{U_P}\right)^2 = I_{DSS}\left(1-\frac{U_{GS}}{U_P}\right)^2 - 2\frac{I_{DSS}}{U_P}\left(1-\frac{U_{GS}}{U_P}\right)u_{gs} + I_{DSS}\frac{u_{gs}}{U_P^2}u_{gs}$ (3)

DC I_D component — small-signal i_d component

For suitably small amplitude of the input voltage u_{in} we can linearize transistor characteristics. We consider then linear model of transistor and small-signal analysis.

The small-signal condition results from the selection of u_{in}, in such a way that the second part of small-signal component ($\sim u^2_{gs}$) is negligible (knowing that $u_{in} = u_{gs}$):

$$2\frac{I_{DSS}}{U_P}\left(1-\frac{U_{GS}}{U_P}\right)u_{gs} >> I_{DSS}\frac{u_{gs}}{U_P^2}u_{gs} \quad (4)$$

After transformation:

$$2(U_P - U_{GS}) >> u_{gs} \quad (5)$$

small-signal condition

JUNCTION FIELD EFFECT TRANSISTOR
AMPLIFYING DEVICE – ANALYTICAL DESCRIPTION

Therefore, taking into account small-signal condition, the total drain current can be described as **linear** function of u_{gs}:

$$i_D = I_D - 2\frac{I_{DSS}}{U_P}\left(1 - \frac{U_{GS}}{U_P}\right)u_{gs} \quad (6)$$

Small-signal condition allows as „to get rid off" component that is proportional to u_{gs}^2. There only remains component proportional to u_{gs} – therefore it is right to talk about linearization of characteristics and the linear model of the transistor.

If we denote the proportionality factor in front of u_{gs} in (6) as g_m, then the drain current is:

$$i_D = I_D - g_m u_{gs} \quad (7)$$

Coefficient g_m is expressed in [A/V] and it depends on the operation point as well as physical properties represented by U_P i I_{DSS}.

Parameter g_m is called ***transconductance***:

$$g_m = -2\frac{I_{DSS}}{U_P}\left(1 - \frac{U_{GS}}{U_P}\right) \quad (8)$$

We considered transconductance for saturation range, the conditions the transistor works in as an amplifier. The reader will examine the case of the transistor operating in the linear range using the given definition of the transconductance.

JUNCTION FIELD EFFECT TRANSISTOR
SMALL-SIGNAL PARAMETERS, PART 1

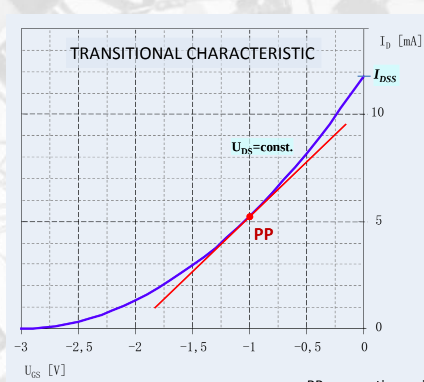
Transconductance (def.):

$$g_m = \left.\frac{\partial I_D}{\partial U_{GS}}\right|_{U_{DS}=const.} \quad [A/V]$$

Graphical interpretation

The slope of the tangent to the transitional characteristic of the transistor at the operation point.

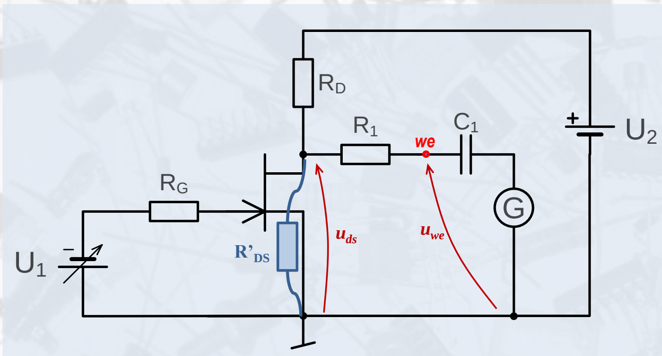
Transconductance describes the amplifying properties of the transistor



PP – operation point

JUNCTION FIELD EFFECT TRANSISTOR
CONTROLLED RESISTOR

controlled voltage divider of alternating signals



divider:

$$u_{ds} = u_{we}\frac{R'_{DS}}{R'_{DS}+R_1}$$

$$R'_{DS} = R_1\frac{u_{ds}}{u_{we}-u_{ds}}$$

only for $R_D >> R'_{DS}$

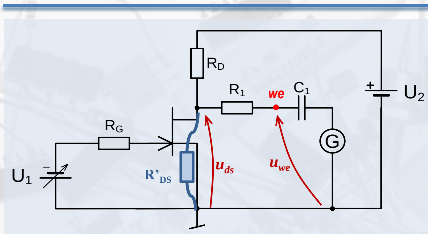
Whether:

$R'_{DS} = R_{DS}$ **?**

or:

$R'_{DS} = r_{ds}$ **?**

JUNCTION FIELD EFFECT TRANSISTOR
CONTROLLED RESISTOR



Resistance:

- static

$$R_{DS} = \frac{U_{DS}}{I_{DS}}$$

- dynamic

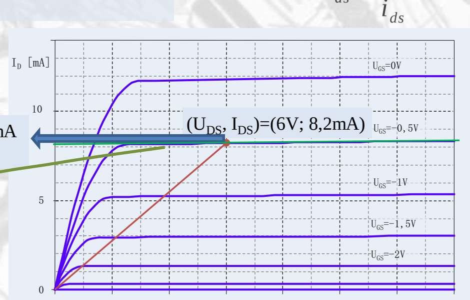
$$r_{ds} = \frac{u_{ds}}{i_{ds}}$$

or (from def.):

$$r_{ds} = \frac{\partial U_{DS}}{\partial I_{DS}} \cong \frac{\Delta U_{DS}}{\Delta I_{DS}}$$

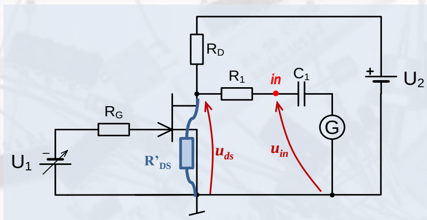
R_{DS} = 6V/8,2mA
R_{DS} = 731Ω

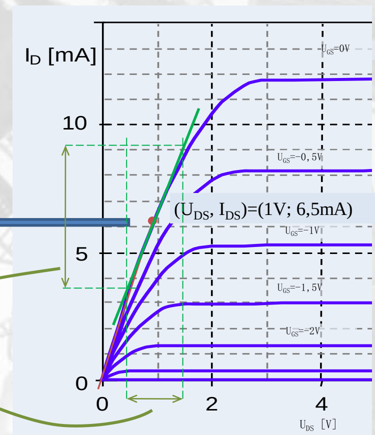
very small slope
r_{ds} – very large



Output characteristic

JUNCTION FIELD EFFECT TRANSISTOR
CONTROLLED RESISTOR





R_{DS} = 1V/6,5mA
R_{DS} = 154Ω

r_{ds} = 1V/5,5mA
r_{ds} = 181 Ω

Resistance:

- static

$$R_{DS} = \frac{U_{DS}}{I_{DS}}$$

- dynamic

$$r_{ds} = \frac{u_{ds}}{i_{ds}}$$

or:

$$r_{ds} = \frac{\Delta U_{DS}}{\Delta I_{DS}} = \frac{\partial U_{DS}}{\partial I_{DS}}$$

In linear area: $R'_{DS} \approx R_{DS}$: JFET – controlled resistance

In saturation area: $R'_{DS} = r_{ds}$: JFET - amplifier

JUNCTION FIELD EFFECT TRANSISTOR
SMALL-SIGNAL PARAMETERS, PART 2

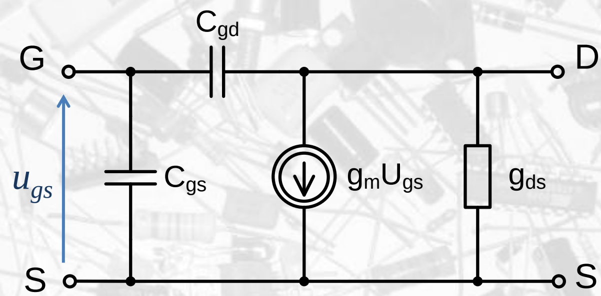
- Transconductance
- Output (drain) conductance

def.
$$g_{ds} = \left.\frac{\partial I_D}{\partial U_{DS}}\right|_{U_{GS}=const}$$

- Series resistances of drain and source (r_{dd} i r_{ss})
  (very often they are negligible)
- Capacitance gate-drain C_{gd} and gate-source C_{gs}

REMARK: conductances are described by different relations and they have different values in linear as well as in saturation areas.

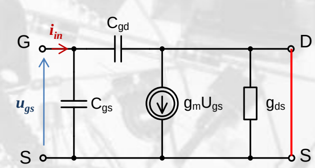
JUNCTION FIELD EFFECT TRANSISTOR
SMALL-SIGNAL EQUIVALENT CIRCUIT



JUNCTION FIELD EFFECT TRANSISTOR
FREQUENCY LIMITS

Cut-off frequency f_T

This is the frequency at which the input current is equal to the controlled current source from small-signal model, provided that the output terminals are shorted.



At shorted output terminals, the input current: $i_{in} = j\varpi(C_{gs}+C_{gd})u_{gs}$

At cut-off frequency f_T absolute value of input current has to be equal to the absolute value of controlled current source, therefore:

$$|i_{we}| = \varpi_T(C_{gs}+C_{gd})U_{gs} = g_m U_{gs}$$

$$2\pi f_T(C_{gs}+C_{gd})U_{gs} = g_m U_{gs}$$

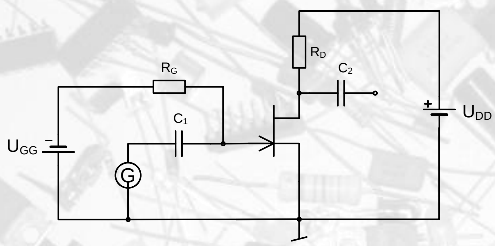
Finally:

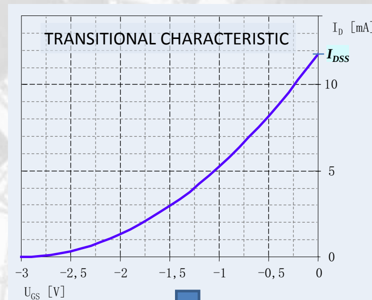
$$f_T = \frac{g_m}{2\pi(C_{gs}+C_{gd})}$$

JUNCTION FIELD EFFECT TRANSISTOR
WHAT IS THE PURPOSE OF SMALL-SIGNAL MODELING?

Example:

Calculate the voltage gain for the circuit shown below , if U_{DD}=10V, R_D=1kΩ, U_{GG}=1V.





I_{DSS} = 12mA
U_P = -3V

JUNCTION FIELD EFFECT TRANSISTOR
WHAT IS THE PURPOSE OF SMALL-SIGNAL MODELING?

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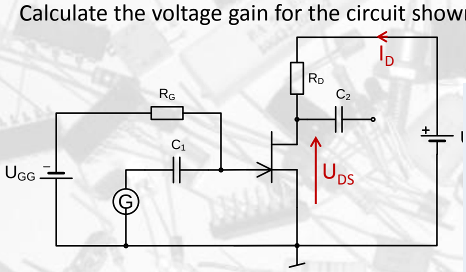
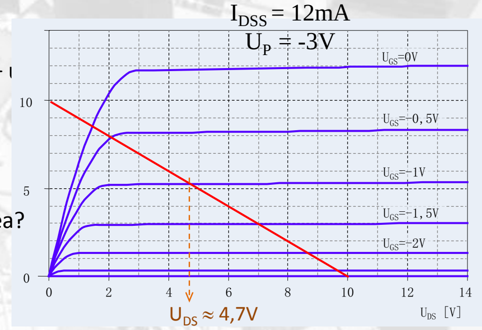
Calculate the voltage gain for the circuit shown below , if U_{DD}=10V, R_D=1kΩ, U_{GG}=1V.





Is the transistor working in the saturation area?

$$U_{DS} > U_{GS} - U_P$$

Equation for the output circuit:

$$U_{DS} + I_D R_D = U_{DD}$$

after transformation: $I_D = -\frac{1}{R_D} U_{DS} + \frac{U_{DD}}{R_D}$

and after introduction data: $I_D = -1 \cdot U_{DS} + 10 \ \text{[mA]}$

For the given data, if: U_{DS} > (-1V)-(-3V), (U_{DS} > 2), then transistor works in saturation.

This condition is fulfilled – transistor works in saturation

JUNCTION FIELD EFFECT TRANSISTOR

WHAT IS THE PURPOSE OF SMALL-SIGNAL MODELING?

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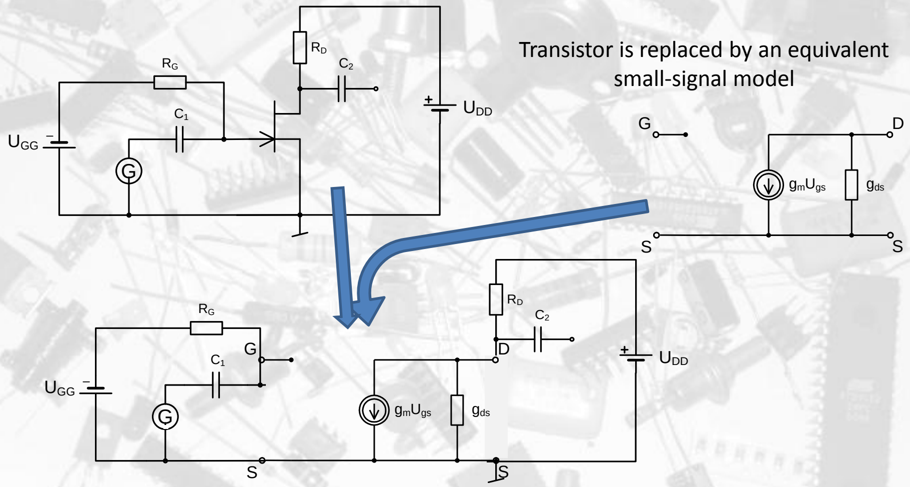
Calculate the voltage gain for the circuit shown below , if U_{DD}=10V, R_D=1kΩ, U_{GG}=1V.

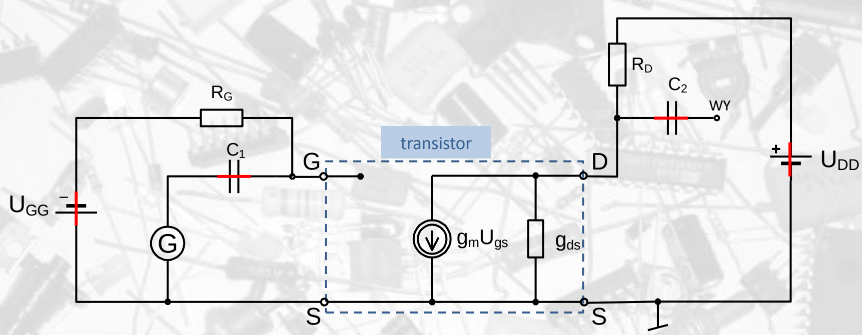


JUNCTION FIELD EFFECT TRANSISTOR

WHAT IS THE PURPOSE OF SMALL-SIGNAL MODELING?

Example:

Calculate the voltage gain for the circuit shown below , if U_{DD}=10V, R_D=1kΩ, U_{GG}=1V.



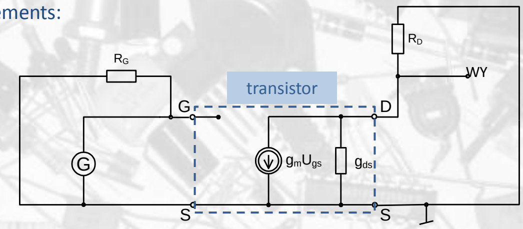
for alternating signals we can make short-circuits across capacitors and DC voltage sources (R_{in} = 0)

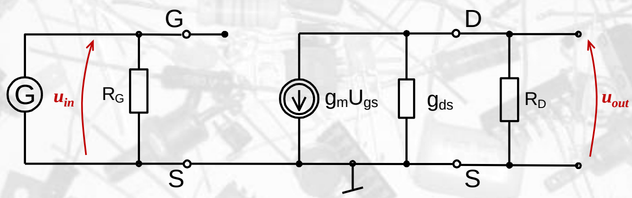
JUNCTION FIELD EFFECT TRANSISTOR
WHAT IS THE PURPOSE OF SMALL-SIGNAL MODELING?

Example:

Calculate the voltage gain for the circuit shown below , if U_{DD}=10V, R_D=1kΩ, U_{GG}=1V.

After removing unnecessary elements:





voltage gain

$$k_u = \frac{u_{wy}}{u_{we}}$$