Osnovi elektronike

Predispitne obaveze: U JANUARU OSTALO

Redovno pohađanje nastave (predavanja+vežbe)	10%	10%
Odbranjene laboratorijske vežbe	10%	10%
Kolokvijum I (26.11.2018.)	50%	20%
Kolokvijum II (21.01.2019.)	50%	20%
	120%	60%



Ukupan skor u januaru može biti 120% PRE ISPITA

Savet: Izađite na kolokvijum MNOGO JE LAKŠE!

8. novembar 2018. 1

1

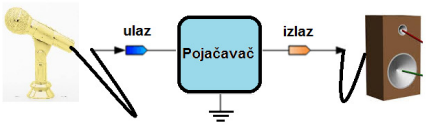
Modeli poluprovodničkih komponenata

2

Osnovi elektronike

Od čega se sastoji pojačavač?
Koje komponente sadrži?

- **Pasivne: R, C, L**
- **Aktivne: tranzistori**
  - **Kako i šta oni rade?**
  - **Kako se koriste u analizi?**

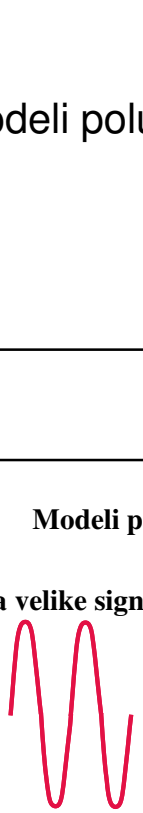


8. novembar 2018. http://leda.elfak.ni.ac.rs/ 3

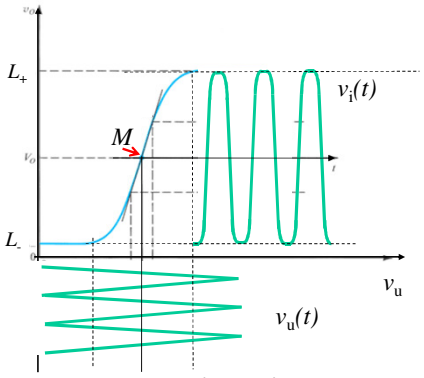
3

Modeli poluprovodničkih komponenata

Za velike signale



"Vide" celu prenosnu karakteristiku sa svim nelinearnostima

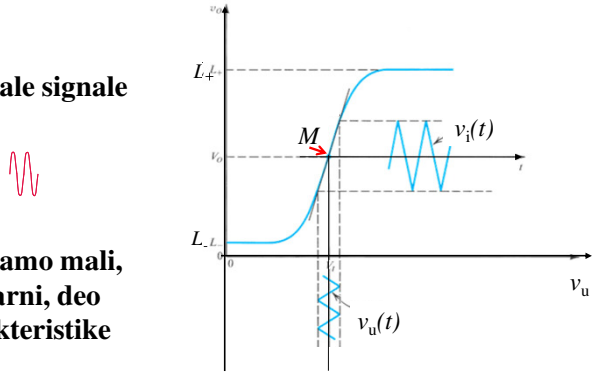


Nelinearni

4

Modeli poluprovodničkih komponenata

Za male signale



Vide samo mali, linearni, deo karakteristike

Linearni

5

Modeli poluprovodničkih komponenata

Za velike signale



Nelinearni — **Složeni modeli – pomoću računara**

Linearizovani — **Jednostavni modeli – modeli prvog reda**

Idealizovani — **- Gruba procena – "ručna analiza"**

Za male signale **Linearni**



6

Koje poluprovodničke kompomente znamo?

"Elektronske komponente" II semestar

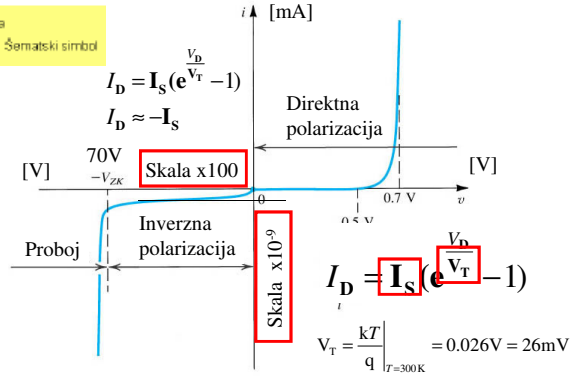
-Diode

-Bipolarni tranzistor

-MOSFET tranzistor

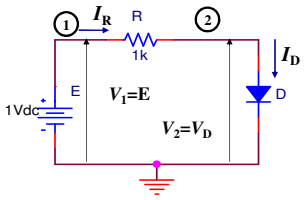
-Diode (zavisnost struje od napona na diodi)





Model diode

-Kako se ponaša dioda u elektronskom kolu?



$$\frac{V_1 - V_2}{R} = I_R$$

$$\frac{V_2 - V_1}{R} + I_D(V_D) = 0$$

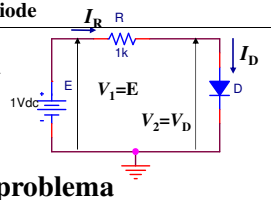
$$I_D(V_D) = \mathbf{I}_s(e^{\frac{V_D}{V_T}} - 1)$$

$$V_D = ?$$

Model diode

-Dioda u elektronskom kolu

DC režim



$$\frac{V_1 - V_2}{R} = I_R$$

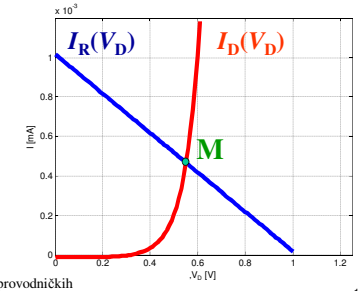
$$\frac{V_2 - V_1}{R} + I_D(V_D) = 0$$

$$I_D(V_D) = \mathbf{I}_s(e^{\frac{V_D}{V_T}} - 1)$$

Grafička interpretacija problema

$$\frac{\mathbf{E} - V_D}{R} = I_R$$

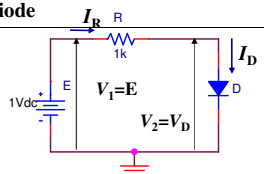
$$I_D = \mathbf{I}_S(e^{\frac{V_D}{V_T}} - 1)$$



Model diode

-Dioda u elektronskom kolu

DC režim



$$\frac{V_1 - V_2}{R} = I_R$$

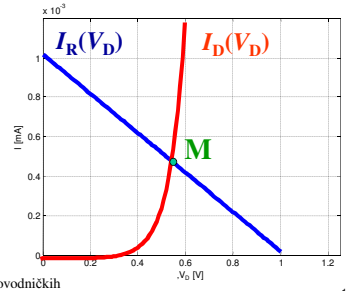
$$\frac{V_2 - V_1}{R} + I_D(V_D) = 0$$

$$I_D(V_D) = \mathbf{I}_s(e^{\frac{V_D}{V_T}} - 1)$$

Model diode – nelinearan – za velike signale

$$\frac{\mathbf{E} - V_D}{R} = I_R$$

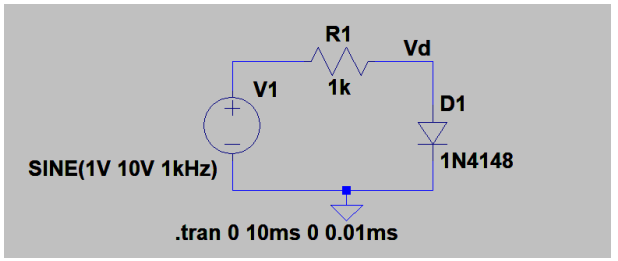
$$I_D = \mathbf{I}_S(e^{\frac{V_D}{V_T}} - 1)$$



Model diode

-Dioda u elektronskom kolu

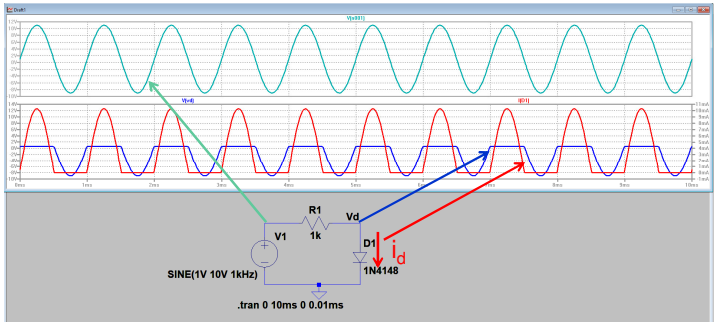
Model diode – nelinearan – za velike signale



Model diode

-Dioda u elektronskom kolu

Model diode – nelinearan – za velike signale

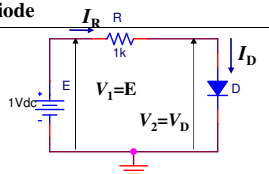


Struja nije k*V (linearno proporcionalna naponu) za velike signale

Model diode

-Dioda u elektronskom kolu

DC režim



$$\frac{V_1 - V_2}{R} = I_R \qquad \frac{V_2 - V_1}{R} + I_D(V_D) = 0 \qquad I_D(V_D) = I_s(e^{\frac{V_D}{V_T}} - 1)$$

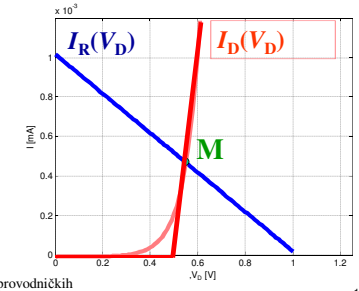
Model diode – linearizovan – za velike signale

$$\frac{E - V_D}{R} = I_R$$

$$I_D = I_S(e^{\frac{V_D}{V_T}} - 1)$$

$I_D = 0$ za $V_D < V_\gamma = 0.5V$

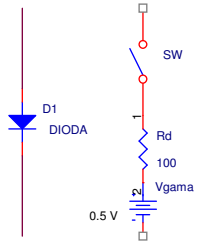
$$I_D = \frac{V_D}{R_d} \text{ za } V_D > V_\gamma$$



Model diode

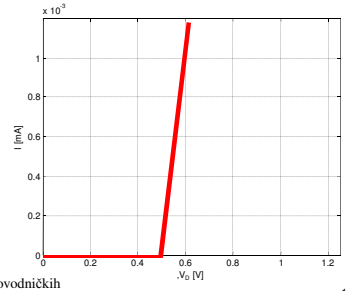
-Dioda u elektronskom kolu

Model diode – linearizovan – za velike signale



$I_D = 0$ za $V_D < V_\gamma = 0.5V$

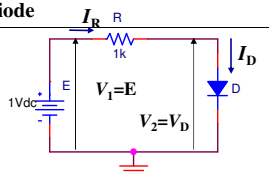
$$I_D = \frac{V_D}{R_d} \text{ za } V_D > V_\gamma$$



Model diode

-Dioda u elektronskom kolu

DC režim



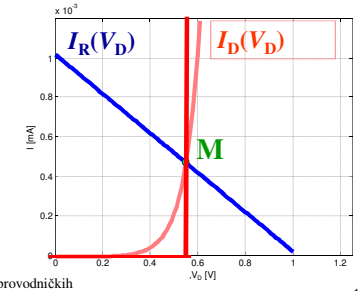
$$\frac{V_1 - V_2}{R} = I_R \qquad \frac{V_2 - V_1}{R} + I_D(V_D) = 0 \qquad I_D(V_D) = I_s(e^{\frac{V_D}{V_T}} - 1)$$

Model diode – idealizovan – za velike signale

$$\frac{E - V_D}{R} = I_R$$

$I_D = 0$ za $V_D < V_\gamma = 0.55V$

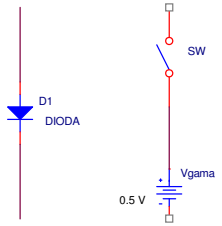
$V_D = V_\gamma$ za $V_D \geq V_\gamma$

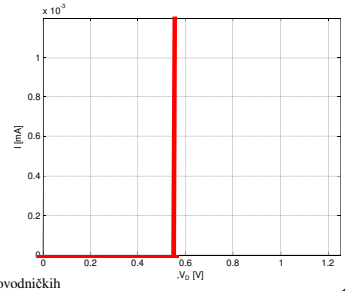


Model diode

-Dioda u elektronskom kolu

Model diode – idealizovan – za velike signale





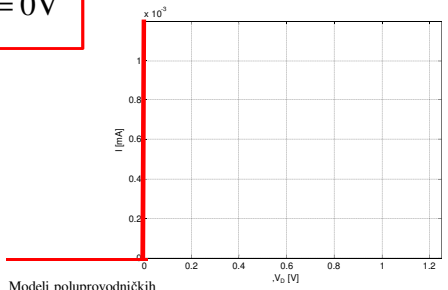
$$I_D = 0 \quad \text{za } V_D < V_\gamma = 0.55V$$
$$V_D = V_\gamma \quad \text{za } V_D \geq V_\gamma$$

Model diode

-Dioda u elektronskom kolu

Model idealne diode

$$I_D = 0 \quad \text{za } V_D < V_\gamma = 0V$$

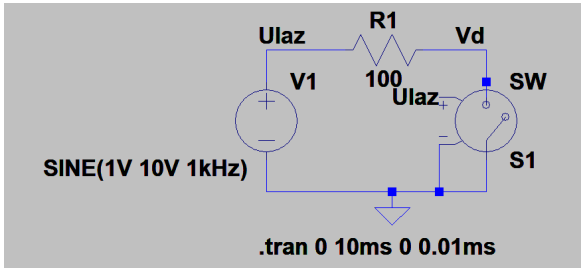


Model diode

-Dioda u elektronskom kolu

Model idealne diode

$$I_D = 0 \quad \text{za } V_D < V_\gamma = 0V$$

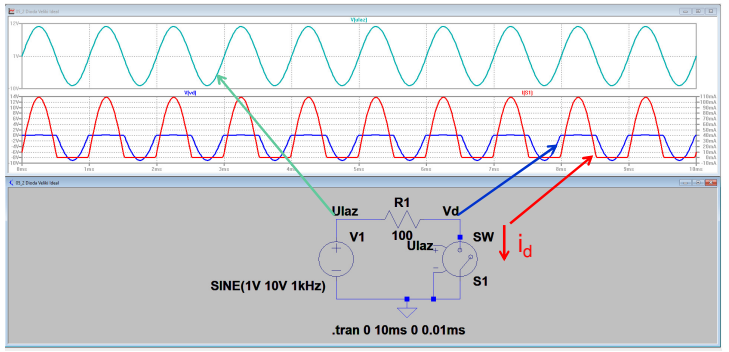


Model diode

-Dioda u elektronskom kolu

Model idealne diode

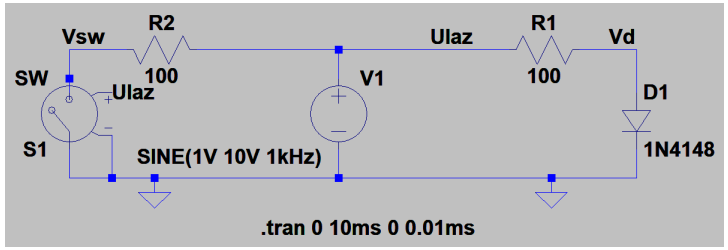
$$I_D = 0 \quad \text{za } V_D < V_\gamma = 0V$$



Model diode

-Dioda u elektronskom kolu $I_D = 0 \quad \text{za } V_D < V_\gamma = 0V$

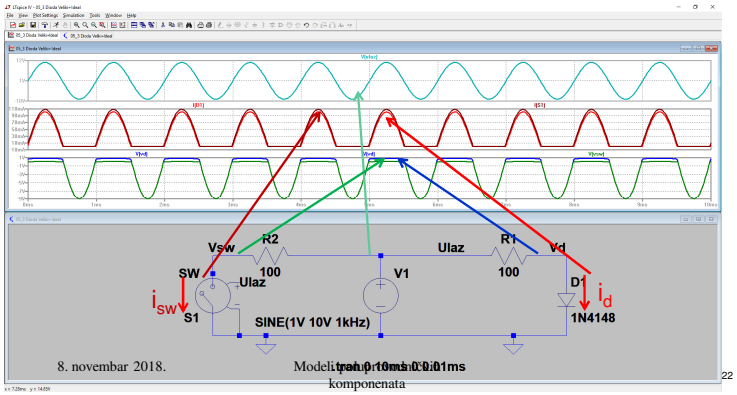
Model za velike signale: realna i idealna dioda (prekidač)



Model diode

-Dioda u elektronskom kolu $I_D = 0 \quad \text{za } V_D < V_\gamma = 0V$

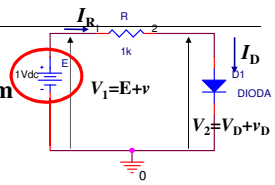
Model za velike signale: realna i idealna dioda (prekidač)



Model diode

-Dioda u elektronskom kolu
Statički - DC režim

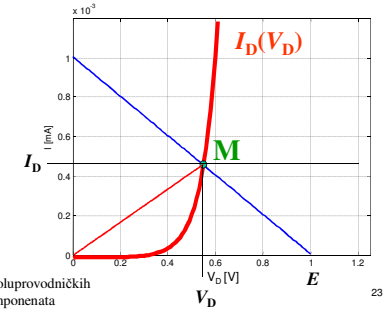
Grafička interpretacija problema



$V_1 = E$

$V_2 = V_D$

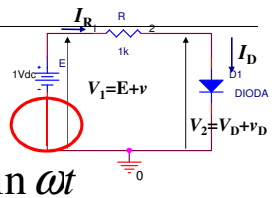
Za DC, u radnoj tački, dioda se ponaša kao otpornik čija je otpornost $R_D = V_D / I_D$



Model diode

-Dioda u elektronskom kolu
dinamički režim

Grafička interpretacija problema



$V_1 = E$

$V_2 = V_D$

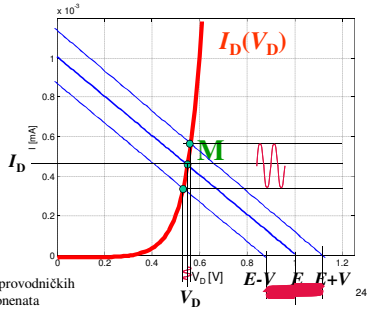
$$V_1 = E + v; \quad v = V \sin \omega t$$

$$E - V \le V_1 \le E + V$$

$$v_D = V_D + v_d$$

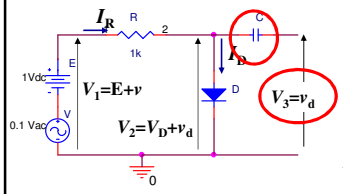
$$v_d = V_d \sin \omega t$$

$$i_D = I_D + I_d \sin \omega t$$

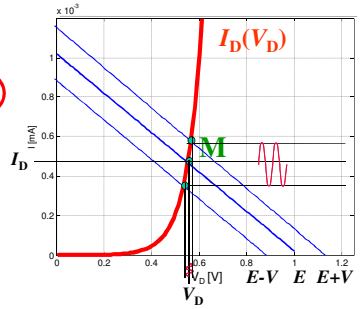


Model diode

-Dioda u elektronskom kolu dinamički režim

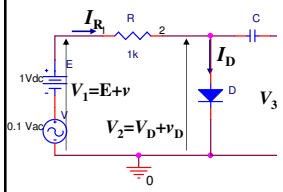


Grafička interpretacija problema

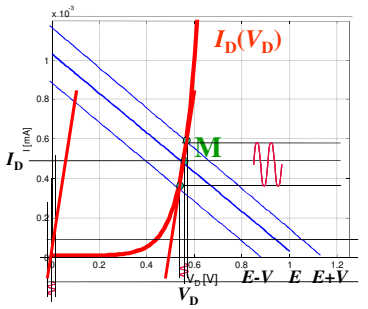


Model diode

-Dioda u elektronskom kolu dinamički režim

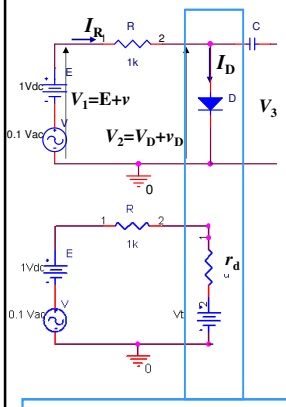


Grafička interpretacija problema



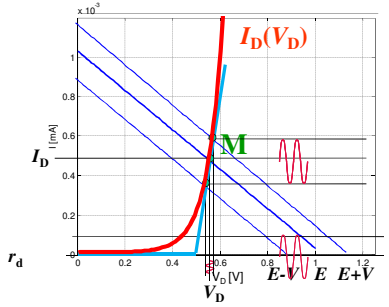
Model diode

-Dioda u elektronskom kolu



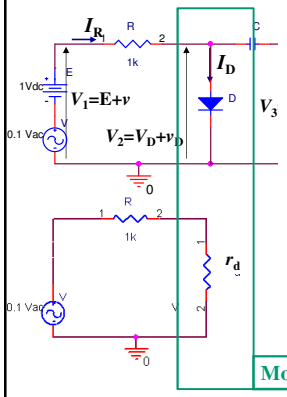
Linearizovan model za velike signale

Grafička interpretacija problema



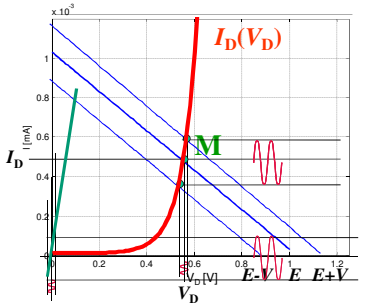
Model diode

-Dioda u elektronskom kolu



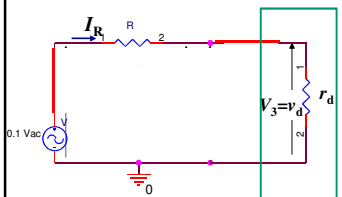
Model za male signale

Grafička interpretacija problema



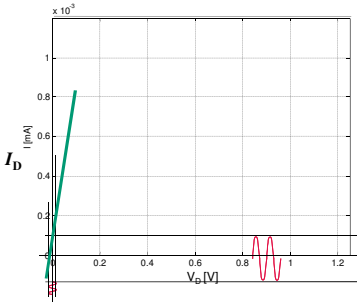
Model diode

-Dioda u elektronskom kolu



Za mali naizmenični (vremenski promenljivi - *dinamički*) signal dioda se ponaša kao otpornost čija je vrednost $r_d=\Delta V_d/\Delta I_d$

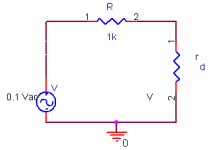
Grafička interpretacija problema

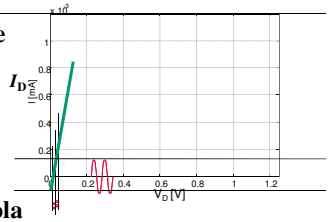


Model za male signale

Model diode

VAŽNO model za male signale





koristi se u analizi ponašanja kola pobuđenih malim naizmeničnim signalima.

Tada se svi elementi kola zamenjuju *dinamičkim parametrima*

Dinamički parametar diode jeste *unutrašnja otpornost* diode u radnoj tački.

$$r_d = \frac{dV_D}{dI_D} \approx \frac{\Delta V_D}{\Delta I_D}$$

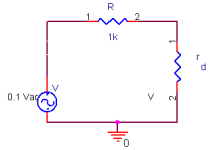
$$r_d = \frac{1}{\frac{dI_D}{dV_D}} \approx \frac{1}{\frac{I_S e^{V_D/V_T}}{V_T}}$$

$$r_d \approx \frac{V_T}{I_D}$$

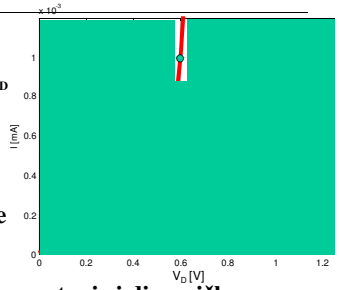
dalje

Model diode

VAŽNO model za male signale



$$r_d \approx \frac{V_T}{I_D}$$



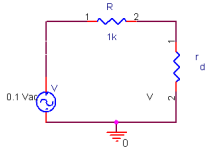
Otpornost zavisi od položaja mirne radne tačke!

Postoji zavisnost između jednosmerne struje i dinamičke otpornosti.

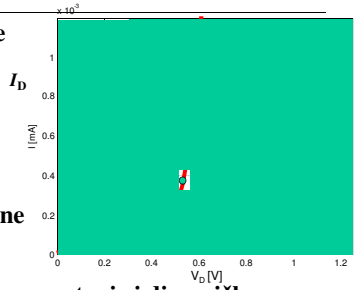
Veća struja – manja otpornost

Model diode

VAŽNO model za male signale



$$r_d \approx \frac{V_T}{I_D}$$



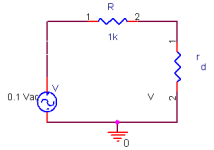
Otpornost zavisi od položaja mirne radne tačke!

Postoji zavisnost između jednosmerne struje i dinamičke otpornosti.

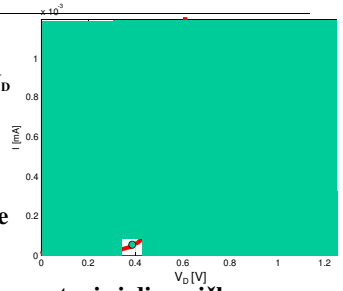
Manja struja – veća otpornost

Model diode

VAŽNO model za male signale



$$r_d \approx \frac{V_T}{I_D}$$



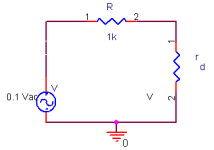
Otpornost zavisi od položaja mirne radne tačke!

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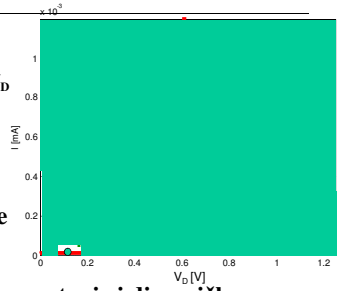
Manja struja – veća otpornost

Model diode

VAŽNO model za male signale



$$r_d \approx \frac{V_T}{I_D}$$



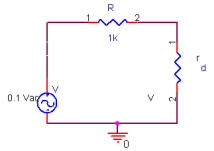
Otpornost zavisi od položaja mirne radne tačke!

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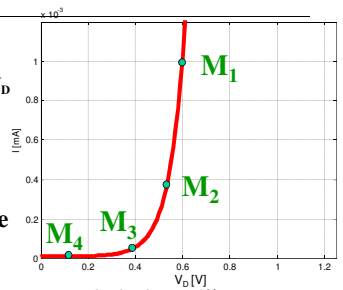
Manja struja – veća otpornost

Model diode

VAŽNO model za male signale



$$r_d \approx \frac{V_T}{I_D}$$



Otpornost zavisi od položaja mirne radne tačke!

Postoji zavisnost između jednosmerne struje i dinamičke otpornosti.



U kojoj tački je otpornost najveća?

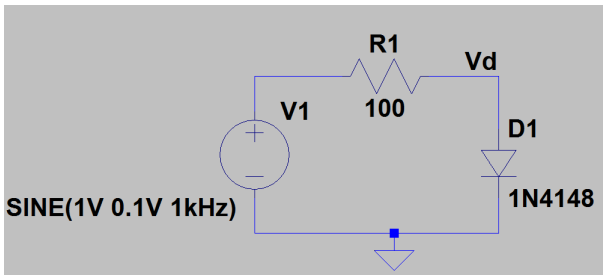
Upišite odgovarajući znak „<„ ili „>“.

$$r_{d1} < r_{d2} < r_{d3} < r_{d4}$$

Model diode

-Dioda u elektronskom kolu

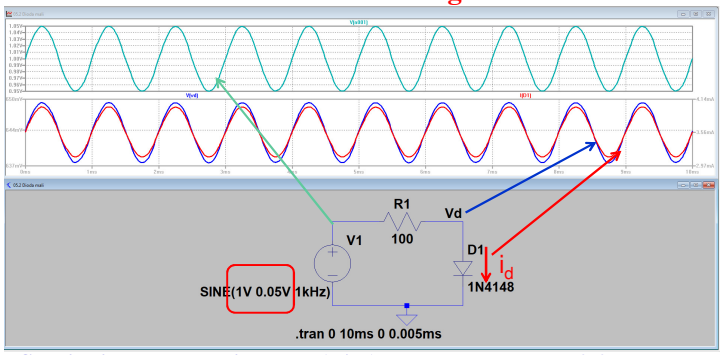
Model diode –linearan – za male signale



Model diode

-Dioda u elektronskom kolu

Model diode –linearan – za male signale

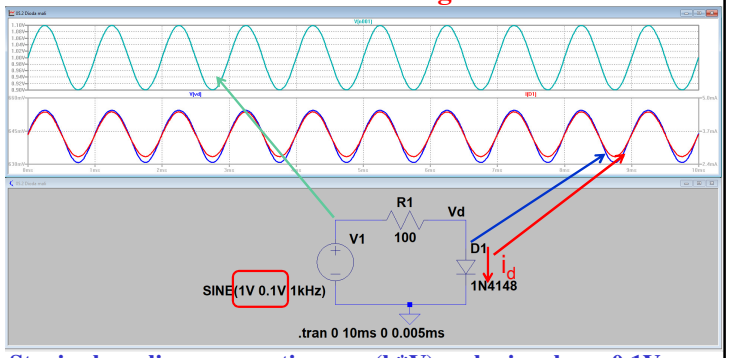


Struja linearno prati napon (k*V) za male signale v_1=0.05V

Model diode

-Dioda u elektronskom kolu

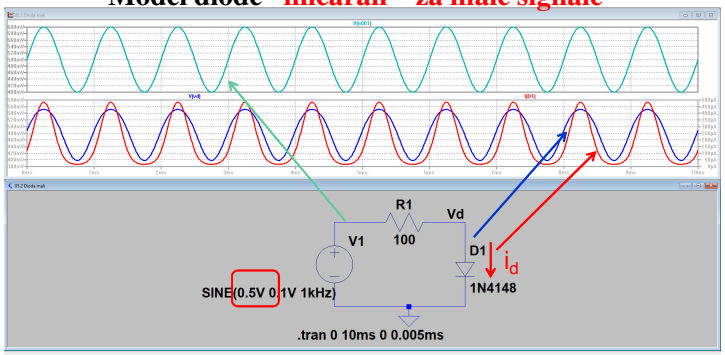
Model diode –linearan – za male signale



Struja skoro linearno prati napon (k*V) male signale v_1=0.1V

-Dioda u elektronskom kolu **Model diode**

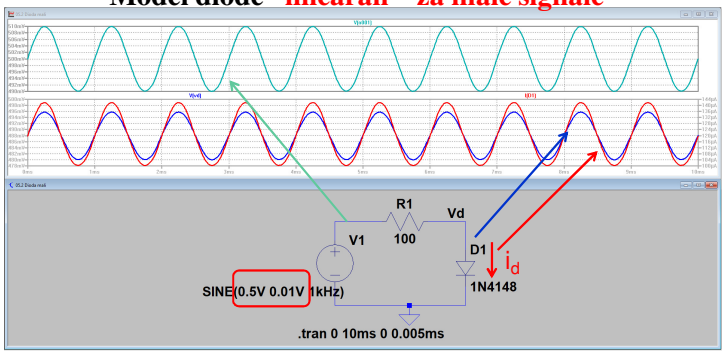
Model diode –linearan – za male signale



Struja ne prati linearno napon (k*V) za signal od 0.1V ako je u nelinearnom delu karakteristike – jednosmerna radna tačka je pomerena na 0,5V

-Dioda u elektronskom kolu **Model diode**

Model diode –linearan – za male signale



Nelinearnost manja za manji signal od 0.01V u istoj radnoj tački

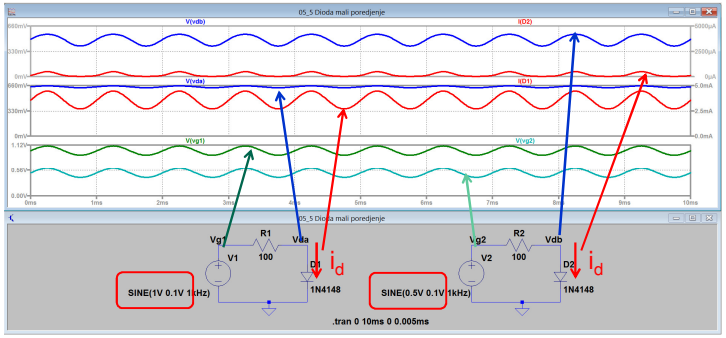
-Dioda u elektronskom kolu Model diode

Model diode –linearan – za male signale

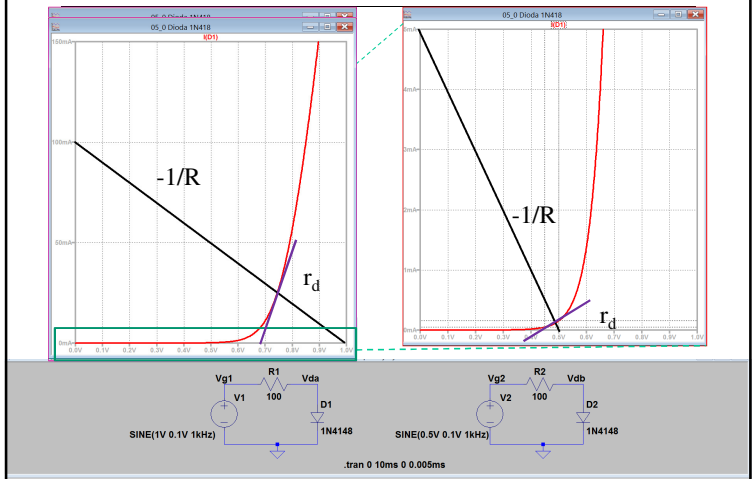


-Dioda u elektronskom kolu Model diode

Model diode –linearan – za male signale



Model diode

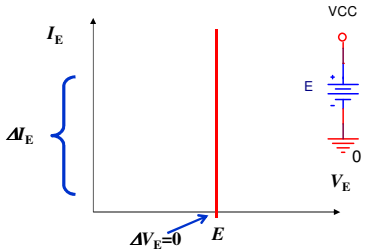


Dinamički model izvora konstantnog napona

VAŽNO
model za male signale

Isto važi i za izvore jednosmernih napona i struja = zamena dinamičkom otpornošću.

Koliko će se promeniti napon na izvoru jednosmernog napona V_E=E ako se struja kroz njega promeni za ΔI_E?



$$r_E = \frac{\Delta V_E}{\Delta I_E} = \frac{0}{\Delta I_E} = 0$$



Dinamički model izvora konstantnog napona (DC) je r_E=0

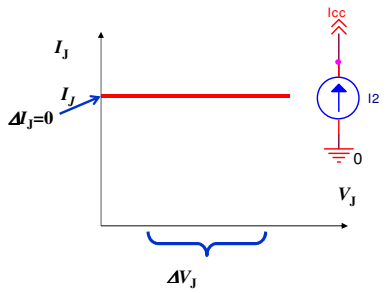
Za male AC signale E se ponaša kao kratak spoj

Dinamički model izvora konstantne struje

VAŽNO
model za male signale

Izvor konstantne struje = zamena dinamičkom otpornošću.

Koliko će se promeniti struja izvora konstantne struje ako se napon na njemu promeni za ΔV_J?



$$r_J = \frac{\Delta V_J}{\Delta I_J} = \frac{\Delta V_J}{0} \to \infty$$

Dinamički model izvora konstantne struje (DC) je $r_J=\infty$

Za male AC signale *I* se ponaša kao prekid



45

Šta smo naučili?

- **Razlika izmedju modela za velike i male signale.**
  - **Električne šeme modela diode za velike i male signale.**

Ispitna pitanja?

1. **Zavisnost dinamičke otpornosti od vrednosti jednosmerne struje diode.**
2. **Dinamički (AC, malosignalni) model izvora konstantnog napona**
3. **Dinamički (AC, malosignalni) model izvora konstantnog napona**

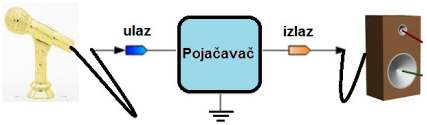
Na web adresi http://leda.elfak .ni.ac.rs

> EDUCATION > ELEKTRONIKA

slajdovi u pdf formatu

Osnovi elektronike

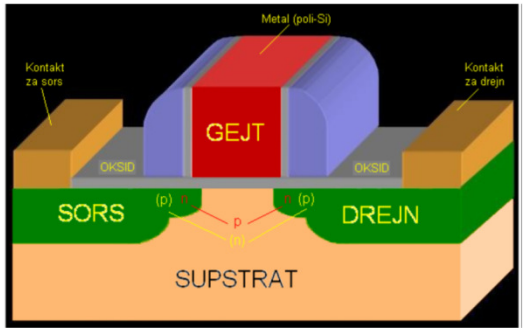
Kako rade MOS tranzistori kako pojacavaju napon?



Modeli poluprovodničkih komponenata

Da se podsetimo

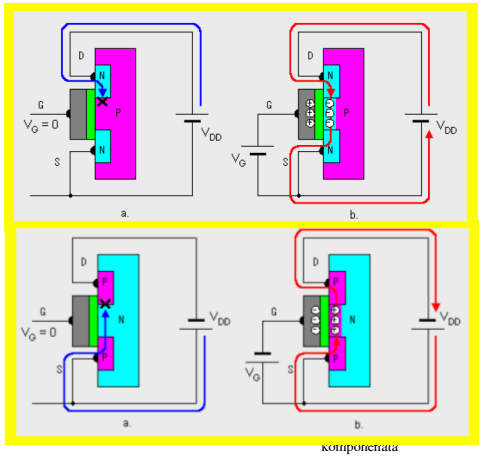
MOS tranzistor



Model MOS tranzistora

Da se podsetimo

MOS tranzistor



nMOS

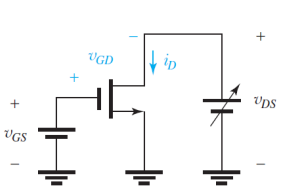
Vodi za $V_G > 0$

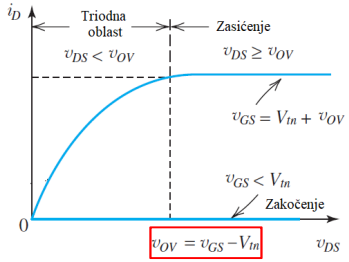
pMOS

Vodi za $V_G < 0$

Model MOS tranzistora

Da se podsetimo: Izlazne karakteristike MOSFET-a



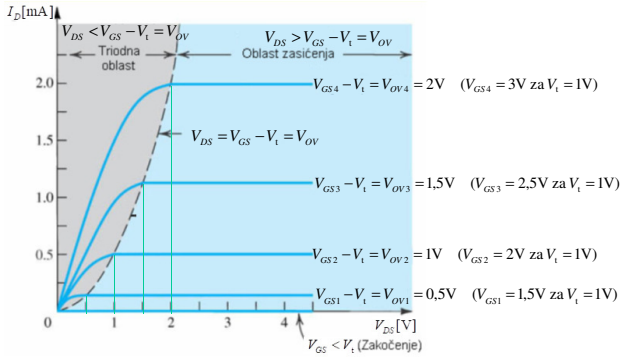


Režimi rada MOSFET		V_{GS}	V_{DS}
	Zakočen	$\lvert V_{GS} \rvert < \lvert V_t \rvert$	
Vodi	Zasićenje	$\lvert V_{GS} \rvert > \lvert V_t \rvert$	$\lvert V_{DS} \rvert > \lvert V_{GS}-V_t \rvert$
	Triodna oblast	$\lvert V_{GS} \rvert > \lvert V_t \rvert$	$\lvert V_{DS} \rvert < \lvert V_{GS}-V_t \rvert$

Model MOS tranzistora

Da se podsetimo

Izlazne karakteristike MOSFET-a



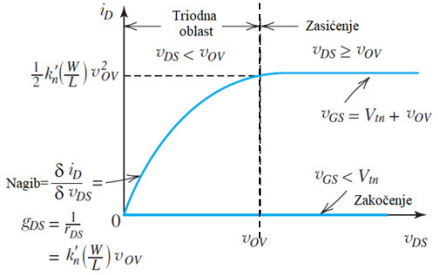
Model MOS tranzistora

Da se podsetimo: Izlazne karakteristike MOSFET-a

$$I_D = k_n' \frac{W}{L}\left[(V_{GS} - V_t)\cdot V_{DS} - \frac{1}{2}V_{DS}^2\right],$$

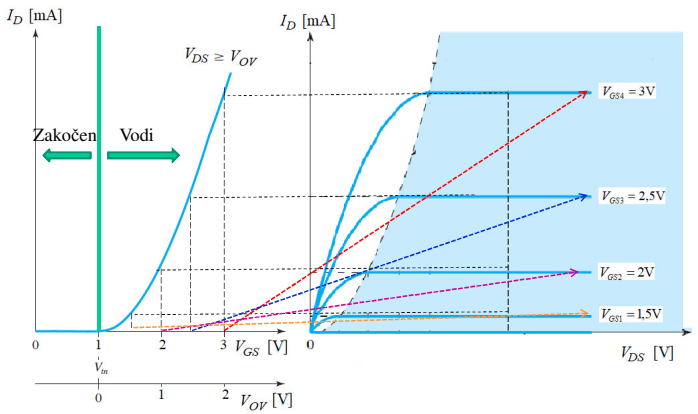
$$I_D = k_n' \frac{W}{L}\left[V_{OV} - \frac{1}{2}V_{DS}\right]\cdot V_{DS}$$

$$I_D = \frac{1}{2}k_n' \frac{W}{L}(V_{GS} - V_t)^2 = \frac{1}{2}k_n' \frac{W}{L}V_{OV}^2,$$



Model MOS tranzistora

Da se podsetimo: Prenosne karakteristike MOSFET-a



Model MOS tranzistora

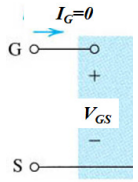
Model za velike signale - DC model

Na ulazu:

Za sve oblasti važi:

$$I_G = 0$$

Model: Strujni generator I_G =0; prekid u kolu



Model MOS tranzistora

Model za velike signale - DC model u oblasti zasićenja

Važi za: $V_{GS} > V_t$

$V_{DS} > V_{GS} - V_t = V_{OV}$

Na izlazu: $V_{OV} = V_{GS} - V_t$

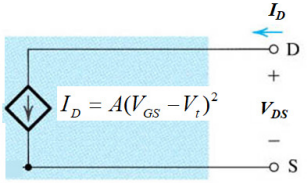
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_t)^2,$$

$$I_D = \frac{1}{2}k_n'\frac{W}{L}(V_{GS} - V_t)^2,$$

$$I_D = A(V_{GS} - V_t)^2,$$

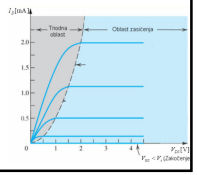
$$I_D = A \cdot V_{OV}^{\ 2},$$

Model: Strujni generator I_D kontrolisan naponom V_{GS}



I_D ne zavisi od V_{DS}

I_D zavisi od V_{GS}



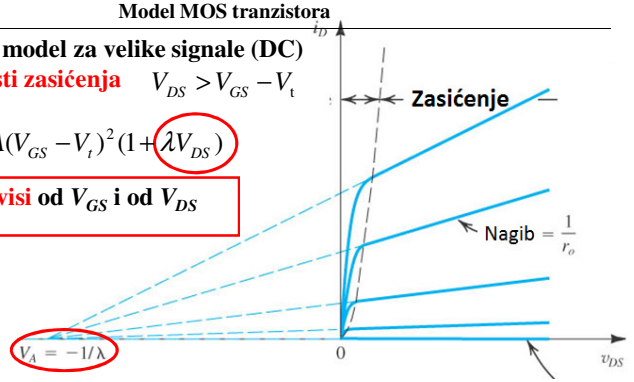
Model MOS tranzistora

Realni model za velike signale (DC)

u oblasti zasićenja $V_{DS} > V_{GS} - V_t$

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

I_D zavisi od V_{GS} i od V_{DS}



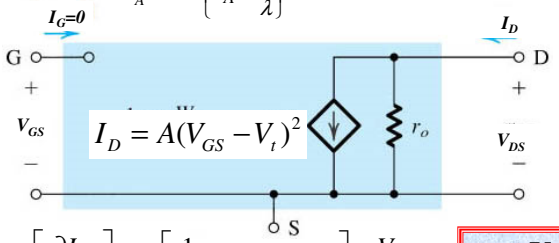
$$I_D = A(V_{GS} - V_t)^2\left(1 + \frac{V_{DS}}{V_A}\right) \quad \left\{V_A = \frac{1}{\lambda}\right\}$$

Model MOS tranzistora

Realni model za velike signale (DC) $V_{DS} > V_{GS} - V_t$

u oblasti zasićenja

$$I_D = A(V_{GS} - V_t)^2 (1 + \frac{1}{V_A} V_{DS}) \left\{ V_A = \frac{1}{\lambda} \right\}$$



$$r_o = \frac{\partial V_{DS}}{\partial I_D} = 1 / \left[\frac{\partial I_D}{\partial V_{DS}} \right] = 1 / \left[\frac{1}{V_A} A(V_{GS} - V_t)^2 \right] = \frac{V_A}{I_D}$$

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

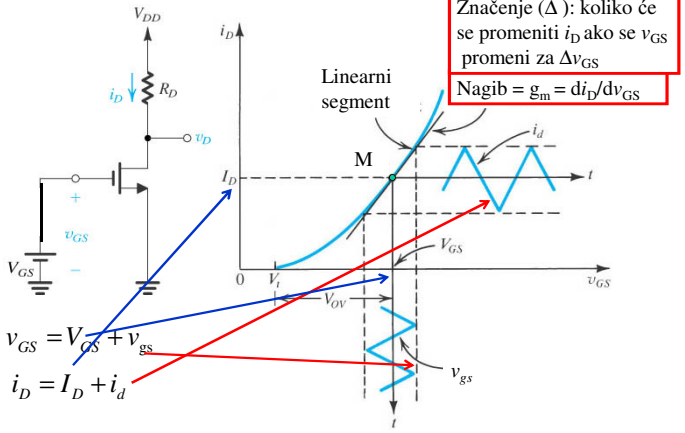
Model MOS tranzistora

Radna tačka – značenje modela za male signa

Značenje (AC): koliku će promenu i_d izazvati v_{gs}

Značenje (Δ): koliko će se promeniti i_D ako se v_{GS} promeni za Δv_{GS}

Nagib = $g_m = di_D/dv_{GS}$



$$v_{GS} = V_{GS} + v_{gs}$$

$$i_D = I_D + i_d$$

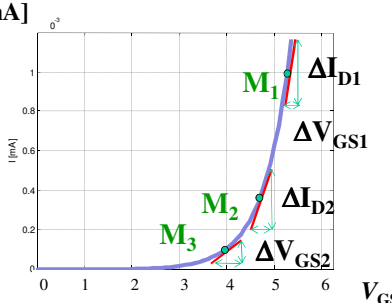
Model MOS tranzistora

Radna tačka – značenje modela za male signale u oblasti zasićenja

$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$

I_D [mA]



***g_m* ZAVISI od položaja radne tačke**

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \approx \frac{\Delta I_D}{\Delta V_{GS}} = \frac{2I_D}{(V_{GS} - V_t)} = \frac{2I_D}{V_{OV}}$$

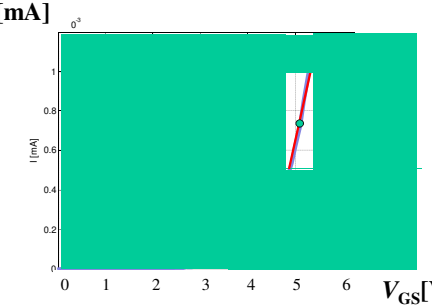
Model MOS tranzistora

Radna tačka – značenje modela za male signale u oblasti zasićenja

$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$

I_D [mA]



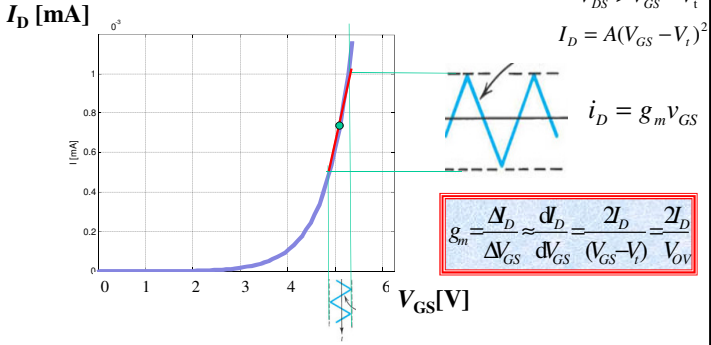
***g_m* ZAVISI od položaja mirne (DC) radne tačke.**
Ista promena v_{gs} izazvaće različitu promenu struje i_d

Model MOS tranzistora

Radna tačka – značenje modela za male signale u oblasti zasićenja

$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$



$i_D = g_m v_{GS}$

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \approx \frac{dI_D}{dV_{GS}} = \frac{2I_D}{(V_{GS}-V_t)} = \frac{2I_D}{V_{OV}}$$

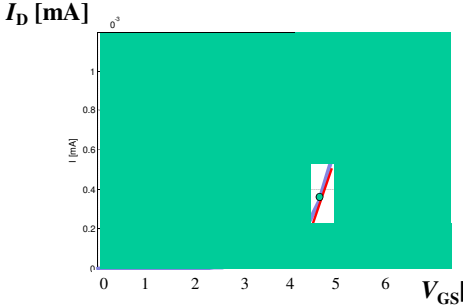
g_m ZAVISI od položaja mirne (DC) radne tačke.
Ista promena v_{gs} izazvaće različitu promenu struje i_d

Model MOS tranzistora

Radna tačka – značenje modela za male signale u oblasti zasićenja

$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$



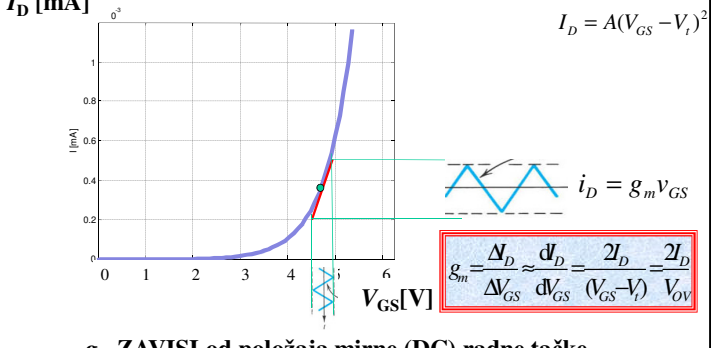
***Ista promena V_{GS}* izazvaće različite promene struje i_D u zavisnosti od položaja radne tačke tranzistora (DC vrednost struje I_D)**

Model MOS tranzistora

Radna tačka – značenje modela za male signale u oblasti zasićenja

$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$



$i_D = g_m v_{GS}$

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \approx \frac{dI_D}{dV_{GS}} = \frac{2I_D}{(V_{GS}-V_t)} = \frac{2I_D}{V_{OV}}$$

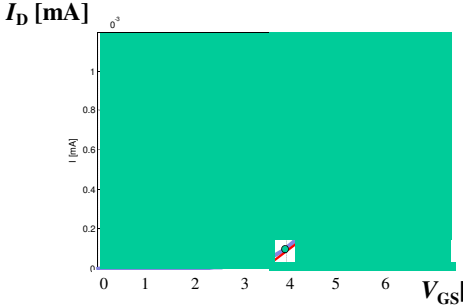
g_m ZAVISI od položaja mirne (DC) radne tačke.
Ista promena v_{gs} izazvaće različitu promenu struje i_d

Model MOS tranzistora

Radna tačka – značenje modela za male signale u oblasti zasićenja

$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$



***Ista promena V_{GS}* izazvaće različite promene struje i_D u zavisnosti od položaja radne tačke tranzistora (DC vrednost struje I_D)**

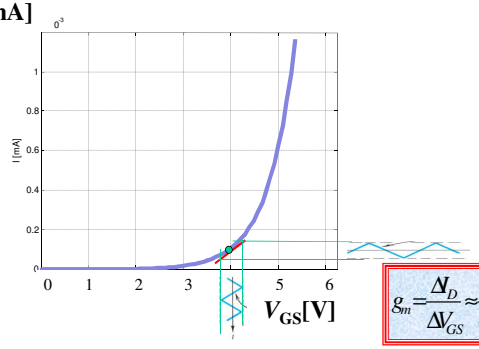
Model MOS tranzistora

Radna tačka – značenje modela za male signale u oblasti zasićenja

$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$

I_D [mA]



$i_D = g_m v_{GS}$

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \approx \frac{dI_D}{dV_{GS}} = \frac{2I_D}{(V_{GS} - V_t)} = \frac{2I_D}{V_{OV}}$$

g_m ZAVISI od položaja mirne (DC) radne tačke.
Ista promena v_{gs} izazvaće različitu promenu struje i_d

Model MOS tranzistora

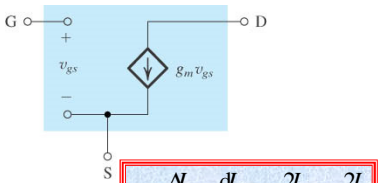
Model za male signale (dinamički model) u oblasti zasićenja

$i_G = 0; \quad i_D = g_m v_{GS}$

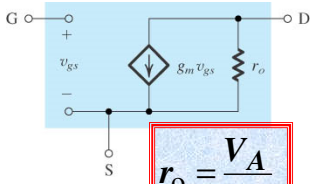
$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$

Model: Strujni generator $i_G = 0$; prekid u kolu
Linearni strujni generator kontrolisan naponom $i_D = g_m v_{GS}$



$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \approx \frac{dI_D}{dV_{GS}} = \frac{2I_D}{(V_{GS} - V_t)} = \frac{2I_D}{V_{OV}}$$



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

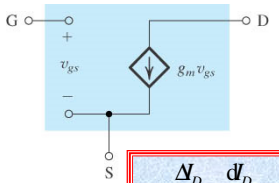
Model MOS tranzistora

Model za male signale (dinamički model) u oblasti zasićenja

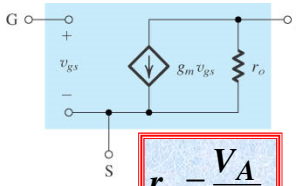
$i_G = 0; \quad i_D = g_m v_{GS}$

$V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$



$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \approx \frac{dI_D}{dV_{GS}} = \frac{2I_D}{(V_{GS} - V_t)} = \frac{2I_D}{V_{OV}}$$



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

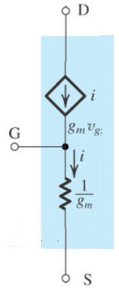
$$\left(g_m r_o \equiv \mu = \frac{dI_D}{dV_{GS}} \frac{dV_{DS}}{dI_D} = \frac{dV_{DS}}{dV_{GS}} = \frac{2V_A}{(V_{GS} - V_t)} \right) \qquad \left(\begin{matrix} r_o \equiv R_i \\ S \equiv g_m \end{matrix} \right)$$

Model MOS tranzistora

T Model za male signale u oblasti zasićenja $V_{DS} > V_{GS} - V_t$

$I_D = A(V_{GS} - V_t)^2$

$$g_m = \frac{dI_D}{dV_{GS}} = 2A(V_{GS} - V_t) = \frac{2I_D}{(V_{GS} - V_t)} = \frac{2I_D}{V_{OV}}$$



$$r_s = \frac{1}{g_m}$$

Model MOS tranzistora



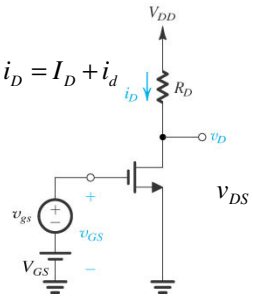
Domaći 5.1

Za nMOS tranzistor kod koga je V_t=1V, $\mu_n C_{ox}$ =120μA/V², W/L=10 i λ=0.02V^{-1} odrediti:
a) opseg napona V_{GS} za koje tranzistor vodi
b) napon V_{DS} u funkciji V_{GS} pri kome tranzistor ulazi u zasićenje,
c) dinamičke parametre tranzistora g_m i r_o u radnoj tački definisanoj sa I_D=75μA, ako se zna da tranzistor radi u zasićenju.
d) Nacrtati model za male signale i upisati vrednosti parametara.

V_{GS}>1V; V_{DS}> V_{GS}+1V; 424μA/V, 0.67MΩ

Model MOS tranzistora

Kako MOSFET pojačava ulazni napon?

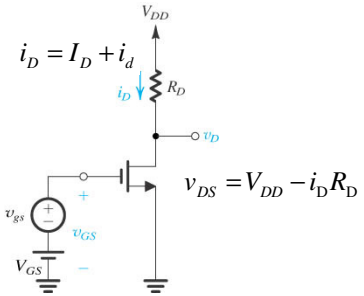


$v_{DS} = V_{DD} - i_D R_D$

$v_{GS} = V_{GS} + v_{gs}$

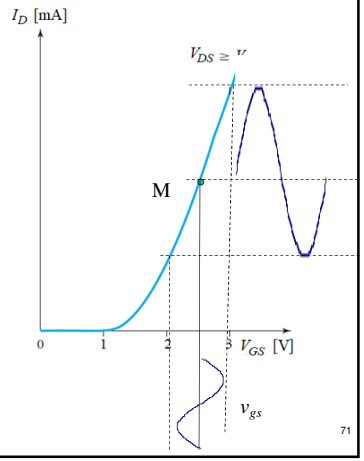
Model MOS tranzistora

Kako MOSFET pojačava ulazni napon?



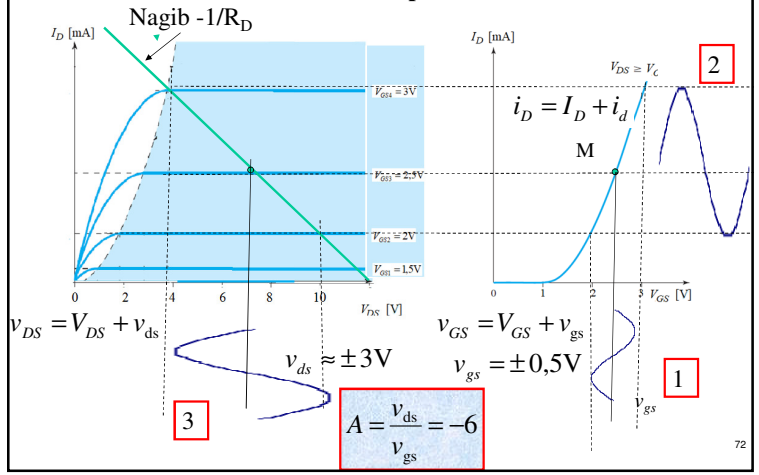
$v_{DS} = V_{DD} - i_D R_D$

$v_{GS} = V_{GS} + v_{gs}$



Model MOS tranzistora

Kako MOSFET pojačava ulazni napon?



$v_{DS} = V_{DS} + v_{ds}$

$v_{ds} \approx \pm 3V$

$v_{GS} = V_{GS} + v_{gs}$

$v_{gs} = \pm 0{,}5V$

v_{gs}

$A = \frac{v_{ds}}{v_{gs}} = -6$

Šta smo naučili?

- **Razlika izmedju modela za velike i male signale.**
  - **Električne šeme modela MOS tranzistora za velike i male signale.**

Ispitna pitanja?

1. **Koji su dinamički parametri MOS tranzistora?**
2. **Zavisnost g_m MOS tranzistora od položaja jednosmerne radne tačke tranzistora**
3. **Zavisnost izlazne otpornosti MOS tranzistora od položaja jednosmerne radne tačke**

Na web adresi http://leda.elfak .ni.ac.rs

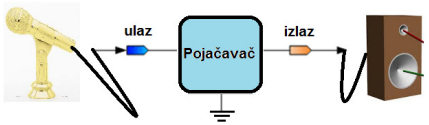
> EDUCATION > ELEKTRONIKA

slajdovi u pdf formatu

Osnovi elektronike

Kako rade bipolarni tranzistori?
Kako pojačavaju napon?

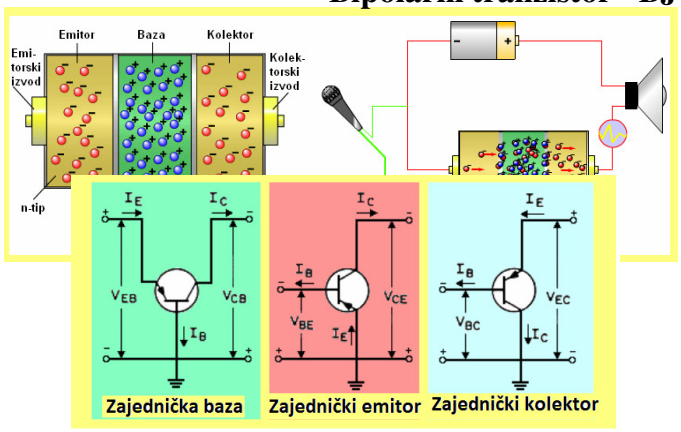
BJT (odakle J?)



Da se podsetimo

Model bipolarnog tranzistora

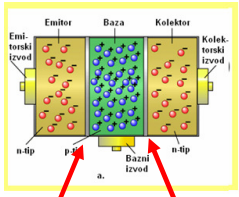
Bipolarni tranzistor - BJT



Da se podsetimo

Model bipolarnog tranzistora

Bipolarni tranzistor - BJT

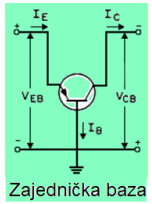


Režimi rada BJT	Emitorski spoj	Kolektorski spoj
aktivni	direktno P(+)N(-)	inverzno P(-)N(+)
zasićenje	direktno P(+)N(-)	direktno P(+)N(-)
zakočenje	inverzno P(-)N(+)	inverzno P(-)N(+)
inverzni	inverzno P(-)N(+)	direktno P(+)N(-)

Bipolarni tranzistor - BJT

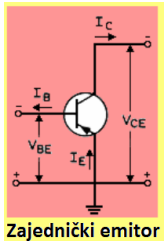
Režimi rada BJT	Emitorski spoj	Kolektorski spoj	NPN	PNP
aktivni	direktno P(+)N(-)	inverzno P(-)N(+)	$V_{BE}>0$ $V_{BC}<0$	$V_{BE}<0$ $V_{BC}>0$
zasićenje	direktno P(+)N(-)	direktno P(+)N(-)	$V_{BE}>0$ $V_{BC}>0$	$V_{BE}<0$ $V_{BC}<0$
zakočenje	inverzno P(-)N(+)	inverzno P(-)N(+)	$V_{BE}<0$ $V_{BC}<0$	$V_{BE}>0$ $V_{BC}>0$
inverzni	inverzno P(-)N(+)	direktno P(+)N(-)	$V_{BE}<0$ $V_{BC}>0$	$V_{BE}>0$ $V_{BC}<0$

Koeficijent strujnog pojačanja: i_{iz}/i_{ul} ili $\Delta I_{IZ}/\Delta I_{UL}$



$$I_B = I_E - I_C$$

$$\beta = \left.\frac{I_C}{I_B}\right|_{V_{BE}=0} = \frac{I_C}{I_E - I_C} = \frac{\alpha}{1-\alpha}$$



$$\alpha = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CE}=\text{Const.}} = \left.\frac{i_c}{i_e}\right|_{v_{eb}=0.} <\approx 1$$

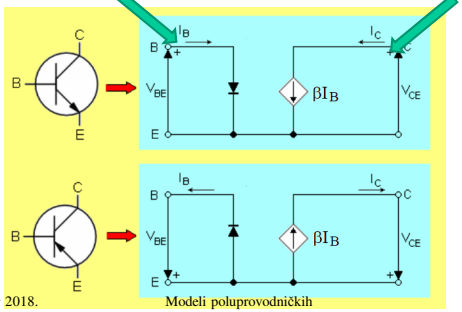
$$\beta = \left.\frac{I_C}{I_B}\right|_{\substack{v_{be}=0 \\ \text{ili } V_{BE}=\text{const.}}} >> 1$$

Uprošćeni Ebers-Mollov model (za velike signale, smerovi struja različiti za NPN i PNP)
Konfiguracija zajednički emitor

$$I_B(V_{BE}) = \mathbf{I_s}(e^{\frac{V_{BE}}{\mathbf{V_T}}} - 1)$$

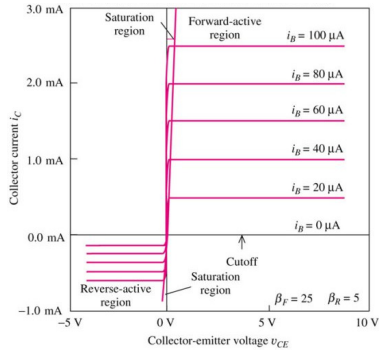
$$I_C(V_{BE}) = \beta \cdot I_B = \beta \cdot \mathbf{I_s}(e^{\frac{V_{BE}}{\mathbf{V_T}}} - 1)$$

Nelinearni model



Kompletan Ebers-Molov model

Idealizovani model: u aktivnom režimu I_C ne zavisi od V_{CE};



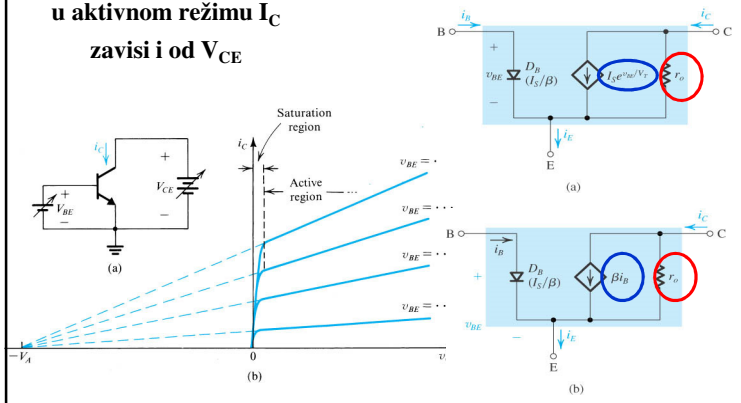
$I_C \neq f(V_{CE})$;

$I_C = f(\beta)$,

$I_C = f(V_{BE})$.

Model bipolarnog tranzistora **Early-ev efekat**

Međutim, kod realnih tranzistoranije tako u aktivnom režimu I_C zavisi i od V_{CE}



81

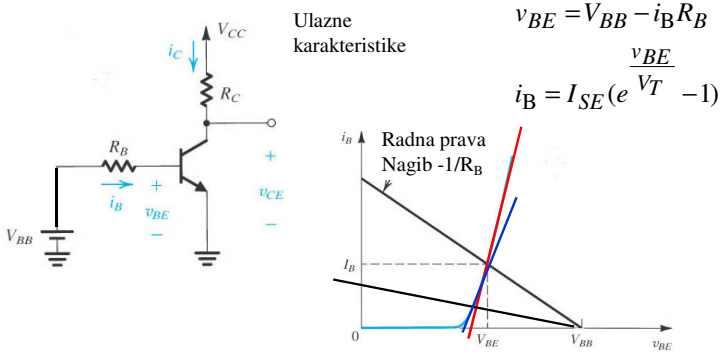
Model bipolarnog tranzistora

Radna tačka – uticaj na model za male signale

Ulazne karakteristike

$$v_{BE} = V_{BB} - i_B R_B$$

$$i_B = I_{SE}(e^{\frac{v_{BE}}{V_T}} - 1)$$



Kao i kod diode, dinamička otpornost zavisi od položaja DC radne tačke

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Model bipolarnog tranzistora

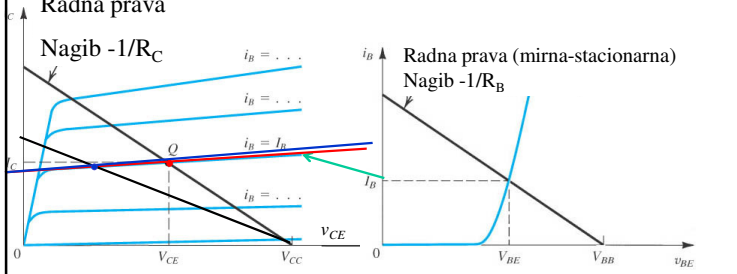
Radna tačka – uticaj na model za male signale

Izlazne karakteristike

$$v_{CE} = V_{CC} - i_C R_C$$

Radna prava

Nagib -1/R_C



Kao i kod diode, dinamička izlazna otpornost zavisi od položaja DC radne tačke

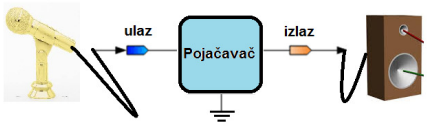
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Osnovi elektronike

Od čega se sastoji pojačavač?

Od tranzistora

Kako tranzistor pojačava?



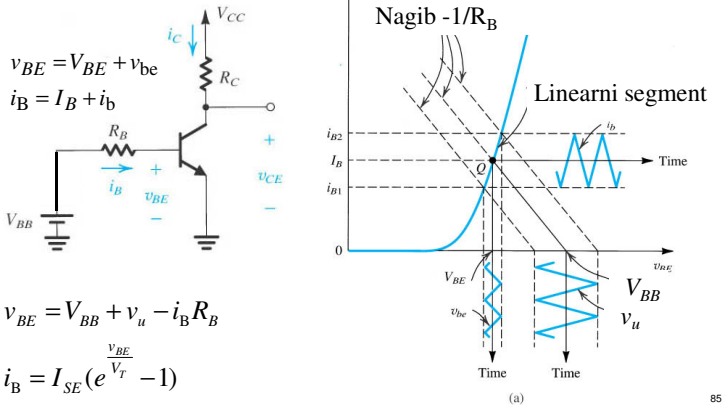
8. novembar 2018. 84

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Model bipolarnog tranzistora

Radna tačka – uticaj na model za male signale



$$v_{BE} = V_{BE} + v_{be}$$
$$i_B = I_B + i_b$$

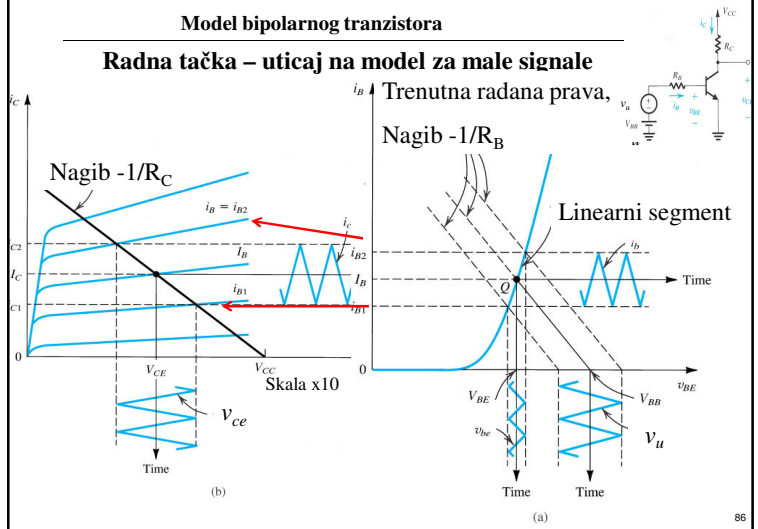
$$v_{BE} = V_{BB} + v_u - i_B R_B$$

$$i_B = I_{SE}(e^{\frac{v_{BE}}{V_T}} - 1)$$

85

Model bipolarnog tranzistora

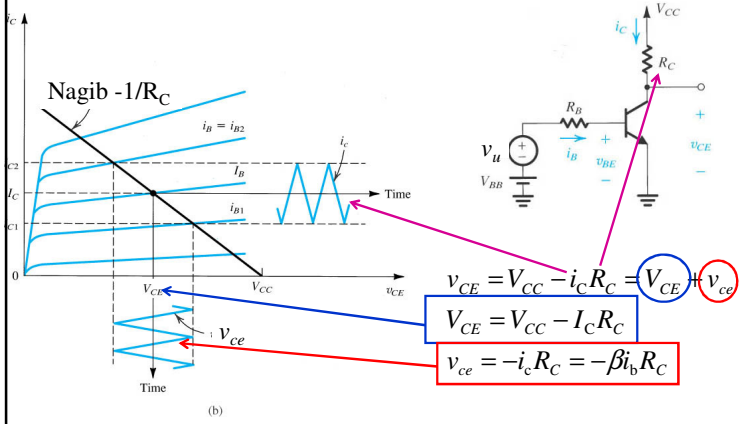
Radna tačka – uticaj na model za male signale



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Model bipolarnog tranzistora

Radna tačka – uticaj na model za male signale

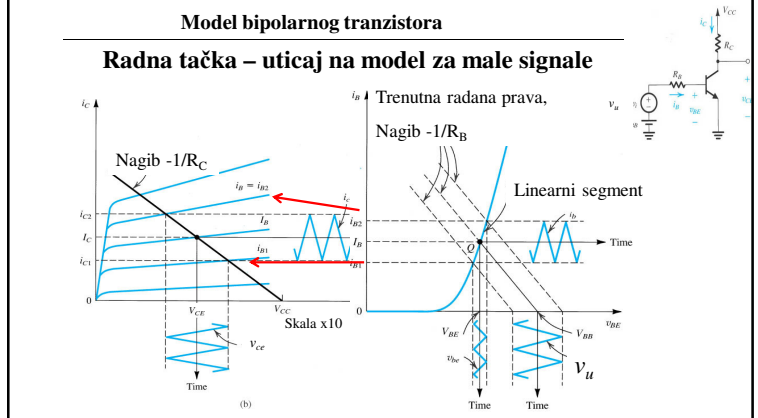


$$v_{CE} = V_{CC} - i_C R_C = V_{CE} + v_{ce}$$
$$V_{CE} = V_{CC} - I_C R_C$$
$$v_{ce} = -i_c R_C = -\beta i_b R_C$$

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Model bipolarnog tranzistora

Radna tačka – uticaj na model za male signale



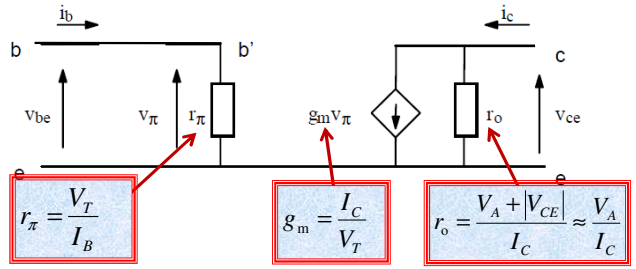
Male promene napona v_u (x100mV), izazivaju linearno proporcionalne velike promene napona v_{ce} (xV=x1000mV) u okolini radne tačke

Linearni modeli za male signale

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Model bipolarnog tranzistora

Veza između položaja radne tačke (DC) i dinamičkih parametara (malosignalini π model)



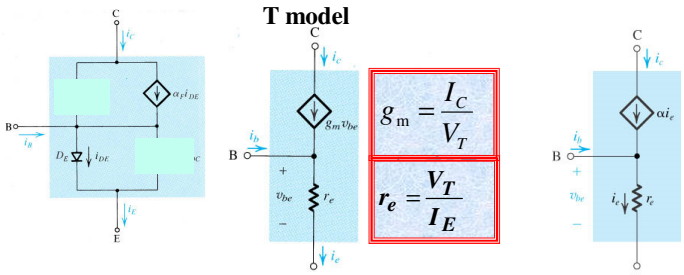
$$r_\pi = \frac{V_T}{I_B} \qquad g_m = \frac{I_C}{V_T} \qquad r_o = \frac{V_A + |V_{CE}|}{I_C} \approx \frac{V_A}{I_C}$$

Tipične vrednosti (Red veličine kod tipičnih tranzistora)

$$r_\pi = \frac{V_T}{I_B} \approx \frac{26\text{mV}}{10\mu\text{A}} = 1.6\text{k}\Omega \qquad g_m = \frac{I_C}{V_T} \approx \frac{1\text{mA}}{26\text{mV}} \approx 40mS \qquad r_o \approx \frac{V_A}{I_C} = \frac{50V}{1mA} = 50k\Omega$$

Model bipolarnog tranzistora

T model



$$g_m = \frac{I_C}{V_T} \qquad r_e = \frac{V_T}{I_E}$$

$$I_C = \alpha I_E \Rightarrow I_E = \frac{I_C}{\alpha}$$

$$r_e = \frac{V_T}{I_E} = \alpha\frac{V_T}{I_C} = \frac{\alpha}{g_m}$$

Model bipolarnog tranzistora

Domaći 5.2

BJT sa β=100, i V_A=100V polarisan je u radnoj tački sa I_C =1mA i V_{CE} =5V. Nacrtati hibridni π i T model i odrediti parametre:

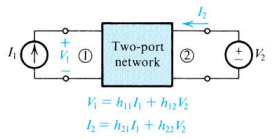
a) g_m
b) r_π
c) r_o
d) α
e) r_e **u radnoj tački.**
f) Uporediti g_m sa odgovarajućim parametrom MOSFETa sa slajda 53.

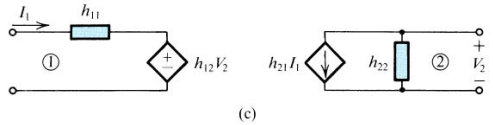
40mA/V; 2.5kΩ; 105kΩ; 100/101; 25Ω.

Model bipolarnog tranzistora

h - parametri

$$V_1 = h_{11} I_1 + h_{12} V_2$$
$$I_2 = h_{21} I_1 + h_{22} V_2$$

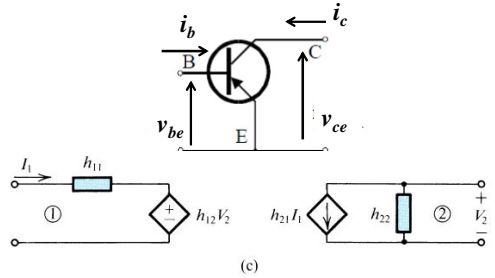




Model bipolarnog tranzistora

Hibridni model – h parametri

$$v_{be} = h_{11E}\, i_b + h_{12E}\, v_{ce}$$
$$i_c = h_{21E}\, i_b + h_{22E}\, v_{ce}$$

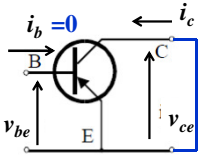


(c)

Model bipolarnog tranzistora

Hibridni model – h parametri

$$v_{be} = h_{11E}\, i_b + h_{12E}\, v_{ce}$$
$$i_c = h_{21E}\, i_b + h_{22E}\, v_{ce}$$



$$h_{11E} = \left.\frac{v_{be}}{i_b}\right|_{v_{ce}=0}$$ **Ulazna otpornost**

$$h_{12E} = \left.\frac{v_{be}}{v_{ce}}\right|_{i_b=0}$$ **Koeficijent inverznog naponskog pojačanja**

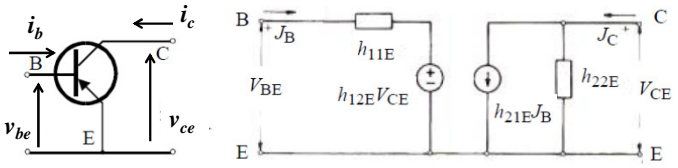
$$h_{21E} = \left.\frac{i_c}{i_b}\right|_{v_{ce}=0}$$ **Koeficijent direktnog strujnog pojačanja**

$$h_{22E} = \left.\frac{i_c}{v_{ce}}\right|_{i_b=0}$$ **Izlazna odvodnost**

Model bipolarnog tranzistora

Hibridni model – h parametri

$$v_{be} = h_{11E}\, i_b + h_{12E}\, v_{ce}$$
$$i_c = h_{21E}\, i_b + h_{22E}\, v_{ce}$$



Model bipolarnog tranzistora

Hibridni model – h parametri

Mogu da se definišu h-parametri i za ostale konfiguracije ZB, ZC tada nose sufikse B, odnosno C.
Vrednosti h_e - parametara daju se u katalozima

$h_{ie} = h_{11E} \neq h_{11B} \neq h_{11C}$ $[\Omega = ohm]$
$h_{re} = h_{12E} \neq h_{12B} \neq h_{12C}$ [V/V]
$h_{fe} = h_{21E} \neq h_{21B} \neq h_{21C}$ [A/A]
$h_{oe} = h_{22E} \neq h_{22B} \neq h_{22C}$ $[\mathrm{S} = 1/\Omega = mho]$

i – input resistance; r - reverse transfer;
o - output conductance; f - forward transfer

Model bipolarnog tranzistora

Hibridni model – h parametri

Brojne vrednosti h-parametara tipičnog Si BJT

Para-metar	Zajed. baza	Zajed. emitor	Zajed. kolektor
h_{11} (Ω)	13	2700	2700
h_{12}	$0.9\cdot10^{-4}$	$1.5\cdot10^{-4}$	1
h_{21}	-0.995	200	-201
h_{22} (Ω^{-1})	$0.06\cdot10^{-6}$	$18\cdot10^{-6}$	$18\cdot10^{-6}$

Zajed. emitor
xkΩ
0
x100
0

Rezime

	DC	AC	Grafička interpretacija
Idealni naponski generator/baterija	VCC, E, $V_{CC}=E$, 0	VCC, $r_e=\frac{\Delta V_E}{\Delta I_E}=\frac{0}{\Delta I_E}=0\Omega$, e=0, 0	I_E, ΔI_E, ΔV_E=0, E
Idealni strujni generator	Icc, J, $I_{CC}=J$, 0	Icc, $r_j=\frac{\Delta V_J}{\Delta I_J}=\frac{\Delta V_J}{0}\leftarrow\infty$, j=0, 0	I_J, J, ΔI_J=0, V_J, ΔV_J

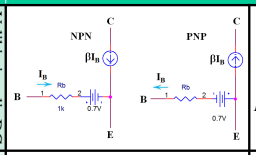
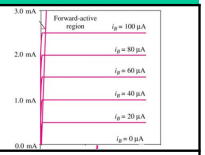
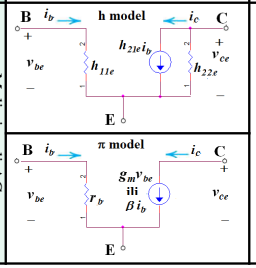
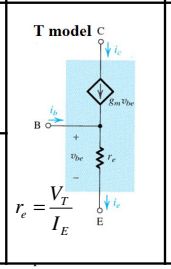
Rezime

	Dioda	Parametri modela	Grafička interpretacija
Veliki signali DC	R_d, V_γ; $I_D=0$ za $V_D<V_\gamma=0.5V$; $I_D=\frac{V_D}{R_d}$ za $V_D>V_\gamma$	$R_d=V_D/I_D$; V_γ=0,5V	I_D [mA], V_D [V]
Mali signali AC	r_d; $i_d=r_d v_d$	$r_d=\frac{dV_D}{dI_D}\approx\frac{\Delta V_D}{\Delta I_D}$; $r_d=\frac{1}{\frac{dI_D}{dV_D}}\approx\frac{V_T}{I_D}$	I_D [mA], M_1, r_{d1}, M_2, r_{d2}, M_3, r_{d3}, V_D [V]

Rezime

	MOSFET	Parametri modela	Grafička interpretacija
Veliki signali DC Oblast zasićenja	nMOS, pMOS	*oblast zasićenja* $\lvert V_{GS}\rvert>\lvert V_t\rvert$, $\lvert V_{DS}\rvert>\lvert V_{GS}-V_t\rvert$; $r_o\rightarrow\infty$ *ili* $r_o=\frac{\partial V_{DS}}{\partial I_D}\approx\frac{V_A}{I_D}$	$r_o\rightarrow\infty$
Mali signali AC Oblast zasićenja	G, D, S, $g_m v_{GS}$, r_o	$r_o=\frac{\partial V_{DS}}{\partial I_D}\approx\frac{V_A}{I_D}$; $g_m=\frac{\partial I_D}{\partial V_{GS}}=\frac{2I_D}{V_{OV}}$	I_D [mA], M_1, ΔI_{D1}, ΔV_{GS1}, M_2, ΔI_{D2}, M_3, ΔV_{GS2}, V_{GS}[V]

Rezime

	BJT		
Veliki signali DC Aktivni režim		*BE spoj direktno* *BC spoj inverzno* $R_B = \frac{V_{BE}}{I_B}, \quad \beta = \frac{I_C}{I_B}$	
Mali signali AC Aktivni režim		 $r_e = \frac{V_T}{I_E}$	$h_{11e} = \frac{\partial V_{BE}}{\partial I_B} \approx \frac{V_T}{I_B}$ $h_{21e} = \frac{\partial I_C}{\partial I_B} \approx \beta$ $r_o = \frac{1}{h_{22e}} \rightarrow \infty$ $r_b = \frac{\partial V_{BE}}{\partial I_B} = \frac{V_T}{I_B}$ $g_m = \frac{\partial I_C}{\partial V_{BE}} = \frac{I_C}{V_T}$

Šta smo naučili?

- **Razlika izmedju modela za velike i male signale.**
  - **Električne šeme modela diode za velike i male signale.**
  - **Električne šeme modela MOSFET-a za velike i male signale.**
  - **Električne šeme modela BJT-a za velike i male signale.**

Na web adresi http://leda.elfak .ni.ac.rs

> EDUCATION > ELEKTRONIKA

slajdovi u pdf formatu

Ispitna pitanja?

1. **Malosignalni model diode.**
2. **Zavisnost dinamičke otpornosti diode od položaja jednosmerne radne tačke.**
3. **Zavisnost dinamičkih parametara MOSFETa (g_m i r_o) od položaja jednosmerne radne tačke (u oblasti zasićenja).**
4. **Električna šema i parametri T-modela MOSFETa.**
5. **Električne šeme modela BJT za velike signale.**
6. **Zavisnost dinamičkih parametara BJT (g_m i r_o) od položaja jednosmerne radne tačke (u aktivnoj oblasti).**
7. **Električna šema i parametri h_e-modela BJT.**
8. **Električna šema i parametri hibridnog π modela BJT.**
9. **Električna šema i parametri T-modela BJT.**

Osnovi elektronike

Predispitne obaveze: U JANUARU OSTALO

Redovno pohađanje nastave (predavanja+vežbe)		10%	10%
Odbranjene laboratorijske vežbe		10%	10%
Kolokvijum I	(26.11.2018.)	50%	20%
Kolokvijum II	(21.01.2019.)	50%	20%
		120%	60%



Ukupan skor u januaru može biti 120% PRE ISPITA

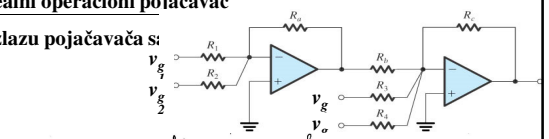
Savet: Izađite na kolokvijum MNOGO JE LAKŠE!

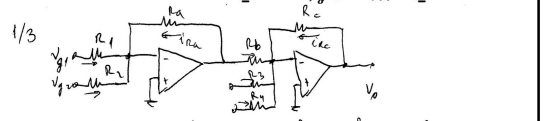
Sledećeg časa

Osnovni pojačavački stepeni sa MOSFET

Rešenje 4.1 Idealni operacioni pojačavač

Odrediti napon na izlazu pojačavača s





$$v_i = \frac{R_a}{R_1}\frac{R_c}{R_b}v_{g1} + \frac{R_a}{R_2}\frac{R_c}{R_b}v_{g2} - \frac{R_c}{R_3}v_{g3} - \frac{R_c}{R_4}v_{g4}$$



Rešenje 4.2

Zadatak: **Za invertorski pojačavač pobuđen naponom v_g=0.1V kod koga je R_1=0.1k i R_2=10k u kome se koriste OpAmp sa pojačanjem u OP od A=60dB, 80dB i 100dB i odrediti:**

a) **Pojačanje u zatvorenoj petlji**

b) **Procentualnu promenu pojačanja u zatvorenoj petlji u odnosu na slučaj sa idealnim OpAmpom**

c) **Veličinu napona na ulazu OpAmpa**

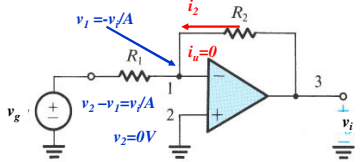
Rešenje

a)(90,83; 99,00; 99,90); b)(-9,17%;-1,00%; -0,10%);

c)(-9,08mV; -0,99mV; -0,10mV)

Efekti konačnog *pojačanja*

Invertorski pojačavač



$v_i = Av_d = A(v_+ - v_-)$

$v_+ = 0$

$v_d = 0 - v_- = -v_-$

$v_i = A(-v_-) \Rightarrow v_- = -v_i / A$

$i_u = i_1 + i_2 = 0A \Rightarrow i_1 = -i_2$

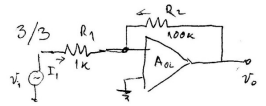
$$i_1 = \frac{v_g - v_1}{R_1} = \frac{v_g - (-v_i/A)}{R_1}$$

$$i_2 = \frac{v_i - v_1}{R_2} = \frac{v_i - v_i/A}{R_2}$$

$$\Rightarrow A_r = \frac{v_i}{v_g} = \frac{-R_2/R_1}{1 + (1 + R_2/R_1)/A}$$

Realni operacioni pojačavač

Rešenje 4.3



$$i_1 = \frac{v_i - \frac{v_o}{A_{OL}}}{R_1} = -\frac{v_o - \frac{v_i}{A_{OL}}}{R_2} = i_2$$

$$v_i R_2 - \frac{R_2}{A_{OL}} v_o = -v_o R_1 + \frac{R_1}{A_{OL}} v_o$$

$$v_i \cdot R_2 = -\left(R_1 + \frac{R_1}{A_{OL}} + \frac{R_2}{A_{OL}}\right) v_o \quad \Rightarrow \quad v_o = \frac{A_{OL} v_i R_2}{A R_1 + (R_1 + R_2)} v_i$$

$$A = \frac{v_o}{v_i} = -\frac{A_{OL} R_2}{A R_1 + R_1 + R_2} = \frac{A_{OL} \cdot 100}{A_{OL} + 101}$$

A_{OL} [bz]	[V/V]	A [V/V]	[dB]	$\frac{\Delta A}{A} 100\%$
60	10^3	90,83	39,16	-9,173
80	10^4	99,00	39,91	-0,999
100	10^5	99,90	39,99	-0,101

Dodatak

Modeli poluprovodničkih komponenata

Za velike signale ?

Za male signale ?

Nelinearni ?
Linearizovani ?
Idealizovani ?

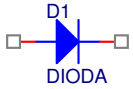
Linearni ?

Model diode

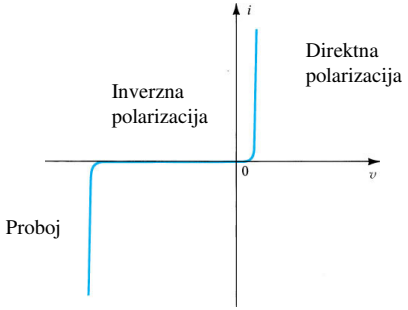
Dodatak

-Diode

-Simbol

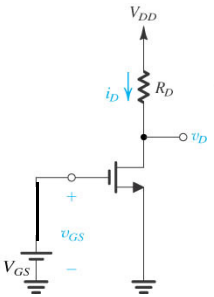


Karakteristika: zavisnost struje od napona



Dodatak Model MOS tranzistora

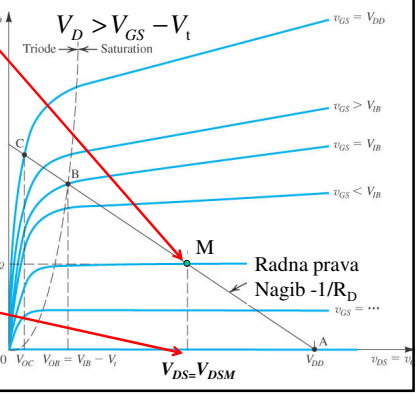
Radna tačka – uticaj na model za male signale



$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_t)^2 = A(V_{GS} - V_t)^2$$

$$i_G = 0$$

$$V_D > V_{GS} - V_t$$

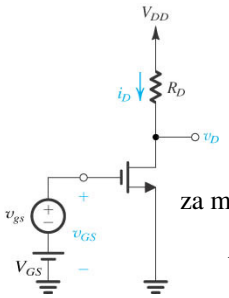


$$V_D = V_{DS} = V_{DSM} = V_{DD} - I_D R_D$$

Jednačina prave u I-V ravni
Radna prava

Dodatak **Model MOS tranzistora**

Radna tačka – uticaj na model za male signale



$$v_{GS} = V_{GS} + v_{gs}$$

$$i_D = A(V_{GS} + v_{gs} - V_t)^2$$

$$i_D = A(V_{GS} - V_t)^2 + 2A(V_{GS} - V_t)v_{gs} + A(v_{gs})^2$$

za male signale $v_{gs} << 2(V_{GS} - V_t) = 2V_{OV}$

$$Av_{gs}^{\ 2} << 2A(V_{GS} - V_t)v_{gs}$$

$$i_D \approx I_D + 2A(V_{GS} - V_t)v_{gs}$$

Dodatak **Model MOS tranzistora**

Radna tačka – značenje modela za male signale

$$i_D = I_D + 2A(V_{GS} - V_t)v_{gs}$$

$$i_D = I_D + i_d = I_D + 2A(V_{GS} - V_t)v_{gs}$$

$$i_d = 2A(V_{GS} - V_t)v_{gs} = g_m v_{gs}$$

$$g_m \equiv \frac{i_d}{v_{gs}} = 2A(V_{GS} - V_t) = 2A \cdot V_{OV}$$

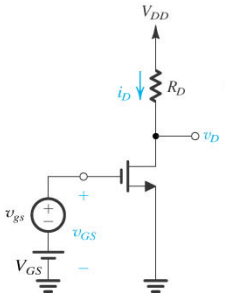
$$g_m = \mu_n C'_{ox} \frac{W}{L}(V_{GS} - V_t) = \frac{2I_D}{V_{OV}}$$

g_m ZAVISI od položaja radne tačke (V_{GS})

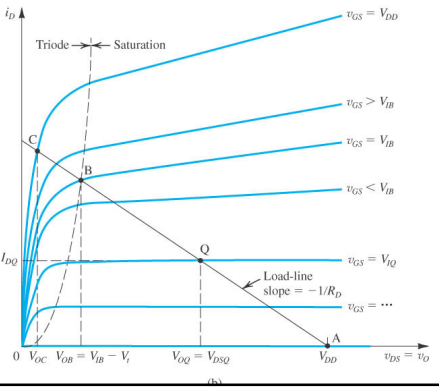
$(g_m \equiv S)$

Dodatak **Model MOS tranzistora**

Radna tačka – značenje modela za male signale



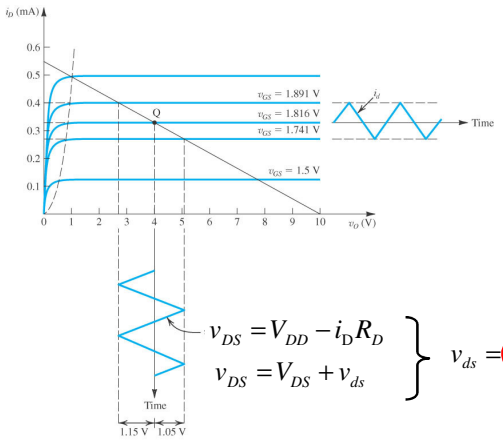
$$v_{DS} = V_{DD} - i_D R_D \qquad i_D = \frac{V_{DD}}{R_D} - \frac{1}{R_D} v_{DS}$$



$$v_{DS} = V_{DSM} + v_{ds}$$

Dodatak **Model MOS tranzistora**

Radna tačka – značenje modela za male signale



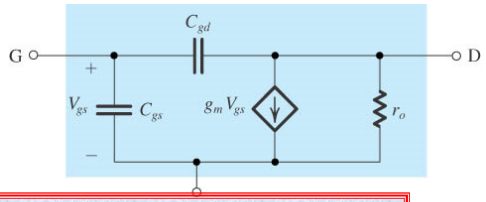
$$v_{DS} = V_{DD} - i_D R_D$$

$$v_{DS} = V_{DS} + v_{ds}$$

$$v_{ds} = -i_d R_D$$

Dodatak **Model MOS tranzistora**

VF model



$$g_m = \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_t) = \frac{2I_D}{V_{GS} - V_t}$$

$$r_o = \frac{V_A}{I_D} = \frac{1}{\lambda \cdot I_D}$$

$$C_{gs} = \frac{2}{3} WLC_{ox} + WL_{ov}C_{ox}$$

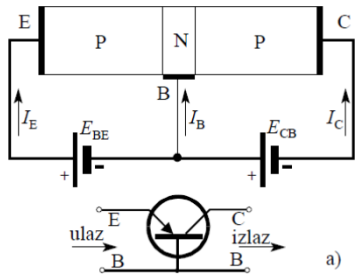
$$C_{gd} = WL_{ov}C_{ox}$$

$$0.05L \le L_{ov} \le 0.1L$$

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

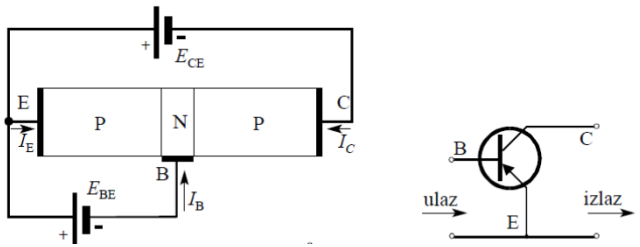
Model bipolarnog tranzistora **Dodatak**

Da se podsetimo - Zajednička baza (ZB)



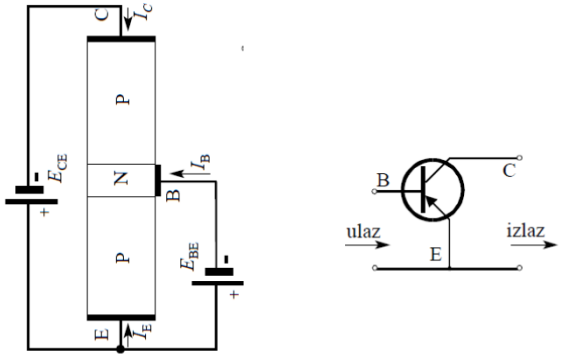
Model bipolarnog tranzistora **Dodatak**

Da se podsetimo - Zajednički emitor (ZE)



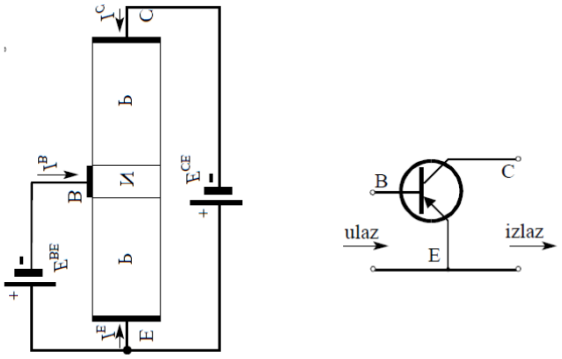
Model bipolarnog tranzistora **Dodatak**

Zajednički emitor (ZE)



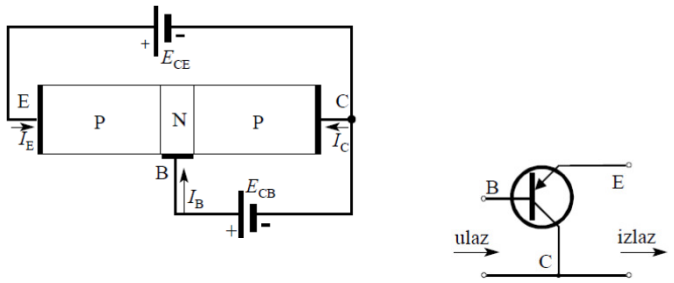
Model bipolarnog tranzistora **Dodatak**

Zajednički emitor (ZE)



Model bipolarnog tranzistora **Dodatak**

Da se podsetimo –Zajednički kolektor (ZC)

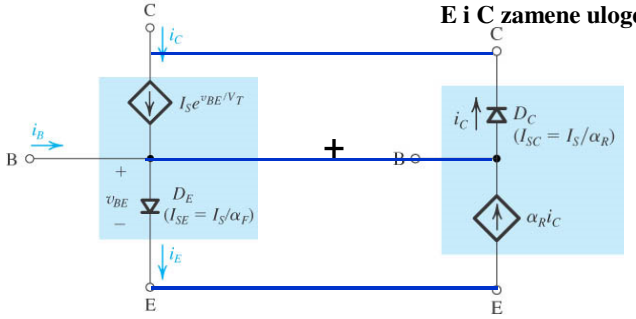


Dodatak **Model bipolarnog tranzistora**

Kompletan Ebers-Molov model

Model *npn* tranzistora u *direktnom* režimu

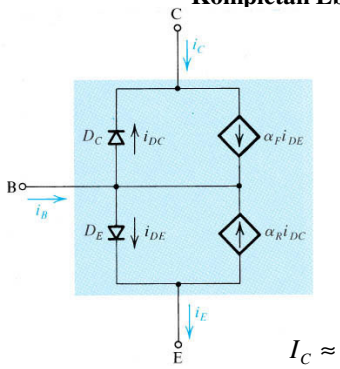
Model *npn* tranzistora u *inverznom* režimu E i C zamene uloge



(a)

Dodatak **Model bipolarnog tranzistora**

Kompletan Ebers-Molov model



Važi u svim režimima rada tranzistora!!!

$$I_C = \alpha_F i_{DE} - i_{DC}$$

$V_{BC}<<0$

$$I_C = \alpha_F I_{SE}(e^{\frac{V_{BE}}{V_T}} - 1) - I_{SC}(e^{\frac{V_{BC}}{V_T}} - 1)$$

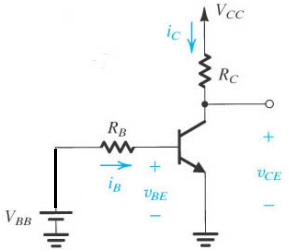
$$I_C \approx \alpha_F I_{SE}(e^{\frac{V_{BE}}{V_T}} - 1) + I_{SC} \approx \alpha_F I_{SE}(e^{\frac{V_{BE}}{V_T}} - 1)$$

$$I_C \approx \alpha_F I_B = \beta I_B$$

U aktivnom režimu I_C ne zavisi od V_{CE}

Dodatak **Model bipolarnog tranzistora**

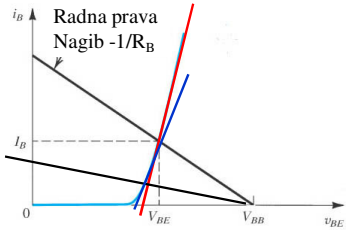
Radna tačka – uticaj na model za male signale



Ulazne karakteristike

$$v_{BE} = V_{BB} - i_B R_B$$

$$i_B = I_{SE}(e^{\frac{v_{BE}}{V_T}} - 1)$$



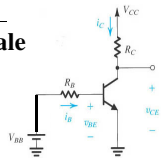
125

Dodatak **Model bipolarnog tranzistora**

Radna tačka – uticaj na model za male signale

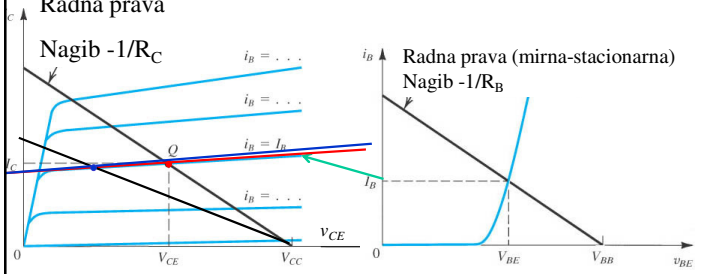
Izlazne karakteristike

$$v_{CE} = V_{CC} - i_C R_C$$



Radna prava

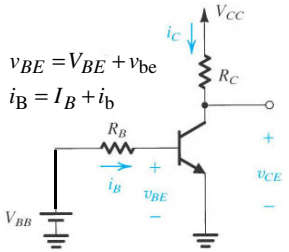
Nagib -1/R_C



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Dodatak **Model bipolarnog tranzistora**

Radna tačka – uticaj na model za male signale

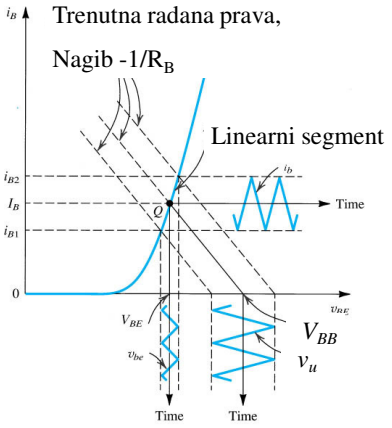


$$v_{BE} = V_{BE} + v_{be}$$

$$i_B = I_B + i_b$$

Trenutna radana prava,

Nagib -1/R_B



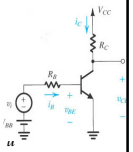
$$v_{BE} = V_{BB} + v_u - i_B R_B$$

$$i_B = I_{SE}(e^{\frac{v_{BE}}{V_T}} - 1)$$

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Dodatak **Model bipolarnog tranzistora**

Radna tačka – uticaj na model za male signale



Trenutna radana prava,

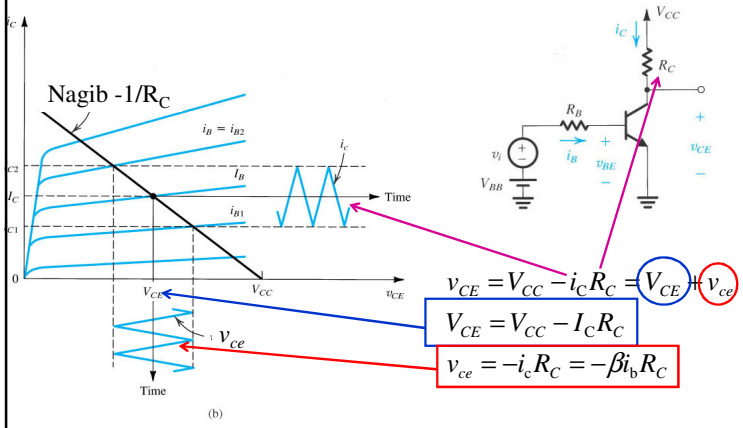
Nagib -1/R_B

Nagib -1/R_C

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Dodatak **Model bipolarnog tranzistora**

Radna tačka – uticaj na model za male signale



$$v_{CE} = V_{CC} - i_C R_C = V_{CE} + v_{ce}$$

$$V_{CE} = V_{CC} - I_C R_C$$

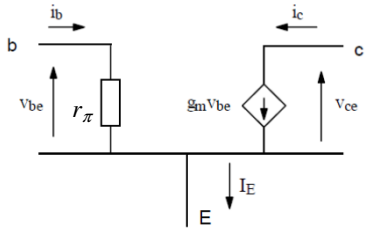
$$v_{ce} = -i_c R_C = -\beta i_b R_C$$

Dodatak **Model bipolarnog tranzistora**

Veza između modela za velike i male signale

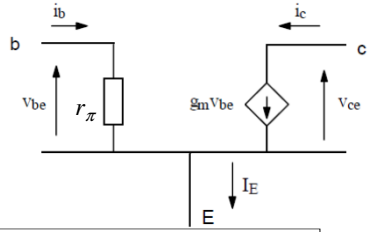
- **Iz modela za velike signale može da se izvede malosignaloni model.**
- **Obrnuto ne važi.**

Hibridni π model



Dodatak **Model bipolarnog tranzistora**

Hibridni π model, varijanta g_m



$$i_B = I_B + i_b$$

$$i_C = I_C + i_c$$

$$v_{BE} = V_{BE} + v_{be}$$

$$i_C = I_S e^{\frac{v_{BE}}{V_T}} = I_S e^{\frac{V_{BE}+v_{be}}{V_T}}$$

$$i_C = I_S e^{\frac{V_{BE}}{V_T}} e^{\frac{v_{be}}{V_T}} = I_C e^{\frac{v_{be}}{V_T}}$$

Dinamička otpornost BE spoja

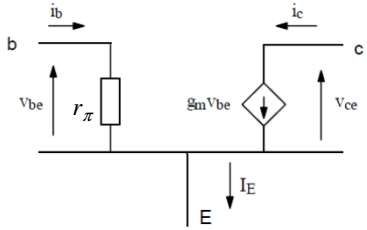
$$r_\pi = \frac{1}{dI_B / dV_{BE}} \approx \frac{V_T}{I_B}$$

I_B, I_C - Jednosmerne – veliki signal

Dodatak **Model bipolarnog tranzistora**

Hibridni π model, varijanta g_m

$$e^x \approx (1+x) \quad \text{za } x << 1$$



$$i_C = I_C e^{\frac{v_{be}}{V_T}}$$

$$i_C \approx I_C (1 + \frac{v_{be}}{V_T}) \quad \text{za } v_{be} << V_T$$

$$i_C = I_C + i_c \approx I_C + \frac{I_C}{V_T} v_{be}$$

Važi za malo v_{be}<<V_T=26mV za T=300K

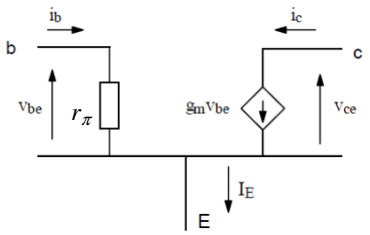
I_C - Jednosmerna – veliki signal

$$i_c = \frac{I_C}{V_T} v_{be} = g_m v_{be}$$

$$g_m = \frac{I_C}{V_T}$$

Dodatak **Model bipolarnog tranzistora**

Hibridni π model, varijanta g_m



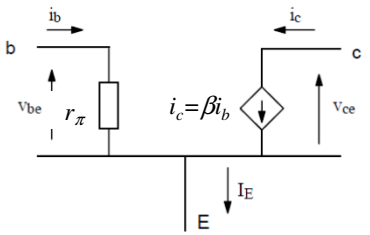
$$i_c = \frac{I_C}{V_T} v_{be}$$

$$g_m = \frac{I_C}{V_T}$$

$$g_m \approx 39 I_C \quad \text{za T} = 300\text{K} \; (V_T = 26mV)$$

Dodatak **Model bipolarnog tranzistora**

Hibridni π model, varijanta β

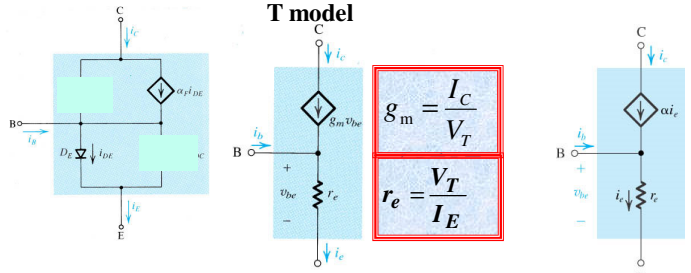


$$i_B = I_B + i_b$$
$$i_C = I_C + i_c$$
$$v_{BE} = V_{BE} + v_{be}$$
$$i_B = \frac{i_C}{\beta} = \frac{I_C + i_c}{\beta}$$
$$i_B = \frac{I_C}{\beta} + \frac{g_m v_{be}}{\beta} = \frac{I_C}{\beta} + \frac{1}{\beta}\frac{I_C}{V_T} v_{be}$$
$$i_b = \frac{1}{\beta}\frac{I_C}{V_T} v_{be} = \frac{g_m}{\beta} v_{be}$$

$$r_\pi = \frac{v_{be}}{i_b} = \frac{v_{be}}{\frac{g_m}{\beta} v_{be}} = \frac{\beta}{g_m} = \frac{\beta V_T}{I_C} = \frac{V_T}{I_B}$$

Dodatak **Model bipolarnog tranzistora**

T model



$$g_m = \frac{I_C}{V_T}$$

$$r_e = \frac{V_T}{I_E}$$

$$I_C = \alpha I_E \Rightarrow I_E = \frac{I_C}{\alpha}$$

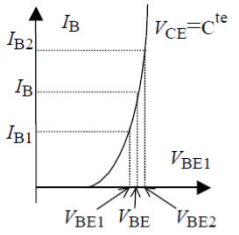
$$r_e = \frac{V_T}{I_E} = \alpha \frac{V_T}{I_C} = \frac{\alpha}{g_m}$$

$$r_e = \frac{\alpha}{g_m}$$

Dodatak **Model bipolarnog tranzistora**

Određivanje h- parametara sa statičkih karakteristika

$$h_{11E} = \left.\frac{v_{be}}{i_b}\right|_{v_{ce}=0} = \left.\frac{\Delta V_{BE}}{\Delta I_B}\right|_{V_{CE}=Const}$$

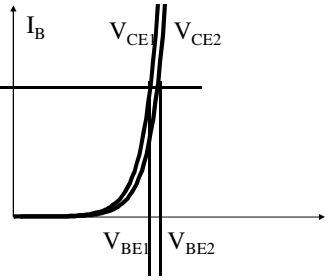


$$h_{11E} = \left.\frac{V_{BE2} - V_{BE1}}{I_{B2} - I_{B1}}\right|_{V_{CE}=Const} \approx x\,\text{k}\Omega$$

Dodatak **Model bipolarnog tranzistora**

Određivanje h- parametara sa statičkih karakteristika

$$h_{12E} = \left.\frac{v_{be}}{v_{ce}}\right|_{i_b = 0} = \left.\frac{\Delta V_{BE}}{\Delta V_{CE}}\right|_{I_B = Const.}$$

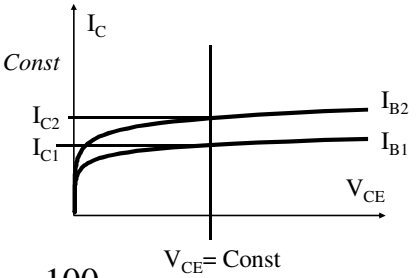


$$h_{12E} = \left.\frac{V_{BE2} - V_{BE1}}{V_{CE2} - V_{CE1}}\right|_{I_B = Const.} \approx 0$$

Dodatak **Model bipolarnog tranzistora**

Određivanje h- parametara sa statičkih karakteristika

$$h_{21E} = \left.\frac{i_c}{i_b}\right|_{v_{ce} = 0} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE} = Const}$$

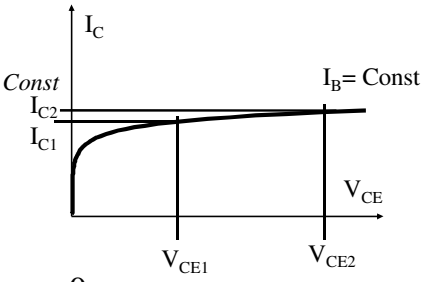


$$h_{21E} = \left.\frac{I_{C2} - I_{C1}}{I_{B2} - I_{B1}}\right|_{V_{CE} = Const} \approx 100$$

Dodatak **Model bipolarnog tranzistora**

Određivanje h- parametara sa statičkih karakteristika

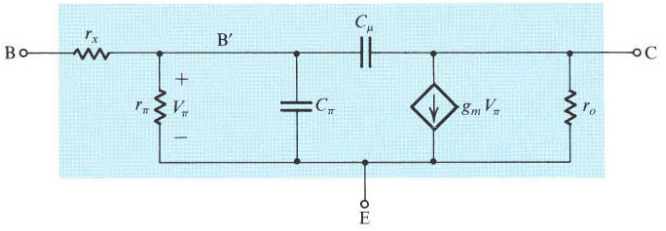
$$h_{22E} = \left.\frac{i_c}{v_{ce}}\right|_{i_b = 0} = \left.\frac{\Delta I_C}{\Delta V_{CE}}\right|_{I_B = Const}$$



$$h_{22E} = \left.\frac{I_{C2} - I_{C1}}{V_{CE2} - V_{CE1}}\right|_{I_B = Const.} \approx 0$$

Dodatak **Model bipolarnog tranzistora**

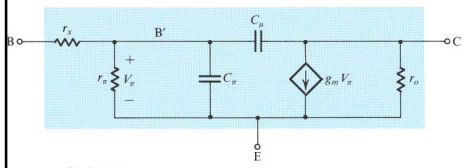
VF model bipolarnog tranzistora



$$C_\pi = C_{de} + C_{je} = \tau_F \frac{I_C}{V_T} + \frac{C_{je0}}{\left(1 - \frac{V_{BE}}{V_{0E}}\right)^m} \qquad C_\mu = \frac{C_{\mu 0}}{\left(1 + \frac{V_{CB}}{V_{0C}}\right)^m}$$

Dodatak **Model bipolarnog tranzistora**

VF model bipolarnog tranzistora

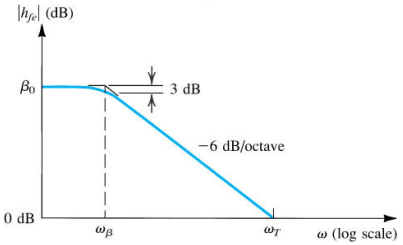


$$h_{21E} = \frac{\beta_0}{1 + s(C_\pi + C_\mu) r_\pi}$$

$$\omega_\beta = \frac{1}{(C_\pi + C_\mu) r_\pi}$$

$$\omega_T = \beta_0 \omega_\beta$$

$$\omega_T = \frac{g_m}{C_\pi + C_\mu}$$



Model bipolarnog tranzistora **Dodatak**

Hibridni model – h parametri

Relacije između *h*-parametara konfiguracija ZC i ZB sa ZE kada se ima u vidu realna činjenica da je

h_{12E}<<1, $h_{11E}h_{22E}$<<1, h_{12B}<<1, $h_{11B}h_{22B}$<<1, h_{12C}≈1

$$h_{11B} \approx \frac{h_{11E}}{1 + h_{21E}} << h_{11E} \qquad h_{11C} = h_{11E} \qquad [\Omega = ohm]$$

$$h_{12B} \approx \frac{h_{11E} h_{22E}}{1 + h_{21E}} - h_{12E} \approx 0 \qquad h_{12C} = 1 - h_{12E} \approx 1 \qquad [\text{V/V}]$$

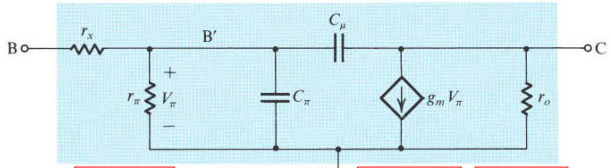
$$h_{21B} \approx -\frac{h_{21E}}{1 + h_{21E}} \approx -1 \qquad h_{21C} = -(1 + h_{21E}) \approx -h_{21E} \qquad [\text{A/A}]$$

$$h_{22B} \approx \frac{h_{22E}}{1 + h_{21E}} \approx 0 \qquad h_{22C} = h_{22E} \approx 0 \qquad [\text{S} = 1/\Omega = mho]$$

Dodatak **Model bipolarnog tranzistora**

Rezime

VF model bipolarnog tranzistora



$$r_\pi = \frac{\beta_0}{g_m} \qquad g_m = \frac{I_C}{V_T} \qquad r_0 = \frac{V_A}{I_C}$$

$$C_\pi + C_\mu = \frac{g_m}{2\pi f_T} \qquad C_\pi = C_{de} + C_{je} \qquad C_{de} = \tau_F g_m \qquad C_{je} \cong 2C_{je0}$$

$$C_\mu = \frac{C_{jC0}}{(1 + V_{CB}/V_{0c})^m}; \quad m = 0.3 - 0.5$$