

Osnovi elektronike

Predispitne obaveze:

U JANUARU OSTALO

Redovno pohađanje nastave (predavanja+vežbe)	10%	10%
Odbranjene laboratorijske vežbe	10%	10%
Kolokvijum I (02.12.2019.)	50%	20%
Kolokvijum II (13.01.2020.)	50%	20%



120% 60%

Ukupan skor u januaru može biti 120% PRE ISPITA

Savet: Izađite na kolokvijum MNOGO JE LAKŠE!

07. novembar 2019.

1

Modeli poluprovodničkih komponenata

2

Osnovi elektronike

**Od čega se sastoji pojačavač?
Koje komponente sadrži?**

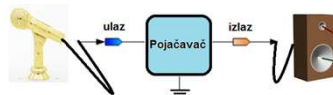
- Pasivne: R, C, L

- Aktivne: tranzistori

Kako i šta oni rade u kolu?

Kako "predvideti" njihovo ponašanje?

A N A L I Z A - simulacija



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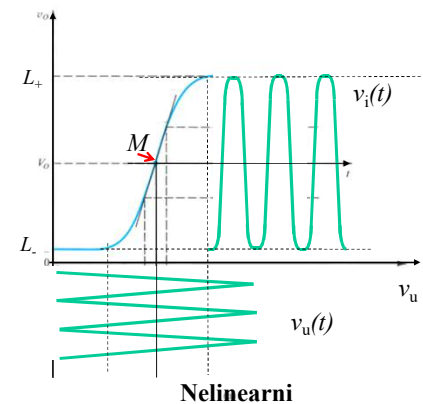
3

Modeli poluprovodničkih komponenata

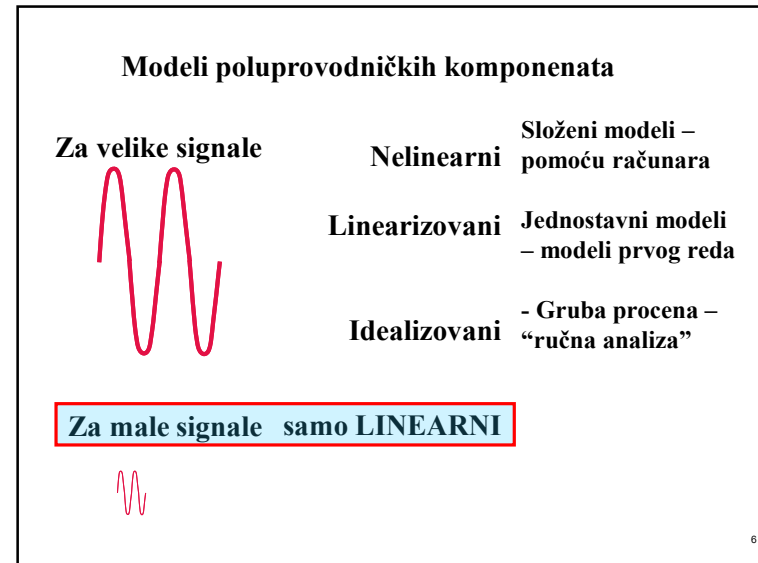
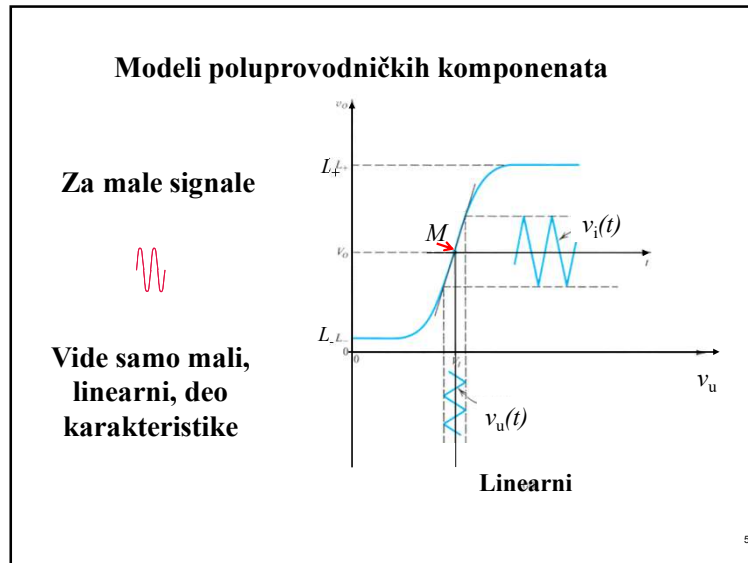
Za velike signale



"Vide" celu prenosnu karakteristiku sa svim nelinearnostima



4



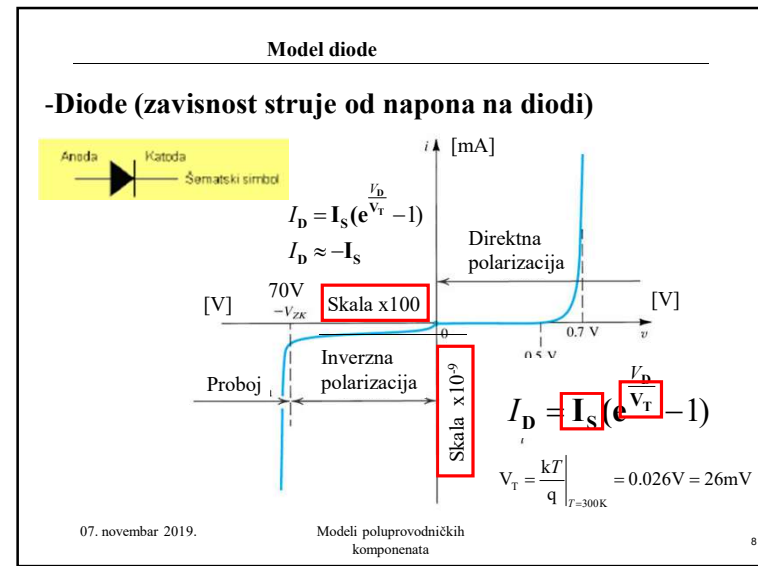
Modeli poluprovodničkih komponenata

Koje poluprovodničke komponente znamo?

“Elektronske komponente” II semestar

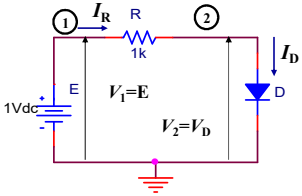
- Diode
- Bipolarni tranzistor
- MOSFET tranzistor

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Model diode

-Kako se ponaša dioda u elektronskom kolu?



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

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

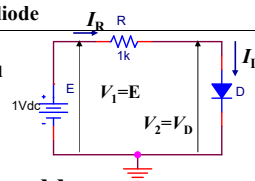
$$I_D(V_D) = I_s \left(e^{\frac{V_D}{V_T}} - 1 \right)$$

$V_D = ?$

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Model diode

-Dioda u elektronskom kolu
DC režim

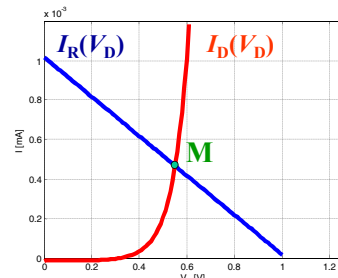


$$\frac{V_1 - V_2}{R} = I_R$$

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

$$I_D(V_D) = I_s \left(e^{\frac{V_D}{V_T}} - 1 \right)$$

Grafička interpretacija problema



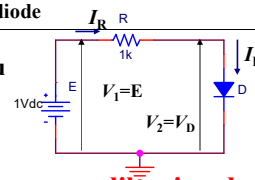
$$I_R = \frac{E - V_D}{R}$$

$$I_D = I_s \left(e^{\frac{V_D}{V_T}} - 1 \right)$$

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Model diode

-Dioda u elektronskom kolu
DC režim



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

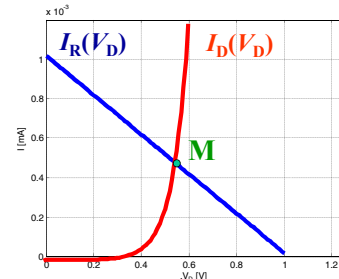
$$\frac{V_2 - V_1}{R} + I_D(V_D) = 0$$

$$I_D(V_D) = I_s \left(e^{\frac{V_D}{V_T}} - 1 \right)$$

Model diode – nelinearan – za velike signale

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

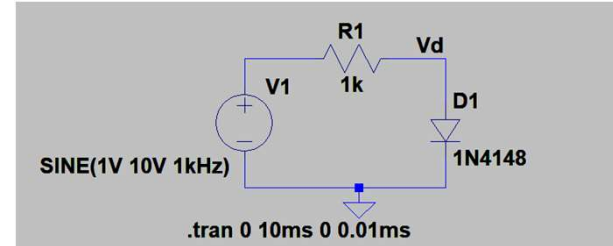
$$I_D = I_s \left(e^{\frac{V_D}{V_T}} - 1 \right)$$



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Model diode

-Dioda u elektronskom kolu
Model diode – **nelinearan – za velike signale**



.tran 0 10ms 0 0.01ms

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Model diode

-Dioda u elektronskom kolu
Model diode – nelinearan – za velike signale

Struja nije $k \cdot V$ (linearno proporcionalna naponu) za velike signale

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Model diode

-Dioda u elektronskom kolu
DC režim

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 $V_D < V_\gamma = 0.5V$

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

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Model diode

-Dioda u elektronskom kolu
Model diode – linearizovan – za velike signale

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

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

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Model diode

-Dioda u elektronskom kolu
DC režim

Model diode – idealizovan – za velike signale

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

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

$$V_D = V_\gamma \text{ za } V_D \geq V_\gamma$$

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Model diode

-Dioda u elektronskom kolu
Model diode – idealizovan – za velike signale

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

$$V_D = V_\gamma \text{ za } V_D \geq V_\gamma$$

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Model diode

-Dioda u elektronskom kolu
Model idealne diode

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

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Model diode

-Dioda u elektronskom kolu
Model idealne diode

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

.tran 0 10ms 0 0.01ms

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Model diode

-Dioda u elektronskom kolu
Model idealne diode

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

.tran 0 10ms 0 0.01ms

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Model diode

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

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

.tran 0 10ms 0 0.01ms

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Model diode

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

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

.tran 0 10ms 0 0.01ms

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Model diode

-Dioda u elektronskom kolu
Statički - DC režim

Grafička interpretacija problema

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

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Model diode

-Dioda u elektronskom kolu
dinamički režim

Grafička interpretacija problema

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

$$E - V \leq V_1 \leq E + V$$

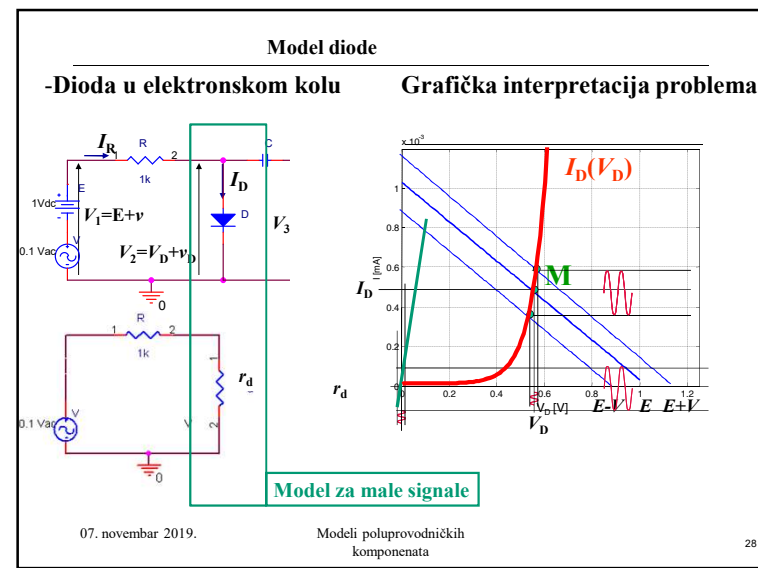
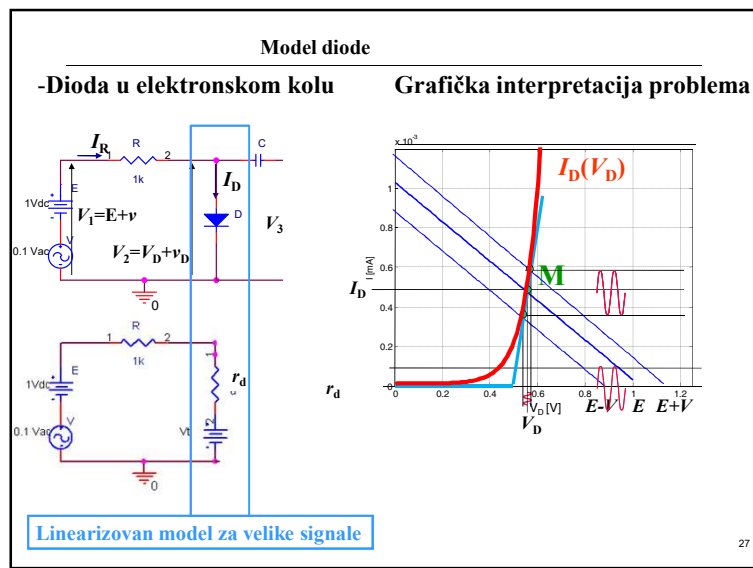
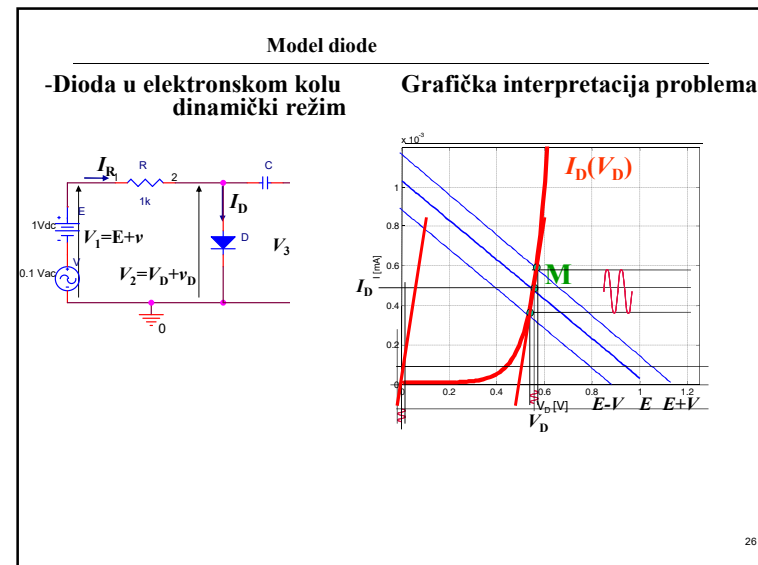
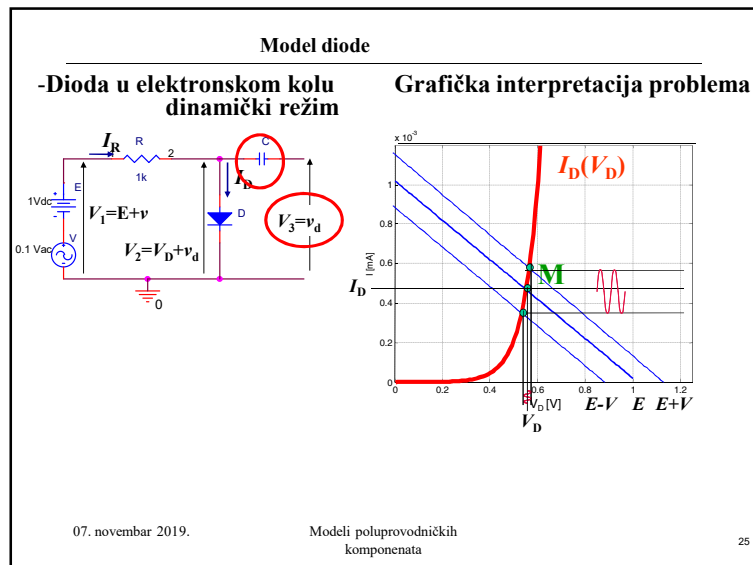
$$v_D = V_D + v_d$$

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

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

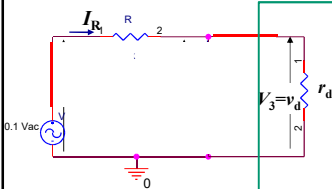
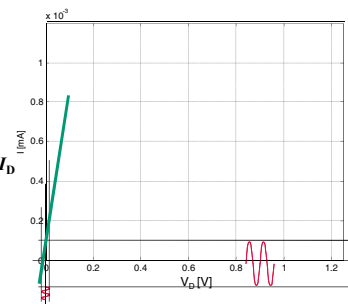
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Modeli poluprovodničkih komponenta



Model diode

-Dioda u elektronskom kolu **Grafička interpretacija problema**

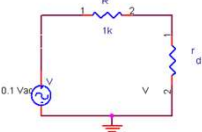
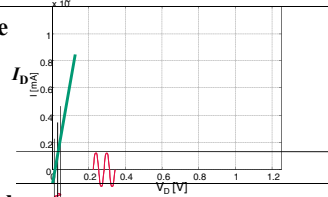
Za mali naizmenični (vremenski promenljivi - *dinamički*) signal dioda se ponaša kao otpornost čija je vrednost $r_d = \Delta V_D / \Delta I_D$

Model za male signale

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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.*

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

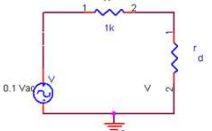
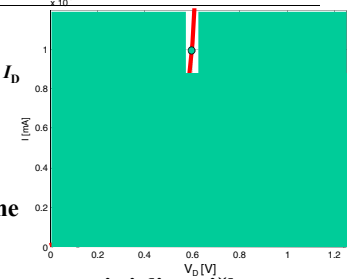
$$r_d = \frac{1}{dI_D} \approx \frac{1}{I_S e^{V_D/V_T}}$$

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

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Model diode

VAŽNO model za male signale

Otpornost zavisi od položaja mirne radne tačke!

Postoji zavisnost između jednosmerne struje i dinamičke otpornosti.

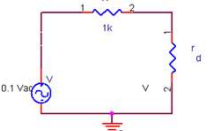
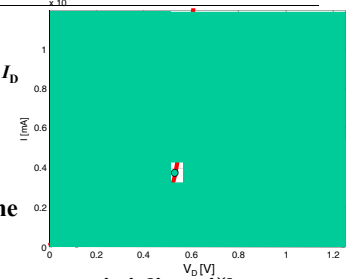
Veća struja – manja otpornost

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

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Model diode

VAŽNO model za male signale

Otpornost zavisi od položaja mirne radne tačke!

Postoji zavisnost između jednosmerne struje i dinamičke otpornosti.

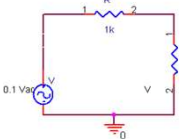
Manja struja – veća otpornost

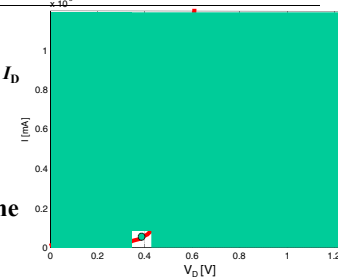
$r_d \approx \frac{V_T}{I_D}$

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Model diode

VAŽNO model za male signale



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


Otpornost zavisi od položaja mirne radne tačke!

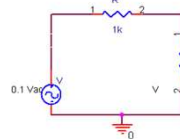
Postoji zavisnost između jednosmerne struje i dinamičke otpornosti.

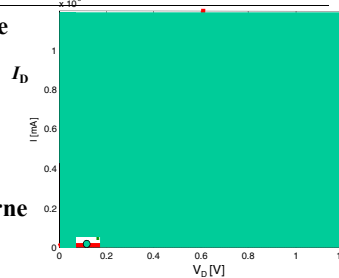
Manja struja – veća otpornost

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Model diode

VAŽNO model za male signale



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


Otpornost zavisi od položaja mirne radne tačke!

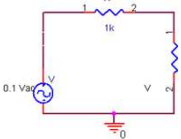
Postoji zavisnost između jednosmerne struje i dinamičke otpornosti.

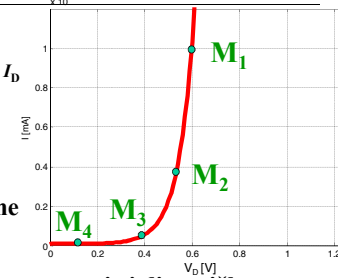
Manja struja – veća otpornost

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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.

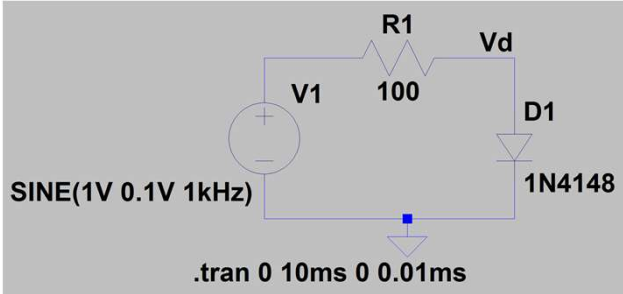
U kojoj tački je otpornost najveća?
 Upišite odgovarajući znak „<“, „>“, ili „=“.

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

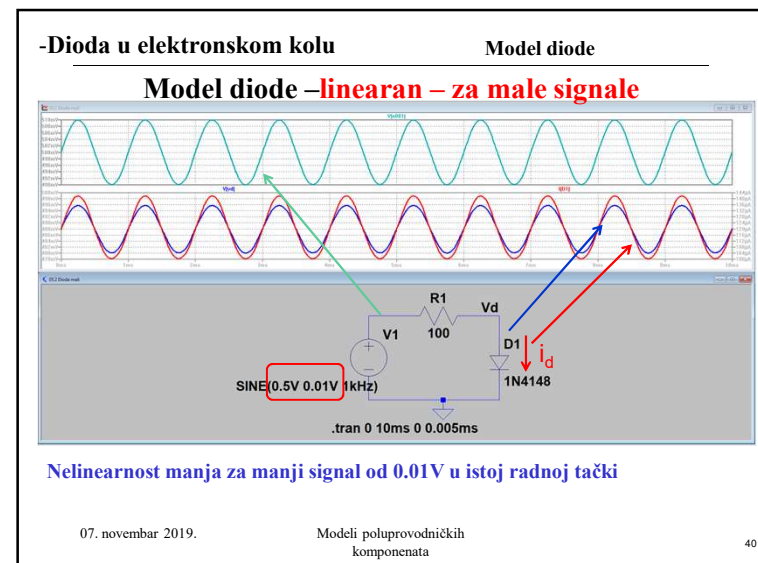
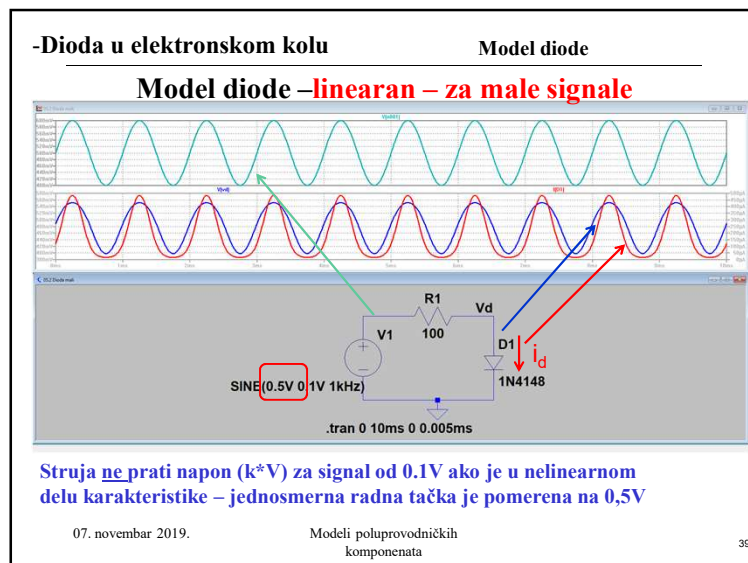
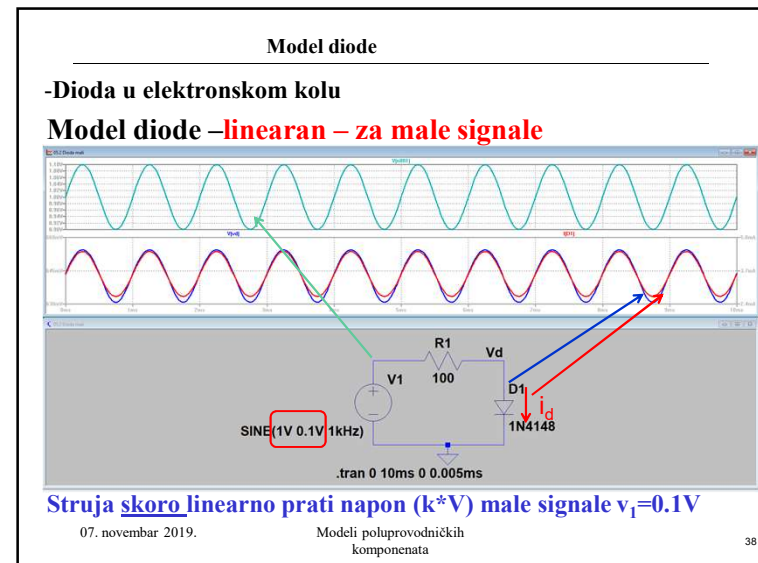
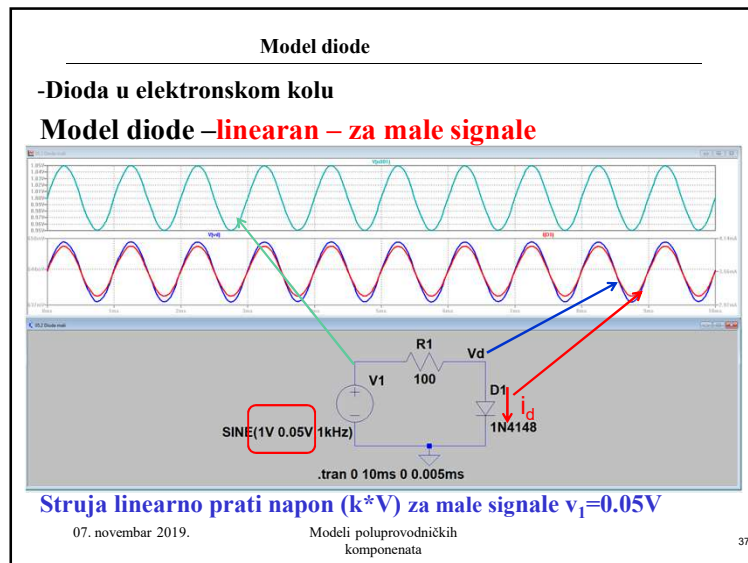
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Model diode

-Dioda u elektronskom kolu
Model diode –linearan – za male signale



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-Dioda u elektronskom kolu Model diode

Model diode –linearan – za male signale

.tran 0 10ms 0 0.005ms

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-Dioda u elektronskom kolu Model diode

Model diode –linearan – za male signale

.tran 0 10ms 0 0.005ms

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Model diode

.tran 0 10ms 0 0.005ms

komponenta

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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

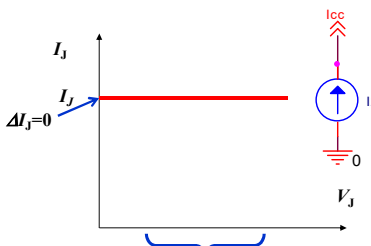
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Dinamički model izvora konstantne struje

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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 ?



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

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

Za male AC signale I se ponaša kao prekid

Šta smo naučili?

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

Ispitna pitanja?

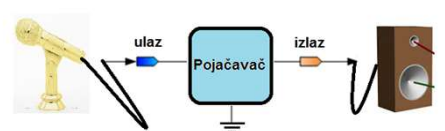
1. Zavisnost dinamičke otpornosti od vrednosti jednosmerne struje diode.
2. Dinamički (AC, malosignalni) model izvora konstantnog napona
3. Dinamički (AC, malosignalni) model izvora konstantnog napona

Na web adresi <http://leda.elfak.ni.ac.rs>
> EDUCATION > ELEKTRONIKA
slajdovi u pdf formatu

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Osnovi elektronike

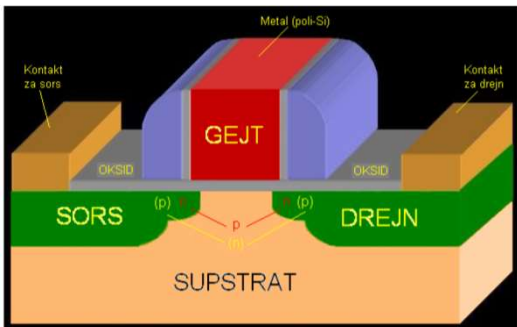
Kako rade MOS tranzistori kako pojačavaju napon?



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Modeli poluprovodničkih komponenata

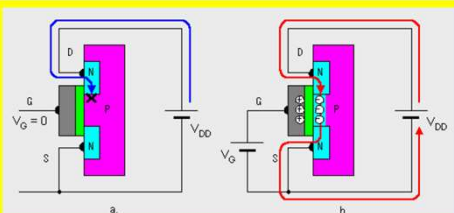
Da se podsetimo MOS tranzistor



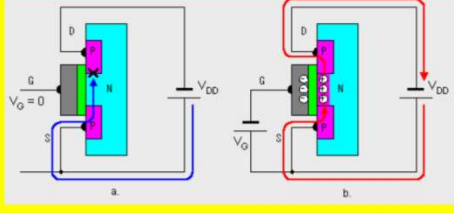
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Model MOS tranzistora

Da se podsetimo



nMOS
Vodi za $V_G > 0$

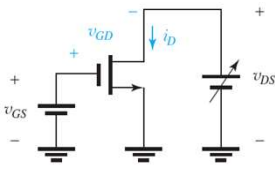


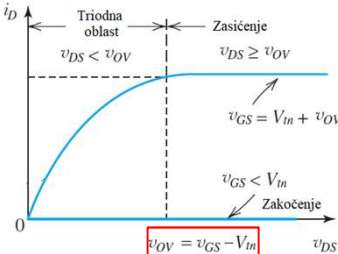
pMOS
Vodi za $V_G < 0$

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Model MOS tranzistora

Da se podsetimo: Izlazne karakteristike MOSFET-a





Režimi rada MOSFET		V_{GS}	V_{DS}
Vodi	Zakočen	$ V_{GS} < V_t $	
	Zasičenje	$ V_{GS} > V_t $	$ V_{DS} > V_{GS} - V_t $
	Triodna oblast	$ V_{GS} > V_t $	$ V_{DS} < V_{GS} - V_t $

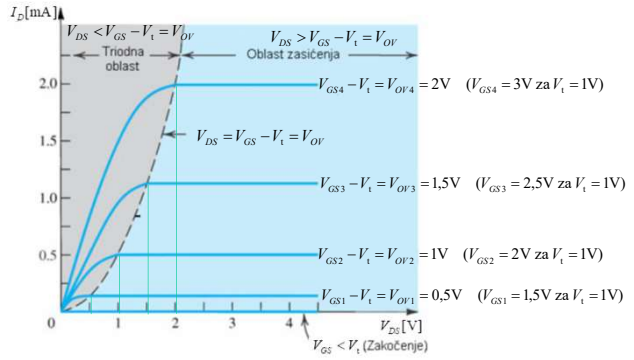
07. november 2019.
Modeli poluprovodniških komponentata

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Model MOS tranzistora

Da se podsetimo

Izlazne karakteristike MOSFET-a



07. november 2019. Modeli poluprovodniških komponentata

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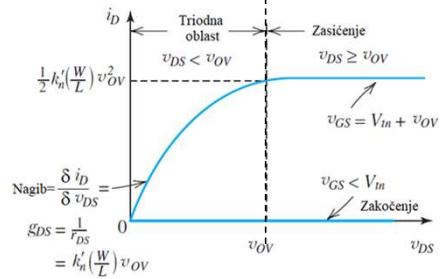
Model MOS tranzistora

Da se podsetimo: Izlazne karakteristike MOSFET-a

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

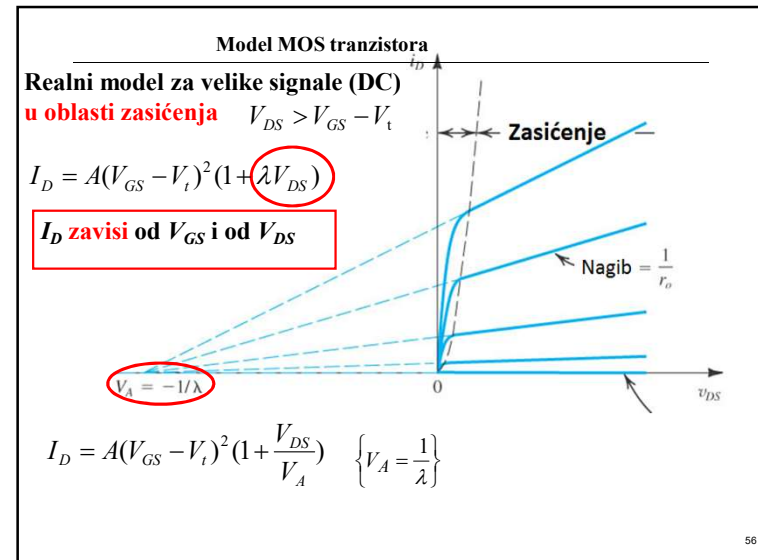
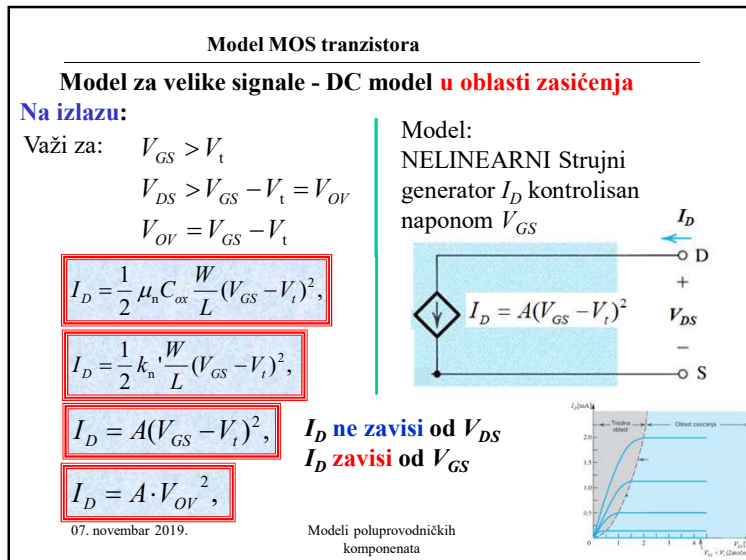
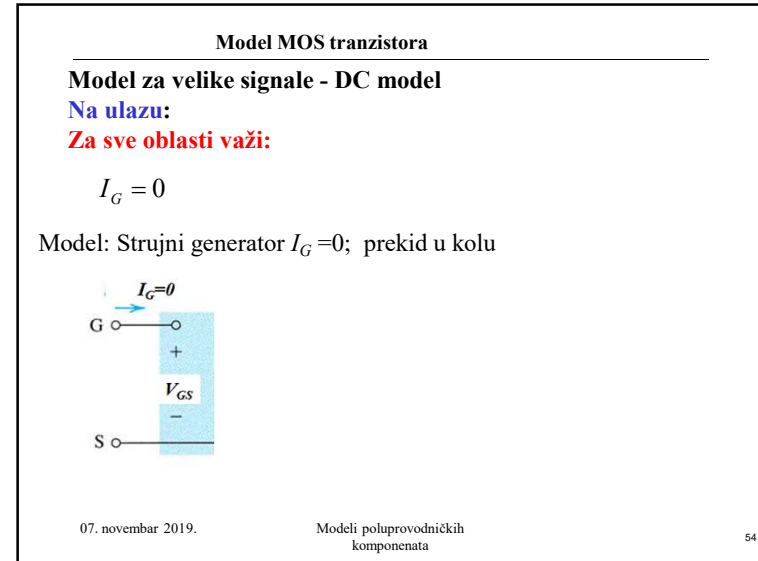
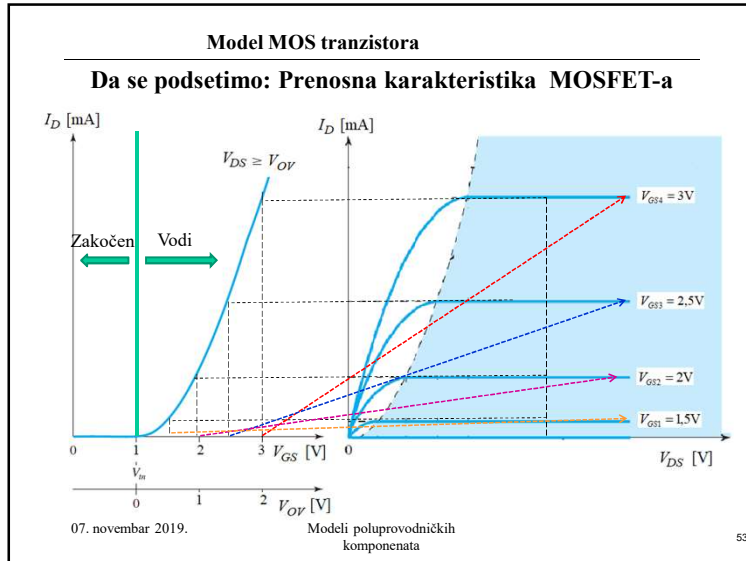
$$I_D = k_n' \frac{W}{L} \left[V_{OV} - \frac{1}{2} V_{DS} \right] \cdot V_{DS}$$

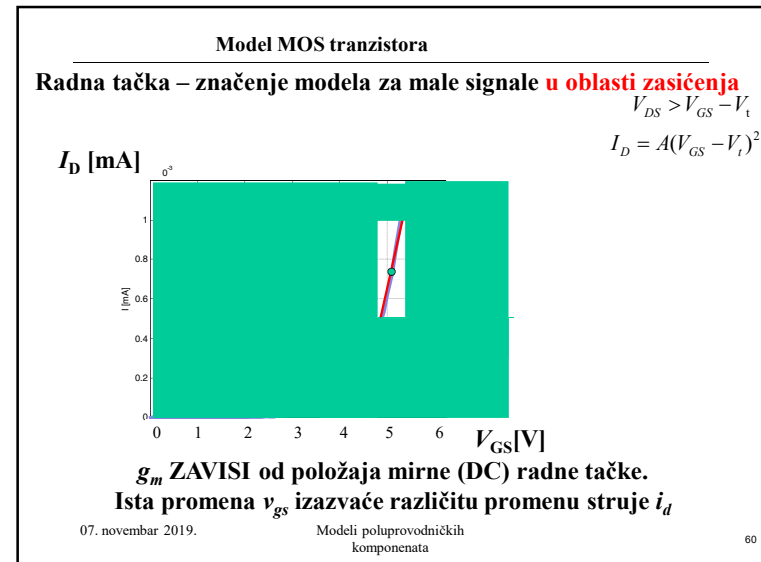
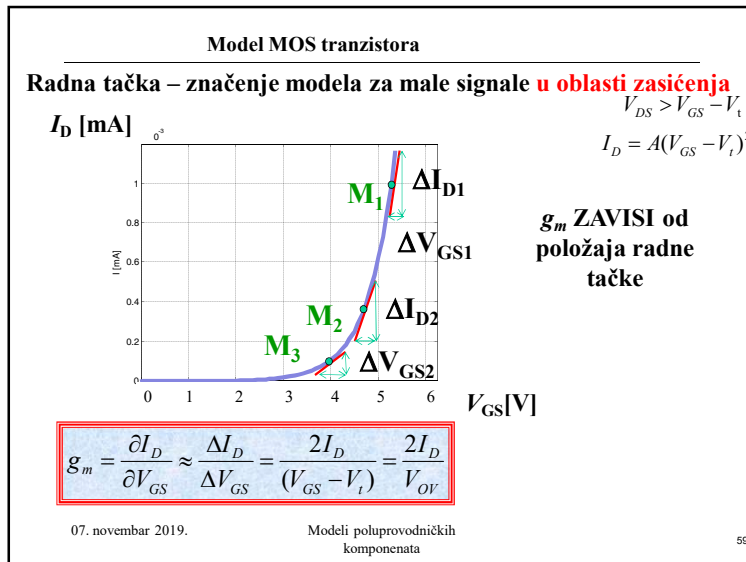
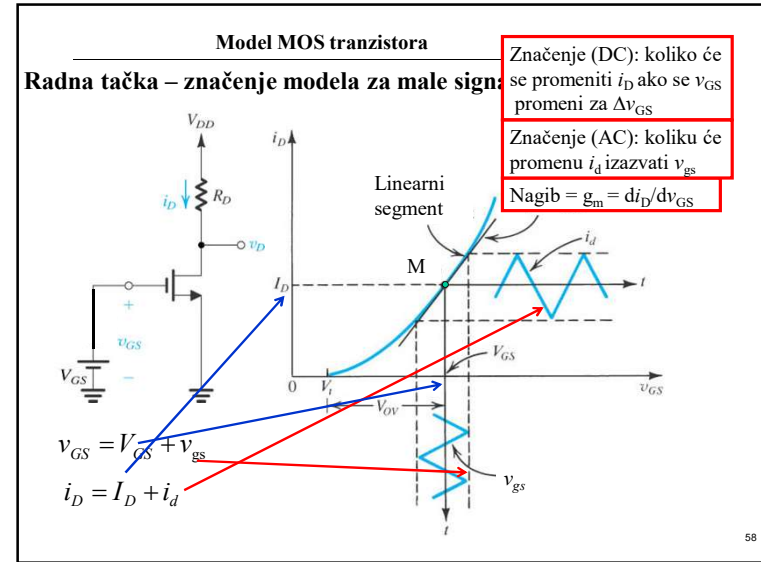
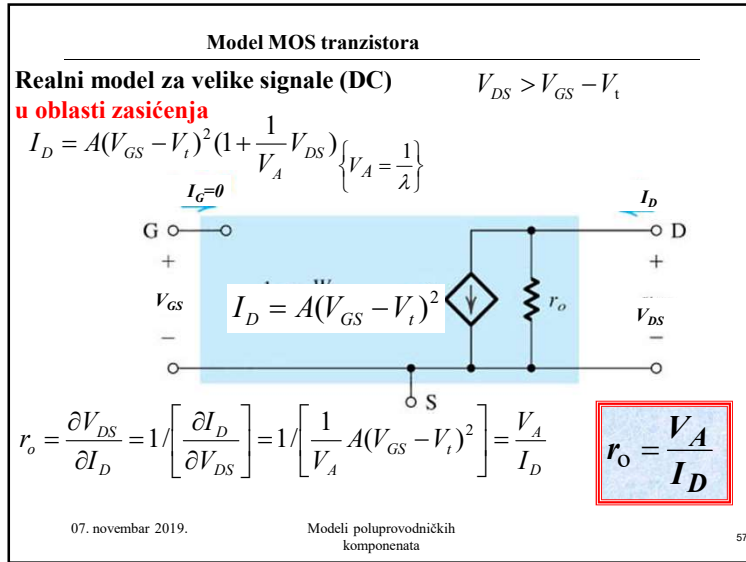
$$I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2 = \frac{1}{2} k_n' \frac{W}{L} V_{OV}^2$$

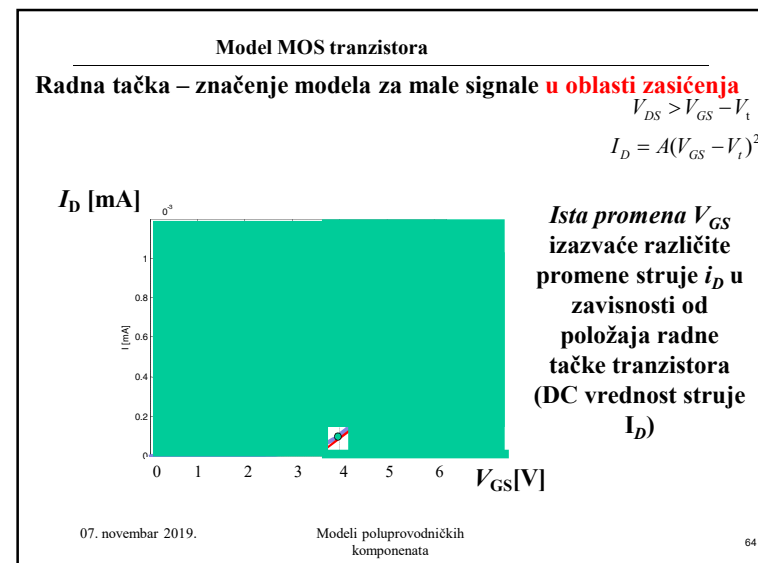
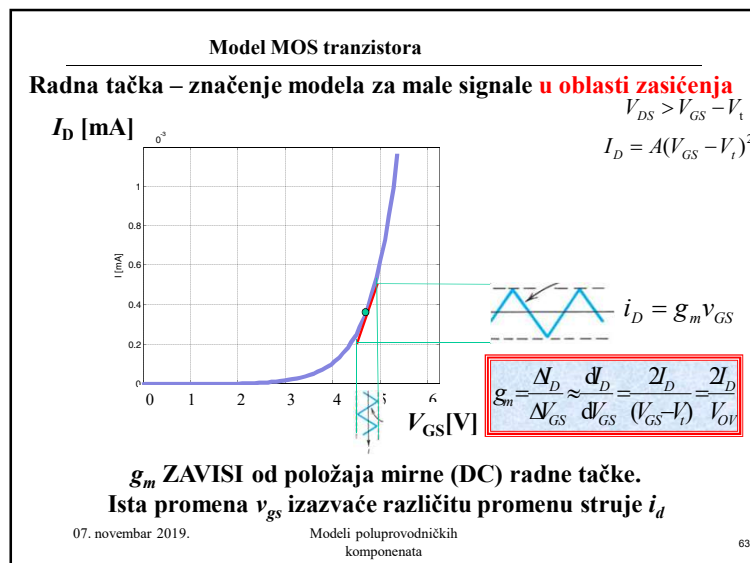
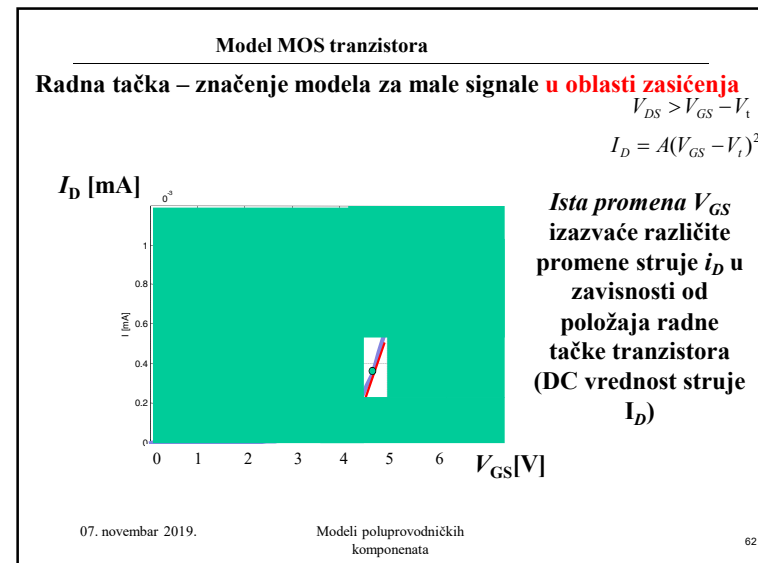
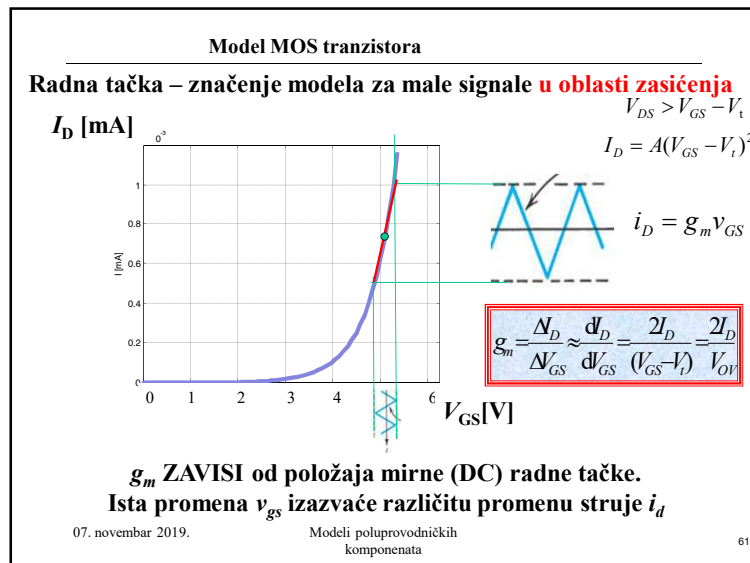


07. november 2019. Modeli poluprovodniških komponentata

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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]

V_{GS} [V]

$i_D = g_m v_{GS}$

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

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

07. novembar 2019. Modeli poluprovodničkih komponenta 65

Model MOS tranzistora

Model za male signale (dinamički model) u oblasti zasićenja
 $V_{DS} > V_{GS} - V_t$
 $I_D = A(V_{GS} - V_t)^2$

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

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

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

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

07. novembar 2019. Modeli poluprovodničkih komponenta 66

Model MOS tranzistora

Model za male signale (dinamički model) u oblasti zasićenja
 $V_{DS} > V_{GS} - V_t$
 $I_D = A(V_{GS} - V_t)^2$

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

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

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

07. novembar 2019. Modeli poluprovodničkih komponenta 67

Model MOS tranzistora

Model za male signale (dinamički model) u oblasti zasićenja
 $V_{DS} > V_{GS} - V_t$
 $I_D = A(V_{GS} - V_t)^2$

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

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

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

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

07. novembar 2019. Modeli poluprovodničkih komponenta 68

Model MOS tranzistora

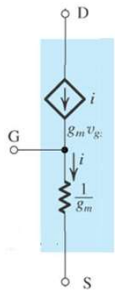
T Model za male signale u oblasti zasićenja $V_{DS} > V_{GS} - V_t$

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

$$g_m = \frac{dI_D}{dV_{GS}}$$


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

$$r'_s = \frac{1}{g_m}$$



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Model MOS tranzistora



Domaći 5.1

Za nMOS tranzistor kod koga je $V_t=1V$, $\mu_n C_{ox} = 120\mu A/V^2$, $W/L=10$ i $\lambda=0.02V^{-1}$ odrediti:

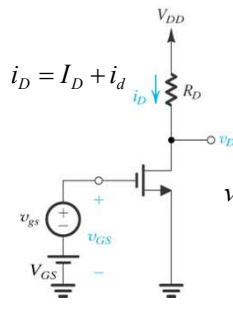
- opseg napona V_{GS} za koje tranzistor vodi
- napon V_{DS} u funkciji V_{GS} pri kome tranzistor ulazi u zasićenje,
- dinamičke parametre tranzistora g_m i r_o u radnoj tački definisanoj sa $I_D=75\mu A$, ako se zna da tranzistor radi u zasićenju.
- Nacrtati model za male signale i upisati vrednosti parametara.

$V_{GS} > 1V$; $V_{DS} > V_{GS} + 1V$; $424\mu A/V$, $0.67M\Omega$

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Model MOS tranzistora

Kako MOSFET pojačava ulazni napon?



$$i_D = I_D + i_d$$

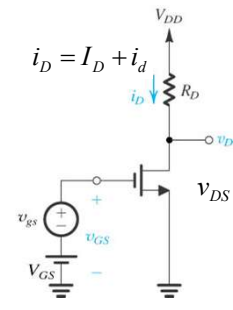
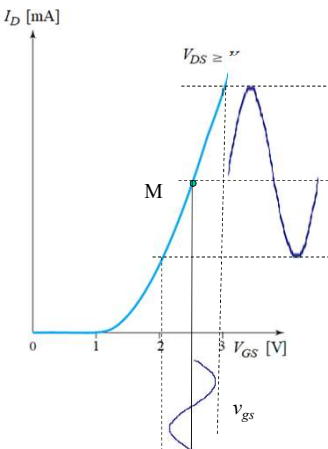
$$v_{DS} = V_{DD} - i_D R_D$$

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

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Model MOS tranzistora

Kako MOSFET pojačava ulazni napon?

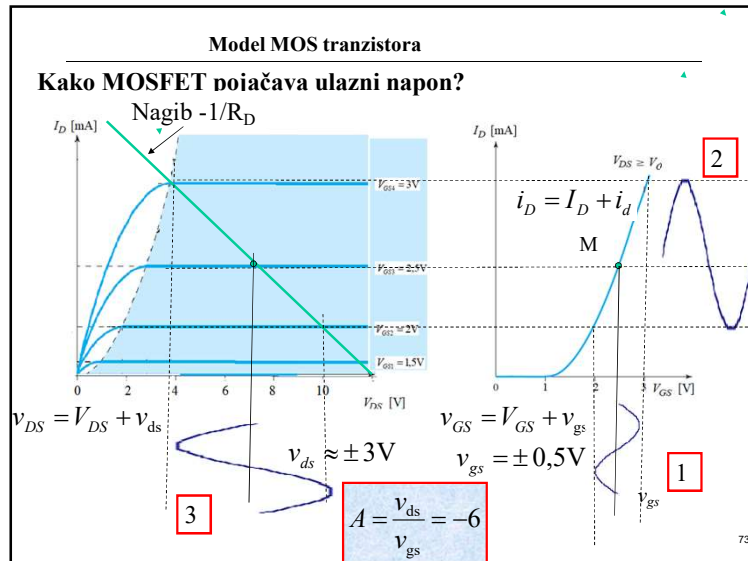



$$i_D = I_D + i_d$$

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

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

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Šta smo naučili?

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

Ispitna pitanja?

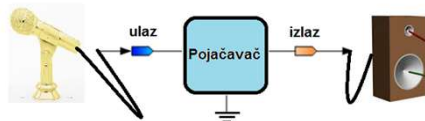
1. **Koji su dinamički parametri MOS tranzistora?**
2. **Zavisnost g_m MOS tranzistora od položaja jednosmerne radne tačke tranzistora**
3. **Zavisnost izlazne otpornosti MOS tranzistora od položaja jednosmerne radne tačke**

Na web adresi <http://leda.elfak.ni.ac.rs>
> EDUCATION > ELEKTRONIKA
slajdovi u pdf formatu

Osnovi elektronike

**Kako rade bipolarni tranzistori?
Kako pojačavaju napon?**

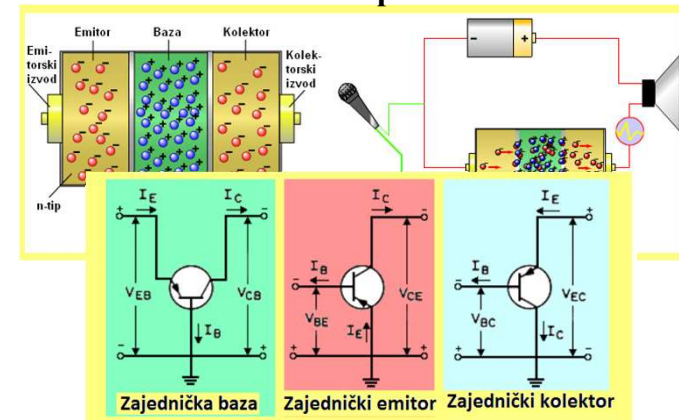
BJT (odakle J?)



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(-)

07. novembar 2019. Modeli poluprovodniških komponentata 77

Da se podsetimo

Model bipolarnog tranzistora

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(-)	$V_{BE} < 0$ $V_{BC} > 0$	$V_{BE} > 0$ $V_{BC} < 0$

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Da se podsetimo

Model bipolarnog tranzistora

Koefficient strujnog pojačanja: i_c/i_{in} ili $\Delta I_Z/\Delta I_{UL}$

Zajednička baza

Zajednički emitor

$$I_B = I_E - I_C$$

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

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \Big|_{V_{CE}=\text{const.}} = \frac{i_c}{i_e} \Big|_{v_{cb}=0} \ll 1$$

$$\beta = \frac{I_C}{I_B} \Big|_{v_{bc}=0 \text{ ili } V_{BE}=\text{const.}} \gg 1$$

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Model bipolarnog tranzistora

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

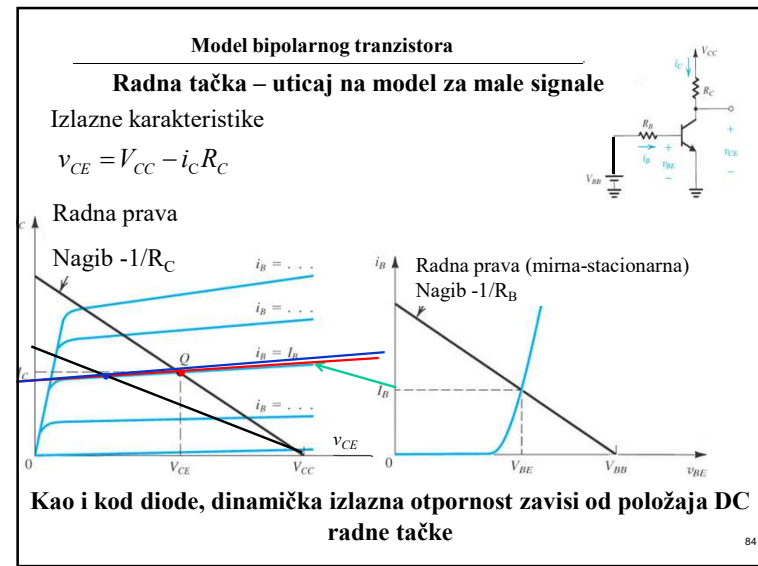
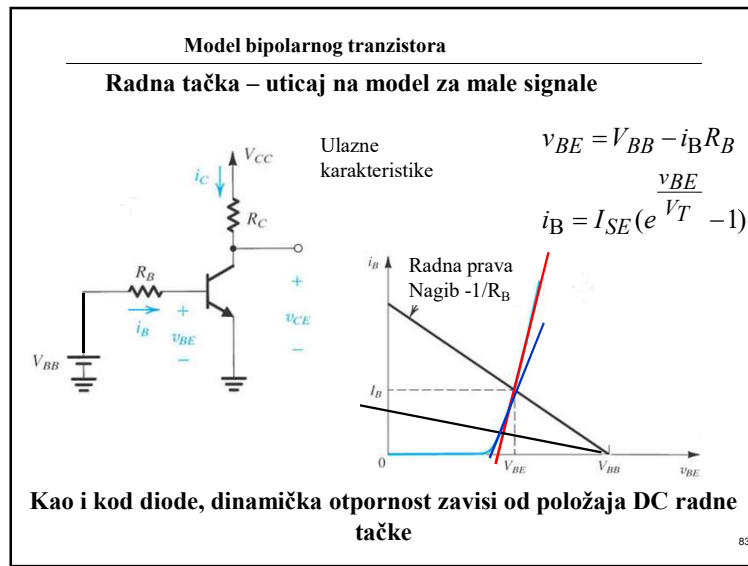
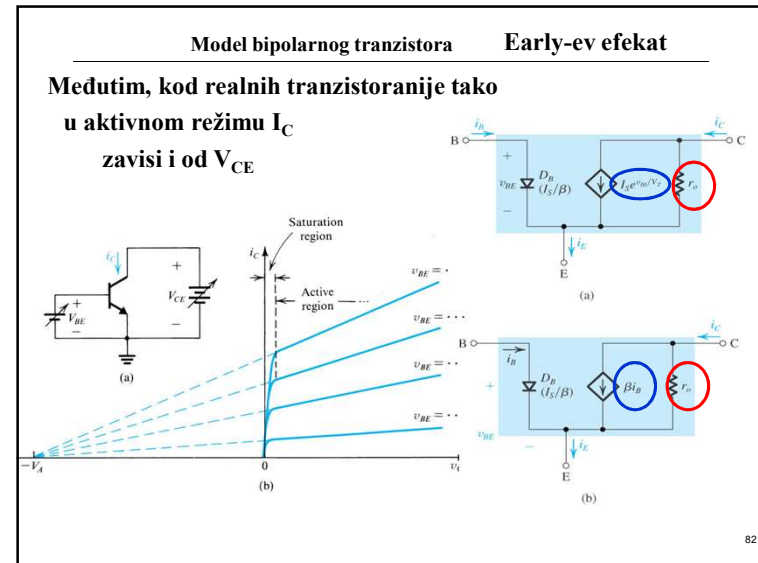
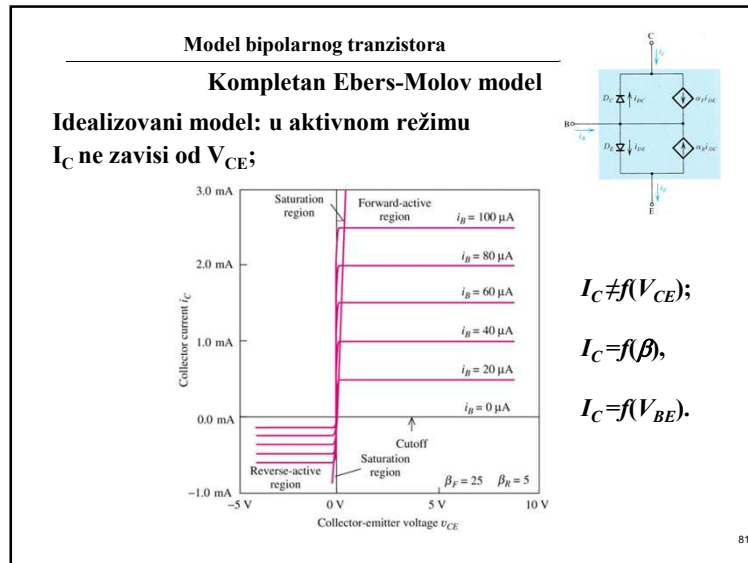
Konfiguracija zajednički emitor

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

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

Nelinearni model

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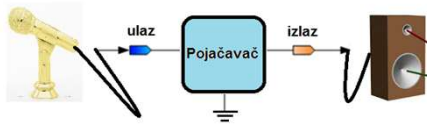


Osnovi elektronike

Od čega se sastoji pojačavač?

Od tranzistora

Kako tranzistor pojačava?



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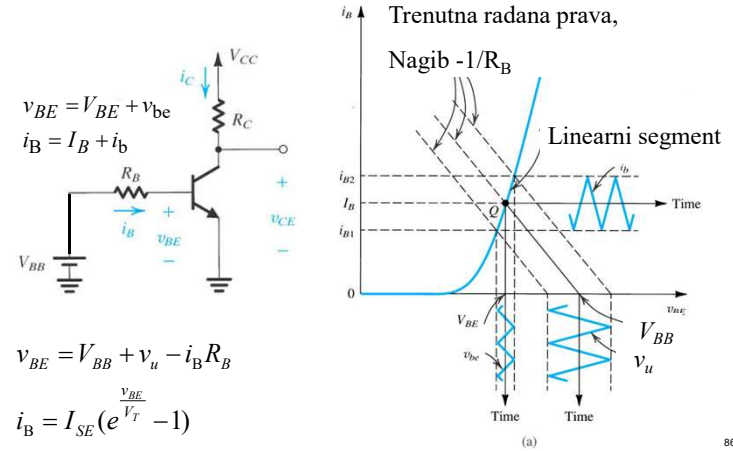
<http://leda.elfak.ni.ac.rs/>

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85

Model bipolarnog tranzistora

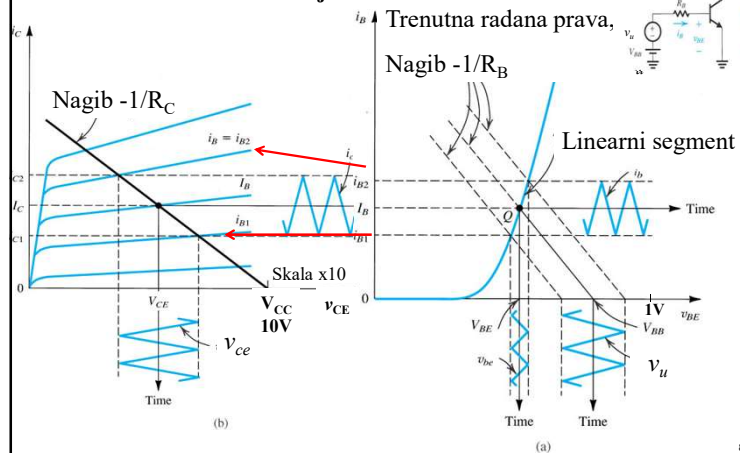
Radna tačka – uticaj na model za male signale



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Model bipolarnog tranzistora

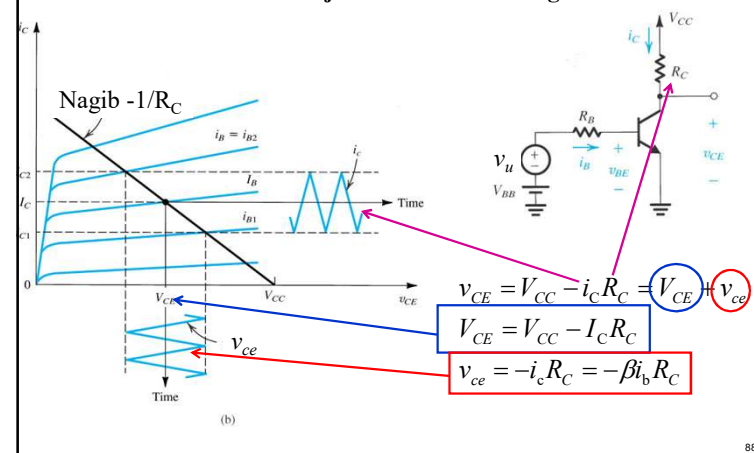
Radna tačka – uticaj na model za male signale



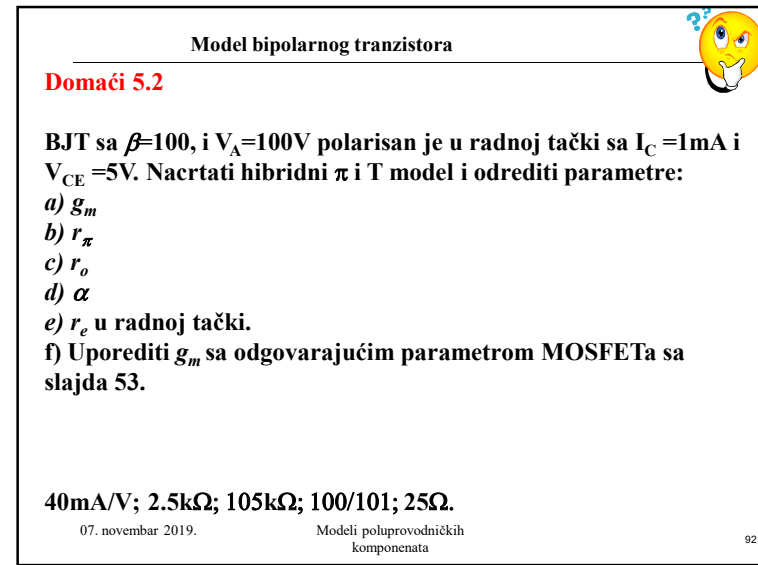
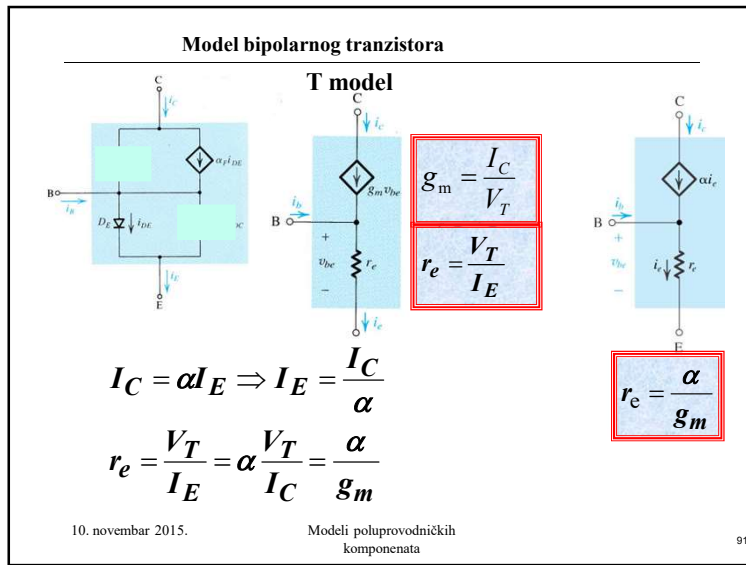
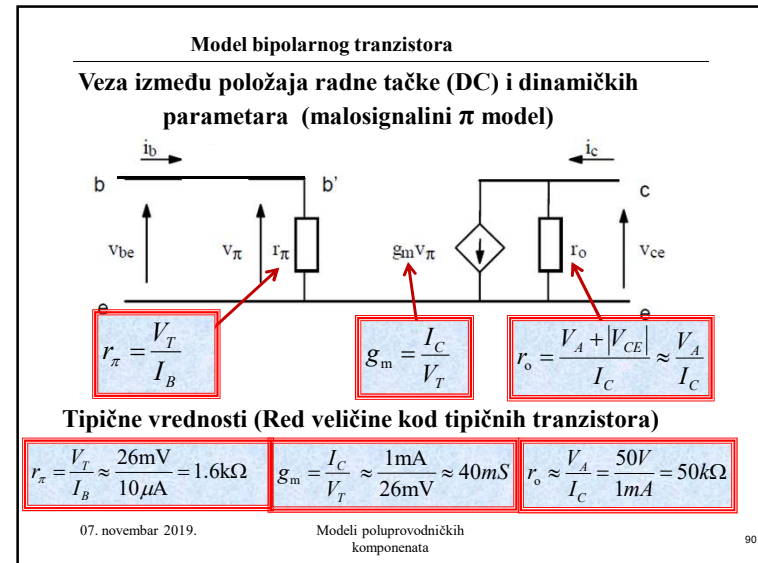
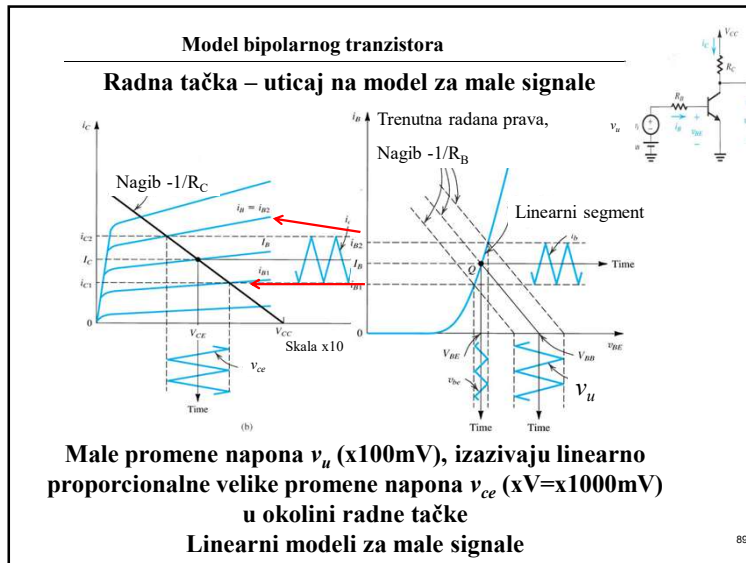
87

Model bipolarnog tranzistora

Radna tačka – uticaj na model za male signale



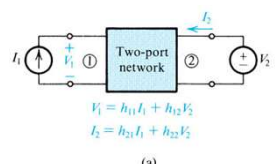
88



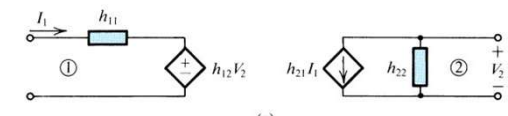
Model bipolarnog tranzistora

h - parametri

$$V_1 = h_{11} I_1 + h_{12} V_2$$

$$I_2 = h_{21} I_1 + h_{22} V_2$$


(a)



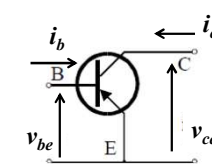
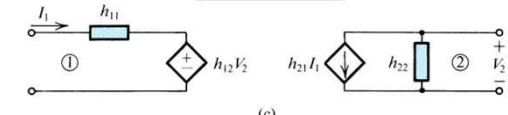
(c)

07. novembar 2019. Modeli poluprovodničkih komponenta 93

Model bipolarnog tranzistora

Hibridni model – h parametri

$$v_{be} = h_{11E} i_b + h_{12E} v_{ce}$$

$$i_c = h_{21E} i_b + h_{22E} v_{ce}$$



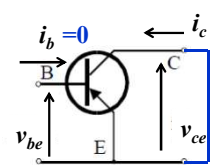
(c)

07. novembar 2019. Modeli poluprovodničkih komponenta 94

Model bipolarnog tranzistora

Hibridni model – h parametri

$$v_{be} = h_{11E} i_b + h_{12E} v_{ce}$$

$$i_c = h_{21E} i_b + h_{22E} v_{ce}$$


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

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

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

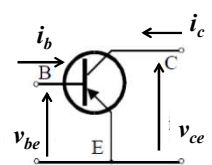
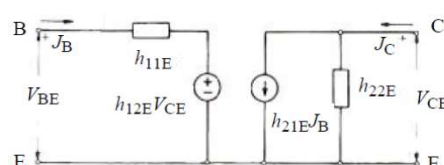
$$h_{22E} = \left. \frac{i_c}{v_{ce}} \right|_{i_b = 0} \quad \text{Izlazna odvodnost}$$

07. novembar 2019. Mo 95

Model bipolarnog tranzistora

Hibridni model – h parametri

$$v_{be} = h_{11E} i_b + h_{12E} v_{ce}$$

$$i_c = h_{21E} i_b + h_{22E} v_{ce}$$



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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 katalogizima

$$h_{ie} = h_{11E} \neq h_{11B} \neq h_{11C} \quad [\Omega = ohm]$$

$$h_{re} = h_{12E} \neq h_{12B} \neq h_{12C} \quad [V/V]$$

$$h_{fe} = h_{21E} \neq h_{21B} \neq h_{21C} \quad [A/A]$$

$$h_{oe} = h_{22E} \neq h_{22B} \neq h_{22C} \quad [S = 1/\Omega = mho]$$

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

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Model bipolarnog tranzistora

Hibridni model – h parametri

Brojne vrednosti h-parametara tipičnog Si BJT

Para- metar	Zajed. baza	Zajed. emitor	Zajed. kolektor
$h_{11} (\Omega)$	13	2700	2700
h_{12}	$0.9 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$	1
h_{21}	-0.995	200	-201
$h_{22} (\Omega^{-1})$	$0.06 \cdot 10^{-6}$	$18 \cdot 10^{-6}$	$18 \cdot 10^{-6}$

Zajed. emitor
xk Ω
0
x100
0

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Rezime

	DC	AC	Grafička interpretacija
Idealni naponski generator/baterija	 $V_{CC} = E$	 $r_e = \frac{\Delta V_E}{\Delta I_E} = \frac{0}{\Delta I_E} = 0 \Omega$ $e=0$	 $\Delta V_E = 0$
Idealni strujni generator	 $I_{CC} = J$	 $r_j = \frac{\Delta V_j}{\Delta I_j} = \frac{\Delta V_j}{0} \leftarrow \infty$ $j=0$	 $\Delta I_j = 0$

07. novembar 2019. Modeli poluprovodničkih komponentata 99

Rezime

	Dioda	Parametri modela	Grafička interpretacija
Veliki signali DC	 R_d V_γ $I_0 = 0$ za $V_D < V_\gamma = 0.5V$ $I_0 = \frac{V_D}{R_d}$ za $V_D > V_\gamma$	$R_d = V_D / I_D$ $V_\gamma = 0,5V$	
Mali signali AC	 r_d $i_d = r_d v_d$	$r_d = \frac{dV_D}{dI_D} \approx \frac{\Delta V_D}{\Delta I_D}$ $r_d = \frac{1}{\frac{dI_D}{dV_D}} \approx \frac{V_T}{I_D}$	

07. novembar 2019. Modeli poluprovodničkih komponentata 100

Rezime			
	MOSFET	Parametri modela	Grafička interpretacija
Veliki signali, DC Oblast zasićenja	<p>nMOS</p> <p>$I_C = 0$ $V_{GS} > V_T$</p> <p>$I_D = A(V_{GS} - V_T)^2$</p> <p>$V_{GS} > V_{GS} - V_T$</p>	<p>oblast zasićenja</p> <p>$V_{GS} > V_T$</p> <p>$V_{DS} > V_{GS} - V_T$</p> <p>$r_o \rightarrow \infty$</p>	
	Mali signali, AC Oblast zasićenja	<p>pMOS</p> <p>$I_C = 0$ $V_{GS} < V_T$</p> <p>$I_D = A(V_{GS} - V_T)^2$</p> <p>$V_{GS} < V_{GS} - V_T$</p>	<p>ili</p> <p>$r_o = \frac{\partial V_{DS}}{\partial I_D} \approx \frac{V_A}{I_D}$</p> <p>$r_o = \frac{\partial V_{DS}}{\partial I_D} \approx \frac{V_A}{I_D}$</p> <p>$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{2I_D}{V_{OV}}$</p>

Rezime			
	BJT		
Veliki signali, DC Aktivni režim		<p>BE spoj direktno</p> <p>BC spoj inverzno</p> <p>$R_B = \frac{V_{BE}}{I_B}$, $\beta = \frac{I_C}{I_B}$</p>	
	Mali signali, AC Aktivni režim	<p>h model</p>	<p>T model</p>

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 (02.12.2019.)	50%	20%
Kolokvijum II (13.01.2020.)	50%	20%



120% 60%

Ukupan skor u januaru može biti 120% PRE ISPITA

Savet: Izađite na kolokvijum MNOGO JE LAKŠE!

07. novembar 2019.

<http://leda.elfak.ni.ac.rs/>

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Modeli poluprovodničkih komponenata

Sledećeg časa

Osnovni pojačavački stepeni sa MOSFET

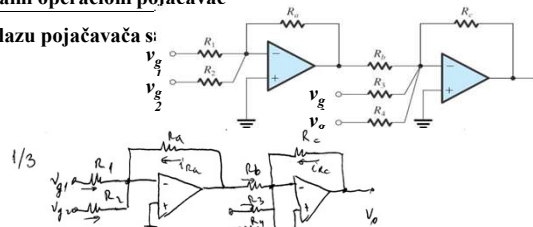
07. novembar 2019.

Modeli poluprovodničkih komponenata

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Rešenje 4.1 Idealni operacioni pojačavač

Određiti napon na izlazu pojačavača s:



$$i_{Rc} = \frac{v_o}{R_c} = -\left(\frac{v_a}{R_b} + \frac{v_3}{R_3} + \frac{v_4}{R_4}\right) \Rightarrow v_o = -\frac{R_c}{R_b} v_a - \frac{R_c}{R_3} v_3 - \frac{R_c}{R_4} v_4$$

$$i_{Rb} = \frac{v_a}{R_b} = -\left(\frac{v_1}{R_1} + \frac{v_2}{R_2}\right) \Rightarrow v_a = -\frac{R_b}{R_1} v_1 - \frac{R_b}{R_2} v_2$$

$$v_o = -\frac{R_c}{R_b} \left(-\frac{R_b}{R_1} v_1 - \frac{R_b}{R_2} v_2\right) - \frac{R_c}{R_3} v_3 - \frac{R_c}{R_4} v_4$$

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

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Operacioni pojačavači

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Realni operacioni pojačavač

Rešenje 4.2

Zadatak: Za invertorski pojačavač pobuden 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:

- Pojačanje u zatvorenoj petlji
- Procentualnu promenu pojačanja u zatvorenoj petlji u odnosu na slučaj sa idealnim OpAmpom
- 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)

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Operacioni pojačavači

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Realni operacioni pojačavač

Efekti konačnog pojačanja

Invertorski pojačavač

$v_i = Av_d = A(v_+ - v_-)$
 $v_+ = 0$
 $v_d = 0 - v_- = -v_-$
 $v_i = A(-v_-) \Rightarrow v_- = -v_i / A$

$i_u = i_1 + i_2 = 0A \Rightarrow i_1 = -i_2$
 $i_1 = \frac{v_g - v_1}{R_1} = \frac{v_g - (-v_i/A)}{R_1}$
 $i_2 = \frac{v_i - v_1}{R_2} = \frac{v_i - (-v_i/A)}{R_2}$

$$A_v = \frac{v_o}{v_g} = \frac{-R_2 / R_1}{1 + (1 + R_2 / R_1) / A}$$

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Realni operacioni pojačavač

Rešenje 4.3

$i_1 = \frac{v_i - v_o}{R_1} = -\frac{v_o - v_i}{R_1} = -i_2$
 $v_i \cdot R_2 - \frac{R_2}{A_{OL}} v_o = -v_o R_1 + \frac{R_1}{A_{OL}} v_o$
 $v_i \cdot R_2 = -(R_1 + \frac{R_1}{A_{OL}}) v_o \Rightarrow v_o = \frac{A_{OL} v_i R_2}{A_{OL} R_1 + (R_1 + R_2)}$
 $A = \frac{v_o}{v_i} = -\frac{A_{OL} R_2}{A_{OL} R_1 + R_1 + R_2} = \frac{A_{OL} \cdot 100}{A_{OL} + 101}$

A_{OL}	v_i [V]	v_o [V]	$\frac{\Delta A}{A}$ [%]	
60	1.03	99.83	99.16	-9.173
80	1.04	99.00	99.91	-0.999
100	1.05	99.90	99.99	-0.101

07. novembar :

Dodatak

Modeli poluprovodničkih komponentata

Za velike signale ?

Za male signale ?

- Nelinearni ?**
- Linearizovani ?**
- Idealizovani ?**

Linearni ?

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Model diode

Dodatak

-Diode

-Simbol

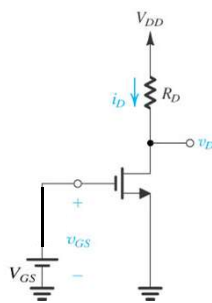
Karakteristika: zavisnost struje od napona

Direktna polarizacija
 Inverzna polarizacija
 Probaj

07. novembar 2019. Modeli poluprovodničkih komponentata 112

Dodatak Model MOS tranzistora

Radna tačka – uticaj na model za male signale

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


$i_G = 0$

$V_D > V_{GS} - V_t$

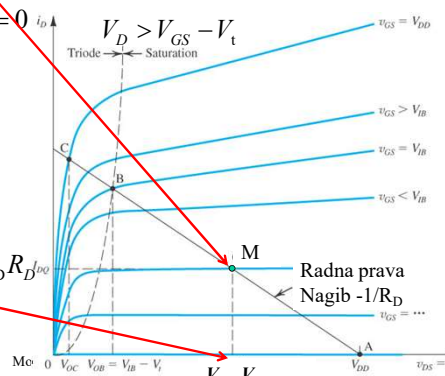
Triode ← Saturation

$v_{GS} = V_{DD}$
 $v_{GS} > V_{th}$
 $v_{GS} = V_{th}$
 $v_{GS} < V_{th}$

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

Radna prava
Nagib $-1/R_D$

Jednačina prave u I-V ravni
Radna prava



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Dodatak Model MOS tranzistora

Radna tačka – uticaj na model za male signale

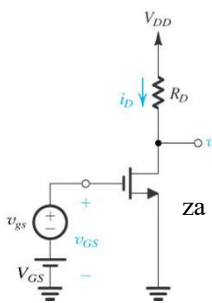
$$v_{GS} = V_{GS} + v_{gs}$$

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

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

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

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

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


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Dodatak Model MOS tranzistora

Radna tačka – značenje modela za male signale

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

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

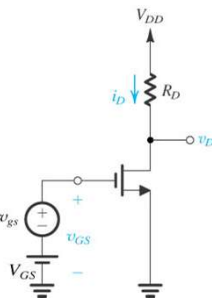
$$i_d = 2A(V_{GS} - V_t)v_{gs} = g_m v_{gs}$$

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

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

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

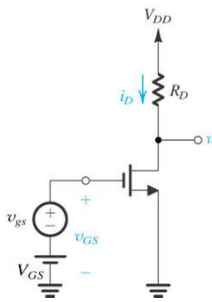
$(g_m \equiv S)$



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Dodatak Model MOS tranzistora

Radna tačka – značenje modela za male signale

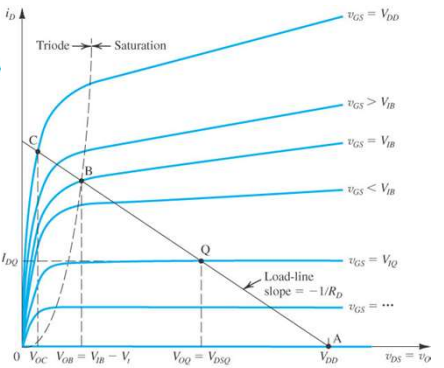
$$v_{DS} = V_{DD} - i_D R_D \quad i_D = \frac{V_{DD}}{R_D} - \frac{1}{R_D} v_{DS}$$


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

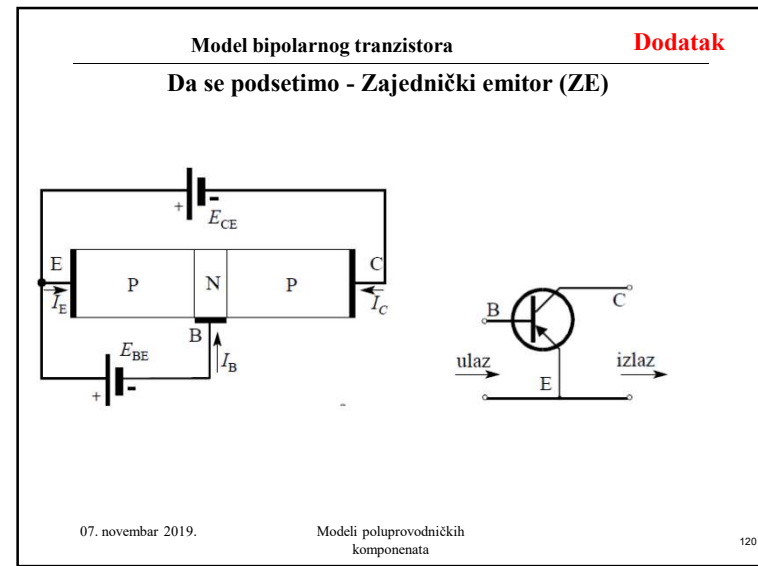
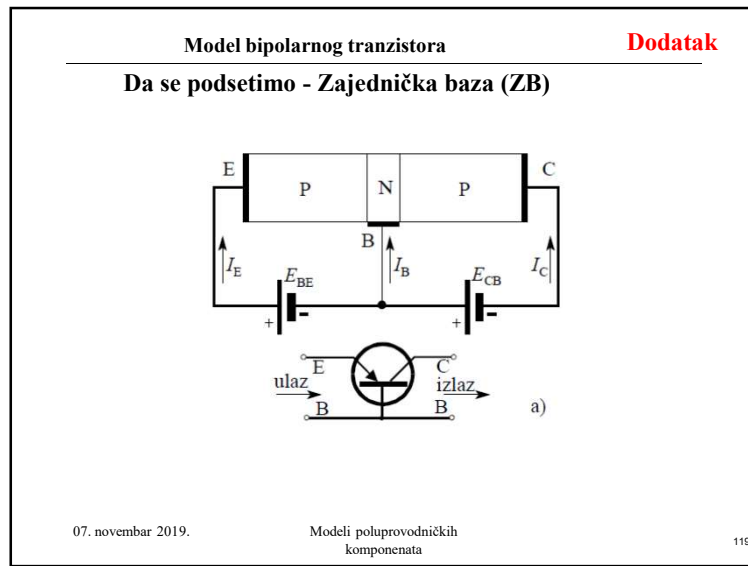
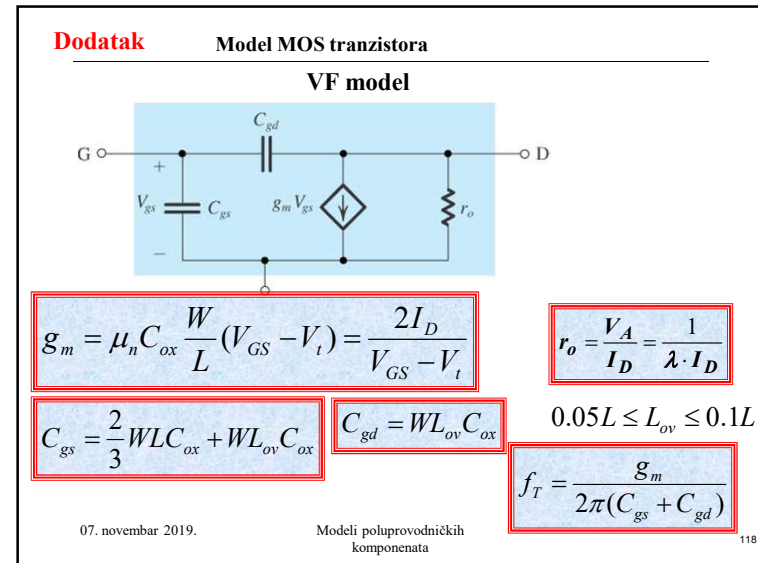
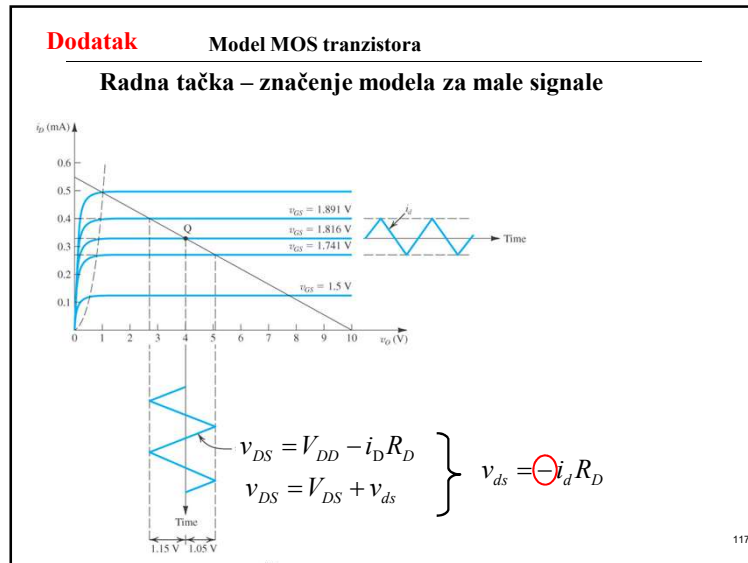
Triode ← Saturation

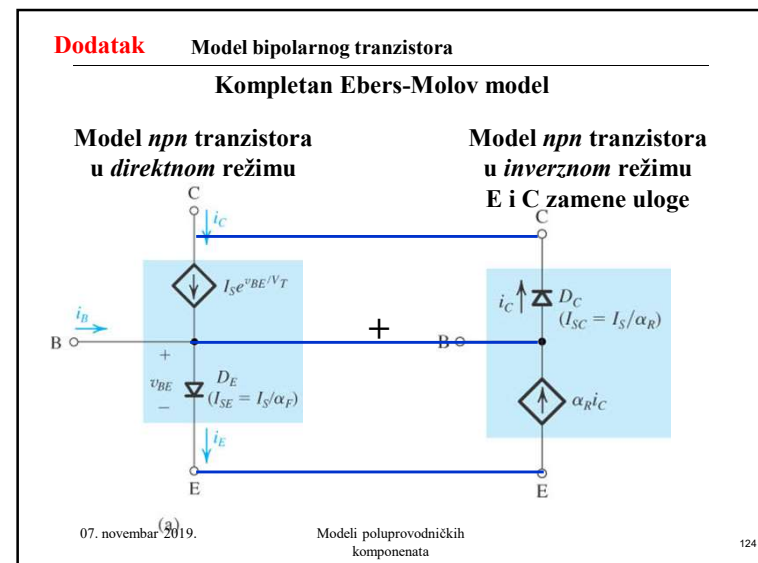
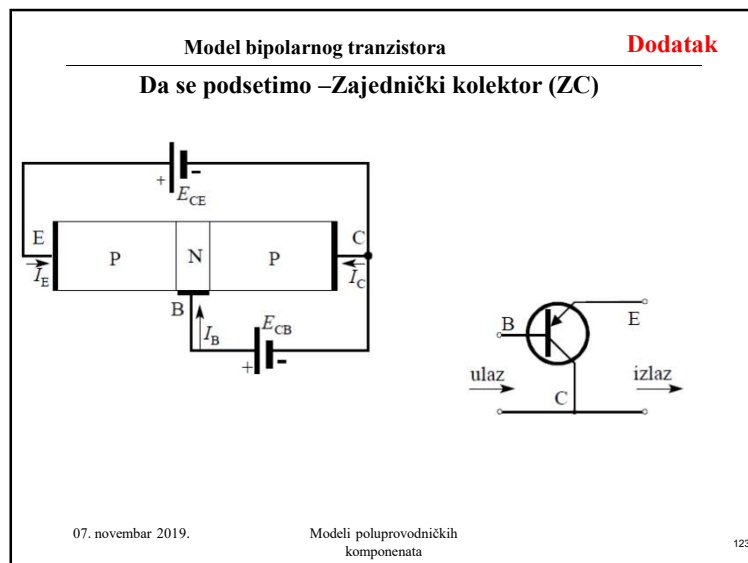
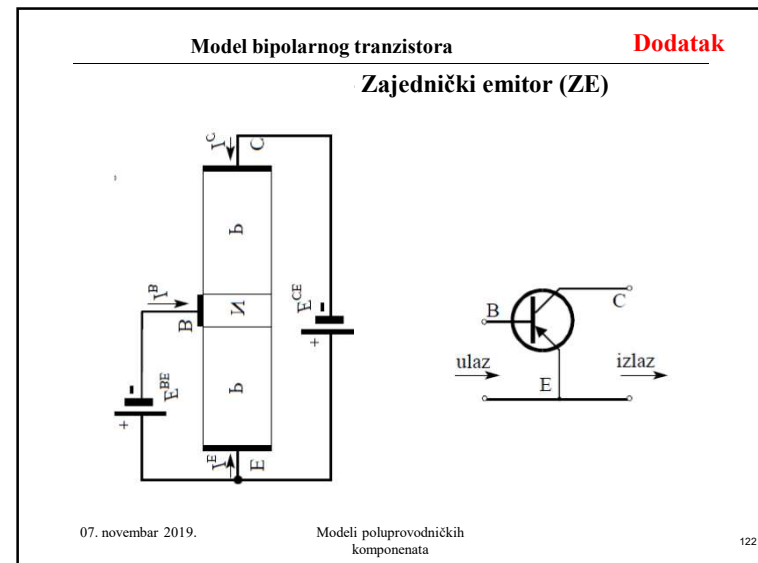
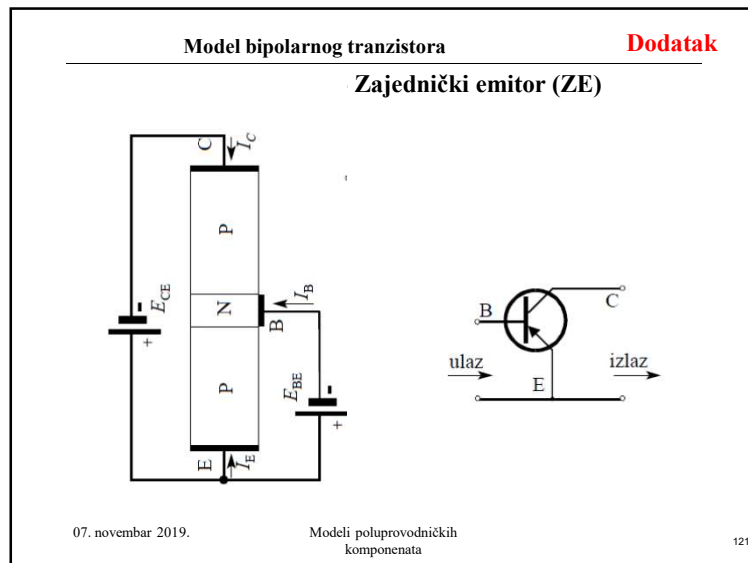
$v_{GS} = V_{DD}$
 $v_{GS} > V_{th}$
 $v_{GS} = V_{th}$
 $v_{GS} < V_{th}$
 $v_{GS} = V_{th}$
 $v_{GS} < V_{th}$

Load-line slope = $-1/R_D$



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Dodatak Model bipolarnog tranzistora

Kompletan Ebers-Molov model

Važi u svim režimima rada tranzistora!!!

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

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

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

U aktivnom režimu I_C ne zavisi od V_{CE}

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

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Dodatak Model bipolarnog tranzistora

Radna tačka – uticaj na model za male signale

Ulazne karakteristike

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

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

Radna prava Nagib $-1/R_B$

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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 $-1/R_C$

Radna prava (mirna-stacionarna) Nagib $-1/R_B$

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Dodatak Model bipolarnog tranzistora

Radna tačka – uticaj na model za male signale

Trenutna radana prava, Nagib $-1/R_B$

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

$$i_B = I_B + i_b$$

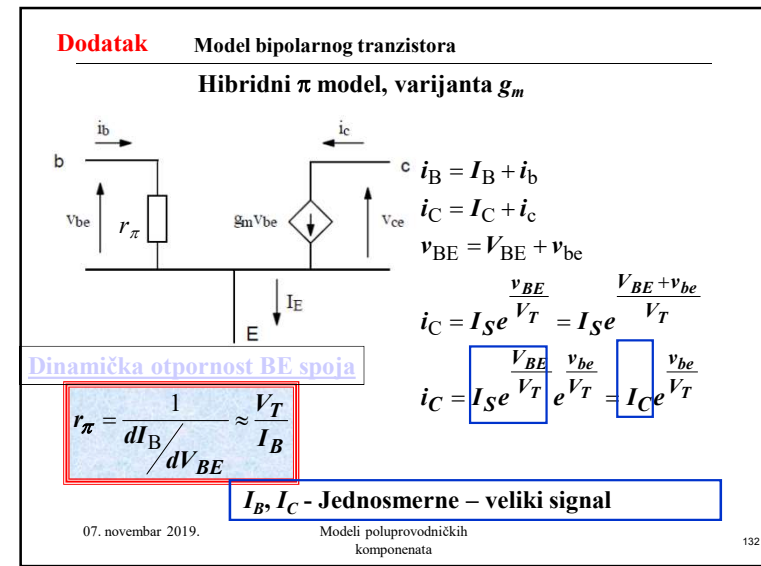
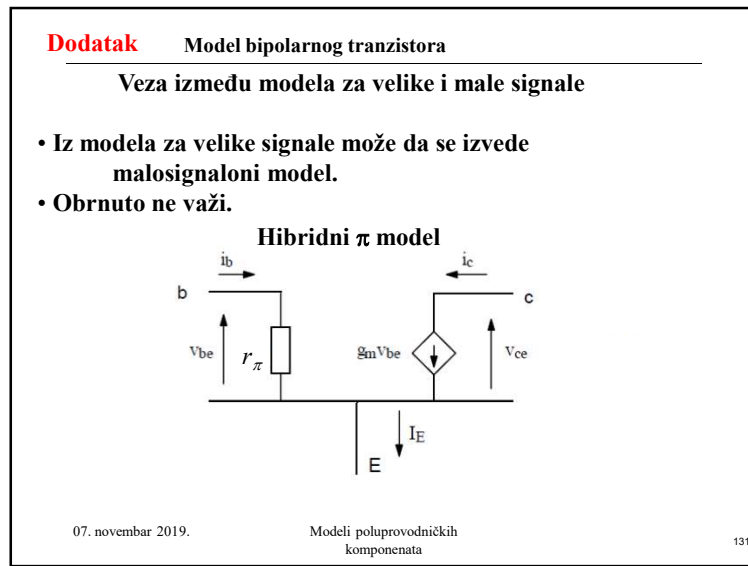
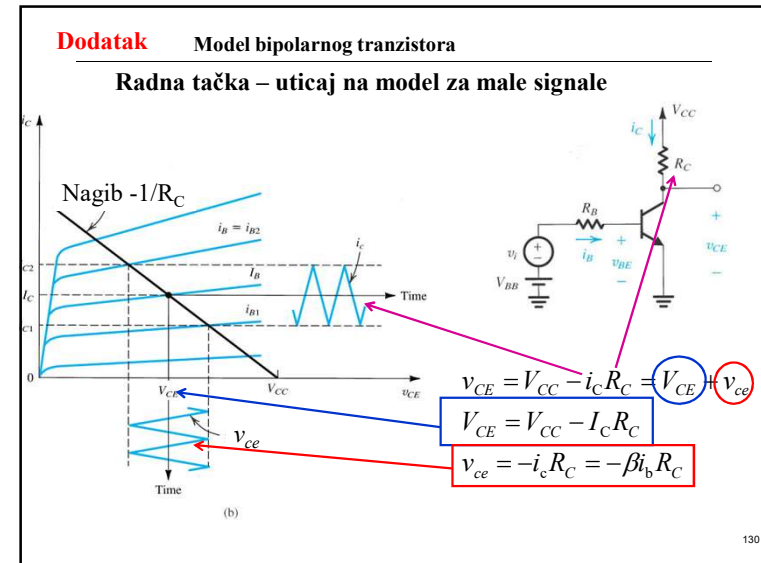
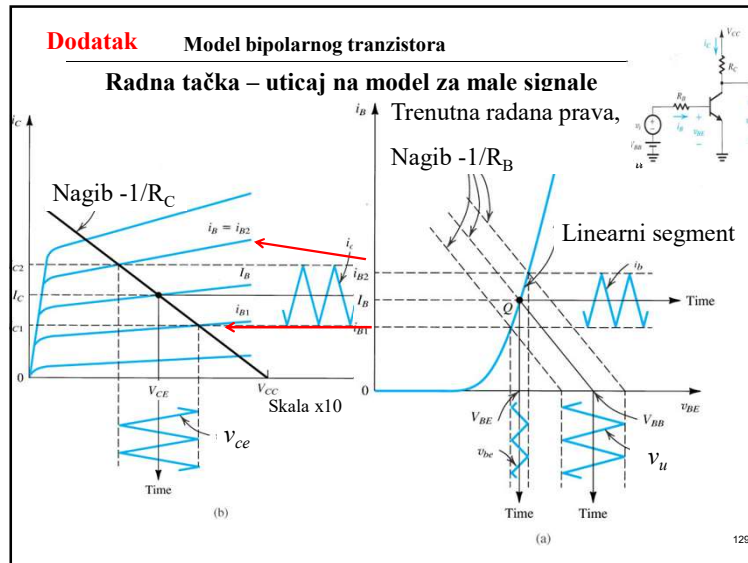
Linearni segment

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

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

(a)

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Dodatak Model bipolarnog tranzistora

Hibridni π model, varijanta g_m

$e^x \approx (1+x)$ za $x \ll 1$

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

$i_c \approx I_C (1 + \frac{v_{be}}{V_T})$ za $v_{be} \ll V_T$

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

Važi za malo $v_{be} \ll V_T = 26mV$ za $T = 300K$

I_C - Jednosmerna – veliki signal

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

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

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Dodatak Model bipolarnog tranzistora

Hibridni π model, varijanta g_m

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

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

$g_m \approx 39 I_C$ za $T = 300K$ ($V_T = 26mV$)

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Dodatak Model bipolarnog tranzistora

Hibridni π model, varijanta β

$i_B = I_B + i_b$

$i_c = I_C + i_c$

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

$i_c = \beta i_b$

$i_B = \frac{i_c}{\beta} = \frac{I_C + i_c}{\beta}$

$i_B = \frac{I_C}{\beta} + \frac{g_m v_{be}}{\beta} = \frac{I_C}{\beta} + \frac{1}{\beta} \frac{I_C}{V_T} v_{be}$

$i_b = \frac{1}{\beta} \frac{I_C}{V_T} v_{be} = \frac{g_m}{\beta} v_{be}$

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

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Dodatak Model bipolarnog tranzistora

T model

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

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

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

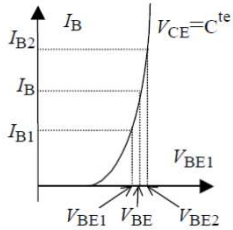
$I_C = \alpha I_E \Rightarrow I_E = \frac{I_C}{\alpha}$

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

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Dodatak Model bipolarnog tranzistora

Određivanje h- parametara sa statičkih karakteristika

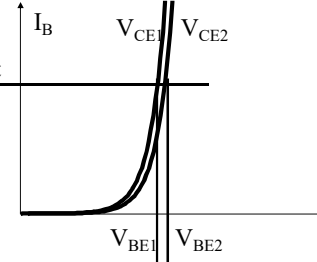
$$h_{11E} = \left. \frac{v_{be}}{i_b} \right|_{v_{ce}=0} = \left. \frac{\Delta V_{BE}}{\Delta I_B} \right|_{V_{CE} = Const}$$


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

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Dodatak Model bipolarnog tranzistora

Određivanje h- parametara sa statičkih karakteristika

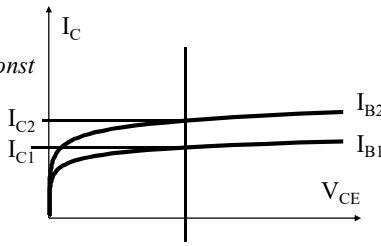
$$h_{12E} = \left. \frac{v_{ce}}{v_{be}} \right|_{i_b=0} = \left. \frac{\Delta V_{CE}}{\Delta V_{BE}} \right|_{I_B = Const.}$$


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

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Dodatak Model bipolarnog tranzistora

Određivanje h- parametara sa statičkih karakteristika

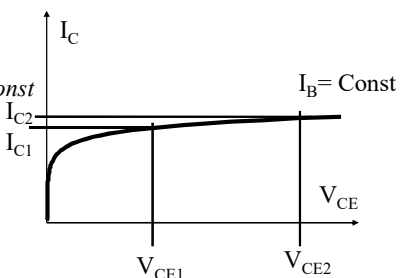
$$h_{21E} = \left. \frac{i_c}{i_b} \right|_{v_{ce}=0} = \left. \frac{\Delta I_C}{\Delta I_B} \right|_{V_{CE} = Const}$$


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

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Dodatak Model bipolarnog tranzistora

Određivanje h- parametara sa statičkih karakteristika

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


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

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Dodatak Model bipolarnog tranzistora

VF model bipolarnog tranzistora

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

$$C_{\mu} = \frac{C_{\mu 0}}{\left(1 + \frac{V_{CB}}{V_{0C}}\right)^m}$$

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Dodatak Model bipolarnog tranzistora

VF model bipolarnog tranzistora

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

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

$$\omega_T = \beta_0 \omega_{\beta}$$

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

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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

$$h_{12E} \ll 1, h_{11E} h_{22E} \ll 1, h_{12B} \ll 1, h_{11B} h_{22B} \ll 1, h_{12C} \approx 1$$

$$h_{11B} \approx \frac{h_{11E}}{1 + h_{21E}} \ll h_{11E} \quad h_{11C} = h_{11E} \quad [\Omega = \text{ohm}]$$

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

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

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

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Dodatak Model bipolarnog tranzistora

Rezime

VF model bipolarnog tranzistora

$$r_{\pi} = \frac{\beta_0}{g_m}$$

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

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

$$C_{\pi} + C_{\mu} = \frac{g_m}{2\pi f_T}$$

$$C_{\pi} = C_{de} + C_{je}$$

$$C_{de} = \tau_F g_m$$

$$C_{je} \approx 2C_{je0}$$

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

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