

POLPREVODNIŠKA ELEKTRONIKA

(3-1-2)

Predavatelj: **Franc Smole** (kabinet BN308)
(govorilne ure: torek, 12^h – 14^h)

Asistent: **Benjamin Lipovšek**
(kabinet BN311 – 3. nad.)



Literatura:

Franc Smole, **Polprevodniška elektronika**

Založba FE in FRI, 2013

Franc Smole, Marko Topič,

Elementi polprevodniške elektronike,

Založba FE in FRI, 2014

Benjamin Lipovšek, Janez Krč,

Polprevodniška elektronika,

Delovno gradivo za laboratorijske vaje

Založba FE, 2015



Osnovni cilji predmeta:

- prikazati zgradbe, delovanje in lastnosti polprevodniških elementov ter na primeru osnovnih povezav elementov prikazati glavne namene uporabe.

Poznavanje polprevodniških elementov je pomembno za razumevanje:

- analogne in digitalne elektronike,
- močnostne elektronike,
- optoelektronike, fotonike ter
- razvijajoče se nanoelektronike.

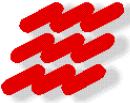


VSEBINA PREDMETA:

Uvod

Dvopoli in četveropoli

Prevajalne lastnosti dvopolov in četveropolov



Lastnosti polprevodnikov

Polprevodniški materiali

Zgradba polprevodnikov

Tvorba energijskih pasov v kristalih

Monokristalni silicij in njegova uporaba

Gostota energijskih stanj

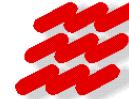
Verjetnost zasedenosti energijskih stanj

Določitev koncentracij prostih elektronov in vrzeli

Polprevodnik s primesmi

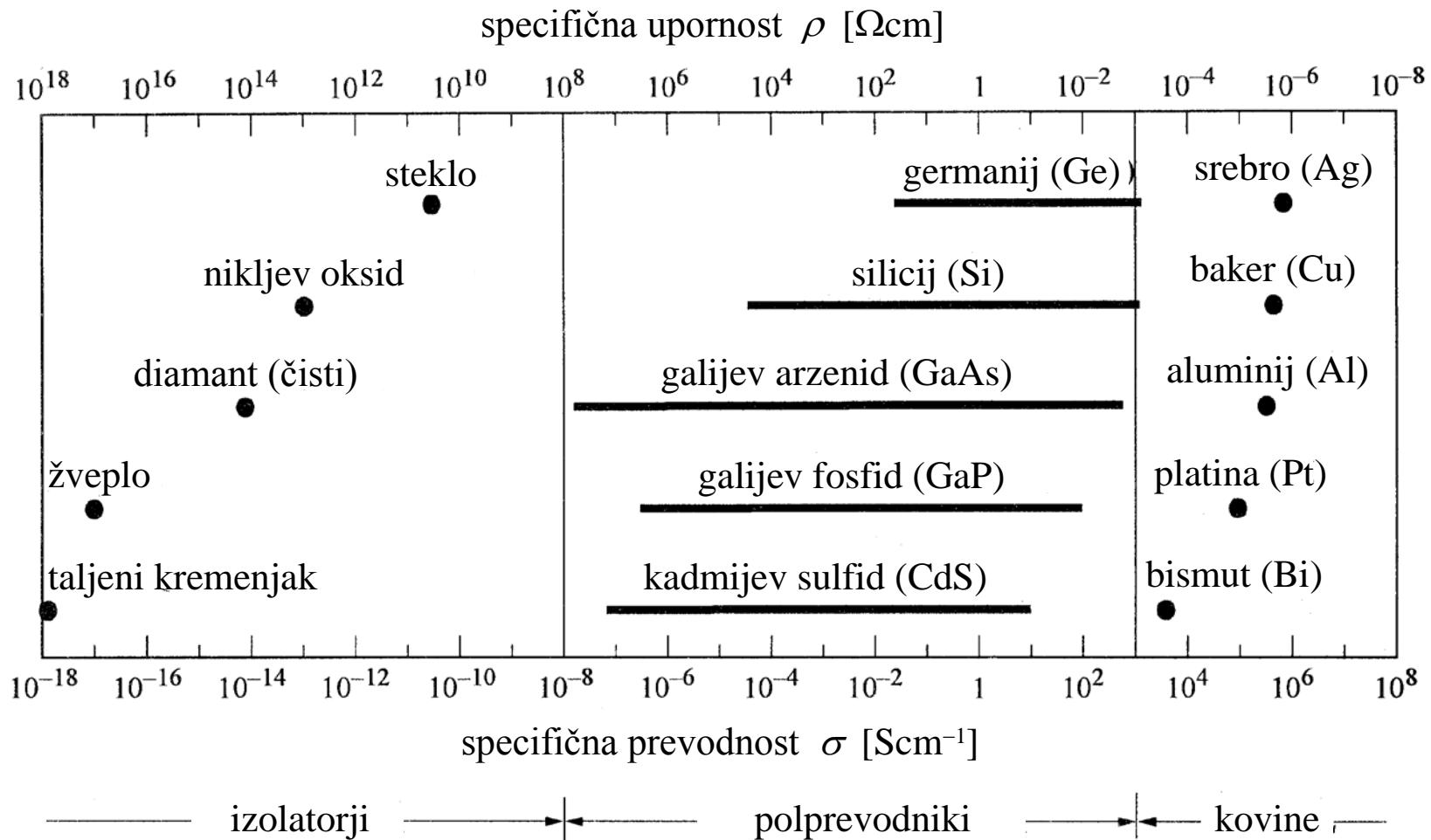
Fermijeva energija in koncentracije

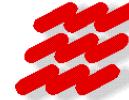
nosilcev naboja v polprevodniku s primesmi



Lastnosti polprevodnikov

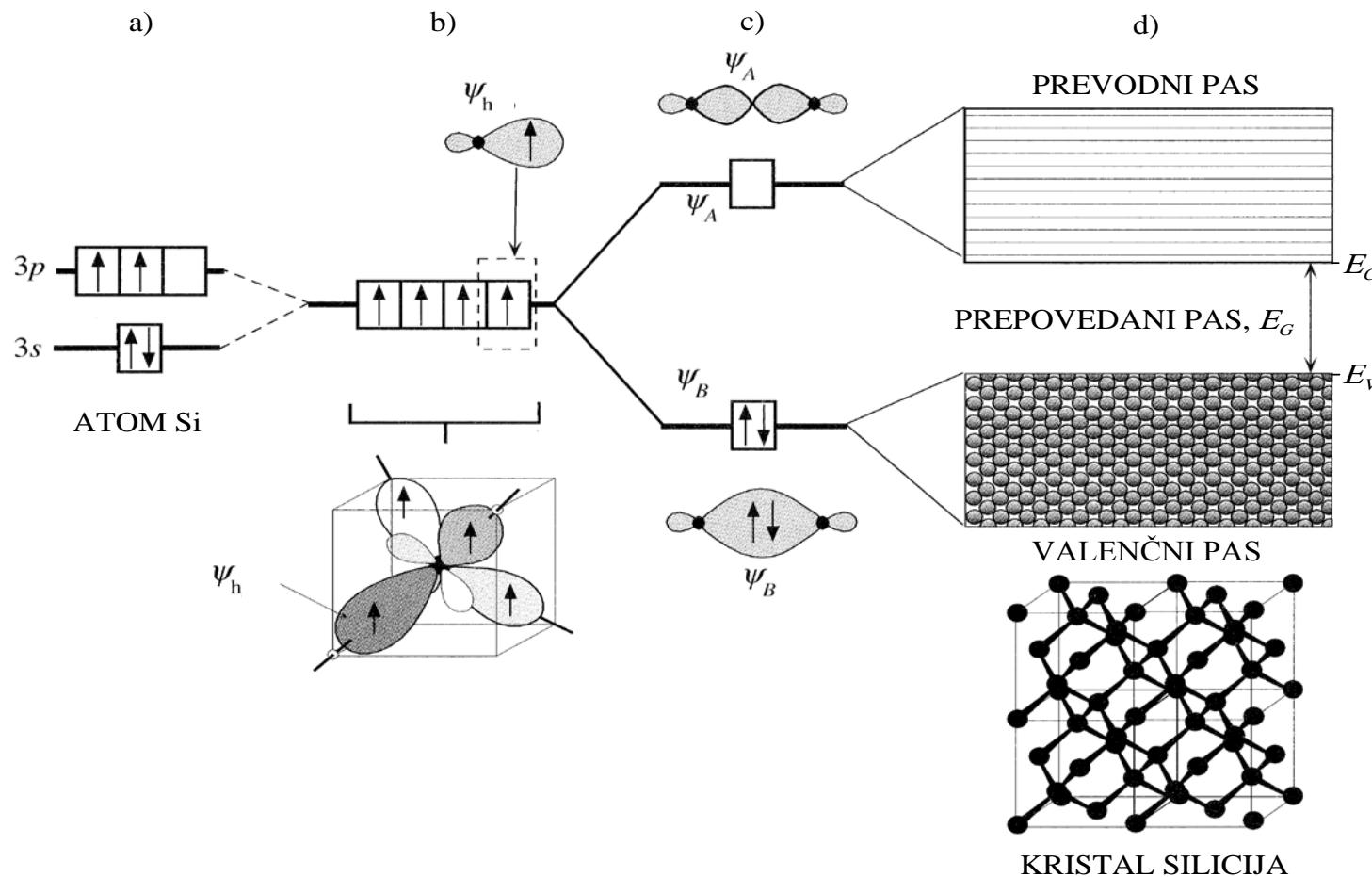
Polprevodniški materiali





Lastnosti polprevodnikov

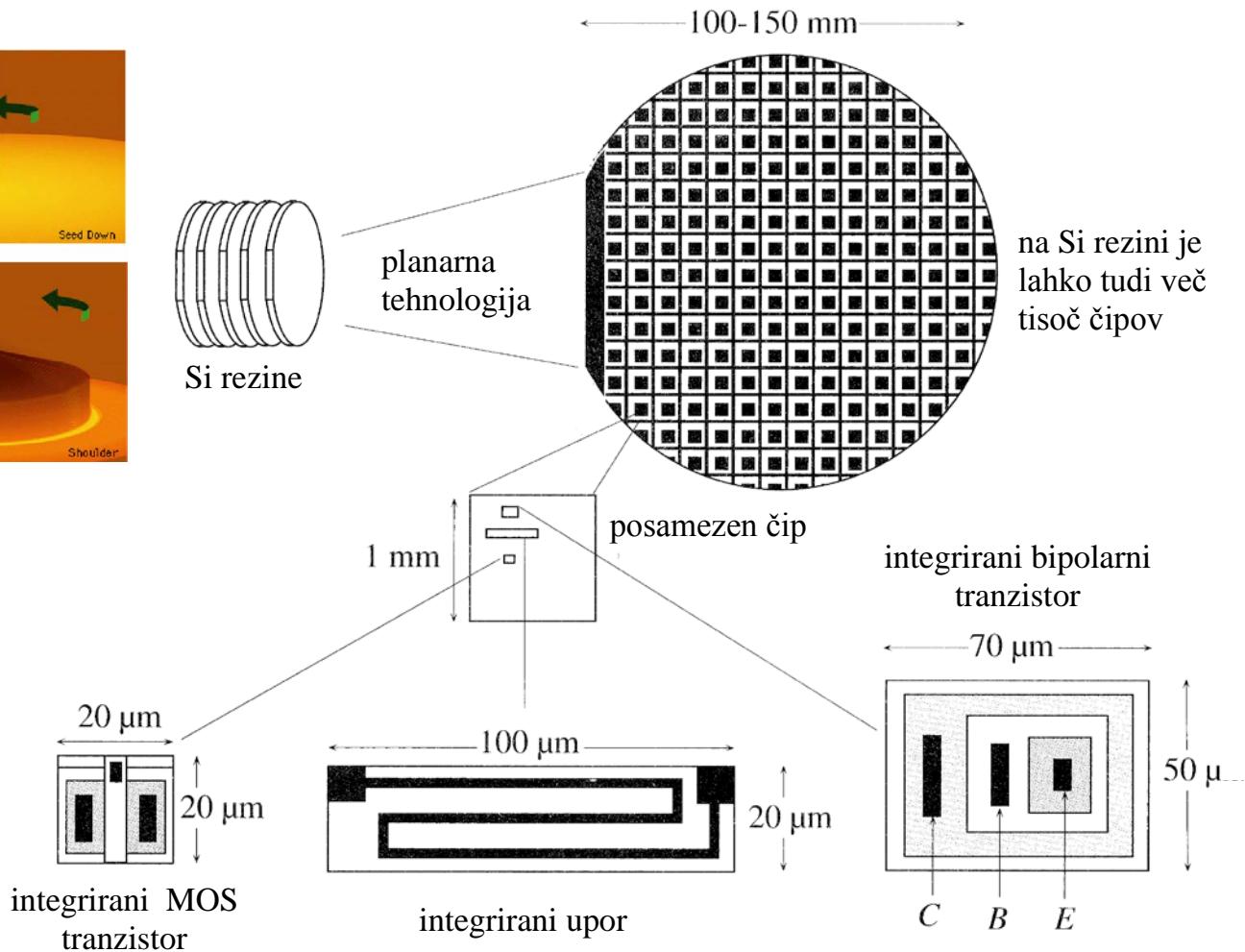
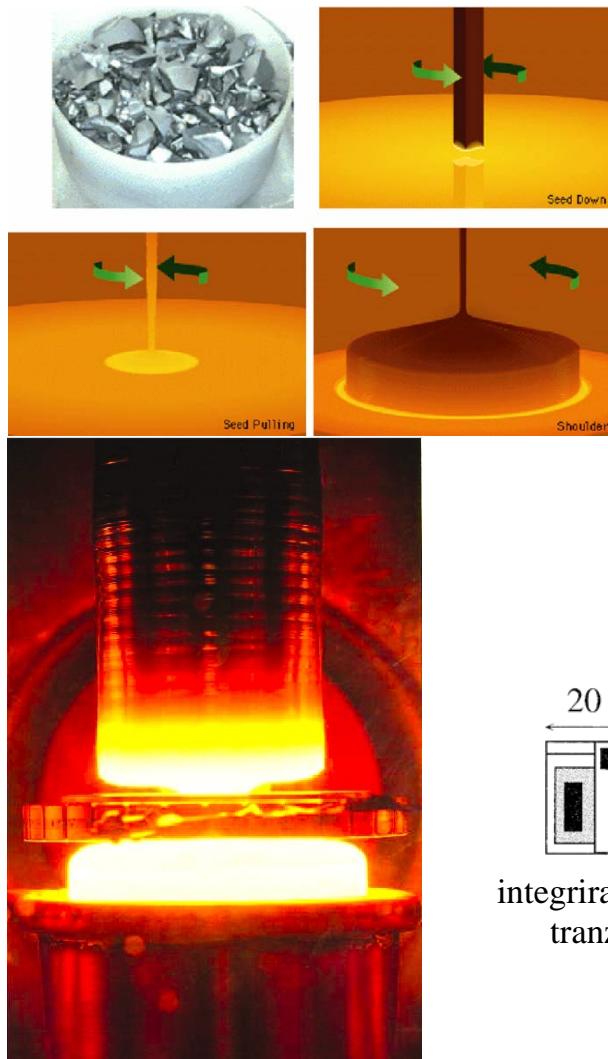
Zgradba polprevodnikov
Tvorba energijskih pasov v kristalih

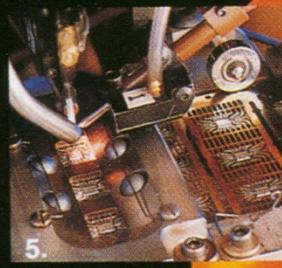
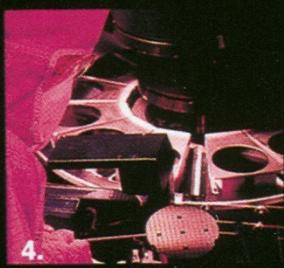
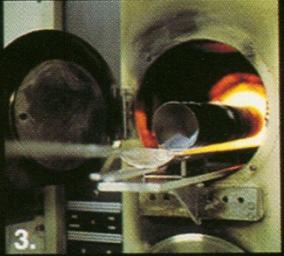
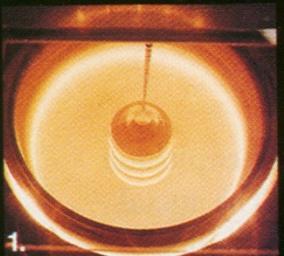
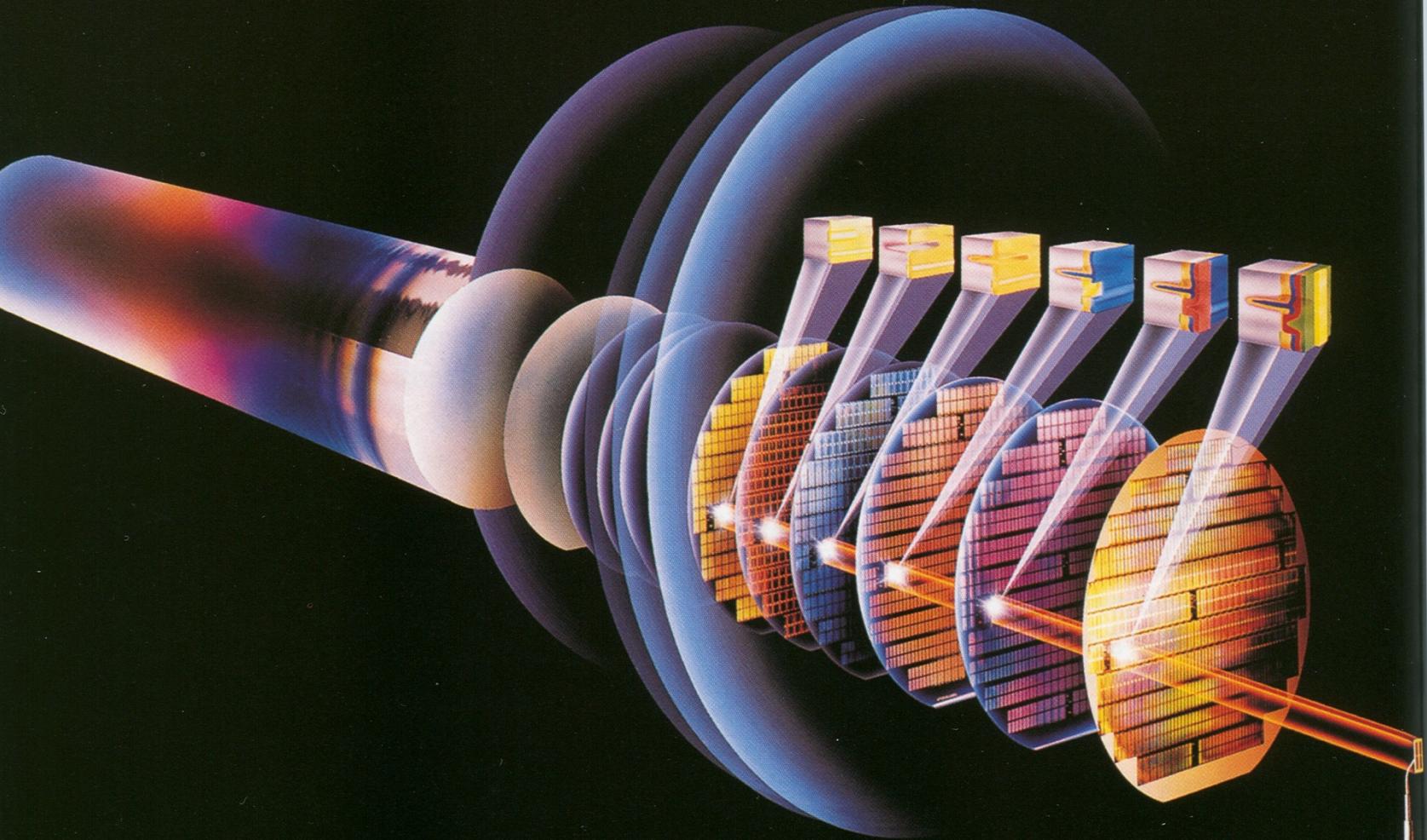


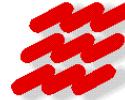


Lastnosti polprevodnikov

Monokristalni silicij in njegova uporaba







Električni toki v polprevodniku

- Konduktivni tok v polprevodniku
- Difuzijski tok v polprevodniku
- Skupne gostote tokov elektronov in vrzeli

Generacije in rekombinacije prostih nabojev

Kontinuitetna enačba

Pregled enačb za analizo električnih lastnosti v polprevodniku

Difuzijska enačba in difuzijska dolžina



Pregled enačb za analizo električnih lastnosti v polprevodniku

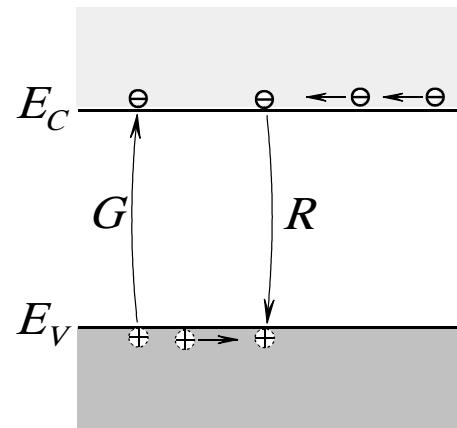
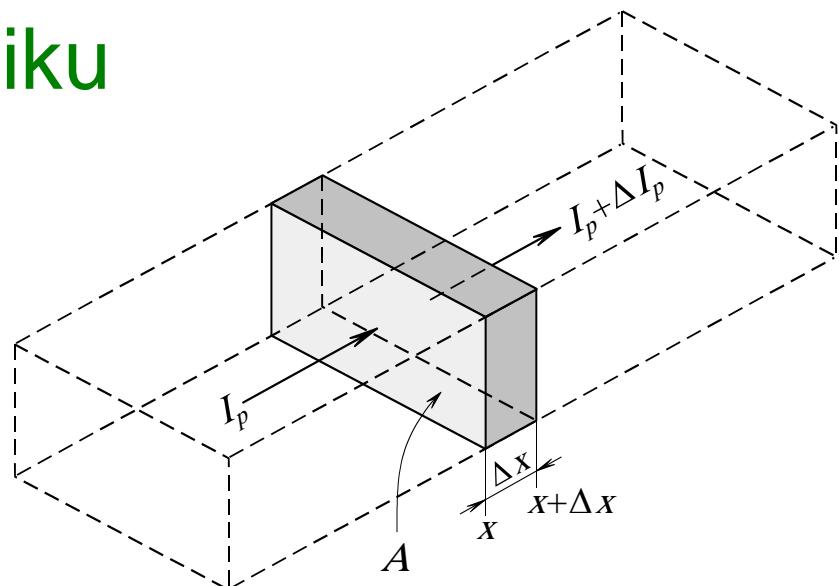
$$J_n = q \mu_n n E + q D_n \frac{dn}{dx}$$

$$J_p = q \mu_p p E - q D_p \frac{dp}{dx}$$

$$\frac{\partial n}{\partial t} = G - R + \frac{1}{q} \frac{\partial J_n}{\partial x} = -\frac{n - n_0}{\tau_n} + \frac{1}{q} \frac{\partial J_n}{\partial x}$$

$$\frac{\partial p}{\partial t} = G - R - \frac{1}{q} \frac{\partial J_p}{\partial x} = -\frac{p - p_0}{\tau_p} - \frac{1}{q} \frac{\partial J_p}{\partial x}$$

$$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon} = \frac{q}{\varepsilon} (p - n + N_D - N_A)$$





Polprevodniška *pn*-dioda

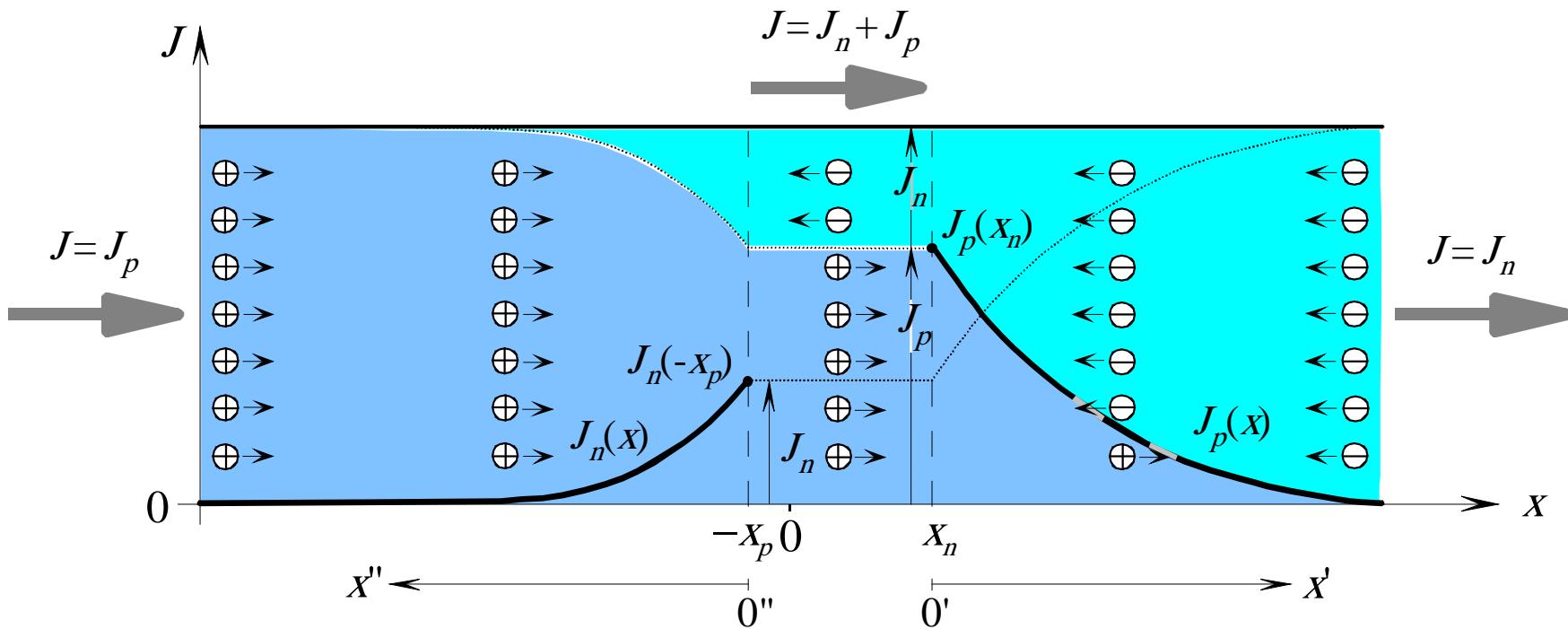
- pn*-dioda brez priključenega vira napetosti ali toka
- pn*-dioda pri priključenem viru napetosti
- Analiza tokovno-napetostne karakteristike *pn*-diode**
- Odstopanja od idealne karakteristike *pn*-diode
- Prebojna napetost diode, Zenerjev in plazovni preboj
- Temperaturna odvisnost diodne karakteristike
- Odvajanje topote od *pn*-spoja v okolico
- Lastnosti diode pri vzbujanju z majhnimi signali**
- Diferencialna upornost,
spojna in difuzijska kapacitivnost diode**
- Vzbujanje diode z velikimi pravokotnimi signali
- Tehnologija izdelave *pn*-diode
- Primeri uporabe diod



Polprevodniška *pn*-dioda

Analiza tokovno-napetostne karakteristike *pn*-diode

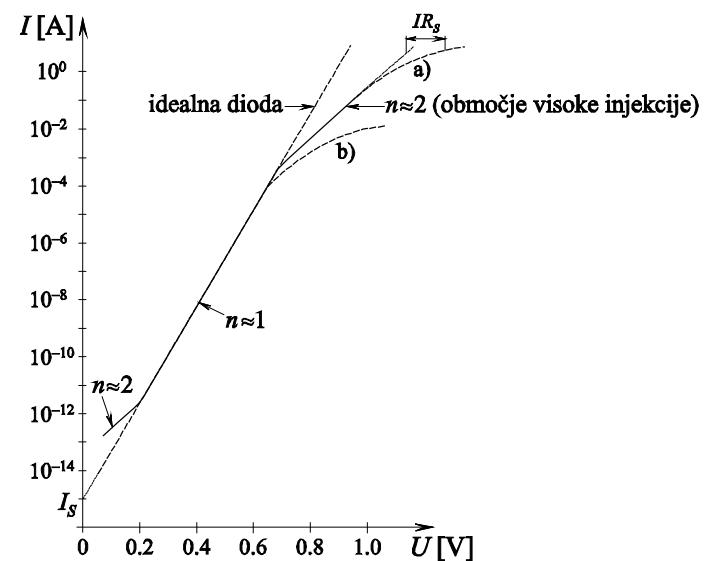
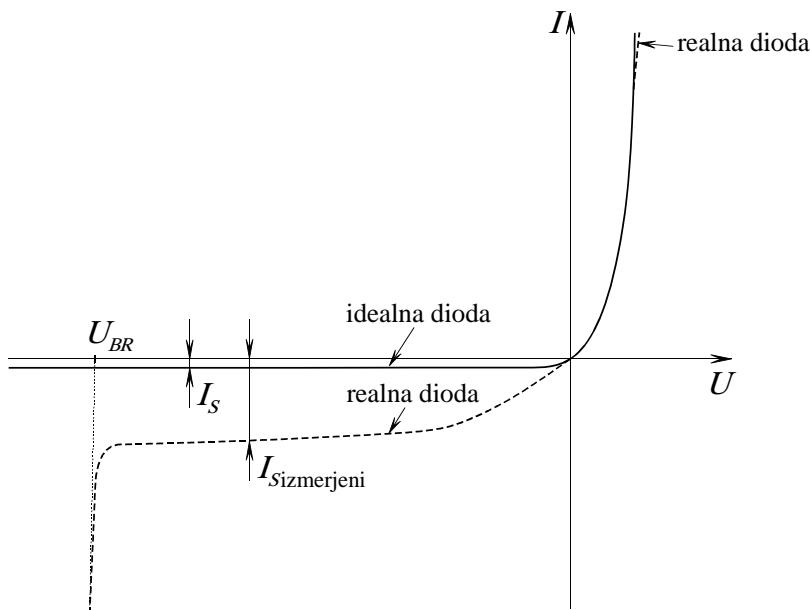
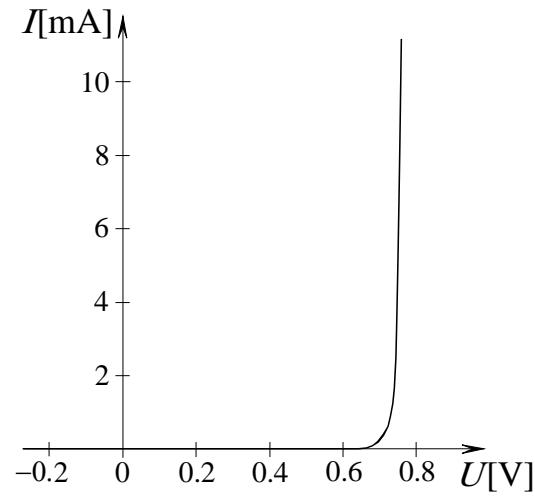
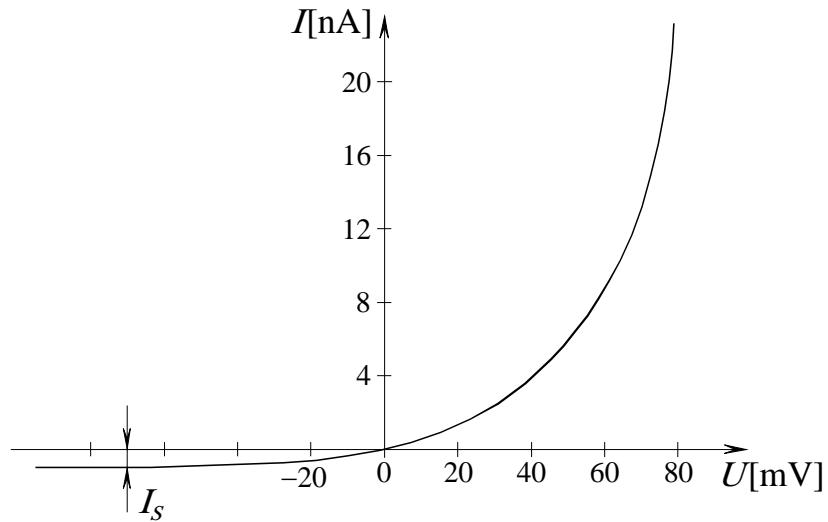
$$J = J_p(x_n) + J_n(-x_p) = \left(\frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \right) \left(e^{\frac{U}{U_T}} - 1 \right) = \underline{\underline{J_S \left(e^{\frac{U}{U_T}} - 1 \right)}}$$





Polprevodniška *pn*-dioda

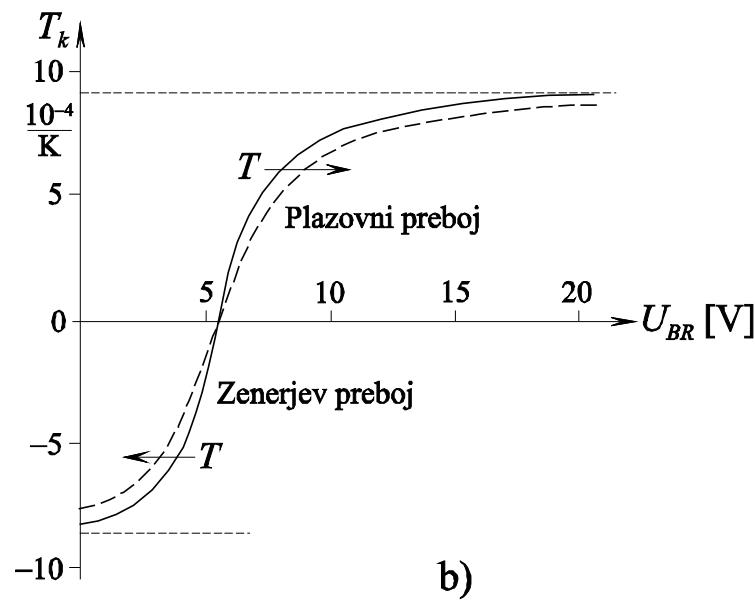
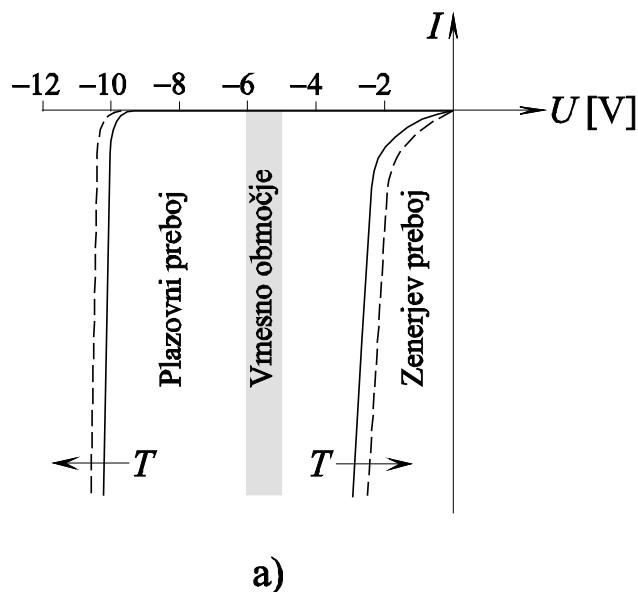
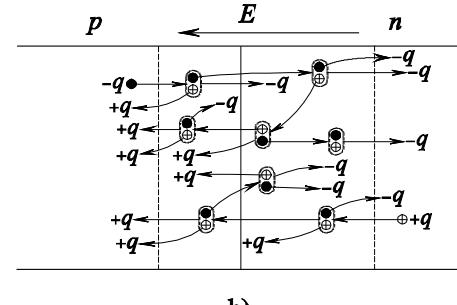
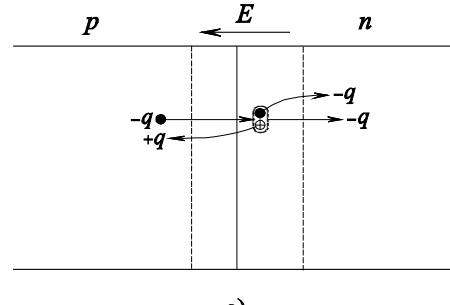
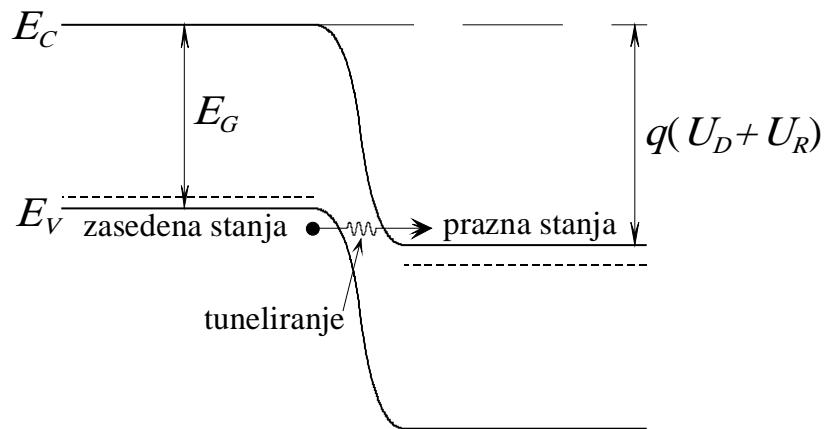
$I(U)$ karakteristika *pn*-diode, odstopanja od idealne karakteristike





Polprevodniška *pn*-dioda

Prebojna napetost diode, Zenerjev in plazovni preboj diode

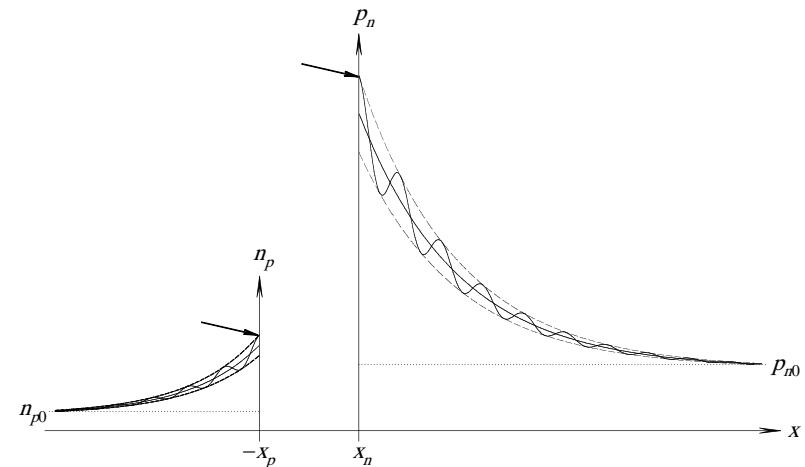
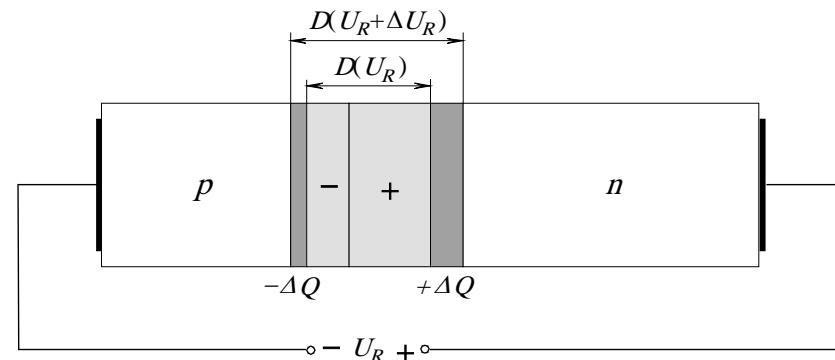
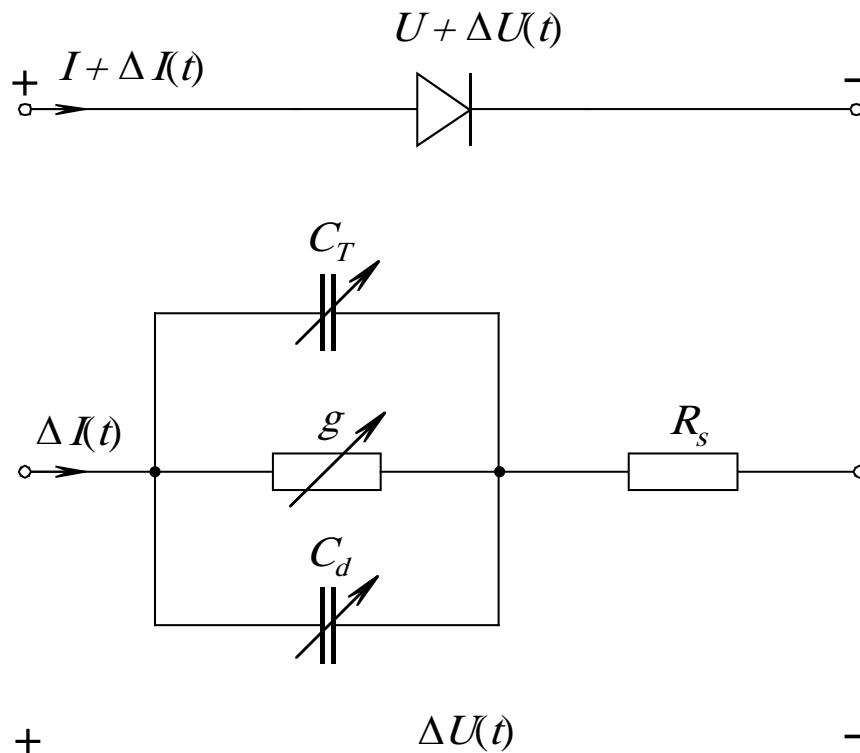




Polprevodniška *pn*-dioda

Lastnosti diode pri vzbujanju z majhnimi signali

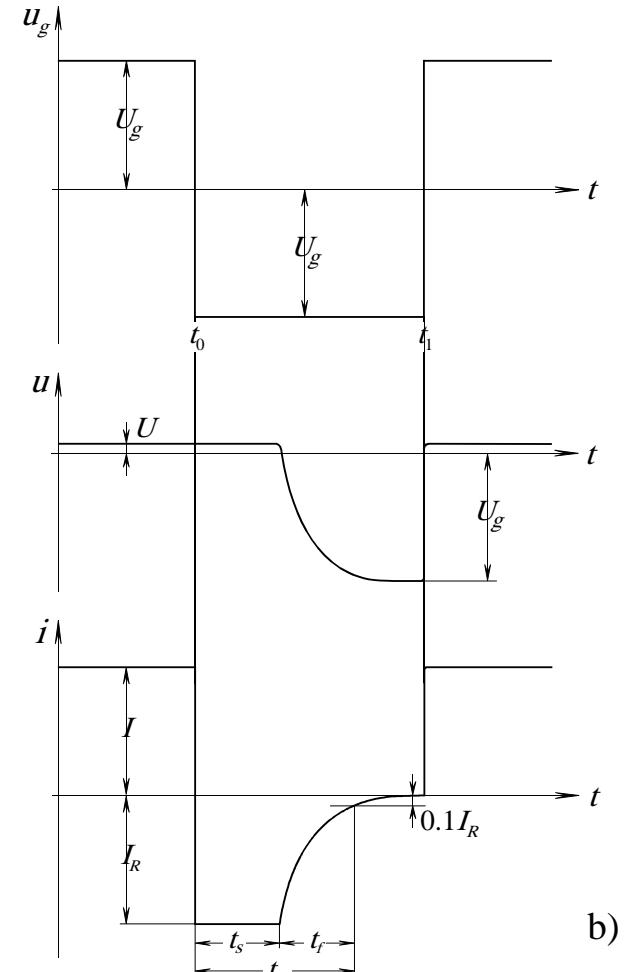
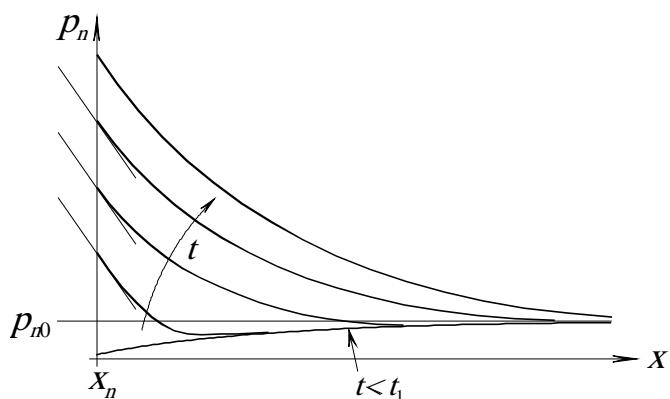
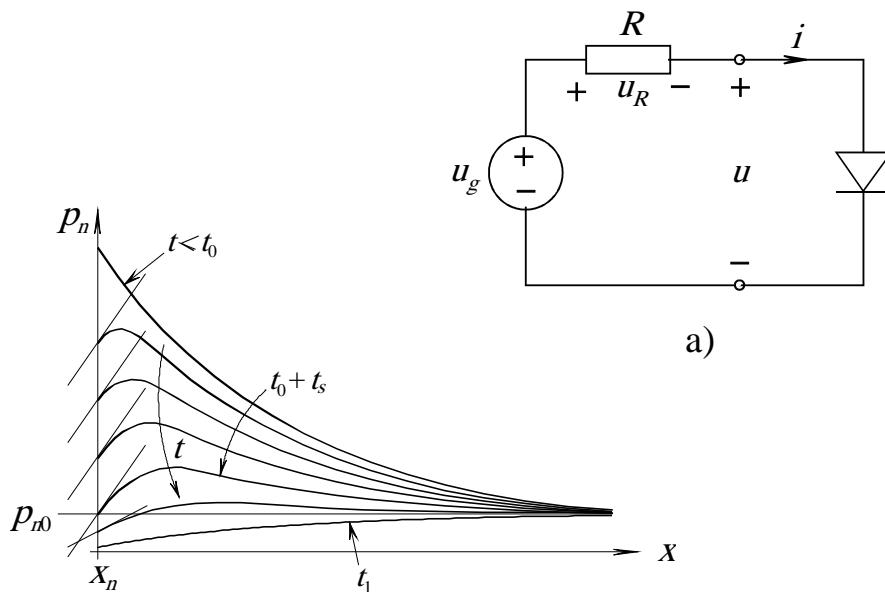
Diferencialna upornost, spojna in difuzijska kapacitivnost





Polprevodniška pn -dioda

Vzbujanje diode z velikimi pravokotnimi signali

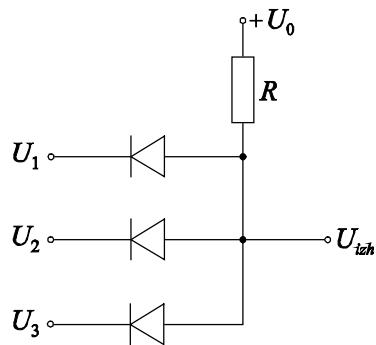


b)

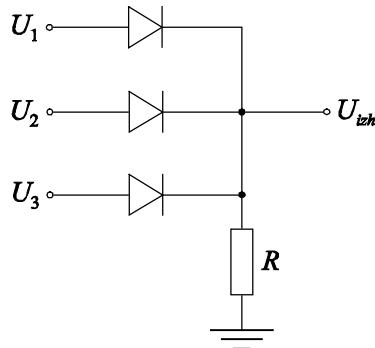


Polprevodniška *pn*-dioda

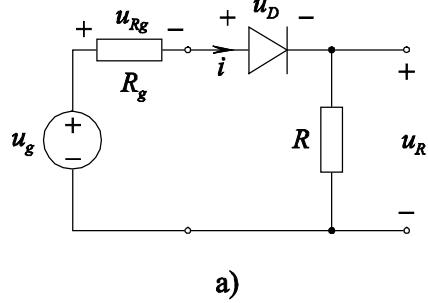
Primeri uporabe diod



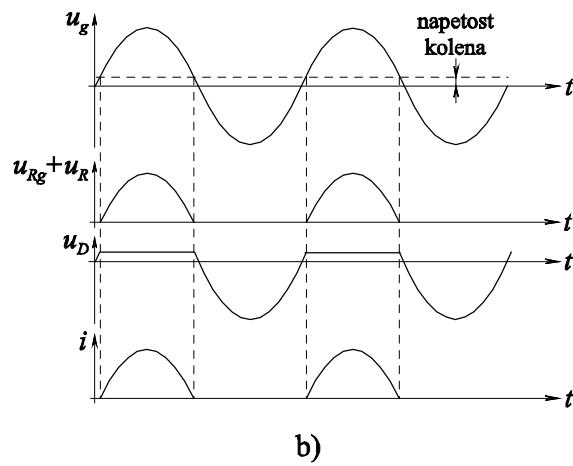
a)



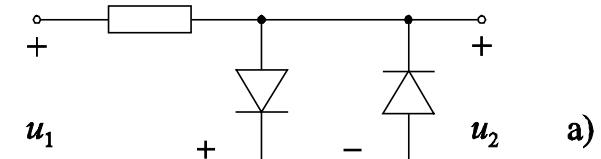
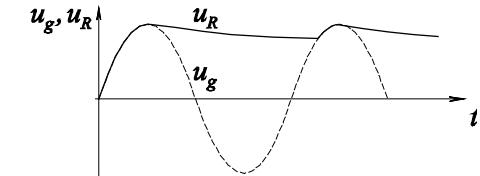
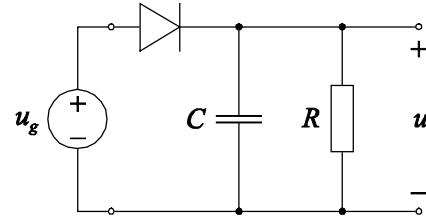
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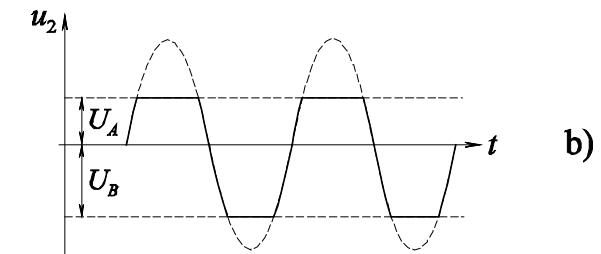
a)



b)



a)



b)



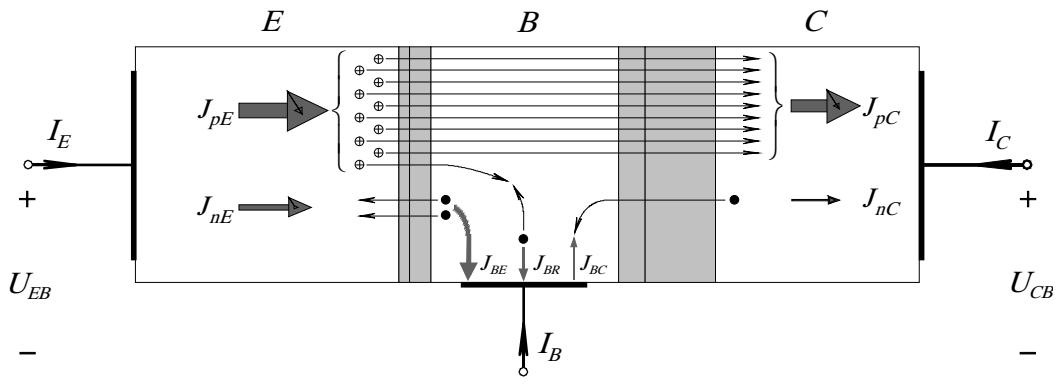
Bipolarni tranzistor

- Analiza enosmerne tokovno-napetostne karakteristike BT
- Orientacije tranzistorja
- Nelinearni Ebers-Mollov model tranzistorja
- Aktivno, inverzno aktivno območje,
območje nasičenja in zaporno območje
- Tokovna ojačevalna faktorja tranzistorja α_F in β_F
- Prebojne napetosti bipolarnega tranzistorja
- Maksimalne dopustne moči, napetosti in toki tranzistorja
- Linearna nadomestna vezja tranzistorja
- Visokofrekvenčna inkrementalna nadomestna vezja
- Tranzistor kot stikalo
- Tehnologija izdelave bipolarnih tranzistorjev
- Uporaba bipolarnega tranzistorja



Bipolarni tranzistor

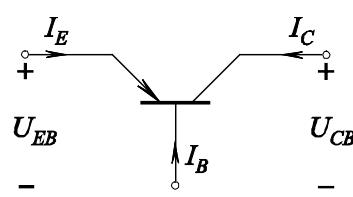
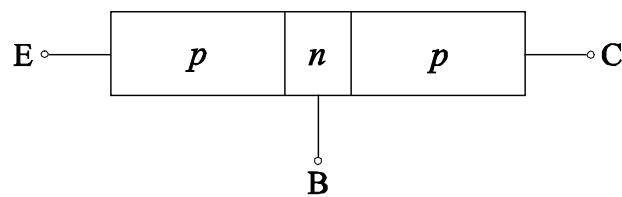
Analiza enosmerne tokovno-napetostne karakteristike



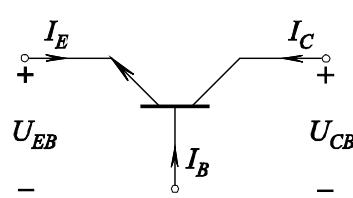
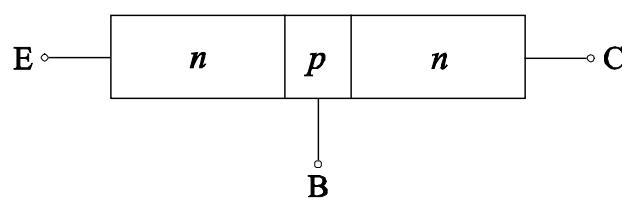
$$I_E = A(J_{pE} + J_{nE}) = I_{11}(e^{\frac{U_{EB}}{U_T}} - 1) + I_{12}(e^{\frac{U_{CB}}{U_T}} - 1)$$

$$I_C = -A(J_{pC} + J_{nC}) = I_{21}(e^{\frac{U_{CB}}{U_T}} - 1) + I_{22}(e^{\frac{U_{EB}}{U_T}} - 1)$$

$$I_{11} = A q \left(\frac{D_p}{L_p} \frac{p_{B0}}{\text{th} \frac{W}{L_p}} + \frac{D_n}{L_n} \frac{n_{E0}}{L_n} \right)$$



$$I_{12} = I_{21} = -A q \frac{D_p}{L_p} \frac{p_{B0}}{\text{sh} \frac{W}{L_p}}$$



$$I_{22} = A q \left(\frac{D_p}{L_p} \frac{p_{B0}}{\text{th} \frac{W}{L_p}} + \frac{D_n}{L_n} \frac{n_{C0}}{L_n} \right)$$

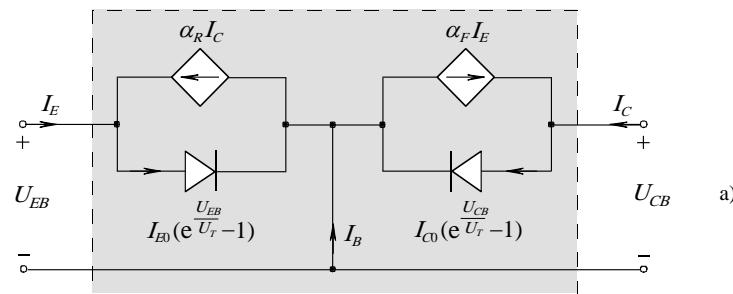
a)

b)

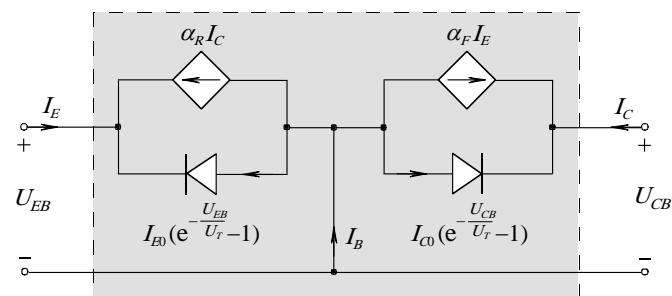


Bipolarni tranzistor

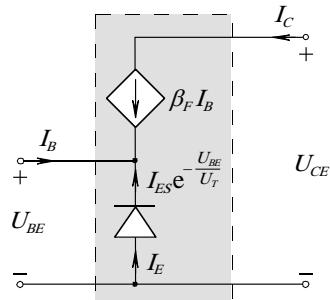
Nelinearni Ebers-Mollov model tranzistorja



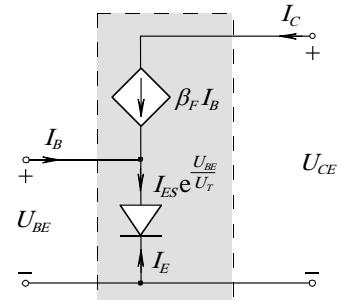
a)



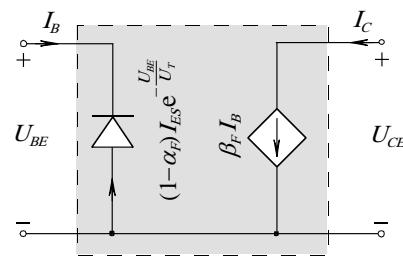
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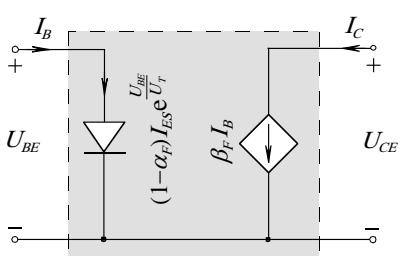
a)



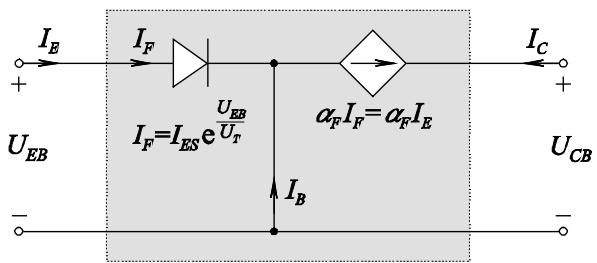
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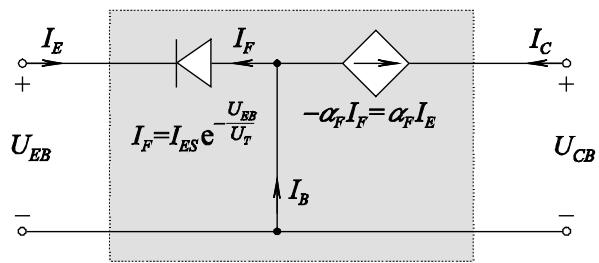
c)



d)



a)

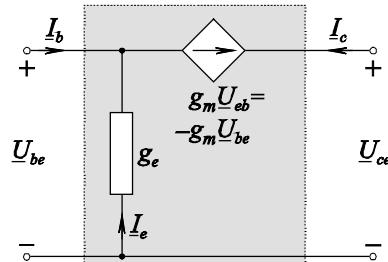


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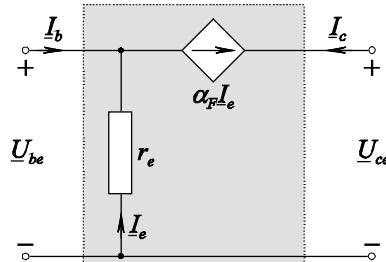


Bipolarni tranzistor

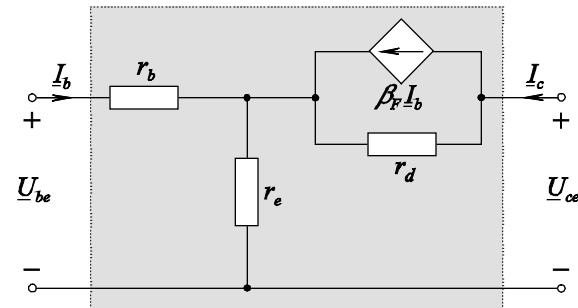
Linearna nadomestna vezja tranzistorja



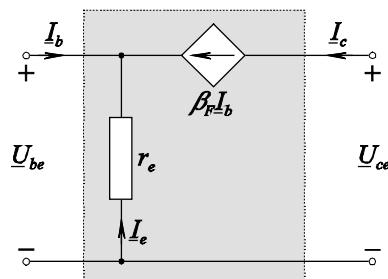
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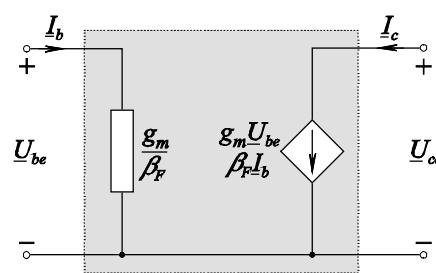
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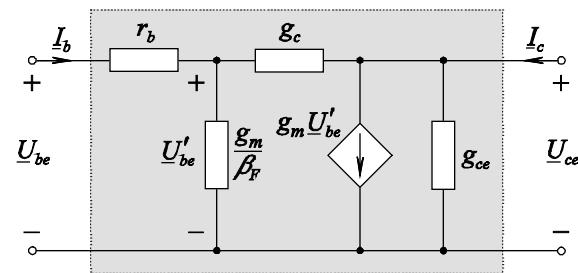
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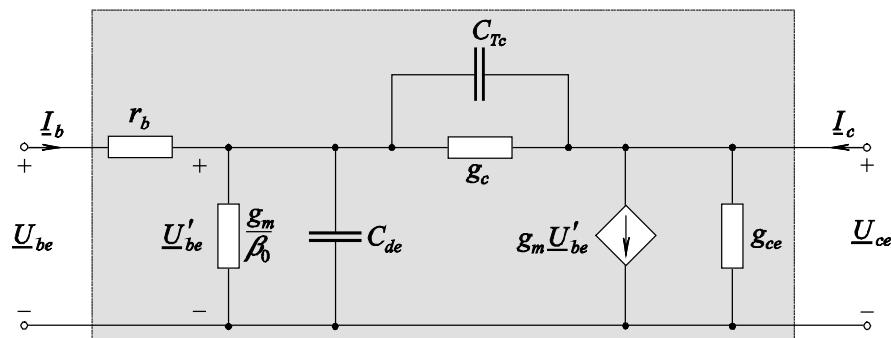
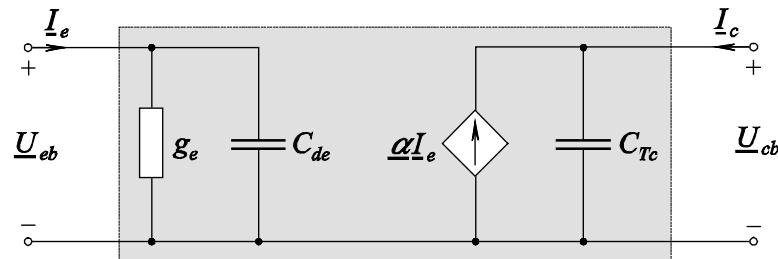
c)



d)



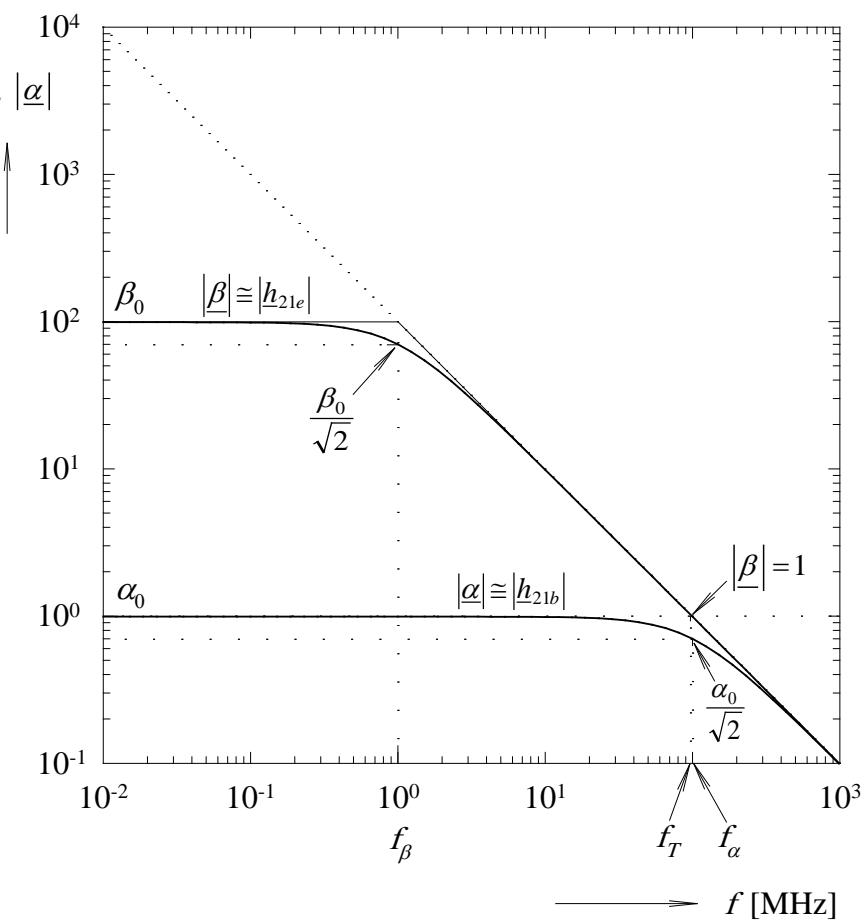
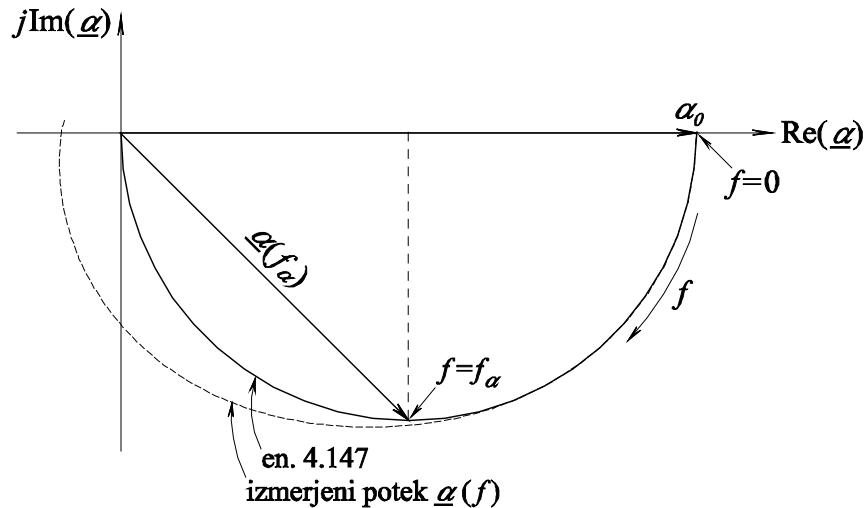
b)





Bipolarni tranzistor

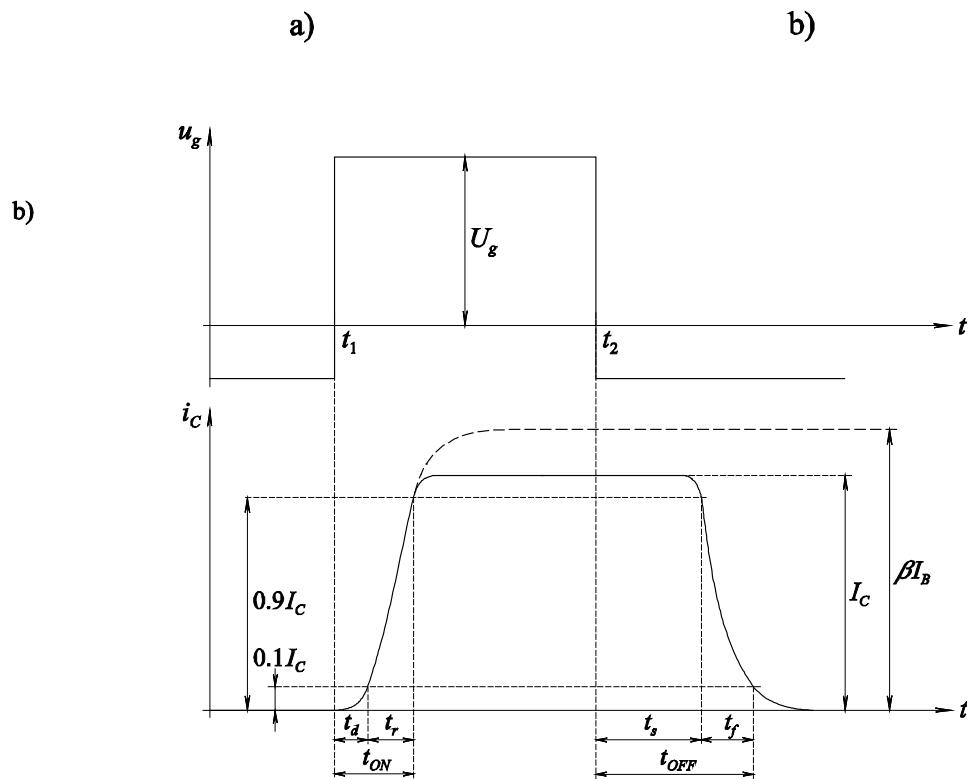
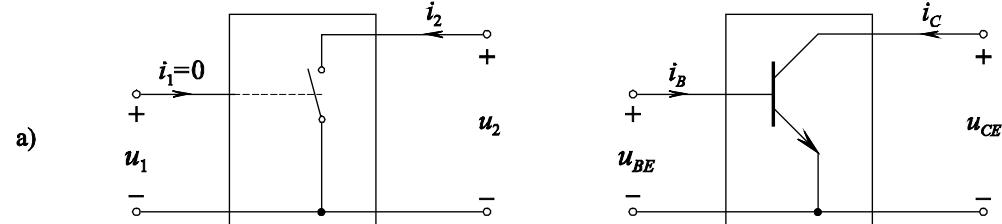
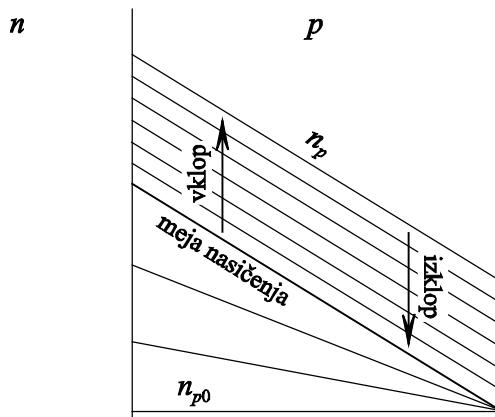
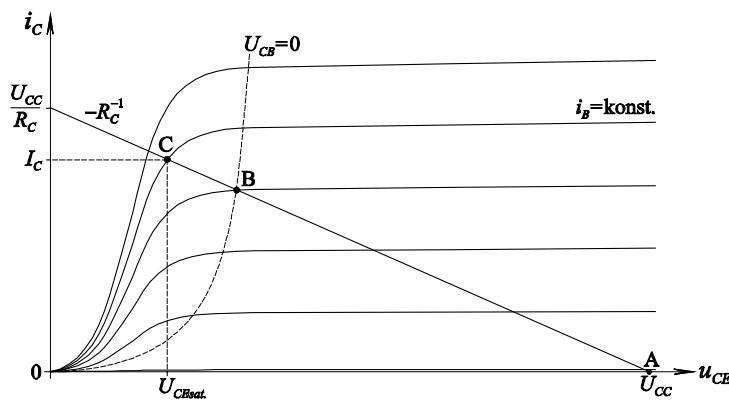
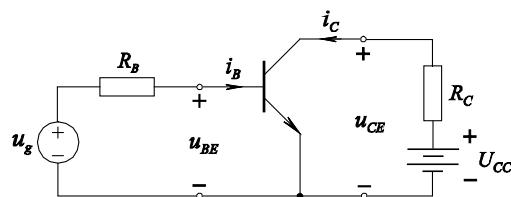
Visokofrekvenčne lastnosti tranzistorja

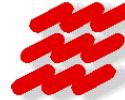




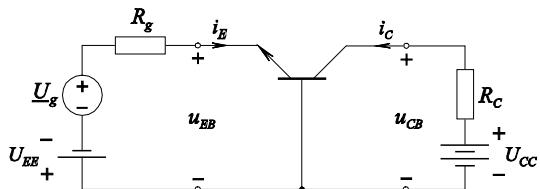
Bipolarni tranzistor

Tranzistor kot stikalo

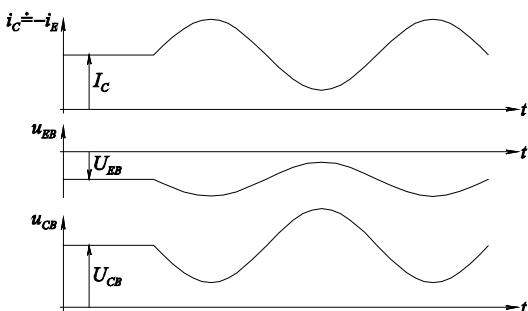




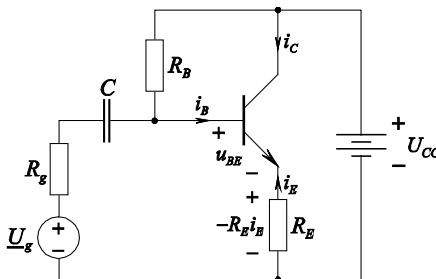
Uporaba bipolarnega tranzistorja



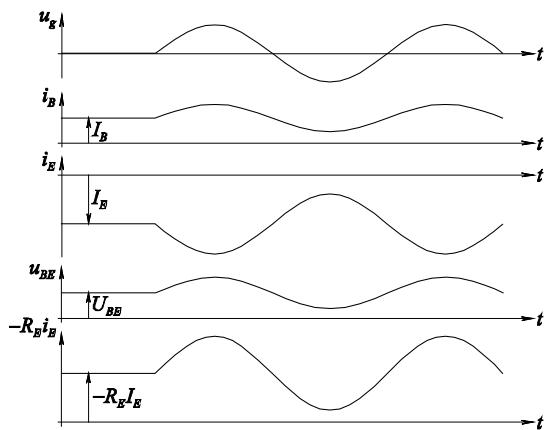
a)



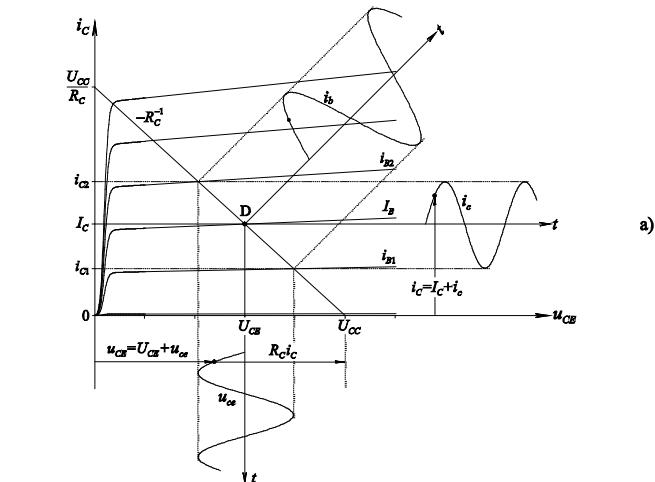
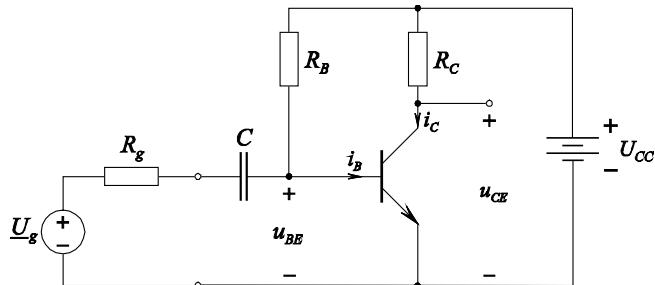
b)



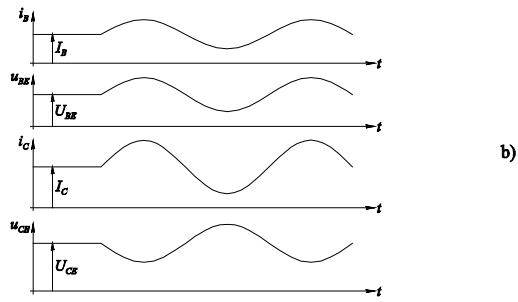
a)



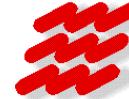
b)



a)



b)



Unipolarni tranzistor

Spojni FET (JFET)

- Napetost zadrgnitve in napetost nasičenja
- Tokovno-napetostna karakteristika JFET-a
- Nadomestno vezje JFET-a pri majhnih signalih

MOS transistor

- MOS tranzistor z induciranim (z bogatenim) kanalom
- MOS tranzistor z vgrajenim (s siromašenim) kanalom
- Analiza statične karakteristike MOS tranzistorja
- Četveropolni parametri in nadomestna vezja
- Orientacije unipolarnega tranzistorja
- Unipolarni tranzistor kot stikalo
- Tehnologija izdelave unipolarnega tranzistorja
- Uporaba unipolarnega tranzistorja

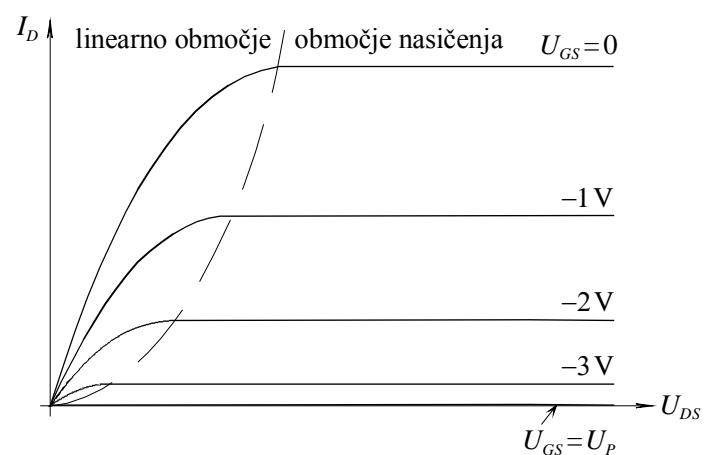
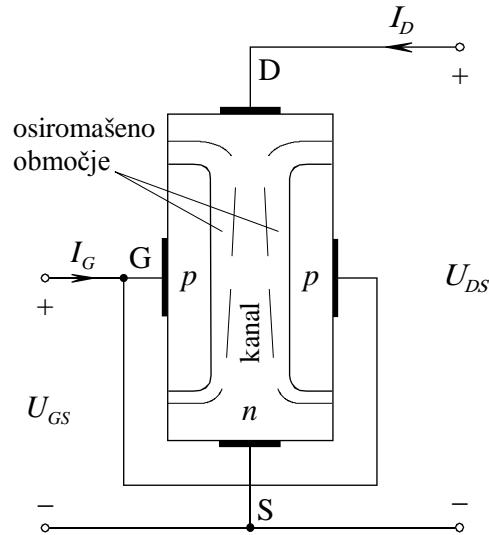


Unipolarni tranzistor

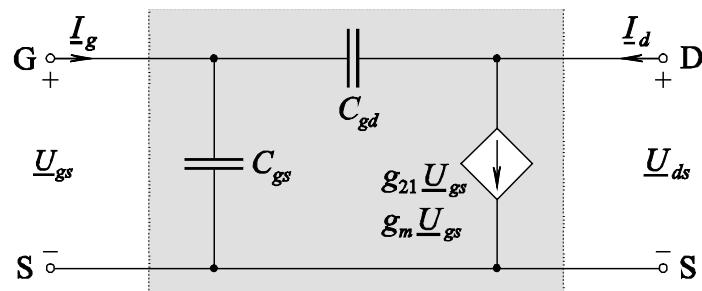
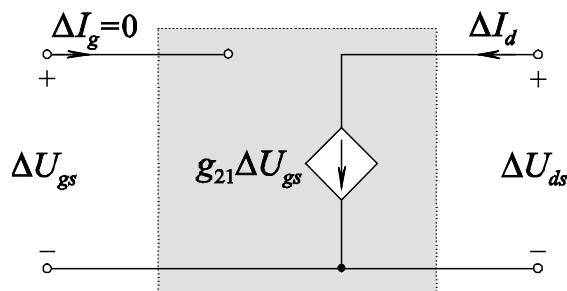
Spojni FET

Napetost zadrgnitve in napetost nasičenja

Tokovno-napetostna karakteristika spojnega FET-a



Nadomestno vezje unipolarnega tranzistorja pri majhnih signalih





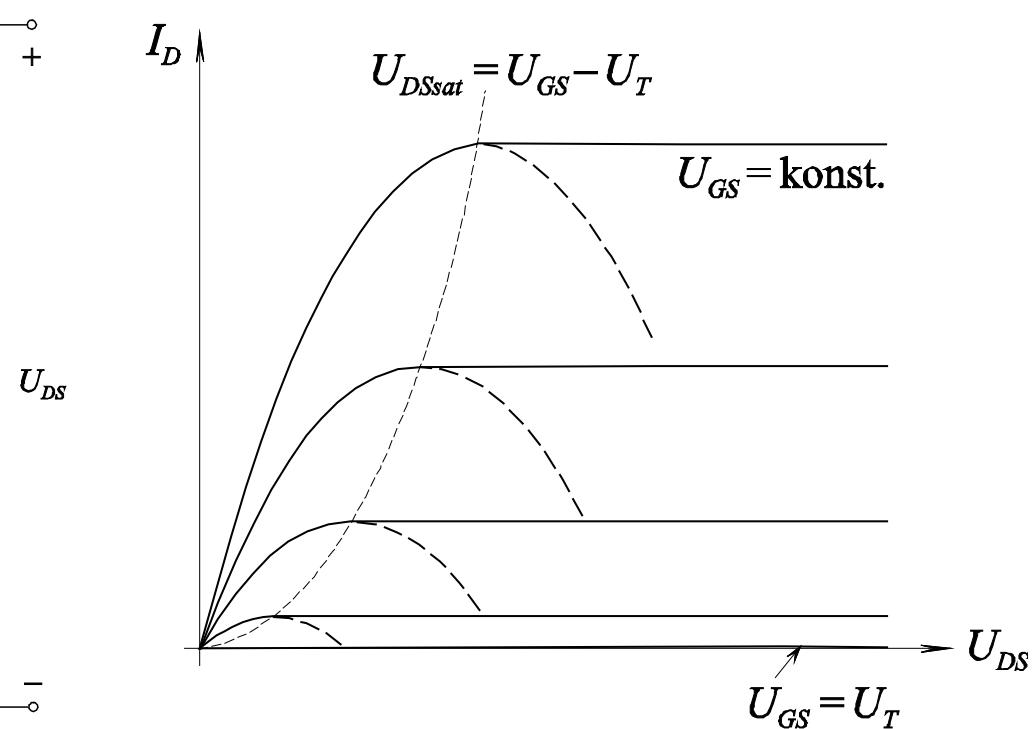
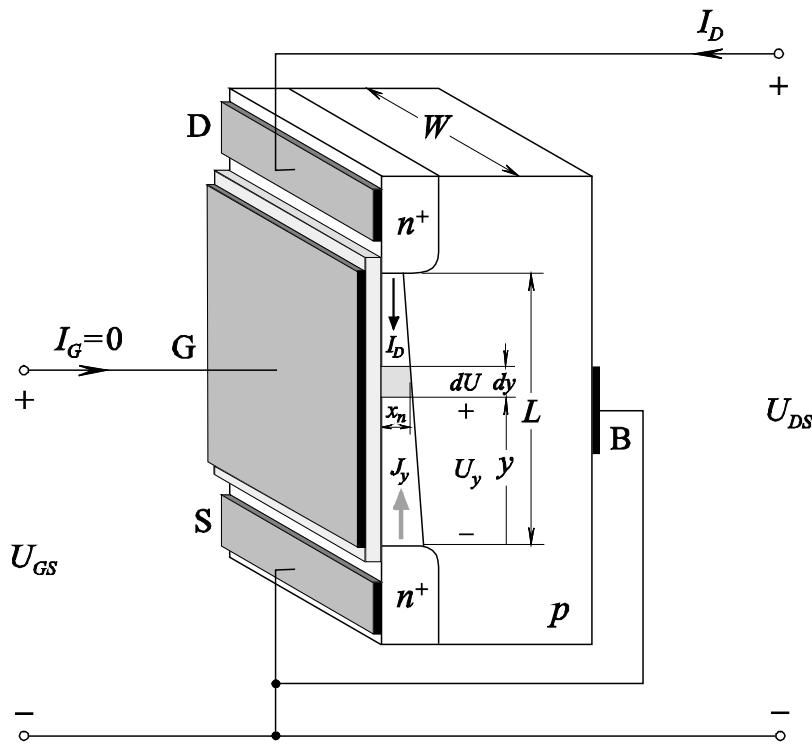
Unipolarni tranzistor

MOS tranzistor

MOS tranzistor z induciranim (z bogat enim) kanalom

MOS tranzistor z vgrajenim (s siromašenim) kanalom

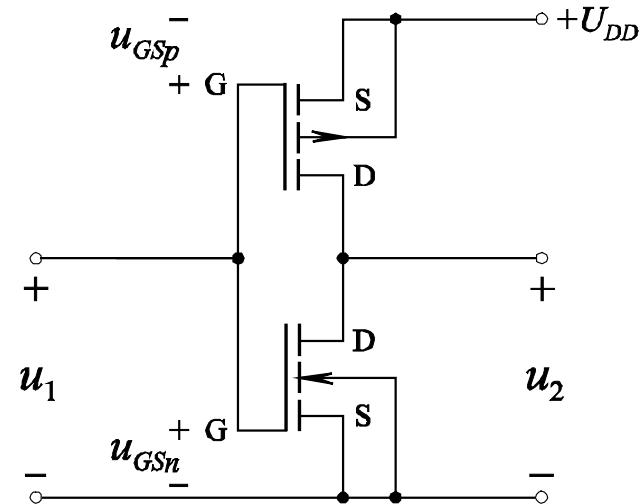
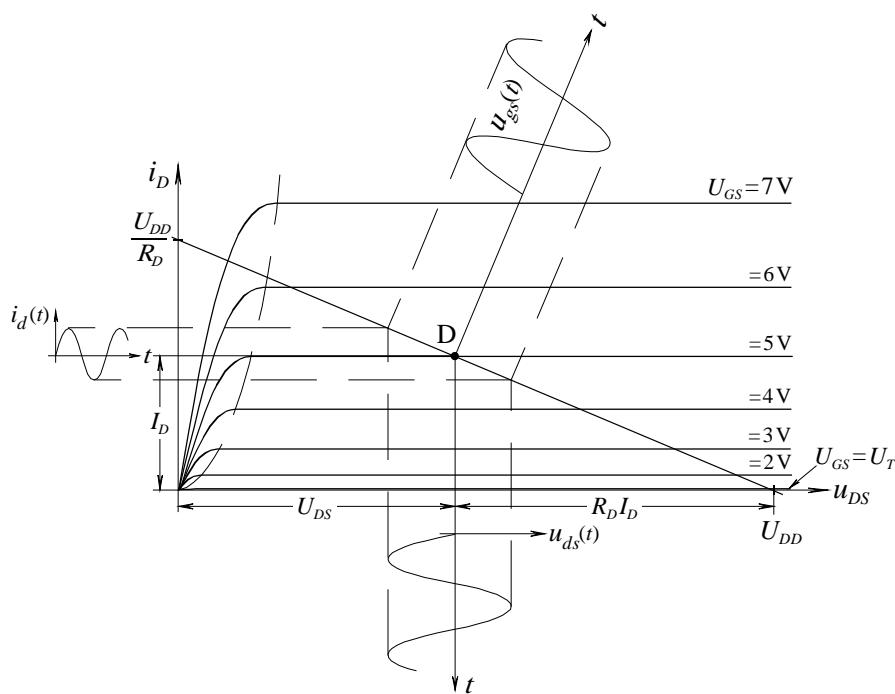
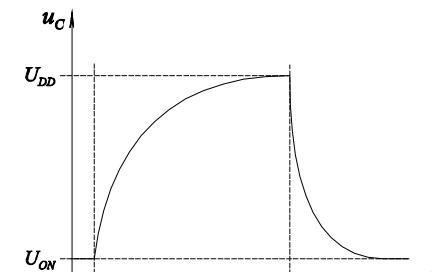
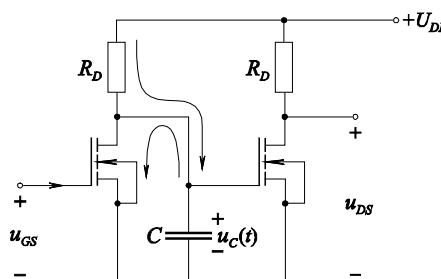
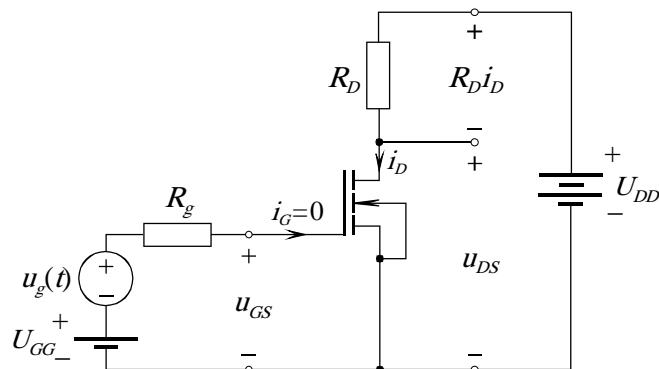
Analiza statične karakteristike MOS tranzistorja

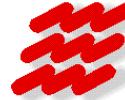




Unipolarni tranzistor

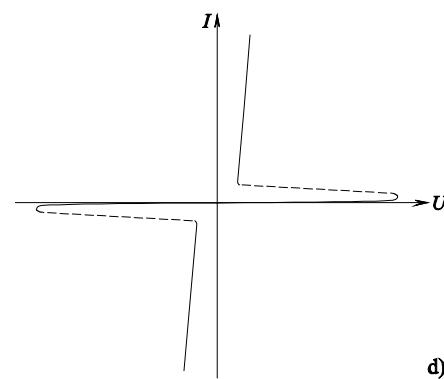
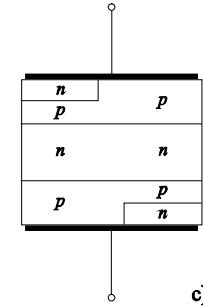
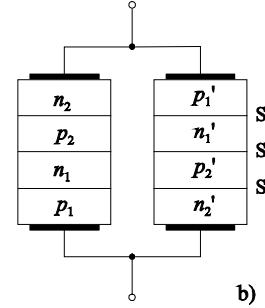
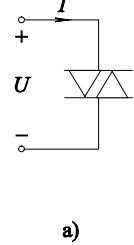
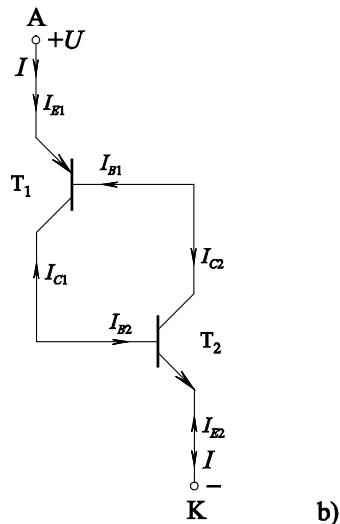
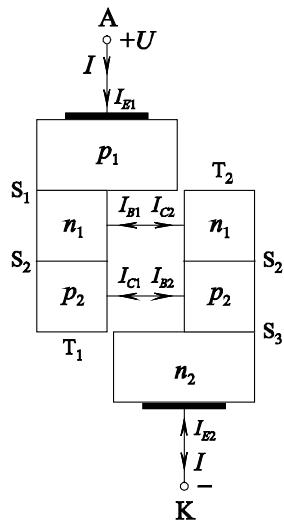
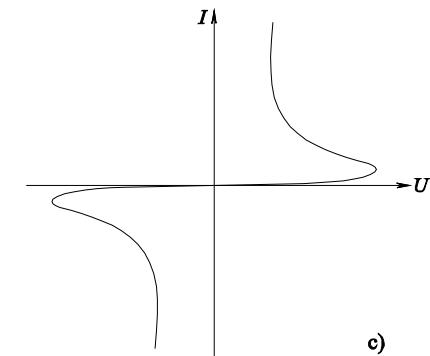
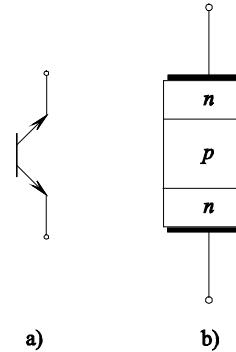
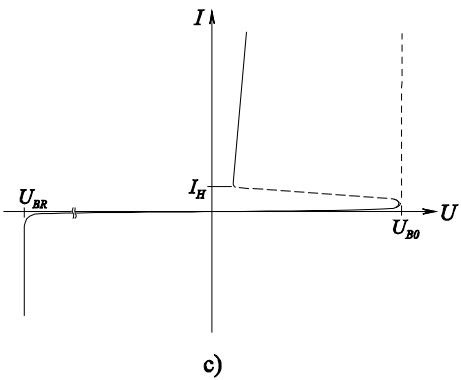
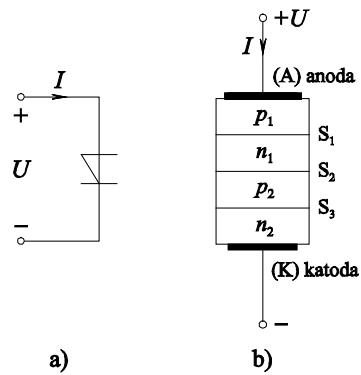
Uporaba MOS tranzistorja



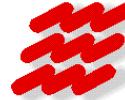


Močnostni polprevodniški elementi

pnpn-dioda, diak

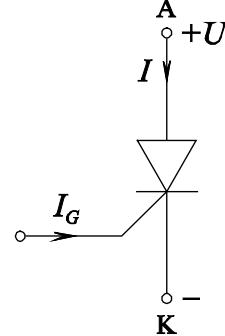


d)

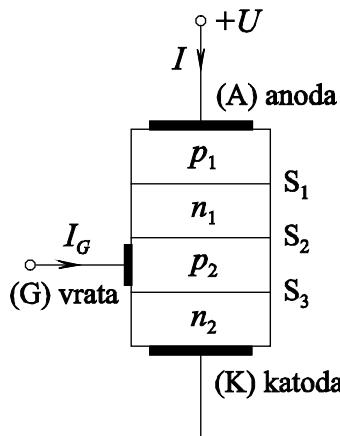


Močnostni polprevodniški elementi

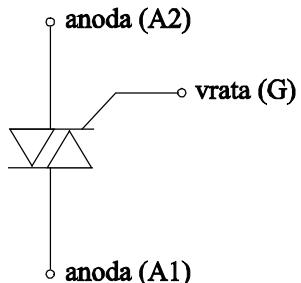
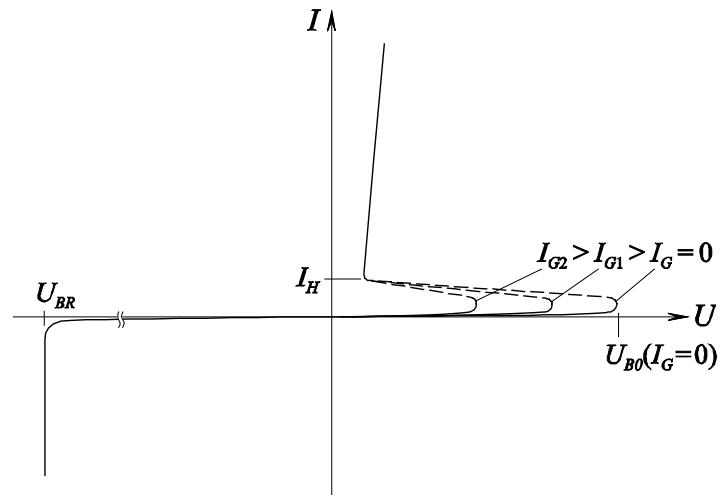
tiristor, triak



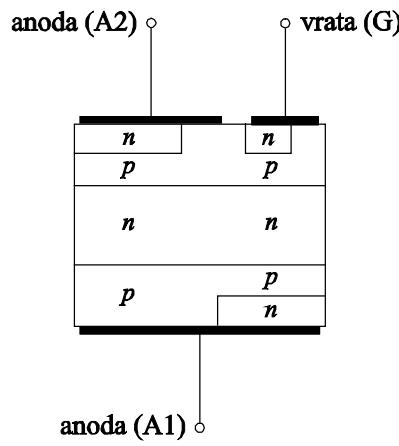
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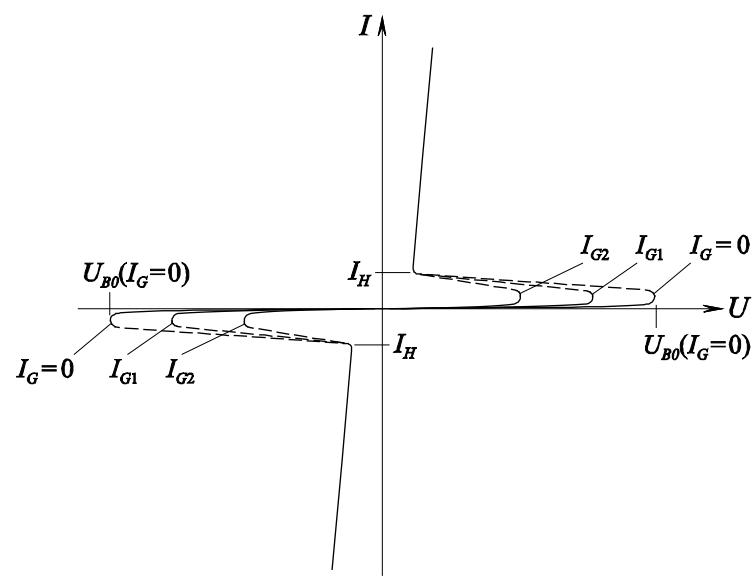
b)

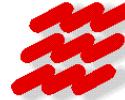


a)



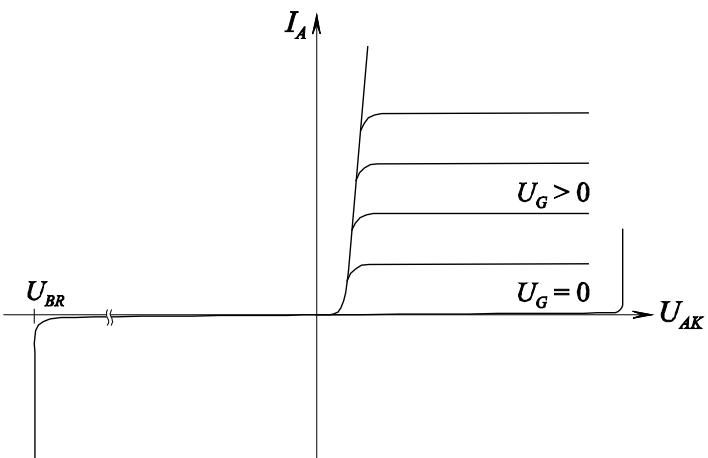
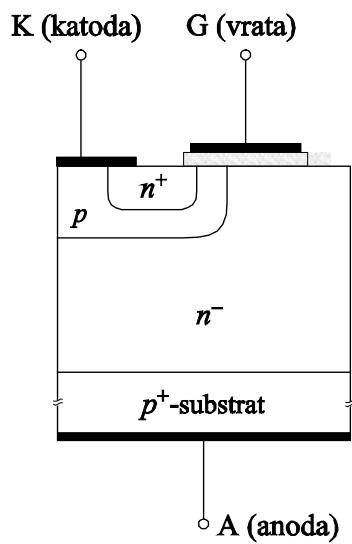
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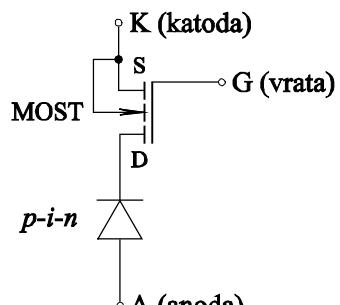
Močnostni polprevodniški elementi

IGBT

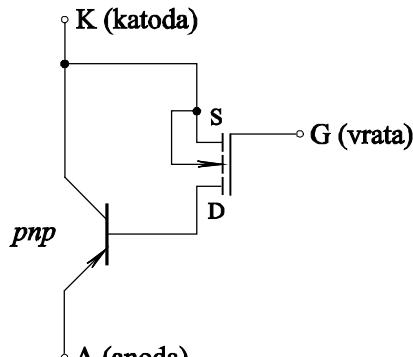


a)

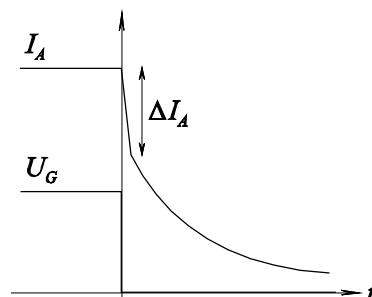
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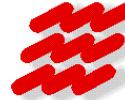
a)



b)

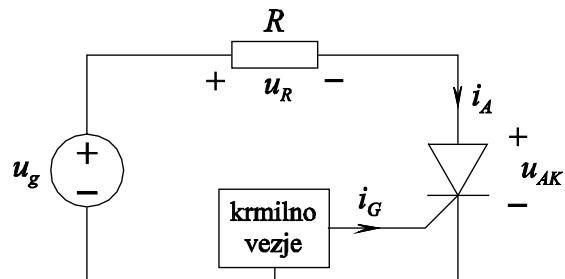


c)

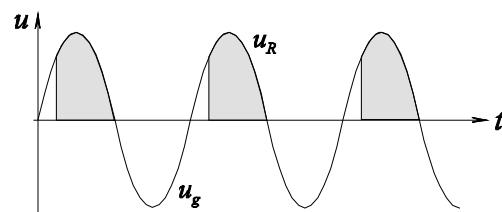


Močnostni polprevodniški elementi

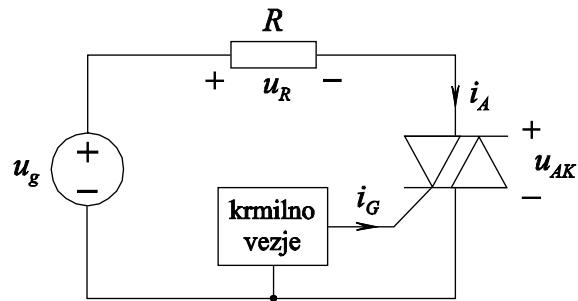
Uporaba močnostnih elementov



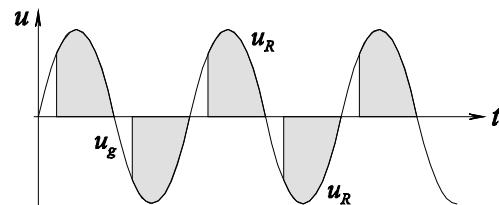
a)



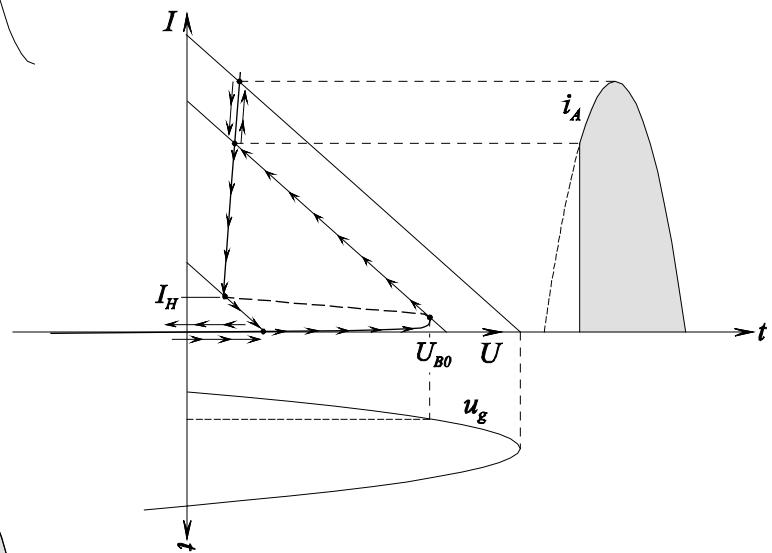
b)



a)



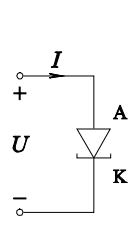
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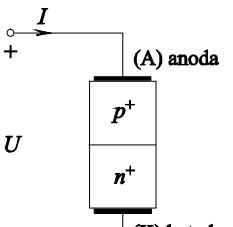


Nekateri drugi polprevodniški elementi

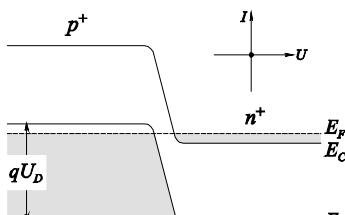
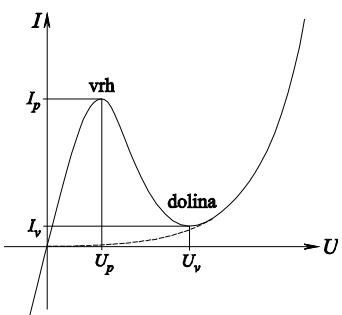
Tunelska dioda, Schottkyjeva dioda



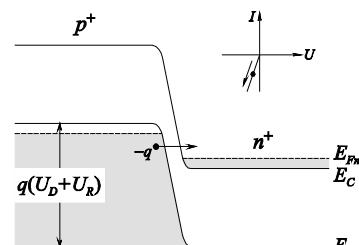
a)



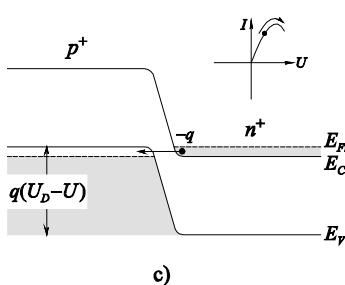
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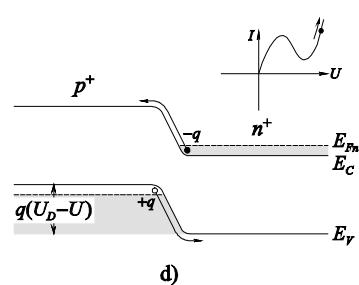
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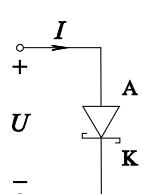
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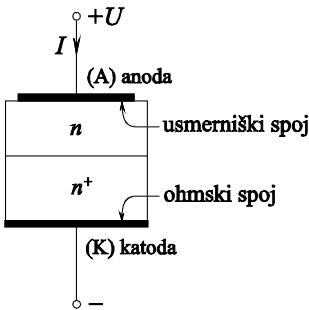
c)



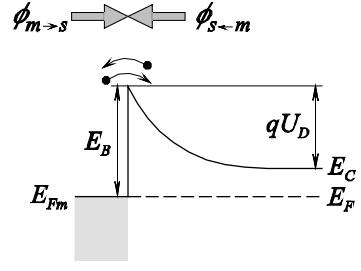
d)



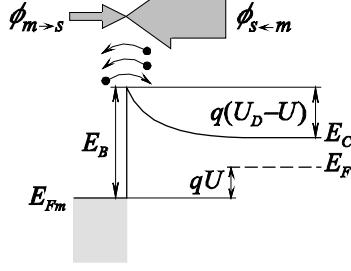
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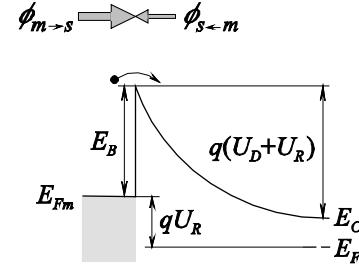
b)



a)



b)



c)



Fotonski elementi

- Spekter elektromagnetnega sevanja
- Absorpcija svetlobe v polprevodniku

Svetleče diode (LED)

- Zgradba, lastnosti in uporaba svetlečih diod

Polprevodniški laserji

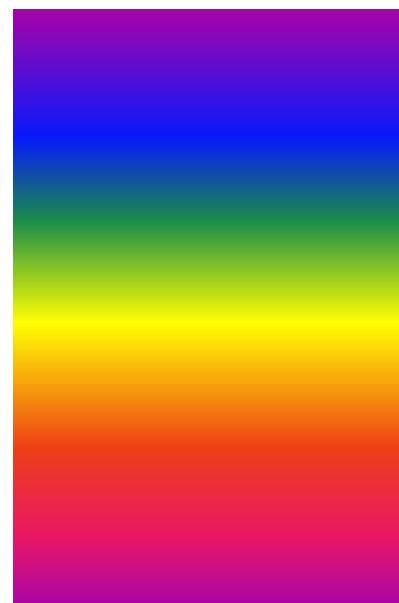
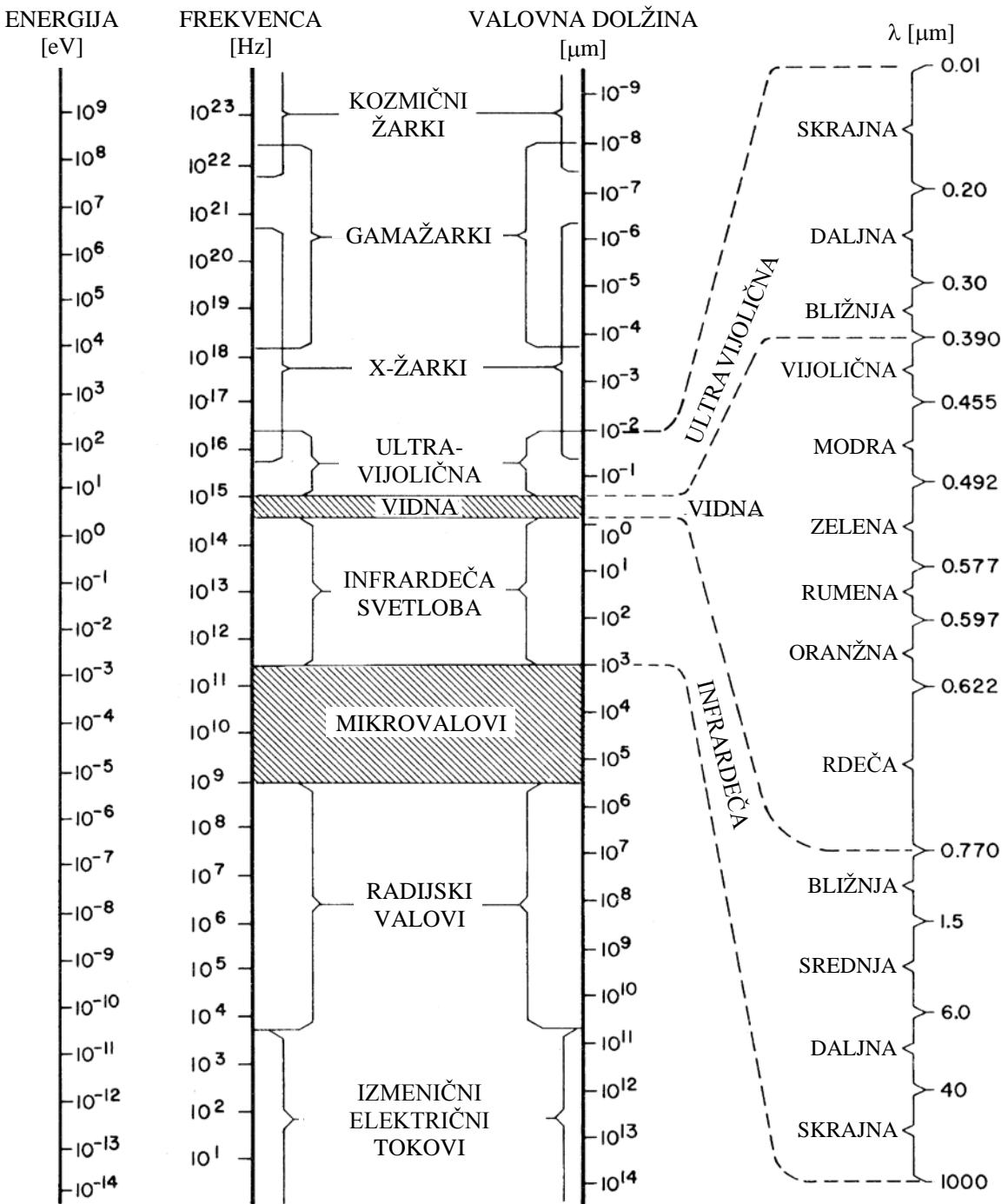
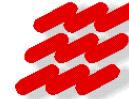
- Spontana in stimulirana emisija
- Laser z dvojno heterospojno strukturo
- Pravovna tokova gostota in spektralna porazdelitev
- Modulacijske lastnosti in primeri uporabe

Fotodetektorji

- fotoupor, fotodioda, fototranzistor

Sončne celice

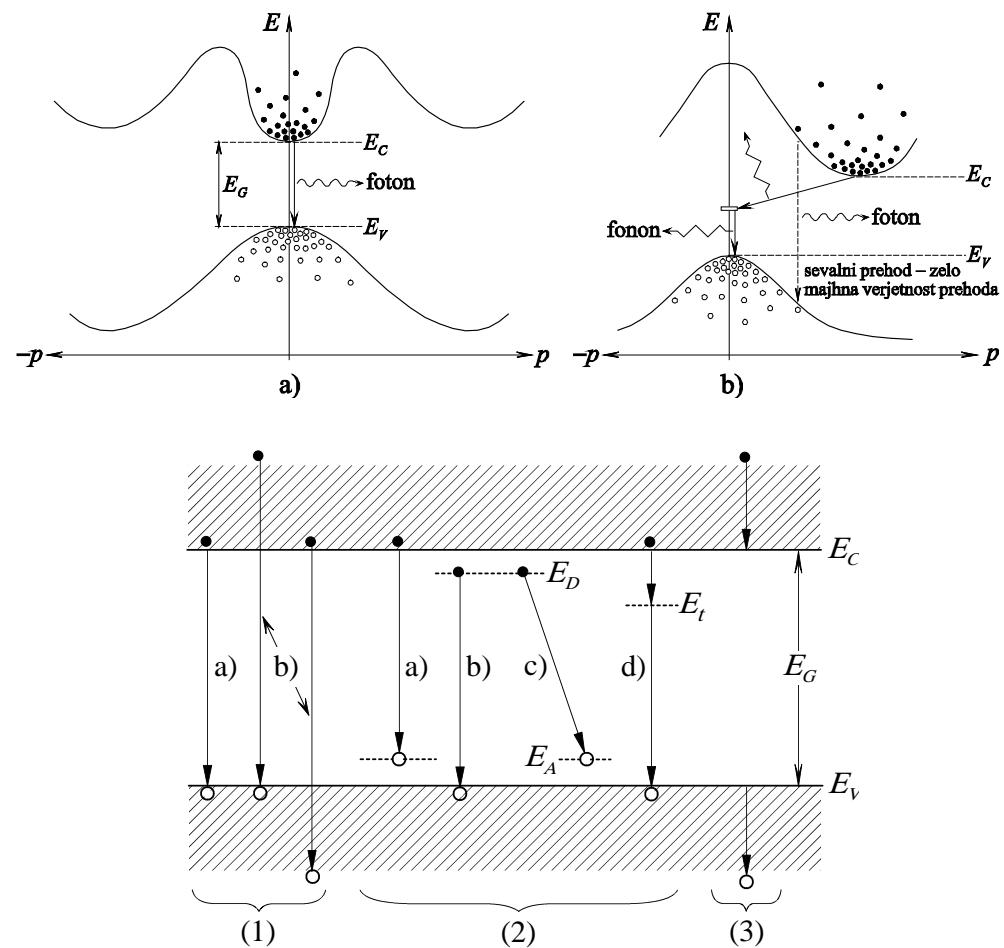
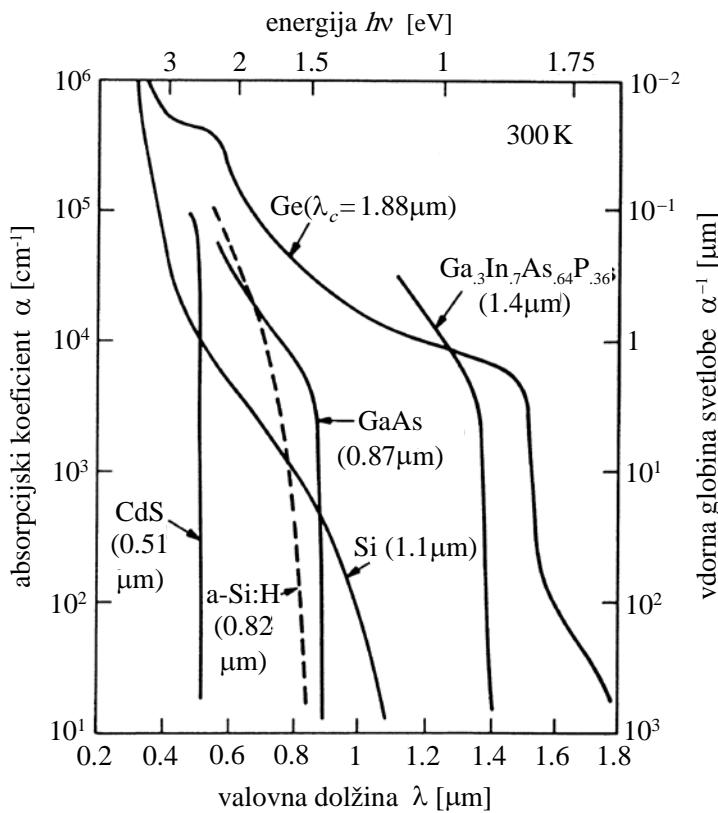
- Osnovni principi delovanja, izhodni parametri





Fotonski elementi

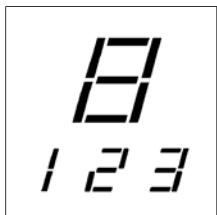
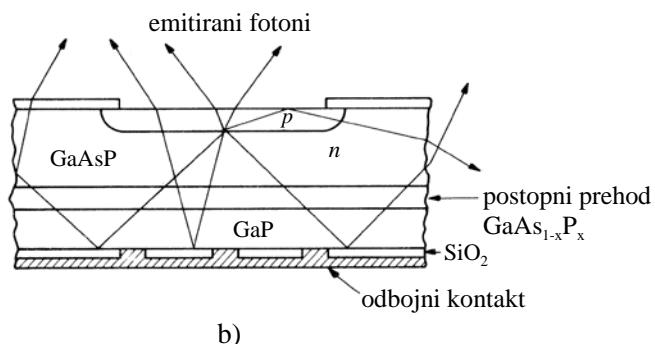
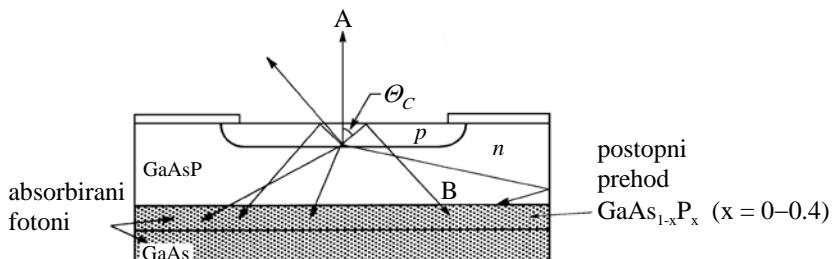
Absorpcija svetlobe v polprevodniku
Sevalni in nesevalni rekombinacijski prehodi



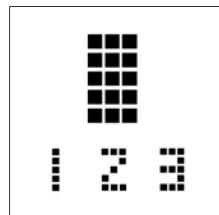


Fotonski elementi

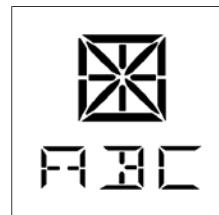
Svetleče diode (LED)



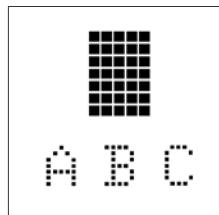
a)



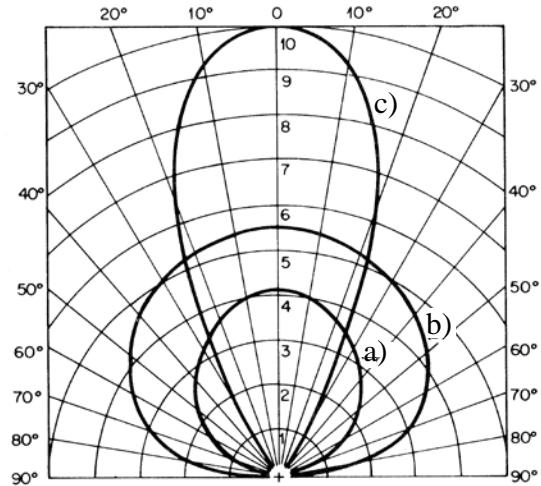
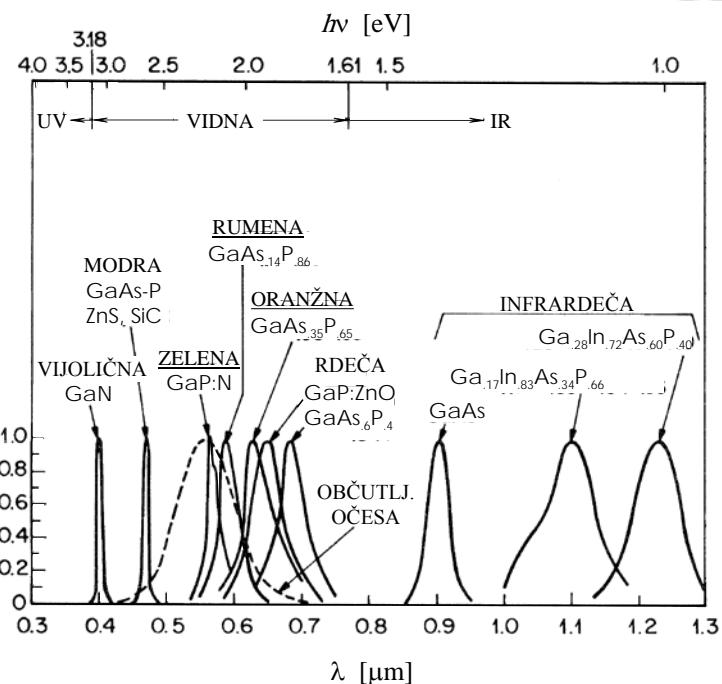
b)



c)



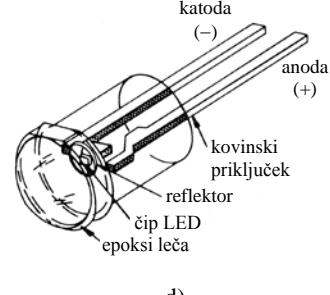
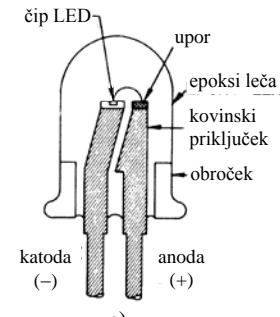
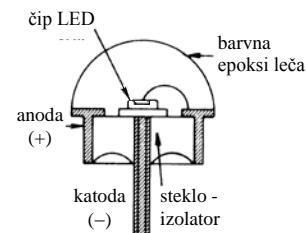
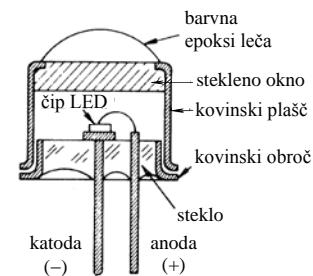
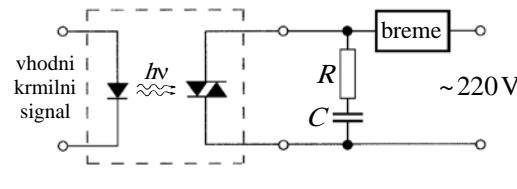
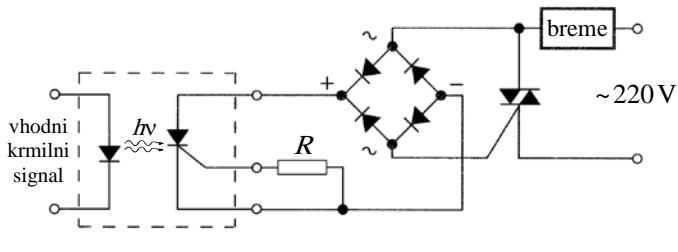
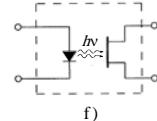
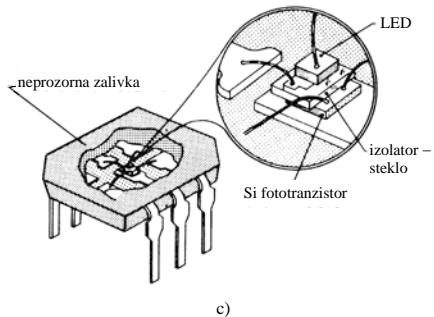
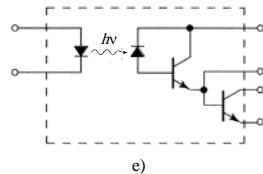
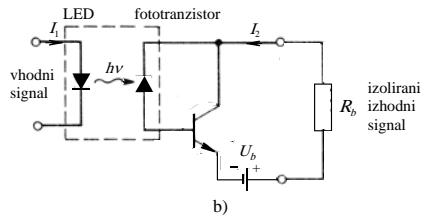
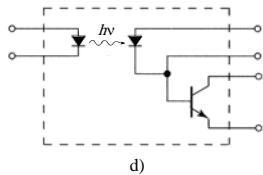
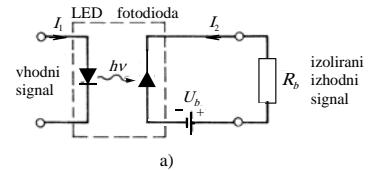
d)

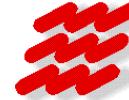




Fotonski elementi

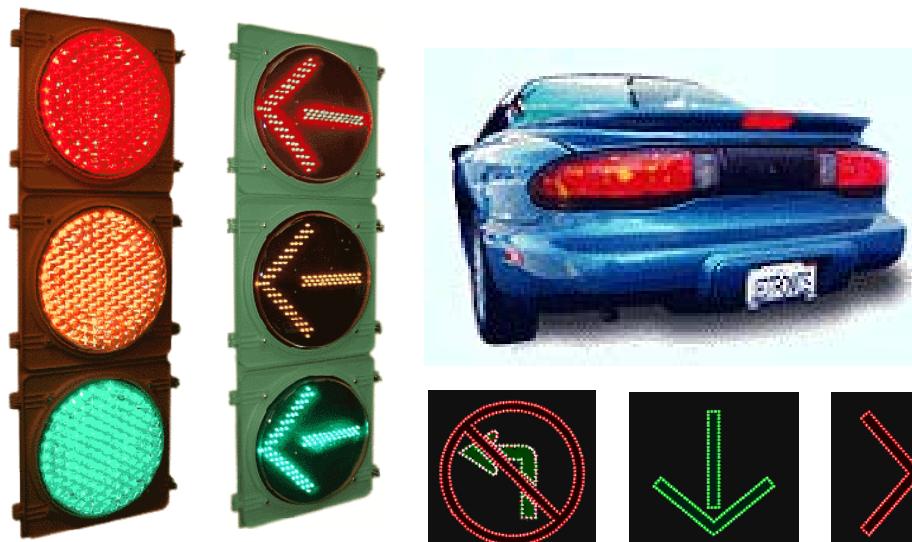
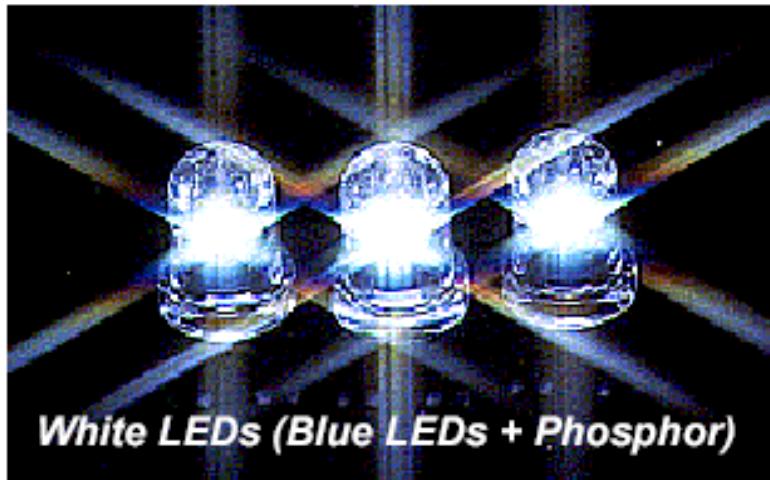
Uporaba LED





Fotonski elementi

Uporaba LED



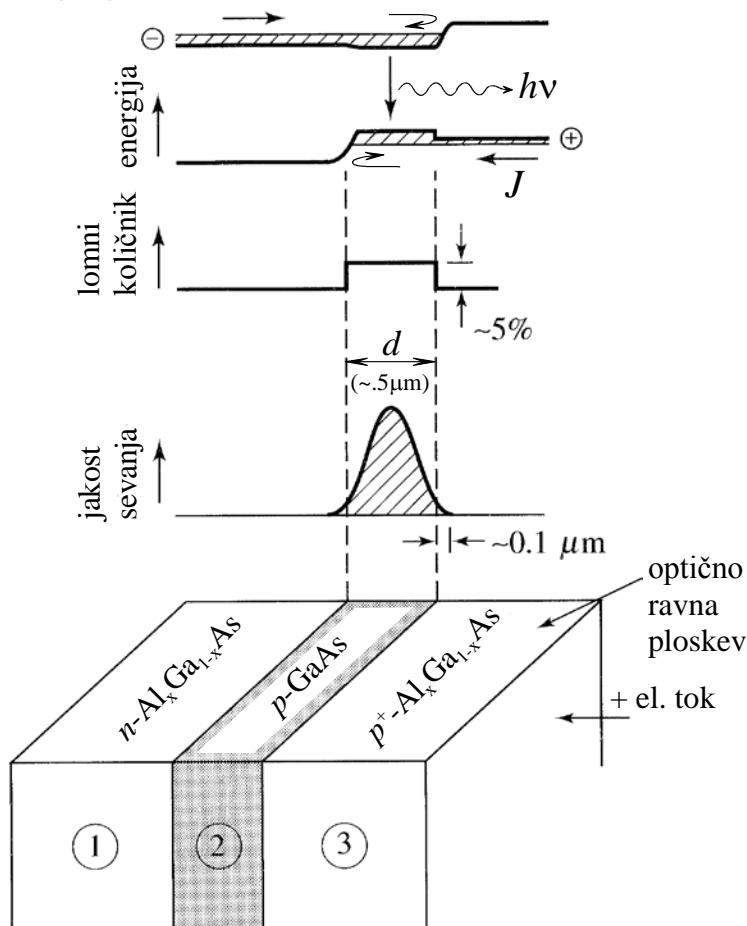
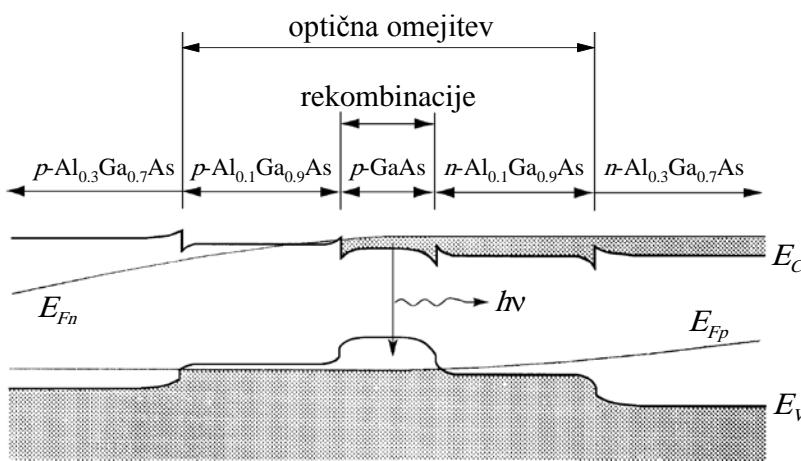
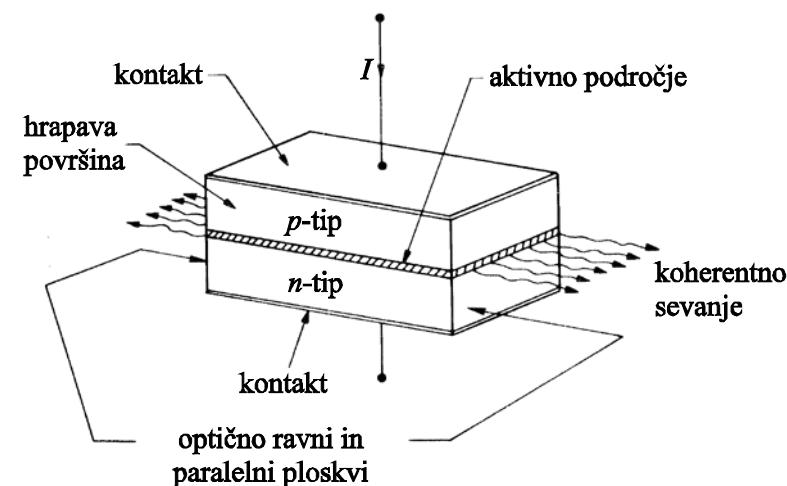


Fotonski elementi

Polprevodniški laserji

Spontana in stimulirana emisija

Laser z dvojno heterospojno strukturo

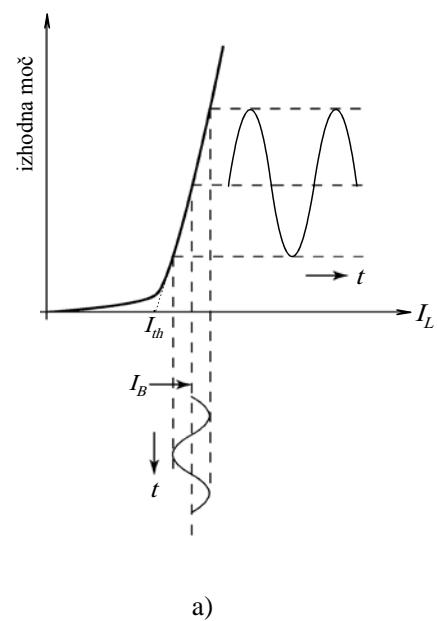
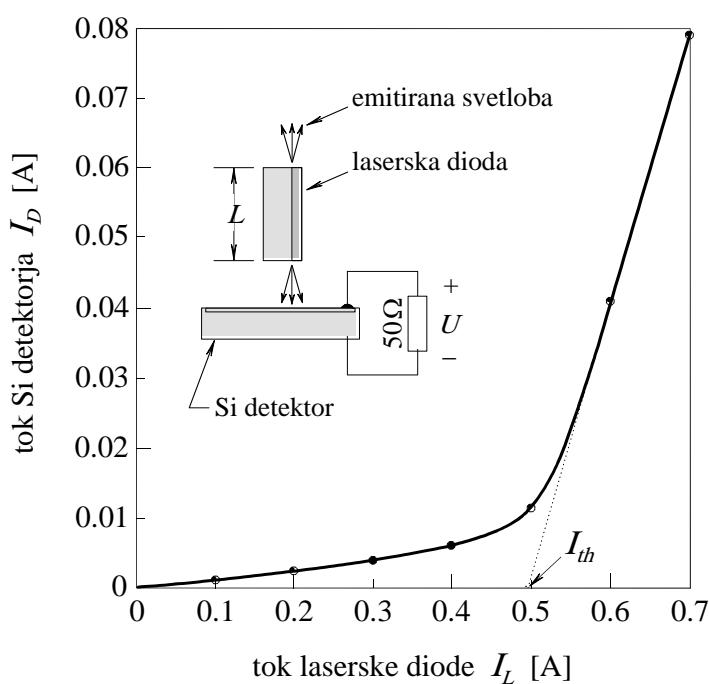




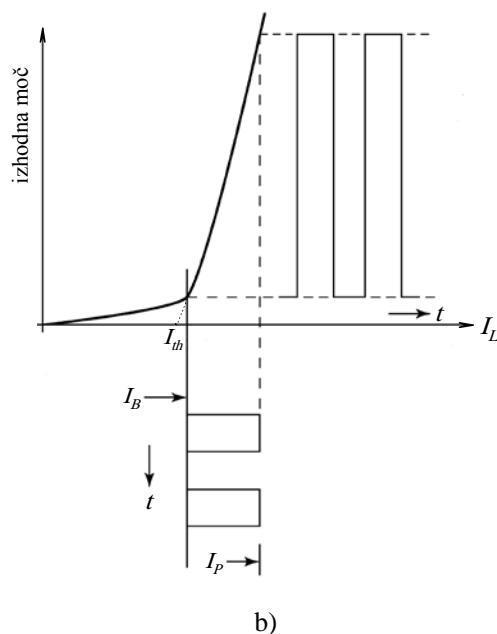
Fotonski elementi

Polprevodniški laserji

Pragovna tokova gostota in spektralna porazdelitev
Modulacijske lastnosti in primeri uporabe



a)



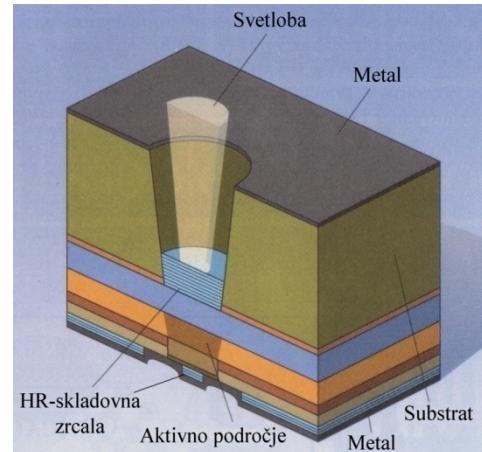
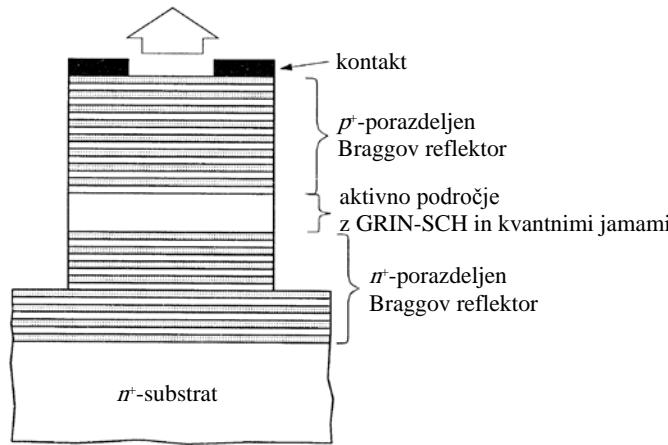
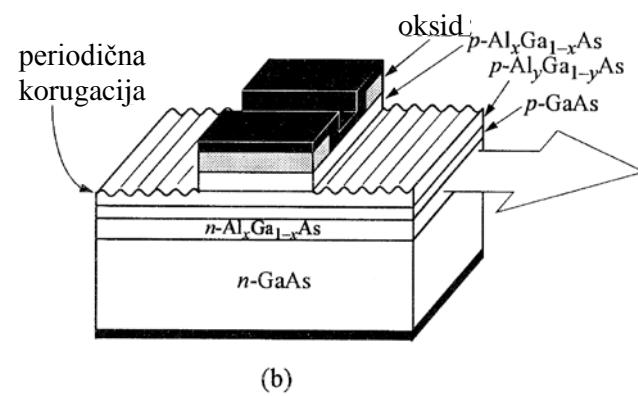
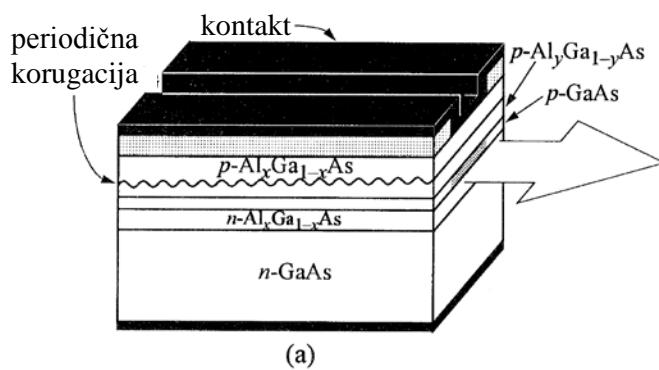
b)

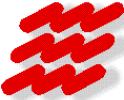


Fotonski elementi

Polprevodniški laserji

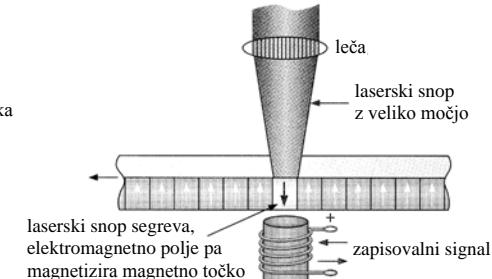
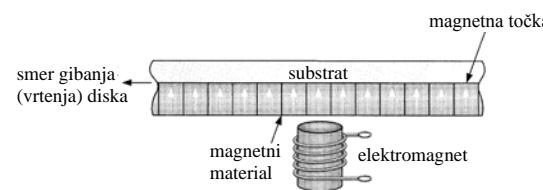
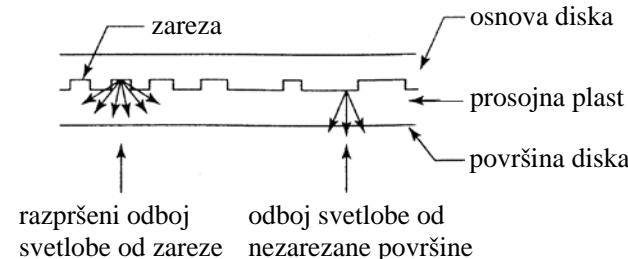
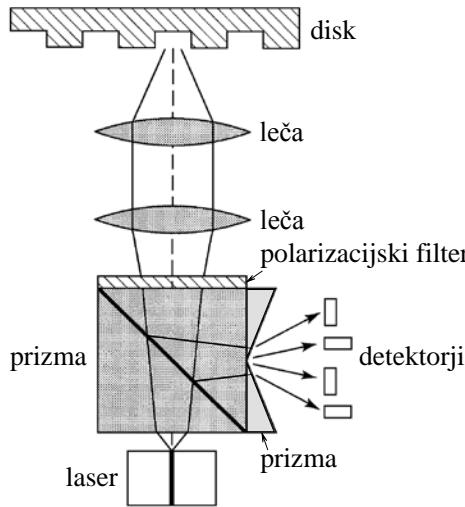
Novejše laserske zgradbe





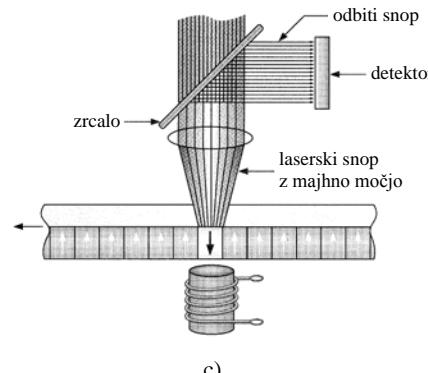
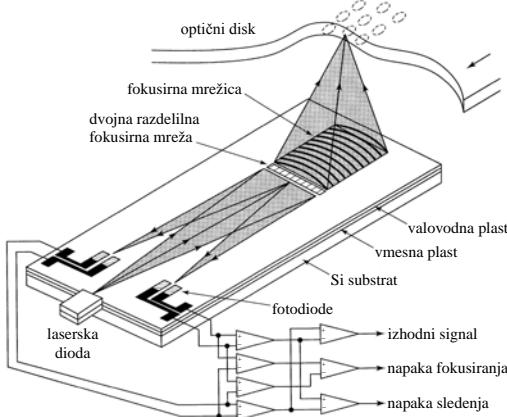
Fotonski elementi

Polprevodniški laserji - primeri uporabe

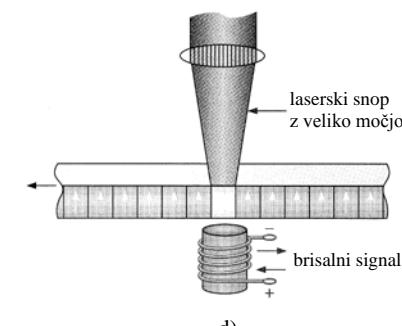


a)

b)



c)



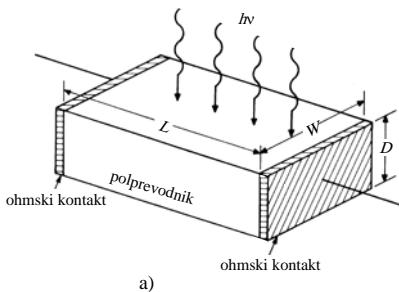
d)



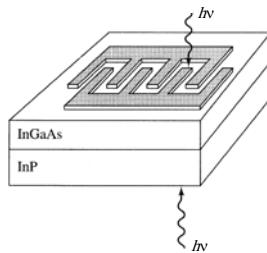
Fotonski elementi

Fotodetektorji

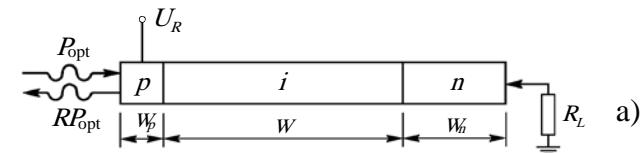
fotoupor, fotodioda, fototranzistor



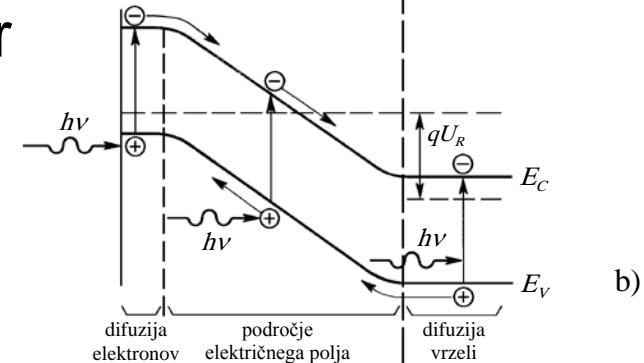
a)



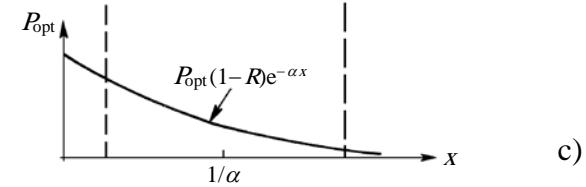
b)



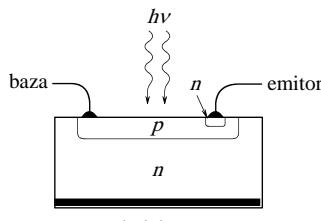
a)



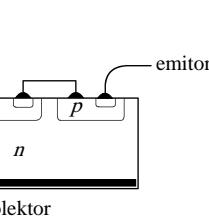
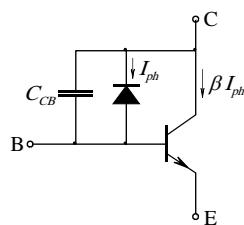
b)



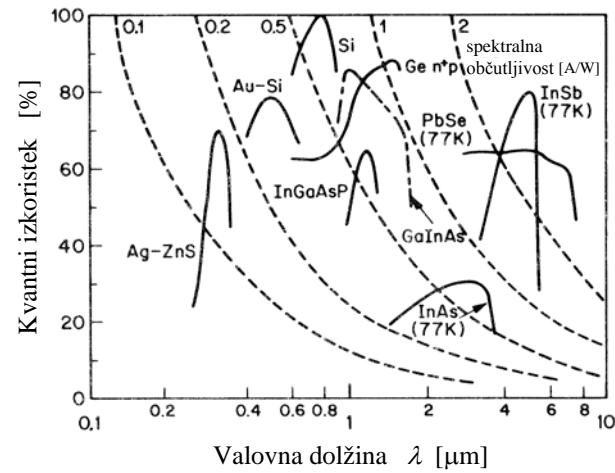
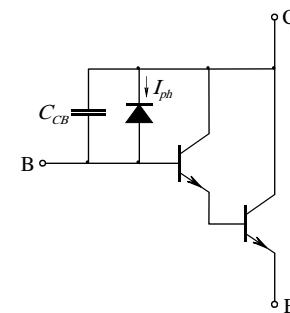
c)



a)



b)

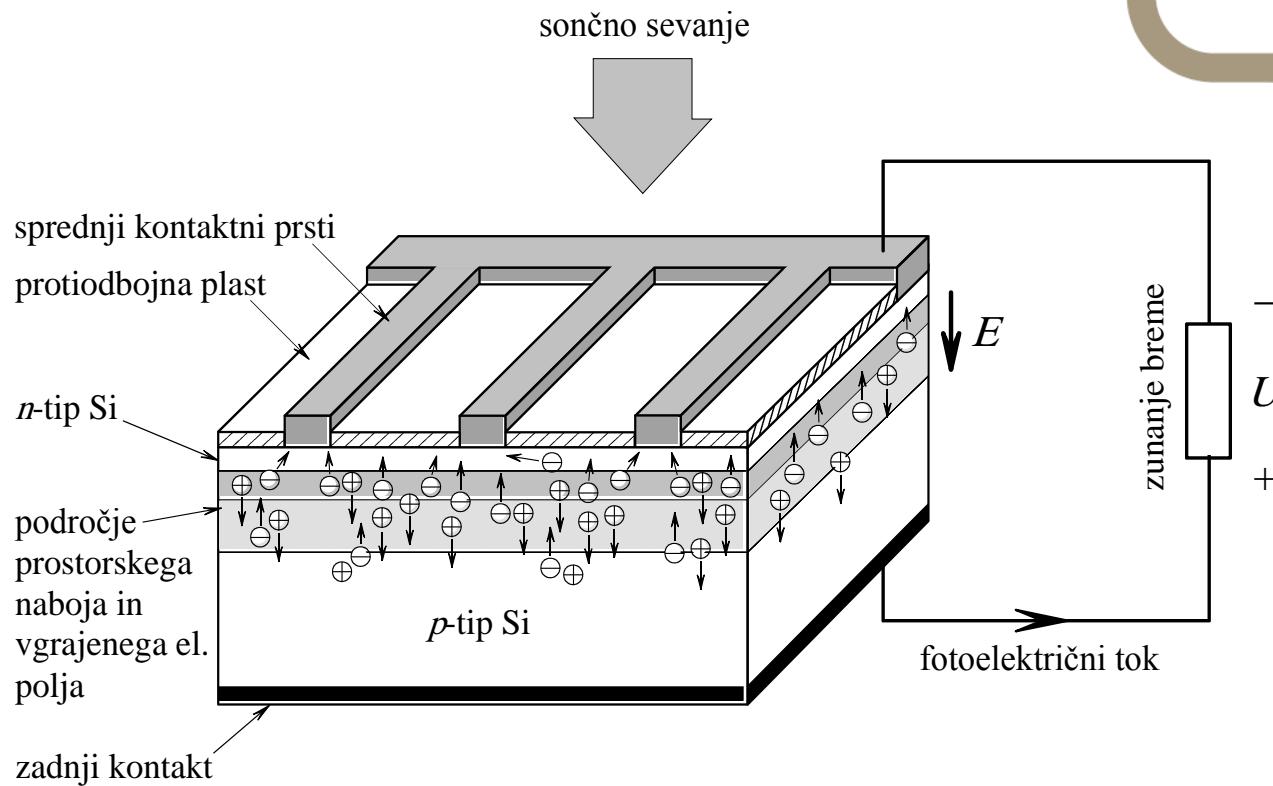
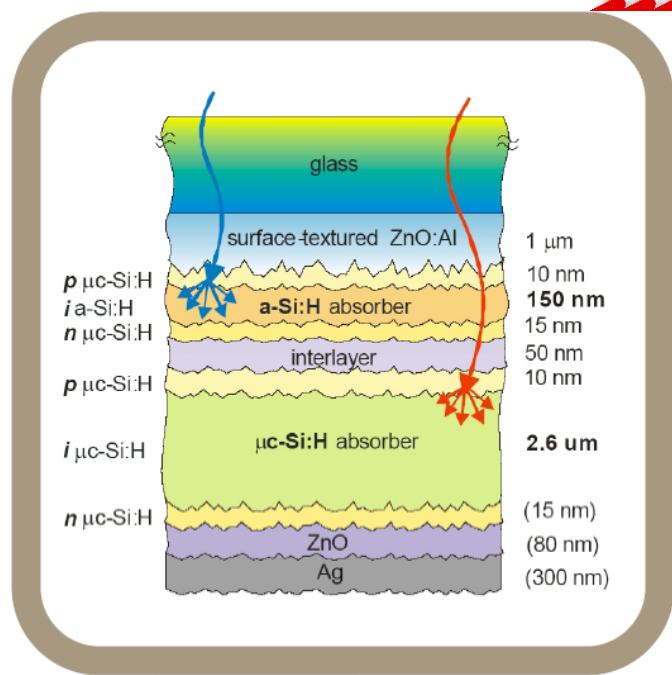


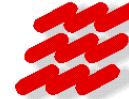


Fotonski elementi

Sončne celice

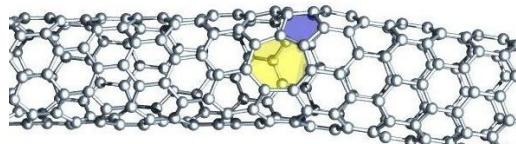
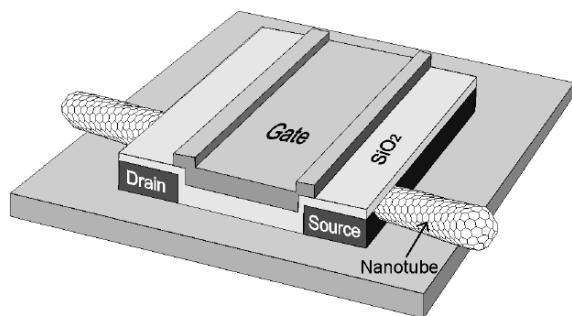
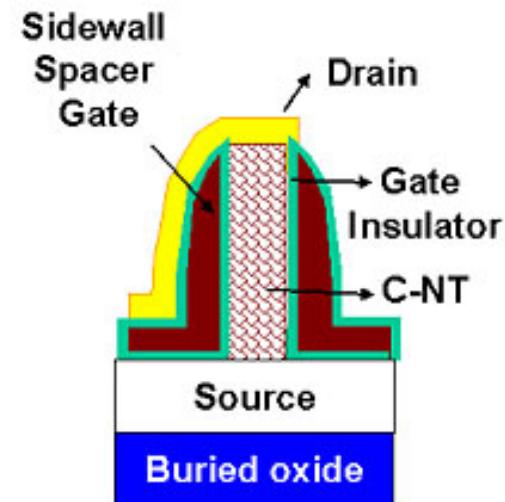
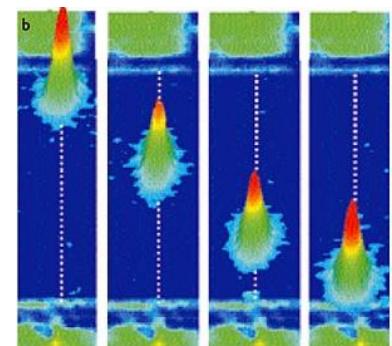
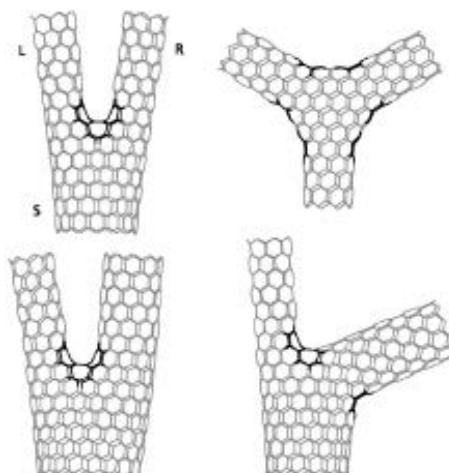
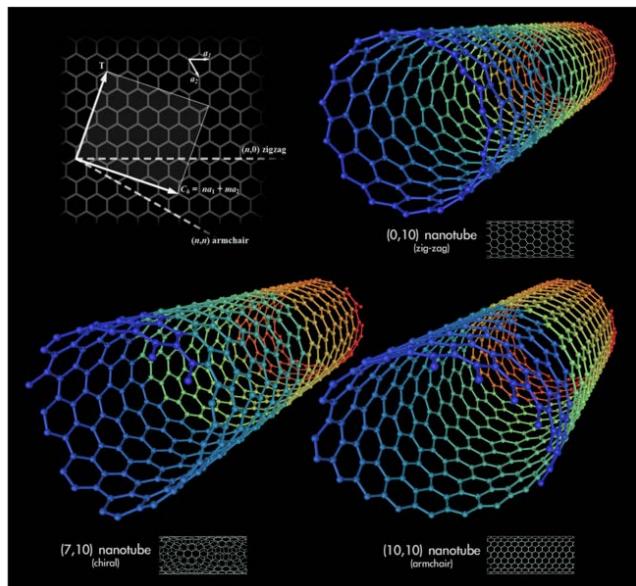
Osnovni principi delovanja, izhodni parametri



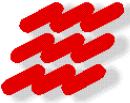


Nanoelektronika in nanotehnologije

osnovne definicije, trendi na področju nanoznanosti,
nanoprevodniki, transportne lastnosti polprevodniških
nanostruktur, nanoelementi, enoelektronski elementi, spintronika



A schematic of a conceptual CNT VFET



LABORATORIJSKE VAJE



Uvodna vaja

1. $I(U)$ karakteristika polprevodniške pn-diode
2. Linearizacija nelinearnega dvopola
3. Kapacitivnost in preklopni časi diode
4. Prebojna dioda in stabilizacija napetosti
5. Parametri prvega in drugega Ebers-Molovega modela BT
6. Inkrementalni četveropolni parametri BT
7. Stikalni časi bipolarnega tranzistorja
8. Mejne frekvence bipolarnega tranzistorja
9. Statična karakteristika spojnega FET
10. Svetleča dioda



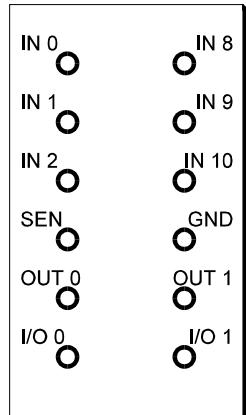
Uvodna vaja

Karakteristične lastnosti polprevodniških elementov merimo na dva načina:

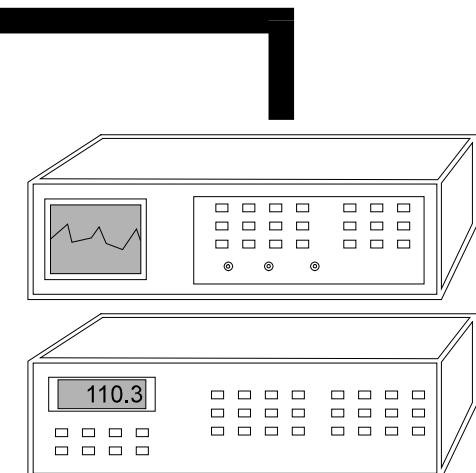
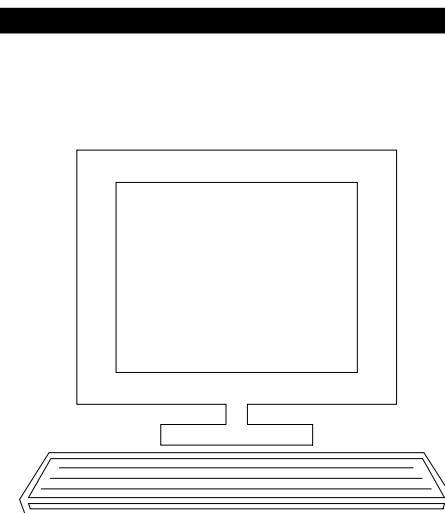
- z meritvami električnih parametrov s klasičnimi merilnimi instrumenti
- z računalniško podprtimi meritvami parametrov nelinearnih elementov

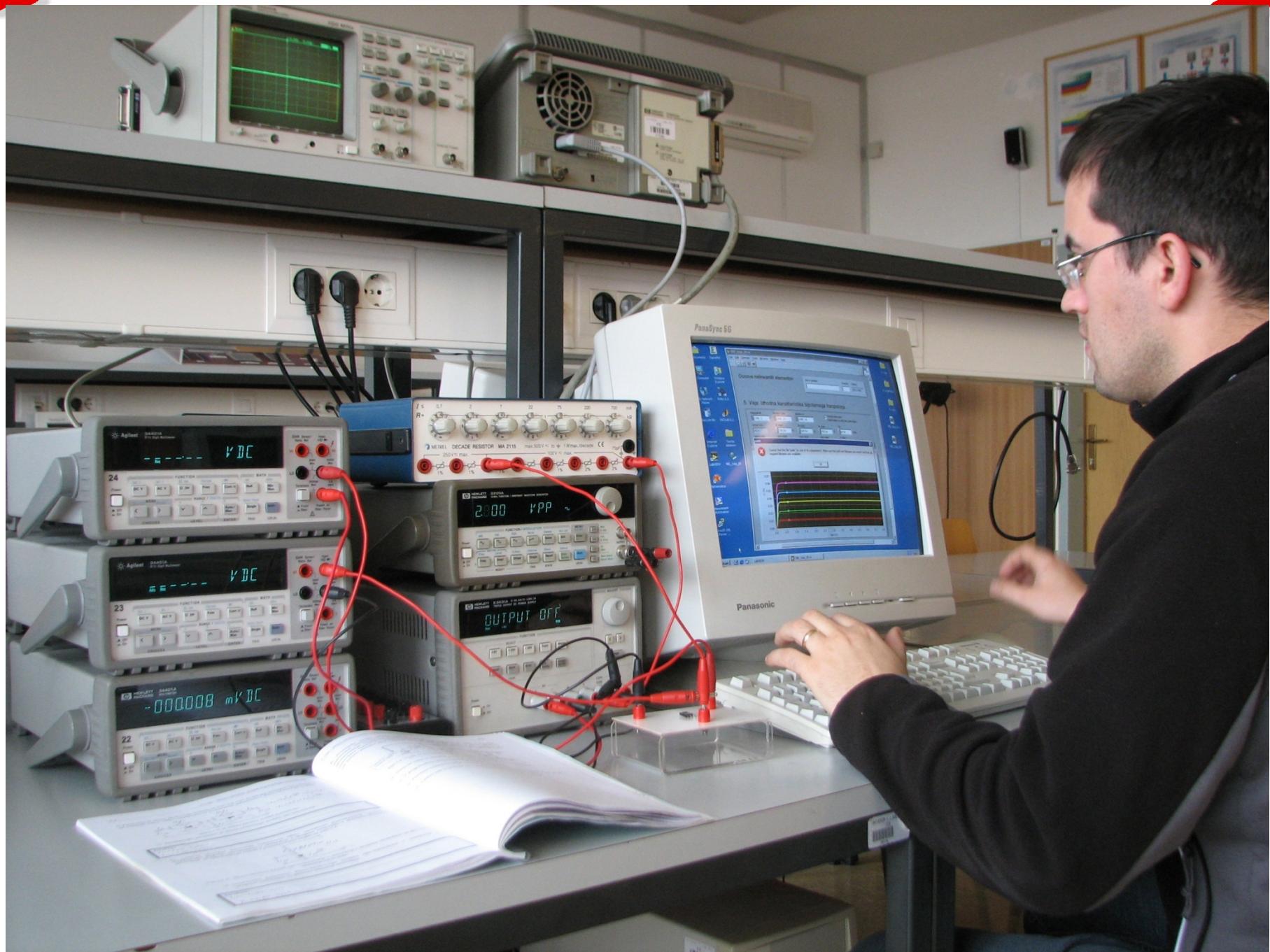
Za računalniško podprte meritve smo izbrali programsko okolje **LabVIEW**, ki temelji na sodobnem konceptu navideznih ali virtualnih instrumentov.

Vrniključni merilni modul
DAQ kartice



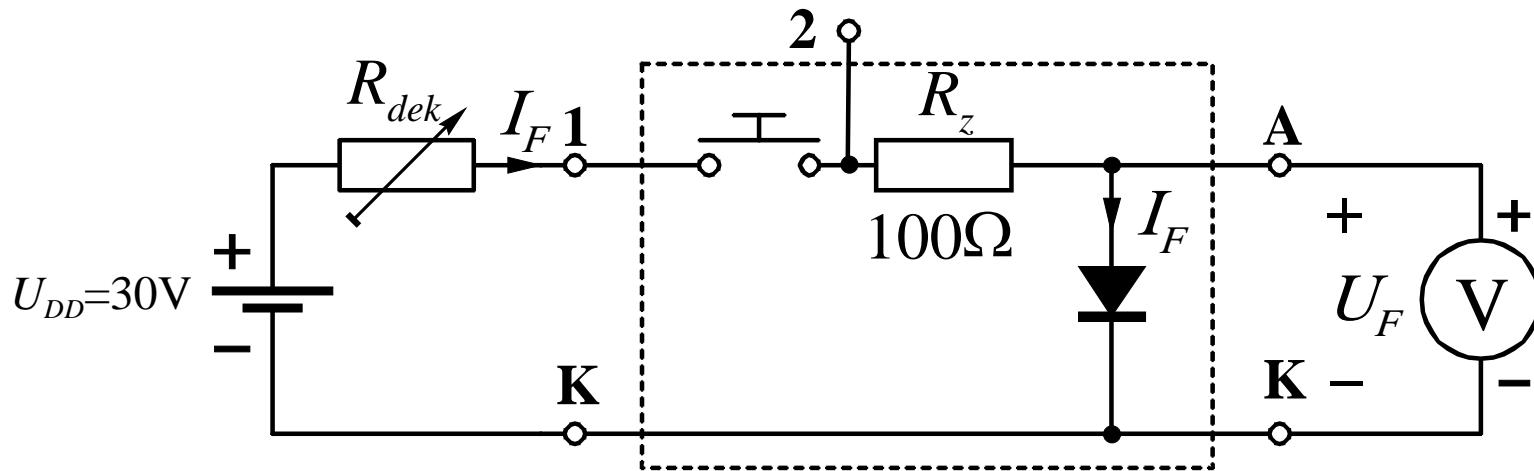
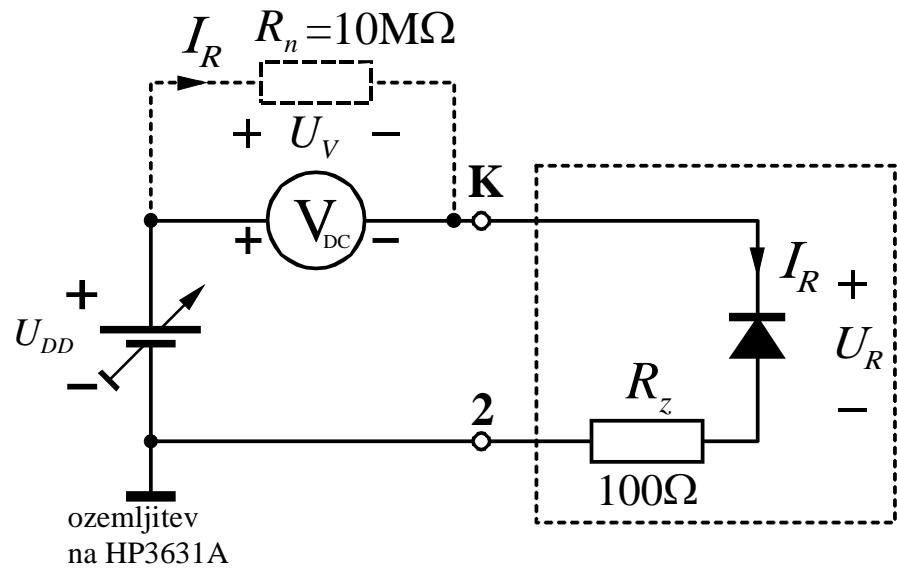
IEEE-488 vodilo







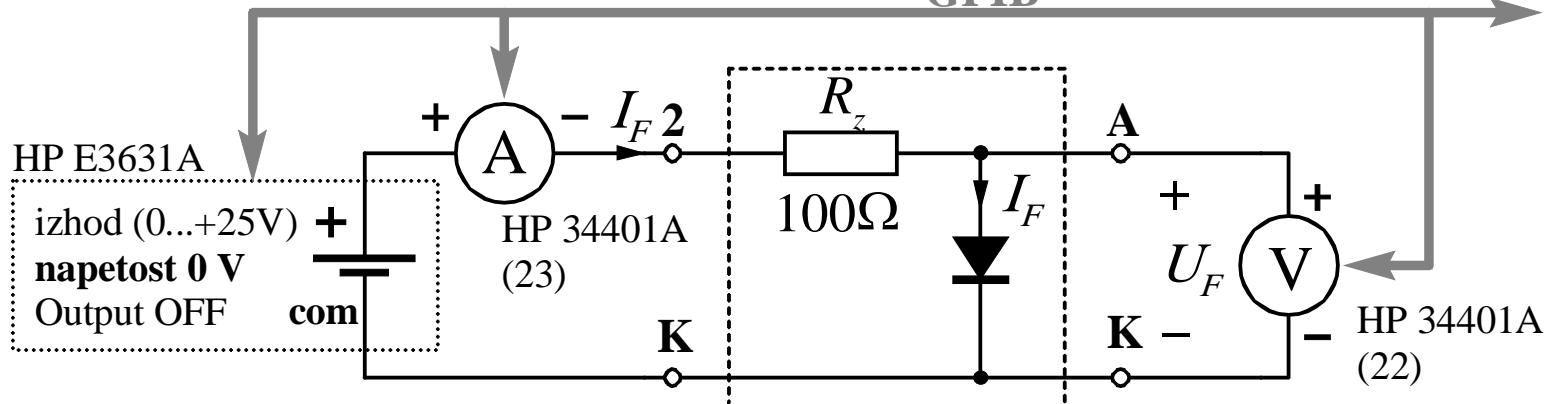
1.vaja: Statična I(U) karakteristika polprevodniške diode





GPIB

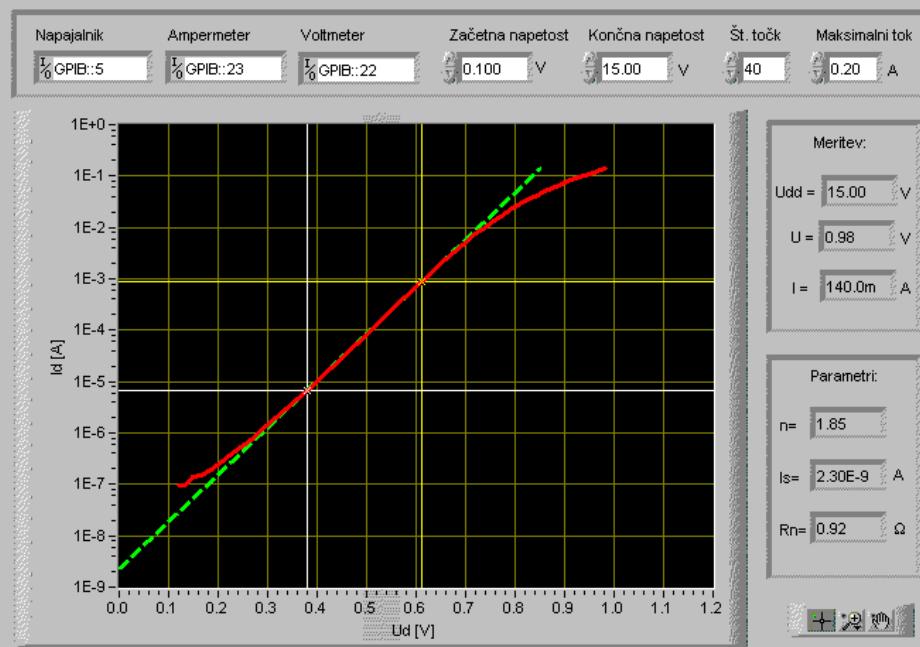
na GPIB kartico v računalniku



Osnove nelinearnih elementov

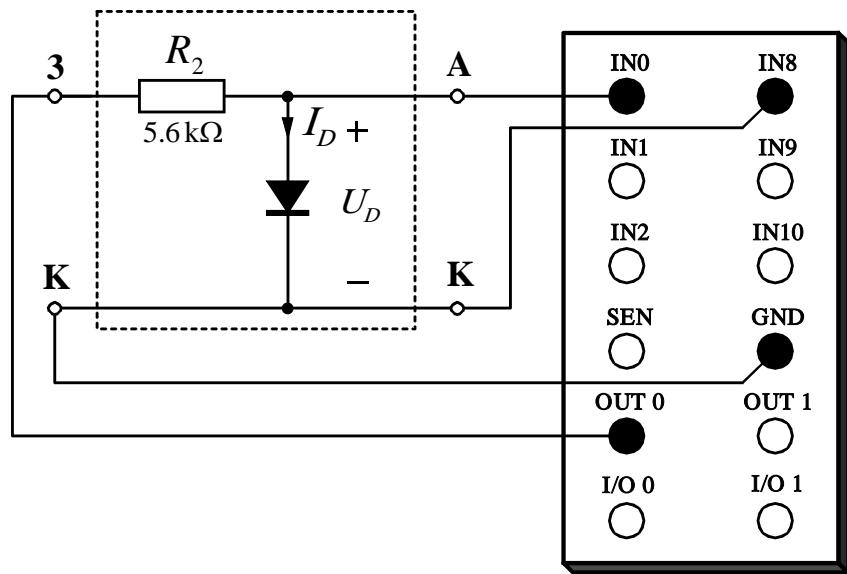
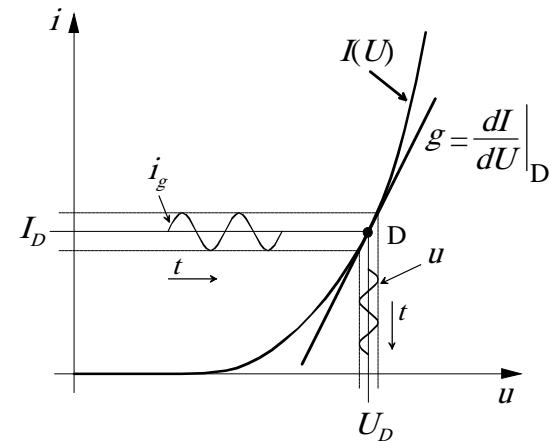
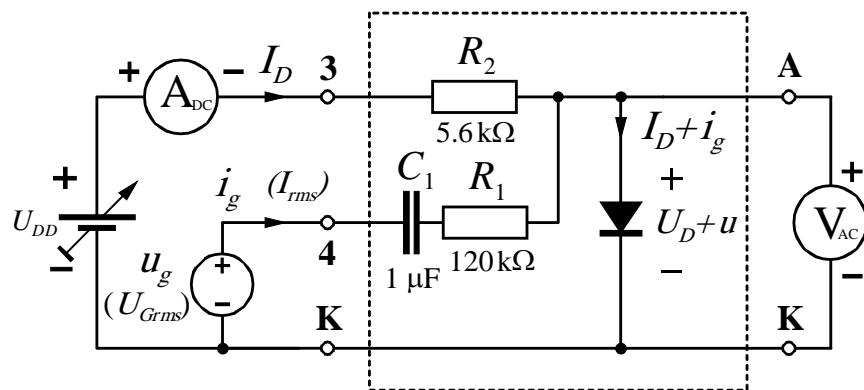
ime in priimek: Skupina: Datum: 20.2.2007

1. Vaja: Statična $I(U)$ karakteristika polprevodniške diode





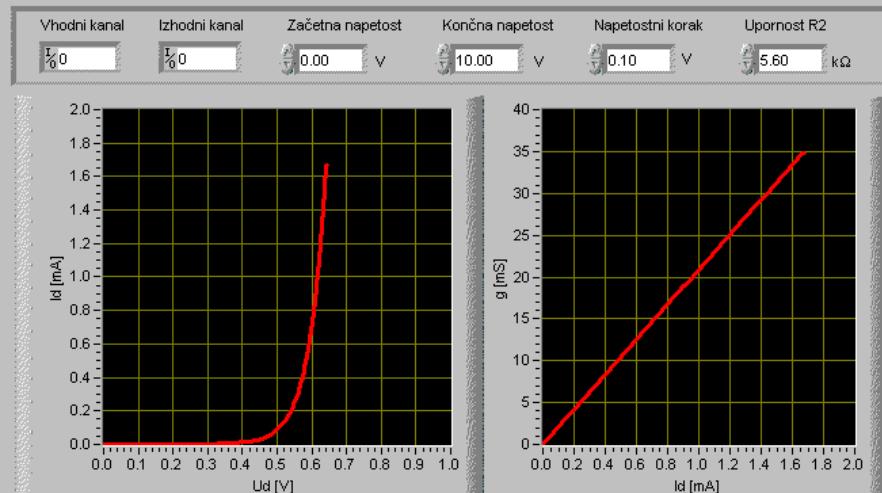
2.vaja: Diferencialna prevodnost polprevodniške diode



Osnove nelinearnih elementov

Ime in priimek:	Skupina:	Datum:
<input type="text"/>	<input type="text"/>	20.2.2007

2. Vaja: Diferencialna prevodnost polprevodniške diode



T = 24.80 °C

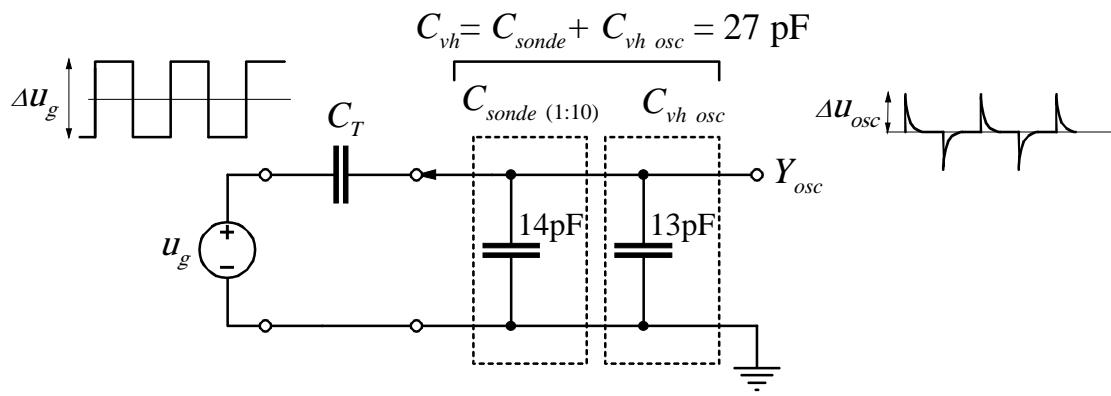
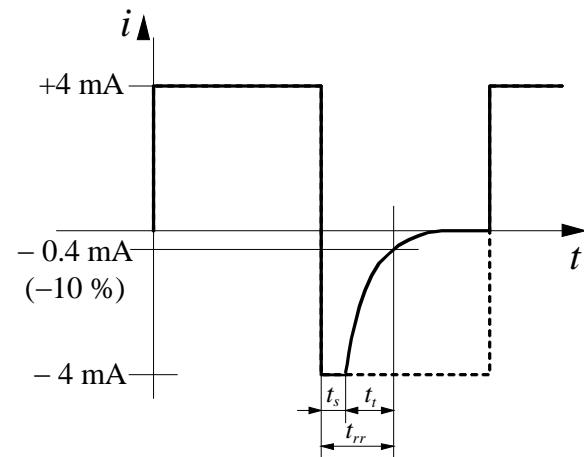
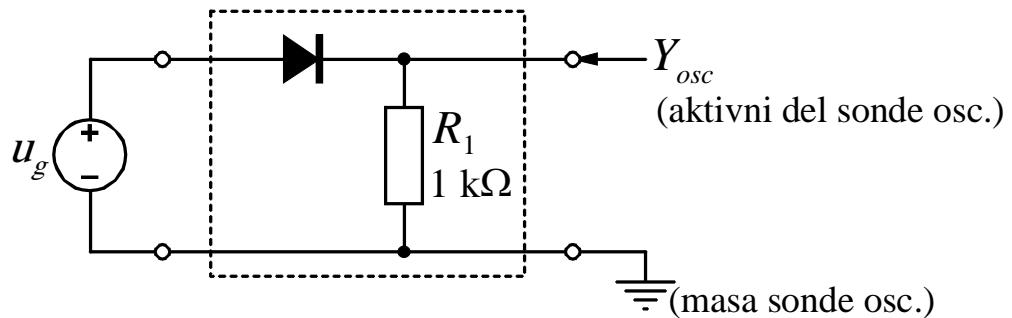
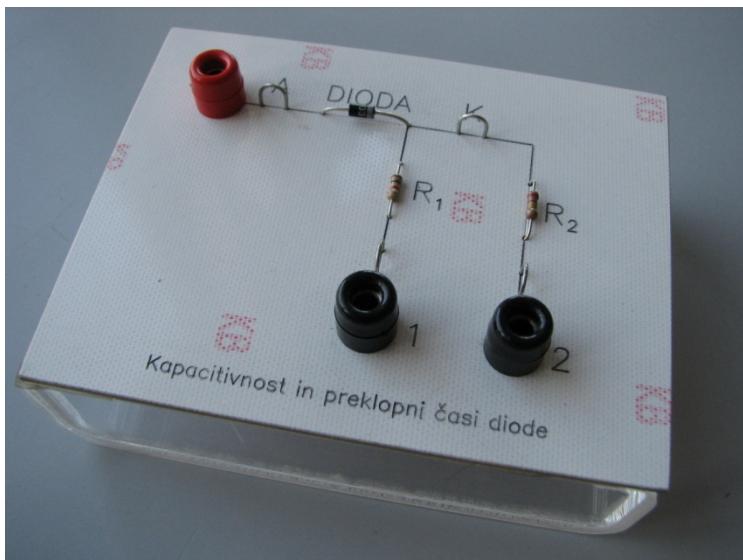
Ut = 25.66 mV

n*Ut = 48.31 mV

n = 1.88

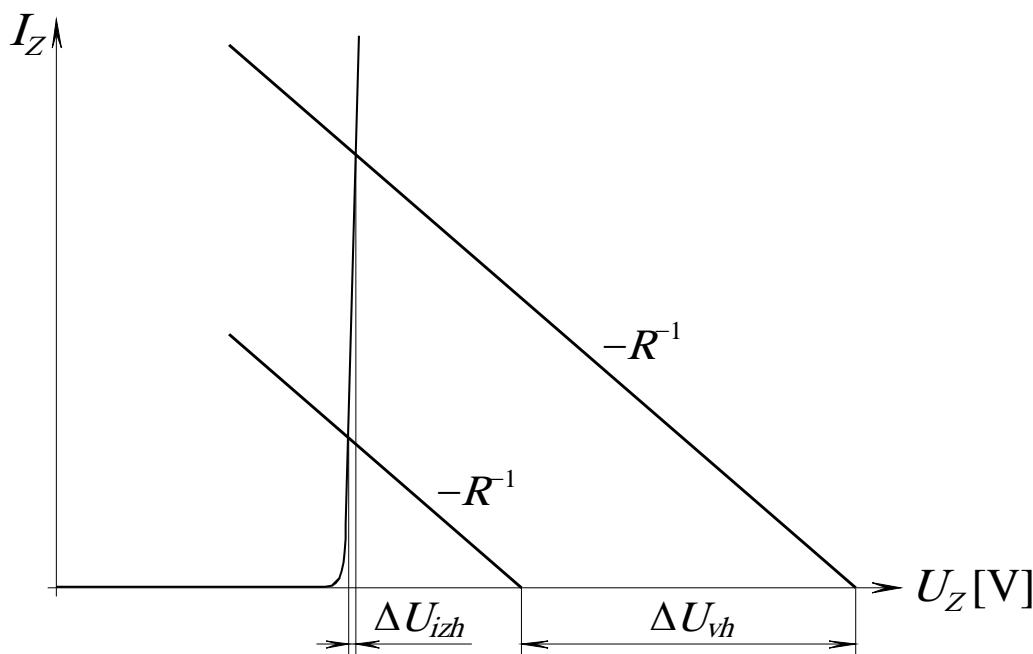
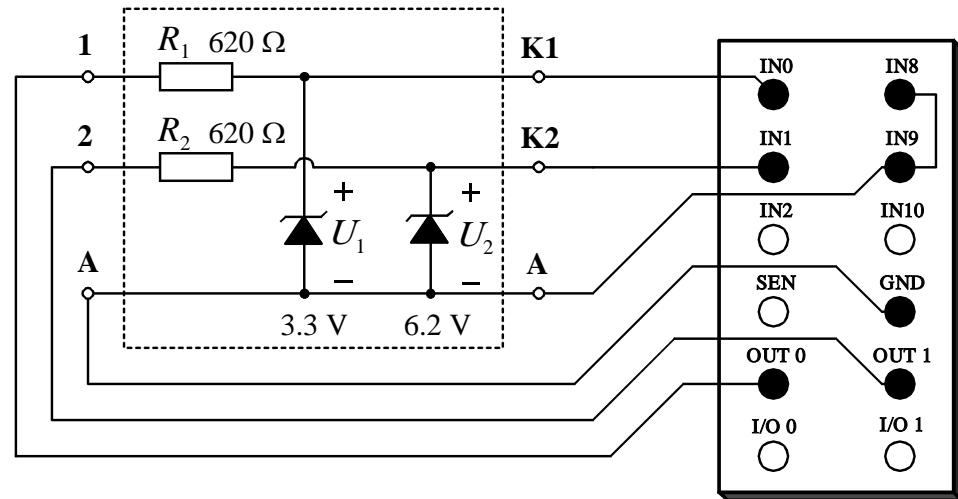
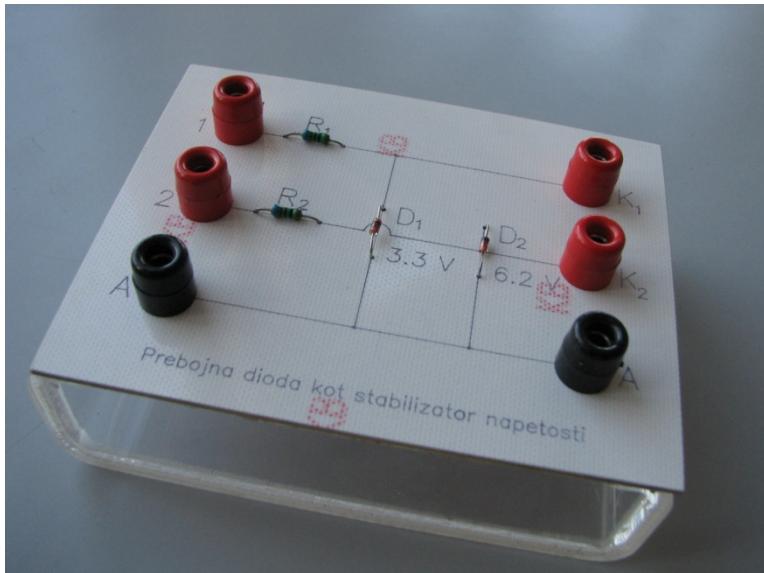


3. vaja: Preklopni časi in spojna kapacitivnost *pn*-diode



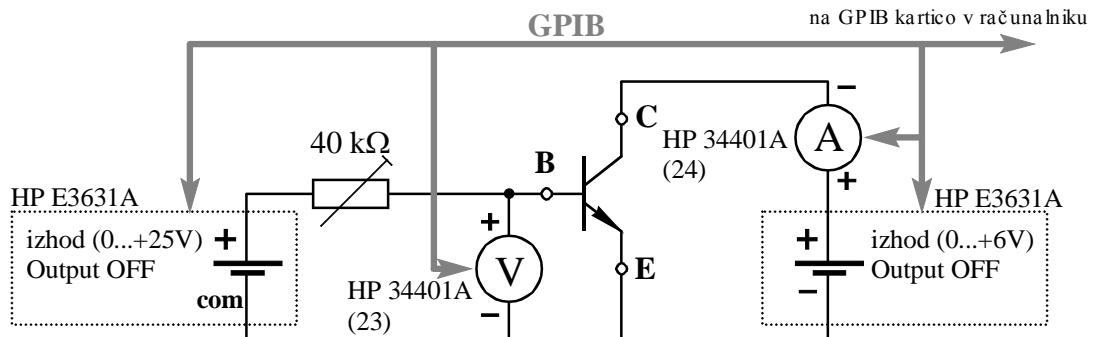
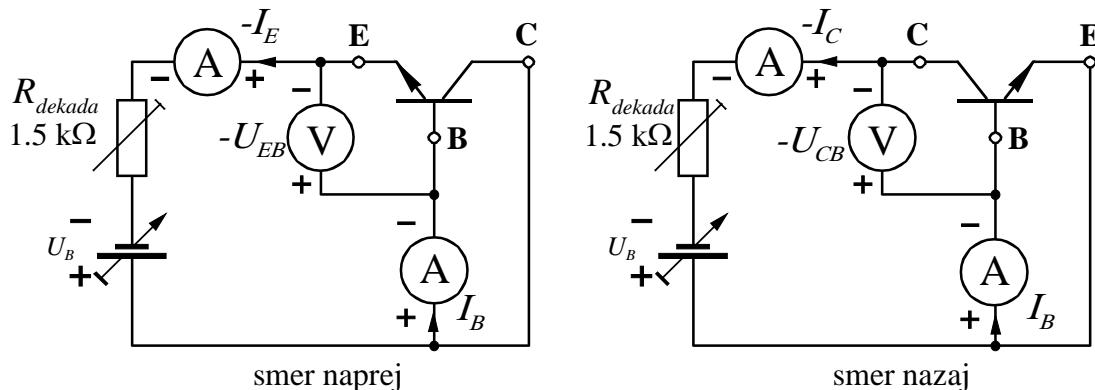


4. vaja: Prebojna dioda kot stabilizator napetosti



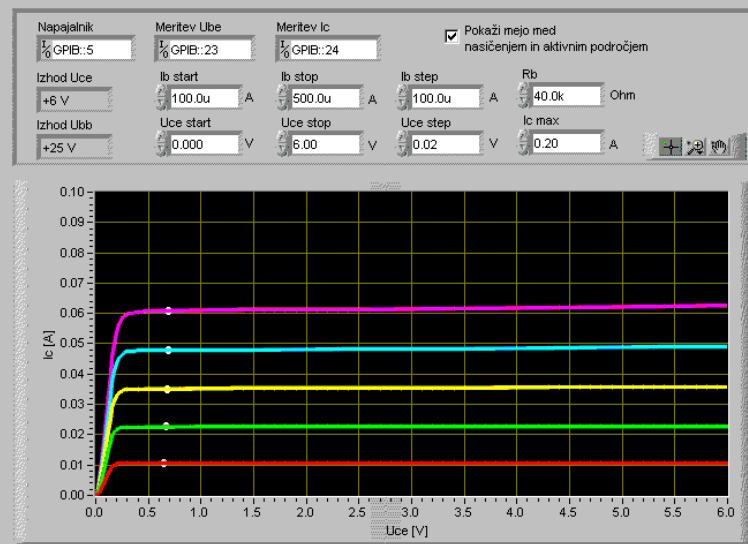


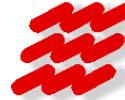
5.vaja: Ebers-Mollov model bipolarnega tranzistorja



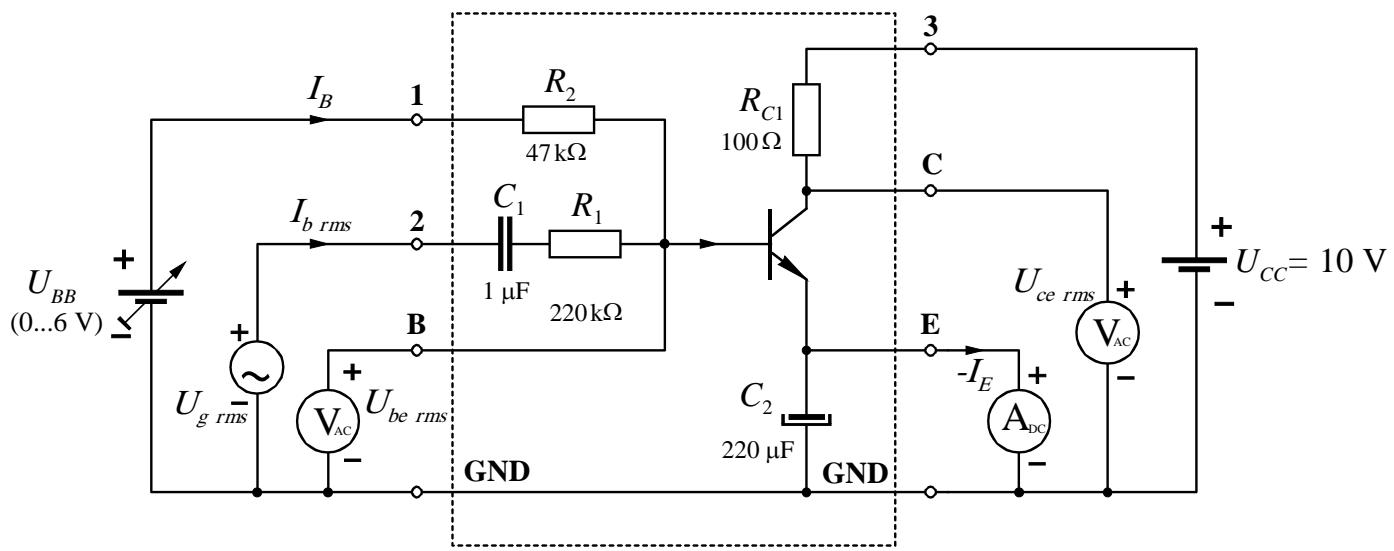
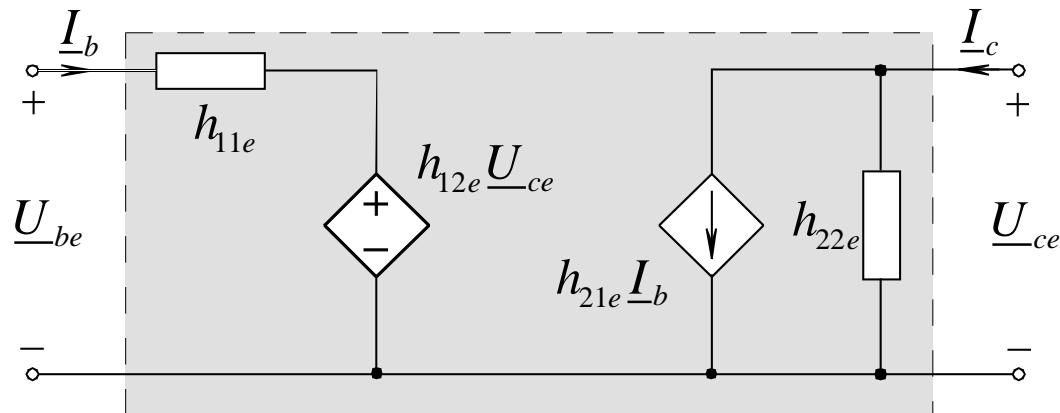
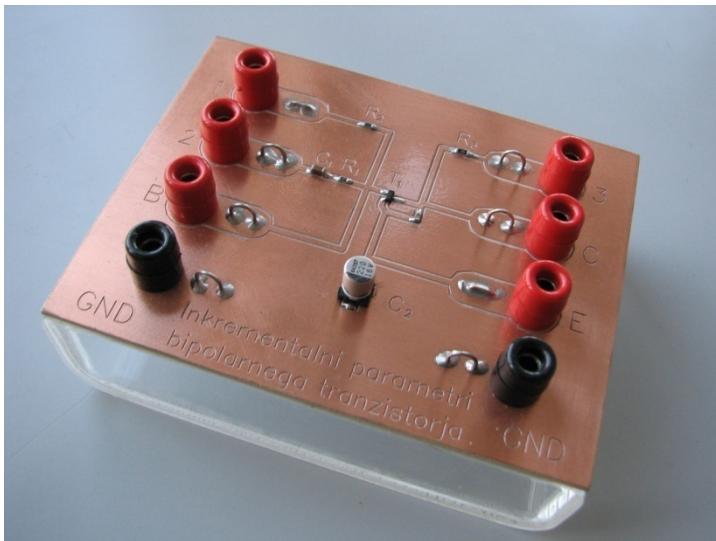
Ime in priimek:	Skupina:	Datum:
[Text input fields]		

5. Vaja: Izvodna karakteristika bipolarnega tranzistorja



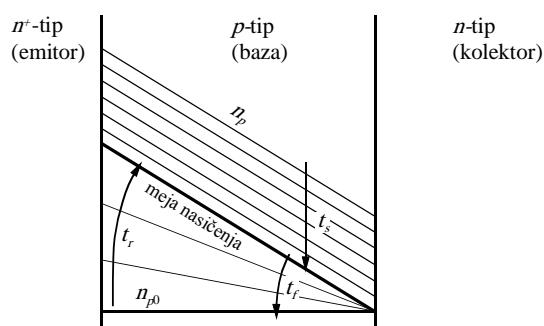
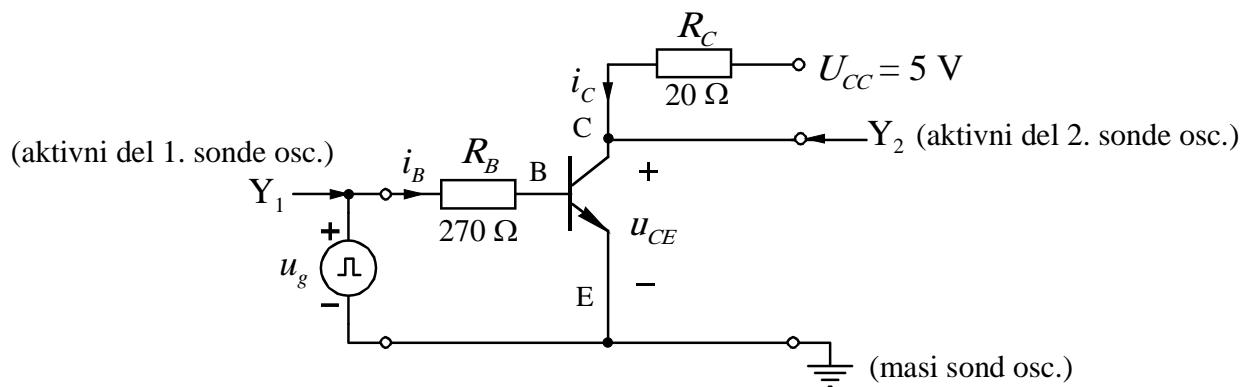
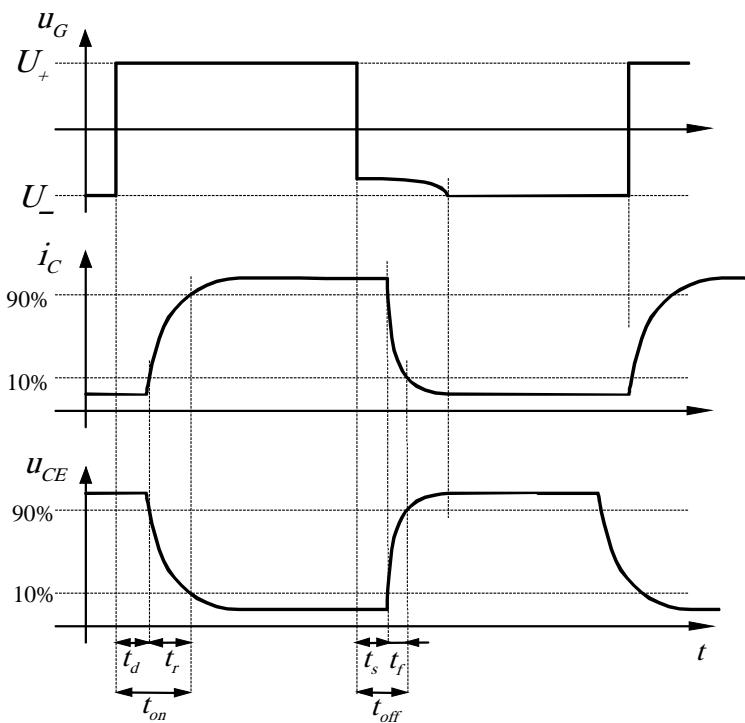
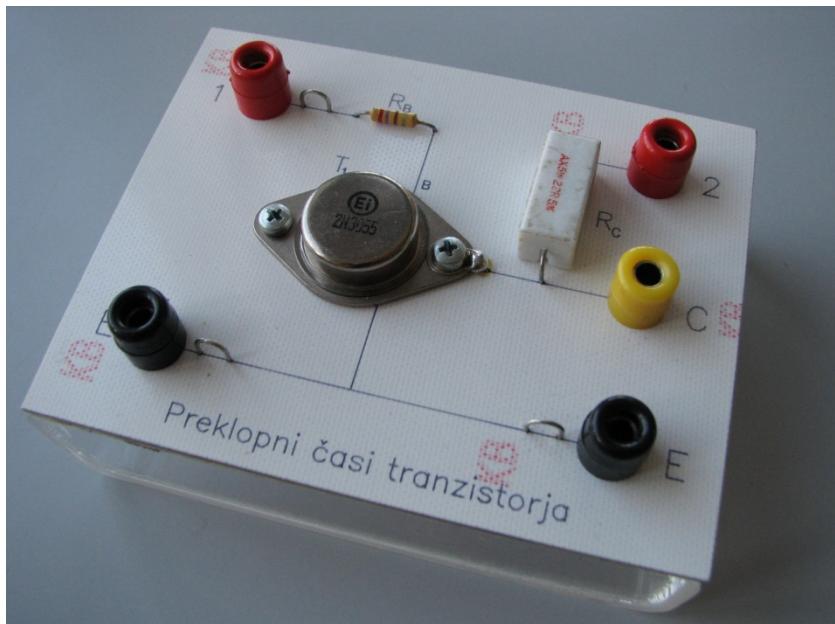


6.vaja: Inkrementalni četveropolni parametri bipolarnega tranzistorja kot ojačevalnika majhnih signalov



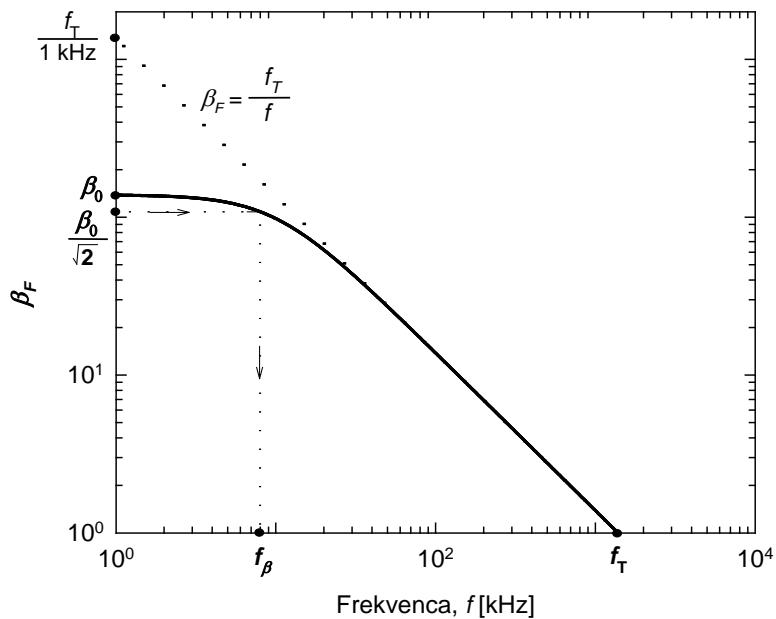
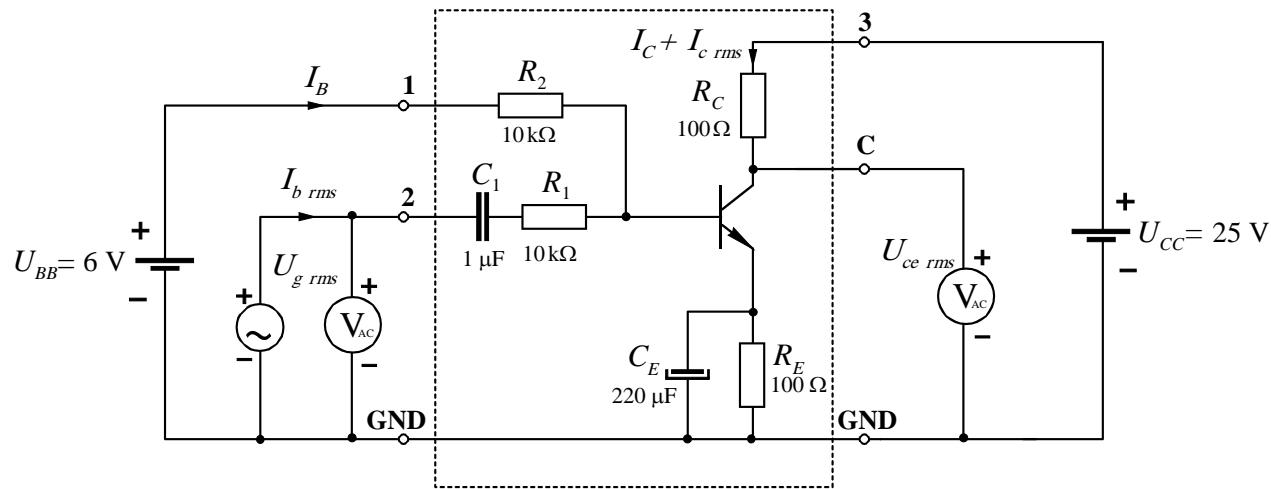


7.vaja: Stikalni časi bipolarnega tranzistorja





8.vaja: Mejne frekvence bipolarnega tranzistorja

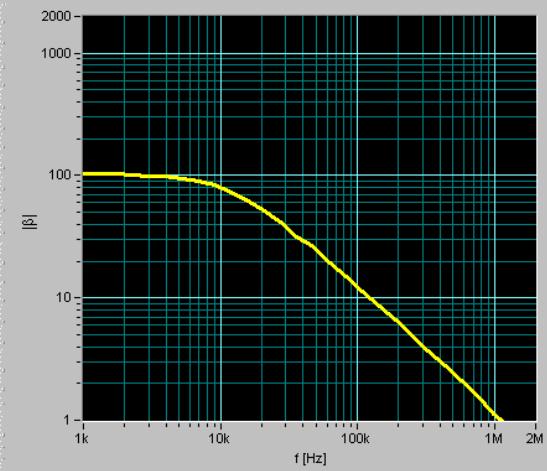


Osnove nelinearnih elementov

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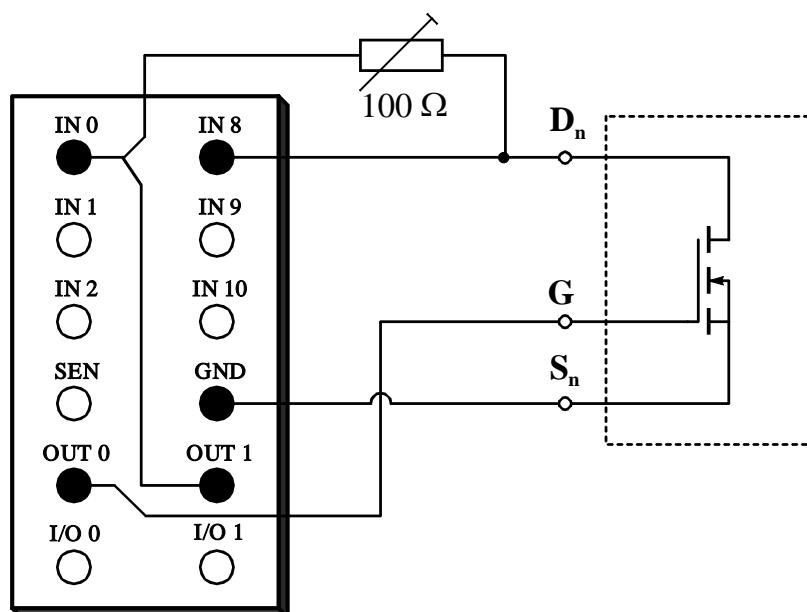
8. Vaja: Mejne frekvence tranzistorja

Sp. frekvanca 1k Hz	Meritev 27
Zg. frekvanca 3M Hz	Frekvanca 1.3M Hz
Št. period 10	U1 170.09m Vrms
Št. meritev 30	U2 1.49m Vrms
Zakasnitve 2.00 s	Funkc. Generator 1/6 GPIB:10
Vhodna amplituda 0.50 V	Osciloskop 1/6 GPIB:7
R1 10k Ohm	Rc 100 Ohm





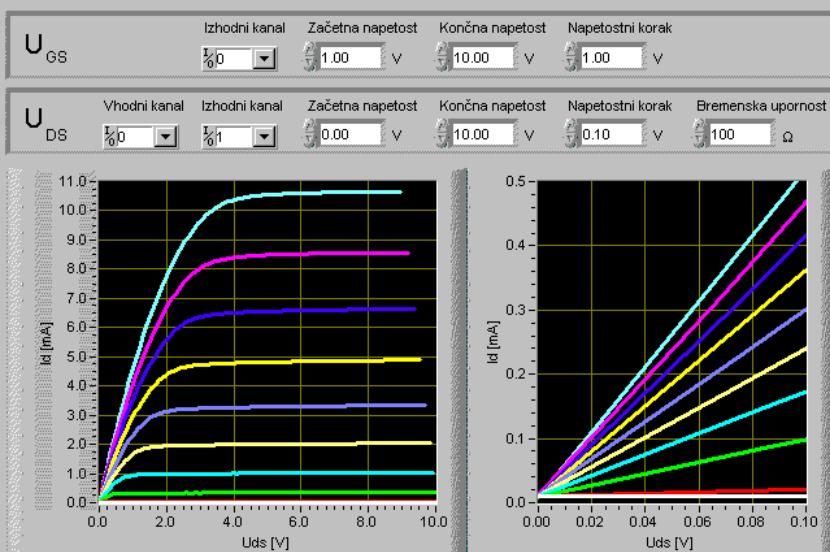
9.vaja: MOS tranzistor



Osnove nelinearnih elementov

Ime in priimek:	Skupina:	Datum:
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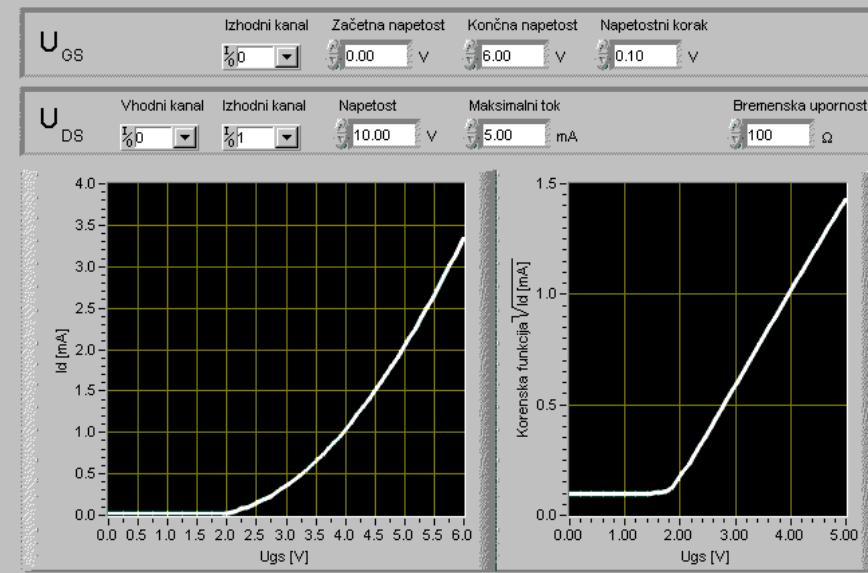
9. Vaja: Statična izhodna karakteristika $Id(U_{ds})$ MOS FET-a



Osnove nelinearnih elementov

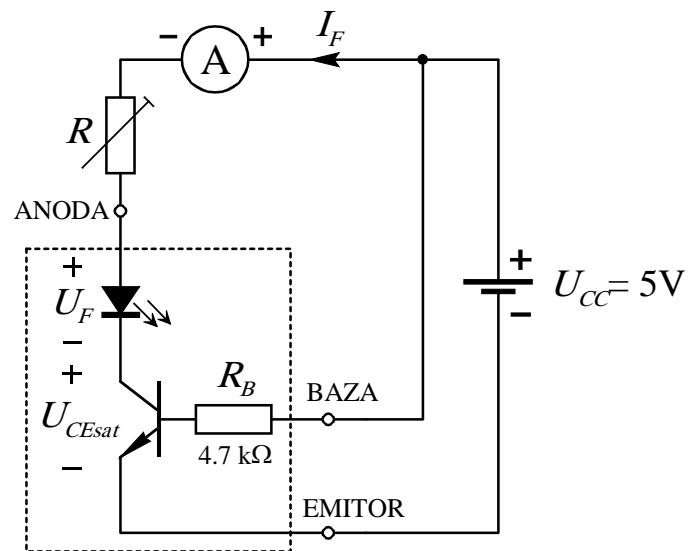
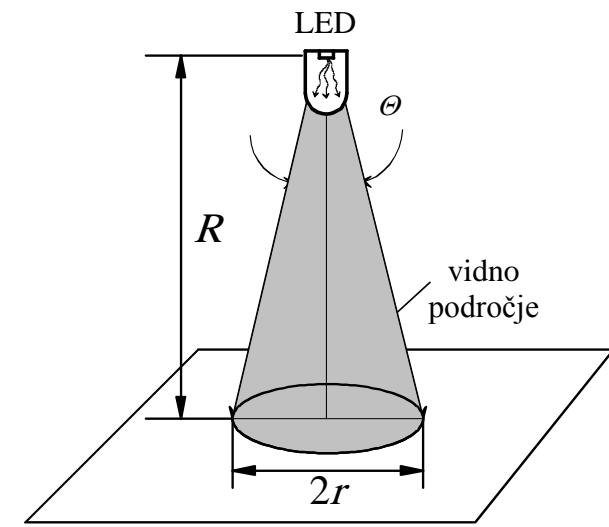
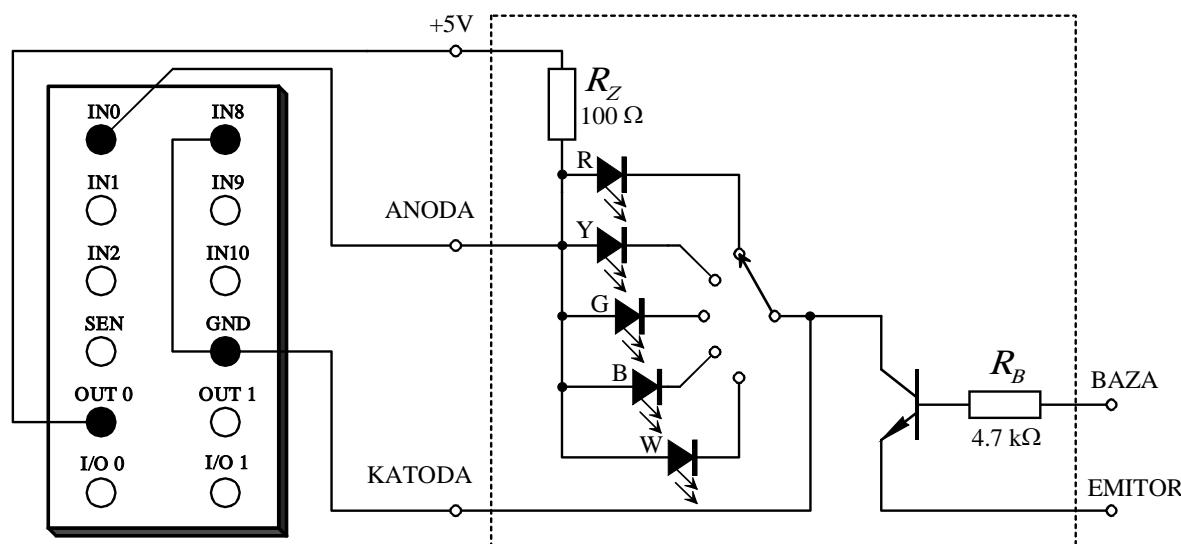
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9. Vaja: Statična prenosna karakteristika $Id(U_{gs})$ MOS FET-a



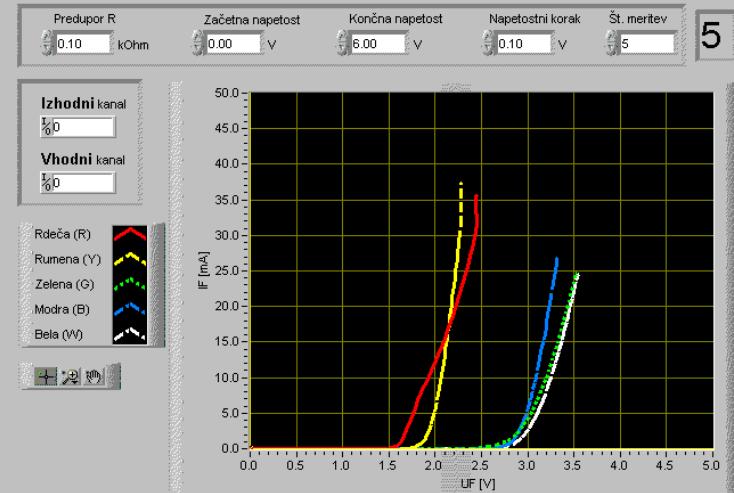


10.vaja: Svetleča dioda (LED)



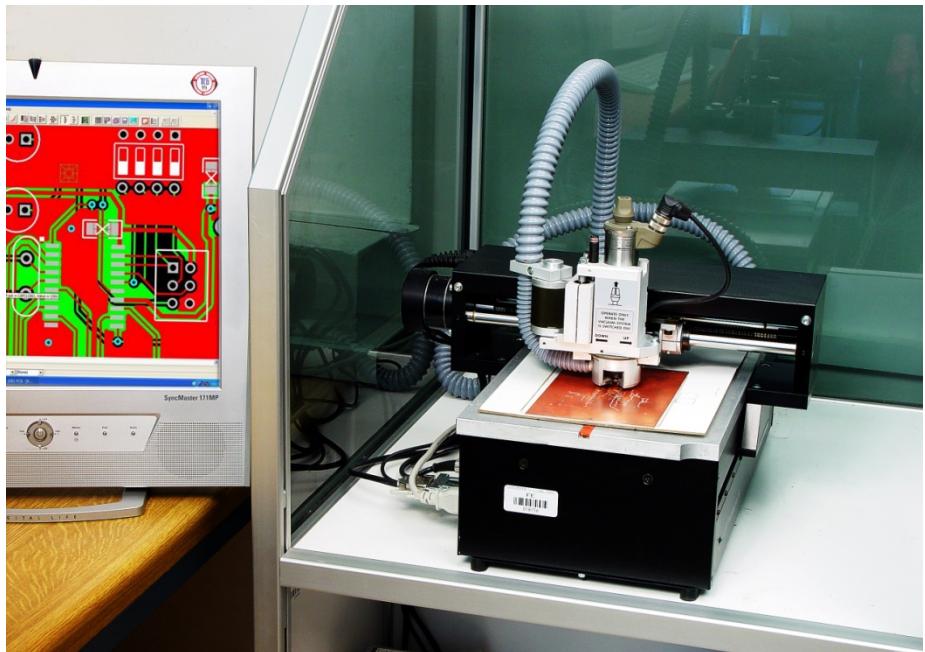
Osnove nelinearnih elementov		Ime in priimek:	Skupina:	Datum:
		<input type="text"/>	<input type="text"/>	20.2.2007

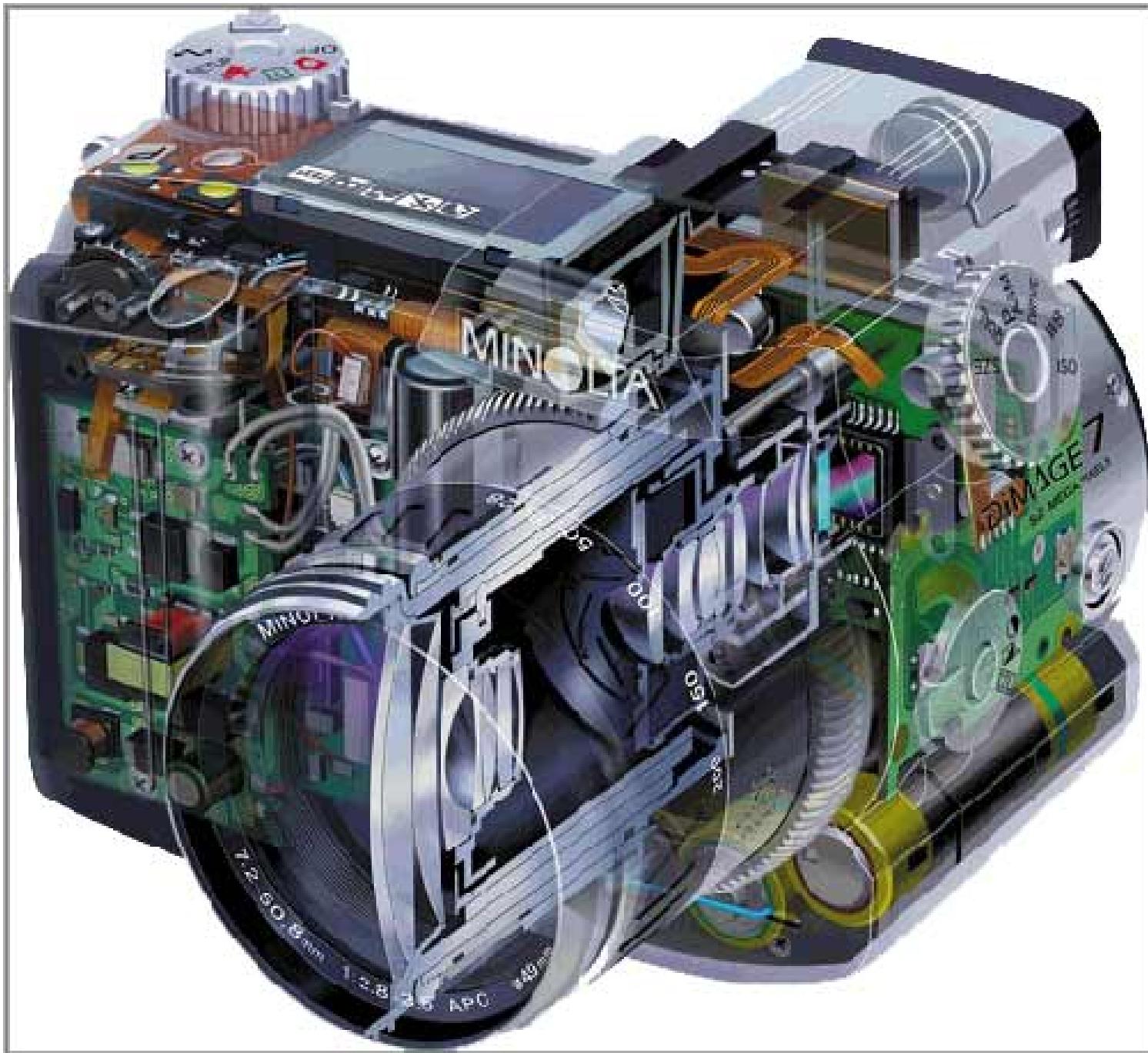
10. Vaja: Svetleča dioda (LED)





Oprema v Laboratoriju za polprevodniško elektroniko





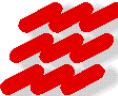


Elektronska industrija doživlja v zadnjih 50-ih letih izjemno hiter razvoj in ima močan vpliv na človekovo življenje. Danes predstavlja največjo industrijo, saj ima prek trilijon dolarjev celotne prodaje.

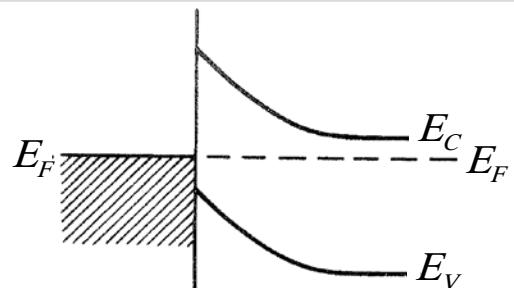
Temelj elektronske industrije so polprevodniški elementi, ki se v elektronskih sklopih lahko pojavljajo kot samostojni elementi ali pa kot gradniki kompleksnih integriranih vezij.

Zaradi stalne potrebe po hitrejših in kompleksnejših sistemih, ki jih zahteva današnja informacijska doba, potekajo še vedno intenzivne raziskave obstoječih polprevodniških elementov, odkrivajo pa tudi nove.

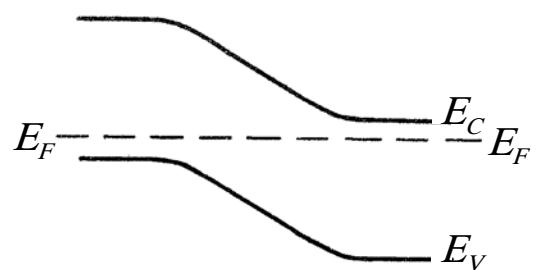
Bodisi zaradi zahtev po višjih hitrostih delovanja, nižjih močeh, večjih gostotah in višjih izkoristkih bodisi zaradi novih funkcij se število in tipi polprevodniških elementov neprestano povečujejo.



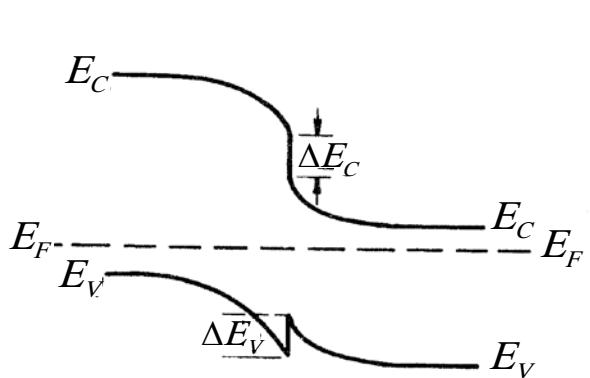
Raziskave polprevodniških elementov sežejo v leto 1874, glavni preboj pa se je zgodil v letu 1947, ko so v Bellovih laboratorijih iznašli bipolarni tranzistor. Do danes je bilo razvitih prek sto glavnih elementov in raznih izpeljank, vsi pa so izdelani iz majhnega števila osnovnih gradnikov.



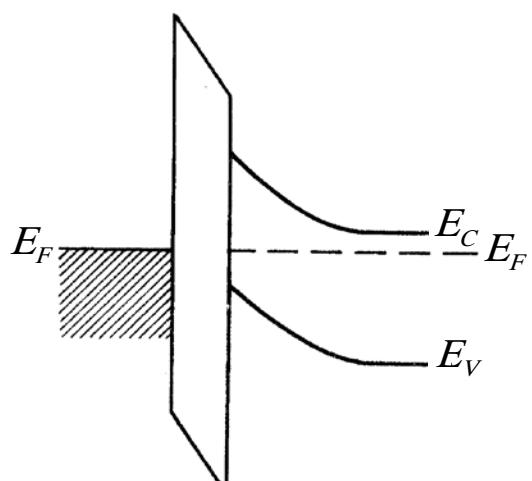
a)



b)



c)



d)