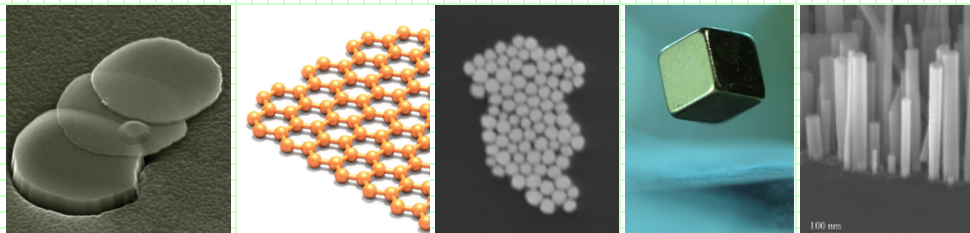


MATERIJALI U ELEKTROTEHNICI



Predavanja: Miloš Vujisić, vanr. prof.

Računske vežbe: Dimitrije Popović, saradnik u nastavi

Laboratorijske vežbe:

Dimitrije Popović, saradnik u nastavi

Milan Ignjatović, viši laboratorijski inženjer

[Stranica predmeta na sajtu ETF](#)

Jesenji semestar 2022.

PREDMET KURSA

Kurs obuhvata fizičke osnove elektrotehničkih materijala (poluprovodnika, provodnika, superprovodnika, dielektrika, magnetika, biomaterijala i novih materijala), njihovu strukturu, karakteristike, primene i inženjering.

ZAŠTO SLUŠATI OVAJ KURS?

MUE je predmet koji pruža znanja o sastavu, strukturi i osobinama elektrotehničkih materijala, metodama njihove sinteze i karakterizacije, kao i o savremenim primenama koje ovi materijali nalaze u računarima, senzorima, aktuatorima, medicinskim uređajima, izvorima svetlosti, ekranima, detektorima zračenja ...

U svakom od ovih domena **istraživanja su usmerena na sintezu novih materijala i inženjering njihovih osobina** kako bi odgovorili na specifične zahteve.

DALJA NADOGRADNJA

[Praktikum iz savremenih materijala i tehnologija](#) (drži se paralelno sa MUE)

Biomaterijali

Fizička elektronika čvrstog tela

Poluprovodničke kvantne strukture

Nanotehnologije i nanokomponente

Optičke telekomunikacije

Nuklearna tehnika

Dozimetrija i zaštita od zračenja

LITERATURA

1. ***Slajdovi sa predavanja.***

2. D. Raković, ***Fizičke osnove i karakteristike elektrotehničkih materijala*** (Akademska misao, Beograd, 2000).

3. D. Raković, P. Osmokrović, N. Arsić, ***Elektrotehnički materijali (Zbirka zadataka)*** (Akademska misao, Beograd, 2003).

4. ***Priručnik za laboratorijske vežbe.***

Sva literatura potrebna za praćenje kursa i polaganje ispita dostupna je u elektronskom obliku (kao pdf fajlovi).

NASTAVA I ISPIT

1. Predavanja (3 časa nedeljno).

2. Računske vežbe (2 časa nedeljno).

3. Laboratorijske vežbe (ima ih 6, svaka nosi po 6 poena, rade se u 3 termina po dve, odbranom vežbi stiče se uslov za polaganje i osvaja maksimalno 36 poena).

4. Polaganje:

2 KOLOKVIJUMA (jedan sredinom semestra, drugi u ispitnom roku, traju po 90 minuta, pitalice nose 20 poena, zadaci nose 12 poena, prag za polaganje kolokvijuma je 16 poena, poeni sa položenog prvog kolokvijuma važe u svim ispitnim rokovima) ili

INTEGRALNI ISPIT (traje 180 minuta, pitalice nose 40 poena, zadaci nose 24 poena, uslov za polaganje je bar 32 poena sa ispita i bar 50 u zbiru sa lab. vežbama).

NASTAVNI PROGRAM

Uvod o primeni materijala u elektrotehnici

Kristalni čvrsti materijali

Hemijske veze i svojstva materijala

Nesavršenosti u kristalnoj strukturi

Nekristalni čvrsti materijali

Osnove kvantne mehanike

Elektronska struktura materijala

Poluprovodnici

Provodnici

Dielektrici

Magnetici

+ Metode određivanja svojstava ovih materijala

Metode dobijanja masivnih monokristala i tankih slojeva materijala

Planarna integrisana kola

Difrakcione, mikroskopijske i spektroskopske metode karakterizacije materijala

Superprovodnici

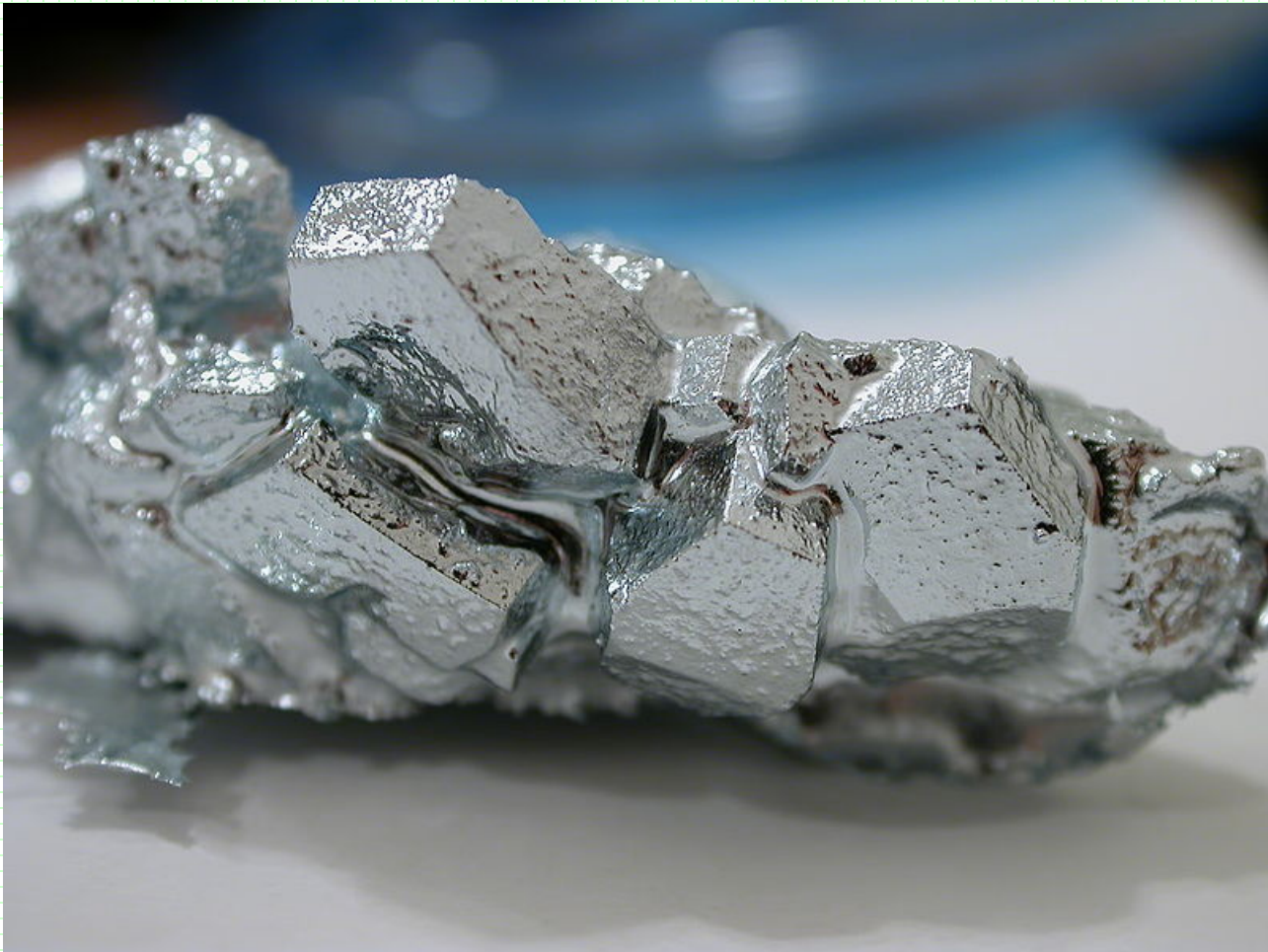
Mehaničke karakteristike materijala

Uvod u biomaterijale

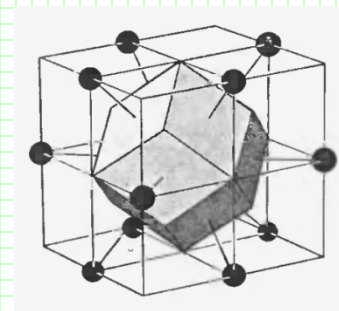
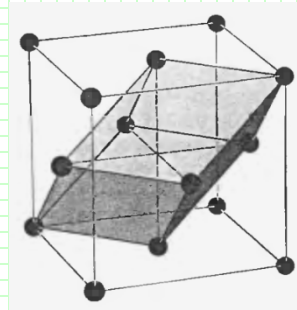
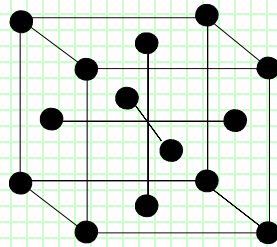
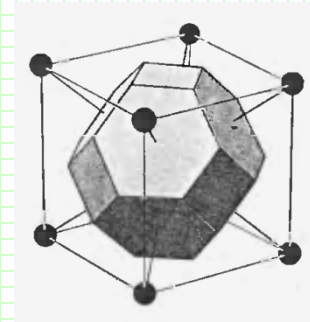
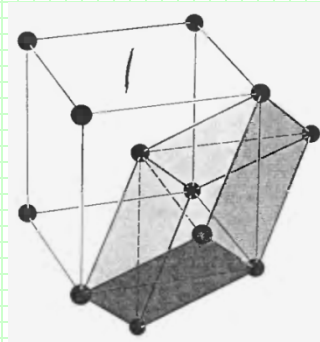
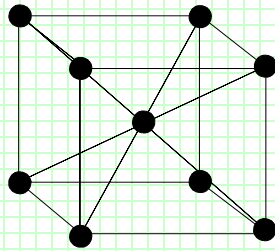
Novi materijali i primene



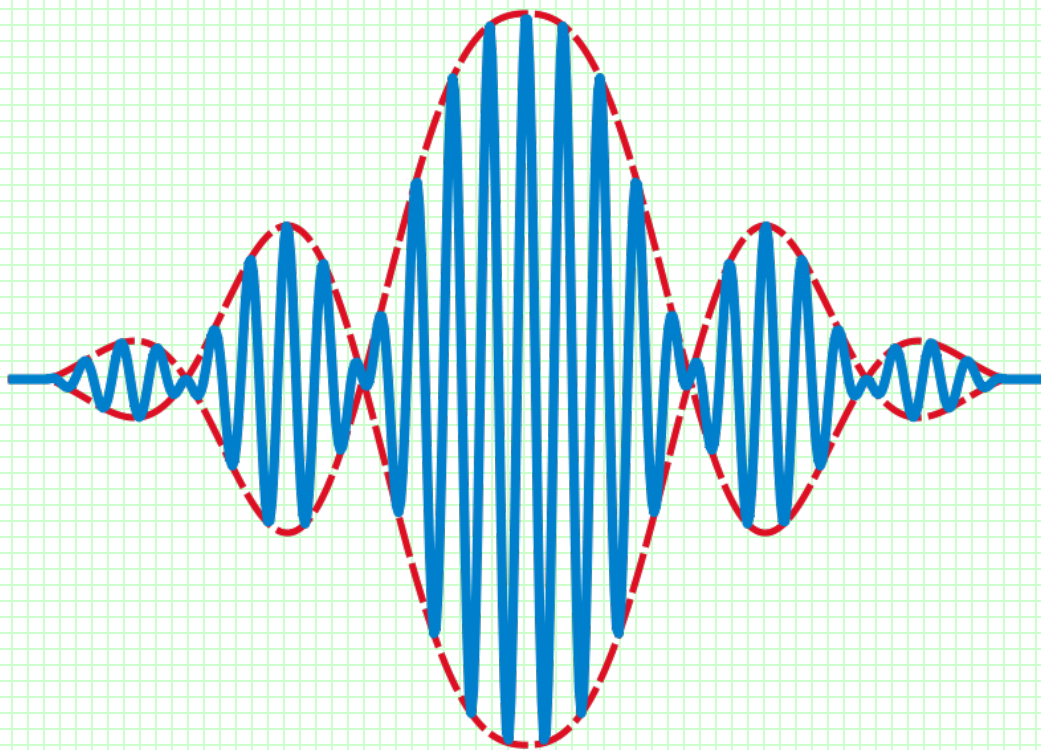
Mineral halit (kamena so, NaCl)

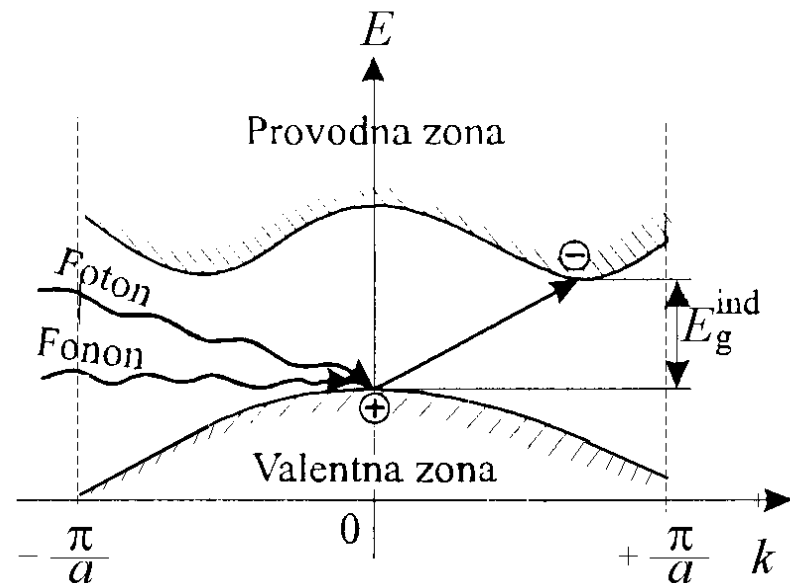
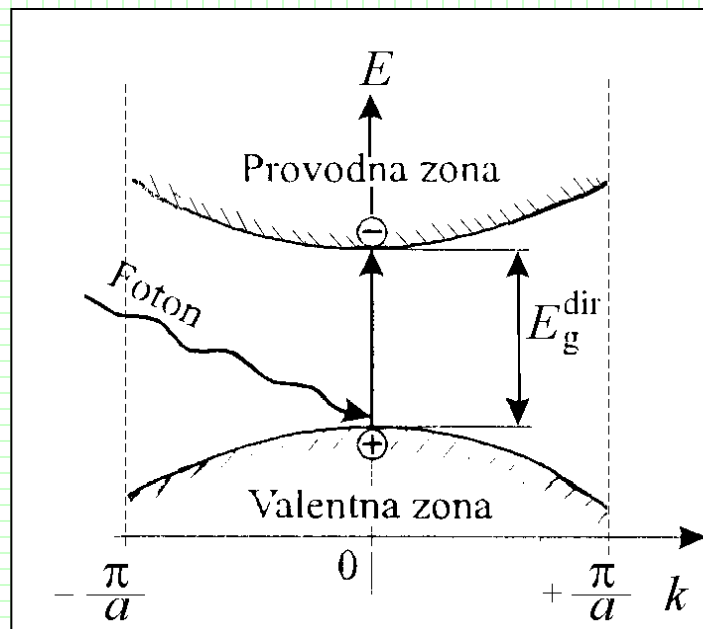
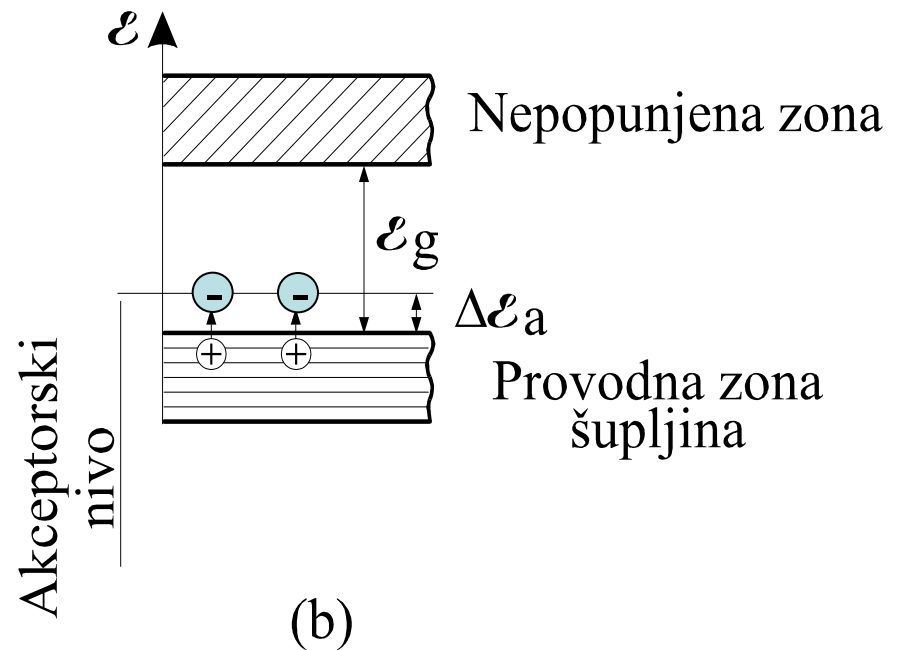
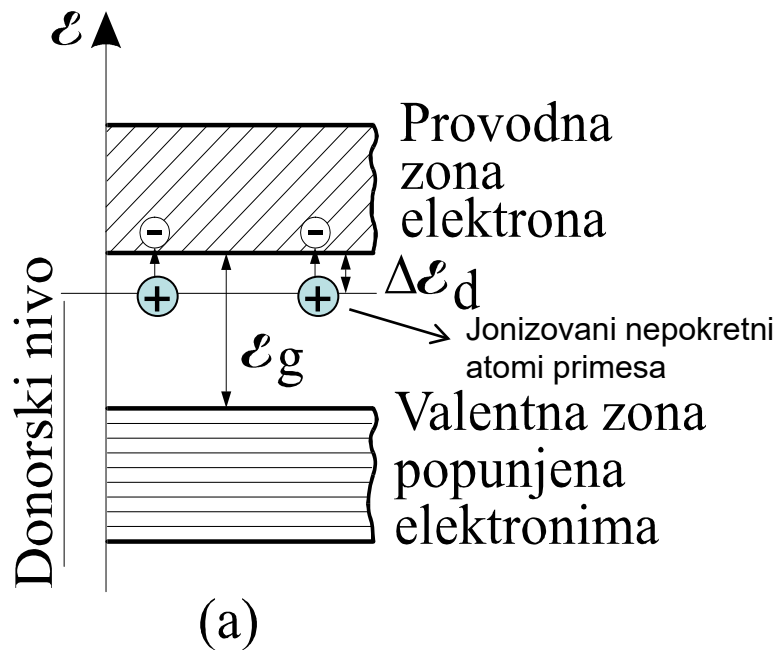


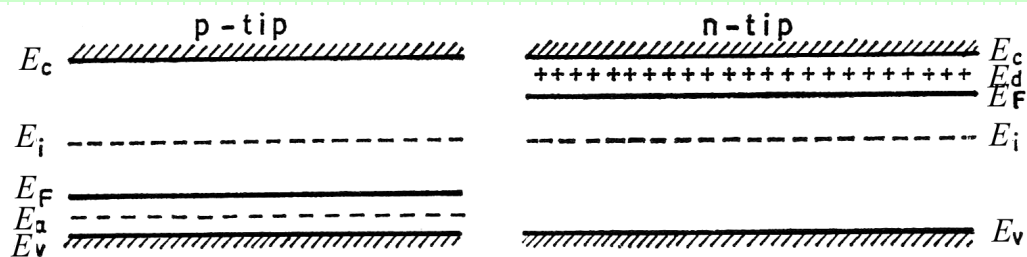
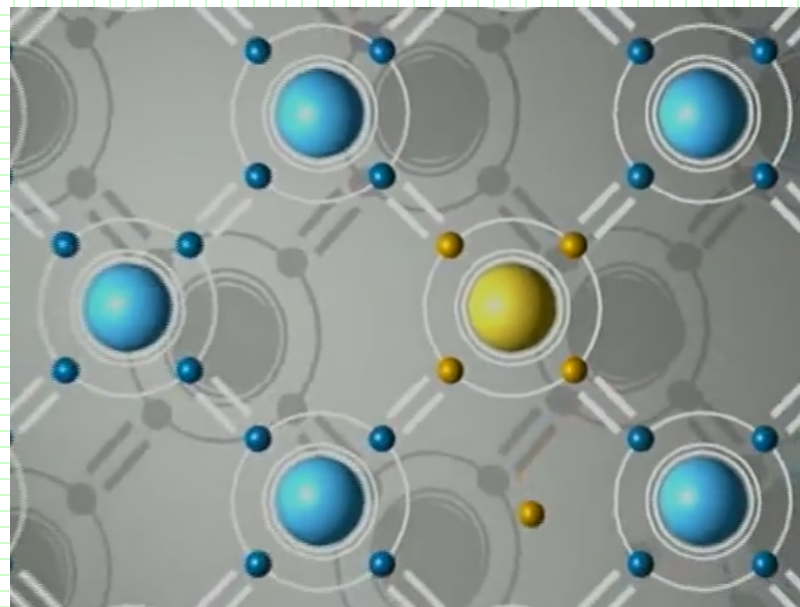
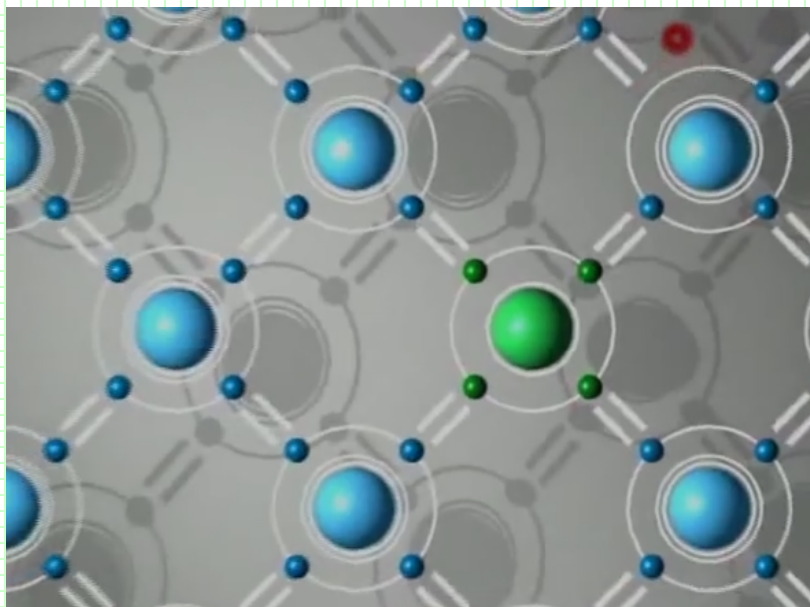
Galijum



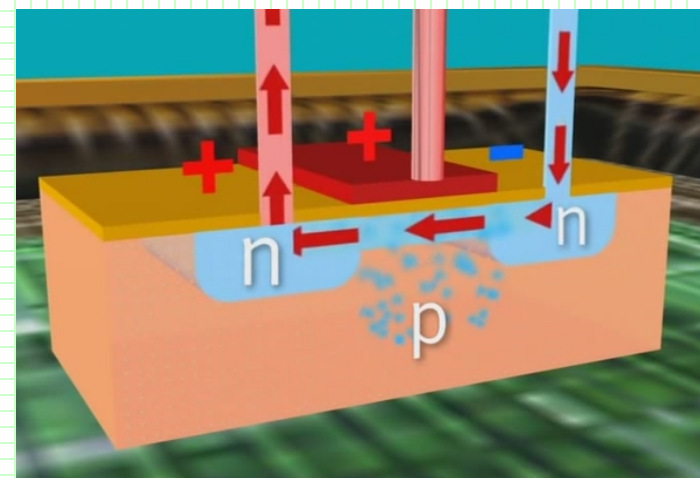
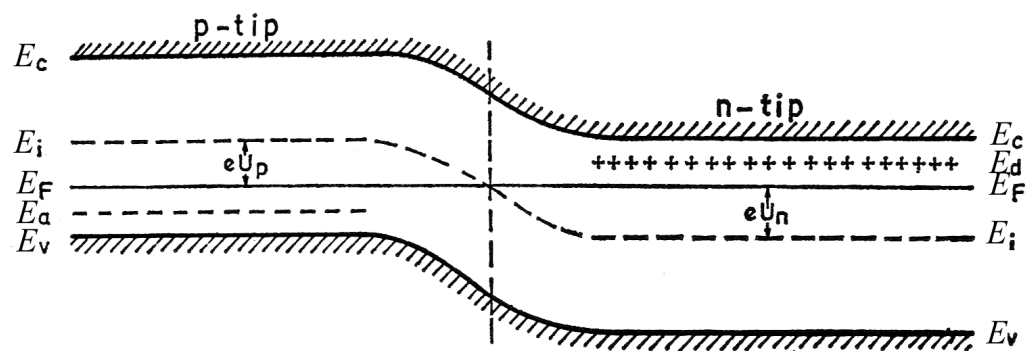
$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial y^2}+\frac{\partial^2\Psi}{\partial z^2}\right)+U(x,y,z)\Psi=i\hbar\frac{\partial\Psi}{\partial t}$$

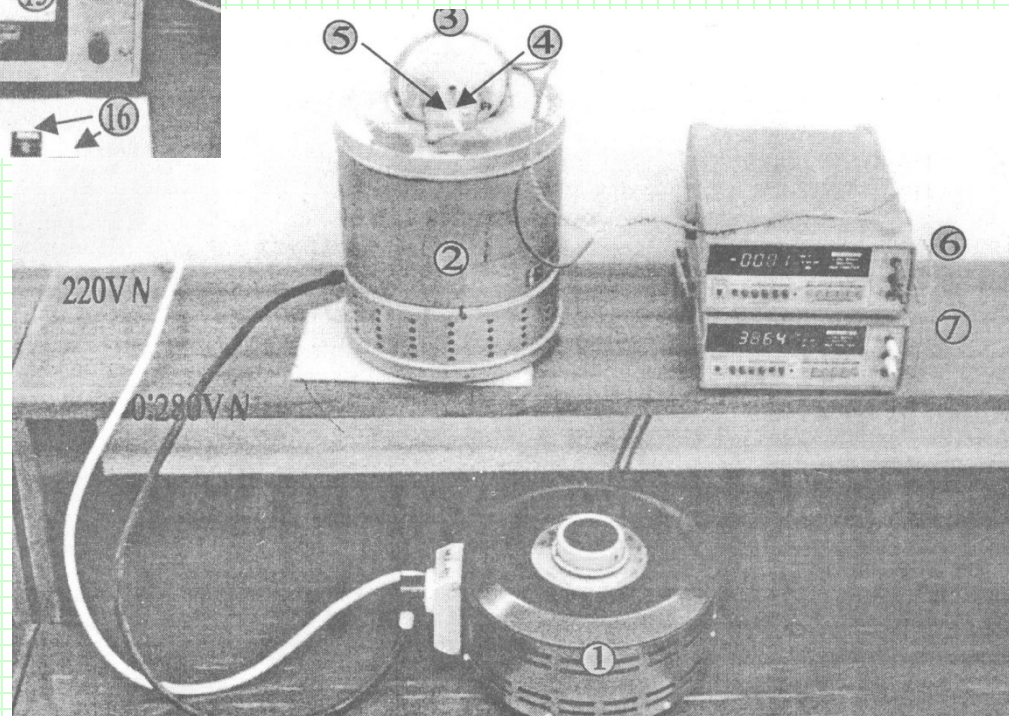
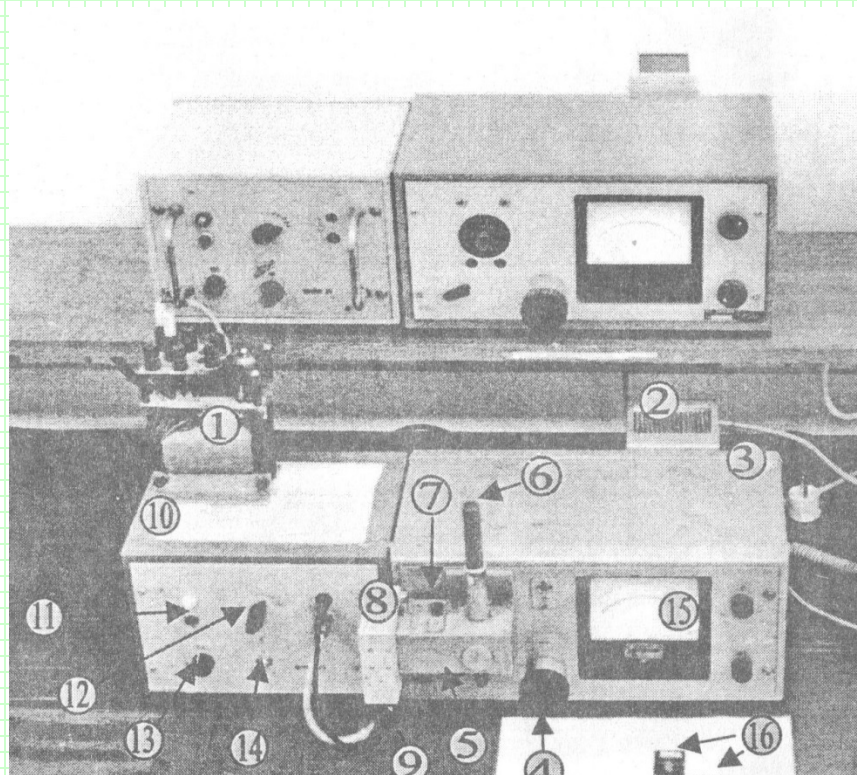




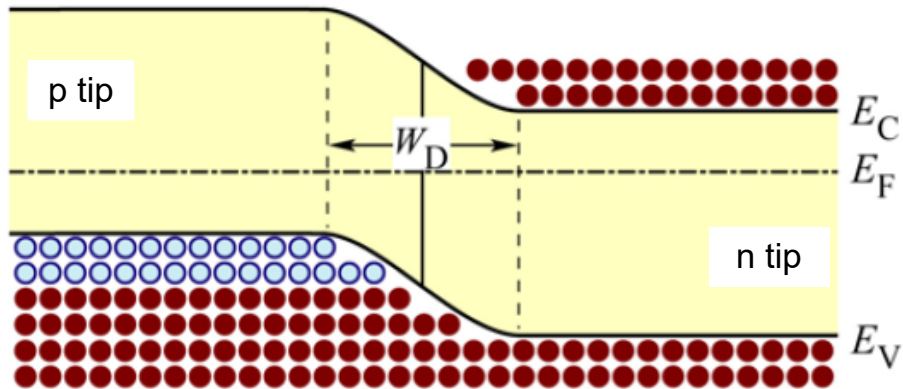


Sredina energetskog
procepa

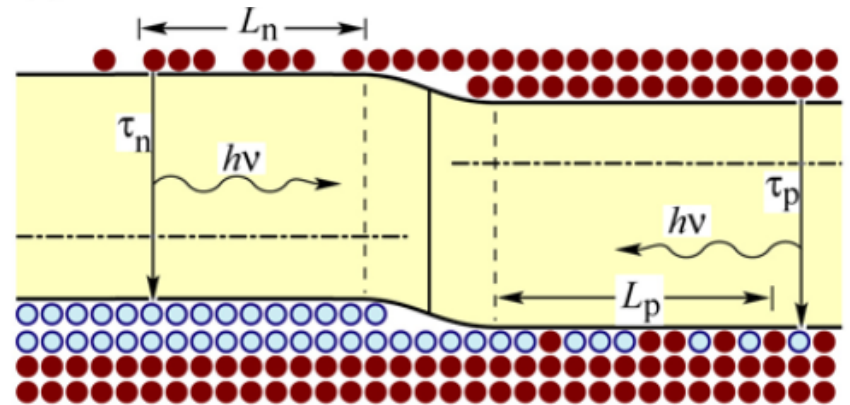




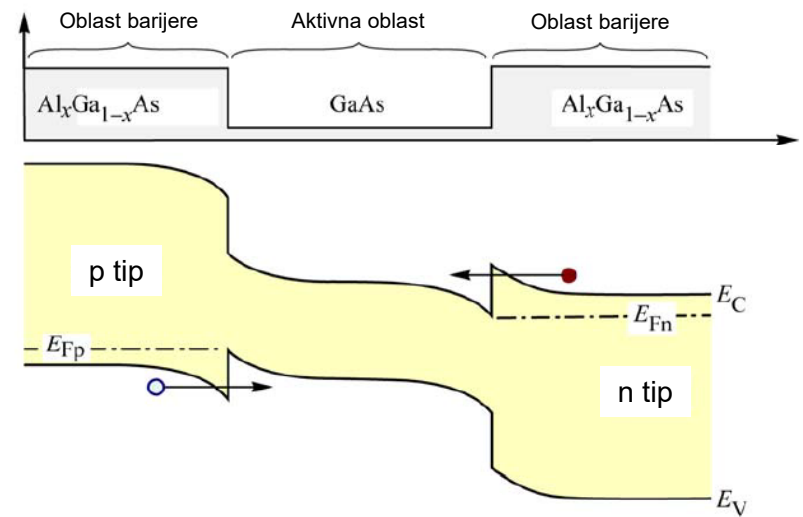
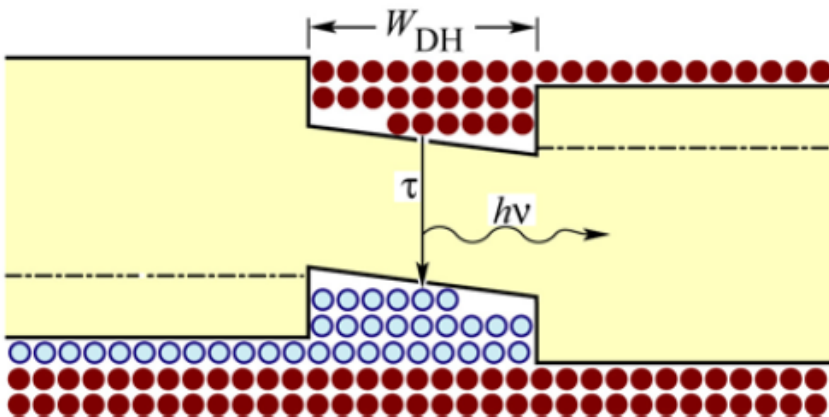
(a) Nepolarisan homospoj

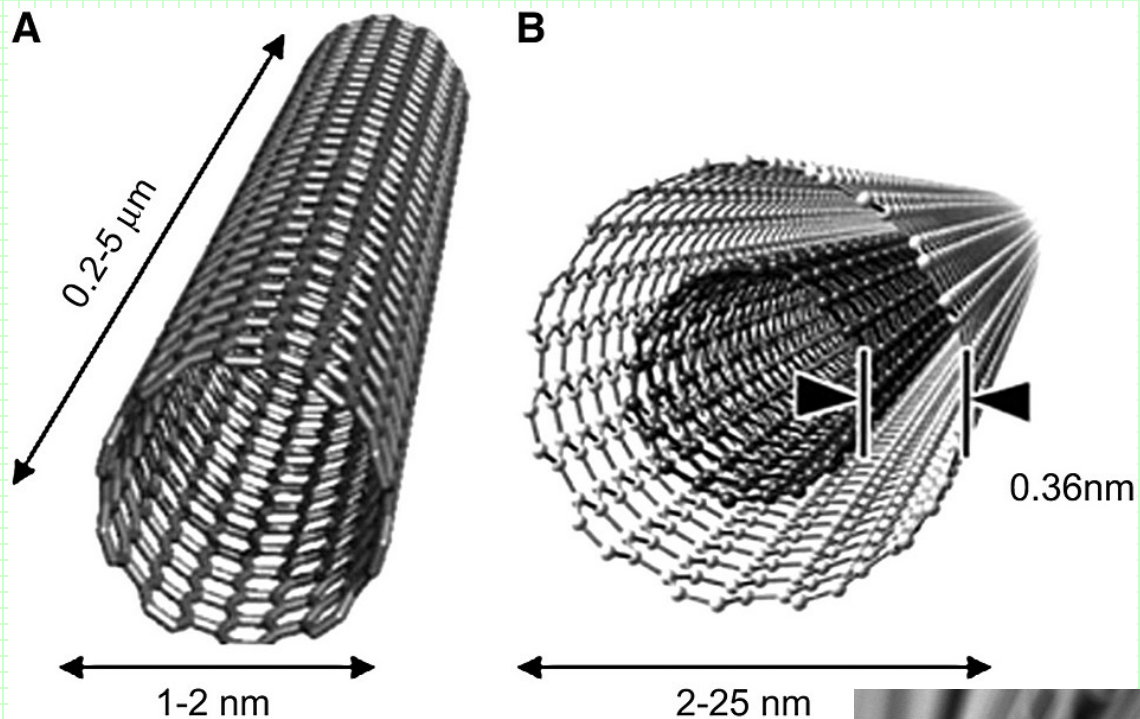


(b) Direktno polarisan homospoj



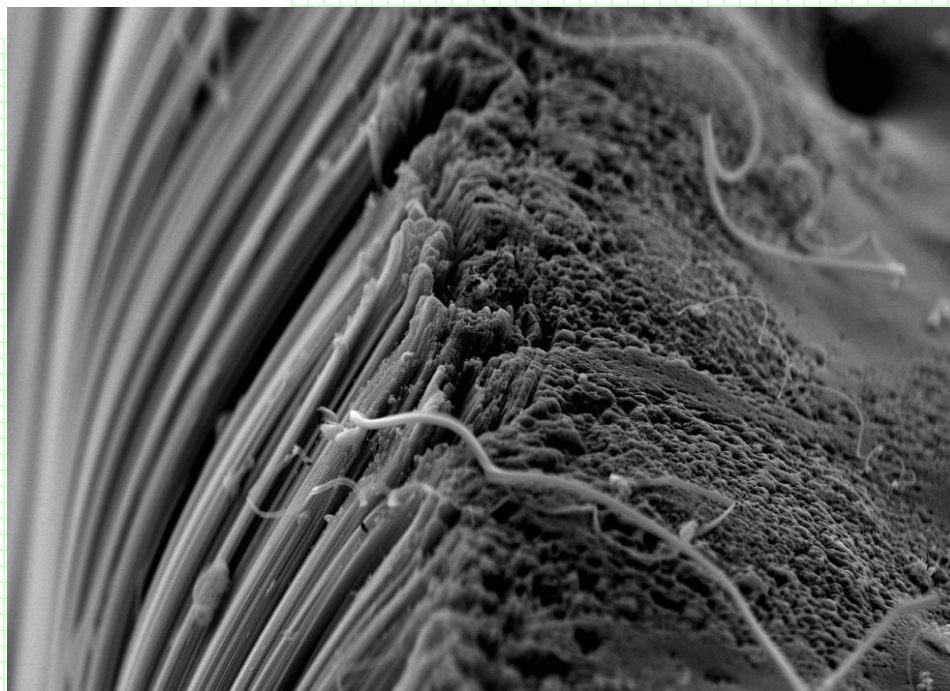
(c) Direktno polarisan heterospoj

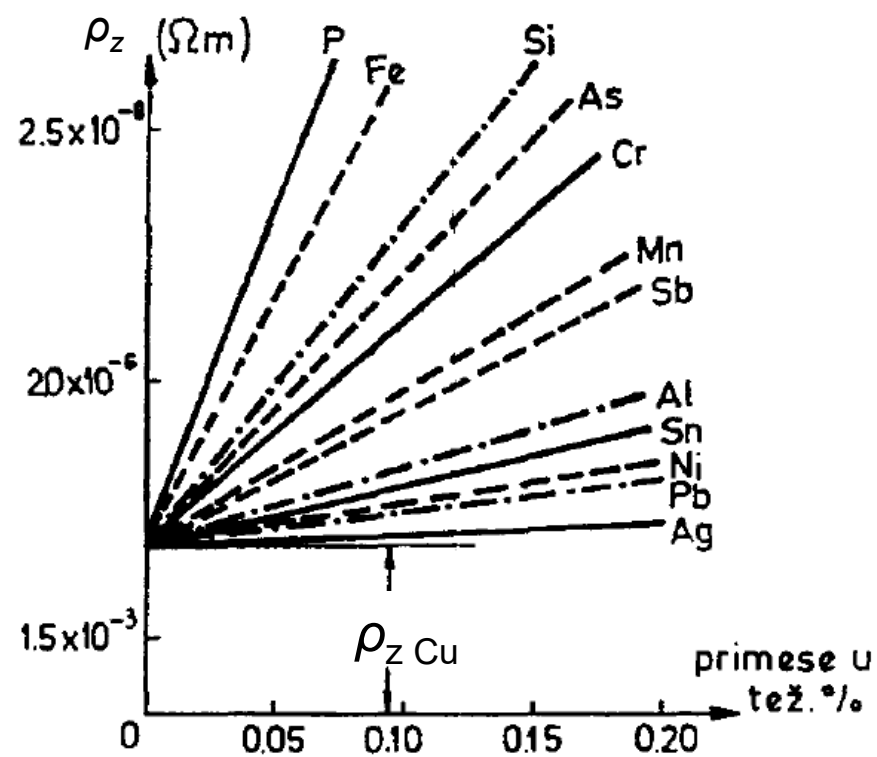
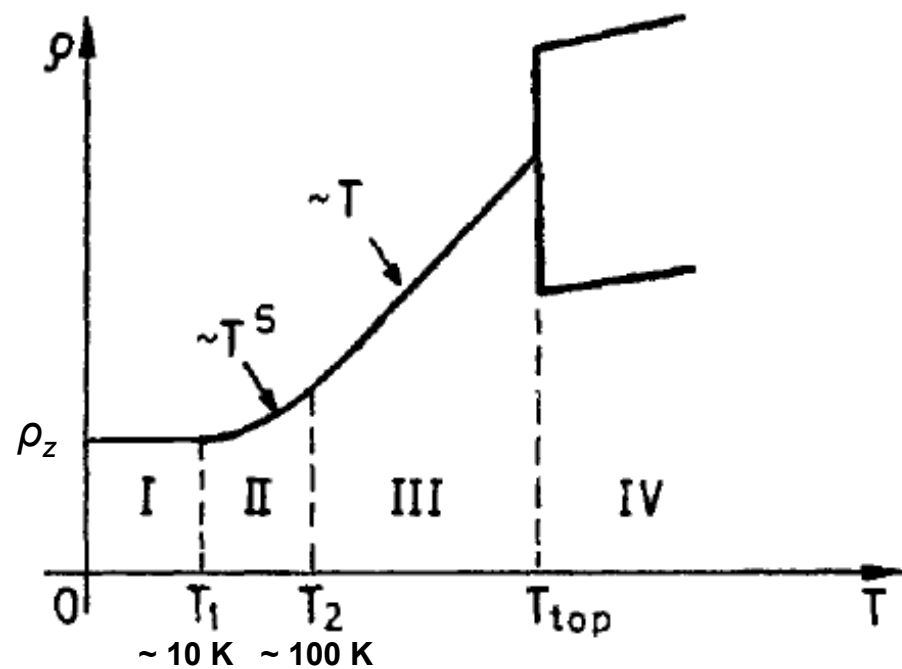


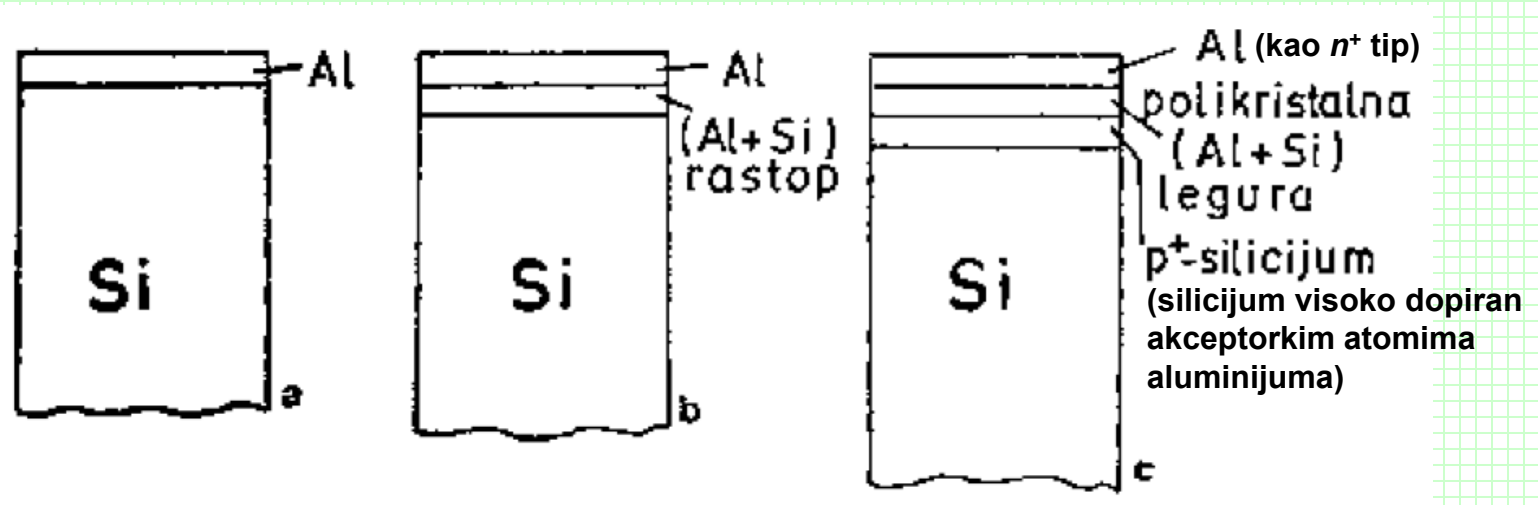


Šematski prikaz
nanocevi sa jednim i dva
zida.

Mikrograf skupine nanocevi.







p^+-n^+ : omski

p^+-p : omski

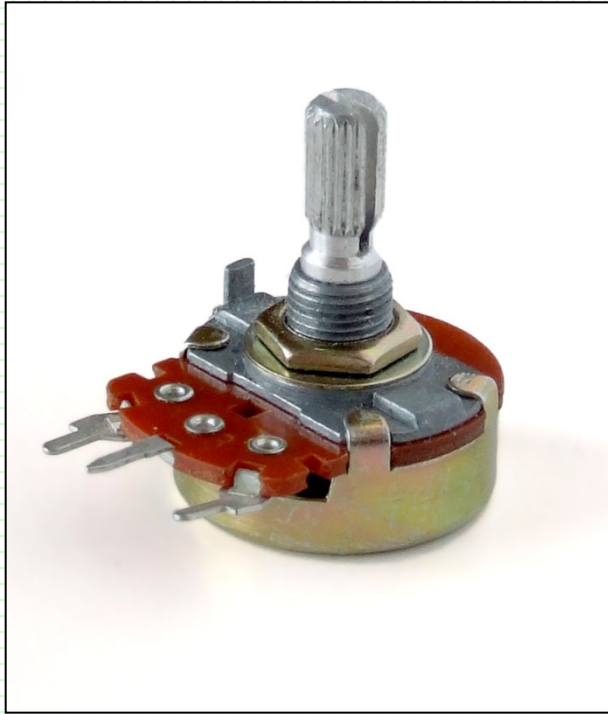
p^+-n : ispravljački
(zahteva sendvič
strukturu p^+-n^+-n
da bi bio omski)

$$d_p = \frac{1}{N_a} \sqrt{\frac{2\varepsilon_0\varepsilon_r}{e} U_B N},$$

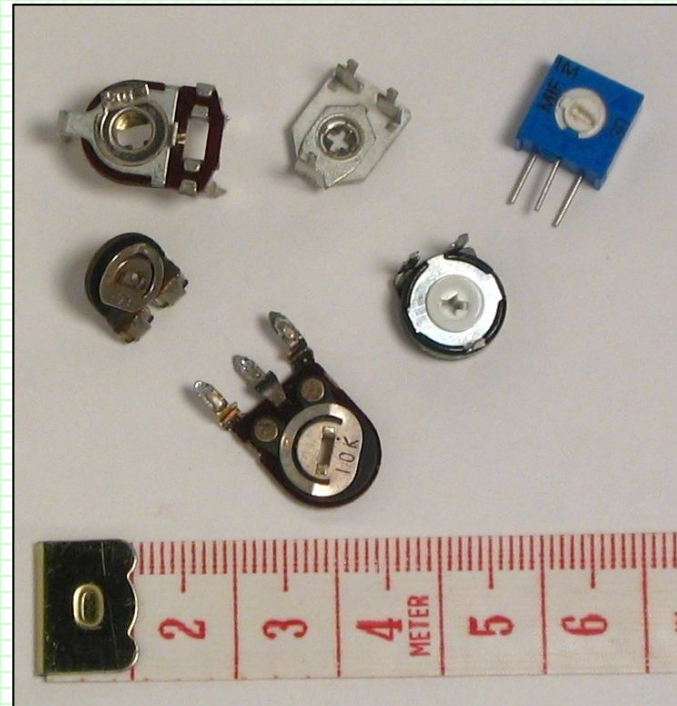
$$d_n = \frac{1}{N_d} \sqrt{\frac{2\varepsilon_0\varepsilon_r}{e} U_B N},$$

$$d = d_p + d_n = \sqrt{\frac{2\varepsilon_0\varepsilon_r}{e} \frac{U_B}{N}},$$

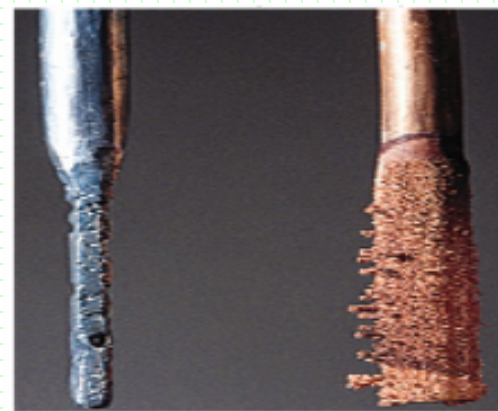
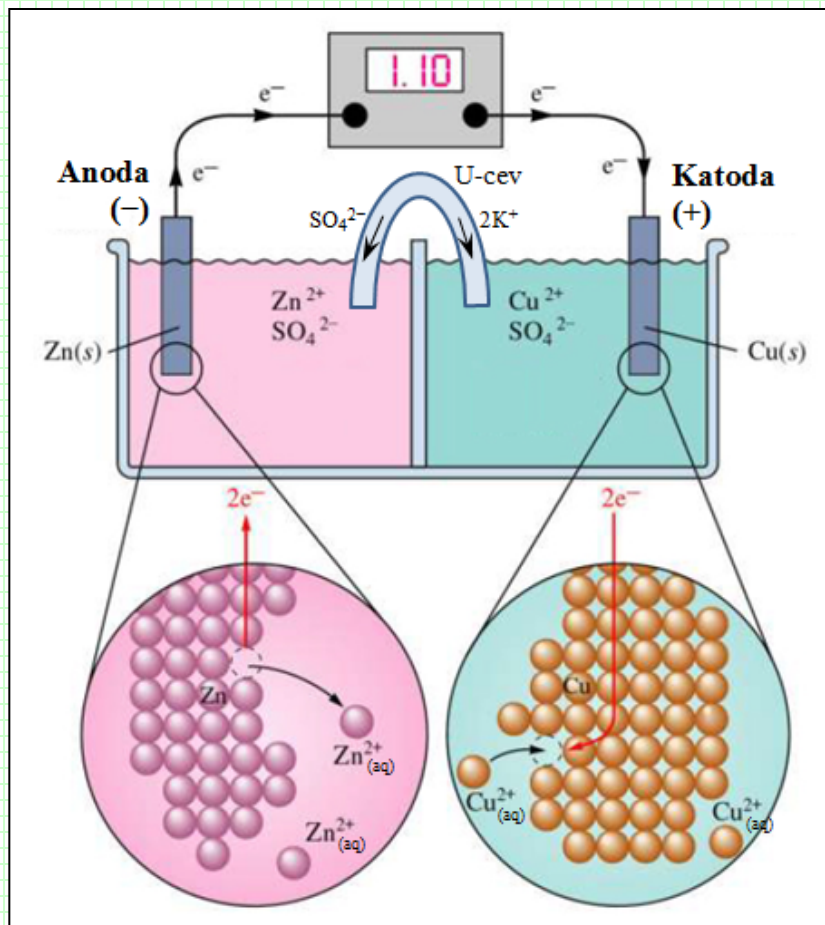
$$N = N_a N_d / (N_a + N_d)$$



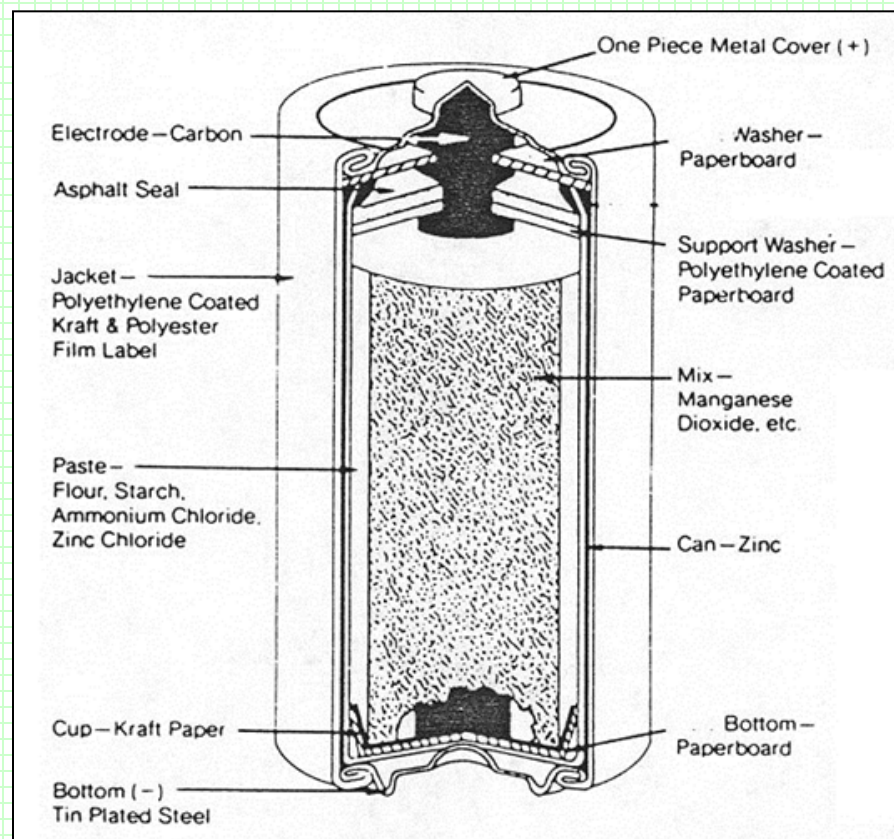
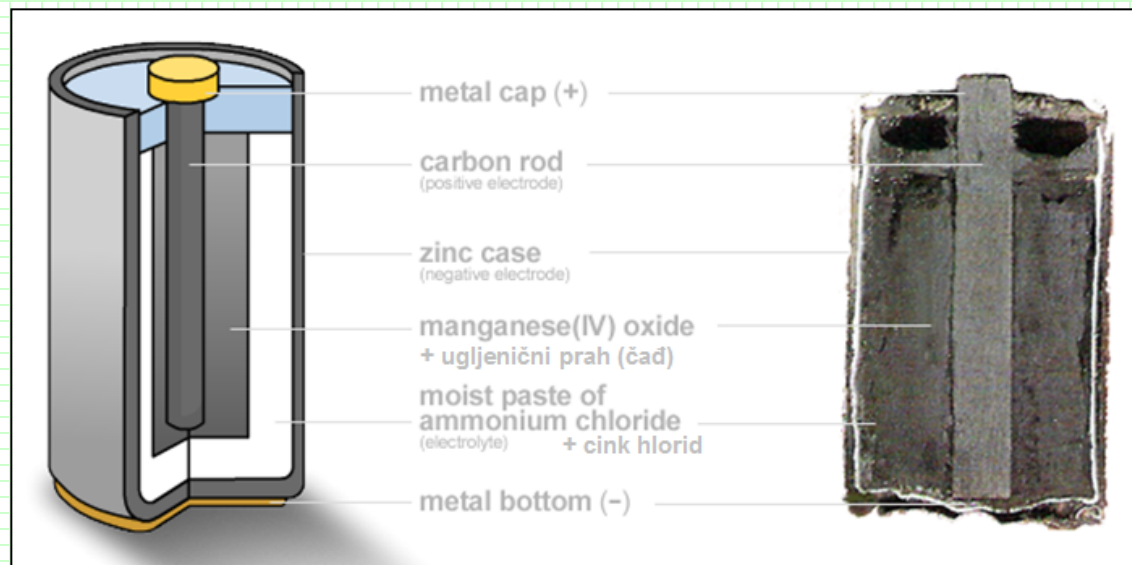
Potenciometar

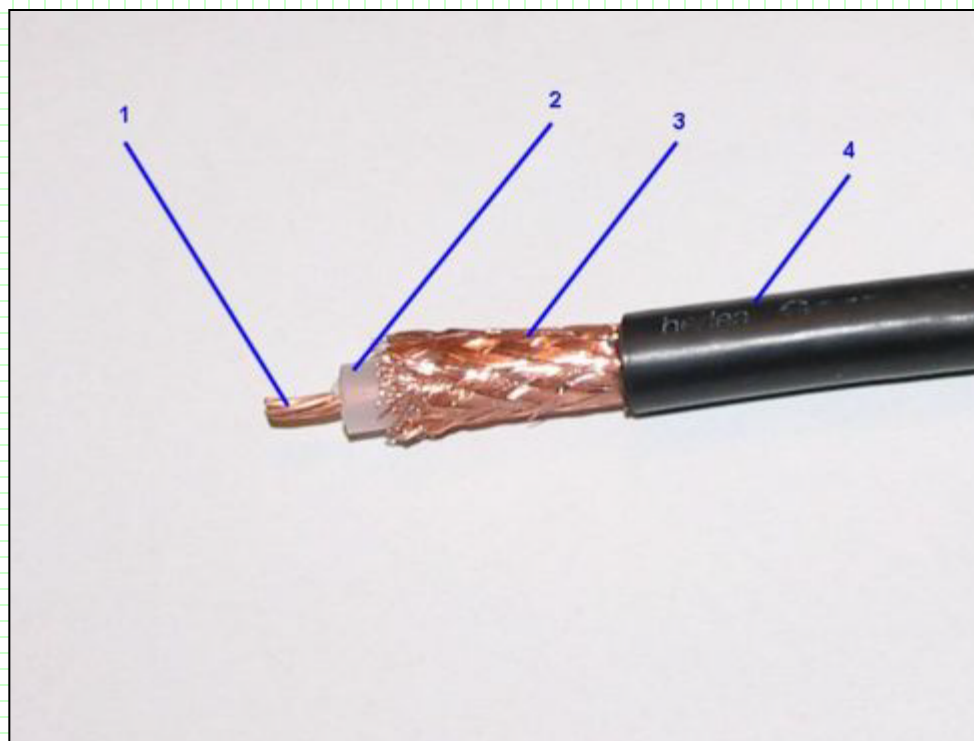


Trimeri

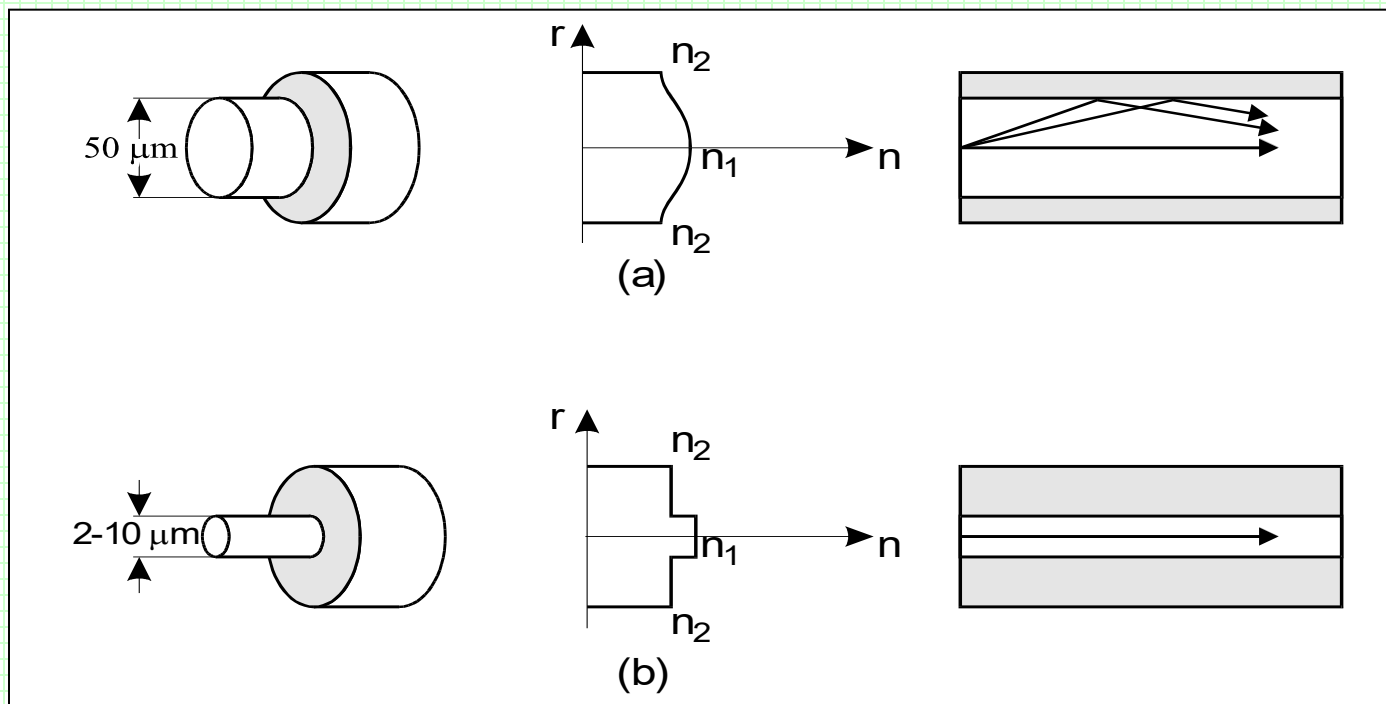


Atomi cinka sa anode odlaze u rastvor, čime se ona troši, dok se atomi bakra iz elektrolita talože na bakarnoj katodi, zbog čega ona raste.

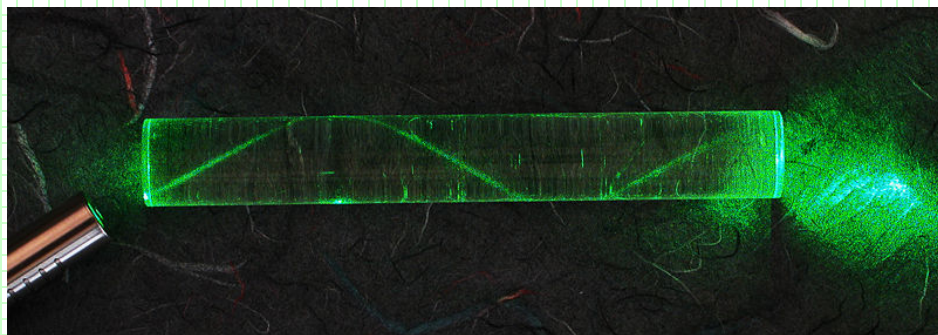




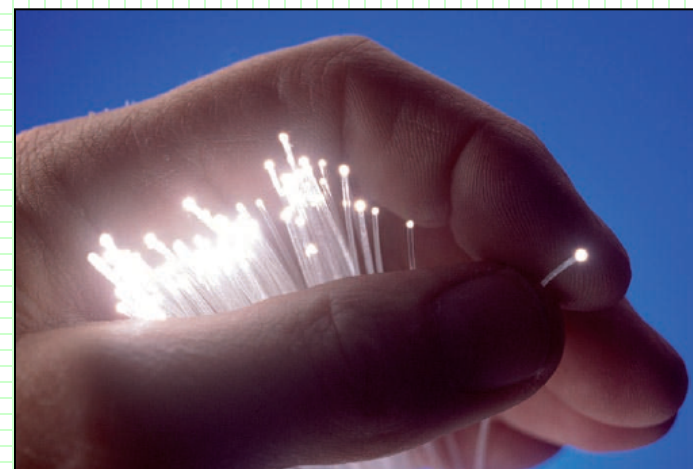
- Koaksijalni kabl RG-213 (karakteristične impedanse 50Ω).
1. Unutrašnji provodnik (jedna žica ili više upredenih)
 2. Izolator.
 3. Spoljašnji provodnik (sa ulogom zaštitnog plašta).
 4. Spoljašnja izolatorska zaštita.

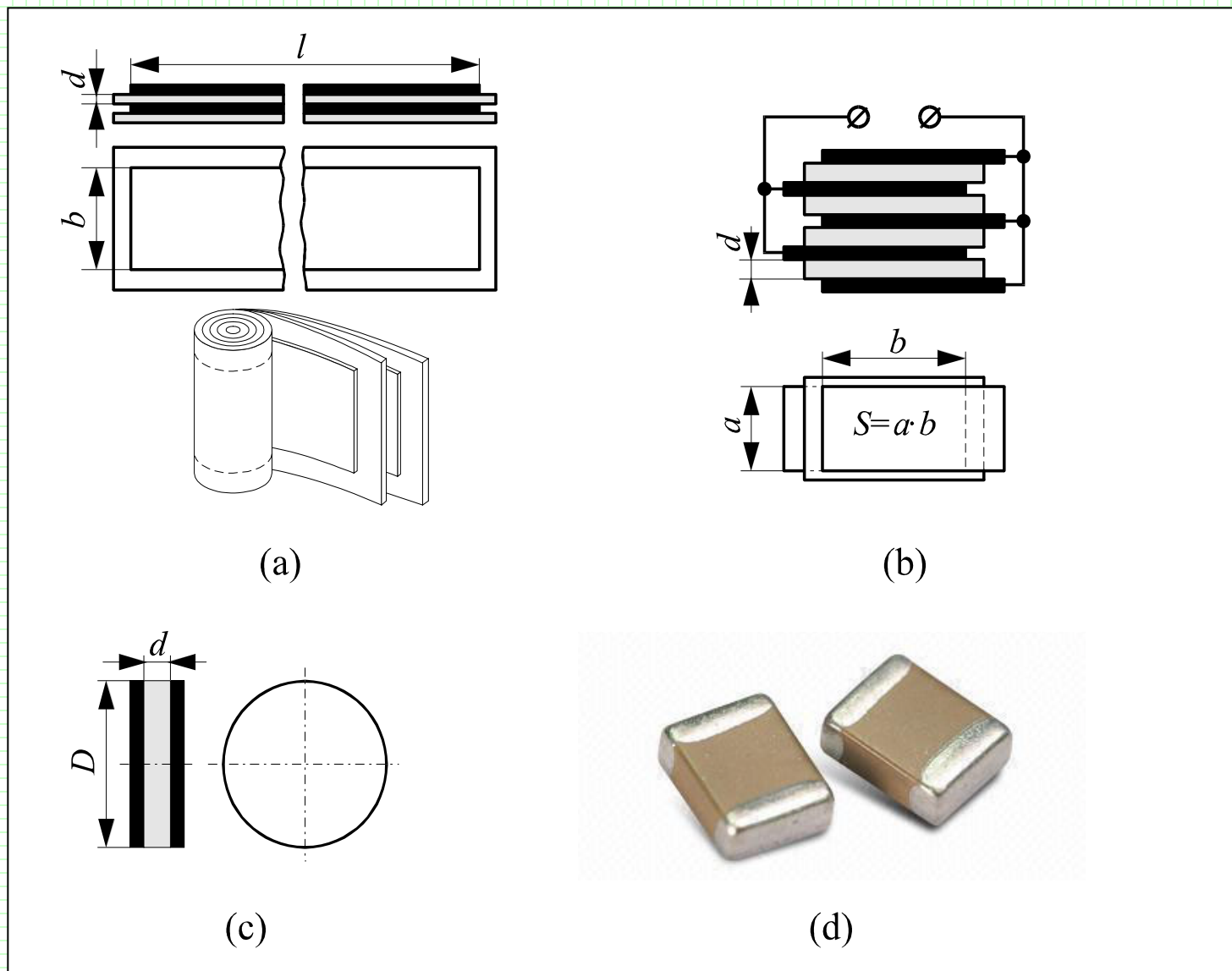


Šematski prikaz: (a) multimodnog i (b) monomodnog optičkog vlakna, sa načinom promene indeksa prelamanja duž prečnika vlakna.

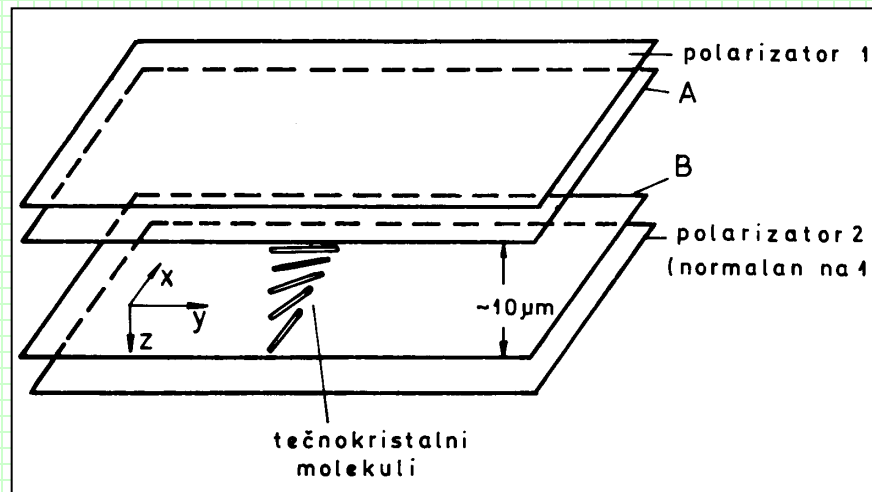


Prostiranje laserskog snopa kroz akrilnu šipku koja služi kao multimodno optičko vlakno





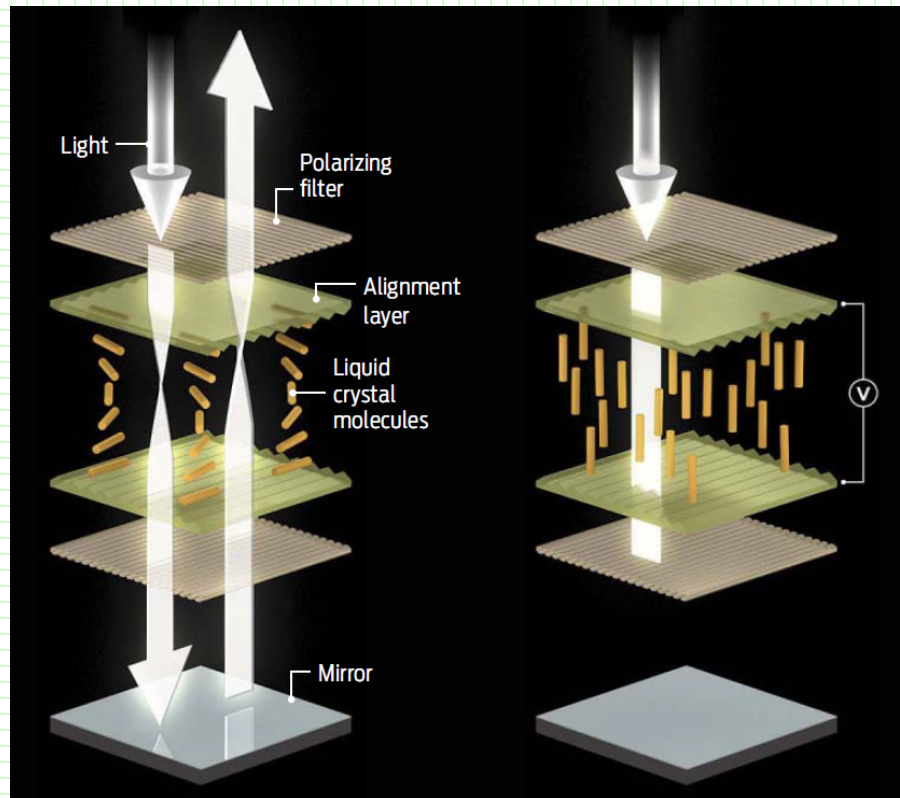
Šematski prikaz različnih konstrukcij kondenzatora stalne kapacitivnosti: (a) cilindrični sa više obloga; (b) pločasti sa više obloga; (c) disk kondenzatori; (d) čip-kondenzatori.

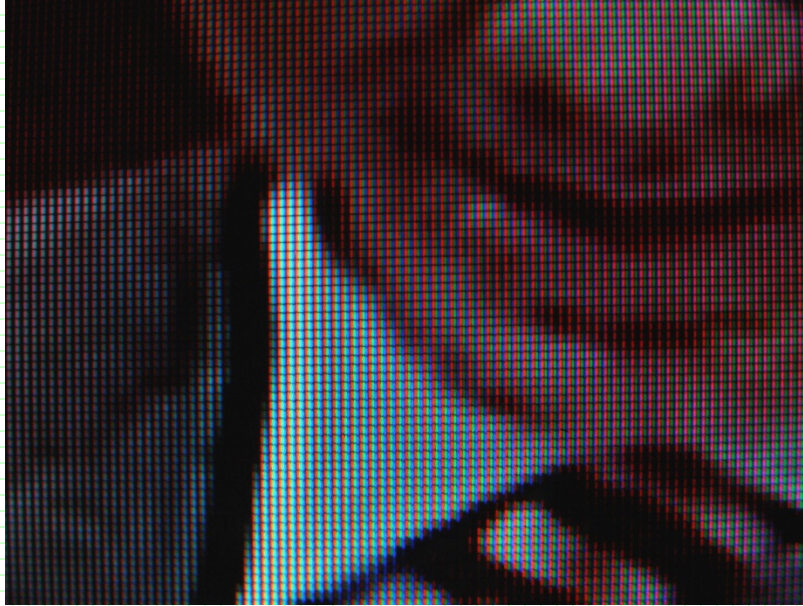


Šematski prikaz ćelije jednog tipa tečnokristalnog displeja

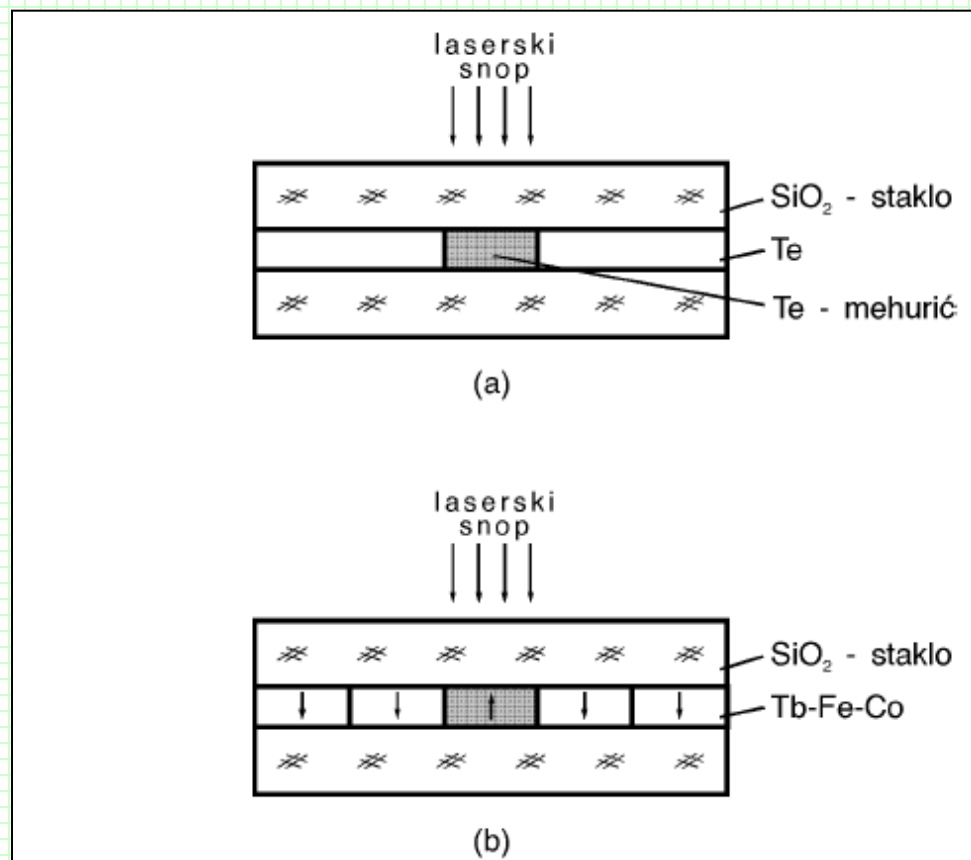
Polarizatorski filter
(krsitalni sloj)

Analizatorski kristal

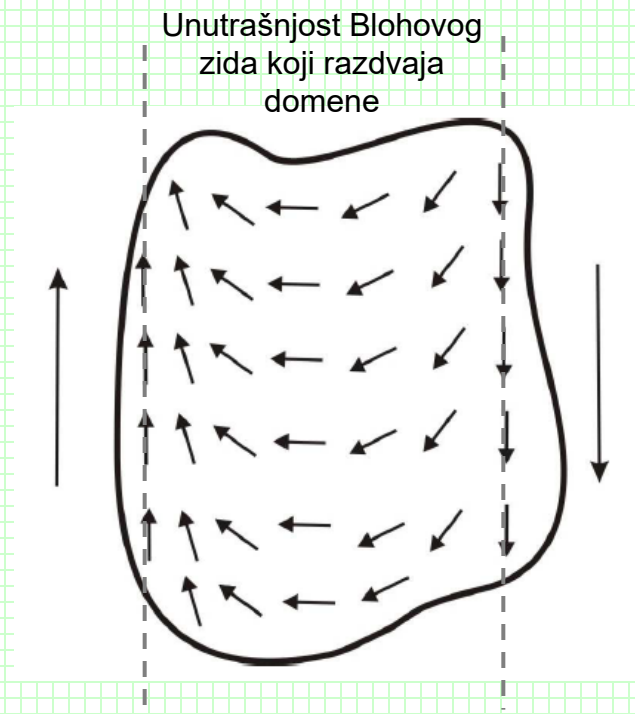
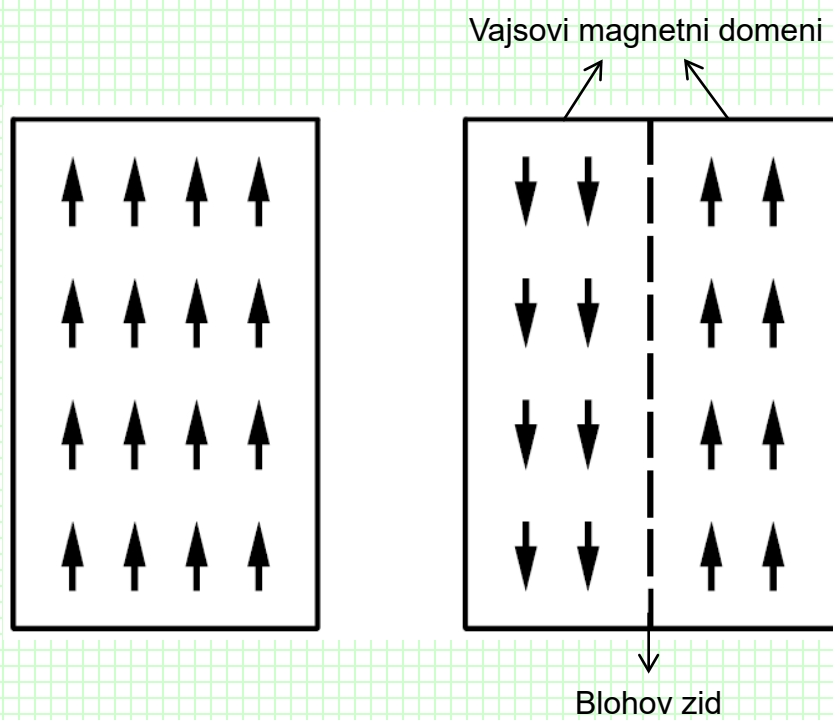
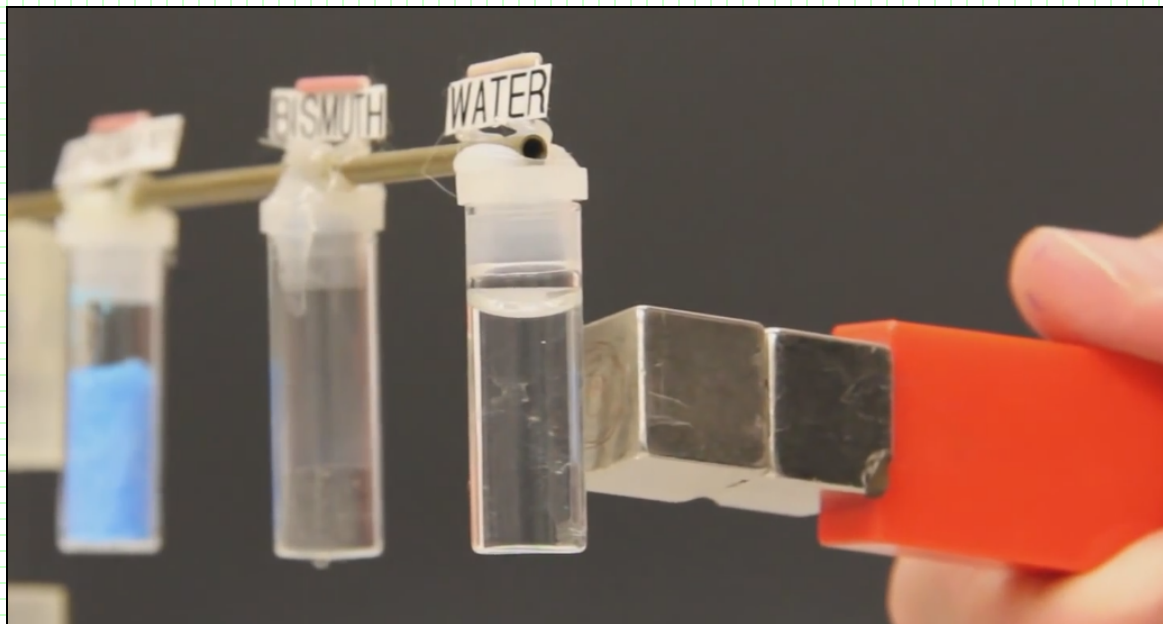


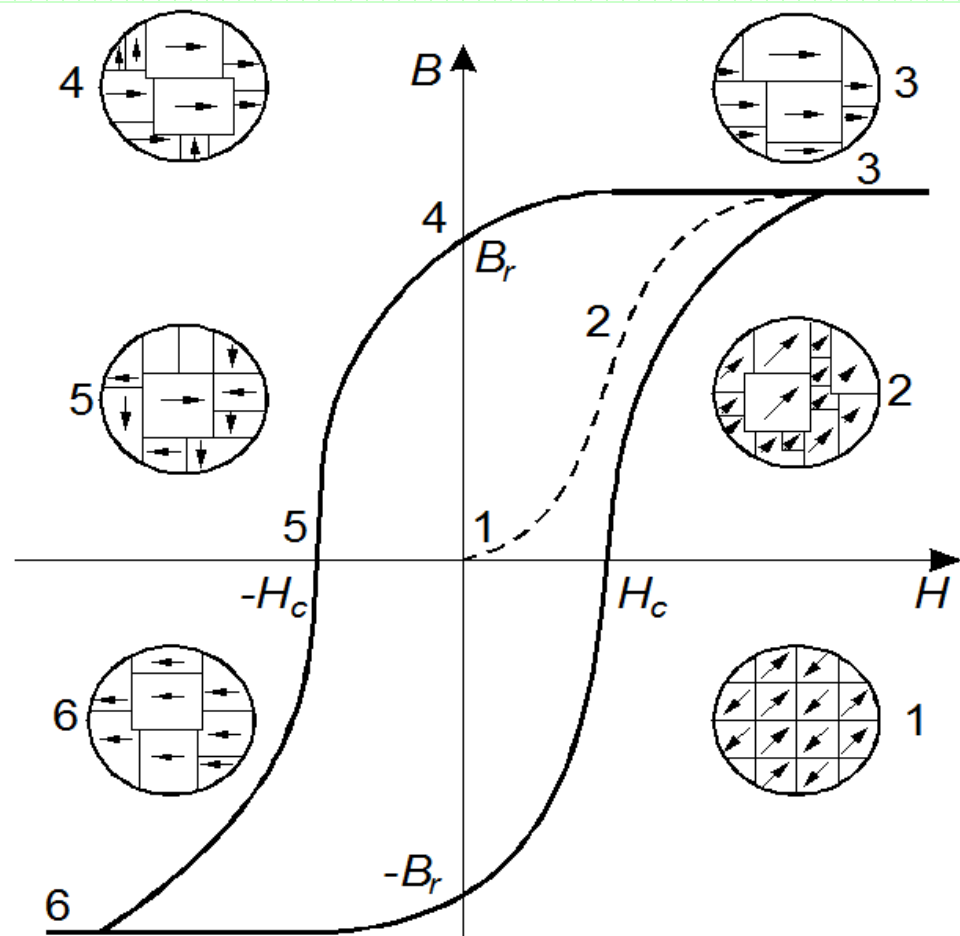
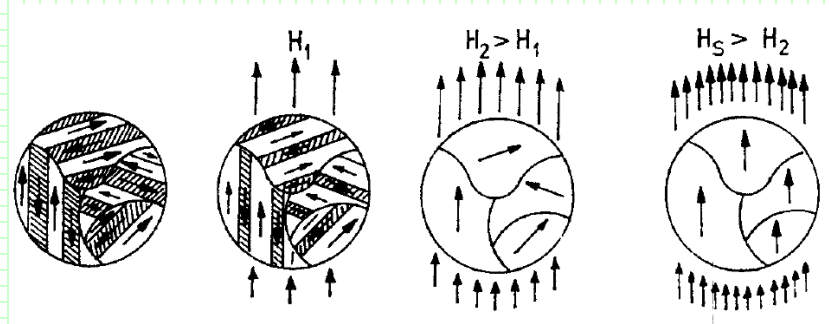


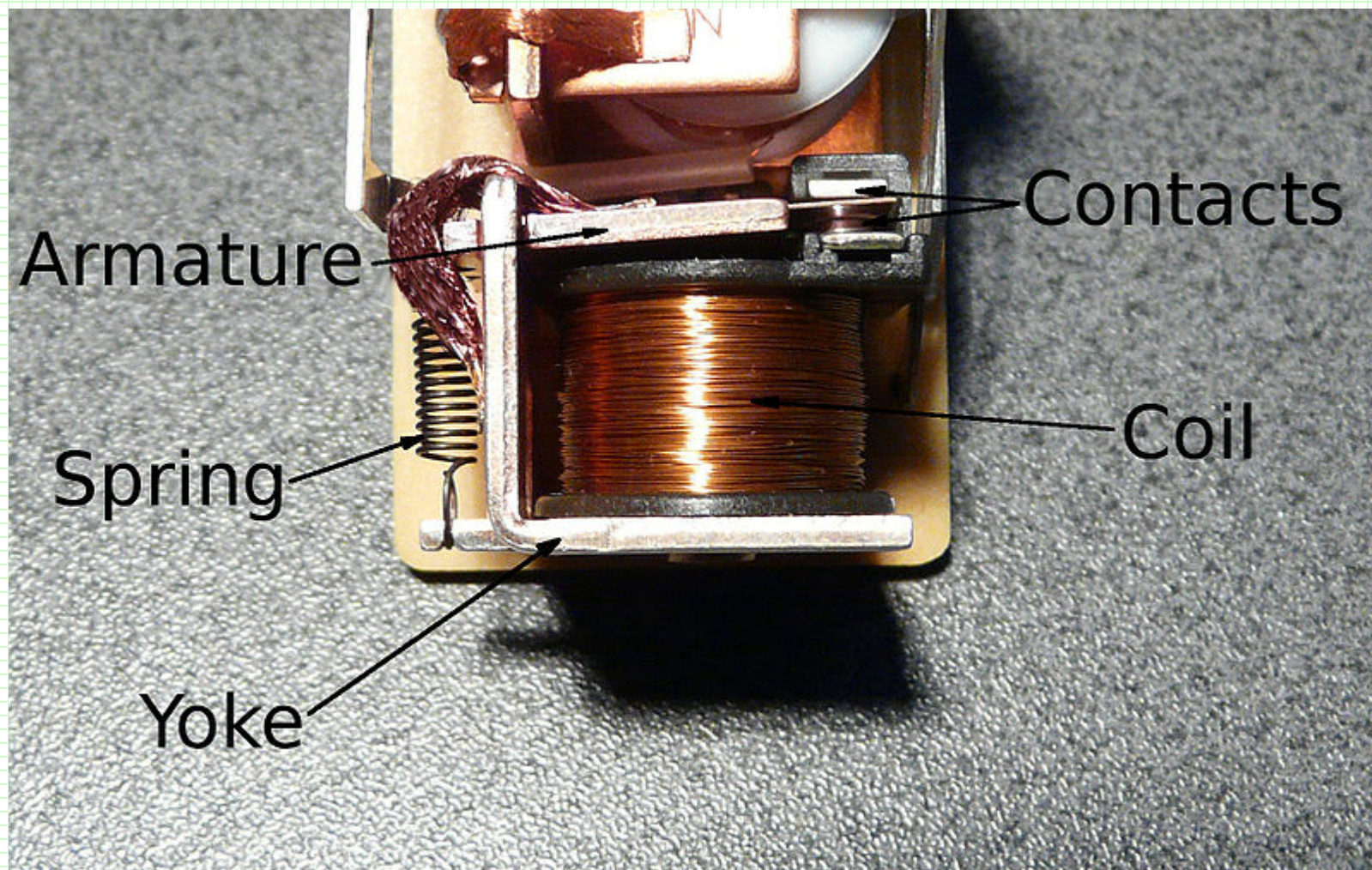




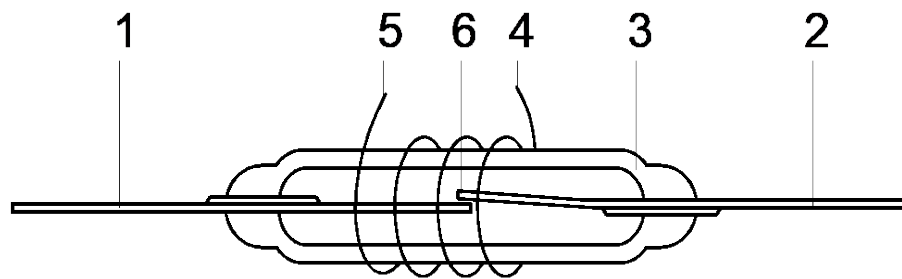
Šematski prikaz: (a) optičke memorije na bazi telura (Te) i (b) magnetooptičke memorije na bazi tiberijum-gvožđe-kobalt legure (Tb-Fe-Co).



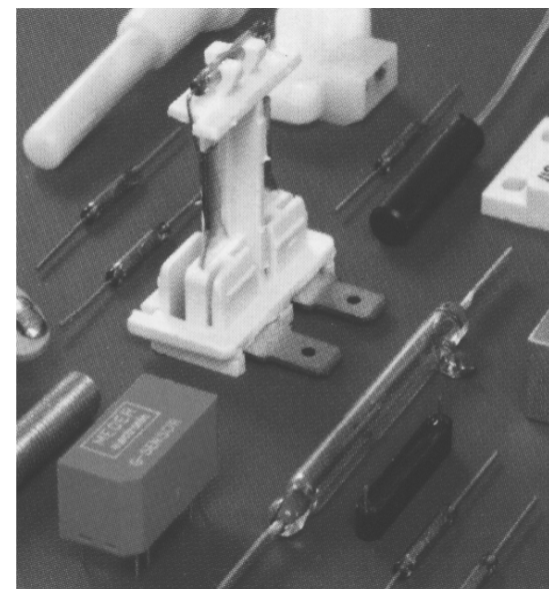




Armature = kotva, Coil = namotaj sa ulogom elektromagneta,
Spring = opruga, Yoke = ram

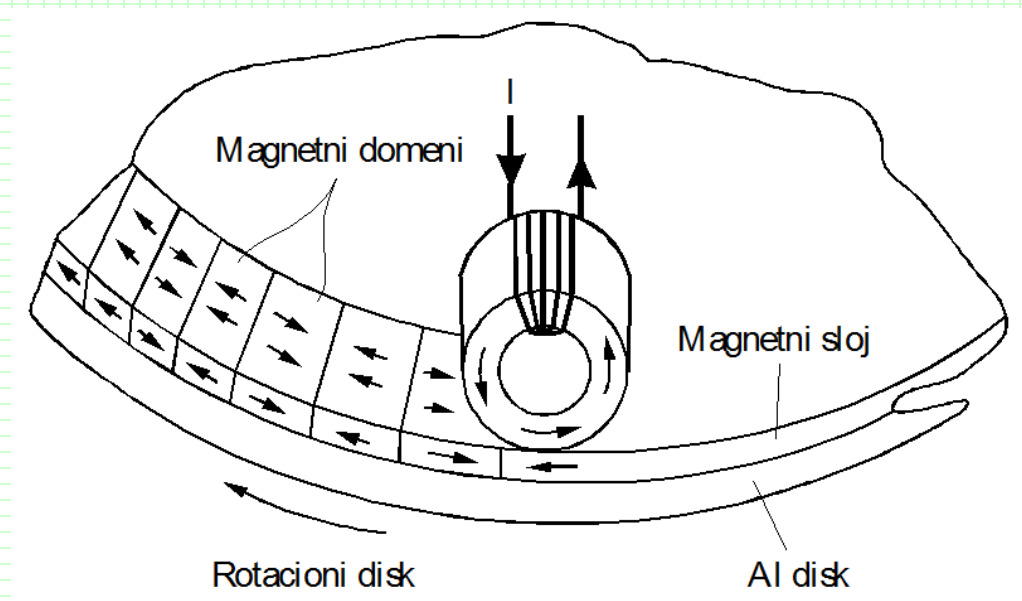


(a)

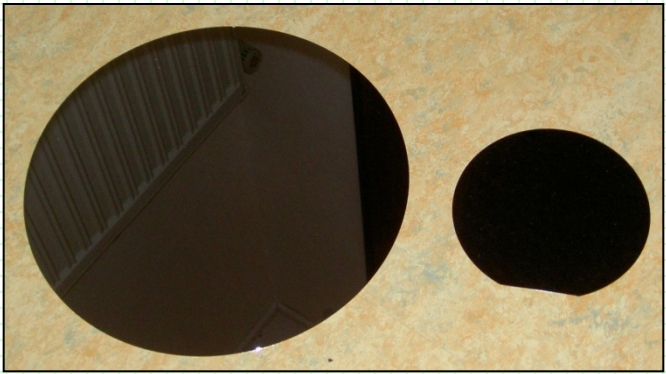


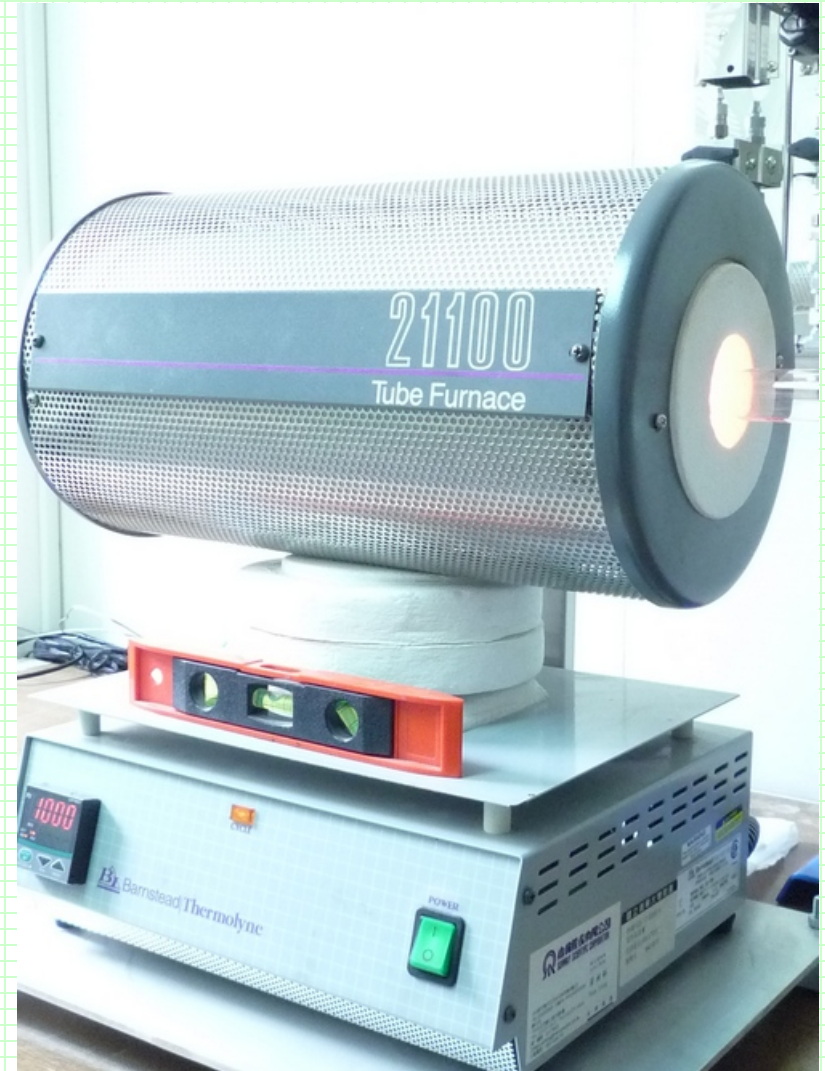
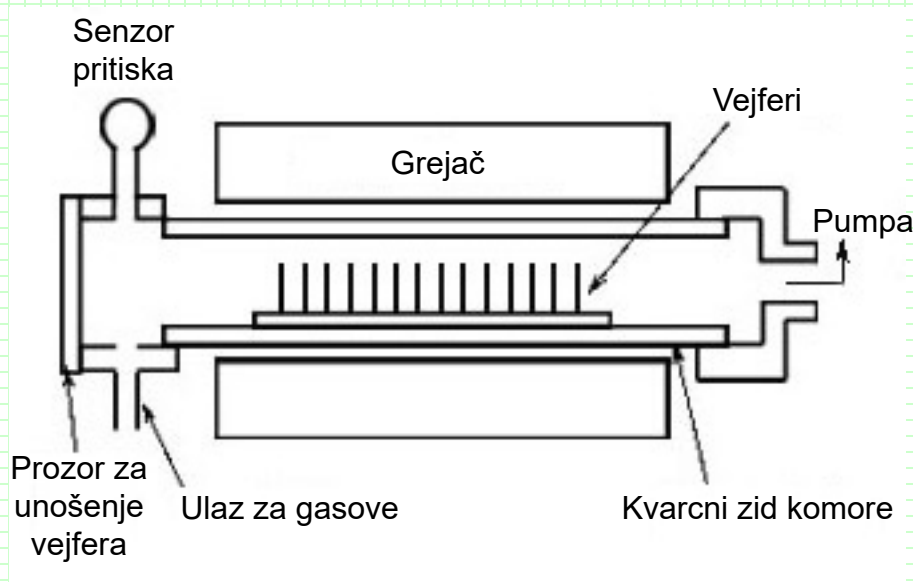
(b)

Prikaz (a) poprečnog preseka rid-relea, sa kalemom oko staklene cevčice i
 (b) fotografija nekoliko tipova rid-relea firme Meder.

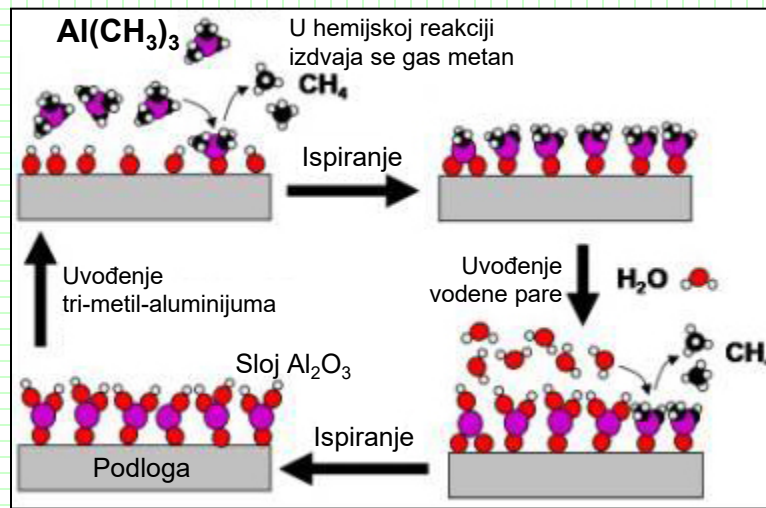


Šematski prikaz upisivanja i očitavanja podataka sa magnetnog diska, korišćenjem magnetne induktivne glave, na principu elektromagnetne indukcije



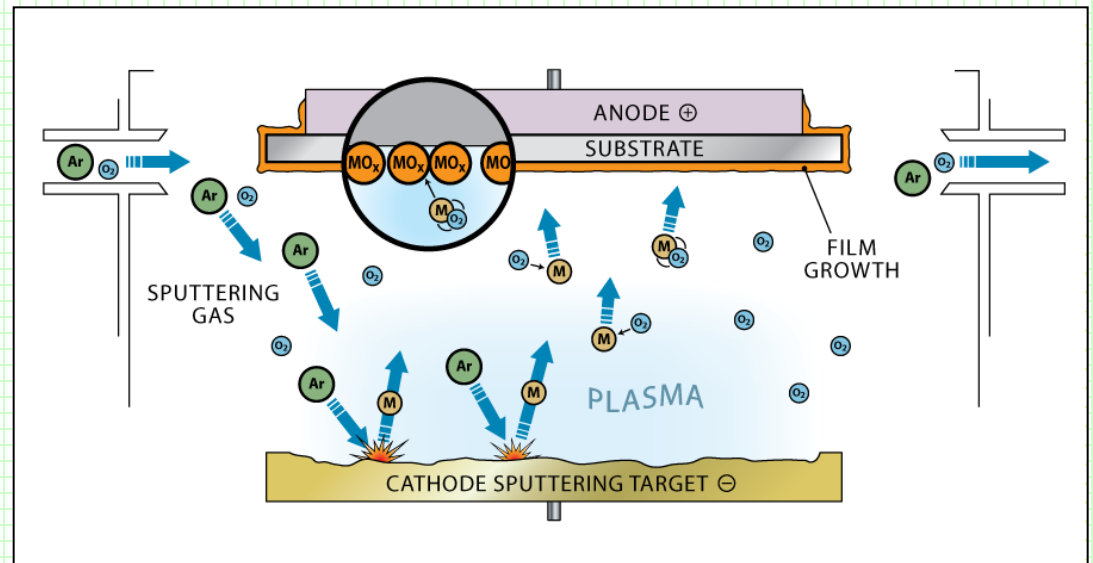
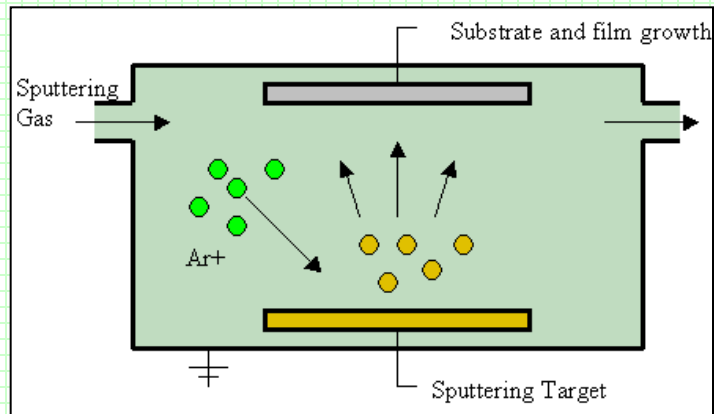


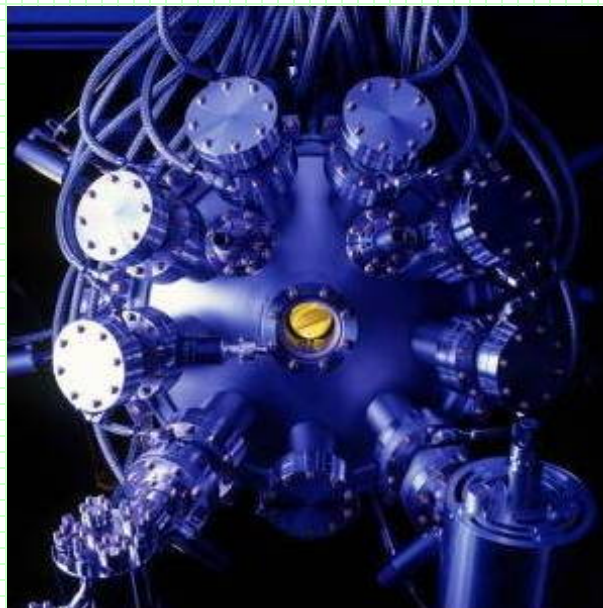
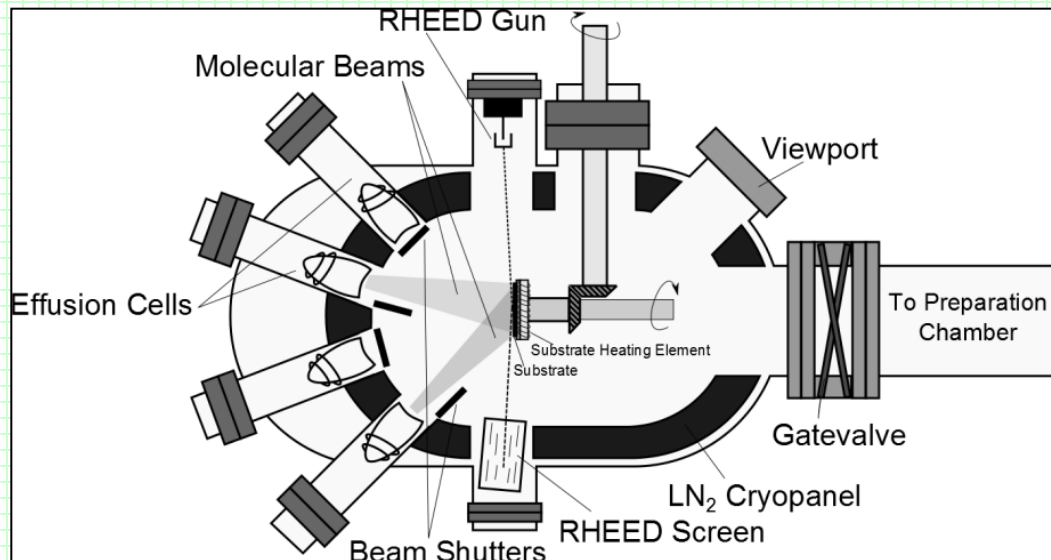
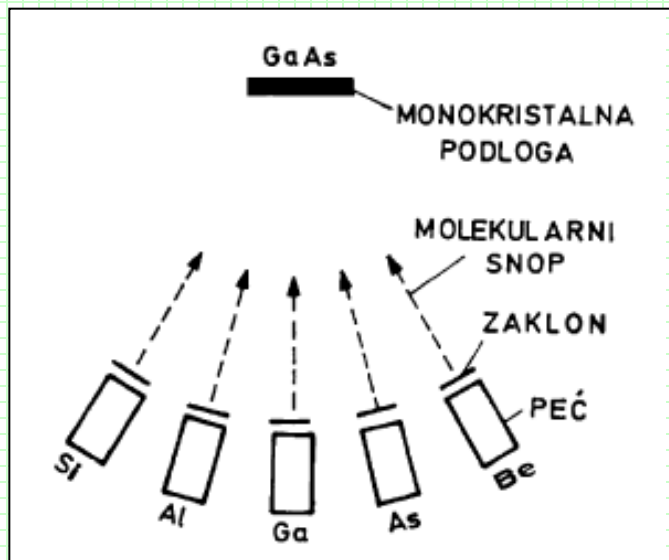
Šema i izgled CVD reaktora



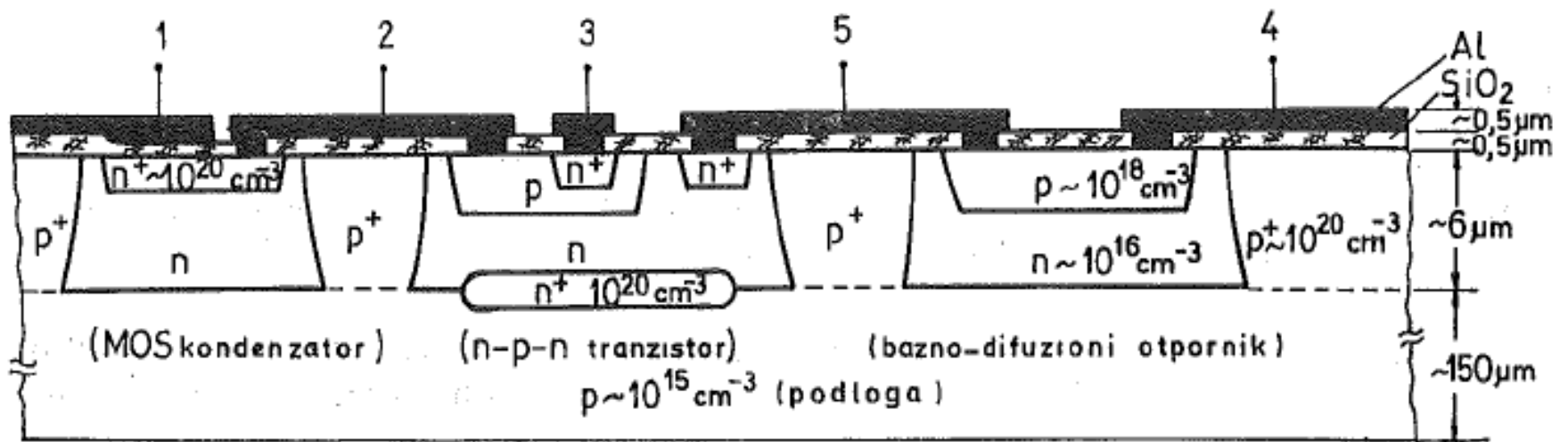
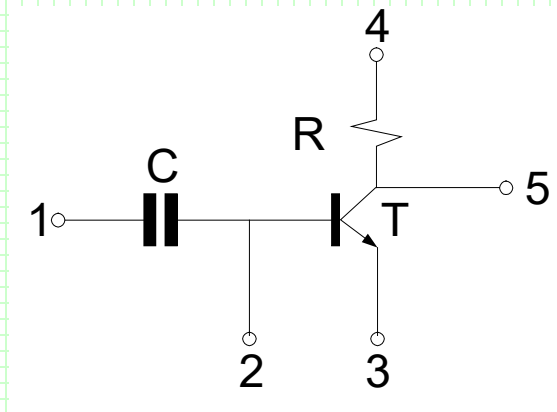
Šematski prikaz dvostepenog ALD postupka na primeru izrade tankog sloja Al_2O_3 , pri čemu se hemijska reakcija odvija na površini podloge (supstrata).

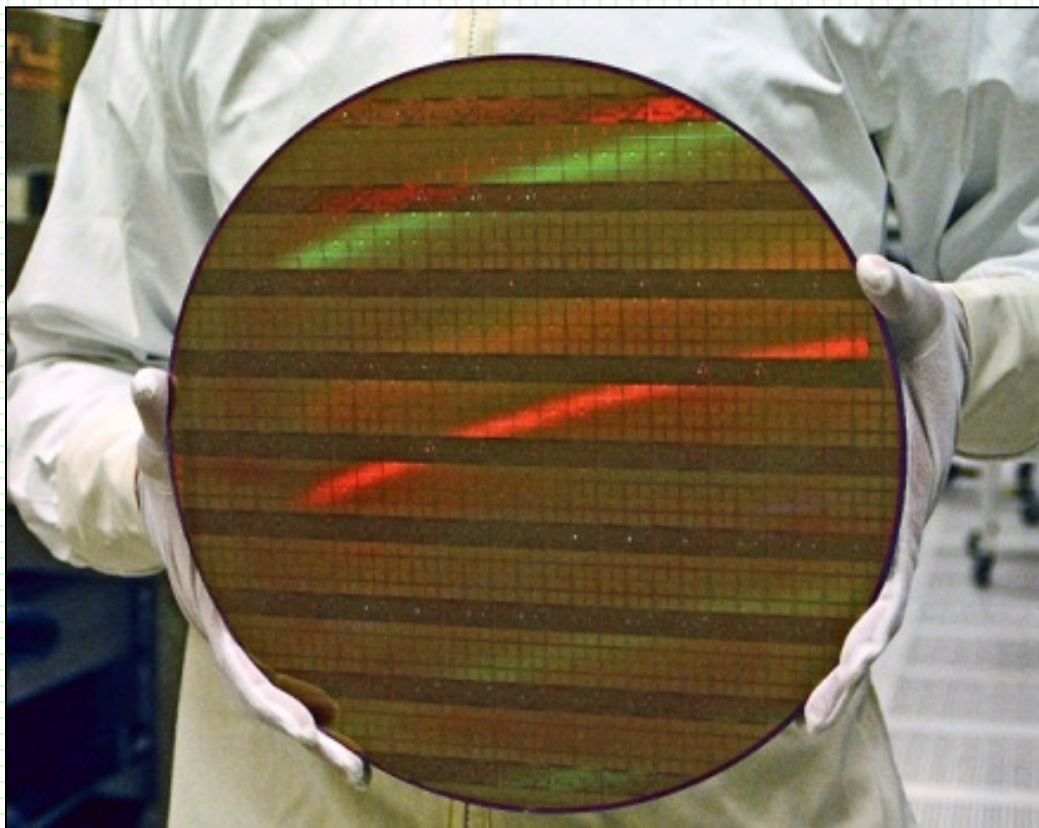
Spaterovanje je postupak depozicije koji pripada klasi PVD metoda.



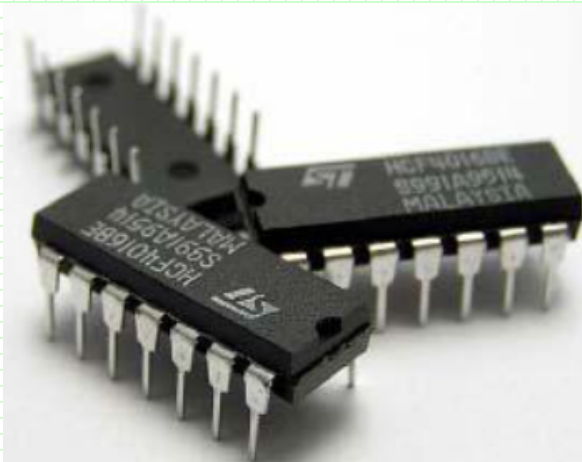


Šematski prikazi i spoljašnji izgled komore za MBE

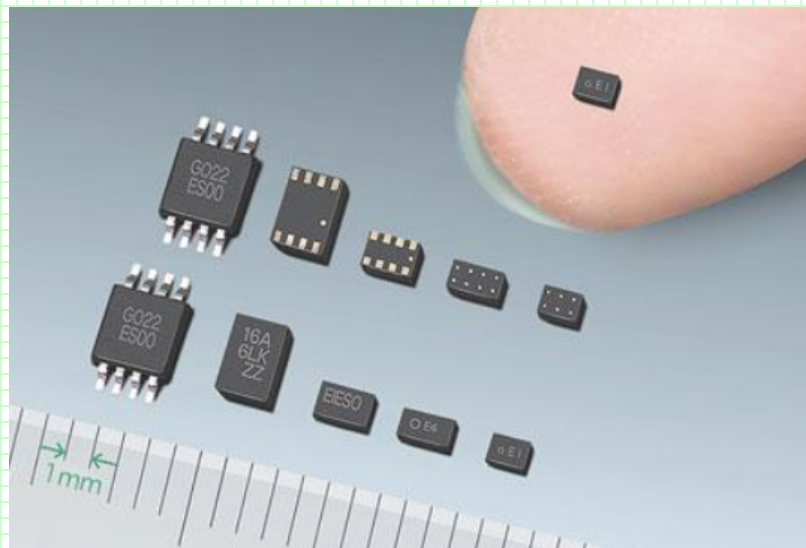




Izgled Si ploče nakon tretiranja planarnim postupcima
i pre sečenja na "kockice" (čipove).



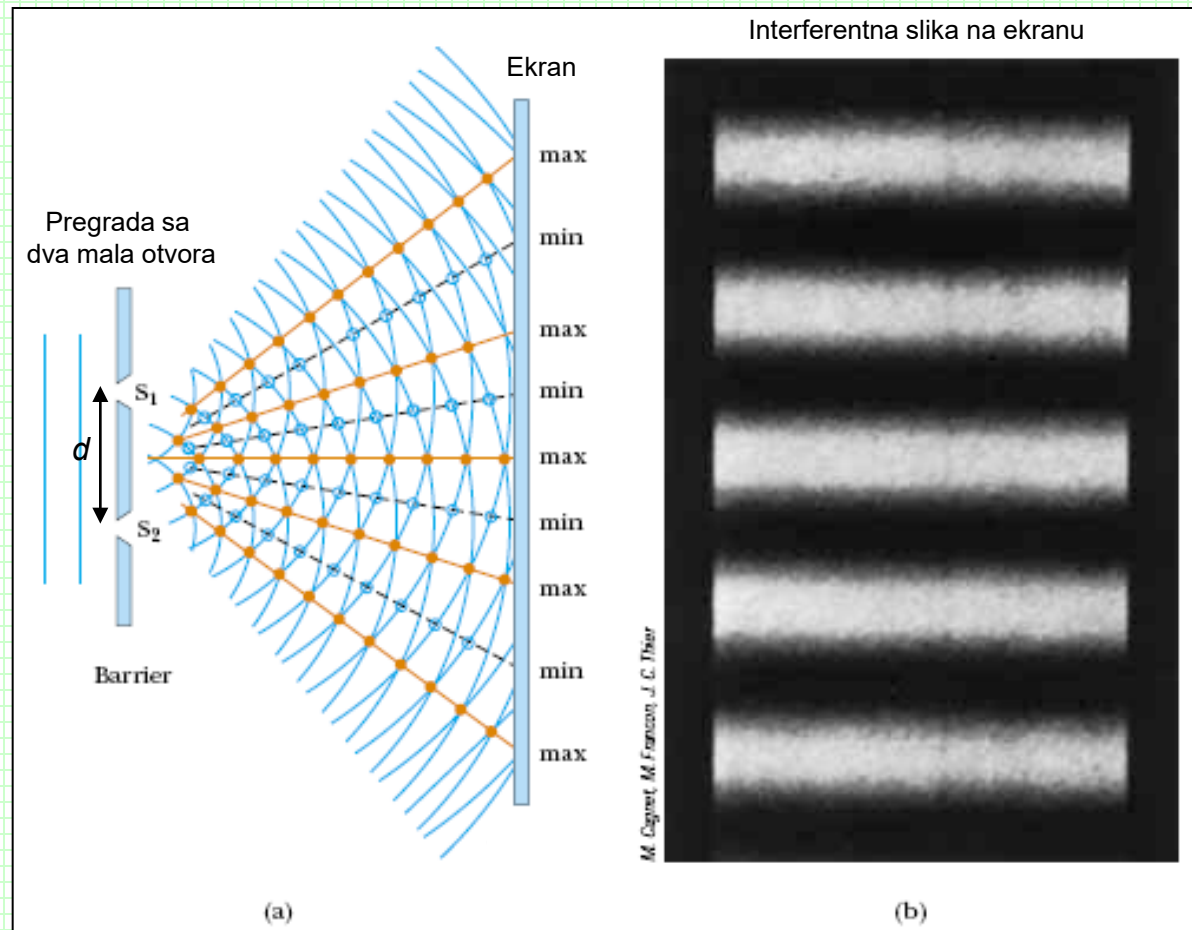
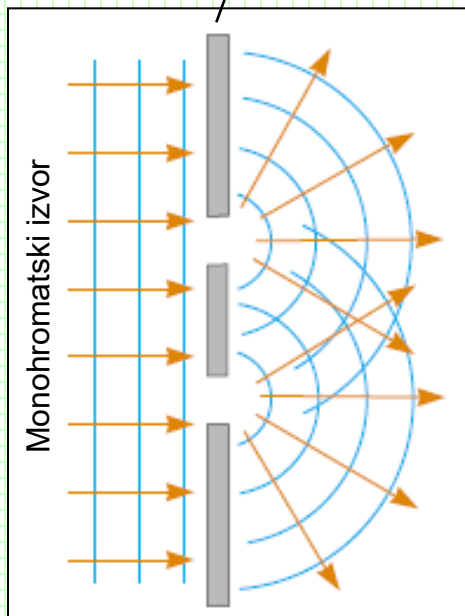
Čipovi sa izvodima
za through-hole montiranje



SMD čipovi za
površinsko montiranje

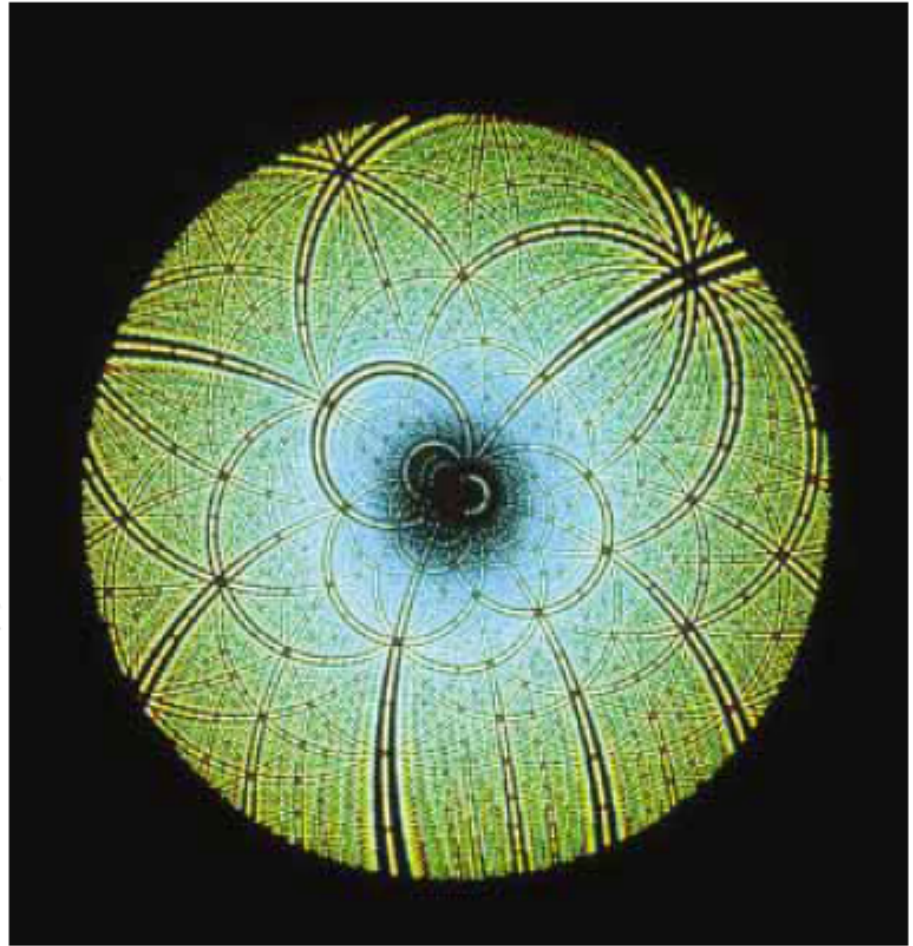
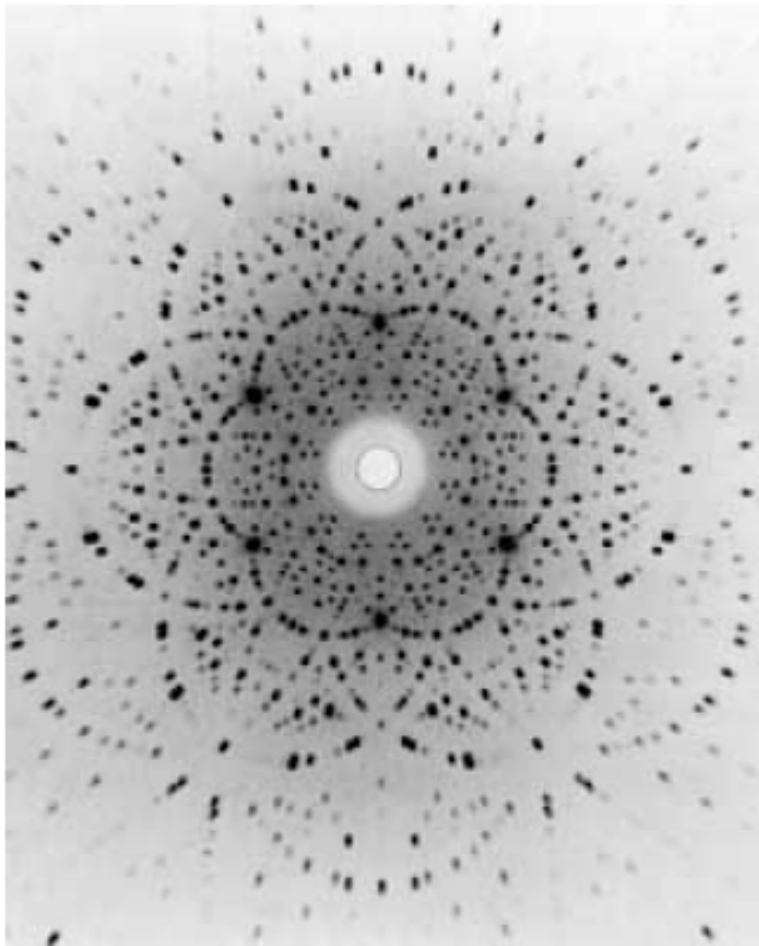
Interferencija

Pregrada sa dva mala otvora (proreza).
Na svakom otvoru dešava se difrakcija.



Uslov za interferentni
maksimum na ekranu:

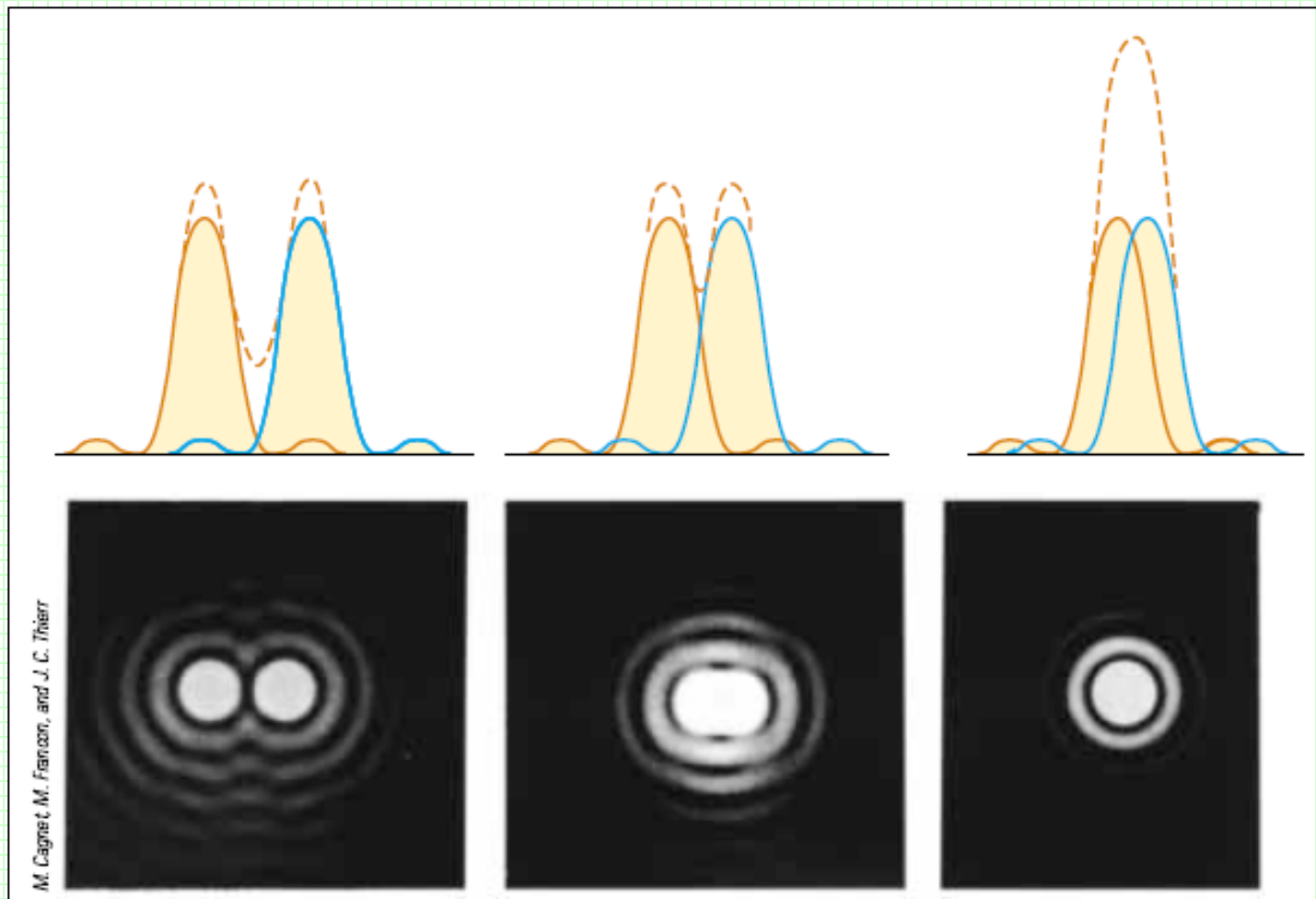
$$\delta = d \sin \theta_{\text{bright}} = m \lambda \quad (m = 0, \pm 1, \pm 2, \dots)$$



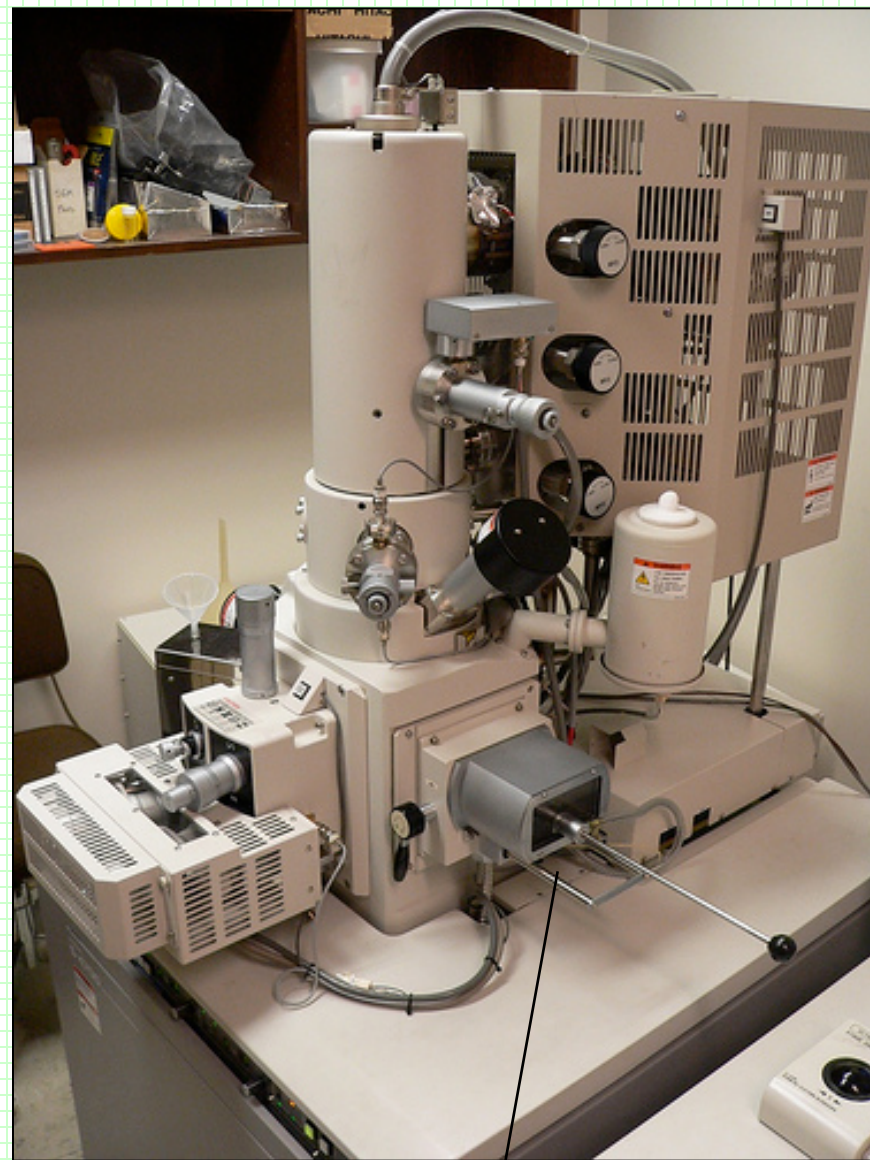
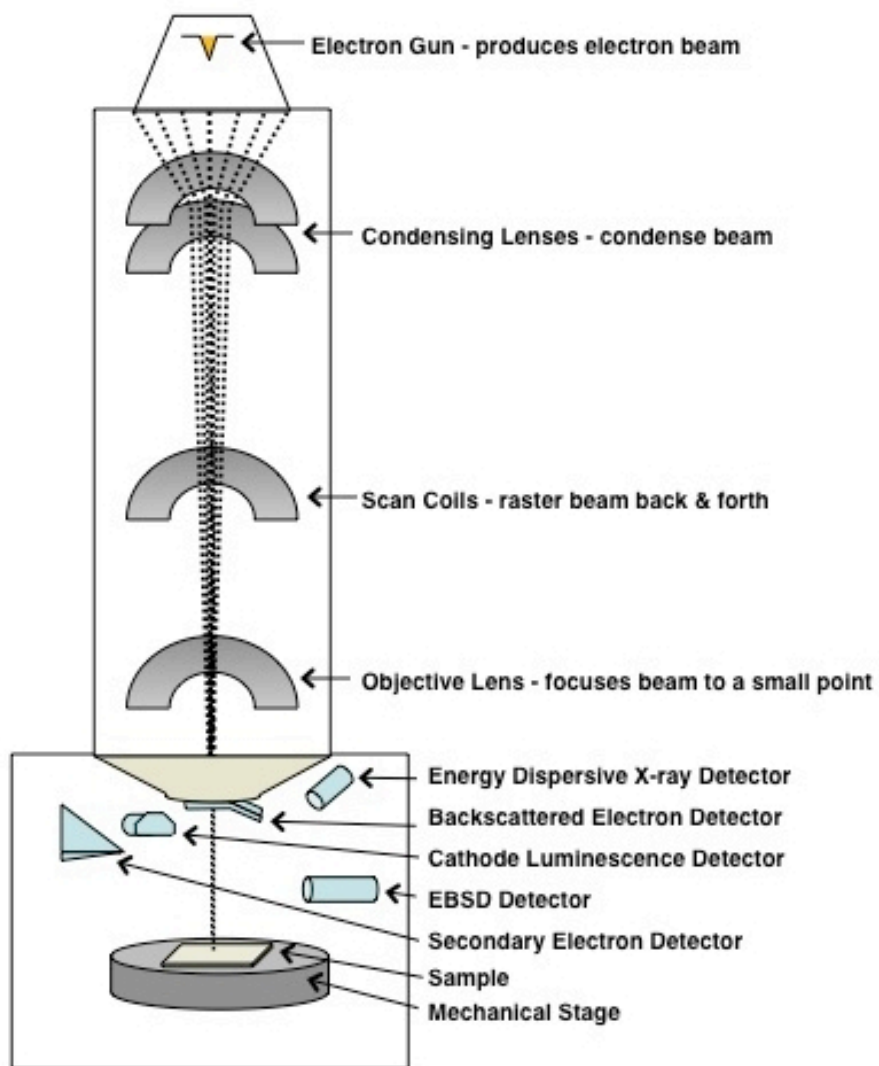
**Difrakciona šara za mineral beril,
dobijena pomoću monohromatskih
X-zraka**

**Difrakciona šara za enzim Rubisko
dobijena pomoću izvora X-zraka
širokog energetskeg spektra
(kontinualni oblici umesto tačaka).**

Kružni prorez: $\theta_{\min} = 1.22 \frac{\lambda}{D}$

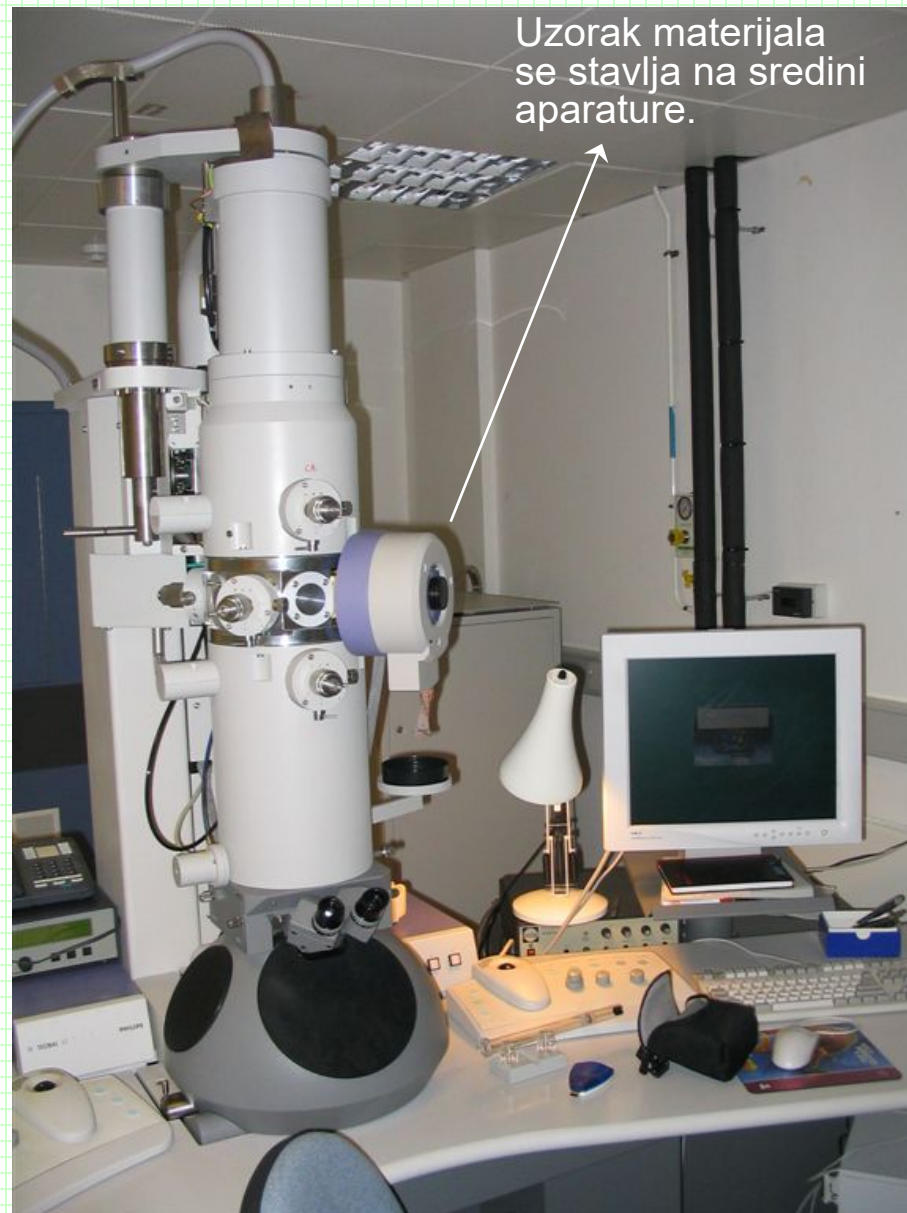
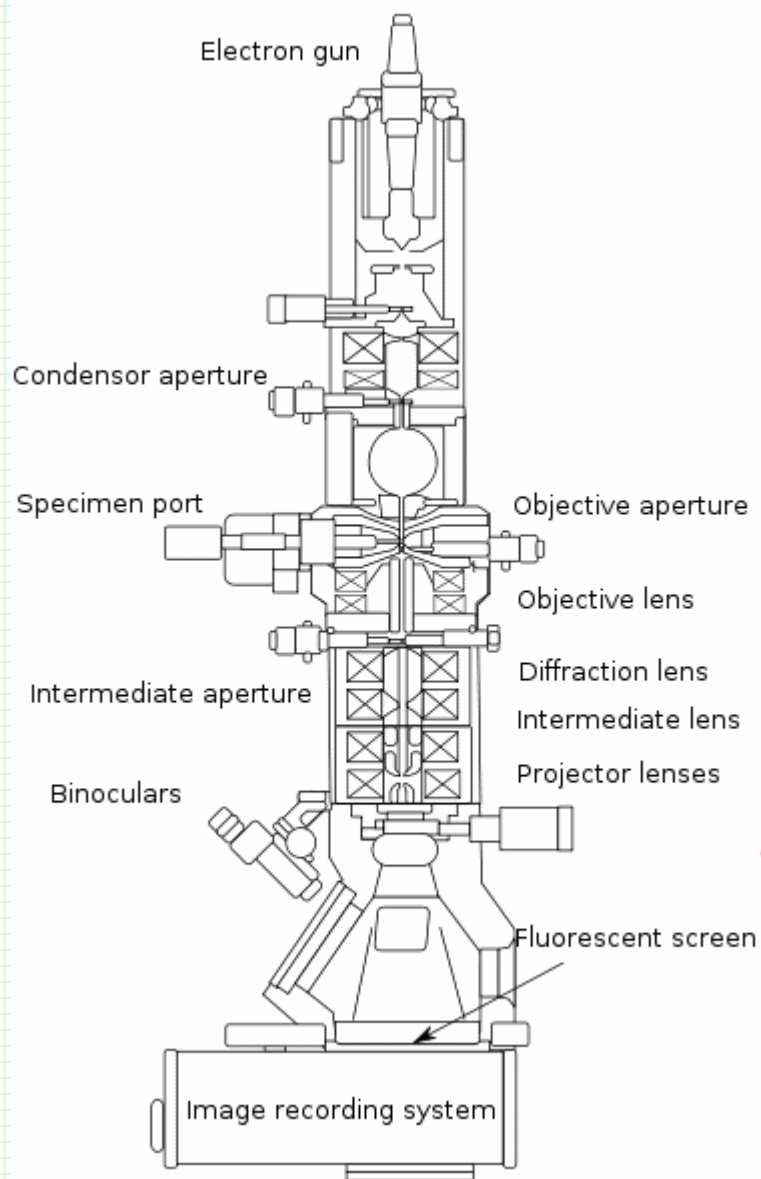


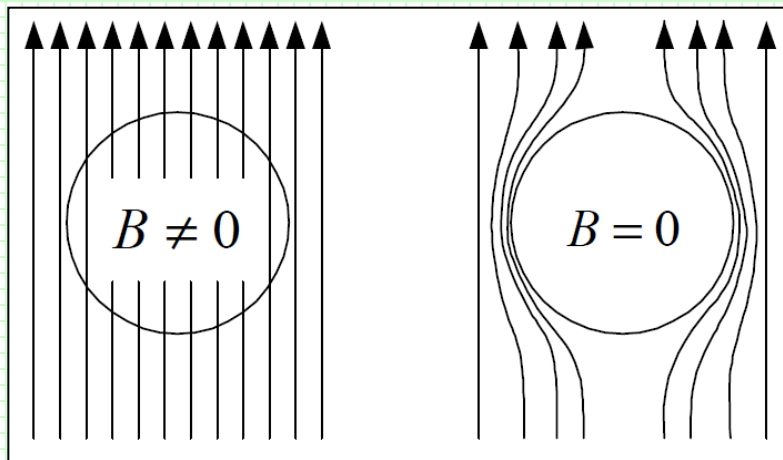
Elektronska mikroskopija - SEM uređaj



Uzorak materijala se stavlja pri dnu aparature.

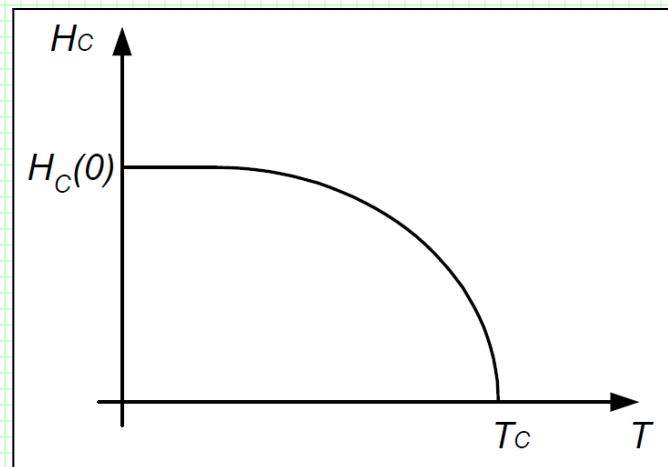
Elektronska mikroskopija - TEM uređaj



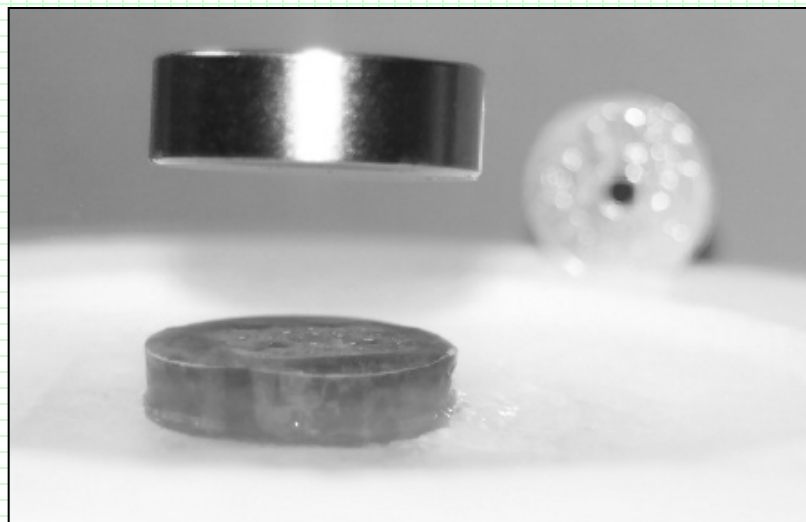
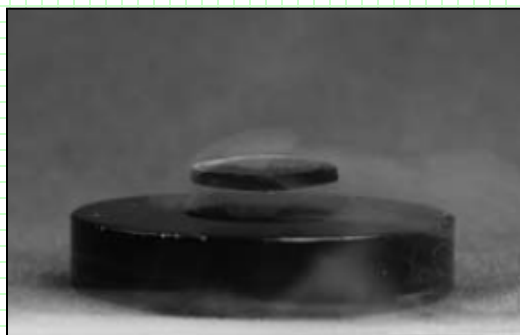


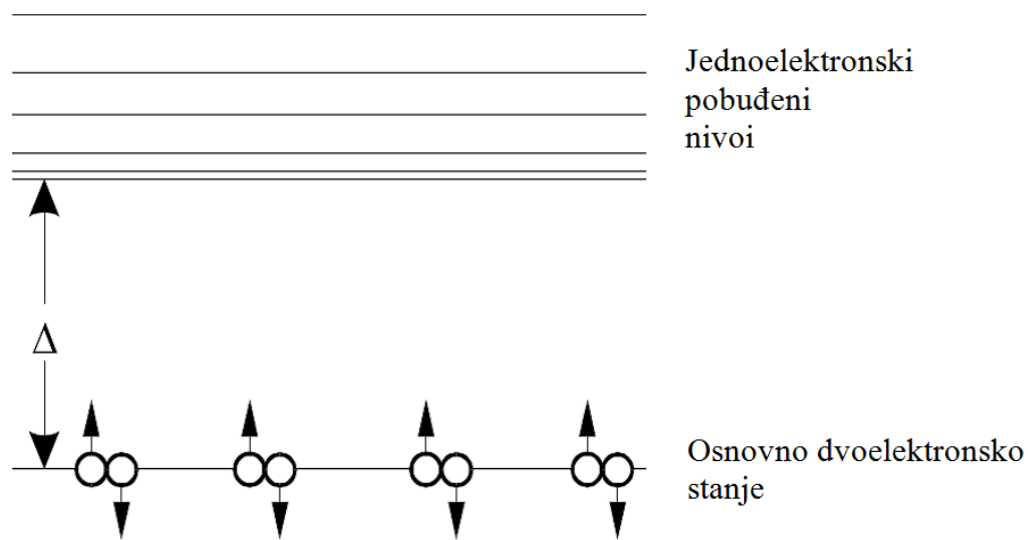
a) Provodnik

b) Superprovodnik

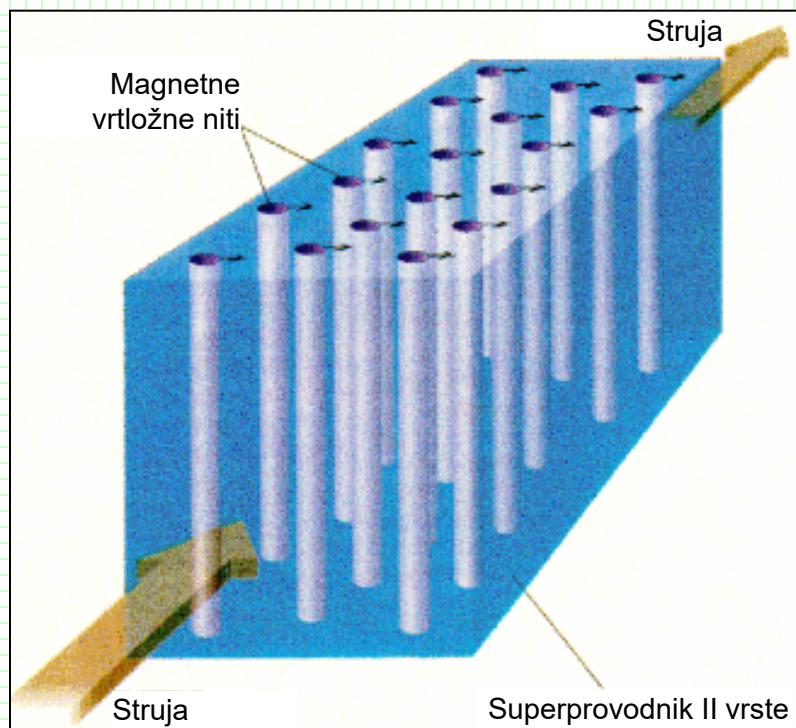


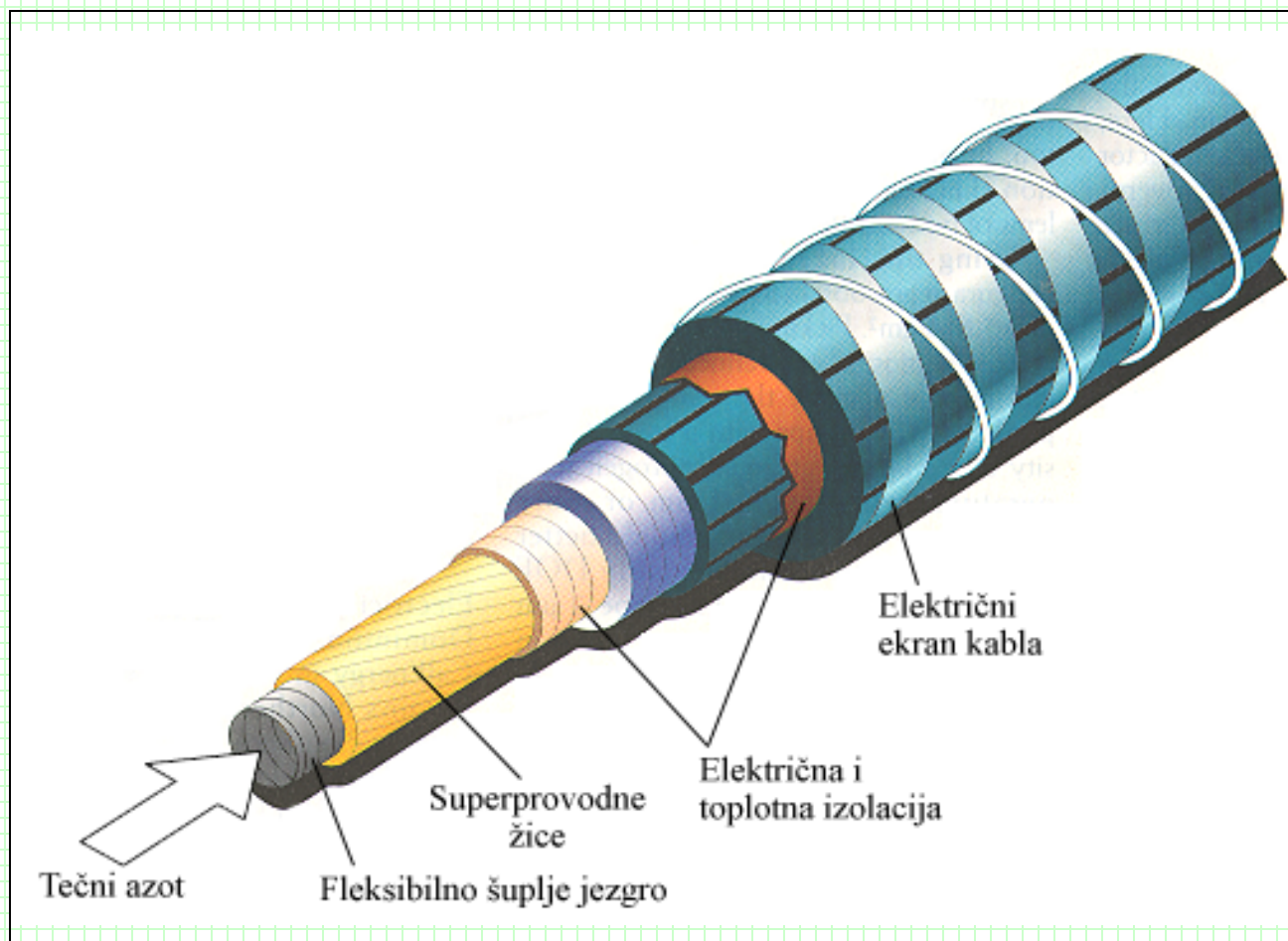
c) Zavisnost $H_c(T)$



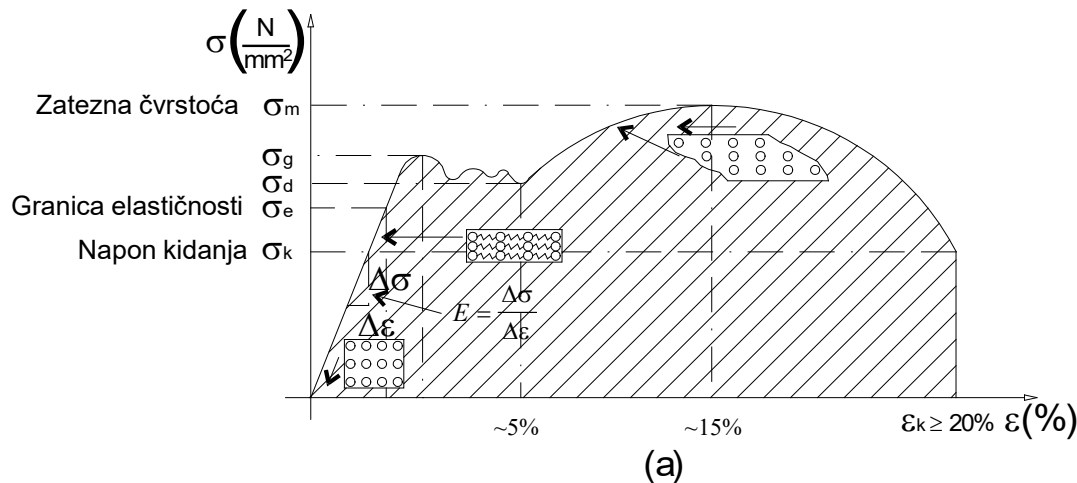


Šema energetskega nivoa superprovodnika





Prikaz konstrukcije visokotemperaturnskog superprovodnog kabla na bazi $\text{Bi}_2\text{CaSr}_2\text{Cu}_2\text{O}_8$, sa mogućnošću prenosa energije snage $\sim 1 \text{ GW}$ pri strujama od 3000 A, firme Pirelli Cables.



Hukov zakon elastičnosti: $\sigma = E_Y \varepsilon$

Elastičnost $\sim 1/E_Y$

Krutost $\sim E_Y$

Plastičnost $\sim \varepsilon_k$

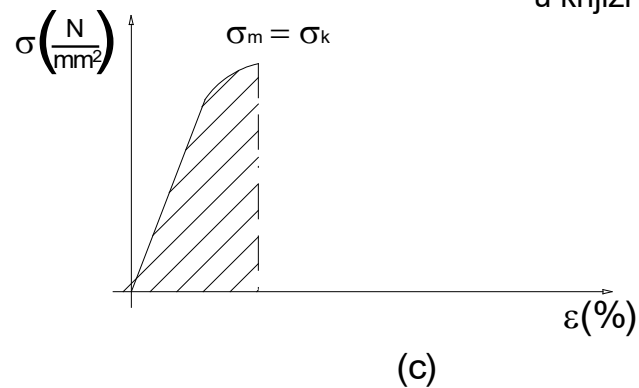
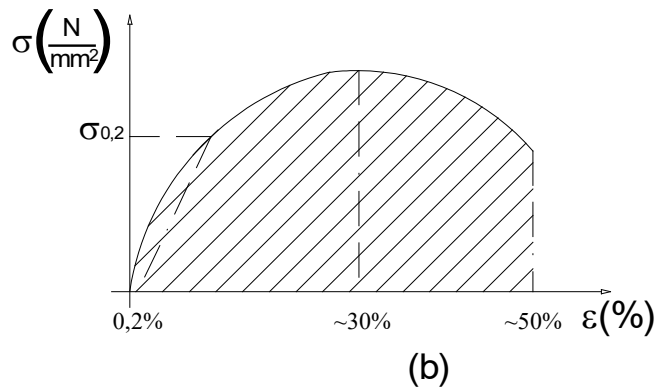
Čvrstoća $\sim \sigma_e$

Tvrdoća $\sim \sigma_m$ (otpornost na utiskivanje)

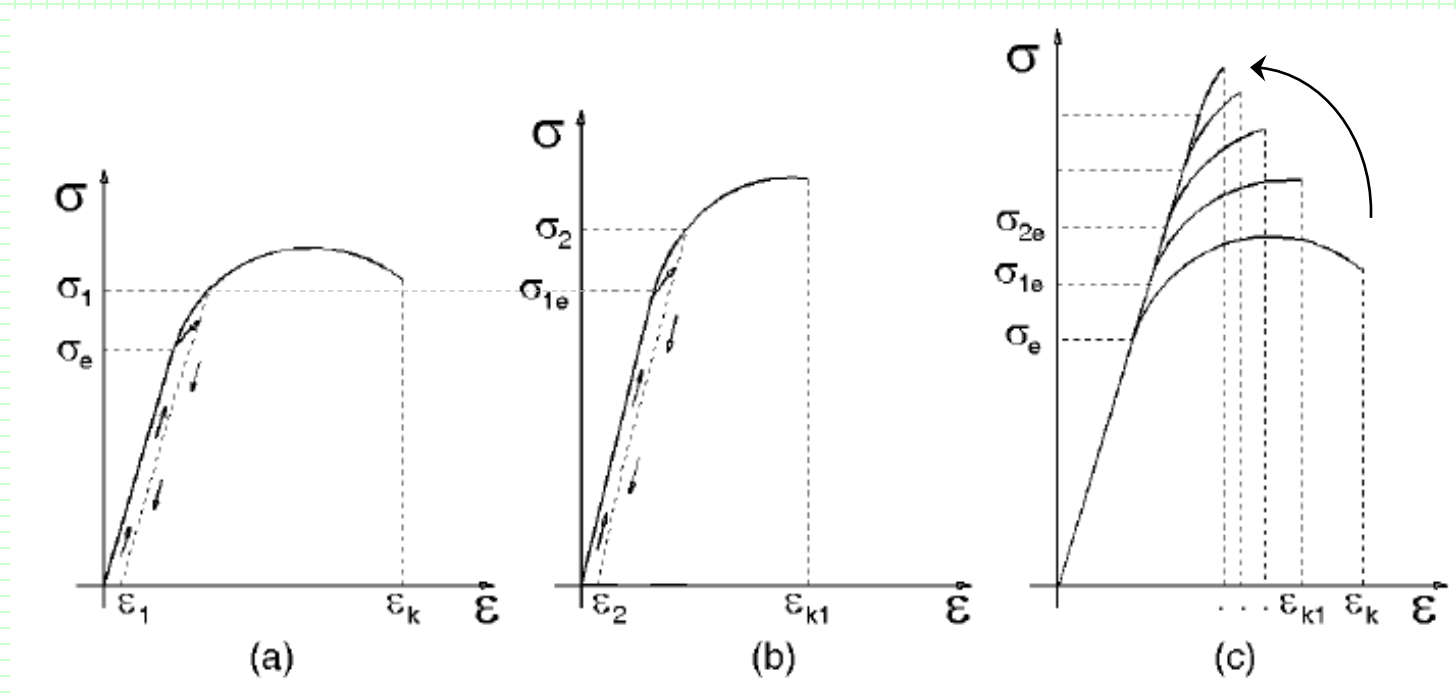
Žilavost $\sim$ površini ispod krive $\sigma(\varepsilon)$
(otpornost na udarna opterećenja)

Krtost $\sim 1 / \text{Žilavost}$

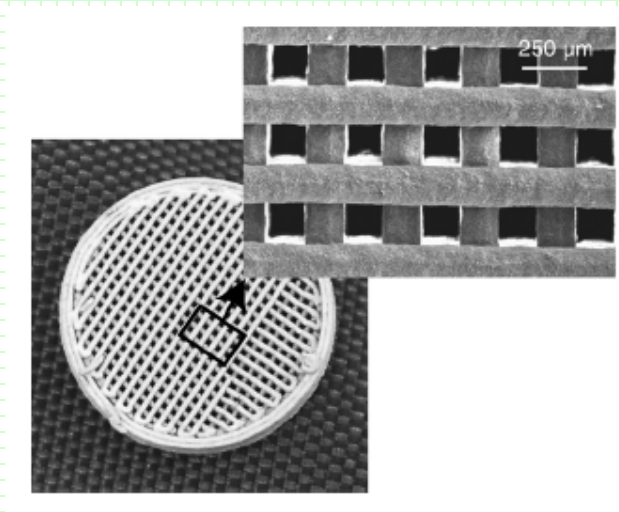
(za detalje videti odeljak 5.7.1.
u knjizi prof. Rakovića)



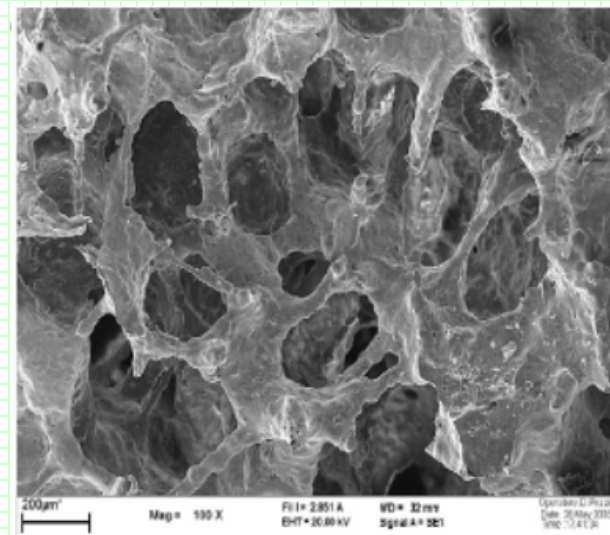
Dijagrami napon-relativno izduženje za (a) elastično-plastične, (b) plastične i (c) krte materijale



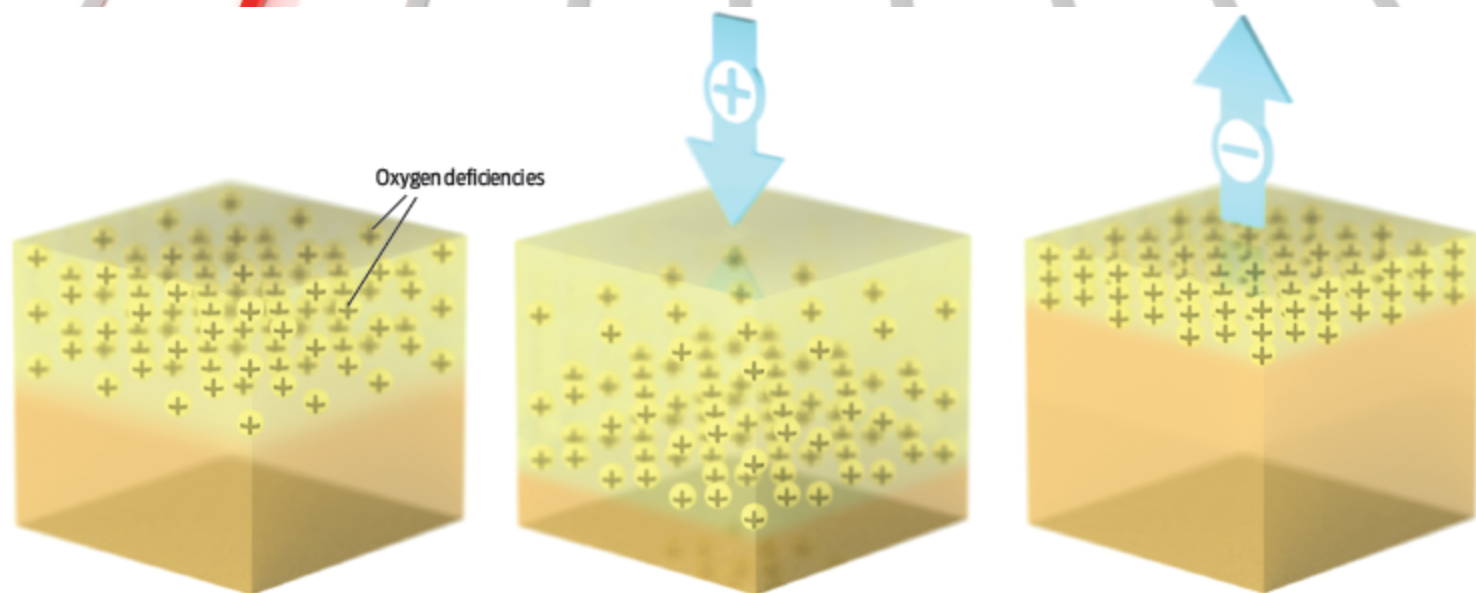
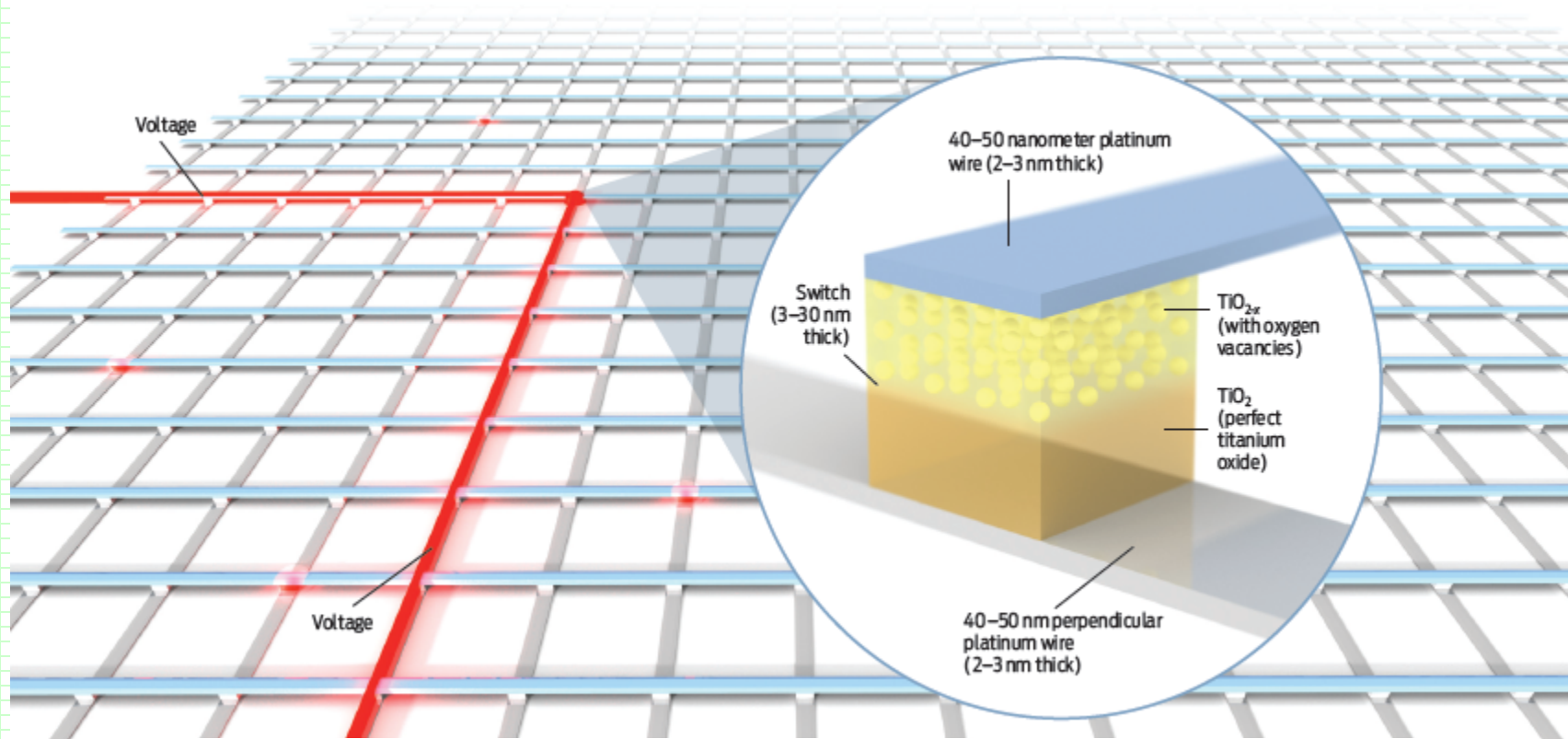
Prikaz ojačavanja hladnom deformacijom na dijagramu napon-relativno izduženje

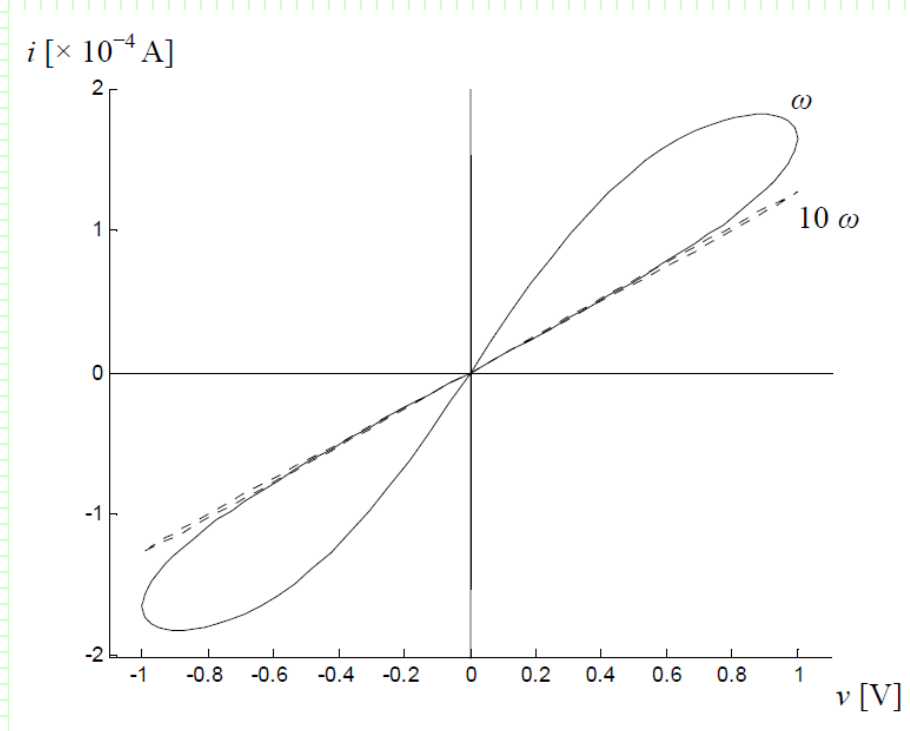


Porozni hidroksiapatit skafold

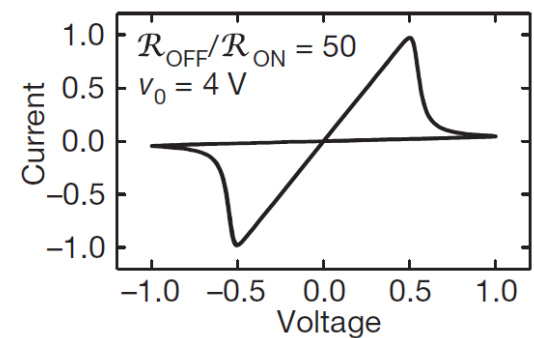
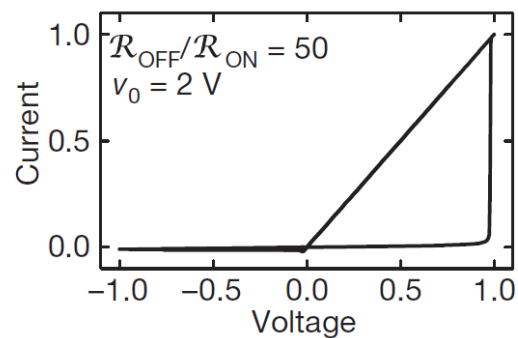
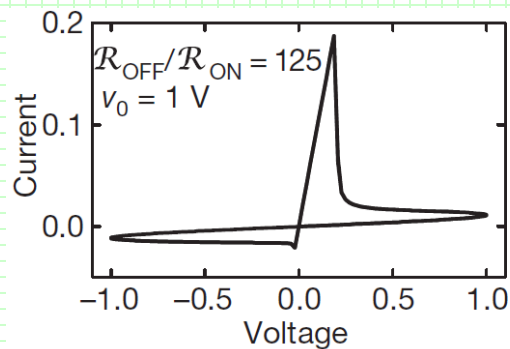


Staklo-keramika skafold



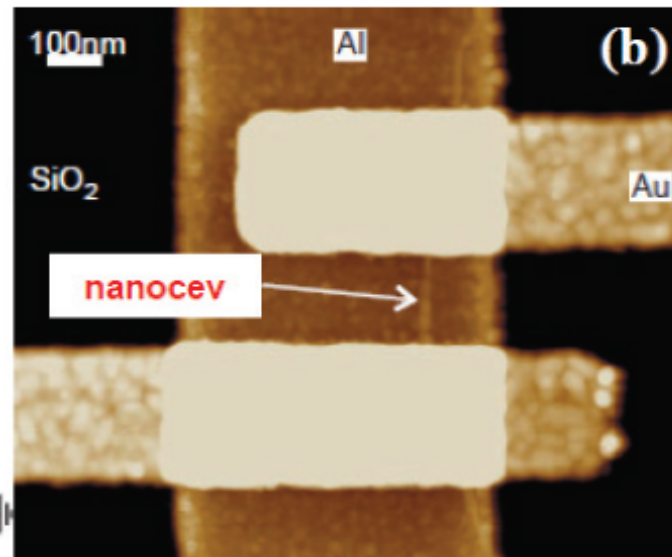
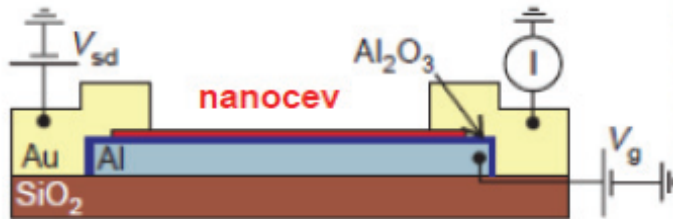


Tipična dvostruka histerezisna i - v karakteristika memristora za napone malih amplituda.

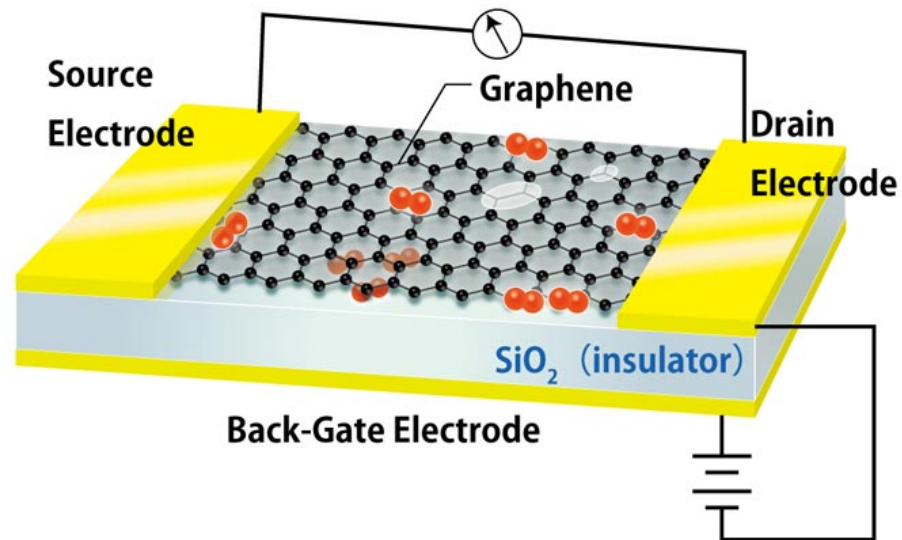


i - v karakteristike memristora kada se uzme u obzir nelinearni drift vakancija.

(a)



(a) Šematski prikaz CNT FET-a. (b) STM slika FET-a.



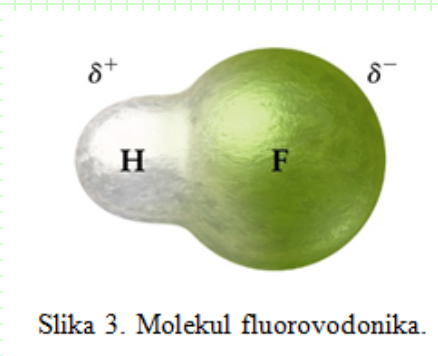
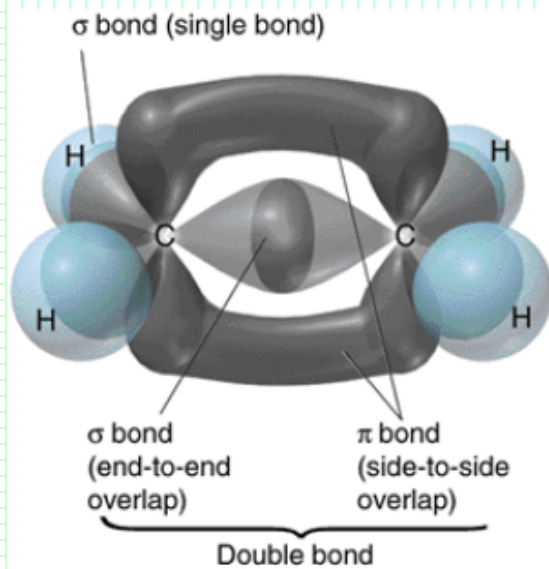
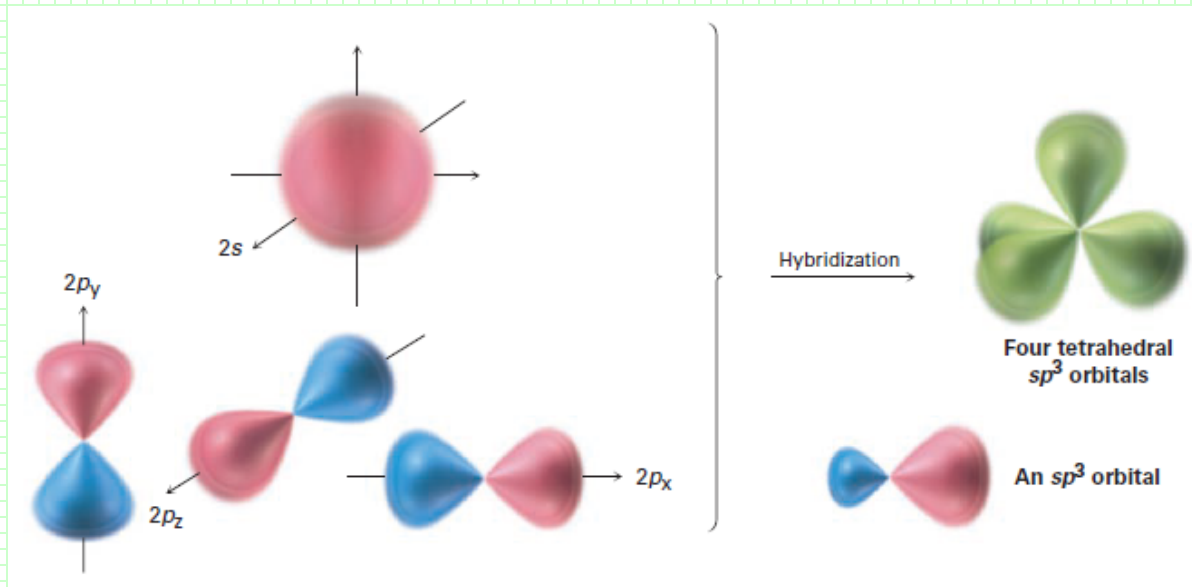
FET sa grafenom koji je apsorbirao molekule kiseonika.

**Odsek za fizičku elektroniku
(3. semestar)**

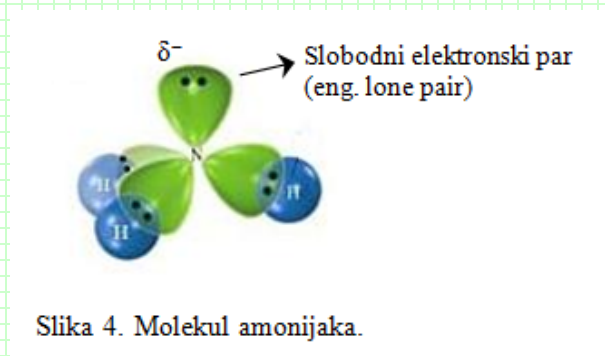
PRAKTIKUM IZ SAVREMENIH MATERIJALA I TEHNOLOGIJA

**Miloš Vujisić, vanr. prof.
Dimitrije Popović, saradnik u nastavi**

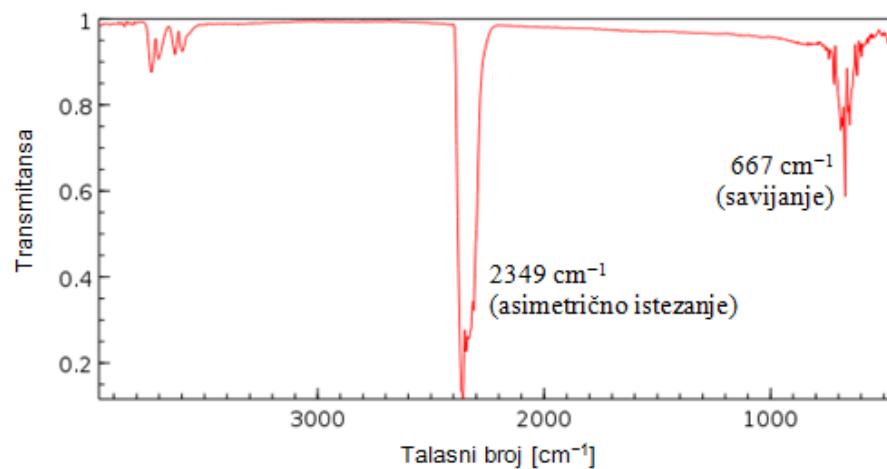
[Stranica predmeta na sajtu ETF](#)



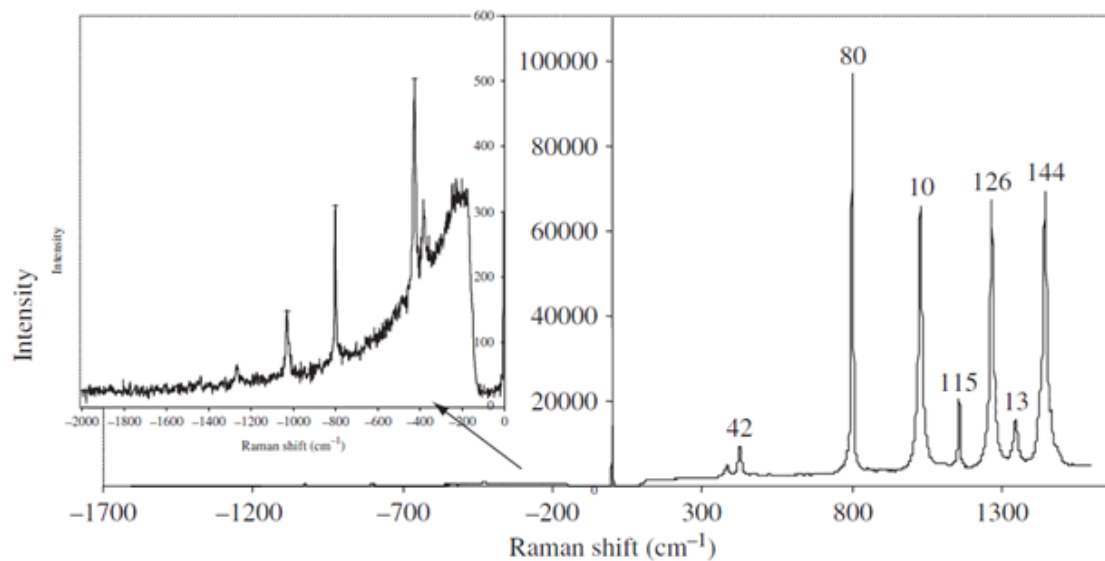
Slika 3. Molekul fluorovodonika.



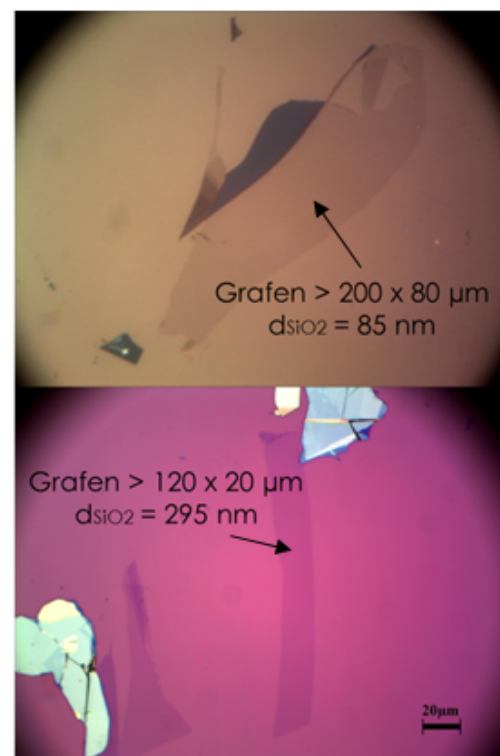
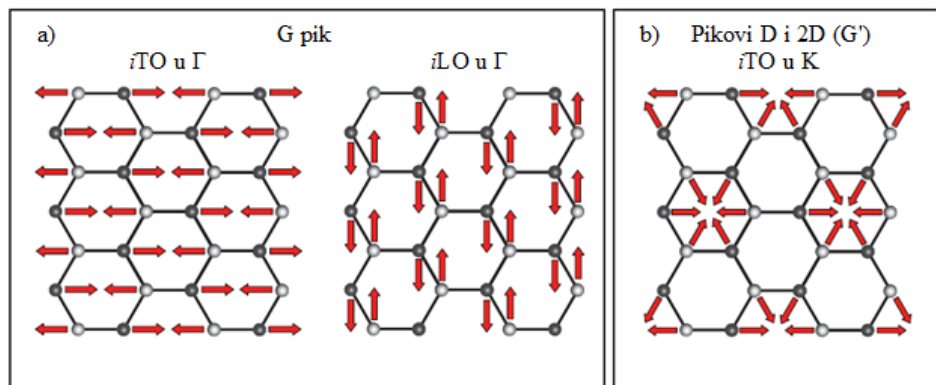
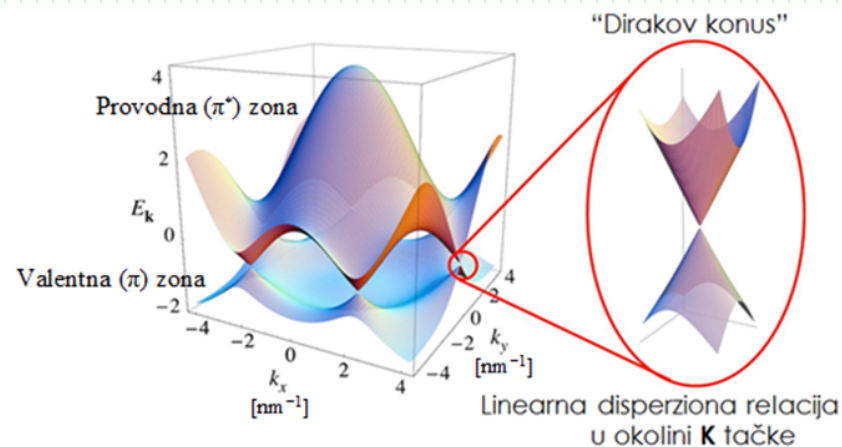
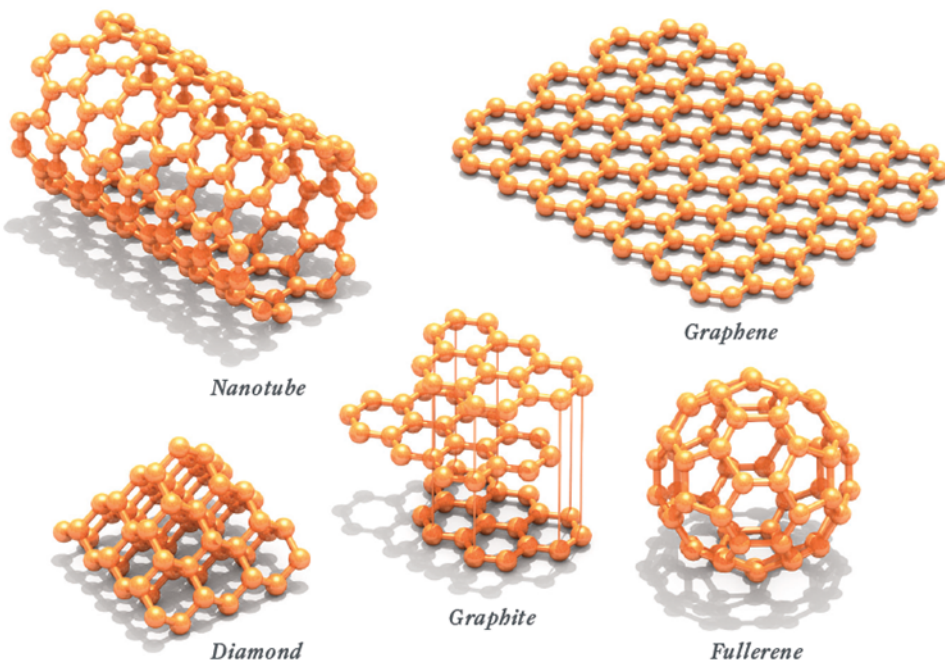
Slika 4. Molekul amonijaka.



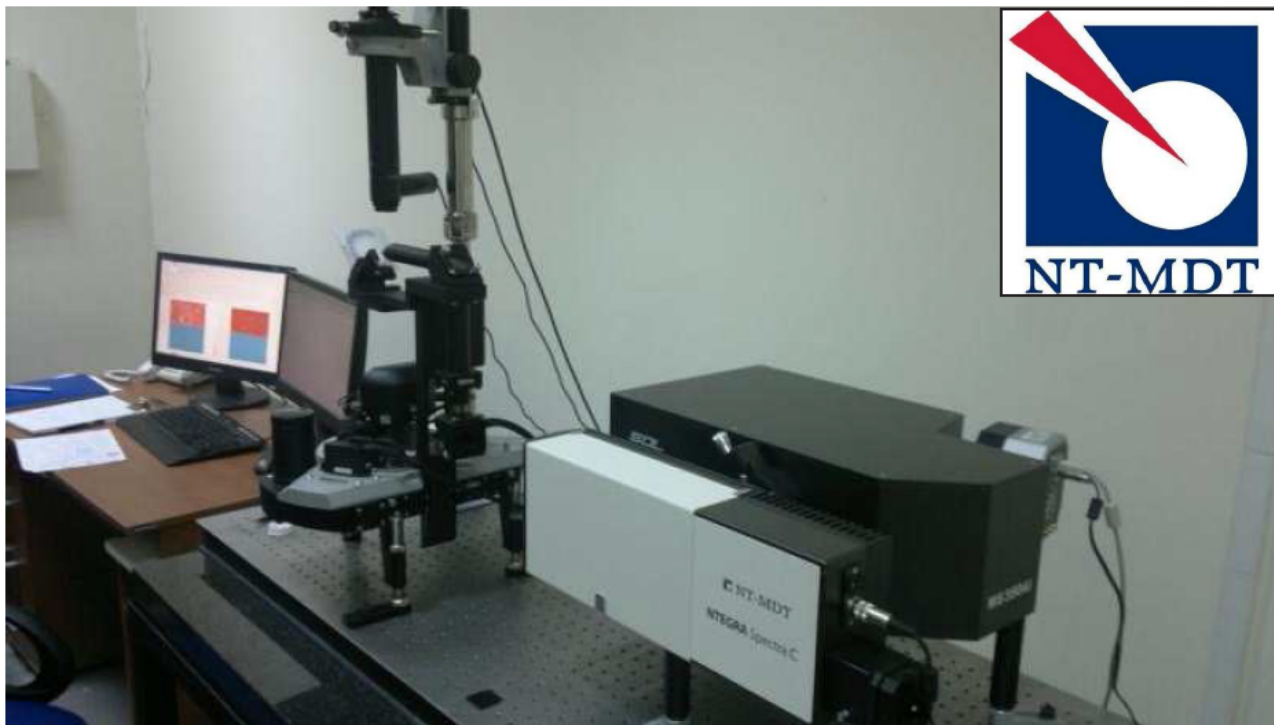
Slika 7. IC spektar ugljen-dioksida. Uz apsorpcione pikove je naznačeno kojim vibracionim modovima odgovaraju.



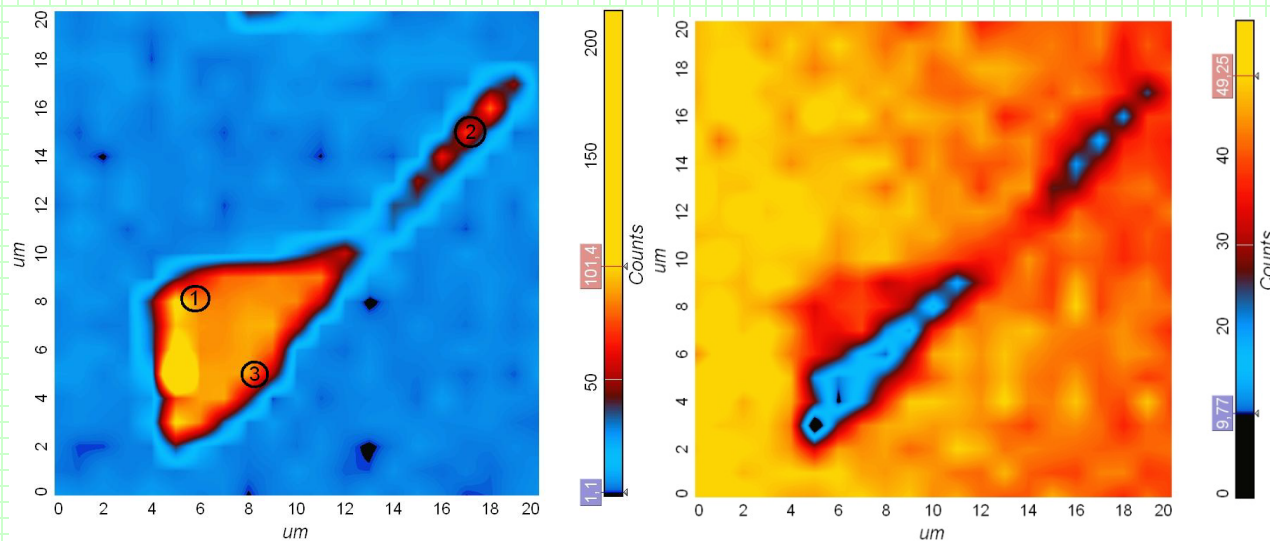
Slika 12. Ramanov spektar cikloheksana (C_6H_{12}).

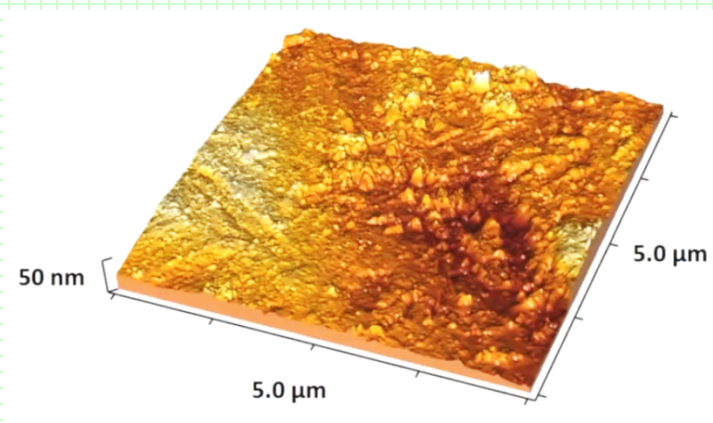
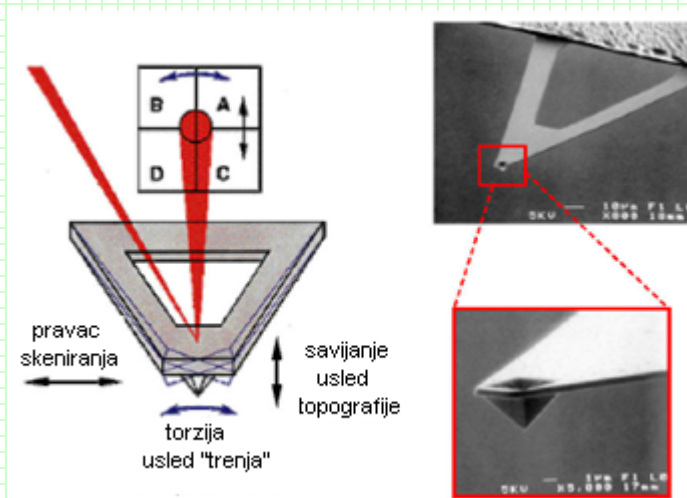
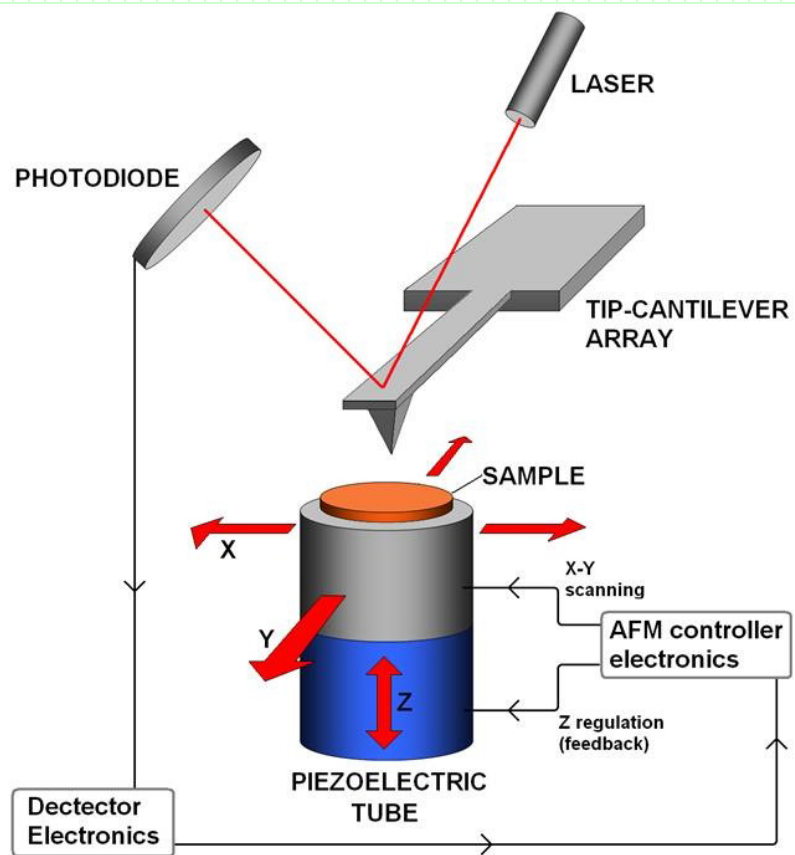


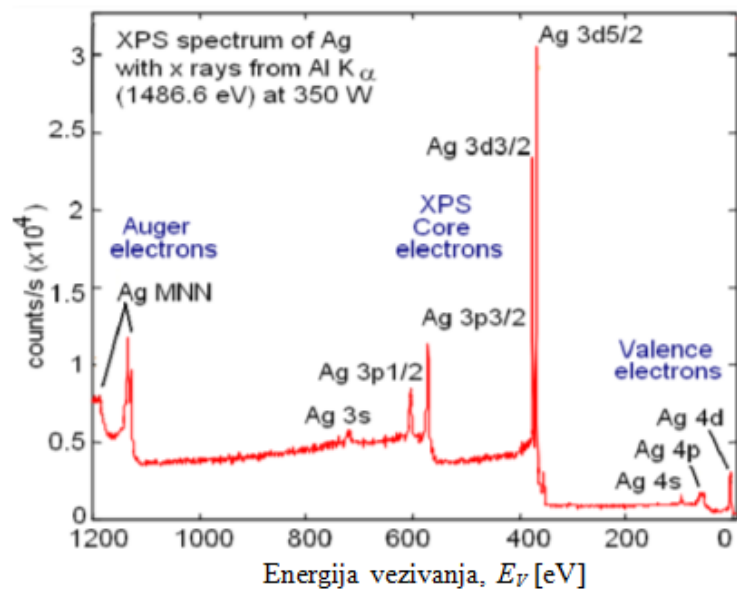
Slika 13. Grafen dobijen mehaničkom eksfolijacijom na SiO₂/Si podlozi, viđen pod optičkim mikroskopom, za dve različite debljine silicijum dioksida (85 nm i 295 nm). Blago zasenčene regije ukazuju na tankoslojni grafen (moguće monoatomski sloj), dok tamnije regije odgovaraju većem broju slojeva. Brojne vrednosti izražene u mikrometrima odnose se na površinske dimenzije grafenskog sloja.



Aparatura za mikroskopiju atomskim silama (AFM) i Ramonovu spektroskopiju u Institutu za fiziku (proizvođač: NT-MDT).



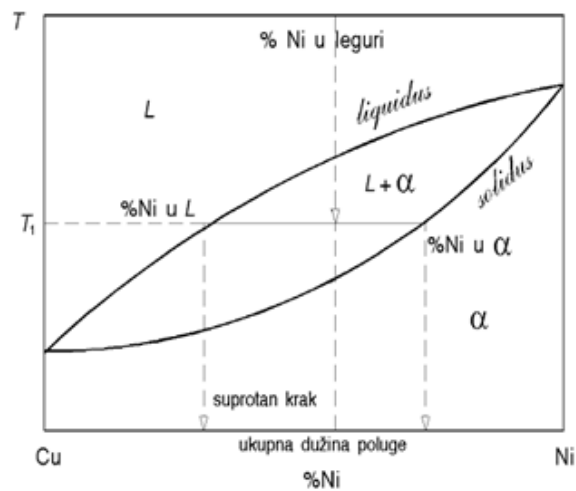
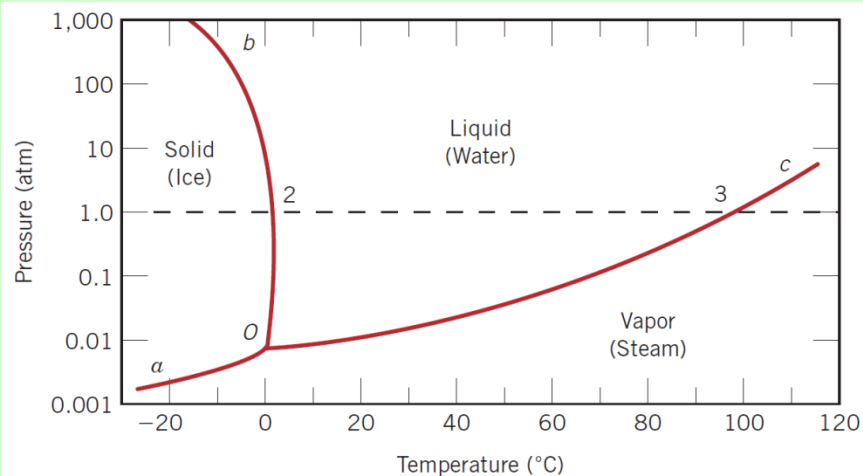




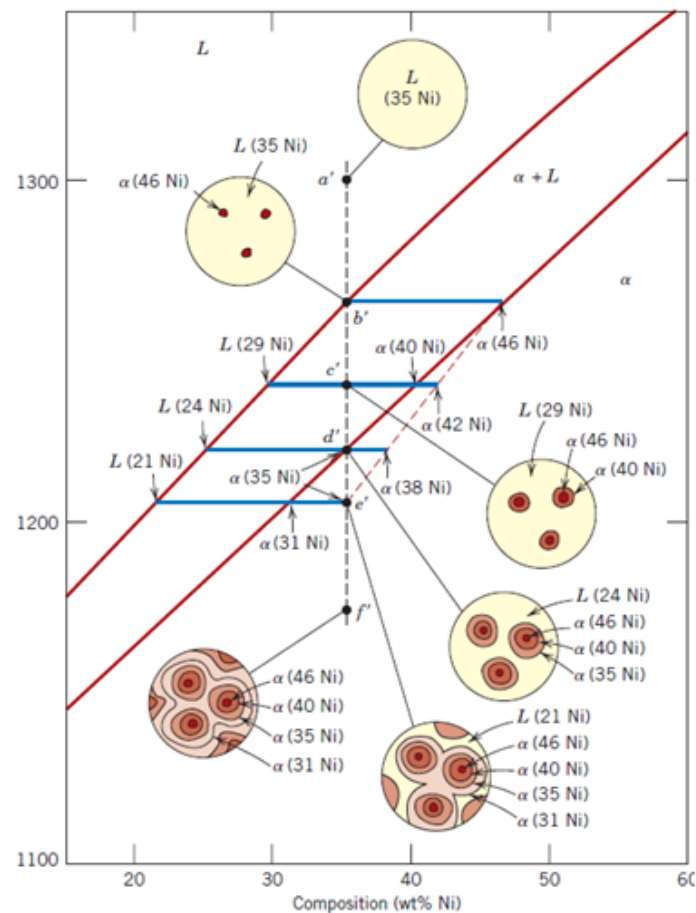
Slika 3. Pregledni XPS spektar uzorka čistog srebra.



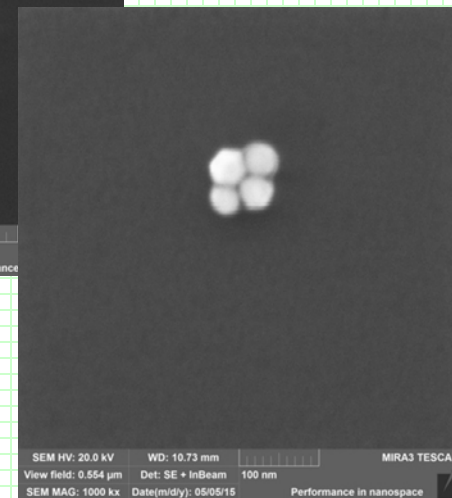
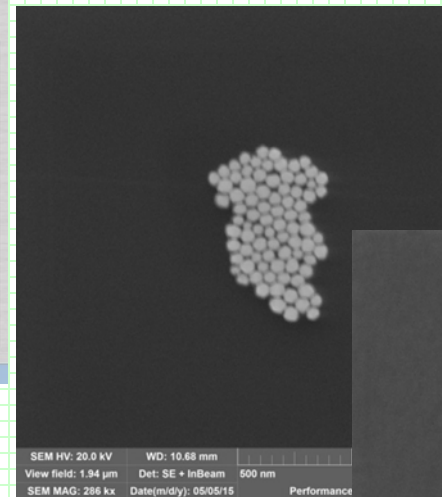
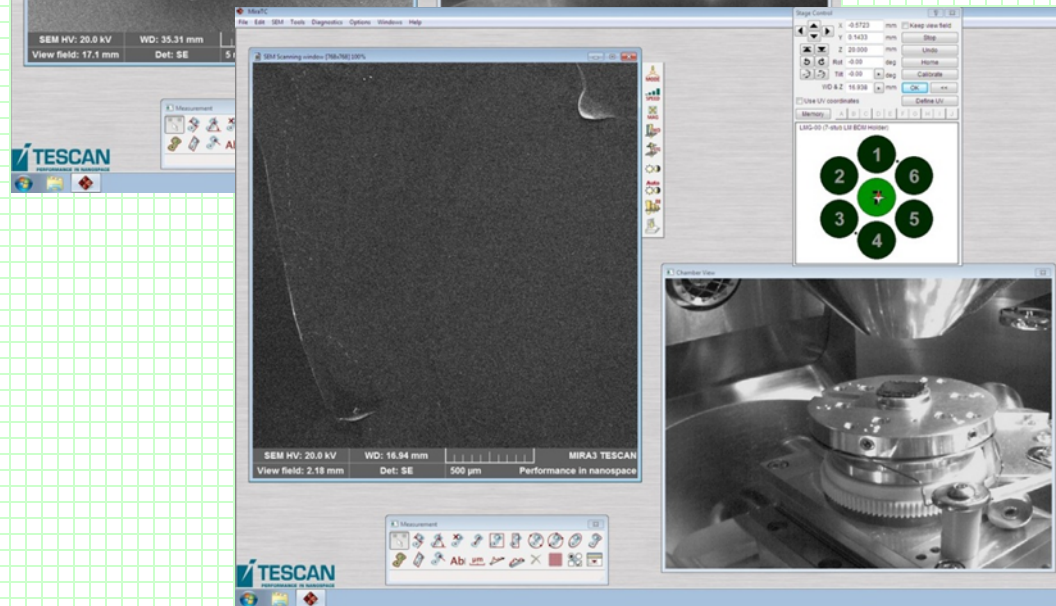
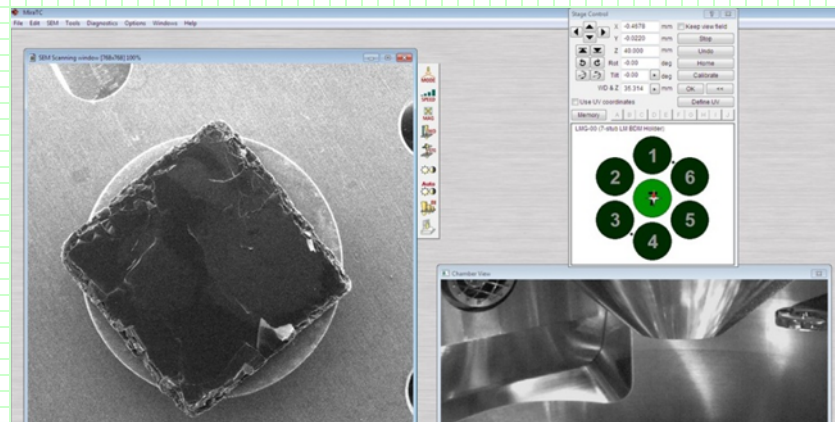
XPS sistem u Laboratoriji za atomsku fiziku, INN Vinča.

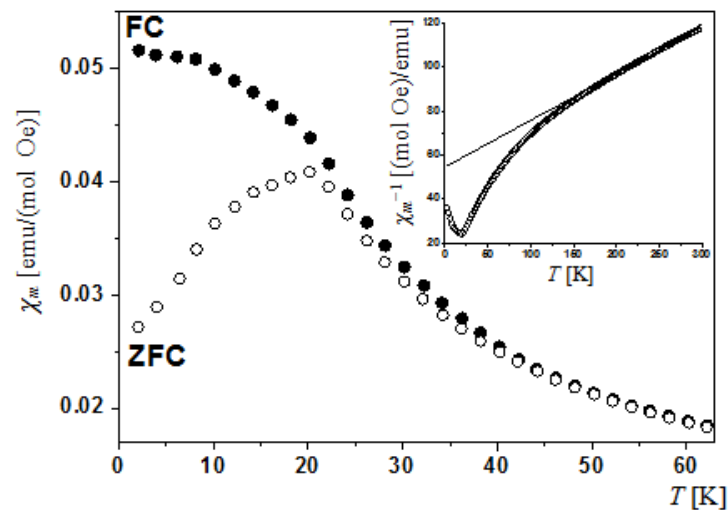


Fazni dijagram koji ilustruje pravilo poluge.

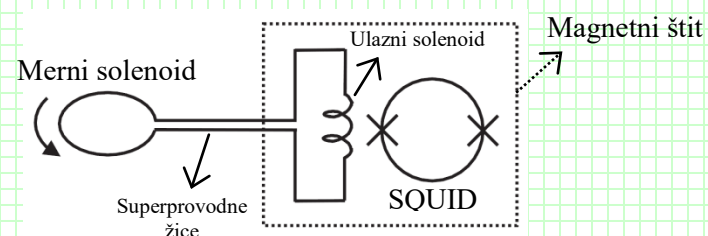


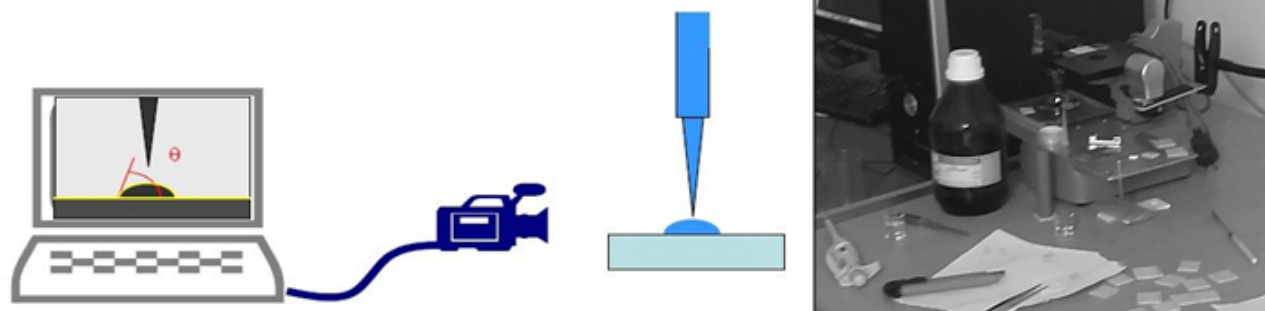
Fazni dijagram za slučaj neravnotežnog (brzog) hlađenja Cu-Ni legure.





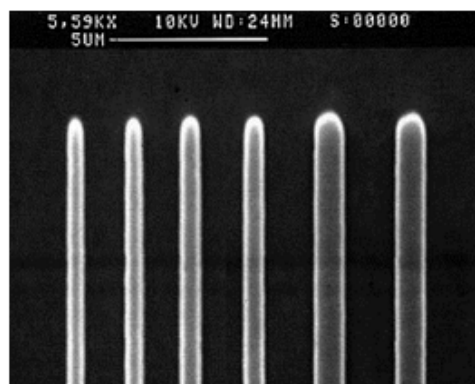
Slika 5. Temperaturna zavisnosti molarne magnetne susceptibilnosti u uslovima hlađenja bez i sa spoljašnjim magnetnim poljem. Umetnuti grafik prikazuje temperaturnu zavisnost inverzne molarne susceptibilnosti za ZFC režim merenja, na kojoj je kroz paramagnetni deo krive provučena optimalana prava.



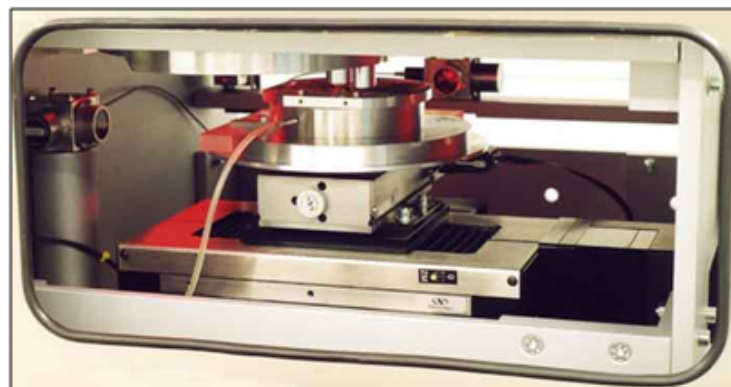


Slika 3. Šematski prikaz sistema za određivanje kontaktnog ugla i izgled aparature u Laboratoriji za atomsku fiziku, INN Vinča.

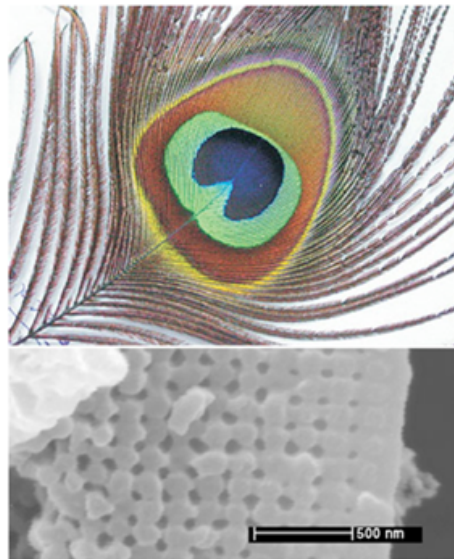
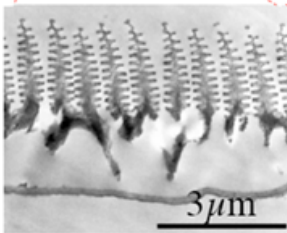
a)



b)

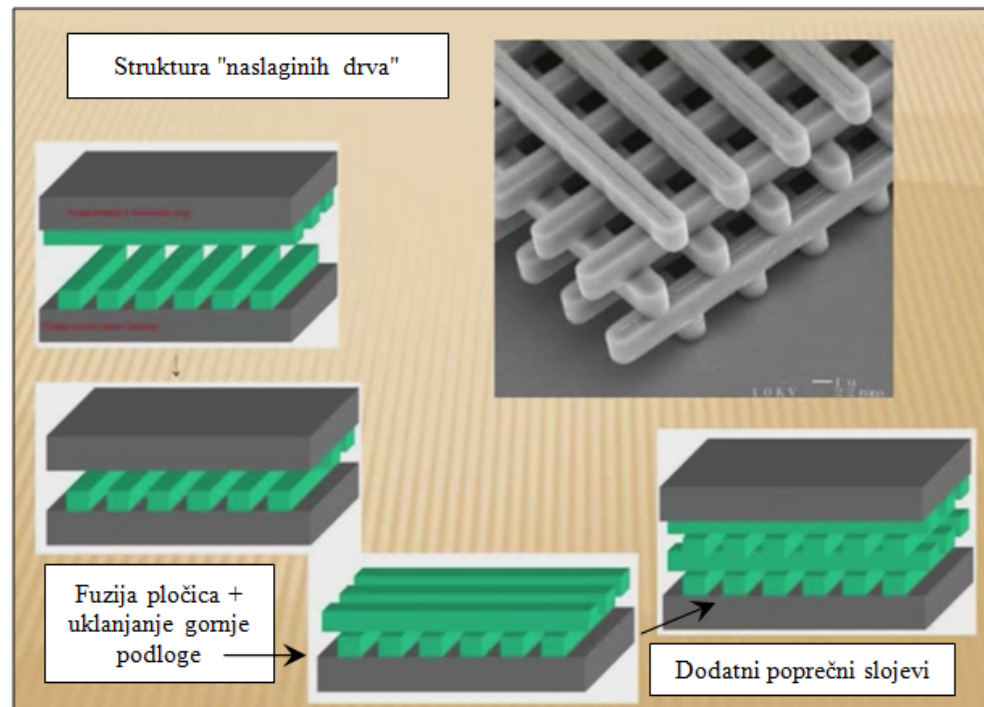


- a) This photograph shows a resolution test for 0.7 μm nominal resolution. The lines of each couple are respectively 0.5, 0.7 and 1 μm wide. The pattern is negative, on 0.5 μm thick positive resist.
- b) Detail of the LaserWriter work chamber.



IC (FT-IR) spektrometar
Nicolet 6700 u IHTM-u

Silka 1. Prirodne strukture sa osobinama fotonskog krsistala.



Slika 5. Postupak dobijanja i mikrofograf strukture "naslaginih drva" (eng. *woodpile structure*).

