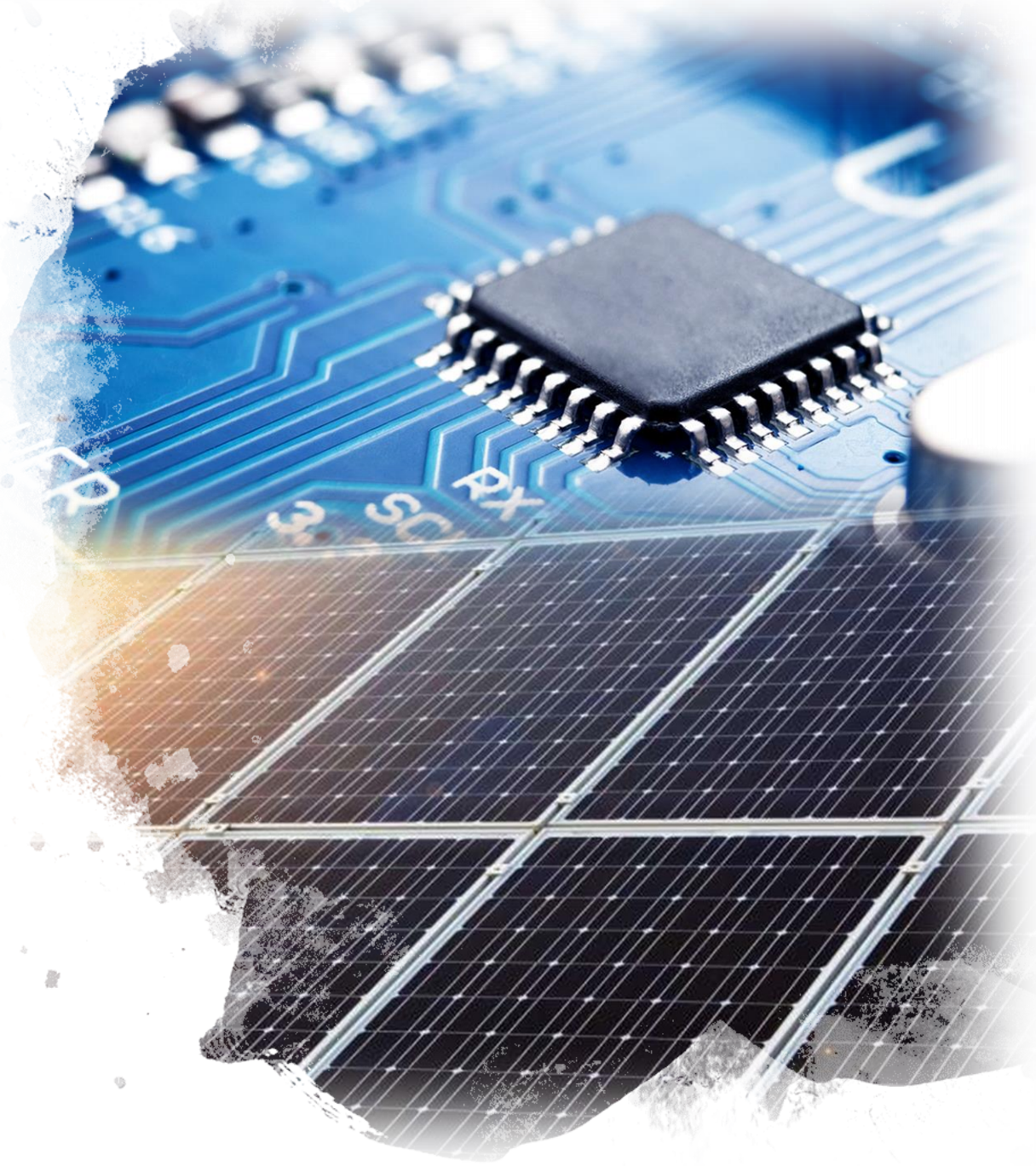
Karakterizacija električki aktivnih defekata u poluvodičima

Luka Bakrač

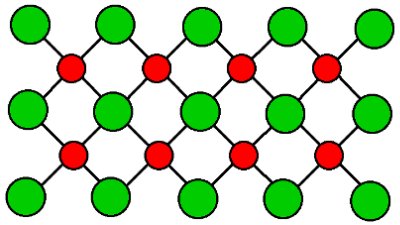
- Poluvodiči i zašto su važni
- Fizika poluvodiča i defekata
- Schottky dioda
- Tranzijentna spektroskopija
- Eksperimentalna metoda - uzorci
- Rezultati – utjecaj zračenja

Poluvodiči

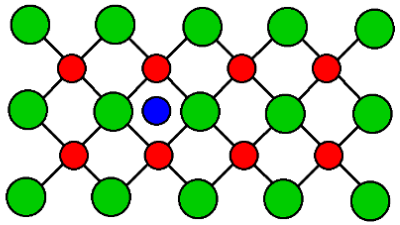
- Elektronika
- Laserske diode
- Solarne ćelije
- Detektori (zračenja)



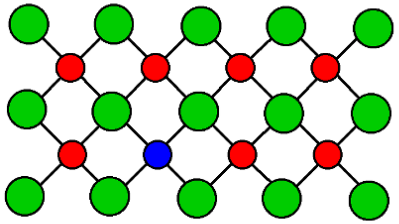
Defekti kristalne rešetke



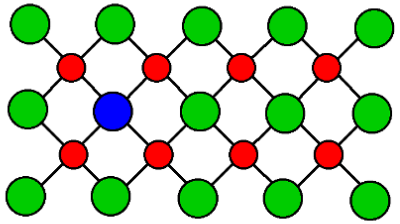
(a) perfect lattice



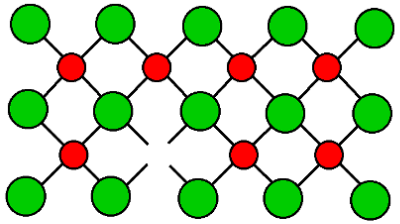
(b) interstitial impurity



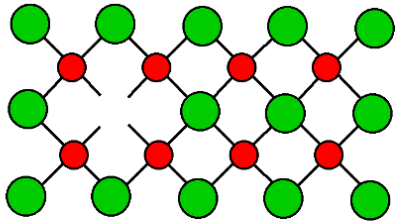
(e) substitution of cation



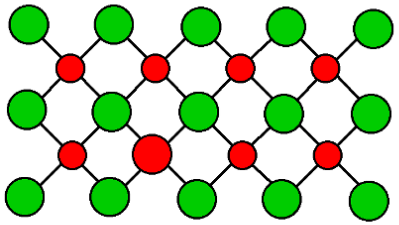
(f) substitution of anion



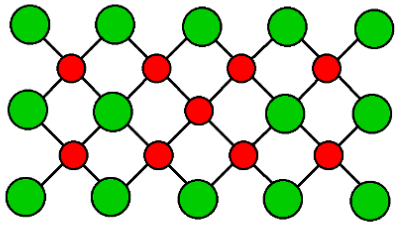
(c) cation vacancy



(d) anion vacancy



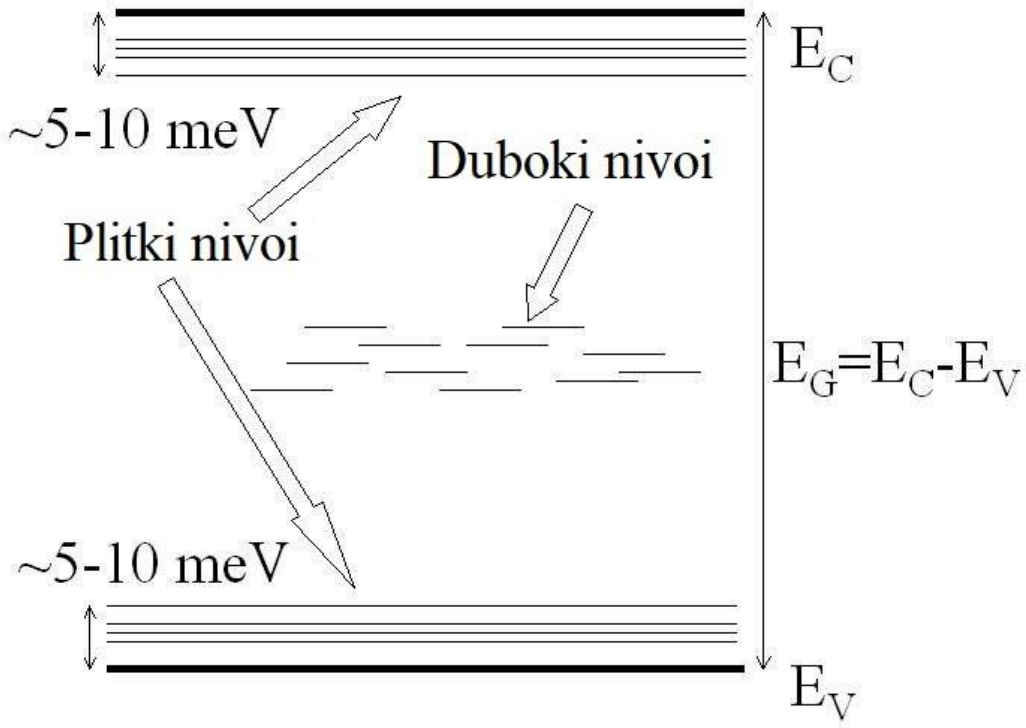
(g) B_A antisite defect



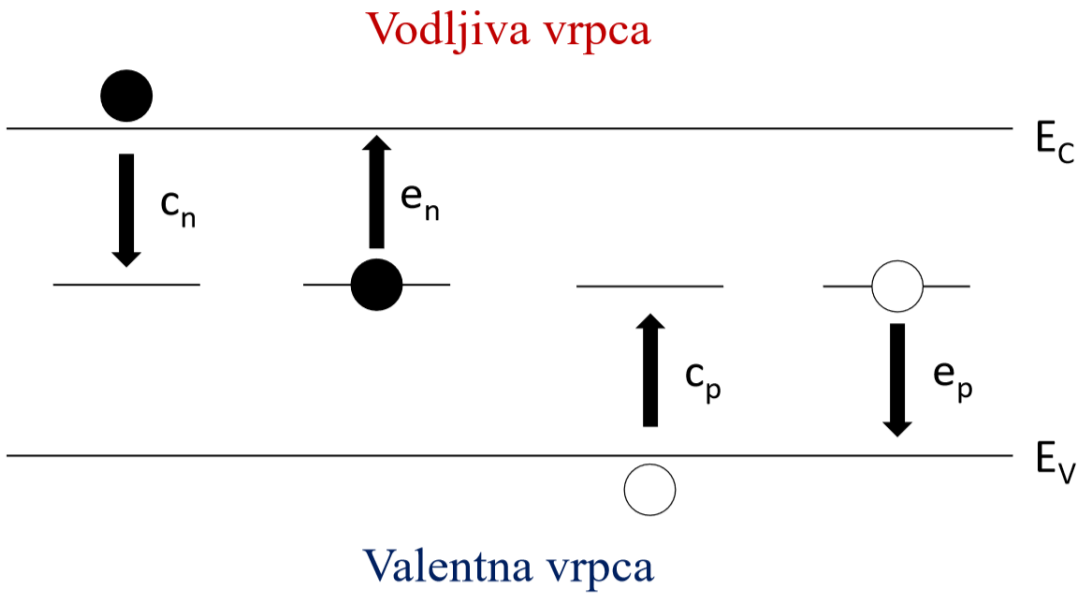
(h) A_B antisite defect

Fizika poluvodiča

- Vodljiva i valentna vrpca
  - Periodičnost kristalne rešetke
- Nivoi unutar energetskog procjepa
  - Narušena periodičnost rešetke



Fizika poluvodiča

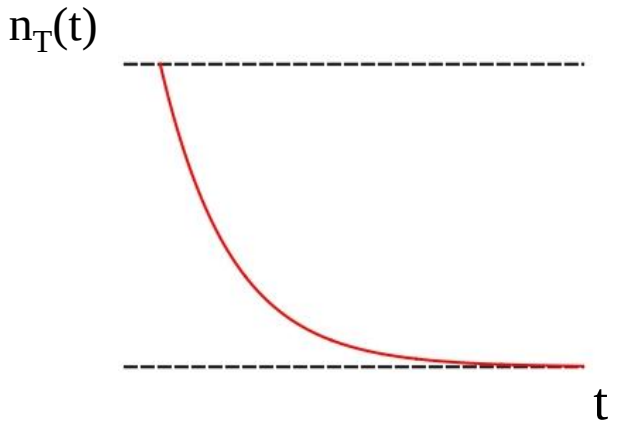


- Uhvati i emisije
  - (vjerojatnosti u jedinici vremena)
  - Elektroni (c_n, e_n)
  - Šupljine (c_p, e_p)
- Popunjenost ovisi o Fermi-Diracovoj raspodjeli

Vremenska promjena popunjenosti dubokog nivoa

$$\frac{dn_T}{dt} = -(e_n + c_p)n_T + (c_n + e_p)(N_T - n_T)$$

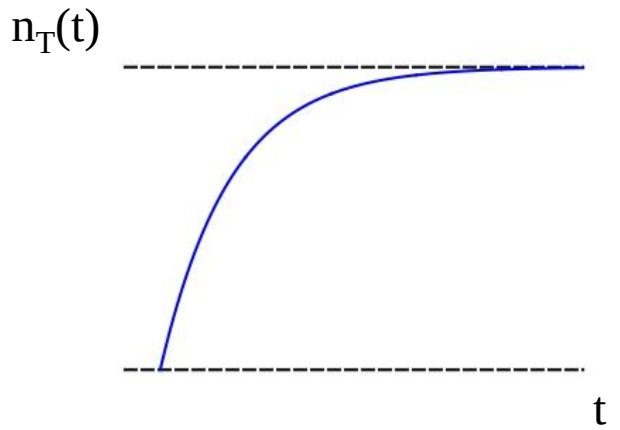
Rješenja diferencijalne jednadžbe (n-tip)



$$n_T(t) = N_T exp(-e_n t)$$

$$e_n >> c_n, e_p, c_p$$

Popunjenost dubokih nivoa



$$n_T(t) = N_T(1 - exp(-c_n t))$$

$$c_n >> e_n, e_p, c_p$$

Temperaturna ovisnost emisije elektrona

$$ln(\frac{e_n}{T^2}) = ln(\sigma_\infty K_T) - \frac{E_C - E_T}{k_B T}$$

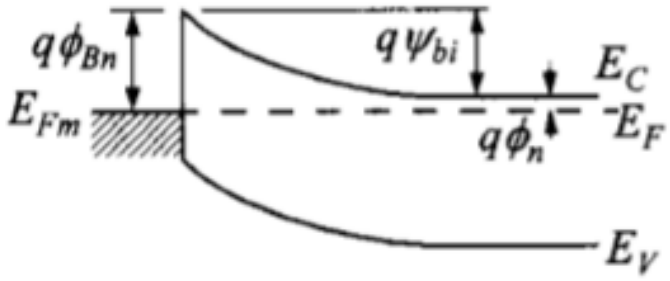
E_C = energija vodljive vrpce
E_T = energija defekta

T = temperatura
$k_B = 8.617 \cdot 10^{-5} eV K^{-1}$

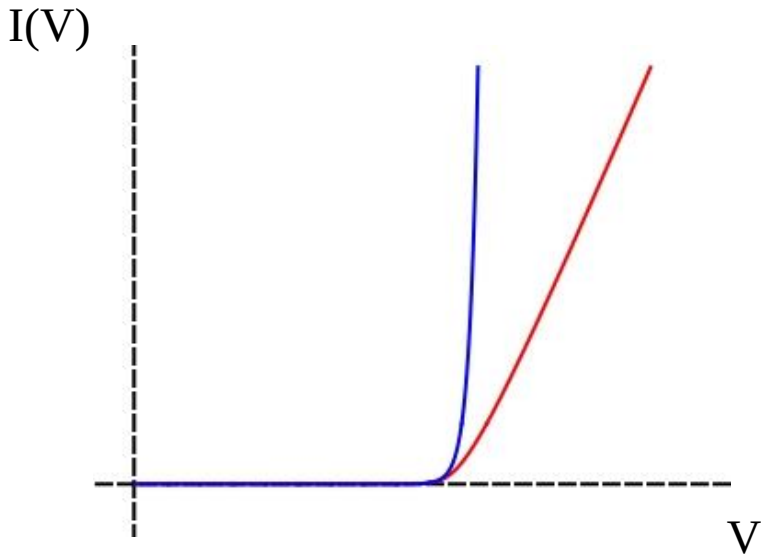
$$\sigma_n(T) = \sigma_\infty exp(-\frac{\Delta E_\sigma}{k_B T})$$

$$K_T = 3.625 \cdot 10^{21} cm^{-2} s^{-1} K^{-2}$$

Schottky dioda



- Spoj metala i poluvodiča
- Potencijalna barijera Φ_{bi} (ili V_{bi})



$$I(V) = I_S(exp(q\frac{V - IR_S}{nk_BT}) - 1)$$

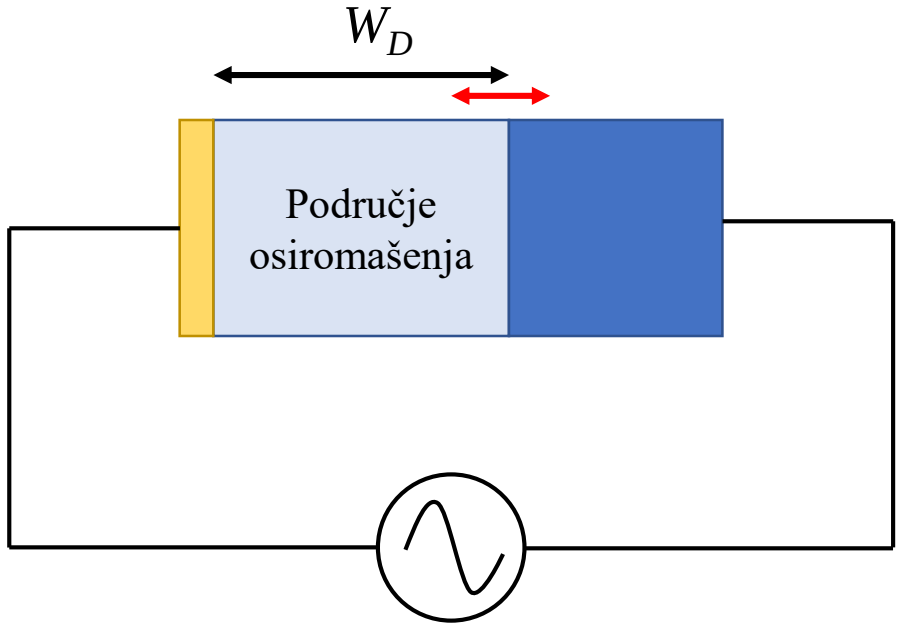
I = struja kroz diodu
V = napon na krajevima diode
$q = 1.6 \cdot 10^{-19}C$

I_s = struja saturacije
n = faktor idealnosti diode
R_S = serijski otpor diode

Kapacitet diode

$$C(V) = \frac{dQ}{dV} = \frac{A\epsilon}{W_D(V)}$$

$$C(V) = A\sqrt{\frac{\epsilon}{2}\frac{qN}{V_{bi}-V}}$$



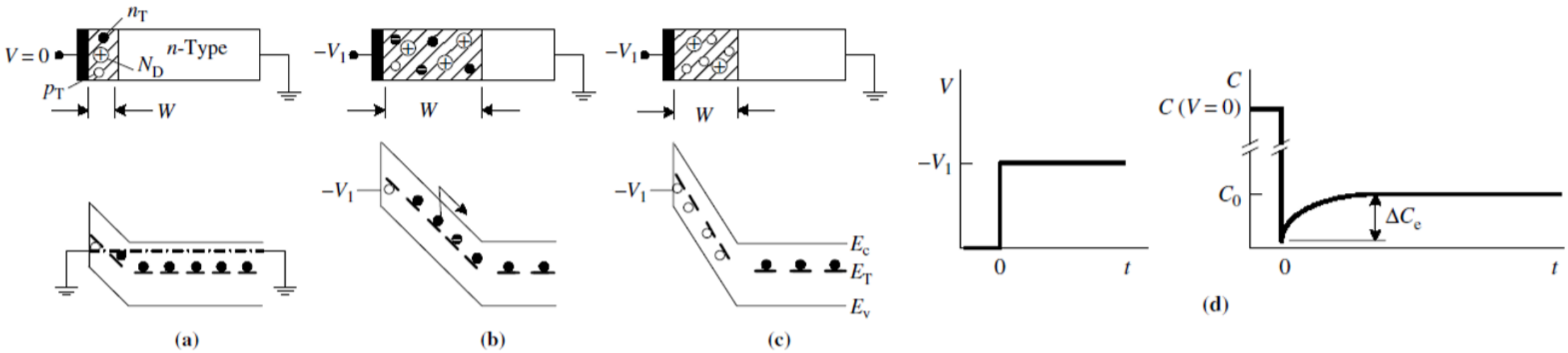
A = površina diode
ϵ = električna permitivnost materijala
N = koncentracija slobodnih nosioca naboja

Tranzijentna spektroskopija (DLTS)

Koncentracija naboja $$qN = q(N_D - n_T)$$

$n_T << N$

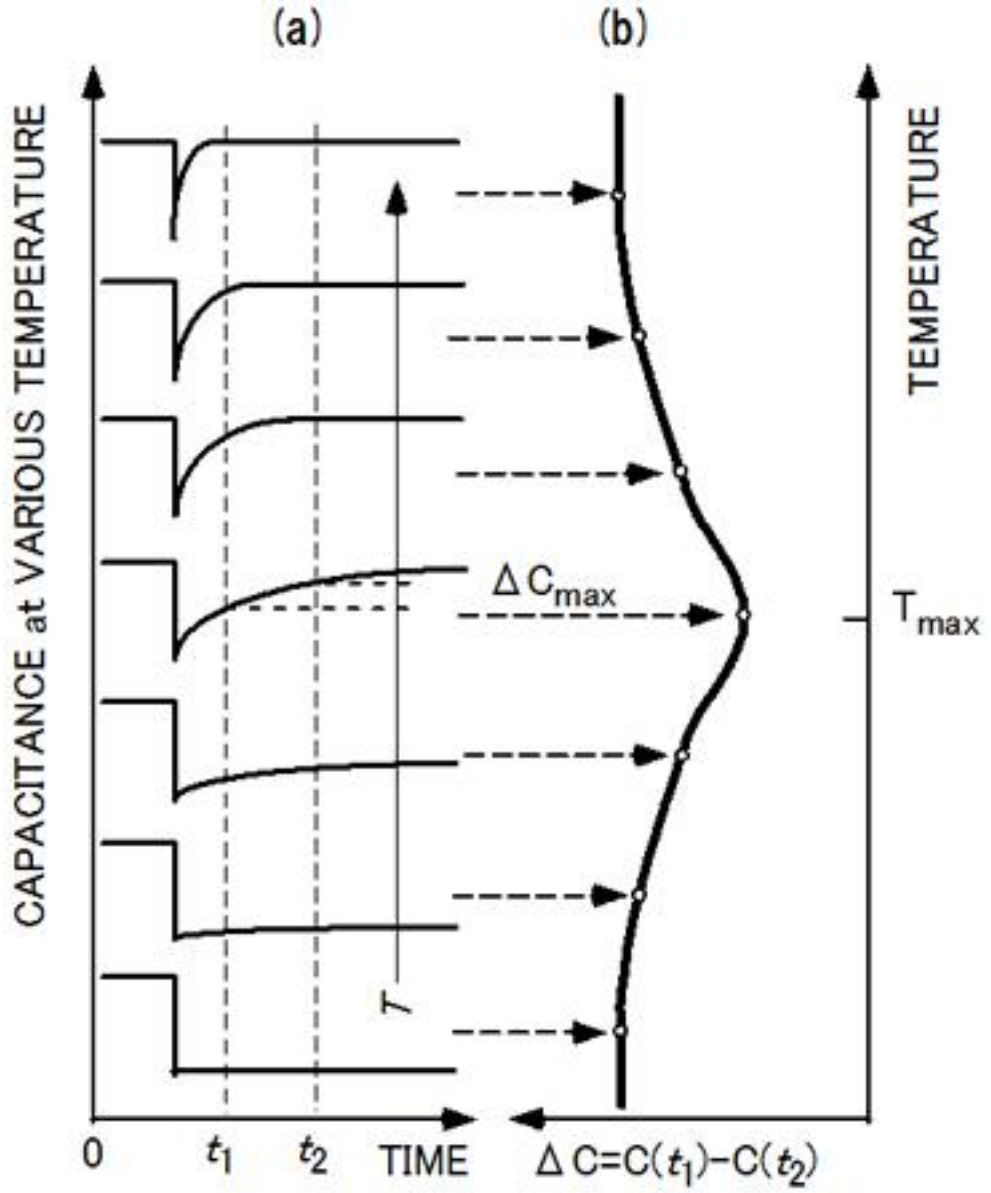
Kapacitet $$C(t) = C_0(1 - \frac{n_T(t)}{2N_D})$$



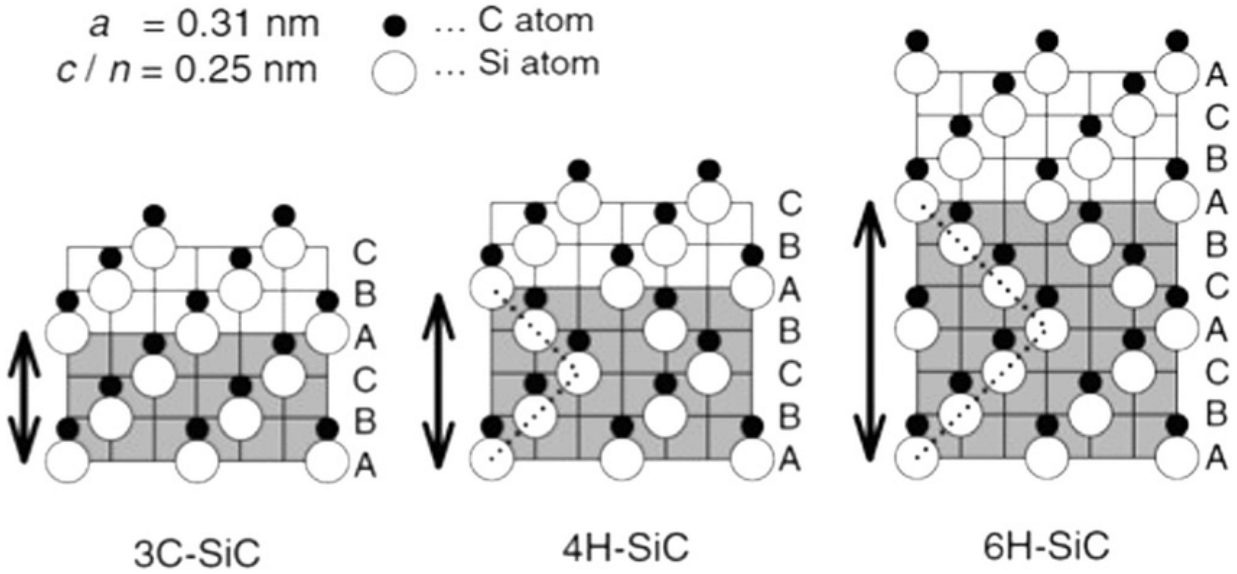
Određivanje emisije

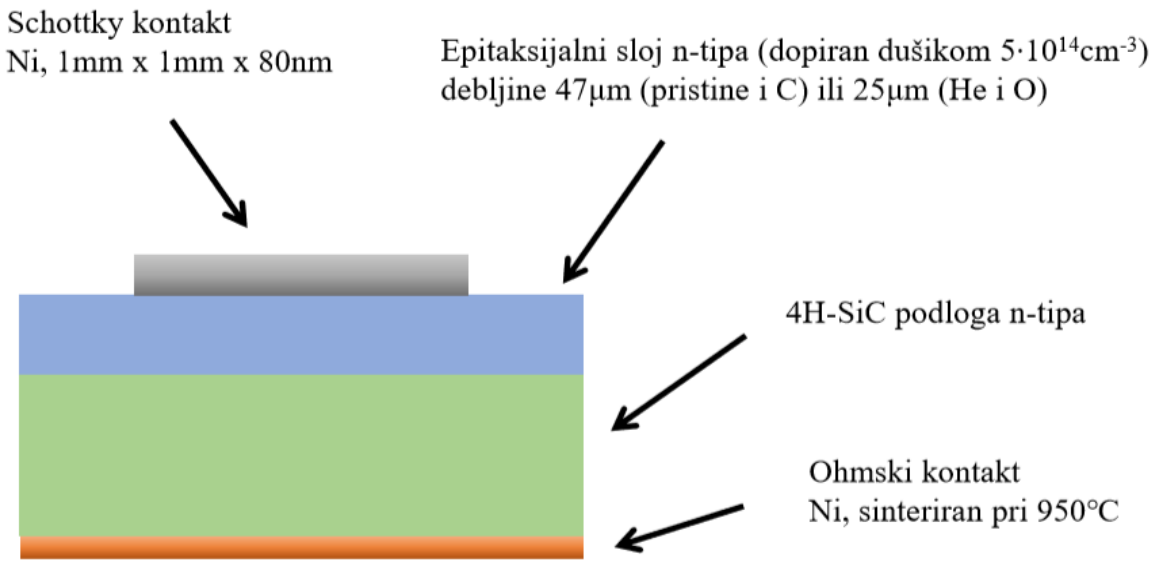
- Inverzni Laplace transformat
  - Numerička metoda
  - Zahtjeva nizak šum
- Vremenski prozor
  - Razlika vrijednosti kapaciteta u dvije fiksne vremenske točke

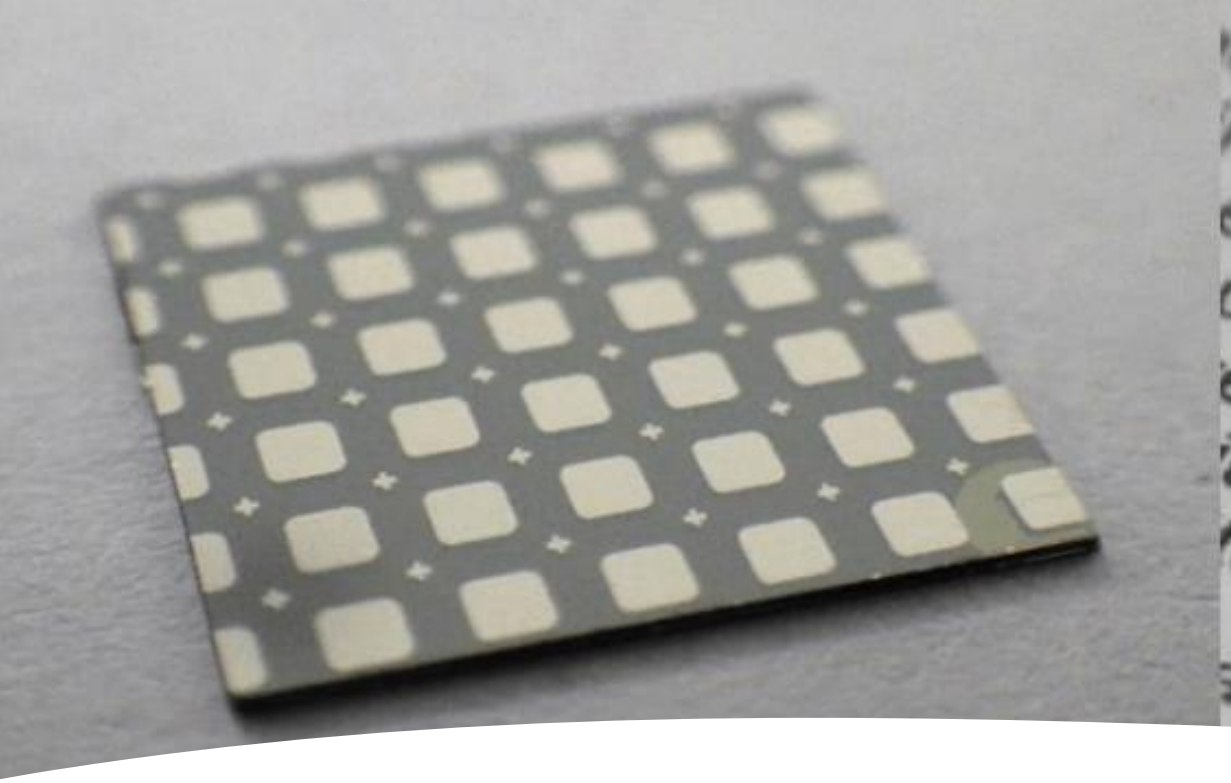
$$e_n(T_0) = \frac{ln(t_2/t_1)}{t_2 - t_1}$$

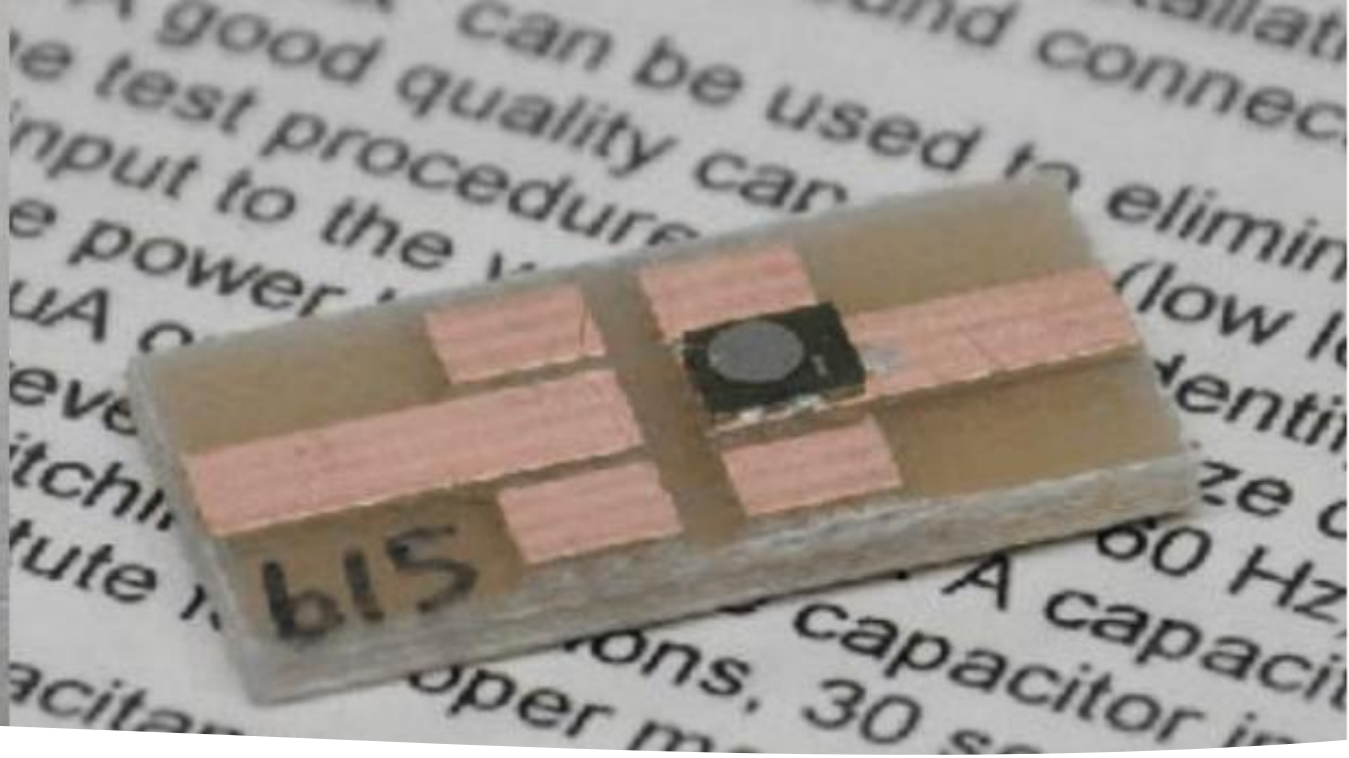


Uzorci


a = 0.31 nm
c / n = 0.25 nm
... C atom
... Si atom
C B A C B A
C B A B C B A
A C B A B C A C B A
3C-SiC
4H-SiC
6H-SiC


Schottky kontakt
Ni, 1mm x 1mm x 80nm
Epitaksijalni sloj n-tipa (dopiran dušikom $5 \cdot 10^{14} cm^{-3}$)
debljine 47μm (pristine i C) ili 25μm (He i O)
4H-SiC podloga n-tipa
Ohmski kontakt
Ni, sinteriran pri 950°C

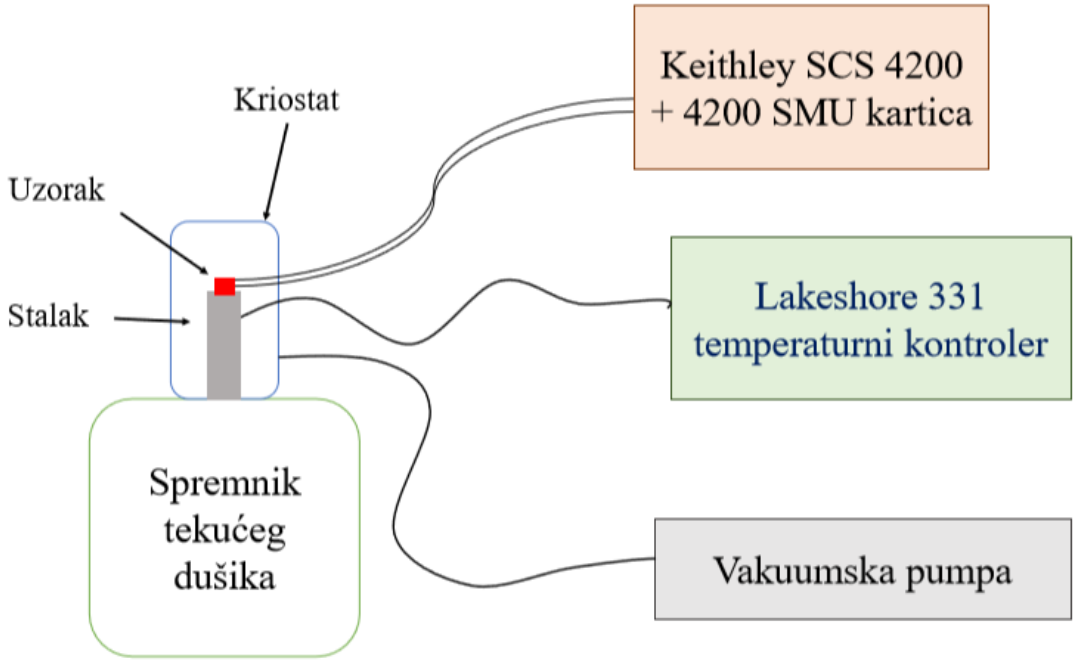


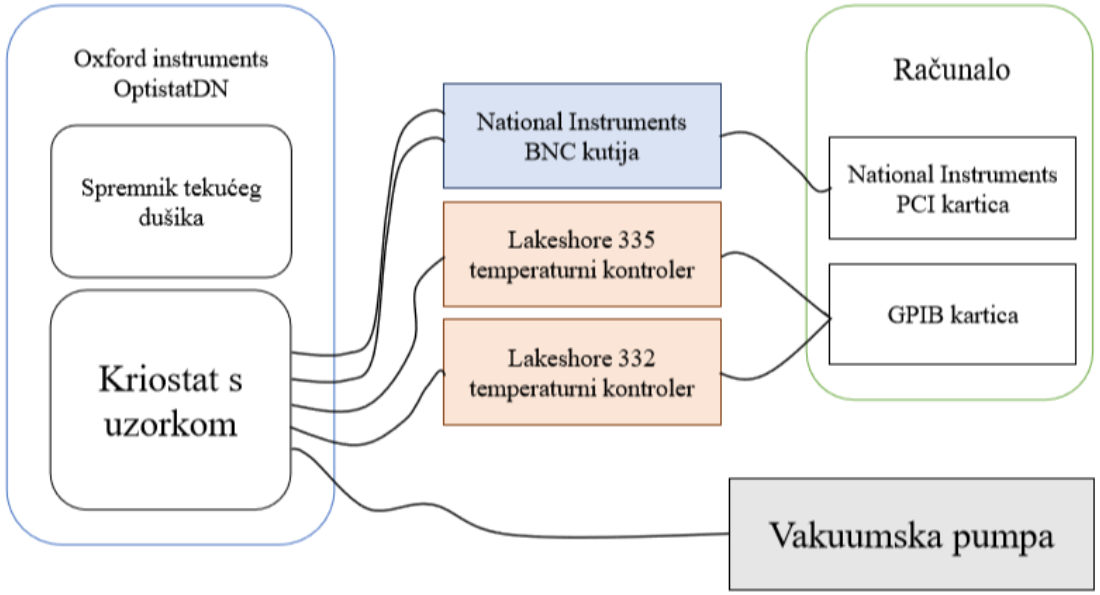


- CRIEPI
  - Central research institute of electric power industry, Japan
- ANSTO
  - Australian nuclear science and technology organisation

- Neozračeni
- Ozračeni ionima
  - 2MeV helij
  - 7.5MeV ugljik
  - 20MeV kisik

Eksperimentalni postav

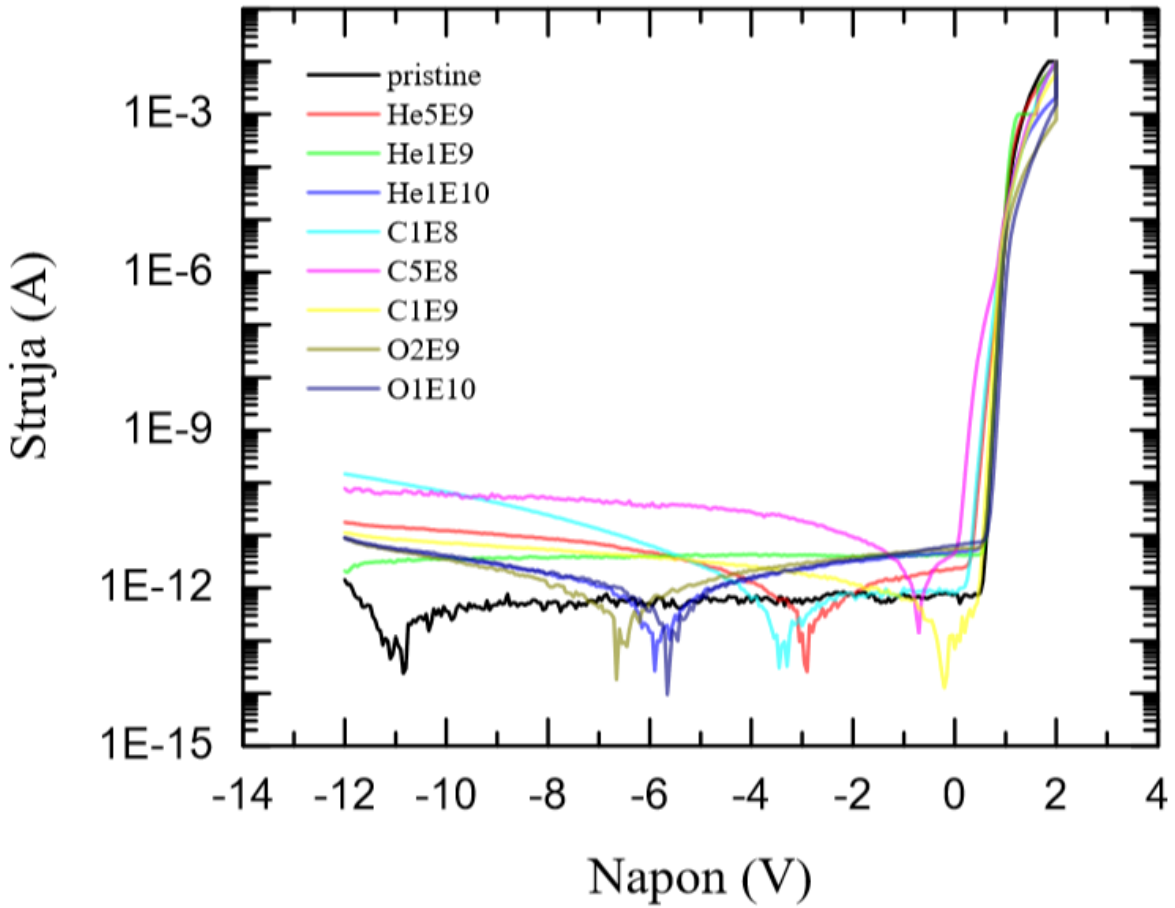




Rezultati

Strujno-naponska karakteristika

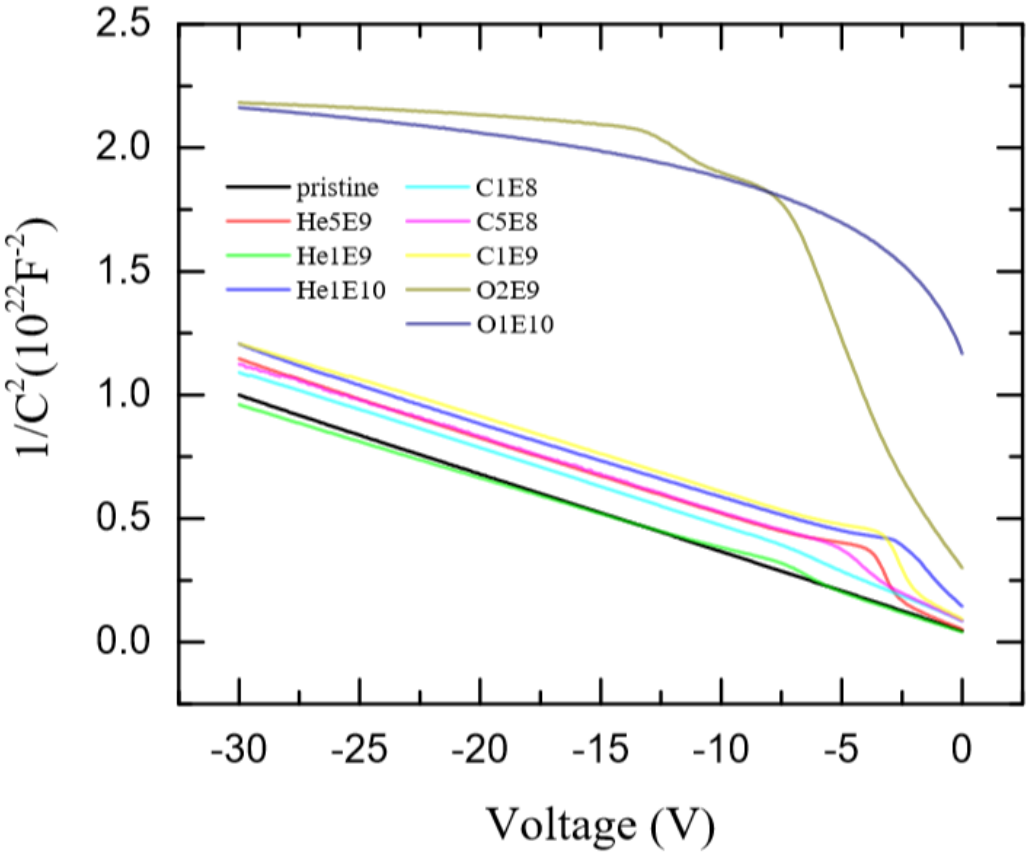
- Dobra karakteristika svih dioda
  - Otpornost na zračenje
- Niska reverzna struja
  - < 1pA
- Veće doze pokazuju veći serijski otpor
  - Određen Nordeovom metodom



Kapacitivno-naponska karakteristika

- Neozračen uzorak posjeduje linearnu karakteristiku
- Ozračeni posjeduju „koljena”
  - Kompenzacija nosioca naboja
  - Izvan kompenzacije koncentracija naboja oko razine dopiranja $5 \cdot 10^{14} cm^{-3}$

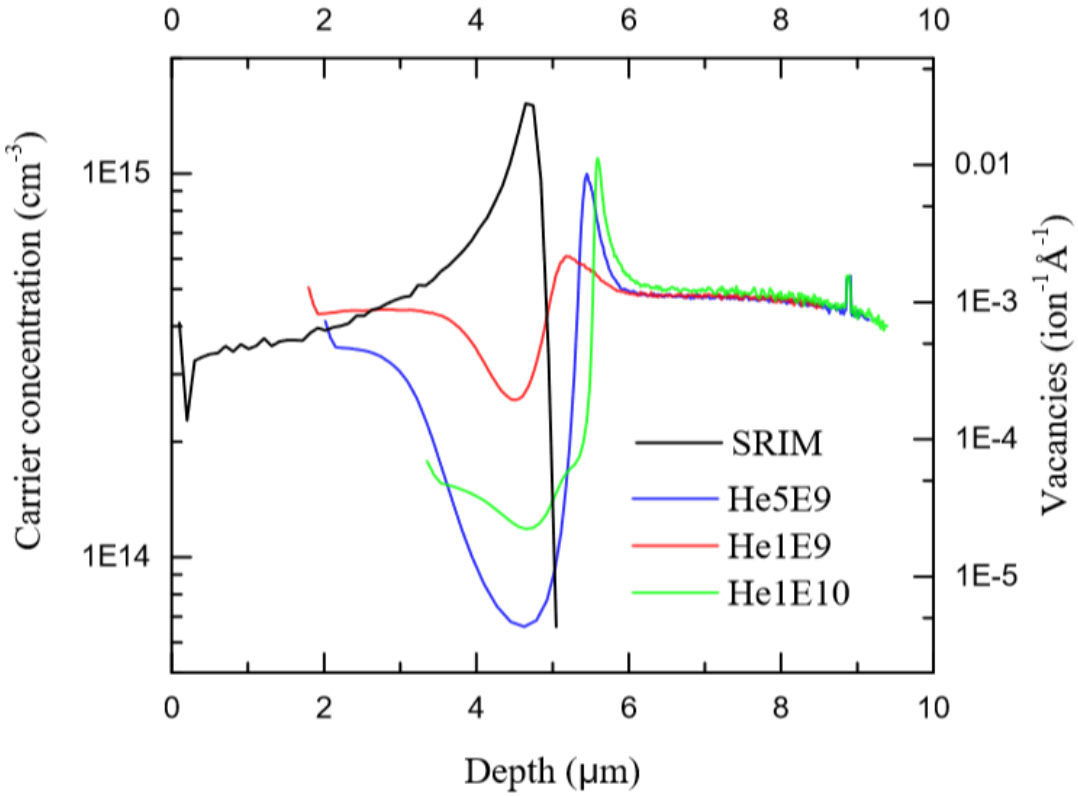
$$\frac{1}{C^2(V)} = \frac{2}{\epsilon A^2} \frac{V_{bi} - V}{qN}$$



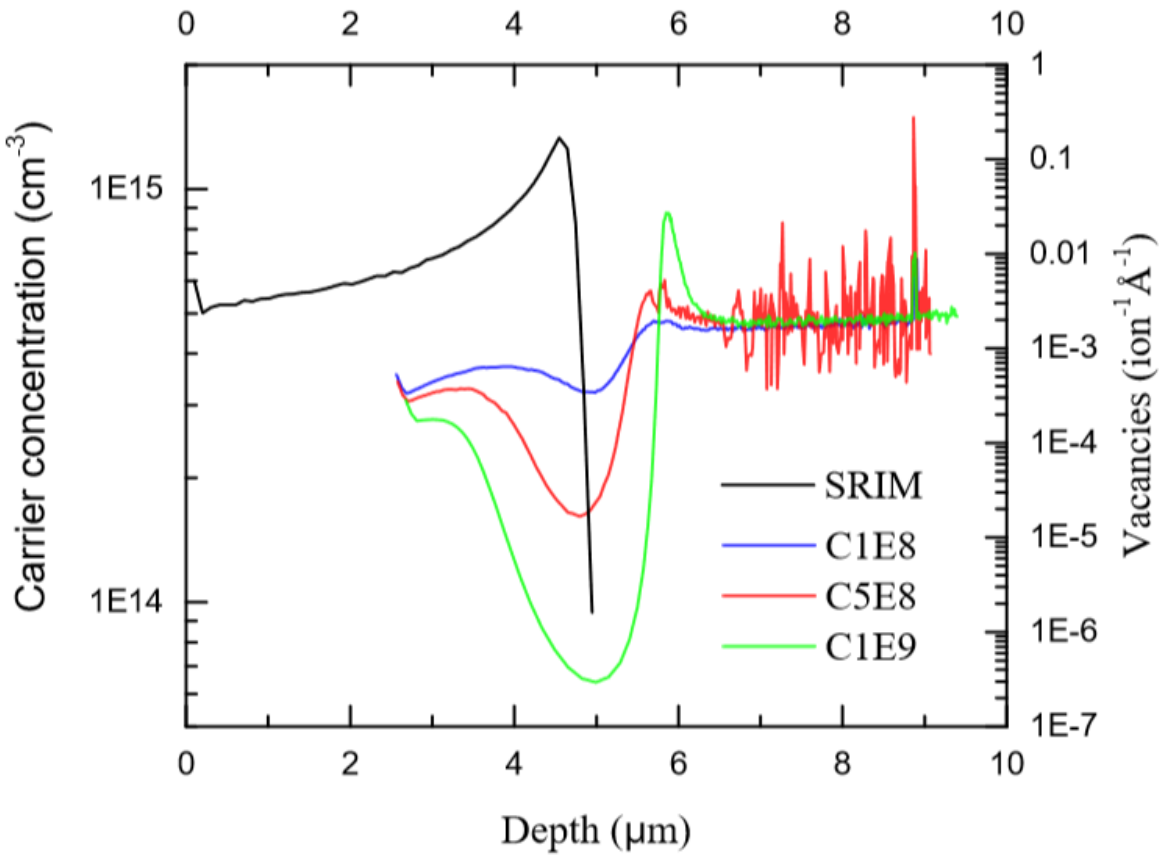
Dubinski profil slobodnih nosioca naboja

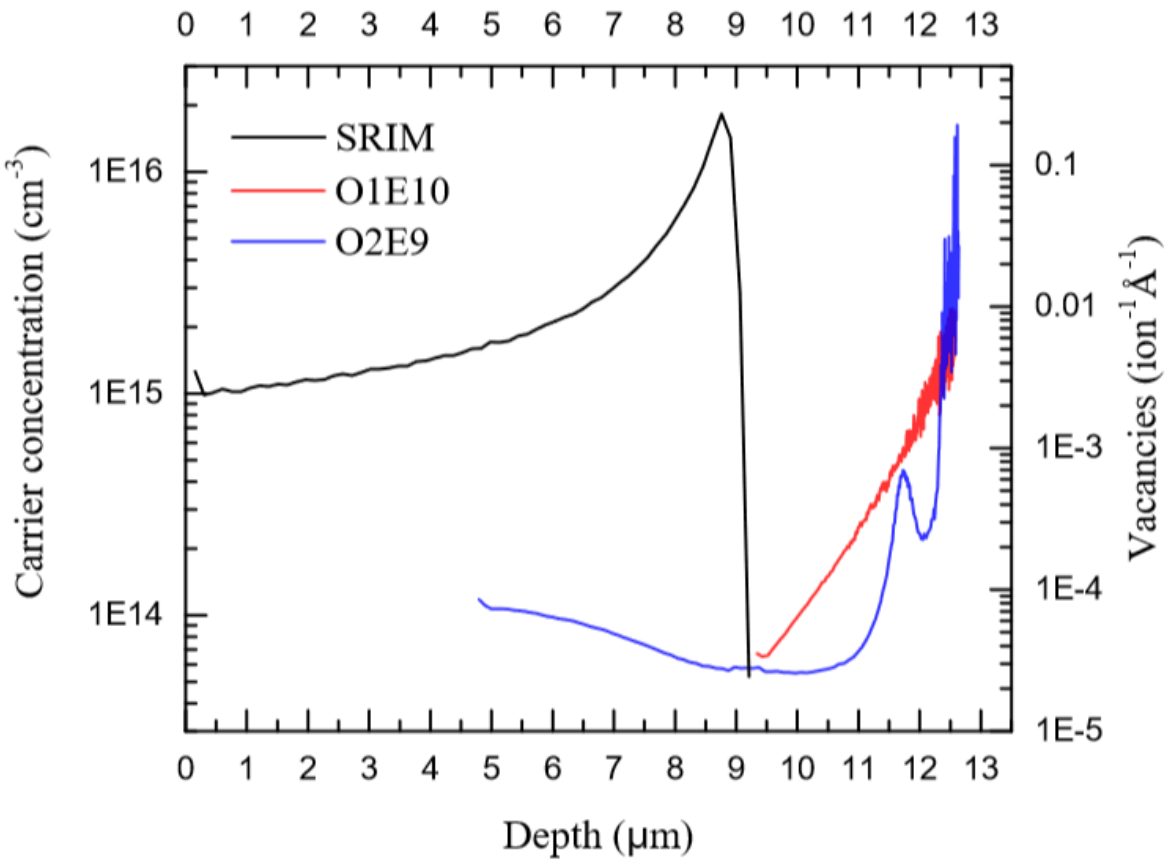
- Predviđanje
  - SRIM (Transport of ions in matter)
  - Monte Carlo simulacije
- Eksperiment

$$N(W) = \frac{2}{q\epsilon A^2}\left(\frac{d(1/C^2)}{dV}\right)^{-1}$$

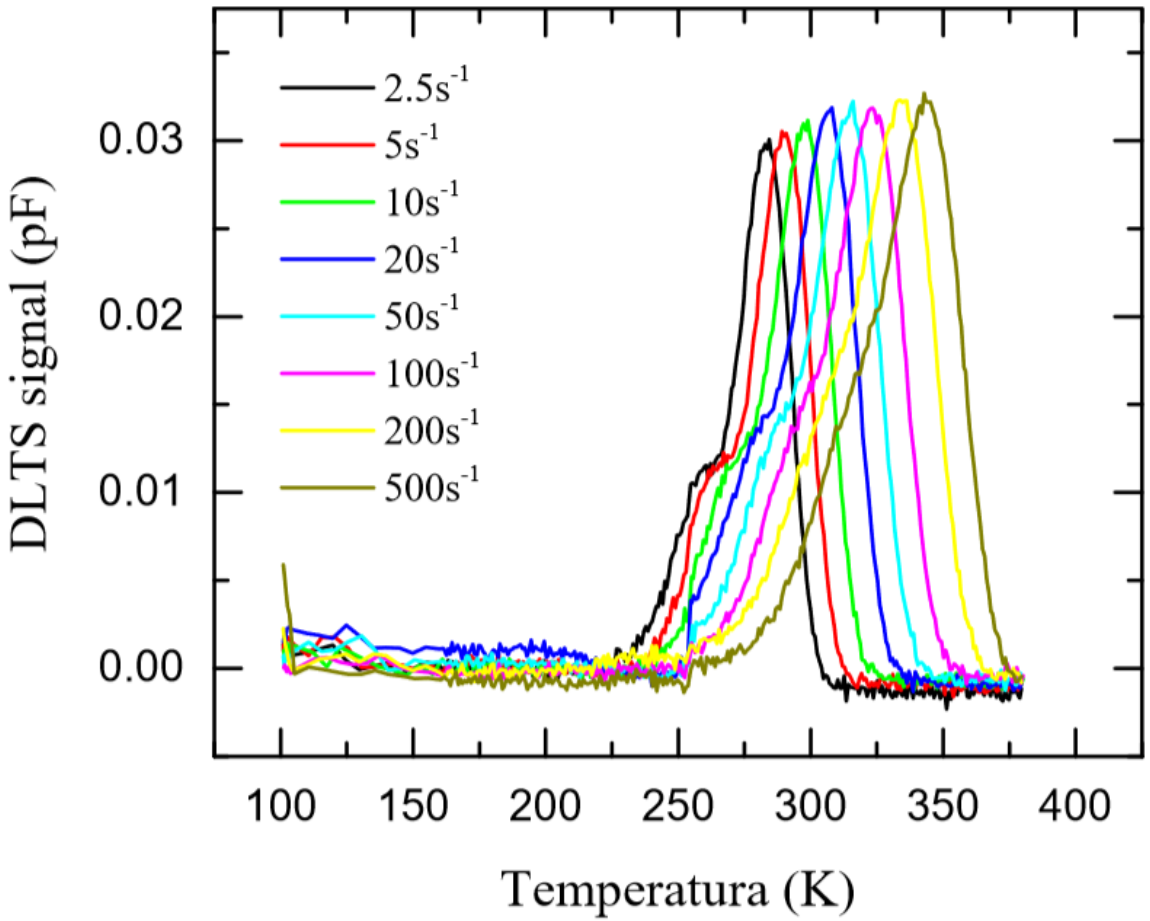


Dubinski profil slobodnih nosioca naboja

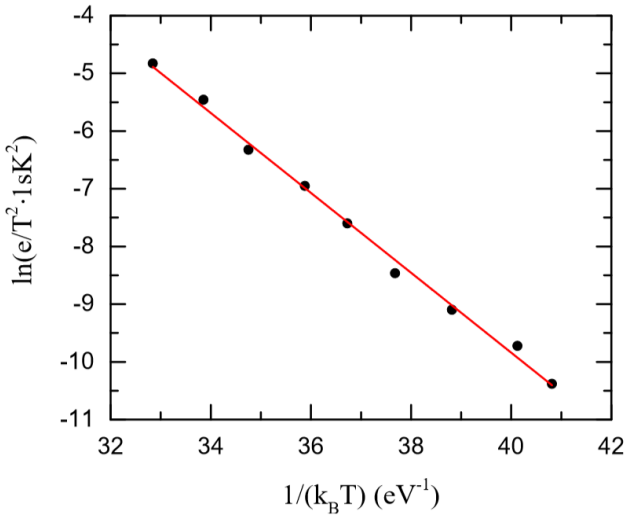




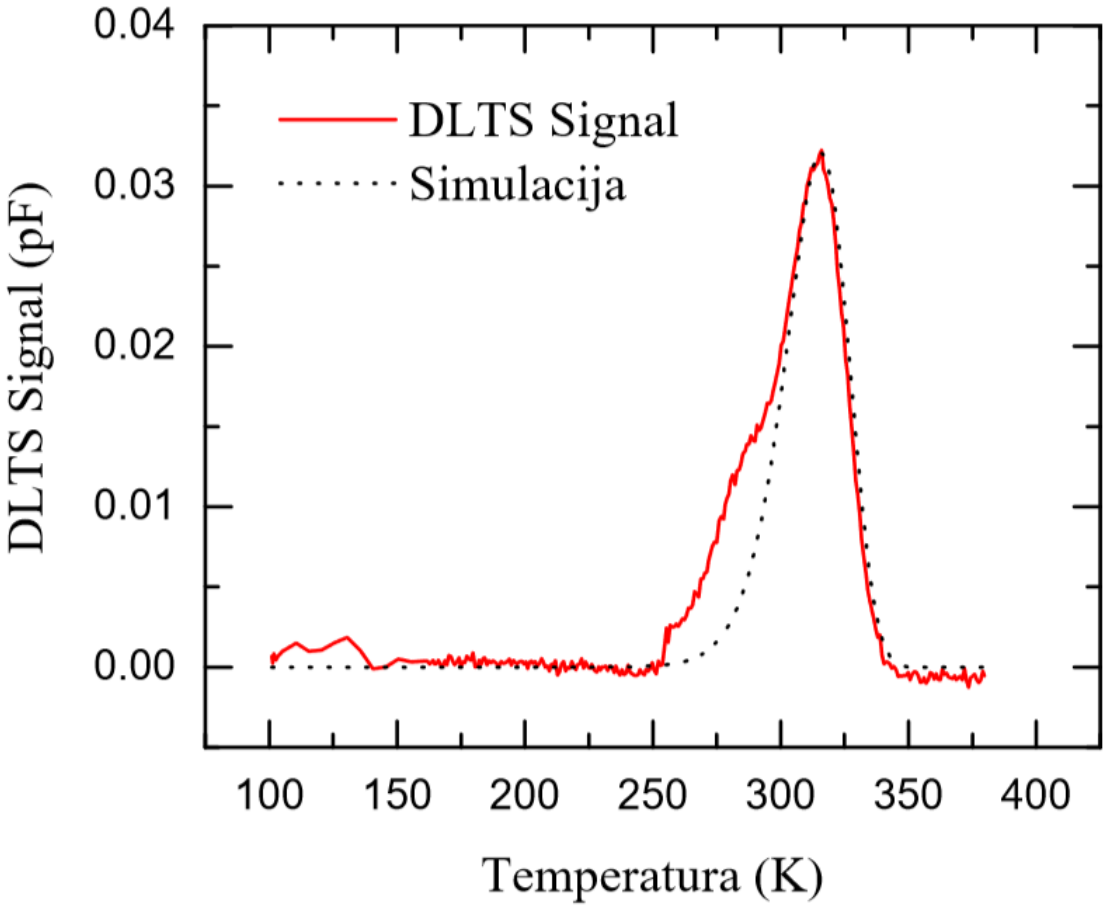
Tranzijentna spektroskopija



- Neozračen uzorak
  - Uočen jedan duboki nivo energije 0.69eV ispod vodljive vrpce
  - Iz literature je poznat kao vakancija ugljika

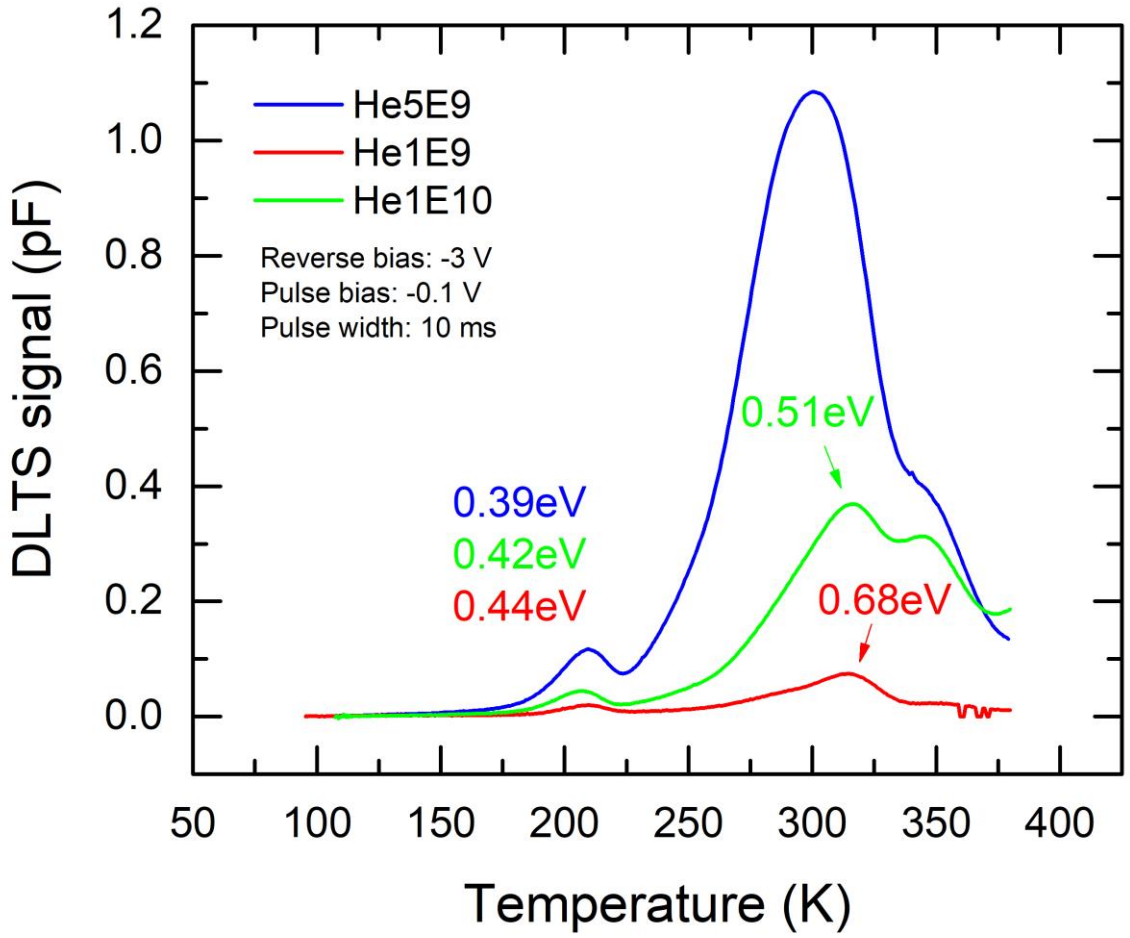


Simulacija tranzijentne spektroskopije

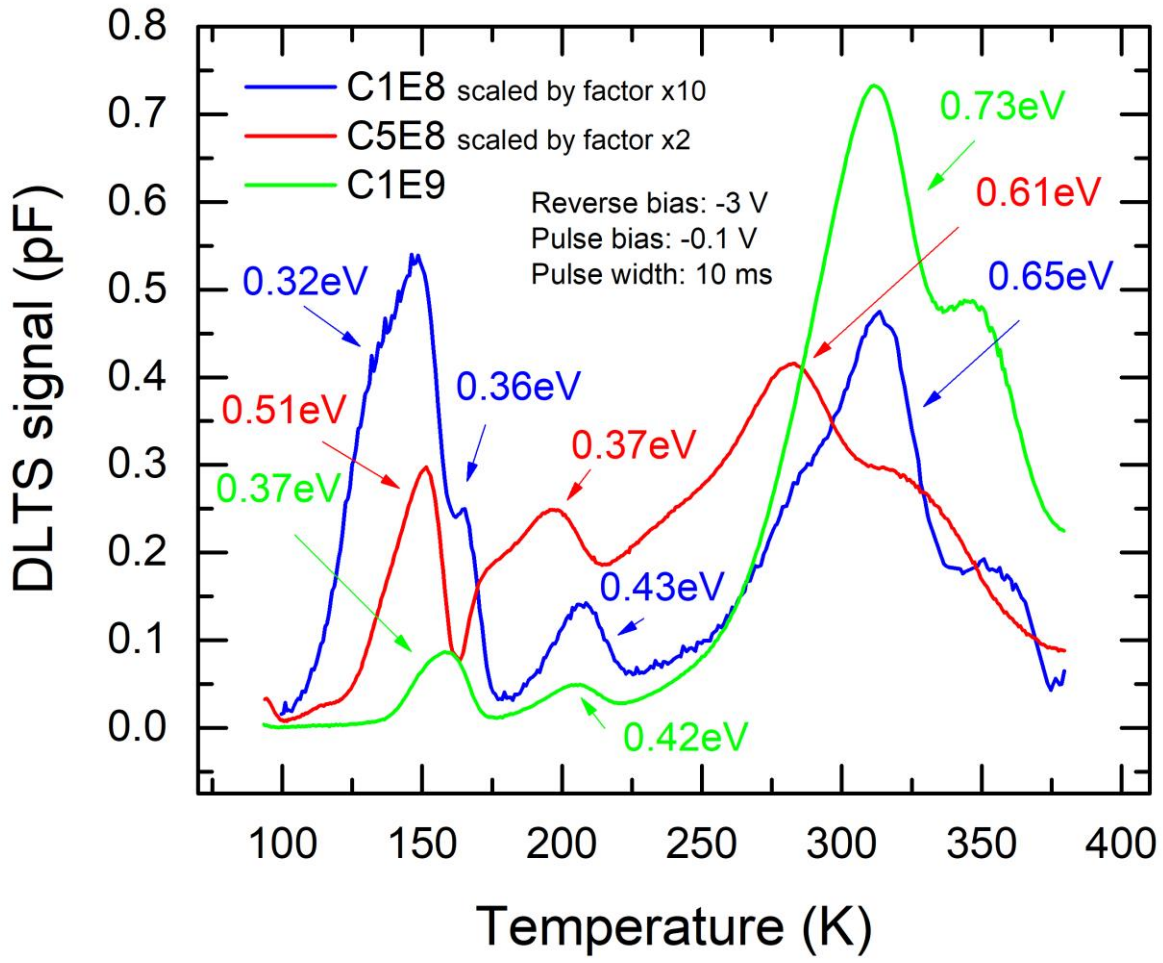


- Može se uočiti dobro poklapanje osim što je eksperimentalni vrh nešto širi
  - Uzrok su dva vrha sličnih energija u spektru
  - U literaturi određene energije 0.55eV i 0.69eV ispod vodljive vrpce
  - Isti defekt na različitim točkama kristalne rešetke

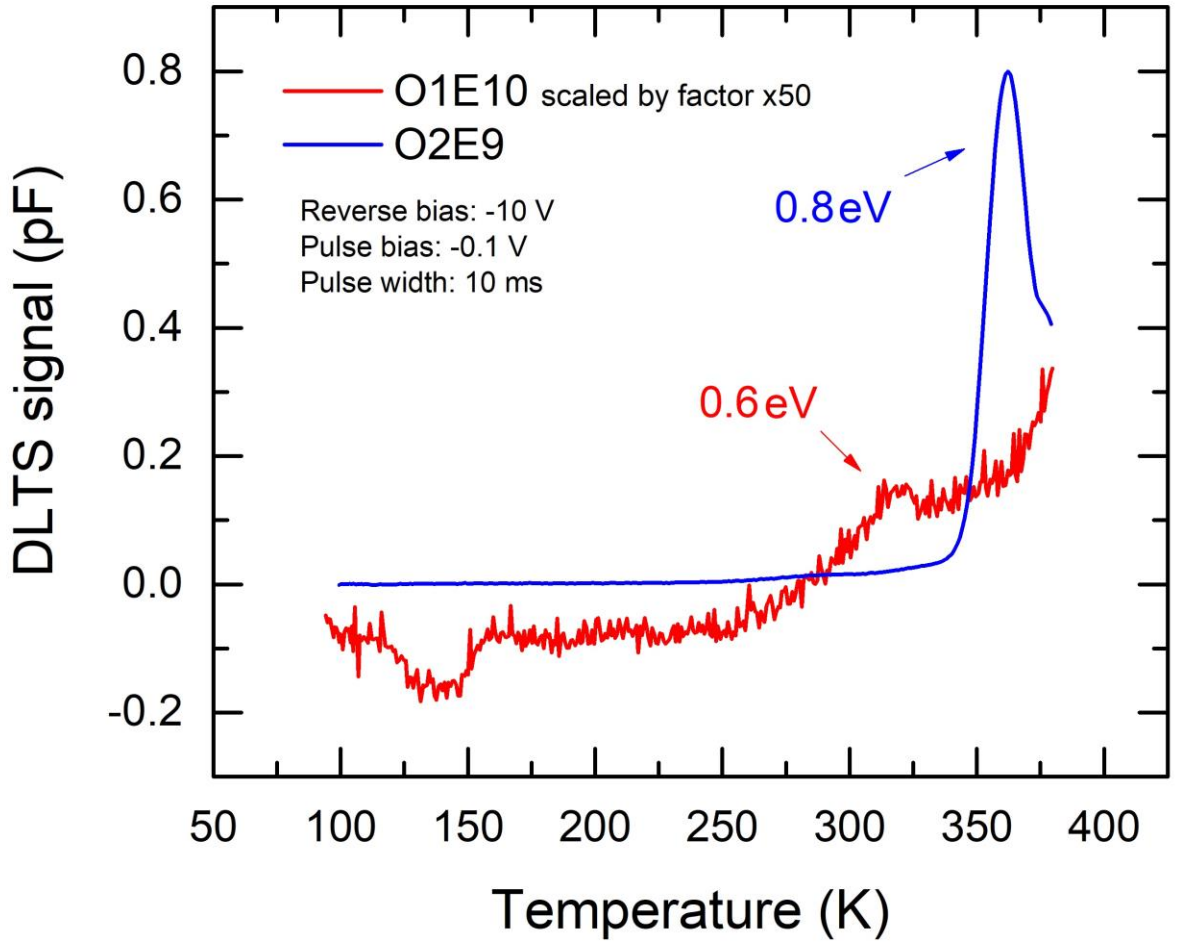
Uzorci ozračeni ionima helija energije 2MeV



Uzorci ozračeni ionima ugljika energije 7.5MeV

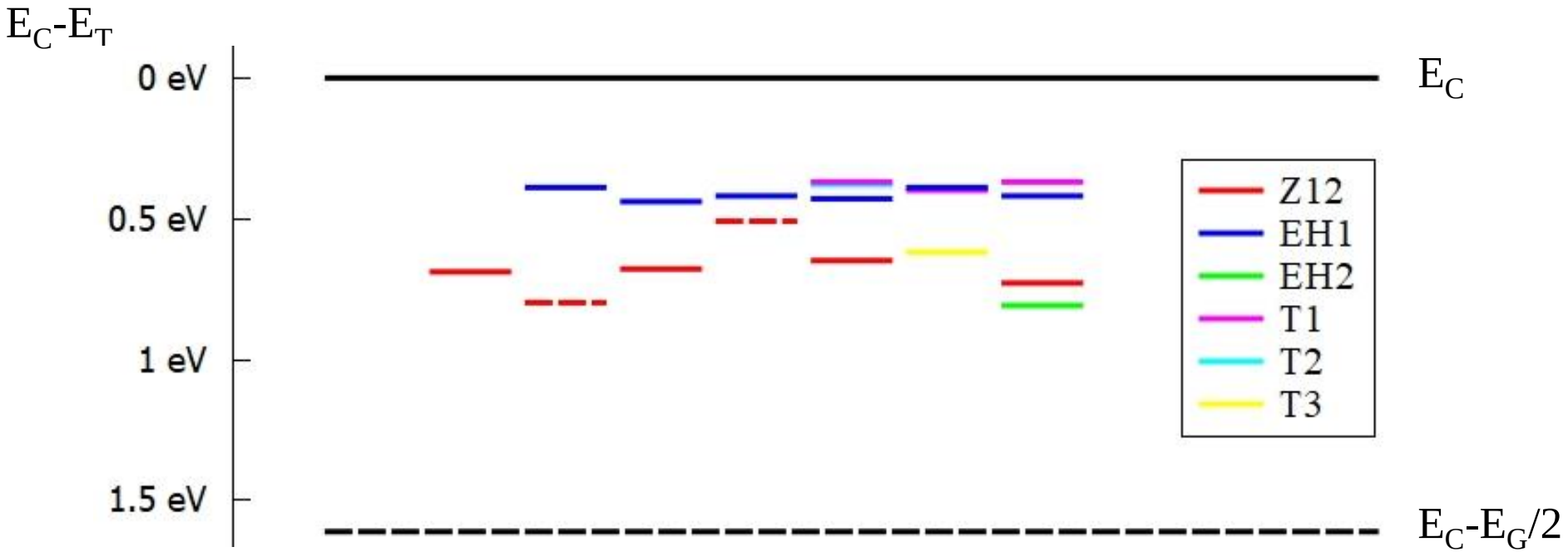


Uzorci ozračeni ionima kisika energije 20MeV



Rezultat analiziranih nivoa

- U svim uzorcima prisutan je Z_{12} (0.7eV)
- U svim ozračenim uzorcima prisutni su EH1 (0.4eV) i EH3 (0.7eV)
  - Intrinzični defekti
- U uzorcima ozračenim ugljikom prisutni su nepoznati nivoi



Zaključak

- Proučena je osnovna karakterizacija poluvodičkih dioda
  - I-V, C-V karakteristike
  - Dolazi do kompenzacije naboja u slaganju s teorijom
  - Silicij karbid pokazuje dobru otpornost na zračenje
- Karakterizirani su duboki nivoi uneseni zračenjem
  - Riječ je o intrinzičnim defektima
  - Tri nivoa su poznata iz literatura, a uočena su i tri nova (nepoznata porijekla)

Hvala

Dodatak

- Literatura
- Malo detalja oko fizike poluvodiča i dioda
- Primjer određivanja serijskog otpora diode
- Tablica doza ozračenih uzoraka
- Tablica strujnih karakteristika
- Tablica svih analiziranih dubokih nivoa
- Tablica vremenskih prozora
- Ovisnost koncentracije dubokog nivoa o dozi zračenja
- Propusno polarizirane strujne karakteristike
- Ovisnost širine područja osiromašenja o reverznom naponu

Literatura

- http://info.ifpan.edu.pl/Dodatki/WordPress/laplacedlts/
- J. B. Casady, R. W. Johnson, Solid State Electron 39, 1409 (1996)
- D. K. Schroder, Semiconductor material and device characterization, 3rd ed. (John Wiley & sons, INC., 2006)
- S.M. Sze, Physics of Semiconductor Devices, 3rd ed. (John Wiley & sons, INC., 2006)
- L. G. et al., Materials Science-Poland 23 (2005)
- A.R .Peaker, V.P. Markevich, J. Coutinho, Journal of Applied Physics 123, 161559 (2018)
- L. Romano, V. Privitera, C. Jagadish, Defects in Semiconductors (Semiconductors and Semimetals), 1st ed., Vol. 91 (Academic Press, 2015)
- Capan et al, Journal of Applied Physics 124, 245701 (2018)
- Ž. Pastuović, Journal of Physics: Condensed Matter 29, 475701 (2017)
- B. Zippelius, J. Suda, T. Kimoto, Journal of Applied Physics 111, 033515 (2012)

Formule

$$e_n n_T = c_n(N_T - n_T)$$

$$e_n(T) = \sigma_n(T) < v_n > (T)\frac{g_0}{g_1}N_c(T)exp(-\frac{E_c - E_T}{k_B T})$$

$$c_n = n\sigma_n < v_n >$$

$$N_c = 2(\frac{2\pi m k_B T}{h^2})^{3/2}$$

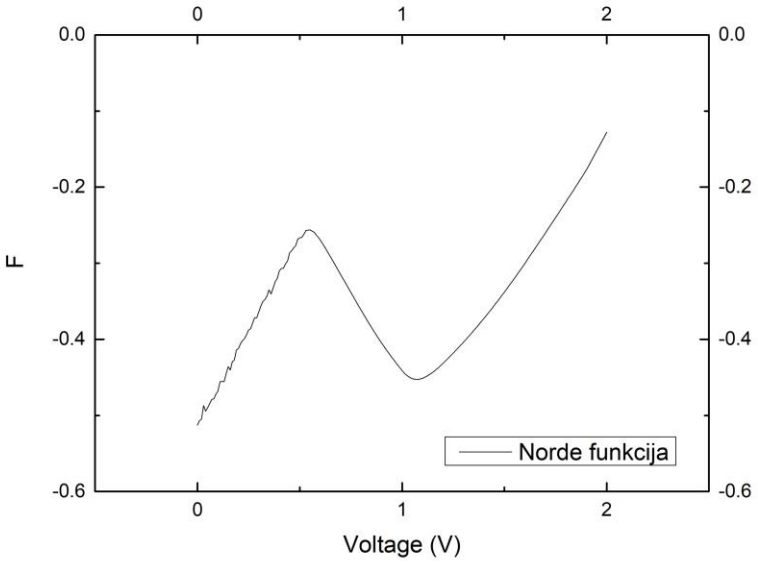
$$< v_n >= \sqrt{\frac{3k_B T}{m^*}}$$

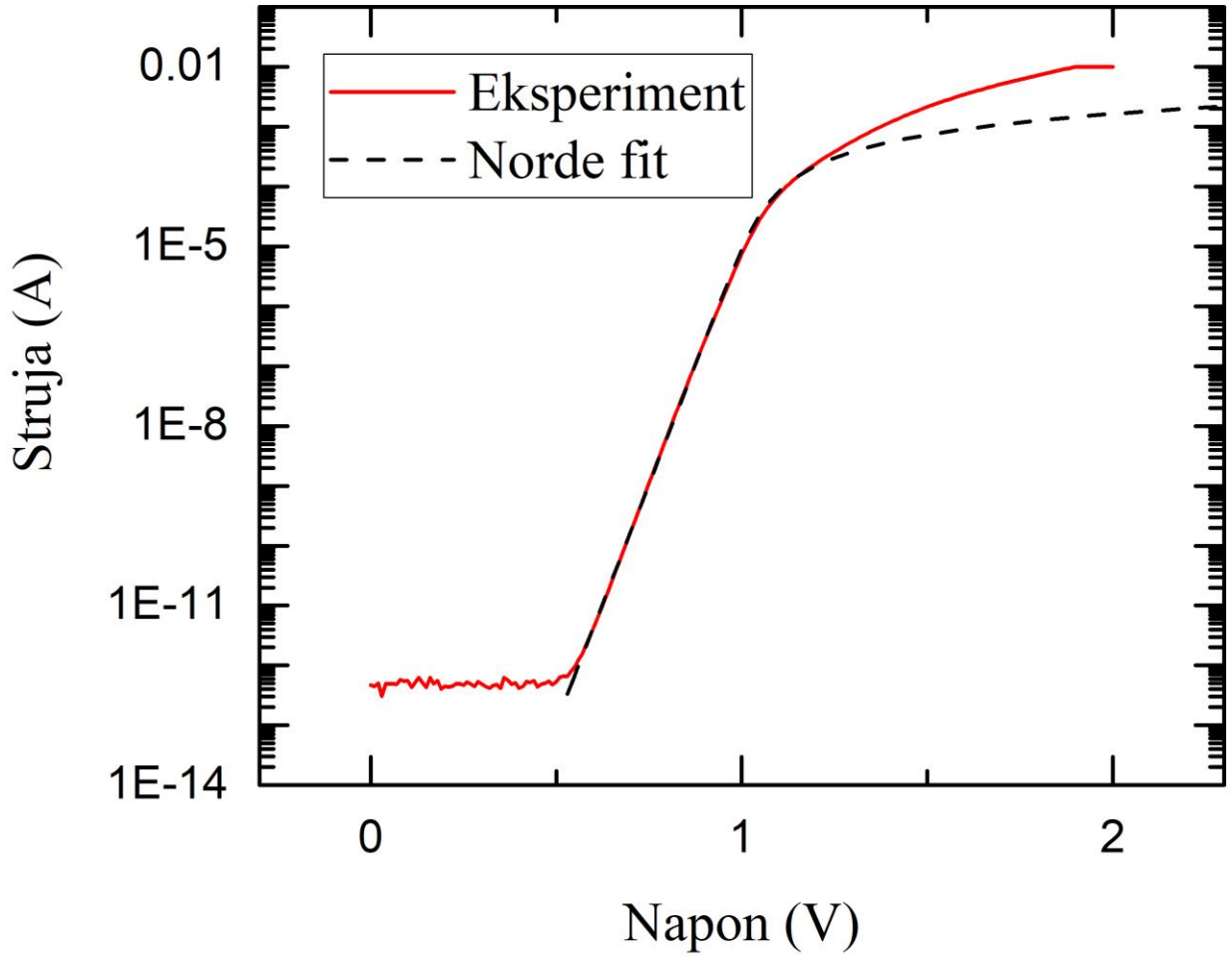
$$W_D = \sqrt{\frac{2\epsilon}{qN}(V_{bi} - V - \frac{k_B T}{q})}$$

Norde metoda određivanja serijskog otpora

$$F = \frac{V}{2} - \frac{kT}{q} ln\left(\frac{I}{I_S}\right)$$

$$R_S = \frac{2-n}{I_{min}} \frac{kT}{q}$$





Tablica doza ozračenih uzoraka

Uzorak	Ion	Energija iona	Doza iona
He5E9	He	$2MeV$	$5 \cdot 10^9 cm^{-3}$
He1E9	He	$2MeV$	$1 \cdot 10^9 cm^{-3}$
He5E10	He	$2MeV$	$1 \cdot 10^{10} cm^{-3}$
C1E8	C	$7.5MeV$	$1 \cdot 10^8 cm^{-3}$
C5E8	C	$7.5MeV$	$5 \cdot 10^8 cm^{-3}$
C1E9	C	$7.5MeV$	$1 \cdot 10^9 cm^{-3}$
O2E9	O	$20MeV$	$2 \cdot 10^9 cm^{-3}$
O1E10	O	$20MeV$	$1 \cdot 10^{10} cm^{-3}$

Tablica strujnih karakteristika dioda

Uzorak	Struja saturacije	Faktor idealnosti	Serijski otpor
pristine	$(1.2 \pm 0.1) \cdot 10^{-21}$	1.055 ± 0.003	500Ω
He5E9	$(4.6 \pm 0.1) \cdot 10^{-17}$	1.501 ± 0.003	200Ω
He1E9	$(5.0 \pm 0.1) \cdot 10^{-22}$	1.012 ± 0.001	160Ω
He1E10	$(5.3 \pm 0.2) \cdot 10^{-22}$	1.023 ± 0.001	400Ω
C1E8	$(1.16 \pm 0.06) \cdot 10^{-17}$	1.484 ± 0.006	$5k\Omega$
C5E8	$(7.1 \pm 0.2) \cdot 10^{-14}$	1.617 ± 0.009	$4M\Omega$
C1E9	$(5.1 \pm 0.2) \cdot 10^{-21}$	1.013 ± 0.002	$8k\Omega$
O2E9	$(8.08 \pm 0.5) \cdot 10^{-22}$	1.031 ± 0.002	$10k\Omega$
O1E10	$(1.4 \pm 0.2) \cdot 10^{-22}$	1.073 ± 0.004	$8k\Omega$

Tablica svih analiziranih dubokih nivoa

	pristine	He5E9	He1E9	He1E10	C1E8	C5E8	C1E9
$Z_{1/2}$	$(0.69 \pm 0.02)eV$	$(0.8 \pm 0.1)eV$	$(0.68 \pm 0.01)eV$	$(0.51 \pm 0.04)eV$	$(0.65 \pm 0.01)eV$	$*$	$(0.73 \pm 0.01)eV$
	$10^{-14}cm^2$	$10^{-11}cm^2$	$10^{-14}cm^2$	$10^{-17}cm^2$	$10^{-15}cm^2$	$*$	$10^{-15}cm^2$
$EH1$	–	$(0.39 \pm 0.01)eV$	$(0.44 \pm 0.01)eV$	$(0.42 \pm 0.01)eV$	$(0.43 \pm 0.01)eV$	$(0.39 \pm 0.02)eV$	$(0.42 \pm 0.01)eV$
	–	$10^{-15}cm^2$	$10^{-14}cm^2$	$10^{-15}cm^2$	$10^{-14}cm^2$	$10^{-14}cm^2$	$10^{-14}cm^2$
$EH3$	–	$*$	$*$	$*$	$*$	$*$	$(0.81 \pm 0.06)eV$
	–	$*$	$*$	$*$	$*$	$*$	$10^{-14}cm^2$
$T1$	–	–	–	–	$(0.37 \pm 0.04)eV$	$(0.4 \pm 0.03)eV$	$(0.37 \pm 0.02)eV$
	–	–	–	–	$10^{-12}cm^2$	$10^{-9}cm^2$	$10^{-13}cm^2$
$T2$	–	–	–	–	$(0.37 \pm 0.01)eV$	$(0.5 \pm 0.3)eV$	$*$
	–	–	–	–	$10^{-13}cm^2$	$10^{-9}cm^2$	$*$
$T3$	–	–	–	–	$*$	$(0.62 \pm 0.3)eV$	$*$
	–	–	–	–	$*$	$10^{-14}cm^2$	$*$

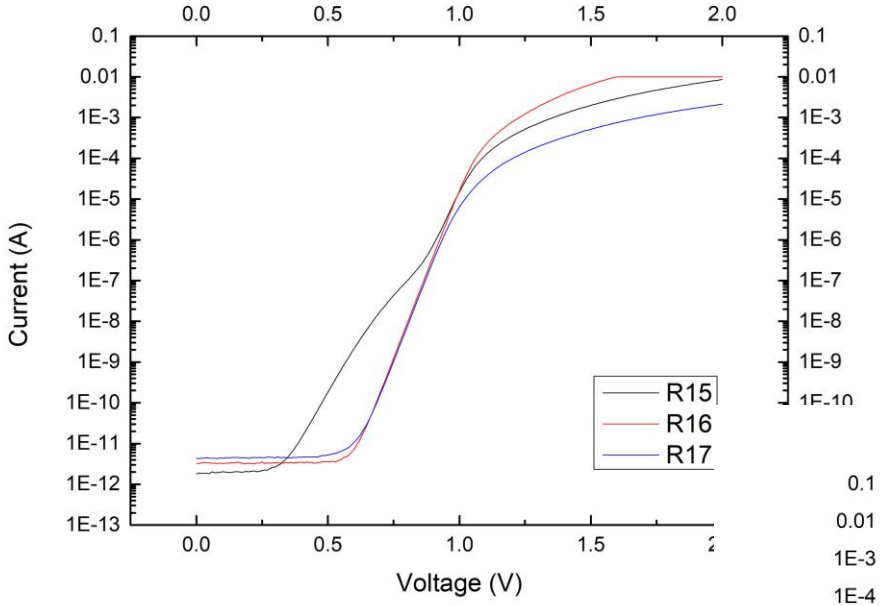
Tablica vremenskih prozora

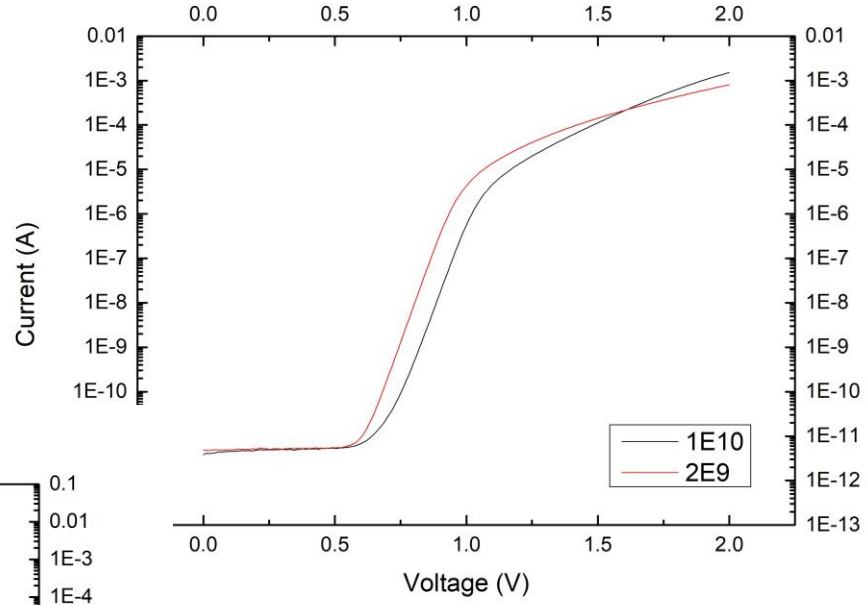
emisije (s^{-1})	$t_1(ms)$	$t_2(ms)$
2.5	244	611
5	122	305
10	61.1	153
20	3.05	76.4
50	12.2	30.5
100	6.11	15.3
200	3.05	7.64
500	1.22	3.05

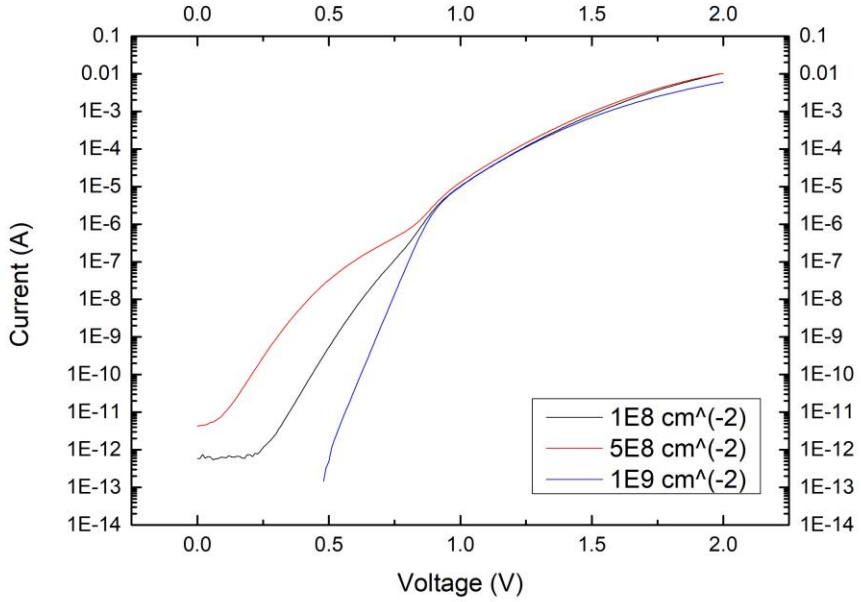
Ovisnost koncentracije dubokog nivoa o dozi zračenja

Uzorak	$N_T(Z_{1/2})$	$N_T(EH1)$
pristine	$2 \cdot 10^{12} cm^{-3}$	–
He5E9	$8 \cdot 10^{13} cm^{-3}$	$1 \cdot 10^{13} cm^{-3}$
He1E9	$5 \cdot 10^{12} cm^{-3}$	$1 \cdot 10^{12} cm^{-3}$
He1E10	$3 \cdot 10^{13} cm^{-3}$	$4 \cdot 10^{12} cm^{-3}$

Propusno polarizirane strujne karakteristike







Ovisnost širine područja osiromašenja o reverznom naponu