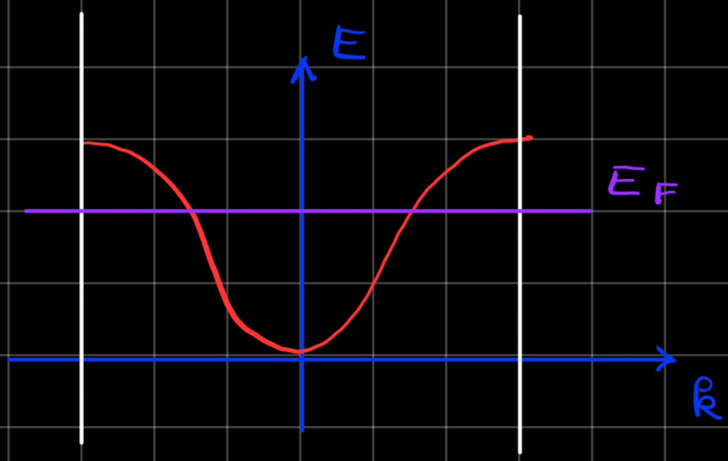
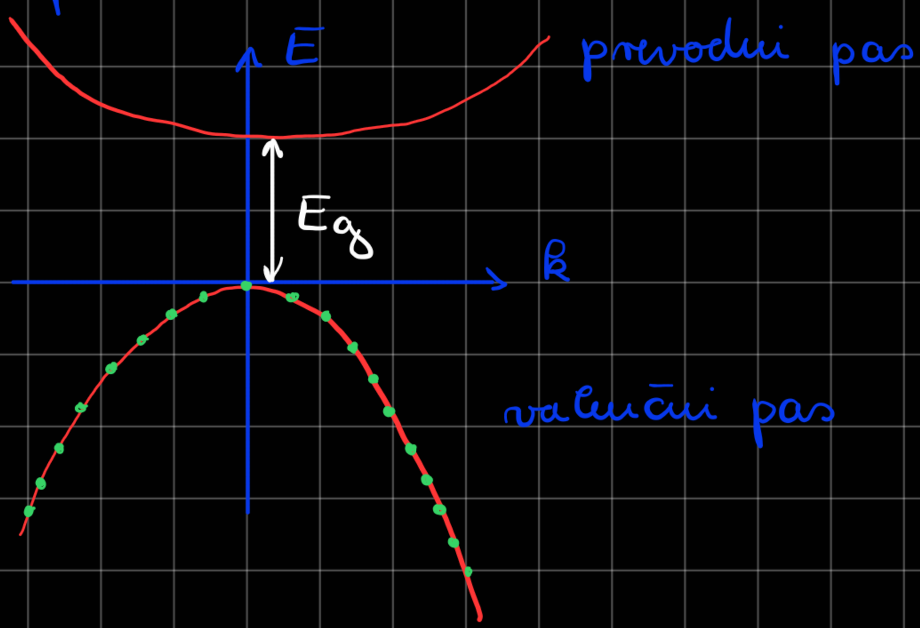
Polprevodniki

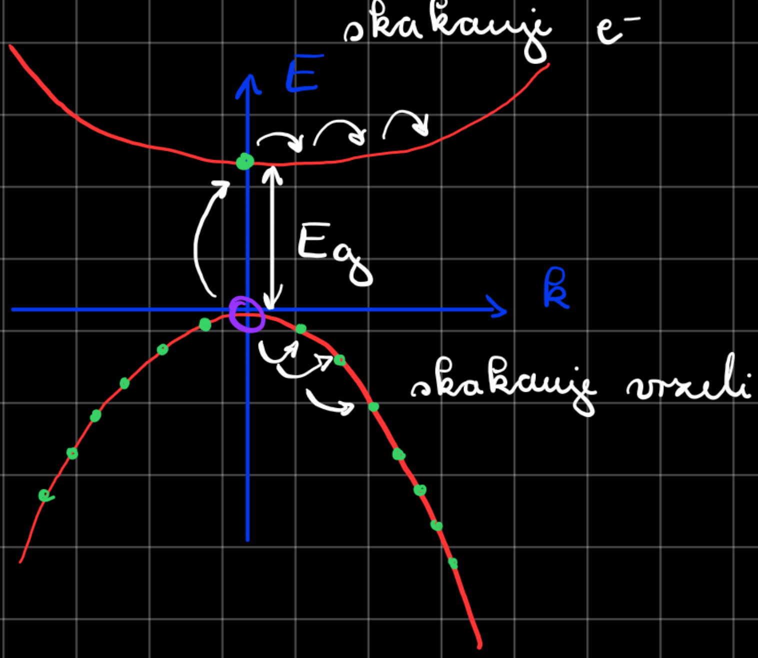
Praksa: omejiš se na 1. Brillouinovo cono, pozabiš na spodnje pasove in napolniš valenčni pas do E_F (min. val. pasu je v 0)



Polprevodniki



$T = 0$: valenčni pas napolnjen, ne prevaja



$T > 0$: termična ekscitacija

- e^-
- h^+ (vrzel)

} kvazidelca = kolektivna stanja, ne obnašata se kot fizična delca

K prevodnosti prispeva skakanje e^- iz enega stanja v drugo in prav tako skakanje vrzeli.

Prosti e^-: $E = \frac{\hbar^2 k^2}{2m}$

Vrzel/e^- v prevodnem/valenčnem pasu: $E = \frac{\hbar^2 k^2}{2m^*}$

m^* ... ef. masa je povezana z ukrivljenostjo pasu $E(k)$

$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k^2}$$

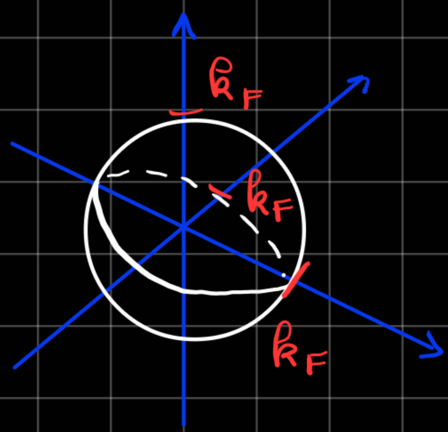
Zanima nas $\frac{dN}{dE} = \rho(E)\, f(E)$

$\rho(E)$ → gostota stanj

$f(E)$ → verjetnostna porazdelitev (Fermi-Diracova)

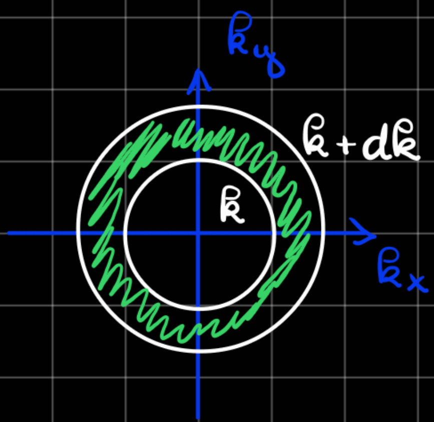
$\rho(E) = \frac{dg}{dE}$, g ... # e^- stanj na en. intervalu alt. zapis $g(E) = \frac{dg}{dk}\frac{dk}{dE}$

v 3D: Fermijeva krogla: //za podrobno izpeljavo, glej STD vaje 5.6 zvezni čvrstega telesa



Projekcija v 2D

1 stanje: $\frac{(2\pi)^3}{L}$



v 3D imamo $4\pi k^2 dk$

$$dg = 2\,\frac{4\pi k^2 dk}{(2\pi)^3/L}$$

↳ degeneracija

$$E = \frac{\hbar^2 k^2}{2m^*} \Rightarrow \boxed{k^2 = \frac{E\, 2m^*}{\hbar^2}}$$

$$\frac{dE}{dk} = \frac{2\hbar^2 k}{2m^*} = \frac{\hbar^2 k}{m^*} \Rightarrow \boxed{dk = \frac{m^*}{\hbar^2 k} dE}$$

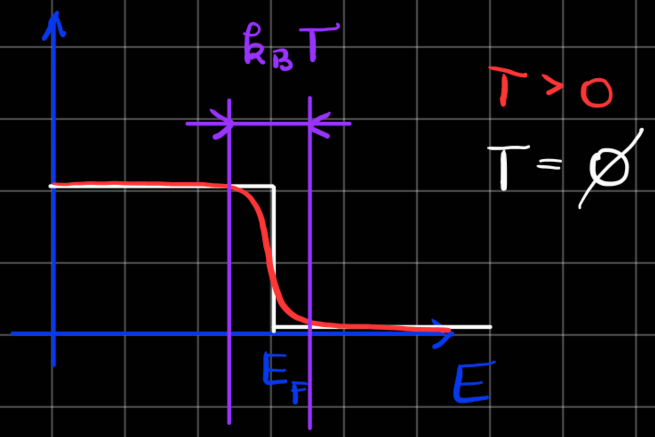
$$g(E) = \frac{4\pi (2m^*)^{\frac{3}{2}}}{h^3} \sqrt{E}$$

// Na kolokviju lahko, da moraš sam izpeljati npr. za 2D (izpelji!)

$$f(E) = \frac{1}{e^{\beta(E-\mu)}+1} \quad , \quad \mu \ldots \text{kemijski potencial}$$

$$\mu(T=0) = E_F$$

// za čisto snov



Za prevodniški e^- je $f(E)$

$\mu \sim E_F \Rightarrow$ blizu $\frac{E_g}{2}$

$$\frac{1}{\beta} = \frac{1}{40}\,\text{eV} \ll E - \mu \approx 1\,\text{eV}$$

Približek $f(E) \doteq e^{-\beta(E_g-\mu)}\, e^{-\beta(E-E_g)}$ //Taylor

$$n_{el} = \frac{N_{el}}{V} = \frac{1}{V}\int_{E_g}^{\infty} g(E)\, f(E)\, dE$$

//prevodniški pas

$$= e^{-\beta(E_g-\mu)}\, \frac{4\pi\,(2m^*)^{\frac{3}{2}}}{h^3}\,(k_B T)^{\frac{3}{2}} \underbrace{\int_0^{\infty} u^{\frac{1}{2}} e^{-u}\, du}_{\Gamma\left(\frac{3}{2}\right)}$$

$$u = \frac{E-E_g}{k_B T}$$

$$= n_{0,e} \exp\left\{-\beta(E_g-\mu)\right\},$$

$$\boxed{n_{0,e} = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}}}$$

Vrzeli v valenčnem pasu (enačba obrnjena)

$$E \longrightarrow -E$$

$$\Rightarrow g(E) = \frac{4\pi\,(2m_v^*)^{\frac{3}{2}}}{h^3}\sqrt{-E}$$

//ni problematično, saj integriramo po intervalu $(-\infty, 0)$

$$f_v(E) = 1 - f(E) = 1 - \frac{1}{e^{\beta(E-\mu)}+1} \doteq e^{\beta(E-\mu)}$$

$$n_{el} = \frac{N_{el}}{V} = \frac{1}{V}\int_{-\infty}^{0} g(E)\, f(E)\, dE =$$

$$= n_{0,v}\, e^{-\beta\mu}, \quad n_{0,v} = \left(\frac{2\pi\, m_v^*\, k_B T}{h^2}\right)^{\frac{3}{2}}$$

// m^* je abs. vrednost ef. mase

Produkt $n_e \times n_v$ je neodvisen od μ !

$$\boxed{n_e \cdot n_v = n_0^2(T)\, e^{-\beta E_g}}$$

$$n_0(T) = \left(\frac{2\pi\sqrt{m_e^* m_v^*}\, k_B T}{h^2}\right)^{\frac{3}{2}}$$

Čisti polprevodnik

$n_e = n_v$ (to upoštevamo)

$$n_{0,e}\exp\{-\beta(E_g - \mu)\} = n_{0,v}\, e^{-\beta\mu}$$

$$\left(\frac{m_{el}^*}{m_v^*}\right)^{\frac{3}{2}} = e^{-\beta(2\mu - E_g)}$$

$$\mu(T) = \frac{1}{2}E_g + \frac{3}{4}k_B T \ln\frac{m_{el}^*}{m_v^*}$$

Či je $T = \varnothing$, potem velja tisto, kar smo zapisali na začetku

$$\mu = \frac{1}{2} E_g$$

Či je ukrivljenost enaka (prevodni & valenčni pas), sta masi enaka $m^*_{el} = m^*_v$ ($\ln 1 = \varnothing$)

$$\mu \neq \mu(T)$$

Topić 5/25

$T_0 = 300\,K$

$E_g = 0{,}67\,eV$

$n_e = n_v = ?$

$m^*_{el} = 0{,}061\, m_e$, $m_e = 9{,}1 \cdot 10^{-31}\,kg$

$m^*_v = 0{,}28\, m_e$

Koreninu produkt $n_e \cdot n_v$

$$n_e = n_v = n_0(T)\, e^{-\beta \frac{E_g}{2}} = 6{,}65 \cdot 10^{20}/cm^3$$

$$\left.\begin{aligned} \mu(T = \varnothing) &= 0{,}36\,eV \\ \mu(T = T_0) &= 0{,}39\,eV \end{aligned}\right\}$$ ni velika sprememba kem. potenciala

5/29

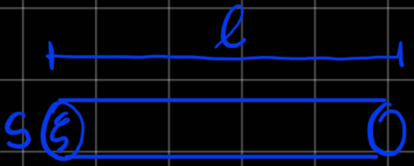
$T_0 = 20^\circ C$

$\frac{\Delta R}{R} = 0'001$

$E_g = 0'72\ eV$

Kako natančno lahko merimo T?

$R = \zeta \frac{1}{S\ell}$



$\zeta = \frac{1}{\sigma}$

Prevodnost: $j = \sigma E$ (lin. odziv na E) (1)

$$j = n e_0 \langle v \rangle = \underbrace{n_{el} e_0 \langle v \rangle}_{el.} + \underbrace{n_v e_0 \langle v \rangle}_{vrzeli} \qquad (2)$$

2 prispevka k prevodnosti

$$\sigma = \frac{n_0 e_0^2 \tau}{m}$$

$$\Rightarrow j = (\sigma_{el} + \sigma_v) E = \left(\frac{n_v e_0^2 \tau_v}{m_v^*} + \frac{n_{el} e_0^2 \tau_{el}}{m_{el}^*} \right)$$

$$n_{el} = n_v = n_0(T)\, e^{-\beta \frac{E_g}{2}}$$

Imamo $\sigma = \sigma(T)$ sedaj. Želimo spraviti v dif. obliko ($/\ln \to /\frac{d}{d}$)

$$\ln(R) = \ln(l) - \ln(\sigma) - \ln(S) \quad /\frac{d}{d*}$$

$$\frac{dR}{R} = \cancel{\frac{dl}{l}} - \frac{d\sigma}{\sigma} - \cancel{\frac{dS}{S}}, \quad l \neq l(T), \quad S \neq S(T)$$

$$\left|\frac{dR}{R}\right| = \left|\frac{d\sigma}{\sigma}\right|$$

$$\sigma = e_0^2 \underbrace{\left(\frac{\tau_v}{m_v^*} + \frac{\tau_d}{m_d^*}\right)}_{m^* \neq m^*(T)} n_0(T)\, e^{-\beta \frac{E_g}{2}}$$

predpostavimo $\tau \neq \tau(T)$ (drugače je)

$$\frac{d\sigma}{\sigma} = \frac{d n_0(T)}{n_0(T)} - d\left(\beta \frac{E_g}{2}\right)$$

Želimo $\frac{d\sigma}{\sigma} = \frac{d\sigma}{\sigma}\left(\frac{dT}{T}\right)$

$$\frac{dn_0(T)}{n_0(T)} \quad \frac{1}{n_0} dT = \frac{1}{\cancel{C T^{\frac{3}{2}}}} \cancel{C} \frac{3}{2} \cancel{T^{\frac{1}{2}}} dT \frac{1}{T} = \frac{3}{2} \frac{dT}{T}$$

velja $n_0(T) = C T^{\frac{3}{2}}$

$$\to \frac{E_g}{2} \frac{1}{k_B T} \Rightarrow \frac{E_g}{2} \frac{1}{k_B T^2} dT$$

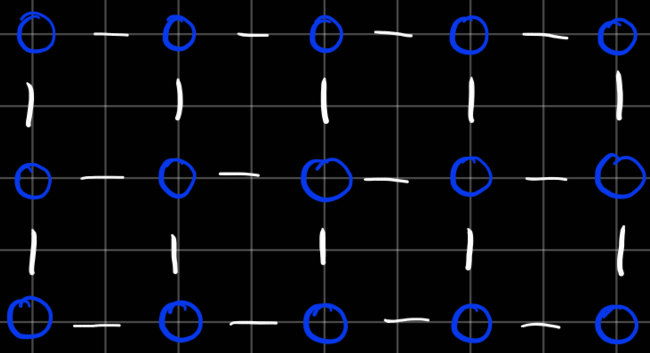
$$\frac{d\sigma}{\sigma} = \frac{dn_0(T)}{n_0(T)} - d\left(\beta \frac{E_g}{2}\right) \frac{dT}{dT}$$

$$\frac{d\rho}{\rho} = \frac{dR}{R} = \left(\frac{3}{2} + \frac{E_g}{2k_BT}\right)\frac{dT}{T}$$

$$\Rightarrow \frac{dT}{T} = \frac{\frac{dR}{R}}{\left(\frac{3}{2} + \frac{E_g}{2k_BT}\right)}$$

pri T_0: $\Delta T = T_0 \frac{dT}{T} = 0'02\,K$

Dopirani polprevodniki

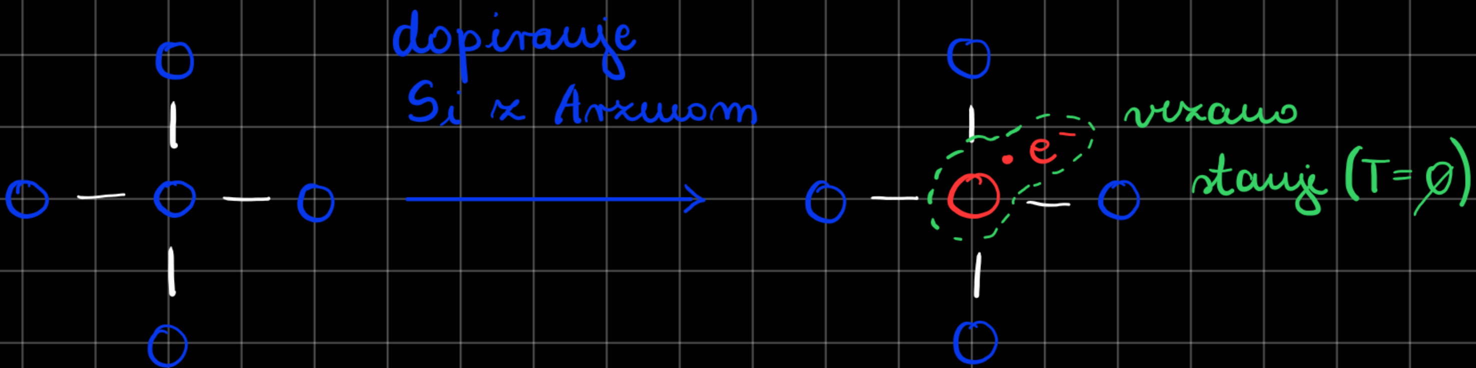


O Si ($4e^-$)

1) polprevodnik tipa n

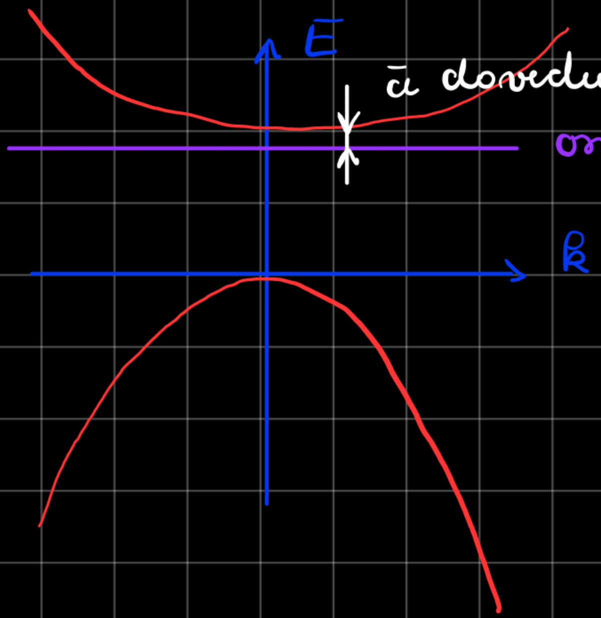
Redko dopirani

O arzen ($5e^-$)



Arzen se obnaša kot Si, ampak z dodatnim e^-

En. disperzija



č dovedemo toliko E, gre 5. e^- v prevodni pas

osnovno stanje e^-