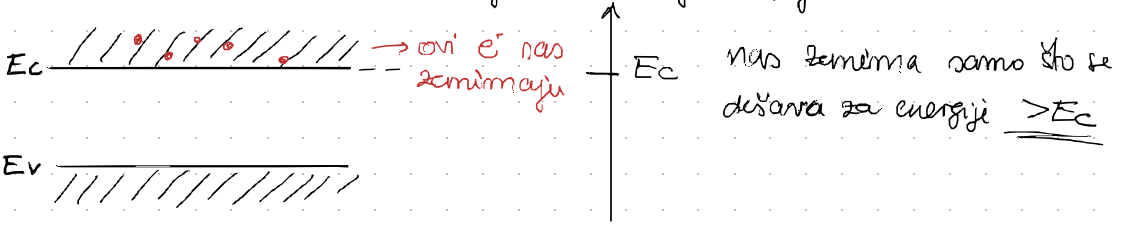


## 2.2. POLUVODIČI

### Raspodjela energija elektrona u vodljivom pojasu

\* želimmo izračunati koncentraciju  $e^-$  u vodljivom pojasu



funkcija kojom opišemo moguća stanja u slučaju  $> E_c$

$dn(E) = S_n(E) f_n(E) dE$   $\rightarrow$  energetska nivo na kome se može pojaviti  $e^-$  je  $S_n(E)$  (funkcija stanja)

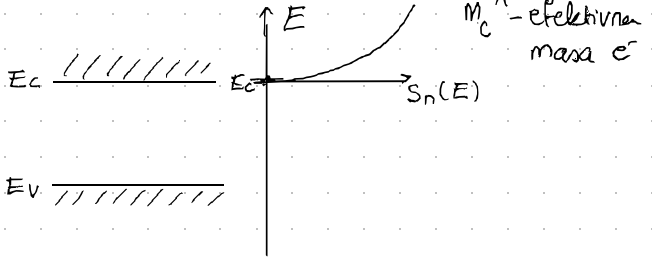
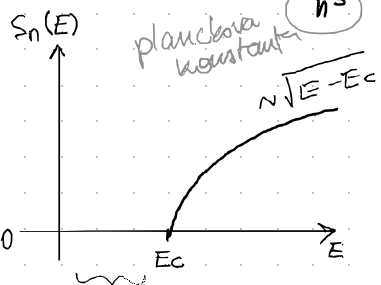
1. uvjet  $\rightarrow$  imamo mjesto gdje li se mogao pojaviti  $e^- \rightarrow S_n(E)$

2. uvjet  $\rightarrow$  -II- vjerojatnost da je to mjesto zauzeto  $\rightarrow f_n(E)$

$\hookrightarrow$  reč šansa da su zauzete niži energetska nivoi

### Gustoća dozvoljenih kvantnih stanja u vodljivom pojasu

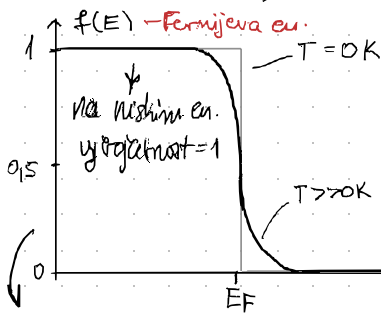
$S_n(E) = \frac{8\sqrt{2}\pi (m_c^*)^{3/2}}{h^3} \sqrt{E - E_c}$  (stavimo je 0 za  $E = E_c$ )



ne zanemara nas jer su vodljivi  $e^-$  samo u vodljivom pojasu

### Fermi-Diracova funkcija vjerojatnosti

$f_n(E) = f(E) = \frac{1}{1 + \exp(\frac{E - E_F}{E_T})}$

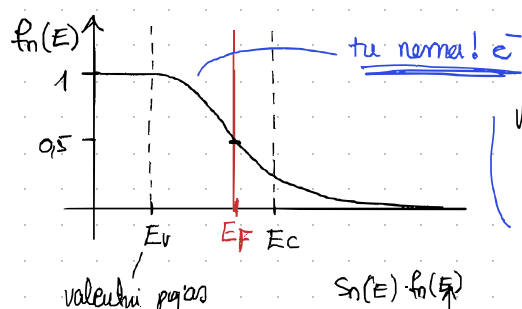


Fermijeva energija  $E_F$  - vjerojatnost popunjavanja = 0,5

za  $E_c - E_F > 3kT$  Maxwell-Boltzmannova tipa vjerojatnosti

$f_n(E) \propto \exp(-\frac{E - E_F}{E_T})$

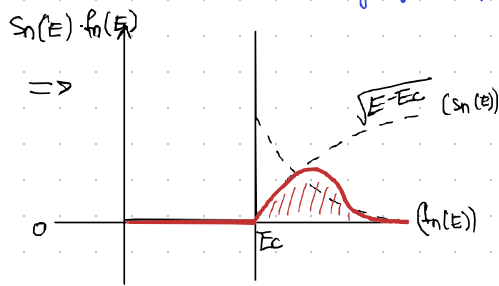
ryja koja pokazuje vjerojatnost da  $e^-$  zauzme neku energiju  $E$



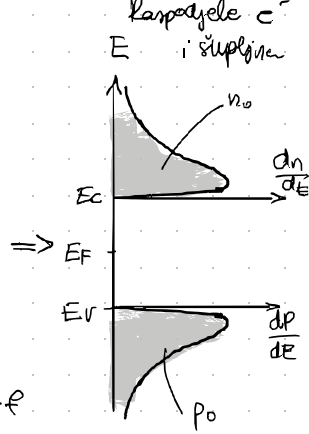
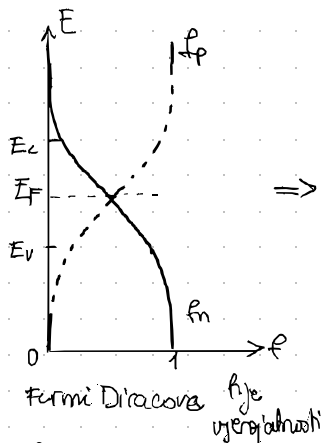
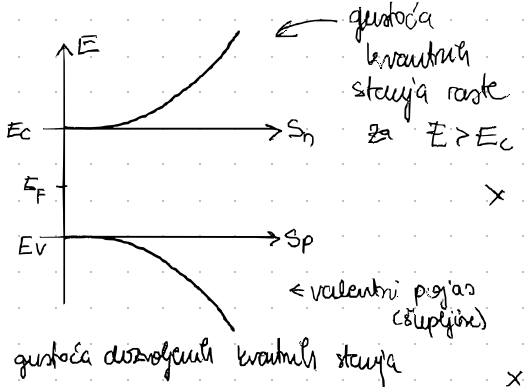
Fermijeva en. dolazi malo ispod ruba vodljivog pojasa ( $E_c$ )

Uvika je uvj da  $e^-$  bude na rubu vodljivog pojasa (to je krajnja  $e^-$ )

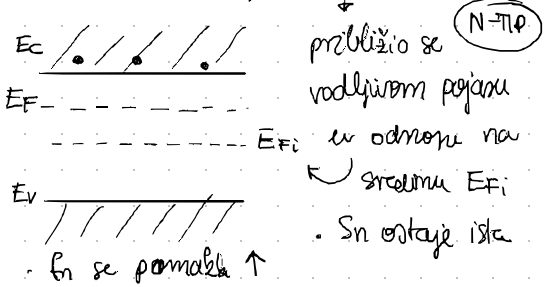
unatoč velikoj uvj, njih nema na  $E < E_c$



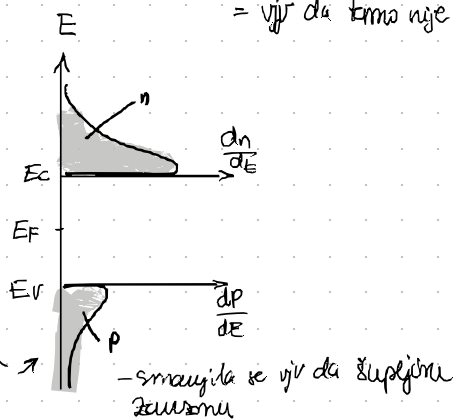
# Fermijeva energija intrinzični poluvodiči



Što se dešava sa Fermijevim nivoom za n-tip, a što za p-tip?

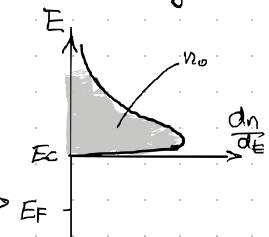


$f_p(E) = 1 - f_n(E)$   
(vjerojatnost da se negdje nalazi šupljina = vjer da tamo nije e<sup>-</sup>)



## Koncentracija elektrona u vodljivom pojasu

Koncentracija e<sup>-</sup>: 
$$n = \int_{E_c}^{\infty} S_n(E) \cdot f_n(E) dE = N_c \exp\left(\frac{E_F - E_c}{E_T}\right)$$
 preko Maxwell-Boltzmann aproks



→ da bismo dobili površinu ispod grafa (n) moramo integrirati

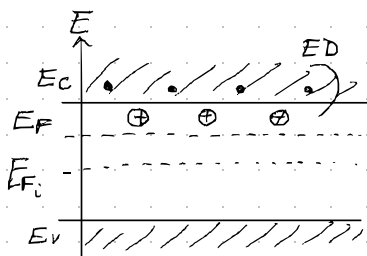
$N_c$  efektivna gustoća kvantnih stanja u vodljivom pojasu  

$$N_c = 2 \left( \frac{2\pi m_e^* k T}{h^2} \right)^{3/2}$$

## Fermijeva energija

→ poluvodič n-tipa

$$n_{0n} = N_c \exp\left(\frac{E_F - E_c}{E_T}\right) = n_i \exp\left(\frac{E_F - E_{Fi}}{E_T}\right)$$
 intrinzični Fermijev nivo



za n-tip →  $E_F > E_{Fi} \Rightarrow n_{0n} \gg n_i$

$$n_{0n} = N_c \exp\left(-\frac{E_c - E_F}{E_T}\right) \cdot N_c / n_i \Rightarrow (-E_T) \cdot \ln\left(\frac{n_{0n}}{N_c}\right) = E_c - E_F$$

$$n_{0n} = n_i \cdot \exp\left(\frac{E_F - E_{Fi}}{E_T}\right)$$

$$E_F - E_{Fi} = E_T \cdot \ln\left(\frac{n_{0n}}{n_i}\right)$$

koliko je udaljen vodljivi pojas (Ec) od Fermijevog nivoa

\* Fermijev nivo je iznad polovice zabravnog pojasa

## Raspodjela energija šupljina u valentnom pojasu

broj šupljina  $dp(E)$  u valjivom pojasu  $E < E_v$  u jediničnom volumenu u intervalu  $en. dE$

$$dp(E) = Sp(E) f_p(E) dE$$

► Gustoća raspoloživih kvantnih stanja u valentnom pojasu

$$Sp(E) = \frac{8\sqrt{2}\pi(m^*)^{\frac{3}{2}}}{h^3} \sqrt{E_v - E}$$

ef. masa šupljina  $\approx m_e^*$

► Funkcija vjerovatnosti

$$f_p(E) = 1 - f_n(E) = \frac{1}{1 + \exp\left(\frac{E_F - E}{E_T}\right)}$$

vjerovatnost da je negdje šupljina  
= vjer. da tamo  $e^-$  nema

→ sve je suprotno od onog za elektrone u valjivom pojasu

P-TIP poluvodič

Maxwell-Boltzmanova approx:

$$p_0 p = N_v \exp\left(\frac{E_v - E_F}{E_T}\right) = n_i \exp\left(\frac{E_F - E_F}{E_T}\right)$$

$$p_0 p = N_v \exp\left(-\frac{E_F - E_v}{E_T}\right)$$

$$p_0 p = n_i \exp\left(\frac{E_F - E_F}{E_T}\right)$$

$E_c$  / / / • / / /

$E_F$  - - - - -

$E_v$  - - - - -

$E_v$  / / / / / / / / / / / / / / /

koncentracija

šupljina ( $p$ )  $\gg n_i$

(u p-tipu poluvodiča)

Konc. šupljina:  $p = \int_{-\infty}^E Sp(E) f_p(E) dE$

$$p = N_v \exp\left(\frac{E_v - E_F}{E_T}\right)$$

ef. gustoća kvant. stanja: ( $N_v$ )

po def. čemo reći  $N_v = N_0$  za  $e^-$  i šupljine

## Umnožak koncentracije nosilaca

$$n_0 \cdot p_0 = (N_c \exp(-\frac{E_c - E_F}{E_T})) \cdot (N_v \exp(-\frac{E_F - E_v}{E_T}))$$

$$= N_c \cdot N_v \exp\left(\frac{-E_c + E_F - E_F + E_v}{E_T}\right) = N_c \cdot N_v \exp\left(-\frac{E_c - E_v}{E_T}\right)$$

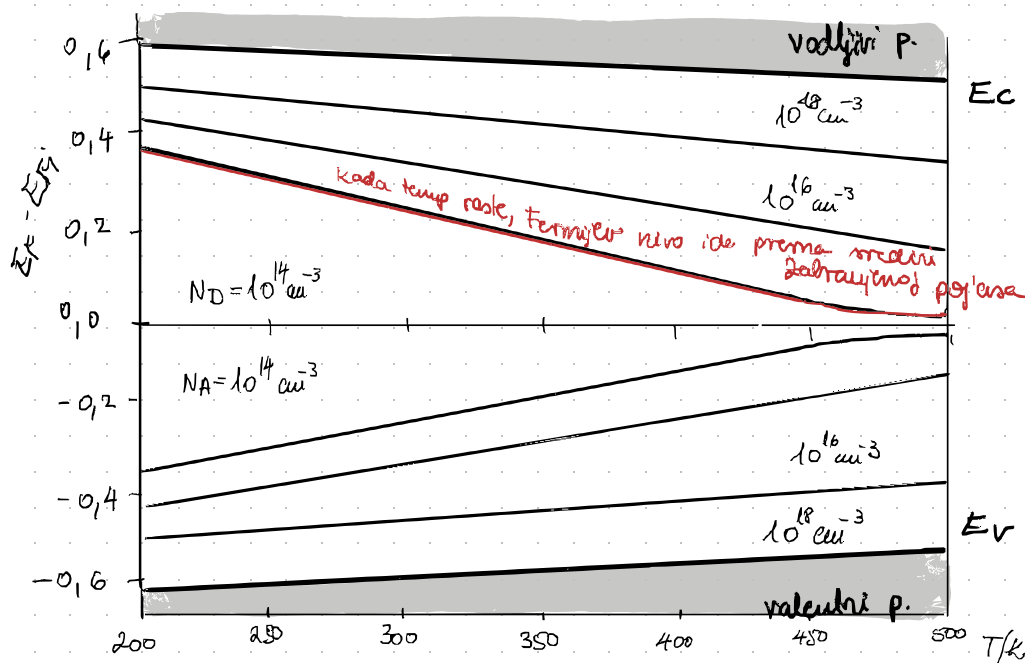
da smo prešli možiti prekor ni → odmah bi se vidjelo  $\hookrightarrow n_i^2$

Usporedba s empirijskom relacijom:

$$n_0 p_0 = n_i^2 = C^2 T^3 \exp\left(-\frac{E_g}{E_T}\right) \rightarrow N_c N_v = C^2 T^3$$

$$\hookrightarrow \text{uz } m_c^* \approx m_v^* \rightarrow N_c \approx N_v = C T^{\frac{3}{2}}$$

# Fermijeva energija - temperaturna ovisnost



- velika konc. donora znači da će donori uložiti  $e^-$  u poluvodič, a rezultat toga je da Fermijev nivo bježi prema vodljivom pojase

- kod akceptora,  $F$  nivo bježi prema valentnom

→  $F$ -nivo neće otići u krajnost (ovo specifičnu duljinu)

→ porastom  $T$  raste  $i$  i  $n \Rightarrow$  poluvodič se približava intrinzičnomu poluvodiču

kako temp raste, teško se svaki poluvod približava intrinzičnomu što vidimo po Fermijevom nivou koji ide prema sredini zabranjene pojase

Primer 2.5)  $T_1 = 300K$   $T_2 = 420K$   $E_F = ?$

$$T_1 = 300K \rightarrow n_i = C_1 T_1^{3/2} \exp\left[-\frac{E_{G0}}{2E_T}\right] = 3,07 \times 10^{16} \text{ cm}^{-3} \cdot (300K)^{3/2} \cdot \exp\left(-\frac{1,196 \cdot 11600}{2 \cdot 300}\right)$$

$$n_{i1} = 1,45 \times 10^{10} \text{ cm}^{-3}$$

$$E_{G1} = aT_1 + E_{G0} \rightarrow E_{G1} = 1,12 \text{ eV}$$

$$N_{C1} = N_{V1} = C T_1^{3/2} = 3,67 \cdot 10^{19} \text{ cm}^{-3}$$

$$T_2 = 420K \rightarrow n_i = 3,07 \times 10^{16} \cdot (420)^{3/2} \cdot \exp\left(-\frac{1,196 \cdot 11600}{2 \cdot 420}\right)$$

$$n_{i2} = 1,77 \times 10^{13} \text{ cm}^{-3}$$

$$N_{C2} = N_{V2} = C T_2^{3/2} = 6,06 \times 10^{19} \text{ cm}^{-3}$$

$$E_{G2} = 1,09 \text{ eV}$$

a) intrinzičan  $n = n_i$  fermijev nivo  
pomica (Fermijevog nivoa)  
 $\hookrightarrow n = n_i \exp\left(\frac{E_F - E_{Fi}}{E_T}\right) \quad / : n_i$   
 $1 = \exp\left(\frac{E_F - E_{Fi}}{E_T}\right) \quad / \ln \rightarrow 0 = \frac{E_F - E_{Fi}}{E_T} \rightarrow E_F - E_{Fi} = 0$   
 $\hookrightarrow E_F = E_{Fi}$   
 ~ Fermijev nivo se nalazi na sredini

b) dopiran s  $N_D = 5 \times 10^{15} \text{ cm}^{-3} \rightarrow n\text{-tip poluvodiča}$   
 $n = ?$   $N_D \gg n_i \checkmark$  OK!  $\rightarrow n = N_D = 5 \times 10^{15} \text{ cm}^{-3}$

$$n = N_D \exp\left(-\frac{E_C - E_F}{E_T}\right) \quad / : N_D \rightarrow \ln\left(\frac{n}{N_D}\right) \cdot (-E_T) = E_C - E_F$$

$$T_1: \ln\left(\frac{5 \times 10^{15}}{3,67 \times 10^{19}}\right) \cdot (-300) = E_C - E_F = 0,23 \text{ eV}$$

$$n_{i2} = 1,77 \times 10^{13} \text{ cm}^{-3} \ll N_D \checkmark$$

$$T_2: \ln\left(\frac{5 \times 10^{15}}{6,06 \times 10^{19}}\right) \cdot (-420) = E_C - E_F = 0,34 \text{ eV}$$

Fermijev nivo se udaljió od nula  
 porasta na višoj temp

Što znamo?  $T \uparrow \rightarrow E_G \downarrow \rightarrow n_i \uparrow \Rightarrow$  poluvodič  
 teži prema intrinzičnom poluvodiču  $\Rightarrow E_F = \frac{E_G}{2}$   
 $\rightarrow$  s porastom temp.  $E_F$  se približava  $\frac{E_G}{2}$

c) dopiran s  $N_A = 5 \times 10^{15} \text{ cm}^{-3} \rightarrow p\text{-tip poluvodiča } p = ?$

$$T_1: 300K \rightarrow N_A \gg n_i \checkmark$$
 OK!  $\rightarrow p = N_D = 5 \times 10^{15} \text{ cm}^{-3}$

$$p = N_V \exp\left(-\frac{E_F - E_V}{E_T}\right) \rightarrow \frac{p}{N_V} = \exp\left(-\frac{E_F - E_V}{E_T}\right) \quad / \ln \quad / (-E_T)$$

$$(-E_T) \ln\left(\frac{p}{N_V}\right) = E_F - E_V \stackrel{300K}{=} 0,23 \text{ eV}$$

$$T_2: 420K \rightarrow N_A \gg n_i \checkmark$$
 OK!  $\rightarrow p = N_D \rightarrow E_F - E_V = 0,34 \text{ eV}$

