ES1
Ferro: reticolo BCC \( \rho_{\text{et}} = 8.5 \cdot 10^{22} \text{cm}^{-3} \)

i) \( \rho_{\text{et}} \)

\[
\rho_{\text{et}}^{\text{bcc}} = \frac{2}{a^3} \Rightarrow a = \sqrt[3]{\frac{2}{\rho_{\text{et}}}} = 2.83 \text{Å}
\]

\[
d = \sqrt{(\frac{\sqrt{2}}{2} a)^2 + a^2} = \sqrt{3} a
\]

\[
\sqrt{3} a = 4 \rho_{\text{et}}
\]

\[
\rho_{\text{et}} = \frac{\sqrt{3}}{4} a = 1.24 \text{Å}
\]

ES2

\( I = 40 \text{mA} \)

\( V_{\text{stop}} = -2.75 \text{V} \)

\( V_{\text{th}} = 534 \text{ mV} \)

\( M_I = 0.5 \)

i) Potenziale soggetto

\[
I = q M_I \phi_{\text{pu}} = \frac{q M_I P}{E_{\text{pu}}}
\]

\[
E_{\text{pu}} = W + E_{\text{cm, max}} = hv_{\text{th}} + q |V_{\text{stop}}| = 2.24 \text{eV} + 2.75 \text{eV} = 4.99 \text{eV}
\]

\[
P = \frac{E_{\text{pu}} \cdot I}{q M_I} \approx 100 \text{mW}
\]
Buca di potenziale a parete finita $(W=3eV)$

$$x_{D,3} = 1,4\text{Å}$$

i) lunghezza $b$

ii) $N$'è minimo stato conosciuto

$$x_{D,3} = \frac{4}{\alpha_3} = \frac{T_1}{\sqrt{2m(W-E_3)}} \Rightarrow E_3 = W - \frac{h^2}{2m x_{b,3}^2} \approx 4,05eV$$

**Approx buca a parete infinita**

$$E_m = \frac{m^2 h^2}{8mb^2}$$

$$E_3 = \frac{9h^2}{8mb^2} = 4,05eV \rightarrow b = \sqrt[3]{\frac{9h^2}{8mE_3}} \approx 1,8\text{nm}$$

$$E_m = \frac{m^2 h^2}{8mb^2} \leq W \Rightarrow m \leq \sqrt[3]{\frac{8mb^2W}{h^2}} = 5,08 \Rightarrow m_{max} = 5$$

**ES 4**

![Diagram](image)

$$P_{\infty} = e^{-2k_3a} = e^{-\frac{2\sqrt{2m(V-E)}}{h}a}$$

$$P_t = e^{-\frac{3}{4} \frac{\sqrt{2m}}{kqV} b (V-E)^{3/2}}$$

$$\frac{P_{\infty}}{P_t} = 1 = \frac{e^{-\frac{2\sqrt{2m(V-E)}}{h}a}}{e^{-\frac{3}{4} \frac{\sqrt{2m}}{kqV} b (V-E)^{3/2}}} \Rightarrow \frac{2\sqrt{2m} V^{1/2} b (V-E)}{a} = \frac{2}{3} \frac{\sqrt{2m} b (V-E)^{3/2}}{kqV}$$

$$a = \frac{2}{3} \frac{b(V-E)}{V} \Rightarrow (4-E) = \frac{3a}{b} \Rightarrow \frac{E}{V} = 1 - \frac{3a}{b} = 1 - \frac{3}{4} = \frac{1}{4}$$
Buca di potenziale 2D a pareti infinite
\( a = \frac{b}{3} \)

i) Calcolare i primi 10 autovolti di crescita dell'energia indicando le degenerazioni

**Eq di Schrödinger 2D**

\[
-\frac{\hbar^2}{2m} \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \psi(x,y) = E \psi(x,y)
\]

\[
\psi(x,y) = X(x) \cdot Y(y)
\]

\[
-\frac{\hbar^2}{2m} \left( \frac{\partial^2 X}{\partial x^2} + X \frac{\partial^2 Y}{\partial y^2} \right) = E \cdot X \cdot Y
\]

\[
-\frac{\hbar^2}{2mX} \frac{\partial^2 X}{\partial x^2} - \frac{\hbar^2}{2mY} \frac{\partial^2 Y}{\partial y^2} = \frac{E}{2m} \cdot \frac{\partial^2 X}{\partial x^2}
\]

**Em\(x\) = \frac{\hbar^2}{8m^2} m_x^2 = \frac{\hbar^2}{8mb^2} \cdot \frac{1}{a^3} m_x^2 = \frac{9E_0 m_x^2}{E_0}**

**Em\(y\) = \frac{\hbar^2}{8mb^2} m_y^2 = E_0 m_y^2**

**Em = Em\(x\) + Em\(y\) = E_0 (9m_x^2 + m_y^2)**

<table>
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<th>My</th>
<th>E</th>
<th>g</th>
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<td>2</td>
<td>4</td>
<td>52 E_0</td>
<td>4</td>
</tr>
</tbody>
</table>
Metallo 3D 010

$Z = 79$

Config. elettronica: [Xe] $4f^{19} 5d^{10} 6s^2$

Reticolo FCC

$a = 4.08$ pm

$f = 21.2$ $\mu m - cm$

$M_u = M_e$

$T = 600$ K

i) $E_F$

ii) $T_F$

$dello$ $configurazione$ $elettronica: 4 e/et$

$\rho_F = \frac{4}{a^3} = 5.83 \times 10^{-28} m^{-3} = 5.83 \times 10^{-22} cm^{-3} = n$

$r_{bcc}$

$M = \frac{(2m^*_e)^{3/2}}{3\pi^2 h^3} E_F^{3/2} \implies E_F = \frac{\hbar^2}{2m^*_e} \left( \frac{3\pi^2 m}{2} \right)^{2/3} = 5.52$ eV

$\langle E \rangle = \int_0^{+\infty} E g(E) f(E) dE \sim \int_0^{E_F} E g(E) dE = \frac{3}{5} E_F = 3.32$ eV

$T_F = \frac{E_F}{k_B} = 6.4 \times 10^4$ K

$T = 600$ K $\ll T_F \implies E_{F_{000}} \sim E_{F_{00k}} \approx$ approx valid
Semiconduttore infussoo Si

T = 300 K

\[
\begin{align*}
E_i &= \frac{E_{\text{gap}}}{2} = \frac{kT}{2} \log \left( \frac{N_V}{N_C} \right) \\
E_i' &= \frac{E_{\text{gap}}}{2} = \frac{kT}{2} \log \left( \frac{N_V}{N_C} \right)
\end{align*}
\]

\[
E_i - E_i' = \frac{kT}{2} \left[ \log \left( \frac{N_V}{N_C} \right) - \log \left( \frac{N_V}{N_C} \right) \right] = \frac{kT}{2} \log \left( \frac{N_V^2}{N_C^2} \right) = \frac{kT}{2} \log \left( \frac{N_C}{N_V} \right)
\]

\[
N_C \propto \frac{M_{\text{Bosm}}^{3/2}}{m_e^{3/2}} \implies E_i' - E_i = \frac{kT}{2} \log \left( \frac{M_{\text{Bosm}}^{3/2}}{m_e^{3/2}} \right) = \frac{kT}{2} \log \left( \frac{M_{\text{Bosm}}^{3/2}}{m_e^{3/2}} \right)
\]

\[
\frac{M_{\text{Bosm}}^{3/2}}{m_e^{3/2}} = \frac{q}{\left( m_e m_e^{3/2} \right)^{3/2}}
\]

\[
\frac{M_{\text{Bosm}}^{3/2}}{m_e^{3/2}} = \frac{1}{\left( m_e m_e^{3/2} \right)^{3/2}}
\]

\[
\frac{M_{\text{Bosm}}^{3/2}}{m_e^{3/2}} = \frac{1}{\left( m_e m_e^{3/2} \right)^{3/2}}
\]

ES 8

Semiconduttore Si

T = 300 K

\[N_{\text{do}} = 4 \times 10^{18} \text{ cm}^{-3}\]

\[L = 100 \text{ nm}\]

\[\mu_m = 800 \text{ cm}^2/\text{Vs}\]

i) Lunghezza entro cui il semiconduttore è estenso

ii) \( J_{\text{diff}} + J_{\text{diff}} = 0 \)

iii) Diagramma a bolle

\[N_{\text{b}(x)} = N_{\text{do}} e^{-x/L} \implies x^* = L \cdot \log \left( \frac{N_{\text{m}}}{N_{\text{do}}} \right) = 4.8 \mu m\]

Eq termodinamica: \( J_{\text{diff}} + J_{\text{diff}} = 0 \) \[\implies q n m F + q D_m \frac{dn}{dx} = 0\]

\[m(\beta) \sim N_{\text{b}(x)} = N_{\text{do}} e^{-x/L} \implies \frac{dm}{dx} = - \frac{N_{\text{do}}}{L} e^{-x/L} \]

\[T = 300 K\]

\[J_{\text{diff}} = q D_m \frac{dn}{dx} = - q D_m \frac{N_{\text{do}}}{L} e^{-x/L} \]

\[J_{\text{diff}} = - q D_m \frac{N_{\text{do}}}{L} e^{-x/L} \]

\[331.2 \text{ K} \cdot \text{A} \cdot \text{cm}^{-2} \cdot e^{-x/L} \]

\[J_{\text{diff}}(0) e^{-x/L} \]
\[ J_{\text{diff}} = -J_{\text{diff}} = 331.2 \frac{KA}{\mu m^2} e^{-x/L} \]

\[ 0 < x < x^* \]

\[ m(x) \approx N_{\text{D}} e^{-x/L} = N_c e^{-\frac{E_c(x) - E_F}{K T}} \]

\[ \Rightarrow E_c(x) = E_F + kT \log \left( \frac{N_c}{N_{\text{D}}} \right) + kT \frac{x}{86 \text{ meV}} \]

\[ x > x^* \]

\[ m(x) = m_i \Rightarrow E_c - E_F = E_c - E_i \sim 86 \text{ meV} \]

\[ E_S \]

**Cauproni**  
\[ m - S_i \]

\[ T = -93 ^\circ C = 300 K \]

\[ p_i = 75 \% \]

\[ E_c - E_D = 42 \text{ meV} \]

\[ i) \quad N_D \]

\[ p_i = \frac{N_{\text{D}}^+}{N_D} = \frac{A}{A + 2 e^{-\frac{E_c - E_F}{K T}}} = \frac{A}{A + 2 e^{-\frac{E_D - E_c}{K T}} e^{-\frac{E_c - E_F}{K T}}} = \frac{A}{A + 2 \frac{m_i}{N_c} e^{-\frac{E_c - E_D}{K T}}} \]

\[ \Rightarrow N_D = \left( \frac{A}{p_i} - 1 \right) \frac{N_c}{2p_i} e^{-\frac{E_c - E_D}{K T}} \sim 10^{18} \text{ cm}^{-3} \]

\[ N_c(300K) = N_c(300K) \left( \frac{180}{300} \right)^{3/2} = 1.3 \cdot 10^{19} \text{ cm}^{-3} \]
Semi-condottore Germanio \( (T=300\,\text{K}) \)

\[ N_A = 10^{18}\,\text{cm}^{-3} \]

\[ \frac{dF_m}{dx} = 8.625\,\text{eV} \]

\[ E_C - F_m = 300\,\text{meV} \quad \text{a} \quad x = 140\,\mu\text{m} \]

\[ T_m = 0.35\,\mu\text{m} \]

i) \( \mu_n \)

ii) \( m'(o) \)

iii) \( F_m(x), F_p(x) \)

\[ m(x) = m_0 + m'(x) = \frac{m_0^2}{N_A} + m'(x) \sim m'(x) \]

\[ m'(x) = N_C e^{-\frac{E_C - F_m}{kT}} \Rightarrow F_m(x) = E_C - kT \log \left( \frac{N_C}{m'(x)} \right) = E_C - kT \log \left( \frac{N_C}{m'(o)} \right) - \frac{kT}{L_m} \]

\[ \Rightarrow \quad L_m = \frac{kT}{\frac{dF_m}{dx}} = \frac{kT}{\frac{8.625}{0.66}} \approx 30\,\mu\text{m} \]

\[ L_m = \sqrt{\Delta \mu \tau_n} = \sqrt{\frac{kT}{q} \mu_n \tau_n} \Rightarrow \mu_n = \frac{L_m^2}{\frac{kT}{q} \tau_n} \sim 4000\,\text{cm}^2/\text{Vs} \]

\[ E_C - F_m(x) = kT \log \left( \frac{N_C}{m'(o)} \right) + \frac{kT}{L_m} \quad \text{a} \quad x = 0.3\,\text{eV} \]

\[ m'(o) = N_C e^{-\frac{(E_C - F_m(x) - kT x)}{kT}} = 10^{16}\,\text{cm}^{-3} \ll N_A = 10^{18}\,\text{cm}^{-3} \quad \text{OK BASSA INIZIATIVA} \]

\[ m_0 = \frac{m_0^2}{N_A} = 5.76 \times 10^8\,\text{cm}^{-3} \ll m'(o) \quad \text{OK approssinato} \]

\[ p(x) = p_0 + p'(x) \approx N_A + m'(x) \approx N_A \]

\[ N_A = N_V e^{\frac{E_V - F_P}{kT}} \quad \Rightarrow \quad E_V - F_P(x) = kT \log \left( \frac{N_A}{N_V} \right) \]

\[ F_P(x) = E_V - kT \log \left( \frac{N_A}{N_V} \right) = E_V + kT \log \left( \frac{N_V}{N_A} \right) \approx E_V + 46\,\text{meV} \]

\[ F_m(x^*) = F_P \]

\[ E_C - kT \log \left( \frac{N_C}{m'(o)} \right) - \frac{kT}{L_m} \approx E_V + kT \log \left( \frac{N_V}{N_A} \right) \]

\[ E_C - E_V - kT \log \left( \frac{N_C}{m'(o)} \right) - \frac{kT}{L_m} \approx E_V \]

\[ E_C = 0.66\,\text{eV} \quad \Rightarrow \quad x^* = \frac{E_C - 180\,\text{meV} - 46\,\text{meV}}{kT} \ln 500\,\mu\text{m} \]