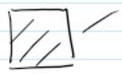
Nanofizika QD

nedelja, 05. april 2020 15:20

Kvantne pike in Coulombska blokada

$$\frac{e^2}{4\pi\varepsilon_0 r \varepsilon}$$



mali kosčki tvorijo
Coulombska energija

$l \sim 10\,nm$

$$E_C = \frac{e^2}{4\pi\varepsilon_0 r} = \frac{e^2}{4\pi\varepsilon_0 \hbar c}\,\frac{\hbar c}{r} = \frac{1}{137}\,\frac{1240\,eV\,nm}{2\pi\, r}$$

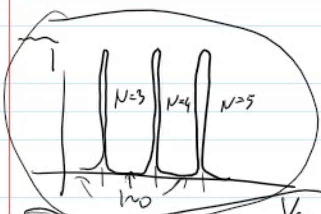
$\frac{e^2}{4\pi\varepsilon_0\hbar c} = 1/137$

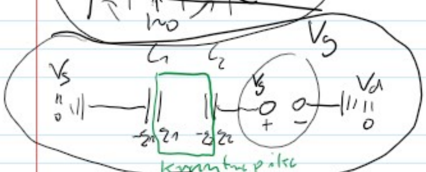
$$\sim \frac{eV\,nm}{r}$$

diskretni nivoji

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}$$

$$\frac{\hbar^2}{2m\,l^2} = \frac{\hbar^2c^2}{2mc^2\,l^2} = \frac{1000^2\,eV^2\,nm^2}{10^6\,MeV\,l^2} = eV\,\frac{nm^2}{l^2}$$



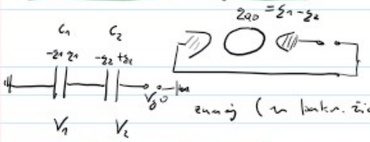


$q_1 - q_2 = eN$ ← cel

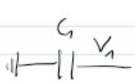
$V_1 = \frac{q_1}{C_1}$ $\quad V_2 = \frac{q_2}{C_2}$ $\qquad \mathcal{H} = E + pV$

$V_g = V_1 + V_2$

$$\boxed{\mathcal{H} = \frac{q_1^2}{2C_1} + \frac{q_2^2}{2C_2} - q_2 V_g}$$



znotraj (v kovin. žici) je $\vec{E} = 0$



$$E = \frac{C_1 V_1^2}{2}$$

$q_1 - q_2 = eN$

$V_1 = \frac{q_1}{C_1}$ $\quad V_2 = \frac{-q_2}{C_2}$

$V_g = V_1 + V_2$ $\qquad V = \frac{q}{C}$

„Entalpija" : $Vdq = \frac{q_1^2}{2C_1}$

$$\boxed{\mathcal{H} = q_1^2/2C_1 + q_2^2/2C_2 - q_2 V_g}$$

$\tilde{\mathcal{H}} =$

$V_g = q_1/C_1 + q_2/C_2$

$V_g C_1 = q_1 + q_2\, C_1/C_2$

$$q_1 = V_g C_1 - q_2 \frac{C_1}{C_2}$$

$q_1 - q_2 = eN$

$q_2\left(-1 - C_1/C_2\right) + V_g C_1 = eN$

$$q_2 = \frac{eN - V_g C_1}{1 + C_1/C_2}$$

$$q_2 = \frac{V_g C_1 - eN}{\ldots}$$

$$\Rightarrow q_2 = \frac{eN - V_g C_1}{1 + C_1/C_2}$$

$$q_2 = -\frac{V_g C_1 - eN}{1 + C_1/C_2}$$

$$q_1 = eN + q_2 = \frac{V_g C_1 - eN + eN + eN\,C_1/C_2}{1 + C_1/C_2}$$

$$\mathcal{H} = \frac{q_1^2}{2C_1} + \frac{q_2^2}{2C_2} - q_2 V_g$$

$$\mathcal{H} = \frac{(eN\,C_1/C_2 + V_g C_1)^2}{2C_1(1 + C_1/C_2)^2} + \frac{(V_g C_1 - eN)^2}{2C_2(1+C_1/C_2)^2} + \frac{V_g C_1 + eN}{1 + C_1/C_2} V_g$$

$$\mathcal{H} = \frac{\frac{C_2}{C_1}(eN\,C_1/C_2 + V_g C_1)^2}{2C_2(1 + C_1/C_2)^2} + \frac{(V_g C_1 - eN)^2}{2C_2(1+C_1/C_2)^2} + \frac{V_g C_1 + eN}{1 + C_1/C_2} V_g$$

$$= \frac{1}{2C_2(1+C_1/C_2)^2}\Big[e^2N^2(1 + C_1/C_2) + eN\,V_g C_1(2-2)$$

$$+ V_g^2 C_1^2\left(\frac{C_2}{C_1} + 1\right)\Big] + \frac{V_g C_1 + eN}{1 + C_1/C_2} V_g$$

$$= V_g^2 C_2 C_1\left(\frac{C_1}{C_2} + 1\right)\Big]$$

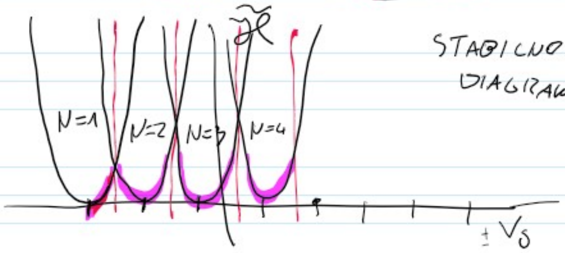
$$= \frac{1}{2C_2(1+C_1/C_2)}\left[e^2N^2 + V_g^2 C_2 C_1\right] + \frac{-2V_g^2 C_2 C_1 + eN V_g C_2 2}{2(C_1 + C_2)}$$

$$= \frac{1}{2(C_2+C_1)}\left[e^2N^2 + 2eN\,V_g C_2 - V_g^2 C_1 C_2\right]$$

eN

$$= \frac{1}{2(C_2+C_1)}\left[(eN + V_g C_2)^2 - V_g^2 C_2 (C_2 + C_1)\right]$$

$$\boxed{\mathcal{H} = \frac{1}{2(C_2+C_1)}(eN + V_g C_2)^2 - \frac{V_g^2 C_2}{2}}$$

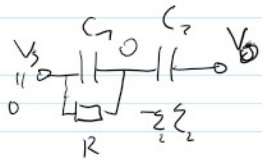


STABILNOSTNI DIAGRAM

$$\tilde{\mathcal{H}} = \mathcal{H} + \frac{V_g^2 C_2}{2}$$

$$V_g = -\frac{eN}{C_2}$$

$\mathcal{H}$ $\qquad q = -V_g C_2$



$$q = -q_2 = -V_g C_2$$

$$\frac{e^2}{C}$$

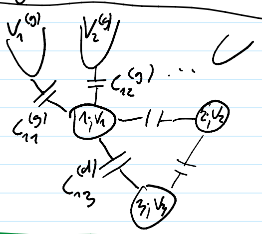
$$T = RC$$

$$\Delta E\, T \gg \hbar$$

$$\frac{e^2}{C} R\cancel{C} \gg \hbar$$

$$\frac{e^2}{\hbar} \gg \frac{1}{R} = G \qquad G \ll \frac{e^2}{\hbar}$$

Stabilnostni diagram za N-kv. pik sklopljenih na M elektr.

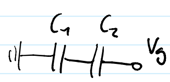


$$\boxed{\mathcal{H} = \frac{1}{2}\,(\underline{e} - \underline{q})^T\, \underline{\underline{C}}^{-1}\, (\underline{e} - \underline{q})}$$

$$\underline{e} = e\begin{pmatrix} N_1 \\ N_2 \\ \vdots \\ N_N \end{pmatrix} \qquad \underline{q} = \begin{pmatrix} q_1 \\ \vdots \\ q_M \end{pmatrix} \qquad q_i = -\sum C_{ik}^{(g)} V_k^{(g)}$$

$$(\underline{\underline{C}})_{ij} = C_{ij} \qquad C_{ij} = \begin{cases} \sum_j C_{ij}^{(d)} + \sum_k C_{ik}^{(g)}; & i = j \\ -C_{ij}^{(d)} \end{cases}$$

zgled:



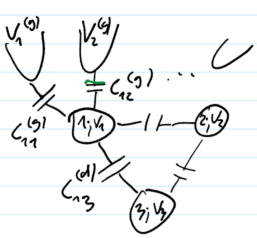
$$\underline{\underline{C}} = C_1 + C_2 \qquad \mathcal{H} = \frac{1}{2}(e + C_2 V_g)\frac{1}{C_1 + C_2}(e + C_2 V_g)$$

Dokaz:

$$\mathcal{H} = \frac{1}{2}\sum_{i<j} C_{ij}^{(d)} (V_i - V_j)^2 + \frac{1}{2}\sum_{ik} C_{ik}^{(g)} (V_i - V_k^{(g)})^2$$

$$- \sum_{ik} q_{ik} V_k^{(g)}$$

$$q_{ik} = (V_k^{(g)} - V_i)\, C_{ik}^{(g)}$$



$$\mathcal{H} = \frac{1}{2}\sum_{i<j} C_{ij}^{(d)} (V_i - V_j)^2 +$$

$$+ \frac{1}{2}\sum_{ik} C_{ik}^{(g)} \left(V_i^2 + V_k^{(g)2} \cancel{- 2 V_i V_k^{(g)}}\right)$$

$$- \sum_{ik} (V_k^{(g)} \cancel{- V_i})\, C_{ik}^{(g)}\, V_k^{(g)}$$

$$\boxed{\mathcal{H} = \frac{1}{2}\sum_{i<j} C_{ij}^{(d)} (V_i - V_j)^2 + \underbrace{\frac{1}{2}\sum_{ik} C_{ik}^{(g)} V_i^2}_{A}} \; \underbrace{- \frac{1}{2}\sum_{ik} C_{ik}^{(g)} V_k^{(g)2}}_{\text{opustimo}}$$

$$C_{ij}^{(d)} = C_{ji}^{(d)} \qquad C_{ii}^{(d)} = 0$$

$$\mathcal{H} = \frac{1}{4}\sum_{ij} C_{ij}^{(d)} (V_i - V_j)^2 + A$$

$$= \frac{1}{4}\sum_{ij} C_{ij}^{(d)} \left[(V_i^2 + V_j^2) - 2 V_i V_j\right] + A$$

$$= \frac{1}{4}\sum_{ij} C_{ij}^{(d)}\left[\underbrace{(V_i^2+V_j^2)}_{}-2V_iV_j\right] + A$$

$$C_{ij}V_j^2 = C_{ji}V_j^2$$

$$=$$

$$= \frac{1}{2}\sum_i V_i^2 \sum_j C_{ij}^{(d)} + \frac{1}{2}\sum_{ik} C_{ik}^{(g)} V_i^2 - \frac{1}{2}\sum_{ij} C_{ij}^{(d)} V_i V_j$$

$$= \frac{1}{2}\sum_{ij} V_i \, C_{ij} \, V_j \qquad C_{ij} = \begin{cases} \sum_{j'} C_{ij'}^{(d)} + \sum_{k} C_{ik}^{(g)} ; & i=j \\ -C_{ij}^{(d)} ; & i \neq j \end{cases}$$

$$\boxed{\mathcal{H} = \frac{1}{2} \underline{V}^T \underline{\underline{C}}\, \underline{V}}$$

naboj na i-ti piki

$$N_i e = \sum_j C_{ij}^{(d)}(V_i - V_j) + \sum_k C_{ik}^{(g)}(V_i - V_k^{(g)})$$

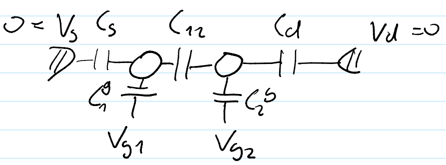
$$N_i e + \underbrace{\sum_k C_{ik}^{(g)} V_k^{(g)}}_{-q_i} = \left(\sum_j C_{ij}^{(d)} + \sum_k C_{ik}^{(g)}\right) V_i - \sum_j C_{ij}^{(d)} V_j$$

$$N_i e - q_i = \sum_j C_{ij} V_j$$

$$\underline{e} - \underline{q} = \underline{\underline{C}}\,\underline{V} \qquad \underline{V} = \underline{\underline{C}}^{-1}(\underline{e}-\underline{q})$$

$$\boxed{\mathcal{H} = \frac{1}{2}(\underline{e}-\underline{q})^T \underline{\underline{C}}^{-1} \cancel{\underline{\underline{C}}\,\underline{\underline{C}}^{-1}} (\underline{e}-\underline{q})}$$

Vaja: Dvojna kvantna pika



$$\underline{\underline{C}} = \begin{pmatrix} C_1 & -C_{12} \\ -C_{12} & C_2 \end{pmatrix} \qquad \begin{aligned} C_1 &= C_s + C_1^g + C_{12} = C_{12}(1+\alpha_1) \\ C_2 &= C_d + C_2^g + C_{12} = C_{12}(1+\alpha_2) \end{aligned}$$

$$\alpha_1, \alpha_2 > 0$$

$$\underline{\underline{C}}^{-1} = \frac{1}{C_1C_2 - C_{12}^2}\begin{pmatrix} C_2 & C_{12} \\ C_{12} & C_1 \end{pmatrix} = \underbrace{\frac{C_{12}}{C_1C_2 - C_{12}^2}}_{1/C_0} \begin{pmatrix} 1+\alpha_2 & 1 \\ 1 & 1+\alpha_1 \end{pmatrix}$$

$$\mathcal{H} = (\underline{e}-\underline{q})^T \frac{\underline{\underline{C}}^{-1}}{2} (\underline{e}-\underline{q}) \qquad q_1 = -C_1^g V_{g1} + C_s \underbrace{V_s}_{0}, \quad q_2 \ldots$$

$$= \frac{1}{2}(eN_1 - q_1, eN_2 - q_2)\, \underline{\underline{C}}^{-1} \begin{pmatrix} eN_1 - q_1 \\ eN_2 - q_2 \end{pmatrix}$$

$$= \frac{1}{2C_0}\left[(1+\alpha_2)(eN_1-q_1)^2 + (1+\alpha_1)(eN_2-q_2)^2 + 2(eN_1-q_1)(eN_2-q_2)\right]$$

$$\boxed{\mathcal{H} = \alpha_2(eN_1-q_1)^2 + \alpha_1(eN_2-q_2)^2 + (eN_1-q_1+eN_2-q_2)^2}$$

Če je N_1, N_2 osnovno stanje pri q_1, q_2 (V_1^g, V_2^g)

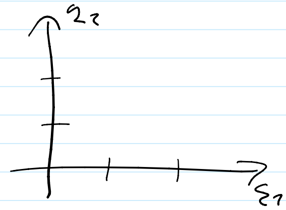
$$q_1 \to q_1 + eM_1, \quad q_2 \to q_2 + eM_2$$

Če je N_1, N_2 osnovno stanje pri q_1, q_2 (V_1^g, V_2^g)

$q_1 \to q_1 + eM_1$, $q_2 \to q_2 + eM_2$

bo osn. stanje pri $N_1 + M_1$, $N_2 + M_2$

periodično tlakovanje



Kdaj je stabilna konf. z (0,0) elektroni?

$$\mathcal{H}(0,0) < \mathcal{H}(1,0)$$

$$\mathcal{H}(0,0) = \alpha_2 q_1^2 + \alpha_1 q_2^2 + (-q_1 - q_2)^2$$

$$\mathcal{H}(1,0) = \alpha_2 (e - q_1)^2 + \alpha_1 q_2^2 + (e - q_1 - q_2)^2$$

$$= \alpha_2 e^2 - 2\alpha_2 e q_1 + \alpha_2 q_1^2 + \alpha_1 q_2^2 + e^2 - 2e(q_1 + q_2) + (q_1 + q_2)^2$$

$$0 < (1 + \alpha_2) e^2 - 2e(1 + \alpha_2) q_1 - 2e q_2 \quad : (1 + \alpha_2)$$

$$0 < e^2 - 2e q_1 - \frac{2e q_2}{(1 + \alpha_2)}$$

$$\boxed{-\frac{e}{2} > q_1 + \frac{q_2}{(1 + \alpha_2)} > \frac{e}{2}}$$

$e = -|e|$

$$\mathcal{H}(0,0) < \mathcal{H}(-1,0)$$

$$q_1 + \frac{q_2}{1 + \alpha_2} = -\frac{e}{2}$$

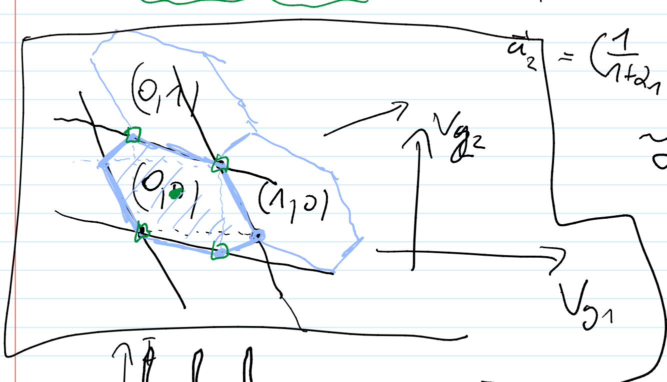
$$\mathcal{H}(0,0) < \mathcal{H}(0,\pm 1)$$

$$\vec{q} \cdot \vec{a} = -e/2$$

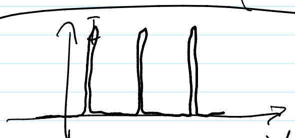
$$\boxed{-\frac{e}{2} > \frac{q_1}{1 + \alpha_1} + q_2 > \frac{e}{2}}$$

$$\vec{a}_1 = \left(1, \frac{1}{1 + \alpha_2}\right)$$

$$\vec{a}_2 = \left(\frac{1}{1 + \alpha_1}, 1\right)$$

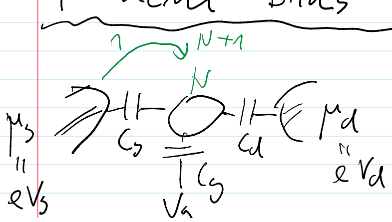


$$\mathcal{H}(0,0) < \mathcal{H}(1,-1)$$
$$< \mathcal{H}(-1,1)$$



(pri malem $V_s - V_d$)

Kvantni bins (Coulombski diamanti)



μ_s // C_s C_d C / μ_d
eV_s $\quad C_g$ $\quad eV_d$
V_g

$$\mu_{QD} = \mathcal{H}(N+1) - \mathcal{H}(N)$$

$$\mu_s > \mu_{QD} > \mu_d$$

$$\mathcal{H} = \frac{(eN - q)^2}{2(\underbrace{C_s + C_d + C_g}_{C_\Sigma})}$$

$$q = -C_g V_g - C_s V_s - C_d V_d$$
$$-C\frac{U_{sd}}{2} - C\left(-\frac{U_{sd}}{2}\right)$$

$$\underbrace{C_s = C_d = C}\quad V_s = U_{sd}/2 \qquad V_d = -U_{sd}/2$$

$$q = -C_g V_g$$

$$\mathcal{H} = \frac{(eN + C_g V_g)^2}{2C_\Sigma}$$

$$\mu_{QD} = \frac{e^2}{2C_\Sigma}\left[\left((N+1) + \frac{C_g V_g}{e}\right)^2 - \left(N + \frac{C_g V_g}{e}\right)^2\right]$$

$$\mu_{QD} = \frac{e^2}{2C_\Sigma}\left[\cancel{N^2} + 2N + 1 + 2(\cancel{N} + 1)\frac{C_g V_g}{e} + \cancel{\left(\frac{C_g V_g}{e}\right)^2} - \cancel{N^2} - \cancel{2N\frac{C_g V_g}{e}} - \cancel{\left(\frac{C_g V_g}{e}\right)^2}\right]$$

$$\mu_{QD} = \frac{e^2}{C_\Sigma}\left[N + \frac{1}{2} + \frac{C_g V_g}{e}\right]$$

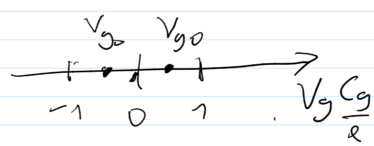
$$e\frac{U_{sd}}{2} > \overbrace{\frac{e^2}{C_\Sigma}\left[N + 1/2 + \frac{C_g V_g}{e}\right]}^{\mu_{QD}} > -e\frac{U_{sd}}{2} \quad /:\frac{e}{2}$$

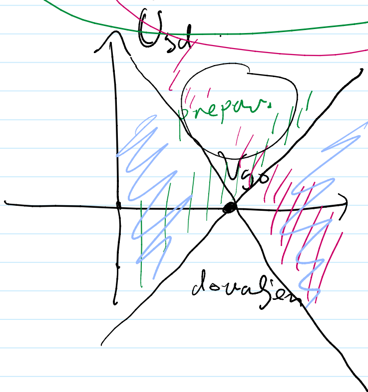
$$U_{sd} < \frac{e}{C_\Sigma}\left[2N + 1 + \frac{2C_g V_g}{e}\right] < -U_{sd}$$

pogoj, da tok teče $|U_{sd}| \to 0$

$$V_g = \left(-\frac{2N+1}{2C_g}\right)\cdot e = V_{g0} = +\frac{e}{C_g}\left(-N - 1/2\right)$$

$$U_{sd} < \frac{2C_g}{C_\Sigma}\left[V_g - V_{g0}\right] < -U_{sd}$$

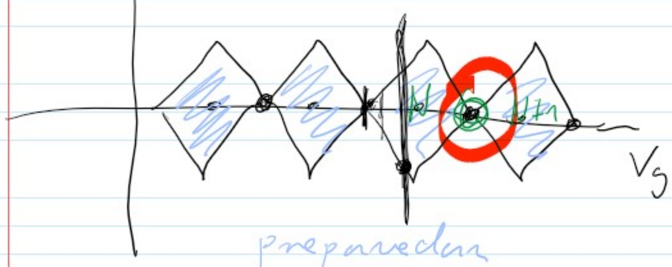




$$U_{sd} < \frac{2C_g}{C_\Sigma}(-1)(V_g - V_{g0})$$

U_{sd} Coulombski diamant

Coulombski diamant



Coulombska blokada

Obravnava transporta z master enačbo

tok končen $\hat{\rho}_{QD}$

p_N ... verj., da je na piki N elektronov

p_{N+1} ... različen od 0

$\sum_n p_n = 1$

iz kontakta ... qd → kontakt

$$\frac{dp_N}{dt} = \Gamma_{N-1}^{\to qd}\, p_{N-1} + \Gamma_{N+1}^{qd\to}\, p_{N+1} - \Gamma_N^{qd\to}\, p_N - \Gamma_N^{\to qd}\, p_N + p_{N-2}\,\Gamma_{N-2}^{\cdots} + \dots$$

št. procesov na enoto časa

$p_{N-2}, \dots$ manjši

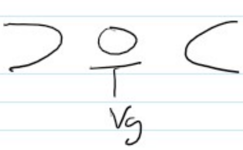
$\underline{p}$

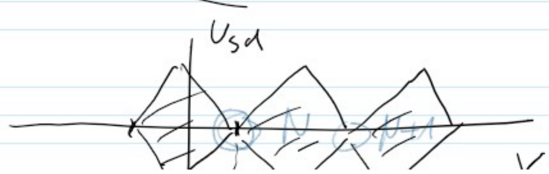
$$\frac{d\underline{p}}{dt} = \underline{\underline{\Gamma}}\,\underline{p}$$

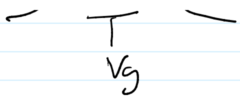
Stacionarna rešitev

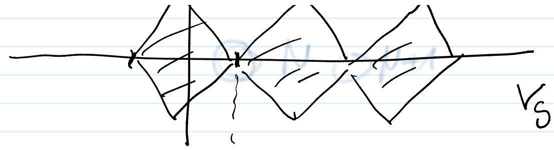
$$\frac{d\underline{p}}{dt} = 0 \qquad \underline{\underline{\Gamma}}\,\underline{p} = 0$$

Transport skozi QD. ($\underbrace{\text{enoel.}}$ tranzistor)









$$V_{g0} = -(N+1/2)\frac{e}{C_g}$$

$$E(N+1)-E(N) = \mu_{QD} = \underbrace{\frac{eC_g}{C_\Sigma}[V_g - V_{g0}]}_{\tilde{V}} = e\tilde{V}$$

$p_N, p_{N+1} > 0$; altfel $p_M = 0$

$p_N + p_{N+1} = 1$ $\qquad 1 - p_N$

$$0 = \frac{dp_N}{dt} = \Gamma_{N+1}^{QD\to}\, p_{N+1} - \Gamma_N^{\to QD}\, p_N$$

$$0 = \frac{dp_{N+1}}{dt} = \Gamma_N^{\to QD}\, p_N - \Gamma_{N+1}^{QD\to}\, p_{N+1}$$

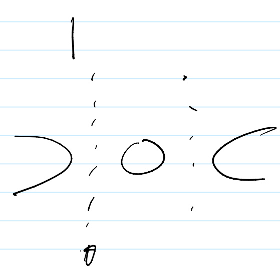
$$\Gamma_{N+1}^{QD\to}(1-p_N) - \Gamma_N^{\to QD}\, p_N = 0$$

$$p_N\left(\Gamma_{N+1}^{QD\to} + \Gamma_N^{\to QD}\right) = \Gamma_{N+1}^{QD\to}$$

$$\boxed{p_N = \frac{\Gamma_{N+1}^{QD\to}}{\Gamma_N^{\to QD} + \Gamma_{N+1}^{QD\to}}} \qquad \boxed{p_{N+1} = \frac{\Gamma_N^{\to QD}}{\Gamma_N^{\to QD} + \Gamma_{N+1}^{QD\to}}}$$

$$\Gamma_{N+1}^{QD\to} = \Gamma_{N+1}^{QD\to S} + \Gamma_{N+1}^{QD\to D}$$

$$\Gamma_N^{\to QD} = \Gamma_N^{S\to QD} + \Gamma_N^{D\to QD}$$



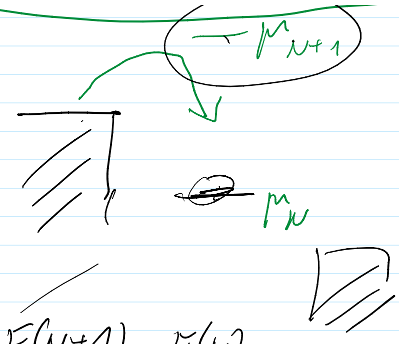
$$\boxed{I = e\left(\Gamma_N^{S\to QD}\, p_N - \Gamma_{N+1}^{QD\to S}\, p_{N+1}\right)}$$

$$I = \frac{e\left[\Gamma_N^{S\to QD}\left(\cancel{\Gamma_{N+1}^{QD\to S}} + \Gamma_{N+1}^{QD\to D}\right) - \Gamma_{N+1}^{QD\to S}\left(\cancel{\Gamma_N^{S\to QD}} + \Gamma_N^{D\to QD}\right)\right]}{\Gamma_N^{\to QD} + \Gamma_{N+1}^{QD\to}}$$

$$\boxed{I = e\,\frac{\Gamma_N^{S\to QD}\,\Gamma_{N+1}^{QD\to D} - \Gamma_{N+1}^{QD\to S}\,\Gamma_N^{D\to QD}}{\Gamma_N^{\to QD} + \Gamma_{N+1}^{QD\to}}}$$

$-\Gamma_{N+1}$

zgled:



el. skoči: $>$ kv. pika

$$I = e\,\frac{\Gamma_N^{s\to qd}\,\Gamma_{N+1}^{qd\to d}}{\Gamma_N^{s\to qd} + \Gamma_{N+1}^{qd\to d}}$$

① $\Gamma_N^{s\to qd} = \Gamma_{N+1}^{qd\to d} = \Gamma$

$$I = e\,\Gamma^2/2\Gamma = e\,\frac{\Gamma}{2}$$

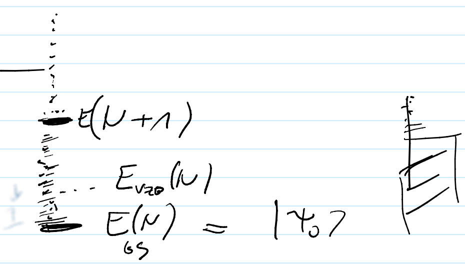
② $\Gamma_N^{s\to qd} \gg \Gamma_{N+1}^{qd\to d}$

$$I = e\,\Gamma_{N+1}^{qd\to d}$$

polprevodnik

Ocene Γ

kovinska kv. pika

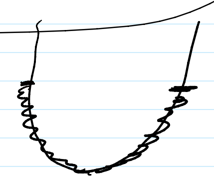


$$H = H_s + H_{qd} + H_d + H'$$

$H' = H'^{s\to qd} + \dots$ tuneliranje, majhna

$$\Gamma_N^{s\to qd} = \frac{2\pi}{\hbar}\sum_f |\langle f|H'|\Psi_0\rangle|^2\,\delta(E_f - E_0)$$

$$|\Psi_0\rangle = |\Psi_0^s\rangle\,|\Psi_0^d\rangle\,|N_0\rangle$$



$$\boxed{|\Psi_0^s\rangle = \prod_{\substack{k_s<k_{F_s}\\ \sigma}} c^+_{k_s\sigma}|0\rangle}$$

c^+

[$\{c_i, c_j^+\}_+ = c_i c_j^+ + c_j^+ c_i = \delta_{ij}$

$\{c_i, c_j\} = \{c_i^+, c_j^+\} = 0 \qquad c_i^+ c_i^+ = 0$

$|\Psi_s\rangle \qquad c^+_{s\sigma}|0\rangle = |\Psi_{s\sigma}\rangle$

$|0\rangle$

$|\uparrow\rangle = |\Psi_{s\uparrow}\rangle = c^+_{s\uparrow}|0\rangle$ ($\downarrow$)

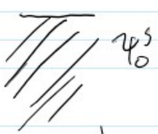
$|2\rangle = c^+_{s\uparrow}c^+_{s\downarrow}|0\rangle \qquad c^+_{s\uparrow}c^+_{s\downarrow} = -c^+_{s\downarrow}c^+_{s\uparrow}$]

$$|2\rangle = c^{+}_{s\uparrow} c^{+}_{s\downarrow} |0\rangle \qquad \left[c^{+}_{s\uparrow} c^{+}_{s\downarrow} = - c^{+}_{s\downarrow} c^{+}_{s\uparrow} \right]$$

$$\Gamma_N^{s\to qd} = \frac{2\pi}{\hbar} \sum_f |\langle f | H'^{\,s\to qd} | \psi_0 \rangle|^2 \, \delta(E_f - E_0)$$

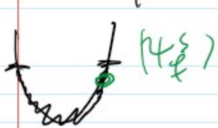
$$|\psi_0\rangle = |\psi_0^s\rangle \, |\psi_0^d\rangle \, |N_0\rangle$$

$$|f\rangle = |\psi_f^s\rangle \, |\psi_0^d\rangle \, |N+1\rangle$$



$$H'^{\,s\to qd} = \sum_{pq} t_{pq} \, c^{+}_{qd\,p} \, c_{sq} = \sum_{pq} t_{pq} \, |p^{qd}\rangle \langle q^s|$$

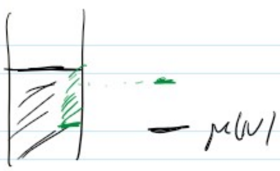
$$\Gamma_N^{s\to qd} = \frac{2\pi}{\hbar} \int \rho_s(\varepsilon_s)\, d\varepsilon_s \int \rho_{qd}(\varepsilon_{qd})\, d\varepsilon_{qd} \, |t|^2 \, \delta(E_F - E_0)$$



$$0 = E_F - E_0 = E_F^s - E_0^s + E_F^{qd}(N+1) - E_0^{qd}(N)$$

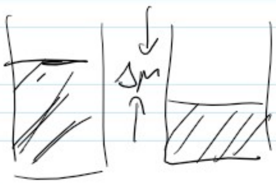
$$= -\varepsilon_s + \mu(N) + \varepsilon_{qd}$$

$$\varepsilon_s = \mu_N + \varepsilon_{qd}$$



$$\boxed{\Gamma_N^{s\to qd} = \frac{2\pi}{\hbar} |t|^2 \rho_s \rho_{qd} \left(\mu_s - \mu(N)\right) \theta\left(\mu_s - \mu(N)\right)} = \frac{G_s \, \Delta\mu^{s\to qd}}{e^2}$$

$$\boxed{\Gamma_{N+1}^{qd\to d} = \frac{2\pi}{\hbar} |t|^2 \rho_s \rho_{qd} \left(\mu(N) - \mu_d\right) \theta\left(\mu(N) - \mu_d\right)} = \frac{G_d \, \Delta\mu}{e^2}$$

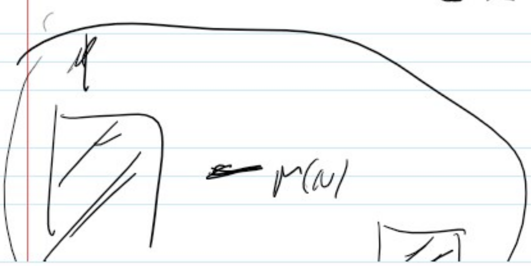


tunelski stik med dvema kovinama

$$I = e\Gamma \qquad \boxed{\Gamma = G \frac{\Delta\mu}{e^2}} \qquad \theta(x) = \begin{cases} 1; & x > 0 \\ 0; & \text{sicer} \end{cases}$$

$$\parallel$$

$$G \Delta V = G \frac{\Delta\mu}{e}$$



$$I = e \frac{\Gamma_N^{s\to qd} \, \Gamma_{N+1}^{qd\to d}}{\Gamma_{N+1}^{qd\to d} + \Gamma^{s\to qd}}$$

$$\Gamma^{QD\to D}_{N+1} + \Gamma^{S\to QD}_{1}$$

$$\Delta\mu^{S\to QD} = e\left(\frac{U_{sd}}{2} - \tilde{V}\right)$$

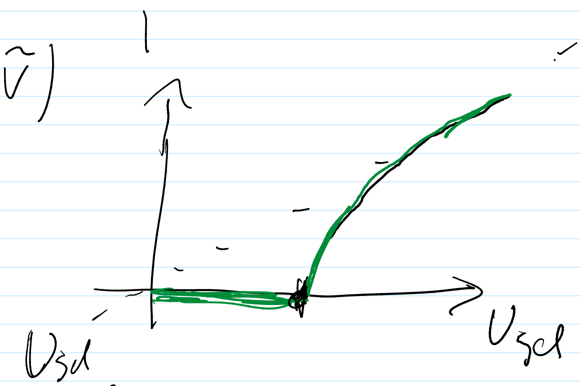
$$\Delta\mu^{QD\to D} = e\left(\tilde{V} + \frac{U_{sd}}{2}\right)$$

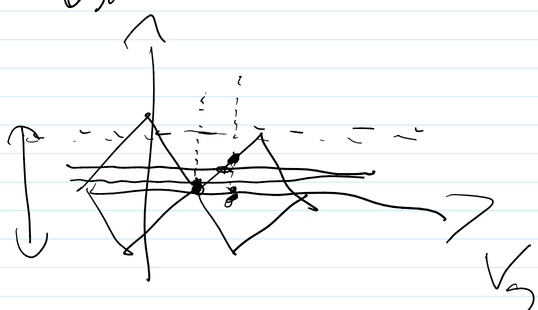
$$\mu_S = e\frac{U_{sd}}{2} \qquad \mu_D = -e\frac{U_{sd}}{2}$$

$$G_S = G_D = G$$

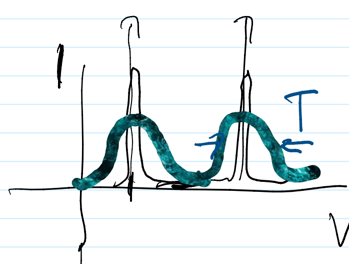
$$I = \frac{\cancel{e}\; G^2/e^4\; e^2\left(\frac{U_{sd}}{2} - \tilde{V}\right)\left(\frac{U_{sd}}{2} + \tilde{V}\right)}{G/e^2\,(U_{sd})\,e}$$

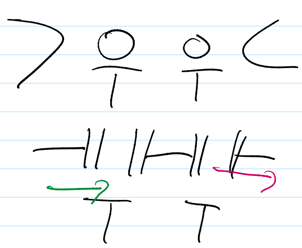
$$\boxed{I = G\,\frac{\left(U_{sd}^2/4 - \tilde{V}^2\right)}{U_{sd}}}$$



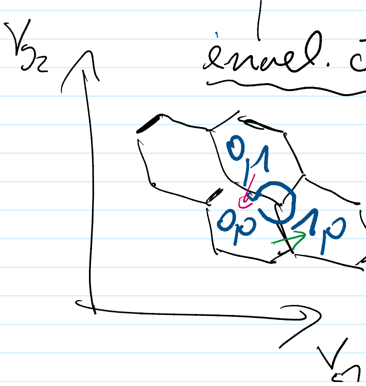


enoelektronski tranzistor





enoel. črpalka



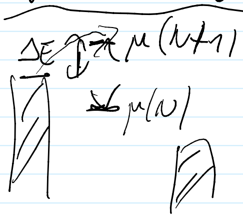
$$\hbar\omega = e\,mV = \frac{e^2}{C}$$

$$I = e\omega = \frac{e^2\;mV}{\hbar} = G_0\;mV \sim 0.1\,\mu A$$

$\longrightarrow V_{SD}$

$$I = e\omega = \frac{e^2}{h} mV = G_0 \, mV \sim 0.1\,\mu A$$

Kvantni pojavi, popravci na sekvencijalni tunel



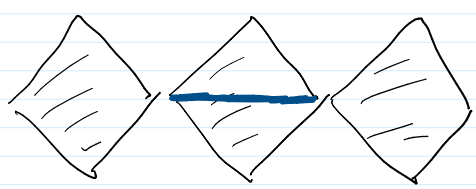
kotuneliranje $\Delta E \Delta t = \hbar$

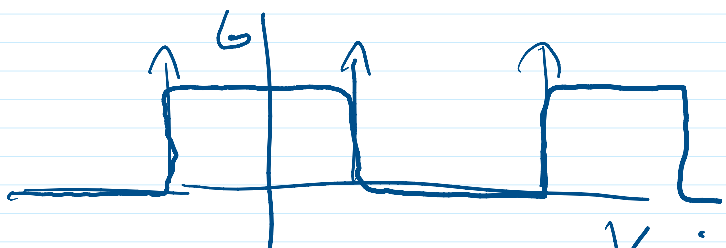
$\Gamma_{cot} =$ $\Delta t = \hbar / \Delta E$

$\Gamma_L \Delta t \, \Gamma_R$

$\Gamma_{cot} / \Gamma_{SEKVENCI} \approx G / G_0$

Kondov pojav



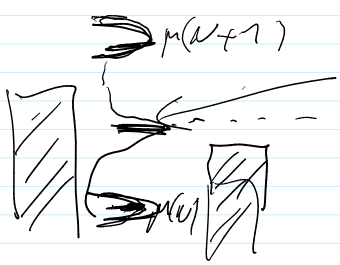


N $N+1$

6 7 8

$N = 7$

$V_g \,;\, V_{sd} \to 0$

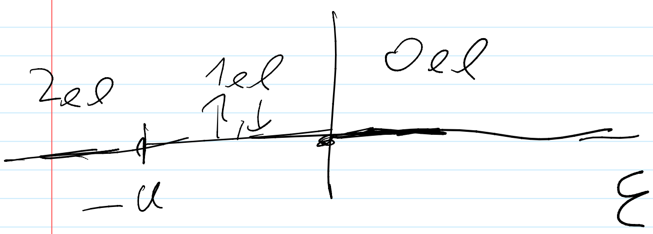


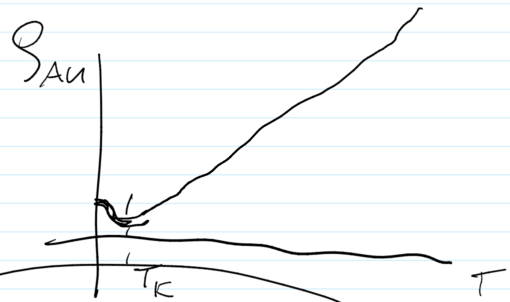
Kondova rezonanca

$$H_{AIM} = \underbrace{\sum_n \varepsilon n + U n_\uparrow n_\downarrow}_{\text{KV. TOČKA}}$$

$$n_\uparrow + n_\downarrow = d_\uparrow^\dagger d_\uparrow + d_\downarrow^\dagger d_\downarrow$$

$$E_{KV.TOČKA} = \begin{bmatrix} 0 \,;\, 0 \\ \varepsilon \,;\, \uparrow\downarrow \\ 2\varepsilon + U \,;\, 2 \end{bmatrix} + \sum_{k\sigma} \varepsilon_k n_k^{\sigma} + \sum_{k\sigma} V_k \left(c_{k\sigma}^\dagger d_\sigma + d_\sigma^\dagger c_{k\sigma} \right)$$

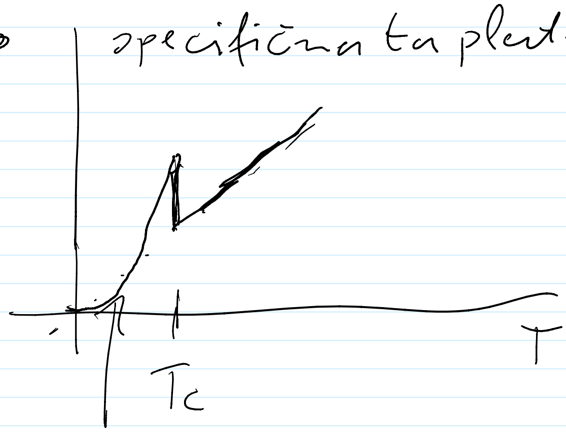




$$T_K = \Gamma e^{-\pi \frac{U}{8\Gamma}}$$

Landauske blatenda in superprevodnost

- $\rho = 0$
- specifična toplota



$$c \sim e^{-T/\Delta}$$